Montana Water Center
Annual Technical Report
FY 2005

Introduction

The Montana University System Water Center, 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 (Butte) to coordinate state-wide 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, the Montana Water Center seeks advice from an advisory council which helps set research priorities. During the 2005/2006 research year, the Montana Water Research Advisory Council members were:

Gretchen Rupp, Director, Montana Water Center (Council Chair)
Susan Higgins, Assistant Director, Montana Water Center (Council Staff)
Rep. Debby Barrett, Co-Chair MT Legislative Environmental Quality Council
Sarah Carlson, Executive Director, Montana Association of Conservation Districts
Bob Davis, Regional Director, U.S. Geological Survey
Julie Dalsoglio, Media Director, Environmental Protection Agency (Peter Ismert)
Jeff Hagener, Director, Montana Fish, Wildlife and Parks
Rep. Chris Harris, Co-Chair MT Legislative Environmental Quality Council
Jane Jelinski, Director, Local Government Center
William Kennedy, President, Montana Association of Counties
Marvin Miller, Associate Director, Montana Water Center, Montana Tech
Bill Milton, Chair, Montana Watershed Coordination Council
Richard Opper, Director, Montana Department of Environment Quality
Nancy Peterson, Director, Montana Department of Agriculture (Greg Ames)
Tom Pick, Water Quality Specialist, Natural Resource Conservation Service
Don Potts, Associate Director, Montana Water Center, University of Montana
Mary Sexton, Director, MT Dept. of Natural Resources and Conservation (Rich Moy)
Mike Volesky, Policy Advisor, Office of The Governor
John Wilson, Conservation Director, Trout Unlimited (Stan Bradshaw)

This report summaries the water research and outreach programs supported by the USGS Water Research Program. The Montana Water Center is also funded with other federal and state grants that support other initiatives, not reported here.

Research Program

Here we report the work of two research teams and twelve student fellows who were awarded funds to conduct water research in Montana during FY 2005. A total of $61,200 was awarded to these fourteen projects. We also supply final reports from investigators who submitted only interim reports last year.

Dr. Brian McGlynn, Montana State University, and Ph.D. candidate Kristin Gardner received $17,000 for their study: Geographic analysis of land use/land cover change and its relation to nitrogen export in a developing mountain landscape.

Researcher Denine Schmitz and Dr. Duncan Patten, Montana State University, were awarded $14,200 for a project titled Using paleoecology and paleoflood hydrology to assess the long-term ecological response of Montana's riparian and aquatic ecosystems to small natural and human dam failures a pilot study.

The twelve student research fellowships, ranging from $1,500 to $5,000, were presented to promising student scientists at Montana campuses. Each student participated in a competitive application process where they showed competence in addressing a regional water resource problem through research in the coming year. Awards were offered to one undergraduate, six masters, and five doctoral students. Alphabetically, they are:

1. Brian Bellgraph, Montana State University, Movement, habitat use, and food habits of sauger and walleye: an investigation of resource overlap in the middle Missouri River, Montana.
2. Jennifer Corbin, University of Montana, The effects of glacial meltwater chemistry, microbial processes and climate change on nitrate loading and ecological response in high alpine aquatic systems.
3. Timothy Covino, Montana State University, Mountain front GW recharge: groundwater /surface-water exchange across an alpine/valley transition.
4. Kiza Gates, Montana State University, Movements of resident and non-resident anglers in Montana: implications for transferring whirling disease among drainages.
5. Motoshi Honda, University of Montana, Relationships between flood frequency and riparian vegetation distribution in montane streams of western Montana.
6. Levia Jones, Montana State University, Temporal effects of wildfire on riparian ecosystem function.
7. Lewis Kogan, University of Montana, Antibiotic resistance in ground- and surface-water microbes in the Missoula area.
8. Vince Pacific, Montana State University, Watershed carbon distribution and flux across environmental gradients.
9. Mary Louise Polzin, University of Montana, Clonal recruitment of Populus angustifolia along the Yellowstone River: extent and requirements.
10. Mohammed Rahman, Montana State University, Towards sustainable materials for drinking water infrastructure.
11. Diego Riveros, Montana State University, Importance of hydrologic controls on CO2 efflux variability at the catchment scale.
12. Brad Shepard, Montana State University, Factors that influence displacement of native cutthroat trout by nonnative brook trout.

Geographic analysis of landuse/land cover change and its relation to nitrogen export in a developing mountain landscape

Basic Information

Title:	Geographic analysis of landuse/land cover change and its relation to nitrogen export in a developing mountain landscape
Project Number:	2005MT47B
Start Date:	3/1/2005
End Date:	3/1/2006
Funding Source:	104B
Congressional District:	At large
Research Category:	Water Quality
Focus Category:	Surface Water, Non Point Pollution, Models
Descriptors:	
Principal Investigators:	Brian Leonard McGlynn, Kristin Gardner

Publication

1. McGlynn, B.L. and K. Gardner. 2006. Landuse change impacts on water quality: The importance of spatial location. Swedish Institute of Hydrology Meeting, Stockholm, Sweden. Invited keynote speaker.
2. McGlynn, B.L., J. Seibert, R. Gresswell, and D. Bateman. 2006. Landscape analysis of stream-upland connections: Implications for runoff generation, biogeochemistry, and in-stream habitat. North American Benthological Society Annual Meeting, Anchorage, Alaska.
3. Gardner, K.K., K. Segal, J.Harder, and L. Shoutis. 2006. Big Sky Institute GK12 Fellows Program: Bringing scientific research into rural classrooms. National Science Foundation (NSF) GK12 Annual Meeting, Washington D.C.
4. Gardner, K., B.L. McGlynn, D. Patten, J. Shanley. 2005. Effects of mountain resort development on streamwater nitrogen export: Importance of spatial location of land use / land cover change. American Geophysical Union Fall Meeting, San Francisco, CA.
5. McGlynn. B.L. and J. Seibert. 2005. Hewlett’s legacy: Remaining challenges and possible ways forward. American Geophysical Union Fall Meeting. Fall, 2005 [Invited].
6. Gardner, K., B.L. McGlynn, D. Patten, J. Shanley. 2005. Impact of mountain resort development on watershed nitrogen export: the importance of spatial location, Montana American Water Resources Association (AWRA) Annual Meeting, Bozeman, Montana.

7. Gardner, K.K. McGlynn, B.L, D. Patten., R. Lawrence, L. Graumlich, and J. Shanley. 2006. Effects of Mountain Resort Development on Streamwater Nitrogen Export: the Importance of Spatial Location, Gordon Conference on Catchment: Interactions of Hydrology, Biology & Geochemistry Science Biannual Meeting, Waterville, Maine.
8. Gardner, K.K. McGlynn, B.L, D. Patten, and J. Shanley. 2004. Impact of land use change on streamwater quality, Big Sky, Montana, American Water Resources Association (AWRA) Annual Meeting, Helena, Montana. Second Prize Student Poster.
9. Gardner, K.K., Harder, J.I. 2006. Collaboration between Ophir School, Blue Water Task Force Watershed group, and Montana State University research. Montana Watercourse Watershed Tour on Collaborative Education, Big Sky, Montana.
10. Gardner, K., B.L. McGlynn. 2005. Water Quality a Growing Concern in Mountain Watersheds, Big Sky Institute Mountains and Minds Lecture, Big Sky, Montana.
11. Gardner, K.K. 2005. Stream Sleuth: Why is there more nitrogen in the West Fork Watershed? Ophir School Assembly, Big Sky, Montana.
12. Gardner, K.K. 2005. Nutrient Movement in the West Fork Watershed. Montana Watercourse Watershed Tour, Big Sky, Montana.

The Impact of Land Use/Land Cover Change on Nitrogen Export in Mountain Watersheds: the Importance of Spatial Location

Kristin K. Gardner Brian L. McGlynn

Abstract

Southwestern Montana has experienced rapid growth in recent years; 16 counties grew by more than 14% between 1990 -2000; Ravalli and Gallatin counties alone grew 34 and 44 percent, respectively (MSGC, 2004). Human alteration of the patterns of land use/land cover (LULC) on the earth surface is one of the most profound impacts on natural ecosystems. Understanding the consequences of LULC change is a critical issue. At the watershed scale, we expect that not only the amount and type of landscape alteration, but also the spatial location, will dictate the corresponding impacts on streamwater quality. Therefore, we hypothesize that the spatial arrangement of LULC in the landscape is a principal control on both the spatial and temporal patterns of streamwater nitrogen (N). This research develops innovative methods to examine the impact of spatial location of LULC change on streamwater quality by combining spatially distributed field sampling of water quality parameters and digital terrain analysis with a new N export coefficient model. The export coefficient model will be validated by performing isotopic analysis using ^{15}N and ^{18}O of NO_3^- to identify streamwater nitrate sources. The relationships quantified in the export coefficient model and validated by field sampling will 1) help assess watershed N status and the spatial and geographic characteristics that control watershed N export, and 2) provide land managers with a tool to identify areas vulnerable to N export and thus the ability to guide lower impact development. The results of our study will provide insight into the impact of human alteration of natural landscapes on streamwater quality. Although our research focuses on mountain resort development in high elevation settings, our concepts and methodologies will be widely applicable to other landscapes.

Research Objectives

LULC change has been shown to be a significant threat to water resources (Cole et al., 1993; Mayer et al., 2002; Wernick et al., 1998; Biggs et al., 2004; Gardner and Vogel, 2004), and yet the understanding of linkages between land use, water quality, and N export in streams is inadequate to inform land management decisions. Development of Big Sky Mountain Resort in Southwestern Montana has resulted in extensive changes in landscape cover. Initial development occurred in the 1970s and is occurring at an increasingly rapid rate today. Preliminary analysis illustrates a similar upward trend in housing development and streamwater NO_3^- concentration in the West Fork River (Figure 1).

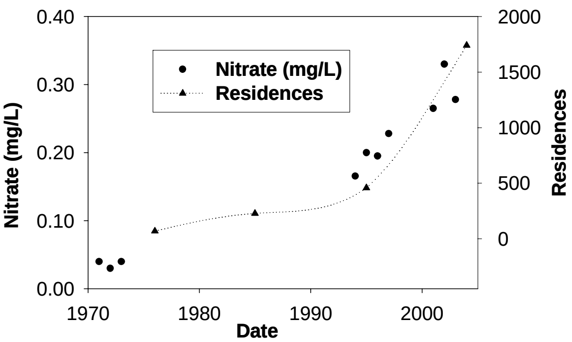

Figure 1: Similar time trends in streamwater nitrate concentration and residential development in the West Fork watershed.

Our analysis approach combines valuable historical data and new data collection in a rapidly developing mountain watershed to assess the characteristics of LULC change governing watershed N export and streamwater quality. Accordingly, we will address the following objectives:

Objective 1: Analyze the current spatial and seasonal variability of N export, land use/land cover (LULC), and watershed characteristics**.**

a. Perform synoptic sampling for water quality (major ions, N species, $\delta^{15}N$ and $\delta^{18}O$ of NO_3^-) in the West Fork and selected tributaries four times throughout the year, to capture major hydrologic events and growing seasons (onset of peak flow, peak flow, baseflow growing season, and baseflow dormant season).
b. Perform weekly streamwater sampling in subwatersheds with varying levels of development (and distribution of LULC), determined from Objective 1a, to ascertain potential differences in the seasonal variability of N export, in developed versus undeveloped watersheds.
c. Determine present LULC and watershed characteristics in the West Fork watershed using a combination of high-resolution remote sensing (QuickBird) and topography data.

Objective 2: Develop and validate a geographically-based nitrogen export model to ascertain and model first-order controls of streamwater NO_3^- concentration and provide a mapping tool for land managers to determine spatial vulnerability in mountainous watersheds.

a. Develop nitrogen export model incorporating results of Objective 1a and b
b. Validate model by performing $^{15}N/^{14}N$, $\delta^{18}O$ isotopic analysis to ascertain sources of streamwater NO_3^-.
c. Apply model spatially to map NO_3^- loading vulnerability to provide tool for land managers to determine spatial patterns of vulnerability in mountainous watersheds.

Study Site

The West Fork River, a tributary of the Gallatin River, drains the Big Sky, Moonlight Basin, Yellowstone Club and Spanish Peaks resort areas and the meadow village located near the outlet. The area is situated in the northern Rocky Mountains of southwestern Montana. The West Fork (212 km^2) is formed by three main tributaries: the South Fork (SF) (121 km^2), the Middle Fork (MF) (48 km^2) and the North Fork (NF) (24 km^2). The watershed (Figure 2) is characterized by well defined steep topography and shallow soils. Elevation in the drainage ranges from ~1800 to 3400 meters, accounting for a great variation in precipitation between the headwaters and mouth. Average annual precipitation exceeds 127 cm at higher altitudes and is less than 50 cm in valley bottoms. Most precipitation falls during the winter and spring months. A hydrograph of the West Fork indicates a general recession throughout the autumn and winter months followed by peak flows during spring snowmelt (Van Voast, 1972).

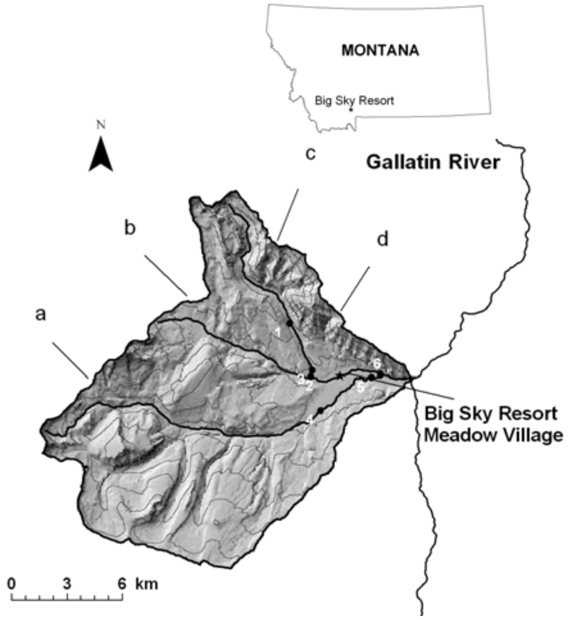

Figure 2: West Fork watershed and subwatersheds (a=SF, b=MF, c=NF, and d=LW) from a 10m DEM. Sampling points: 1-WW, 2=BD, 3=LMR, 4=SS, 5=EH, and 6=JW

Progress to date

Research Objective 1a:

We completed 3 synoptic sampling events in September 2005, February 2006, and June 2006. At each synoptic event, streamwater samples were collected from 54 sites in the West Fork Watershed. Sites were chosen to capture differing land use and watershed characteristics exhibited in the West Fork Watershed (Figure 3). We were unable to collect samples from the southwestern area due to access issues. Samples were collected in 250mL bottles, filtered with a .4um filter and chilled until analysis. We have analyzed a portion of the synoptic samples collected for anions. Stream flow was measured with a Marsh-McBirney Flo-Mate 2000 portable flow in velocity-area gauging of the stream.

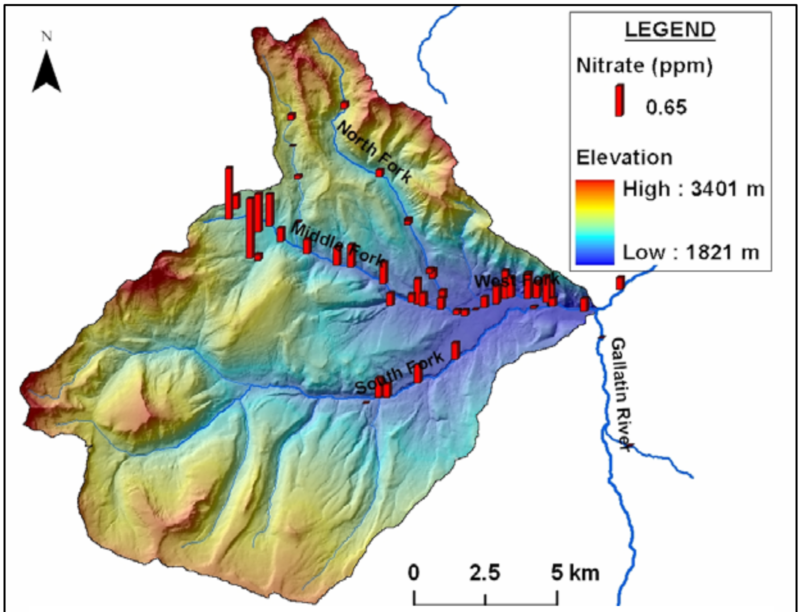

Figure 3: Streamwater nitrate concentrations (ppm) in the West Fork Watershed, September 2005.

Water samples are being analyzed for major ions with a Metrohm-Peak compact ion chromatograph. Nitrate (NO_3), nitrite (NO_2), chloride (Cl), bromide (Br), phosphate (PO_4), and sulfate (SO_4) are measured on a Metrosep C-2-250 anion column. Sodium (Na), ammonium (NH_4), potassium (K), calcium (Ca), and magnesium (Mg) will be measured on a Metrosep C-2-250 cation column.

Research Objective 1b:

Water samples have been collected on a weekly basis since November 2004 at 7 sites within the West Fork Watershed and 2 sites on the Gallatin River. Sites were chosen to capture differing upslope land use and watershed characteristics and also to continue collection at sites with a historical record. Flow, EC, and temperature were measured at each spot. Samples were collected in 250mL bottles, filtered with a .4um filter and chilled until analysis. We have analyzed a portion of the synoptic samples collected for anions.

Research Objective 1b:

- The *QuickBird imagery data* has been collected and is now being orthorectified by Digital Globe.
- The *ALSM topography data* has been collected, processed and delivered to us, however it has not been analyzed yet.

Research Objective 2a: no progress to date

Research Objective 2b: Twenty of the streamwater samples from the February 2006 synoptic sampling event have been sent to Woods Hole Oceanographic Marine Microbial Biogeochemistry Lab for $^{15}N/^{14}N$, $\delta^{18}O$ isotopic analysis to ascertain sources of streamwater NO_3^-. The results of the isotopic analysis will aid in validating the nitrogen export model.

Research Objective 2c: no progress to date

Expected Results

Our research will improve upon existing methods to quantify the impact of land use/land cover (LULC) change on streamwater quality, by applying an innovative method incorporating the spatial patterns and topographical relationships of LULC. Currently, no framework exists for integrating landscape analysis with LULC to provide context for streamwater quality. Our research will contribute an innovative methodology to model critical N export areas by incorporating topography, topology and LULC which fill critical gaps in characterizing landscape nutrient export to surface water.

This study will set the stage to conduct further research by supplying the necessary information to select smaller scale research sites for more in depth hydrological, biogeochemical and ecological process study examining the impacts of LULC change. Thus, our project will initiate the foundation and infrastructure for a long-term, community-driven, integrated research site equipped to monitor the impact of recreational development on mountain ecosystems. We have received several sources of funding for this project since we received the USGS 104(b) seed grant (see tracking below) and we are currently preparing another proposal for the National Science Foundation's Research Initiation Grants and Career Advancement Awards to Broaden Participation in the Biological Sciences program.

Thus far, our research has been presented numerous times at professional conferences, as well as the Big Sky community (see tracking below). As part of our research, we have partnered with the Blue Water Task Force (BWTF), a local watershed group; the Greater Gallatin Watershed Council (GGWC), an umbrella group coordinating water-related projects, the Big Sky Institute for Science and Natural History, and the Ophir School, a local K-8 school in the West Fork Watershed. Public involvement in the synoptic sampling has been incorporated by field training in collaboration with the BWTF. Teacher training and linkages between research and K-12 education has been made through collaboration with the BSI for Science and Natural History and local watershed groups. Gardner is currently a Big Sky Institute NSF GK-12 Fellow and has focused on linking this research to Ophir School. Multiple public seminars and field trips focused on landuse change – water quality impacts have also been conducted by our research group.

Expected Timeline

Method	Timeline
Land Use/Land Cover Mapping	September-May (2006-7)
Synoptic Sampling	August (2005), February, May (2006)
Fine Resolution Sampling	Continuous sampling
Modelling and Results	May 2008

References

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Gardner K., and R.M. Vogel. 2005. Predicting Ground water nitrate concentrations from land use. *Ground water*, 43(3): 343-352.

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Montana Smart Growth Coalition (MSGC). 2004. *The State of Growth in Montana 2001*. Biennial report on growth and land-use planning.

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Wernick B.G., Cook K.E., Schreie,r H. 1998. Land use and streamwater nitrate-N dynamics in an urban-rural fringe watershed. *Journal of the American Water Resources Association*, 34 (3): 639-650.

Tracking

1. Conference Presentations:

McGlynn, B.L. and K. Gardner. 2006. *Landuse change impacts on water quality: The importance of spatial location*. Swedish Institute of Hydrology Meeting, Stockholm, Sweden. Invited keynote speaker.

McGlynn, B.L., J. Seibert, R. Gresswell, and D. Bateman. 2006. *Landscape analysis of stream-upland connections: Implications for runoff generation, biogeochemistry, and in-stream habitat*. North American Benthological Society Annual Meeting, Anchorage, Alaska.

Gardner, K.K., K. Segal, J.Harder, and L. Shoutis. 2006. *Big Sky Institute GK12 Fellows Program: Bringing scientific research into rural classrooms.* National Science Foundation (NSF) GK12 Annual Meeting, Washington D.C.

Gardner, K., B.L. McGlynn, D. Patten, J. Shanley. 2005. *Effects of mountain resort development on streamwater nitrogen export: Importance of spatial location of land use / land cover change*. American Geophysical Union Fall Meeting, San Francisco, CA.

McGlynn. B.L. and J. Seibert. 2005. Hewlett's legacy: *Remaining challenges and possible ways forward*. American Geophysical Union Fall Meeting. Fall, 2005 [Invited].

Gardner, K., B.L. McGlynn, D. Patten, J. Shanley. 2005. *Impact of mountain resort development on watershed nitrogen export: the importance of spatial location*, Montana American Water Resources Association (AWRA) Annual Meeting, Bozeman, Montana.

Gardner, K.K. McGlynn, B.L, D. Patten., R. Lawrence, L. Graumlich, and J. Shanley. 2006. *Effects of Mountain Resort Development on Streamwater Nitrogen Export: the Importance of Spatial Location*, Gordon Conference on Catchment: Interactions of Hydrology, Biology & Geochemistry Science Biannual Meeting, Waterville, Maine.

Gardner, K.K. McGlynn, B.L, D. Patten, and J. Shanley. 2004. *Impact of land use change on streamwater quality, Big Sky, Montana*, American Water Resources Association (AWRA) Annual Meeting, Helena, Montana. Second Prize Student Poster.

2. Community Presentations

Gardner, K.K., Harder, J.I. 2006. *Collaboration between Ophir School, Blue Water Task Force Watershed group, and Montana State University research*. Montana Watercourse Watershed Tour on Collaborative Education, Big Sky, Montana.

Gardner, K., B.L. McGlynn. 2005. *Water Quality a Growing Concern in Mountain Watersheds*, Big Sky Institute Mountains and Minds Lecture, Big Sky, Montana.

Gardner, K.K. 2005. *Stream Sleuth: Why is there more nitrogen in the West Fork Watershed?* Ophir School Assembly, Big Sky, Montana.

Gardner, K.K. 2005. *Nutrient Movement in the West Fork Watershed.* Montana Watercourse Watershed Tour, Big Sky, Montana.

3. Student Support:

Kristin Gardner, PhD
Kristy Segal, Undergraduate

4. Notable Achievement and Awards:

2006-2007 Department of Environmental Quality, Subcontract for EPA 319 Funds for the Upper Gallatin Watershed Nutrient Assessment, $ 66,000.

2005-2006 Department of Environmental Quality, Subcontract for EPA 319 Funds for the Upper Gallatin Watershed Nutrient Assessment, $ 54,000.

2005-2006 US Environmental Protection Agency STAR: *Land Use/Land Cover Change Governing Nitrogen Thresholds and Transport in Mountain Watersheds*, $293,397.

2005 National Science Foundation Geography and Hydrology Program: *Effect of mountain resort development on streamwater nitrogen export: the importance of spatial location,* $33,836.

NSF Graduate Teaching Fellowship in K-12 Education, Kristin Gardner, PhD candidate.

Science to Achieve Results (STAR) fellowship, Kristin Gardner, PhD candidate.

Using paleoecology and paleoflood hydrology to assess the long-term ecological response of Montana’s riparian and aquatic ecosystems to small natural and human dam features -- a pilot study

Basic Information

Title:	Using paleoecology and paleoflood hydrology to assess the long-term ecological response of Montana’s riparian and aquatic ecosystems to small natural and human dam features -- a pilot study
Project Number:	2005MT49B
Start Date:	3/1/2005
End Date:	2/29/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Climate and Hydrologic Processes
Focus Category:	Floods, Sediments, Ecology
Descriptors:	
Principal Investigators:	Denine Schmitz, Duncan T. Patten

Publication

1. Schmitz, Denine, Selita Ammondt, Matt Blank, and Duncan Patten. 2006. Using historic aerial photography and paleoflood hydrology to assess long-term ecological response to two Montana dam removals. USGS Water Resources Research Program.
2. Schmitz, Denine, Selita Ammondt, Matt Blank, and Duncan Patten. 2005. Long-term hydrogeomorphic effects of dam failure/removal a pilot study. Floodplains and rivers: connections and reconnections. Center for Riverine Science and Stream Re-naturalization. September 22 and 23, 2005. Missoula, Montana.
3. Ammondt, Selita, Denine Schmitz, and Duncan Patten. 2005. Studying the effects of small dam removal on woody riparian species in Montana using aerial photo interpretation and field surveys. Floodplains and rivers: connections and reconnections. Center for Riverine Science and Stream Re-naturalization. September 22 and 23, 2005. Missoula, Montana.
4. Schmitz, Denine, Selita Ammondt, Matt Blank, and Duncan Patten. 2005. Long-term

hydrogeomorphic effects of dam failure/removal a pilot study. Surface Water/ Groundwater: One resource. Montana American Water Resources Association. October 2005. Bozeman, Montana.

5. Ammondt, Selita, Denine Schmitz, and Duncan Patten. 2005. The effects of small dam removal on woody riparian species in Montana. Surface Water/ Groundwater: One resource. Montana American Water Resources Association. October 2005. Bozeman, Montana.
6. Schmitz, Denine, Selita Ammondt, Matt Blank, and Duncan Patten. in prep. Assessing ecological response to small dam removal using historic ecological techniques. Wetlands.

USING HISTORIC AERIAL PHOTOGRAPHY AND PALEOFLOOD HYDROLOGY TO ASSESS LONG-TERM ECOLOGICAL RESPONSE TO TWO MONTANA DAM REMOVALS

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Bozeman, Montana 59717

ABSTRACT

The restorative potential of dam removal on ecosystem function depends on the reversibility of the hydrogeomorphic effects of a dam and its operations. While dam removal is an established engineering practice, the long-term ecological response remains speculative. We used paleoflood hydrology, topographic surveys, hydrologic modeling (HEC-RAS), and aerial photograph interpretation to investigate the long-term hydrogeomorphic and ecologic responses to dam failure and removal. We compared downstream hydroecological responses of a controlled dam removal, which used natural sediment removal (Mystic Lake Dam in 1985), with that of a dam failure (Pattengail Dam in 1927). Our data showed greater geomorphic response at Pattengail compared to Mystic. Very few flood stage indicators were observed at Mystic and indicated muted hydrogeomorphic and ecologic responses. In contrast, the size of the flood following the Pattengail dam breach initiated a series of channel adjustments and reworked over 0.2 km^2 of floodplain immediately downstream of the dam. Floodplain vegetation responded similarly. Nearly 100 vegetation points below Mystic Lake Dam showed no statistically significant changes in canopy type in the 20 years since dam removal. However, 165 vegetation points downstream of Pattengail dam indicated active floodplain succession during the first 70 years. Our results suggest that 1) hydrogeomorphic and ecologic responses to dam removal depends on the sizes and timing of high flow events during and following removal. 2) Dam removal effects on channel evolution and floodplain development depend on reach types and their responsiveness to flow regime change. We developed these ideas into testable hypotheses as the basis of a multiyear, interdisciplinary research proposal. Further investigation into the long-term hydrogeomorphic and ecologic response to dam removal/failure will advance the knowledge of dam removal methods and their effects, leading to healthier ecosystems and associated human communities.

INTRODUCTION

The decision whether to repair, augment, or remove a dam is presented to dam owners more and more each year. Nationally, we are faced with an aging population of Dams. In Montana, 76% of our dams are over 40 years old (National Inventory of Dams 2003). As dams age, reservoirs fill with sediment. Increased sedimentation means less storage volume for irrigation, municipal water supplies, and flood control potential. Further, human populations downstream of dams are increasing. The higher potential for loss to life and property downstream of dams increases the hazard rating and, therefore, liability. Thus, dam owners are faced with increasing maintenance costs to address decreased functionality, increased construction costs to meet new hazard ratings, or, in many cases, removing the dam all together. Ecologists are interested the restoration potential of using dam removal as a restoration tool. Our project aimed to identify the long-term ecological responses to two Montana dam removals.

The need for long-term understanding of ecological responses to dam removal is far-reaching. As Montana's population grows, community development downstream of unregulated dams becomes an issue. Communities are faced with making decisions about dams without sufficient information. The result is a series of short-sighted decisions or alarmist responses. Knowledge of the long-term ecological responses to dam removal will give community stakeholders a science-based foundation from which to make well-informed decisions regarding dam operations, their potential removal and the associated ecosystem services afforded to humans in regulated and unregulated river systems.

Early dam removals were done with little pre-removal environmental assessment which resulted in great impacts on downstream infrastructure (Shuman 1995). As a result, current dam removal methods are often over-engineered (The Aspen Institute 2002). The Montana State Dam Safety dam removal guidelines currently require a full engineering report describing methods for drainage, disposal or stabilization of sediment and dam materials, reclamation applied to the dam and impoundment area, and prevention of future impoundments ([DNRC] Department of Natural Resources and Conservation 1989). These guidelines target the short-term issues of sedimentation and downstream flooding, yet make no provisions for long-term ecological responses to a restored dynamic sediment regime. Long-term data on the responses to dam removal will accelerate the evolution of dam removal methods (Bednarek 2001) and allow the pendulum to swing toward a moderate, comprehensive approach.

The issue of dam removal affects multiple facets of Montana's population. Of the 2,863 dams in Montana, 87% are privately owned (National Inventory of Dams 2003) and Montana Department of Natural Resources and Conservation (DNRC) estimates more than 2,000 additional unregistered dams. Given the agricultural base of Montana's population, it is no surprise that the primary purpose of Montana dams is irrigation and water supply for livestock. However, the 6% of Montana's dams that provide electricity and water supply to municipalities and support recreational activities affect a disproportionately large, non-agricultural component of the population. Thus, dams in Montana affect those in need of water in an arid environment, electricity in a modern world, and ecosystem processes in agriculture and ecotourism economies. Because Montana's dams are becoming increasingly obsolete due to decreased storage capacity, unsafe due to age and, liabilities due maintenance costs outweighing benefits, dam removal is becoming viable, attractive, and necessary. With region-specific knowledge of the long-term ecological effects of dam failure and removal Montana can make informed decisions regarding the alternative of dam removal.

The potential for river restoration using dam removal is great (Hart and others 2002). The most immediate ecological effect of dam removal is the restoration of the river's flow regime. Aquatic species migration, water quality and temperature regime are often rapidly improved. Changes in water quality and thermal regime drastically alter nutrient cycling and sediment dynamics affecting riparian plant communities (Shafroth and others 2003), biogeochemistry (Stanley and Doyle 2002), and channel and floodplain evolution. By reversing the effects of dam, longitudinal and lateral connectivity is restored to the system on a watershed scale. Thus, dam removal coupled with other restorative and protective practices can be an integral part of watershed plans (Stanford and others 1996).

However, the long-term responses are unknown. We expect that floodplain erosion and deposition will be restored, but we don't to what extent? We expect there will be more fish habitat area, but we don't know the quality of that habitat? We expect that riparian vegetation recruitment will return to areas with restored floodplain erosional and depositional processes, but we don't know how long it will take for successional trajectories to reestablish. For now, these questions are unanswered and provide fruitful ground upon which landowners, natural resource agencies, dam management officials, and researchers can coordinate efforts when making dam removal decisions.

Our goal was to assess long-term downstream ecological responses to failed and removed dams. Specifically, we asked two questions. 1) Are paleoflood hydrology and aerial photography methods sensitive enough to detect ecological responses to dam failures and removals? 2) Can we detect the reversal of dam impacts on downstream riparian areas?

MATERIALS AND METHODS

Site Description

Mystic Lake Dam is located approximately 10 miles south of Bozeman, Montana on Bozeman Creek (Figure 1 and Figure 2). It was built in 1901 and removed in 1985. This 43 ft tall dam augmented a lake formed naturally from an active landslide (pers. comm. Steve Custer). Once dammed, the reservoir volume was 1200 acre feet. Due to many structural integrity issues and an increasing human population downstream, the dam was removed at low flow in April 1985 (City of Bozeman documents). The reservoir sediment was left untouched. Approximately 100 m of stream channel and riparian area below the removed dam was restored.

Directly downstream of the breached Mystic Lake Dam was a narrow canyon with limited or no floodplain area. We located our 1.5 km Mystic Dam study reach (Mystic) just downstream of this canyon where the valley widened and allowed floodplain development. This study reach was constrained in a narrow valley with cascade and plane-bed channel types (following Montgomery and Buffington (1997)).

Pattengail Dam is located in the Pioneer Mountains forty miles southwest of Butte, Montana on Pattengail Creek (Figure 1 and Figure 2). The dam is 1.5 km upstream of Pattengail Creek's confluence with Wise River. Pattengail Dam was built in 1903 and burst during a rain on snow event in 1927. When in operation, the reservoir stored 12,000 acre feet of water which created a reservoir over 2 miles long. Below the breached dam, the creek flows through a wide valley along an unconstrained reach in plane-bed and riffle-pool channel types.

Much of the 40+ ft original structure exists today. There has been no channel restoration, removal of remaining dam structures, or treatment of reservoir sediments since the breach. We located our 1.5 km Pattengail study reach (Pattengail) immediately downstream of the dam and upstream of the bridge of Forest Road 484.

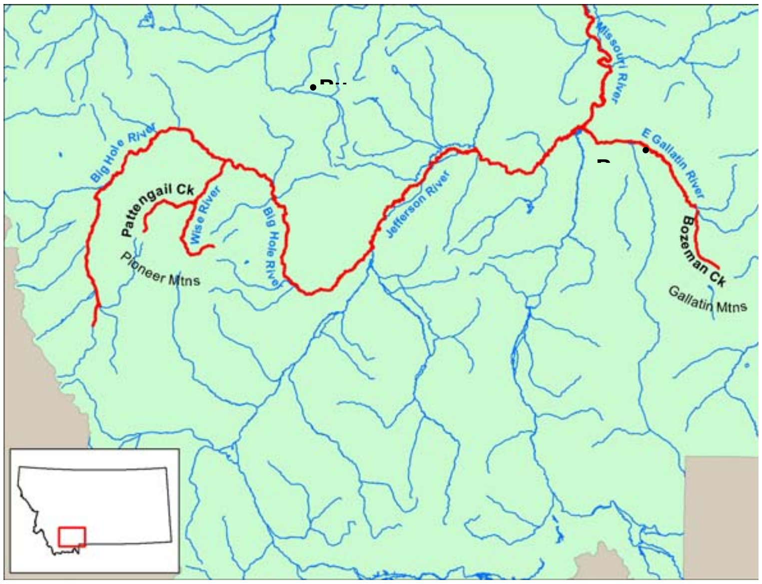

Figure 1. Regional map of study area.

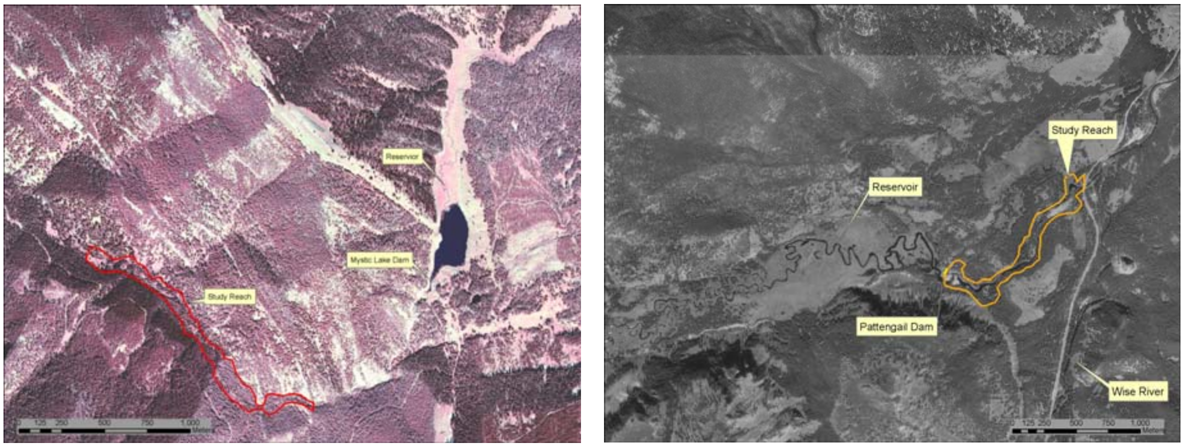

Figure 2. Study reaches for Mystic Lake and Pattengail Dams.

Aerial Photo Interpretation

Aerial photos showing the Mystic site included 1971, 1989, 1995, and 2001 (Table 1). Those for Pattengail were from 1942, 1955, and 1995. The Mystic and Pattengail 1995 digital orthophoto quadrangles (DOQ) were accessed from the Montana NRIS web site. The Mystic 2001 color infrared images were made available by the Gallatin Local Water Quality District. The 1995 and 2001 images were orthorectified. Mystic photos from 1971 and 1989 and Pattengail images from 1942 and 1955 were scanned with high resolution from hard copies and georeferenced to the 1995s using the georeferencing tool in ArcView 9.1. Fifteen control points were used in each image and produced maximum root mean square values of 3.5 and 2.6 for Mystic and Pattengail, respectively.

Table 1.

Mystic		Pattengail	
Photo Year	**# Years Post Removal**	**Photo Year**	**# Years Post Removal**
1971	Pre-removal	1942	15
1989	4	1979	52
1995	10	1995	78
2001	16		
2005*	20	2005*	88

**Field Observation*

Floodplain Delineation

Floodplains were identified for 2 km study reaches downstream of dams. The Pattengail Creek floodplain was delineated visually using aerial photos and field reconnaissance. A 1995 Digital Elevation Model (DEM) in a Geographic Information System (GIS) was used to topographically define the floodplain of Bozeman Creek. Floodplains for each photo year were interpreted and classified into five landcover types: coniferous, deciduous, herbaceous, bare ground, and water, based on texture, color, shape, size, pattern, and association. Canopy woody vegetation was used in interpretation since it is visible on all aerial photos and is indicative of major changes to the riparian landscape. While understory vegetation is disturbance-dependent, its analysis was not possible using the historic aerial photos.

Vegetation Response

We identified eight valley-wide transects perpendicular to floodplains on both sites, spaced 100m apart close to dams, and 500m apart further down the study reaches (Figure 3). We expected more biotic change to occur near the dams, as sediment stored behind the impoundment and released along with the dam breach initially deposits close to its source. Each transect was consequently divided into points ten meters apart to facilitate statistical analysis, and landcover of each point was identified for each photo year.

The vegetation transect points were assessed in the field in summer 2005 and mapped using a Trimble GeoXT Global Positioning System (GPS) receiver, completing a time series of 1971-2005 for Mystic and 1942-2005 for Pattengail. This data was used to determine long term vegetation changes due to dam failure/removal.

Vegetation Response Analysis

Statistical analysis of change in landcover type for each transect point allowed interpretation of riparian vegetation response. A Wilcoxon Rank-Sum test was completed to detect significant differences in vegetation at observed points between years. An Analysis of Variance (ANOVA) test was performed to ascertain significant changes in landcover as a function of distance to thalweg, distance to dam, and elevation above mean sea level.

Hydrologic Characterization

Historic peak flows were estimated using three independent approaches - 1) modeled flow using paleohydrology, 2) empirically derived regional models (Parrett and others 1994), and 3) hydrograph records. Hydrology transects for input into models were placed at points of floodplain constriction and expansion along the length of each study reach (Figure 3). At each transect, we surveyed breaks in slope, banks, channel margins, and channel thalwegs. Flood stage indicators (FSI) were surveyed and used to model flood characteristics following the paleohydrologic methods of Cenderelli and Wohl (Cenderelli and Wohl 2001). They included fluvial sediment deposits and woody debris piles, and scour zones. In Pattengail, we used a Leica survey grade GPS system with sub-centimeter vertical accuracy. We used an autolevel and stadia rod in Mystic because the narrow valley and dense vegetation blocked satellite signals. The equipment yielded sub-meter vertical accuracy. These estimates were evaluated as a group to determine the best possible peak flow estimate.

Paleohydrology. Peak stage determination is a critical component to estimating historic peak discharge (Pruess and others 1998). Yet the accuracy of flood stage indicators is susceptible to several uncertainties (Jarrett and Tomlinson 2000). Paleodischarge estimates are particularly sensitive to flow resistance coefficients because vegetation can only be estimated, channel change, and identifying maximum flood stage. To address these issues we estimated channel roughness using aerial photos, chose bedrock controlled channels whenever possible, and used multiple indicators to determine peak flood stage.

We estimated peak discharge by combining paleoflood hydrologic techniques with a step-backwater hydrology model (Cenderelli and Wohl 2001). This approach combines two independent data sources to arrive at the best possible estimate of the historic flood environment – flood stage indicators (FSI) and nonflooded surfaces. Nonflooded surfaces such as undisturbed vegetation and changes in substrate tend to overestimate discharge. FSIs such as boulder bars, scour lines, and woody debris accumulations tend to underestimate them. High water marks tend to accurately indicate peak stage however, are rather ephemeral (Jarrett and Tomlinson 2000). We estimated a range of flood stages by bracketing the upper and lower limits of the flood environment. The lower elevations of nonflooded surfaces and high water marks served as the upper limits and the upper elevations of FSIs served as the lower limits. We narrowed the range of potential peak discharges using mean square error.

Regional Estimates. Empirically derived, regional estimates were used as a second estimate of peak discharge. Based on channel geometry, Parrett, Omang, and Hull (1994) developed regression models for the region with correlation coefficients of 0.733. Using the active channel width and Equation 1 we estimated peak discharge for a 100-year flood at both Mystic and Pattengail.

Q100 = 21.2 Channel width1.193 Equation 1

Hydrograph Records. Hydrograph records for Mystic are discontinuous and represent 1967-1969 and 1975-1980 (Figure 4). Pattengail Creek is not gauged. The hydrograph for the Big Hole River at Maiden Rock near Divide is continuous since 1923 and shows the flow spike from the Pattengail dam breach over 50 river miles upstream (Figure 5). Because the hydrograph records are not specific to Pattengail Creek, we estimated flows from the time required for the reservoir (12,000 acre feet) to drain over 24 and 48 hours.

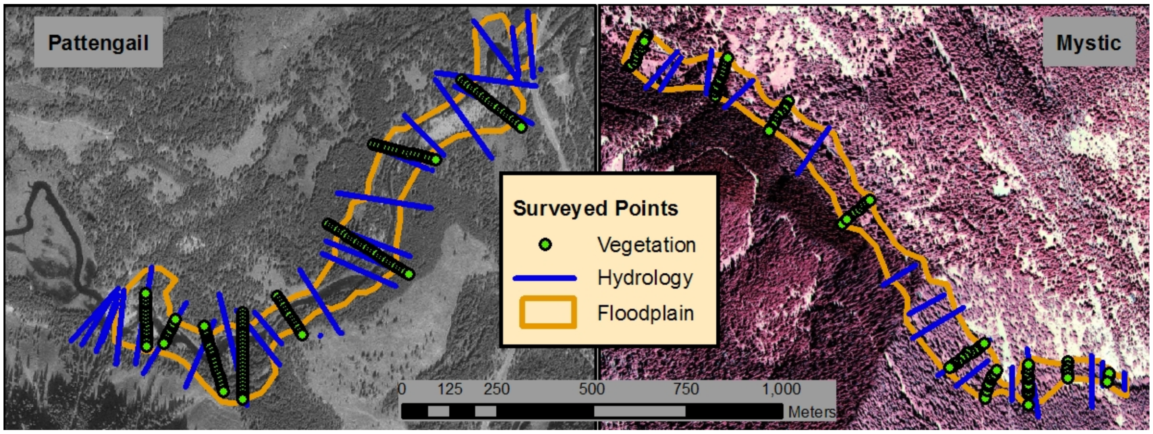

Figure 3. Pattengail and Mystic vegetation and hydrology transects used to characterize historic landcover and estimate peak flows.

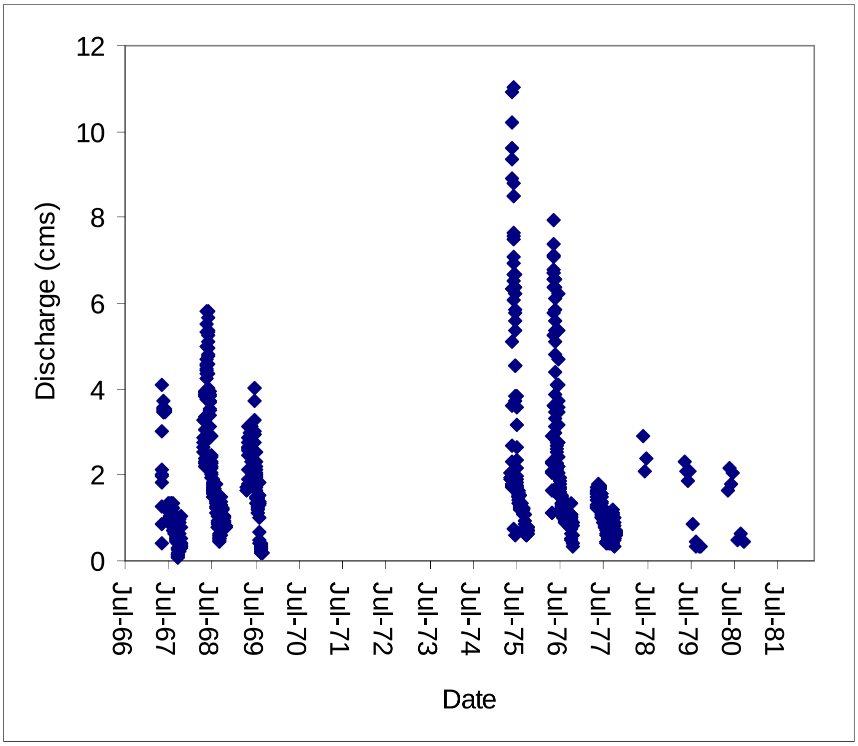

Figure 4. Historic discharge data for Bozeman Creek from 1967 to 1980.

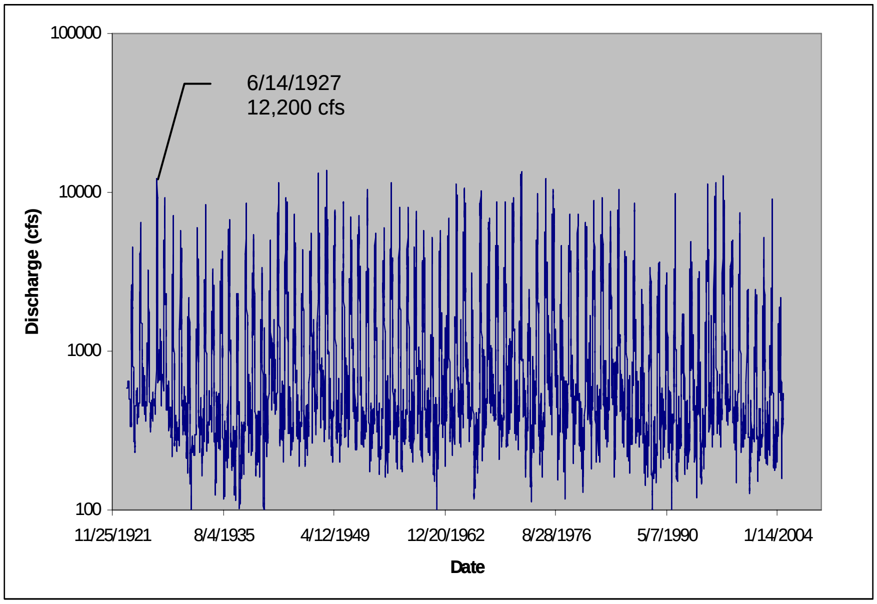

Figure 5. Hydrograph for Big Hole River near Melrose 1923-2004.

RESULTS

Hydrology

Estimates for peak discharge prior to and following removal of Mystic Lake Dam were estimated based on modeling, regional estimates, and gage records. Discharges modeled based on surveyed flood stage indicators yielded incomprehensible numbers. Alternatively, the discharge required for overbank flow from surveyed bank elevations and channel cross sections was between 141-211 cfs. The hydrograph records for Bozeman Creek are spotty despite that fact that Bozeman Creek provides a significant volume of municipal water to over 35,000 people (Figure 4). The largest discharge on record for Bozeman Creek was 388 cfs in June 1975, prior to dam removal in 1985. Over bank flows occurred in three of nine years of record, based on data presented here. An estimate of 671 cfs for a 100-yr flood was determined by applying the empirically derived, regional estimate based on the active channel width (Parrett and others 1983).

The regional estimate based on active channel width for Pattengail (Parrett and others 1985) is 4450 cfs. The estimate based on reservoir drainage time in 24 hours is 6000 cfs. Our modeled flow with the lowest average error (0.31) was 2650 cfs.

Landcover Changes

In Mystic, 99 common points were assessed for landcover (Figure 6). Minimal changes in landcover between photo years were detected (Table 2). No change was detected in 80-97% of observed points. Analysis of Variance (ANOVA) showed minor (if any) effects of environmental variables on land cover types for each photo year as well as for each photo period (Table 3). Elevation (mean sea level) showed significant effects on each landcover ($\alpha = 0.05$). Distance to the Dam showed no significant effects on landcover ($\alpha = 0.1$). Distance to the thalweg showed significant effects on land cover types for 1995 ($\alpha = 0.1$), 2001, 1989-1995, 1995-2001, and 2001-2005. Figure 7 illustrates that no vegetative landcover responds to increasing distance from the dam.

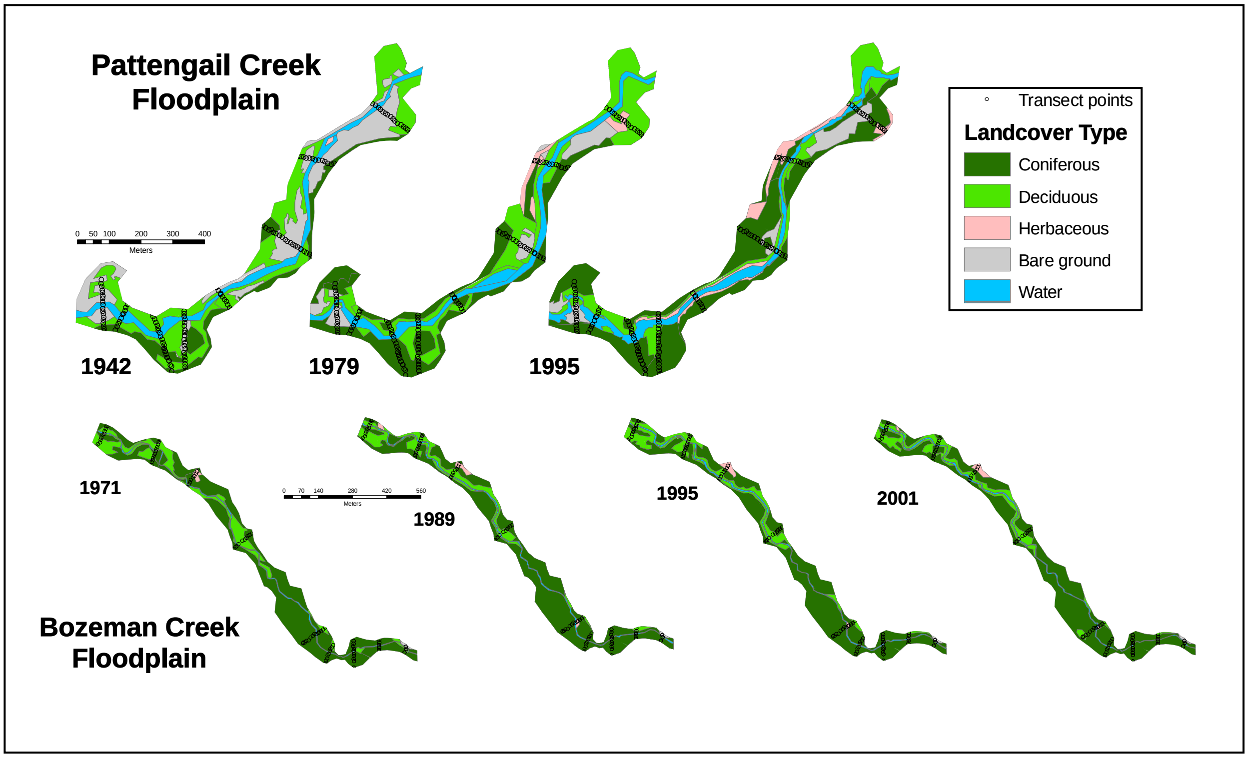

Figure 6. Vegetation changes in Mystic and Pattengail.

Table 2. Mystic Lake Dam study reach landcover changes for each photo period. Landcover changes not observed were excluded.

	Photo Period				
Land Cover Type	**1971-1989** %	**1989-1995** %	**1995-2001** %	**2001-2005** %	**1971-2005** %
Coniferous-Coniferous	62.9	67.7	64.3	61.6	56.7
Coniferous-Deciduous	6.2	0.0	4.1	1.0	10.3
Coniferous-Water	0.0	2.0	0.0	2.0	2.1
Coniferous-Herbaceous	2.1	1.0	0.0	0.0	2.1
Deciduous-Water	14.4	20.2	18.4	21.2	14.4
Deciduous-Herbaceous	0.0	0.0	2.0	0.0	0.0
Water-Deciduous	4.1	0.0	0.0	1.0	4.1
Water-Water	0.0	0.0	0.0	2.0	0.0
Water-Herbaceous	3.1	3.0	4.1	4.0	5.2
Water-Bareground	0.0	0.0	0.0	1.0	0.0
Herbaceous-Herbaceous	2.1	0.0	0.0	0.0	0.0
Herbaceous-Deciduous	2.1	4.0	4.1	3.0	2.1
Herbaceous-Bareground	0.0	0.0	1.0	0.0	0.0
Bare ground-Bareground	1.0	0.0	0.0	1.0	1.0
Bare ground-Deciduous	2.1	2.0	2.0	2.0	2.1
Coniferous-Deciduous	62.9	67.7	64.3	61.6	56.7
Coniferous-Water	6.2	0.0	4.1	1.0	10.3
Coniferous-Herbaceous	0.0	2.0	0.0	2.0	2.1
No Change	85	97	93	92	80

Table 3. ANOVA results for Mystic Lake Dam study reach landcover changes.

	Photo Year		
	Distance to Thalweg	Distance to Dam	Elevation (MSL)
1971	NS	NS	+
1989	NS	NS	+
1995	+*	NS	+
2001	+	NS	+
2005	NS	NS	+
	Photo Period		
1971-1989	NS	NS	+
1989-1995	+	NS	+
1995-2001	+	NS	+
2001-2005	+	NS	+
1971-2005	NS	NS	+
*α = 0.05 *α = 0.1*	*+ Significant*	*NS Not Significant*	

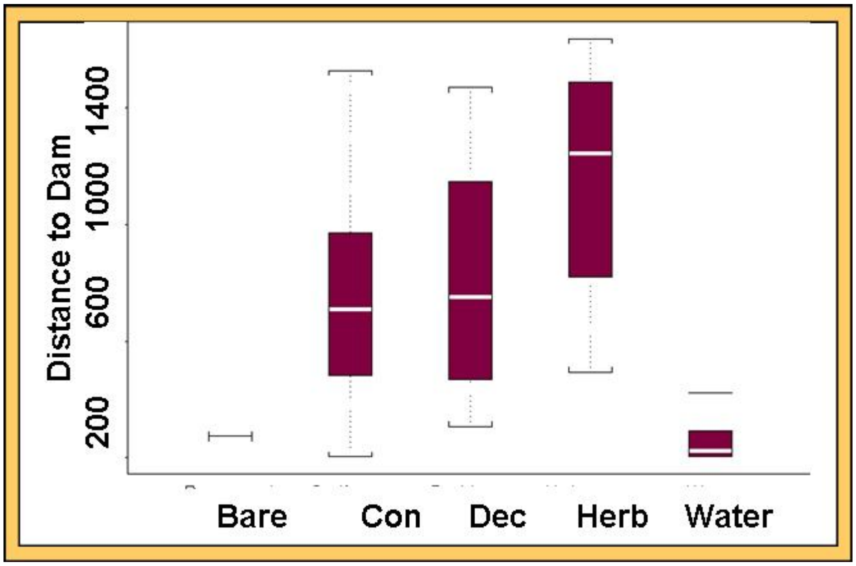

Figure 7. Mystic ANOVA results indicating that no vegetative cover responds to increasing distance from dam.

In Pattengail, 142 common points were assessed for landcover for each photo year. Changes in landcover for each photo period appear in Table 4. There was detectible vegetation change since the 1927 dam breach, particularly along the newly established channel (Figure 6). ANOVA results showed significant effects of distance to the thalweg on landcover type (α = 0.05) for each photo year and photo period (Table 5 and Figure 8). Distance to dam and elevation (mean sea level) also showed significant effects on landcover types (Table 5 and Figure 9).

Table 4. Pattengail Creek Dam study reach landcover changes for each photo period. Landcover changes not observed were excluded.

	Photo Period			
	1942-1979	**1979-1995**	**1995-2005**	**1942-2005**
Land Cover Type	%	%	%	%
Coniferous-Coniferous	60.6	60.6	65.1	42.3
Coniferous-Deciduous	0.0	0.0	0.7	0.7
Coniferous-Water	1.3	1.3	2.0	0.0
Coniferous-Herbaceous	3.2	3.2	0.0	0.0
Coniferous-Bare ground	0.0	0.0	1.3	1.4
Deciduous-Deciduous	8.4	8.4	7.2	5.6
Deciduous-Water	1.9	1.9	2.0	2.8
Deciduous-Herbaceous	1.3	1.3	0.7	2.1
Deciduous-Bare ground	0.6	0.6	0.0	0.0
Deciduous-Coniferous	7.7	7.7	1.3	14.8
Water-Deciduous	1.9	1.9	2.0	2.1
Water-Water	7.1	7.1	7.9	9.2
Water-Coniferous	0.6	0.6	0.7	1.4
Herbaceous-Herbaceous	1.3	1.3	2.6	0.0
Herbaceous-Bare ground	0.0	0.0	0.7	0.0
Herbaceous-Coniferous	0.0	0.0	2.0	0.0
Bare ground-Bare ground	3.2	3.2	2.6	3.5
Bare ground-Deciduous	0.0	0.0	0.7	2.8
Bare ground-Water	0.0	0.0	0.0	0.7
Bare ground-Herbaceous	0.0	0.0	0.0	1.4
Bare ground-Coniferous	0.6	0.6	0.7	9.2
No Change	80.6	80.6	85.5	60.6

Table 5. ANOVA results for Pattengail Creek Dam study reach.

	Photo Year		
	Distance to Thalweg	Distance to Dam	Elevation (MSL)
1942	+	NS	+
1979	+	+	+
1995	+	+	+
2005	+	+	+
	Photo Period		
1942-1979	+	+	+
1979-1995	+	+	+
1995-2005	+	+	+
α = 0.05	*+ Significant*	*NS Not Significant*	

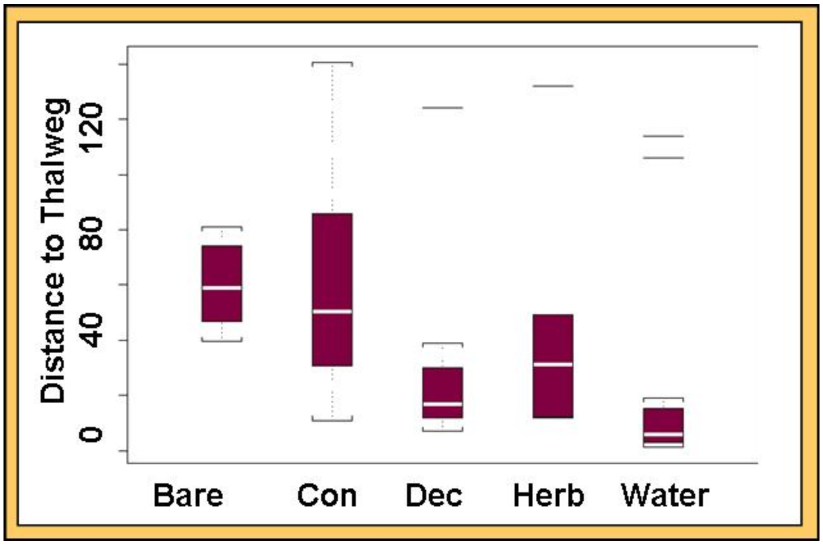

Figure 8. ANOVA results for Pattengail Creek Dam study reach showing the effects of distance to thalweg on landcover.

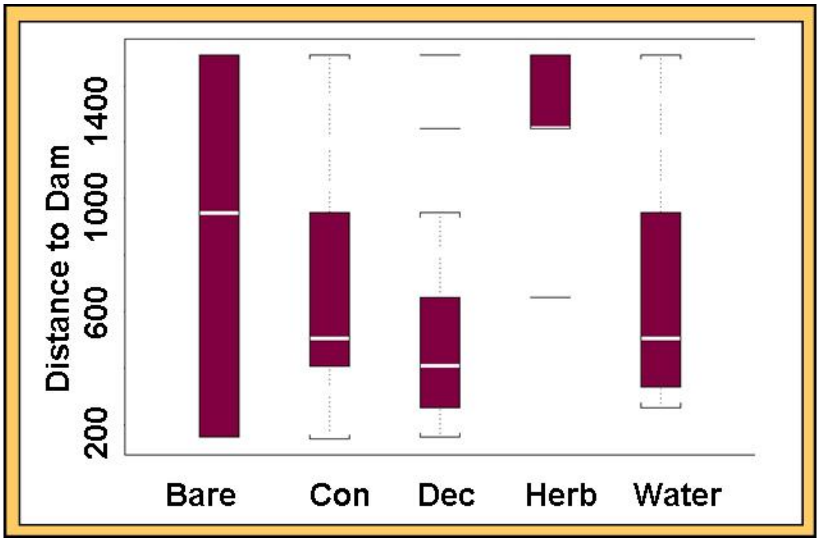

Figure 9. ANOVA results for Pattengail Creek Dam study reach showing the effects of distance to the dam on landcover.

DISCUSSION

Mystic

Modeled flow estimates based on flood stage indicators (FSIs) were used to estimate flood paths following dam removal. The flow estimates for each study site were variable but were especially wide ranging for Mystic. Although coarse, the modeled flood paths lay a foundation for estimating floodplain vegetation response.

The historic flood path for Mystic (based on a modeled flow of 141-211 cfs does not exceed its banks. Even the highest flow estimate (388 cfs from 1976 gage records) does not provide energy for deposition or erosion of sediments beyond 10 m from the channel. The Mystic valley floor width averaged 100+ meters with coniferous vegetation (*Picea engelmannii*) as the dominate landcover. Floodplain vegetation free of disturbance continues along a successional trajectory toward an upland community. Our landcover results show an overwhelming dominance of *Picea engelmannii*, a typical upland species. The lack of floodplain landcover change and modeled flows within surveyed banks suggest that flows since the dam removal have had little influence on riparian vegetation.

Historically, Mystic Lake Dam did not operate much of the time due to poor spillway design, instability, and a partial failure in 1978 (City of Bozeman records). The constrained, narrow valley with cascade and plane-bed channel types are known to be unresponsive to all but the most catastrophic flows (Montgomery and Buffington 1997). The channel and valley characteristics combined with dam operations strongly suggest that the dam had little effect on downstream riparian vegetation. Following the same reasoning, the lack of riparian response following a controlled dam removal at low flow is to be expected, also. Thus, paleohydrologic methods combined with aerial photography accurately showed no change to the downstream system following the removal of Mystic Lake Dam in 1985.

Pattengail

The Pattengail Creek Dam break substantially differs from the Mystic Lake Dam removal in both hydrology and ecology. The modeled flood path (at 2650 cfs) resulting from the break covers the valley floor and was likely very energetic. We were only able to assess vegetation response post-dam break due to the lack of ecological information prior to dam construction in 1927. However, starting with aerials from 1942, we were able to quantify vegetation response along the modeled flow path for the last 65 years (15-78 years following dam failure).

While most vegetation survey points were unchanged between photo years, those that illustrated changes suggest classic riparian successional trajectories. From a freshly disturbed site with coarse sand or fine gravel (bare ground), colonizers such as cottonwood or willow species, tap-rooted annuals, and other ruderal established in dense nurseries. These species are typically poor competitors and fast growing with low survivorship resulting in self-thinning and few mature individuals. Willow thickets and cottonwood groves, if left undisturbed, will give way to upland species such as *Artimesia* spp. (sage brush), *Pinus contorta*, and *Picea engelmannii*. These areas are represented by the change from deciduous to coniferous. In areas with high organic matter and wet soils, *Carex* spp. and *Juncus* spp. dominate and only give way to facultative wetland species if the site progressively becomes drier (Figure 6 and Table 4).

In contrast to Bozeman Creek, the dam failure of 1927 on Pattengail Creek (built in 1901) yielded catastrophic stream flows, produced marked channel change, and evoked substantial floodplain vegetation response. The plane bed and pool riffle channel types of Pattengail Creek wind through a wide, glaciated, unconsolidated valley (Figure 11). Based on relict channels detected during field reconnaissance, local interviews, and aerial photo interpretation, we found there was a meandering channel prior to dam failure. The current channel has low sinuosity. It is in a state of high flux. And, it grades from a series of scour ponds near the dam break to glides, braids, and riffle/pool sequences about a mile downstream. Flow estimates (modeled from flood stage indicators, computed from reservoir drainage times, and calculated using a regional regression equation) ranged from 120 to 170 cubic meters second – catastrophic by all measures for a stream this size. Such flows greatly exceeded the creek banks and reworked 19 hectares of floodplain compared to the current four hectares. Near the dam the flows downcut the channel nearly three meters. 40% of riparian vegetation cover changed over the 78 years since the dam failed (Table 4). The high degree of channel change, catastrophic flows, and major amount of floodplain vegetation change indicated a high degree of ecological change at this site. Further, the loss of sinuosity, shrunken floodplain area, and intense downcutting showed that very high energy flows can leave long-term scars on a river ecosystem.

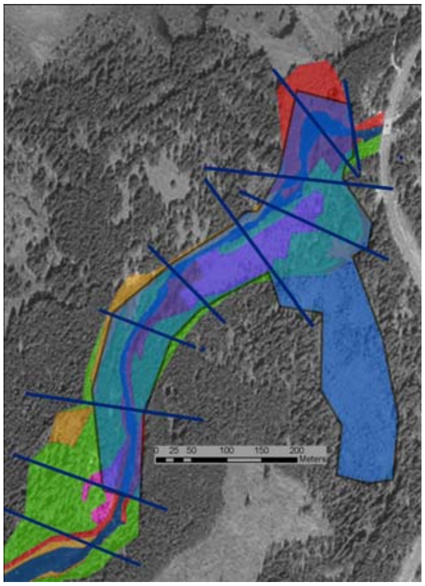

Figure 10. Modeled flow path for Pattengail Creek following 1927 breach.

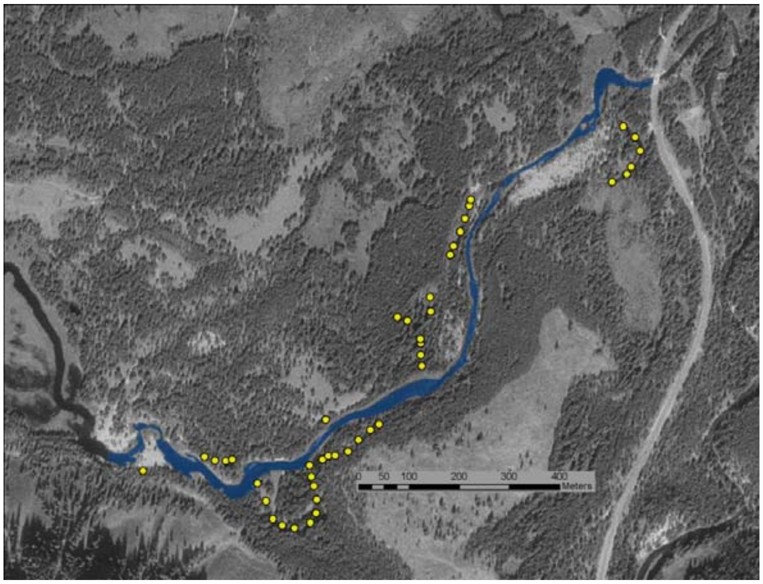

Figure 11. Flood stage indicators for Pattengail suggest a historic meandering channel once flowed through the valley.

CONCLUSIONS

The study sites represented two extremes a along gradient of channel type responsiveness and flow energy. Responsive channel types such as gravel beds and plane beds perpetually create, tear down, and recreate floodplain landforms (Montgomery and Buffington 1997). Energetic, overbank flows are required to rework floodplain sediment and create topographic heterogeneity. Floodplain landform heterogeneity (Poole 2002; Tabacchi and others 1998) and flow regime (Poff and others 1997) drive riparian vegetation establishment, community associations, and redirect successional trajectories. However, past a certain point, high energy flows can do more harm than good in terms of restoring a dam-altered river ecosystem. Through paleohydrology and aerial photo interpretation we were able to detect ecological response to dam removal and failure. We were unable to detect reversal of dam impacts due to the lack of dam impacts on Mystic and the high energy impacts of the dam breach flood in Pattengail. Our initial results suggest that channel type and stream flow magnitude played a significant role in the long term ecological response to the dam removal at these sites.

ACKNOWLEDGEMENTS

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The presentations and proposals were made based on the project funded by the USGS 104b Water Resources Research Program administered through the Montana Water Center.

Citations

Schmitz, Denine, Selita Ammondt, Matt Blank, and Duncan Patten. 2006. Using historic aerial photography and paleoflood hydrology to assess long-term ecological response to two Montana dam removals. USGS Water Resources Research Program.

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Student support

Selita Ammondt conducted ecological research into the effects of dam removal on riparian woody vegetation. She completed the entire research process including literature review, methods assessment, data collection, analysis, and presentation. Ammondt presented her work at the 2005 Center for Riverine Science and Stream Re-naturalization, 2005 Montana American Water Resources Association and 2006 Montana State University Undergraduate Scholar's Conference. She is currently assisting in the preparation of this work for submission to the journal Wetlands.

Steve Jay is currently conducting research into the effects of dam removal on the geomorphology of stream channels. He has completed preliminary analyses of the historic changes to the Upper Blackfoot River prior to the hazard reduction of Mike Horse Dam. He has presented his findings at the 2006 Montana State University Undergraduate Scholar's Conference and plans to present his final results at the 2006 Montana American Water Resources Association conference.

Ongoing work

The findings ascertained during this pilot study laid the foundation for submission of two proposals for further funding to the Sigma Delta Epsilon Graduate Women in Science Fellowship and the Montana DNRC Renewable Resources Grant and Loan program. The following summary describes the ongoing research.

Channel response assessment for the Upper Blackfoot – How to maximize development and preservation of water quality, riparian function, and fish habitat

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Montana State University
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Proposal Abstract

Helena National Forest (HNF) has committed to fully restoring ecosystem function to the floodplains in the Upper Blackfoot Mining Complex. As the focus now turns to concerns over the fate of Mike Horse Dam and the ensuing restoration, it is more important than ever to fully understand the nature of the stream system. Up and downstream from Mike Horse Dam floodplain ecosystem function is the product of centuries of natural variation in hydrology followed by decades of human changes in flow regime. *The goal of this project is to assess the ecological response potential of floodplains associated with Mike Horse Dam*. Two questions pertain to the Upper Blackfoot. 1) How can stream ecosystem restoration be maximized? And, 2) how can risk of further contamination be minimized? We will use the temporal and spatial contexts of the stream reaches to classify their potential ecological response to changes in flow regime induced by dam construction, breach, and hazard reduction. Historic aerial photographs from 1938 (pre-construction), 1961 (post-construction), 1966 (pre-breach), 1979 (post-breach), 1995 (post-breach), and 2005 (pre-reduction) will be used to track channel, floodplain, and riparian vegetation cover. Topographic surveys of flood stage indicators (flood scars and deposits) and valley wide cross sections will be used to model (HEC-RAS) past hydrologic events with step backwater and time varying techniques. From the historic ecological response classification we will predict responses to the proposed dam hazard reduction. To test this prediction we will collect topographic, hydrologic, and biological data at the same locations before and after action on Mike Horse Dam. An evaluation of floodplain ecological response based on its spatial and temporal context within the watershed will distinguish dynamic reaches from stable. Armed with this information decision makers can maximize restoration potential and minimize risk to contaminated sediment.

Goals

Helena National Forest (HNF) has committed to fully restoring ecosystem function to the floodplains in the Upper Blackfoot Mining Complex (**Error! Reference source not found.**). 1) How can stream ecosystem restoration be maximized? And, 2) how can risk of further contamination be minimized? Floodplain ecosystems are dependent on a natural flow regime— natural variability in flood size, frequency, rate of change, timing, and duration of flow (Poff and others 1997). Floodplain ecosystem function up and downstream from Mike Horse Dam is the product of centuries of natural variation in hydrology followed by decades of human changes in flow regime. Because recorded history extends over a century for the Mike Horse Mine area, there is an opportunity to assess floodplain topographic and riparian vegetation responses to past changes in flow regime. Through this assessment, changes in floodplain topography and riparian vegetation distribution may be attributed to specific events through an investigation of historical aerial photos and relicts of past floods. This information can be used to characterize the response potential of each reach in the floodplain area and inform a site specific, process-based restoration strategy. To achieve the long-term goal of a fully-functioning riparian system in the Upper Blackfoot watershed, an assessment of past ecological response is needed. *The goal of this project is to assess the ecological response potential of floodplains associated with Mike Horse Dam*.

Objectives

1. Determine the geomorphic response potential of stream reaches.
2. Determine the vegetative response potential of riparian communities along stream reaches.
3. Predict areas of high and low risk to impacts of dam hazard reduction for use in a monitoring program.
4. Determine the effect of past, current, and predicted geomorphic response potential of stream reaches on aquatic organism habitat and mobility.

Expected Results

1. Pool riffle and plane bed channel types (following Montgomery and Buffington 1997) will show greater response in channel morphometrics (width: depth, planform) and plant community structure (riparian overstory and understory extents) than cascade and colluvial channel types to:
    - a change from a natural to a dam altered flow regime.
    - dam breach.
    - dam hazard reduction.
2. Intermediate (based on hydrograph records and flow estimates) flood sizes following dam hazard reduction have higher restoration potential than small or high flood sizes for a given channel type (following Montgomery and Buffington 1997).
3. Aquatic organism habitat and mobility will be improved due to watershed approach to stream restoration.

Expected Products

1. Full descriptions of location, morphology, fluvial processes, and riparian plant communities for each reach between the Pass Creek/Blackfoot River confluence (study area) for 1938, 1961, 1966, 1979, 1995, 2005, and 2006 (study period).
2. Maps of channel type and riparian community distributions for each year in the study period.
3. Ranking of reaches (and specific locations if possible) on a relative scale of responsiveness.
4. Descriptions of reaches in terms of their risk for retaining or aggrading contaminated sediments over the next 10 years.
5. Considerations for restoration strategies for each reach based on the known and expected processes acting on each reach over time.

Project Implementation

Tasks

1. Objective 1 – Determine the geomorphic response potential of stream reaches.
    a. Classify stream reaches and valley segments according to Montgomery and Buffington (Montgomery and Buffington 1993).
        i. Using survey-grade GPS, topographically survey the entire floodplain of the study area and the channels of all tributaries before and after the dam hazard reduction. Attribute descriptive data for each landform and flood stage indicator with a mapping grade GPS unit.
            1. Map with centimeter precision channel and floodplain landforms.
            2. Map with centimeter precision channel cross sections.
            3. Map with centimeter precision indicators of past channel locations, flood stages, and relict landforms.
        ii. Using survey-grade GPS, topographically survey the channel centerlines of all tributaries above the Pass Creek-Upper Blackfoot River confluence.
        iii. Topographically assess watershed scale distributions in drainage area, channel slope, and upland slope using digital elevation model (dem) analysis.
    b. Determine geomorphic response to past changes in flow regime.
        i. Acquire and georeference aerial photos (1938, 1961, 1966, 1979, 1995, 2005).
        ii. Map channel type and floodplain landform distributions based on aerial photos (1938, 1961, 1966, 1979, 1995, 2005) and ground surveys (2007 and 2008).
        iii. Assess historic peak flows required to produce mapped flood stage indicators.
            1. Input cross section and flood stage indicator data into HEC-RAS hydrologic modeling software.
            2. Use a combination of step backwater and time varying techniques to model flow conditions at each flood stage indicator.
        iv. Apply trend analysis to changes in classification between photo years.
        v. Document events which may alter flow regime, floodplain geomorphology, or riparian vegetation.
        vi. Evaluate channel response to dam construction (1941), dam breach (1975) and dam hazard reduction (2007).
2. Objective 2 – Determine the vegetative response of riparian communities along stream reaches.
    a. Assess riparian community composition and structure in each reach type before and after dam hazard reduction.
    b. Determine riparian vegetation response to past changes in flow regime.
        i. Map riparian vegetation distributions based on aerial photos (1938, 1961, 1966, 1979, 1995, 2005) and ground surveys (2007 and 2008) before and after dam hazard reduction.

ii. Apply trend analysis to changes in riparian canopy cover distribution between photo years.

iii. Evaluate riparian response to dam construction (1941), dam breach (1975) and dam hazard reduction (2007).

3. Objective 3 – Determine the effect of past, current, and predicted geomorphic response potential of stream reaches on aquatic organism habitat and mobility.
   a. Inspect the system for man-made barriers (bridges, culverts, weirs, diversions, pipelines.
   b. Make recommendations for enhancing aquatic organism habitat and mobility.
4. Objective 4 – Predict areas of high and low risk to impacts of dam hazard reduction for use in a monitoring program.
   a. Forecast spring peak discharge and flow stages for each cross section for 2008.
   b. Extrapolate future changes in channel morphology to predict short and long term geomorphic response to hazard reduction of Mike Horse Dam
   c. Extrapolate future changes in riparian vegetation distribution to predict short and long term riparian vegetation response to hazard reduction of Mike Horse Dam

Schedule

Jul 2007	Survey and map watershed channel slopes, cross sections, and flood stage indicators before dam hazard reduction with survey-grade GPS Assess riparian community composition and structure in each reach type before dam hazard reduction
Sep-Nov 2007	Assess historic peak flows
Sep 2007	Acquire and georeference aerial photos
Nov 2007	Map channel type, visible landforms, and riparian vegetation distribution along stream reaches in each aerial photo
Jan 2008	Apply trend analysis to changes in channel type, floodplain landforms, and riparian vegetation distribution between photo years
Feb 2008	Conduct dem analysis of drainage area, channel slope, and upland slope distributions
Mar 2008	Document events which may alter flow regime, floodplain geomorphology, or riparian vegetation
Apr 2008	Extrapolate changes in channel morphology and riparian vegetation distribution to predict short term ecologic response to hazard reduction of Mike Horse Dam
May 2008	Forecast spring peak discharge and flow stages for each cross section for 2008
Jul 2007	Survey and map watershed channel slopes, cross sections, and flood stage indicators after dam hazard reduction with survey-grade GPS Assess riparian community composition and structure in each reach type after dam hazard reduction
Aug-Oct 2008	Extrapolate changes in channel morphology and riparian vegetation distribution to predict long term ecologic response to hazard reduction of Mike Horse Dam

STUDENT FELLOWSHIP: Antibiotic resistance in ground-and surface-water microbes in the Missoula area

Basic Information

Title:	STUDENT FELLOWSHIP: Antibiotic resistance in ground-and surface-water microbes in the Missoula area
Project Number:	2005MT51B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Biological Sciences
Focus Category:	Groundwater, Water Quality, Water Supply
Descriptors:	
Principal Investigators:	Lewis Kogan, William Holben

Publication

Research Summary, Water Center Fellowship Research Work
Lewis Kogan/William Holben Laboratory

Spotted knapweed is a highly invasive weed species in Montana, where invasion often results in massive disruption of stream-side flora, causing increased sediment runoff into waterways, and the associated declines in certain aquatic plant and animal species. Following recent research which showed that Spotted knapweed (Centaurea maculosa) is responsible for the secretion of two enantiomeric forms of the flavenoid chemical *catechin*, and reports that catechin may exhibit antimicrobial properties, we decided to investigate the specific effects of catechin exposure on common soil bacteria. Because soil bacterial communities are critical to the survival of many plant species, we hypothesized that catechin may be responsible for the major disruption of intact soil microbial communities on which native flora rely for survival. Our aim was to determine whether catechin exposure was inhibitory to specific soil bacteria.

Over the course of the past year, we have performed a number of experiments in the laboratory, including the following:

(1) ~ 500 microbial strains isolated from soil samples from knapweed-present and knapweed-absent sites were tested for resistance to catechin at environmentally significant concentrations. Percentages of overall resistance to catechin were calculated using Most Probable Number analyses, plate counts and UV/vis spectroscopy. ~ 20 strains of special interest were then isolated for future experimentation and identified by DNA sequencing.
(2) Isolated strains were tested for growth success over time, under different conditions including no catechin; high and low steady-state catechin levels; decreasing catechin levels; periodically re-applied catechin exposure; and catechin exposure followed by complete removal of catechin from the system.
(3) Isolated strains were tested for growth success over time when exposed to catechin in the presence of varying carbon source substrates. API carbon usage and enzyme tests were performed on several isolates of interest.
(4) Isolates capable of sporulation were tested for spore-formation success and recovery success using spectrophotometry when sporulation and recovery were induced in the presence of catechin.
(5) The abiotic stability of catechin over time in liquid media with varying chemical properties was examined using HPLC analysis, including factors such as varying pH; addition of specific metals and chelators; and addition of specific organic acids.

Results of the experiments showed a varied and somewhat complex relationship between soil bacteria and catechin exposure. At low concentrations (500 ppm) catechin was minimally inhibitory but at higher concentrations (2000-3000 ppm), catechin was highly inhibitory, inhibiting growth in ~ 60 to 80% of bacterial species tested.

Catechin appears to be a microbistatic compound, rather than an antimicrobial: following removal of catechin from an experimental system, inhibited microbes were able without exception to resume normal growth. In microbial systems where catechin is added initially but not reapplied, catechin concentration usually drops steadily, with catechin apparently converting to another compound, and is followed by very slow recovery of microbial growth…though whether this conversion of catechin is due to biological activity or an abiotic chemical reaction is uncertain.

Utilizing different carbon sources available for microbial utilization did not noticeably change resistance/susceptibility to catechin by the isolated organisms, with the exception of the organic acid *pyruvate*. None of the organisms tested were inhibited by catechin when grown in the presence of pyruvate as the sole carbon source. The biochemical basis of this discovery is still under investigation.

Catechin’s effects on sporulation were not uniform. For some organisms, sporulation and recovery from spores were both unaffected. For other organisms, sporulation was inhibited, but not recovery from sporulation, and in other cases only recovery from sporulation was inhibited. The biochemical basis of these results are also still under investigation, but calcium binding by catechin may be a factor.

Catechin proved to be highly stable over time at low pH (~ 4) and highly unstable at high pH (~ 9). Addition of metals to abiotic catechin media produced varying results, with calcium addition causing the highest catechin stability and copper addition resulting in the greatest level of catechin instability. The effect of organic acids on catechin stability did not appear significant.

In conclusion, catechin *does* appear to be highly inhibitory to many soil microbial genera. Some genera, however, appear naturally resistant, including *pseudomonas* and *rhodococcus* species. Catechin is not highly inhibitory under all conditions, and the factors which govern its inhibitory properties are many and varied. Because we now have a much better understanding of microbial inhibition by catechin in the lab environment, the next step is to proceed in *in situ* analysis of microbial communities, using potting experiments and microbial community DNA extraction techniques. The combination of controlled *in vitro* experiments and observation of catechin-microbial interactions in real *in situ* conditions should allow us to make accurate conclusions about the validity of the hypothesis that knapweed invades by means of disruption of soil microbial communities.

STUDENT FELLOWSHIP: Movement, habitat use, and food habits of sauger and walleye: an investigation of resource overlap in the middle Missouri River, Montana

Basic Information

Title:	STUDENT FELLOWSHIP: Movement, habitat use, and food habits of sauger and walleye: an investigation of resource overlap in the middle Missouri River, Montana
Project Number:	2005MT54B
Start Date:	3/15/2005
End Date:	6/31/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Biological Sciences
Focus Category:	Ecology, Management and Planning, None
Descriptors:	
Principal Investigators:	Christopher Guy, Brian Bellgraph

Publication

1. Bellgraph, Brian, 2006, M.S., "Competition potential between sauger and walleye in non-native sympatry: historical trends and resource overlap in the middle Missouri River, Montana," Ecology Department, Montana State University, Bozeman, Montana, 95 pages.

Final Report
Montana Water Center Fellowship
Brian Bellgraph
April 17, 2006

Summary of Project Findings:

Sauger *Sander canadensis* populations throughout Montana and North America have exhibited declines over the past few decades. Sauger population abundance declined in the middle Missouri and Yellowstone rivers of Montana in the mid-1980s following a period of drought. Higher flows resulted in a rebound of the lower Yellowstone River population; however, the middle Missouri River population has remained at low abundance. Various factors may contribute to the reduced population abundance of sauger in the middle Missouri River, including interspecific competition with walleye *Sander vitreus*. Historical trend data of sauger and walleye were assessed to determine long-term trends of sauger and walleye fitness. To assess competition potential, seasonal migrations, habitat use, and diets of both species were compared in the middle Missouri River. Trophic position of sauger was also compared between the middle Missouri and Yellowstone rivers to evaluate the trophic status of sauger in sympatry and allopatry with walleye. Sauger and walleye were tracked using radio telemetry to establish and compare seasonal migrations. Habitat use was compared at three hierarchical scales, diets were collected on fish sampled using electrofishing, and diet overlap was calculated. Trophic position was calculated using stable isotope analysis. Historical trend data indicated that sauger and walleye are currently at low abundance and sauger had low relative weights, which is likely due to low prey availability. Prior to the presumed spawning period, 96% of the sauger and 57% of the walleye migrated downstream as far as 273 km. After spawning, both species returned to previously-occupied river reaches and demonstrated site fidelity during the non-migratory season. Habitat use and selection by sauger and walleye were similar at all three hierarchical scales. Diet overlap was high during the spring [0.72 (SE=0.003)] and summer [0.95 (SE=0.0008)] and moderate during autumn [0.49 (SE=0.003)]. Sauger trophic position differed statistically between the middle Missouri and Yellowstone rivers; however, the biological consequences of the difference are uncertain. Overall, resource overlap of sauger and walleye in the middle Missouri River, Montana suggests that competition potential between these species is high, which may preclude the recovery of native sauger populations if resources are limiting.

STUDENT FELLOWSHIP: The effects of recent watershed deglaciation, climate change, and microbial processes on nitrate loading and ecological response in high alpine aquatic systems of Grand Teton National Park

Basic Information

Title:	STUDENT FELLOWSHIP: The effects of recent watershed deglaciation, climate change, and microbial processes on nitrate loading and ecological response in high alpine aquatic systems of Grand Teton National Park
Project Number:	2005MT56B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Climate and Hydrologic Processes
Focus Category:	Climatological Processes, Geochemical Processes, Nutrients
Descriptors:	
Principal Investigators:	Kathy Tonnessen, Jennifer Corbin

Publication

Project Title:

The effects of recent watershed deglaciation, climate change, and microbial processes on nitrate loading and ecological response in high alpine aquatic systems of Grand Teton National Park.

Student:

Jennifer Corbin – Ph.D. Candidate
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Abstract:

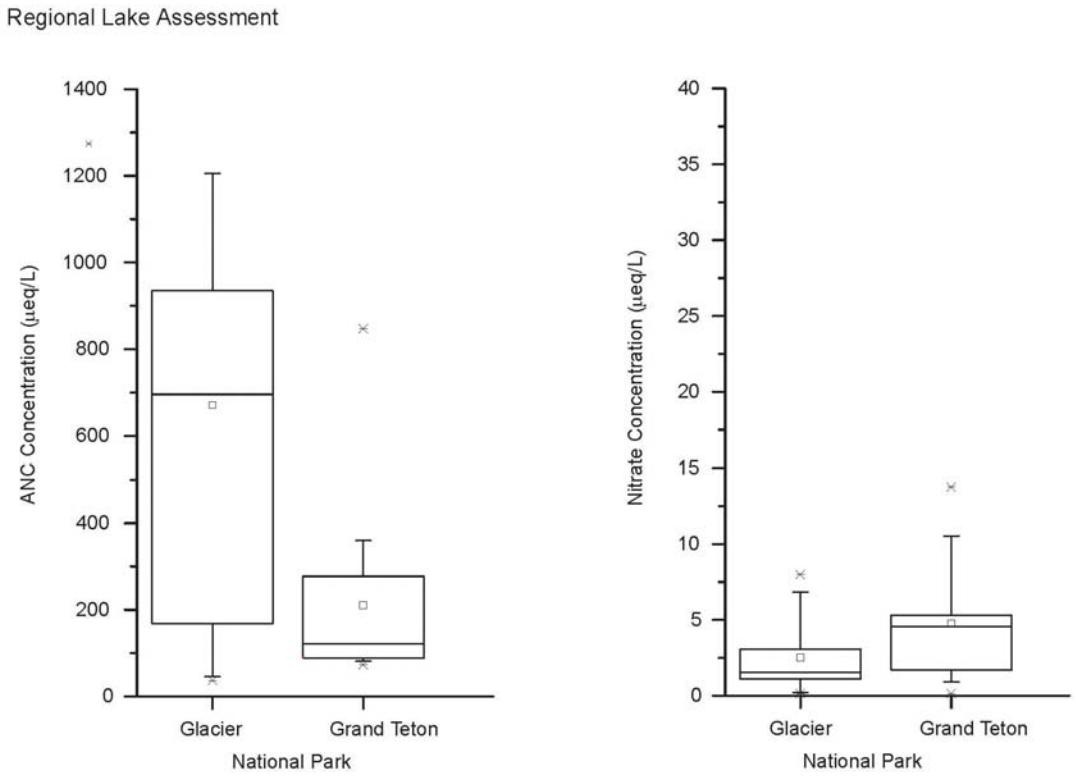
The objective of this project was to build on a completed study of lake chemistry in the alpine zone of the Rocky Mountains and take into account the interactions of atmospheric deposition, change in runoff from glaciers and snowfields, and changes in the way soils and talus interact with precipitation and snowmelt. One initial step focused on the comparison of alpine lakes in both Glacier (GLAC) and Grand Teton (GRTE) National Parks and the selection of chemically sensitive lakes [acid neutralizing capacity (ANC) < 50]. Water chemistry from sensitive lakes would then be analyzed to compare the seasonal influx of nutrients during the snow and glacier melt periods. Finally, the source of nutrients (glacial meltwater, snowmelt, or atmospheric deposition) would be estimated based upon nutrient concentrations (specifically nitrate) in soil, ground water and surface water, atmospheric deposition and nitrogen-fixing plant material.

Research Accomplishments and Conclusions:

During Fall 2004, the USGS sampled lakes in both GRTE and GLAC (Nanus 2005). Comparison of these data with the data collected in 2002 at GRTE (Corbin 2004) emphasizes the sensitivity of GRTE lakes (Figure 1). The GRTE lakes have both a lower acid neutralizing capacity and more “leakage” of inorganic nitrogen than the lakes sampled in GLAC. In addition, National Atmospheric Deposition Program (NADP) trend diagrams of NO_3^- and NH_4^+ for Yellowstone National Park (YELL) at Tower Junction (Station WY08) show that significantly higher concentrations of both nitrogen sources are falling in the YELL area. Because GRTE and YELL are subjected to similar air masses, we have used the Tower Junction data as a surrogate for absent deposition data in GRTE (Peterson and Sullivan 1998). Therefore, lakes in the Teton Range may be subjected to larger concentrations of atmospherically deposited solutes than alpine lakes in Glacier NP.

To interpret these alpine lake data sets in National Parks and Wilderness areas of Montana and Wyoming, we will be carrying out an intensive, paired watershed study in Grand Teton National

Park. This headwater lake study will allow us to estimate the flux of nitrogen species from snowmelt and rain through two side-by-side watersheds - one with glacial melt and one without. We will incorporate detailed climate monitoring into the sampling program and have secured permits to install climate and deposition monitoring stations in the spring of 2006. In addition, snow surveys have been scheduled for March 2006 and will occur in conjunction with the USGS snow chemistry monitoring program (Ingersoll 2002). We are confident that this study should give managers valuable information on the dual stresses of air pollution and global climate change and their effects on lake water quality.



Box plots showing distribution of ANC and nitrate concentrations measured at lakes in Glacier National Park (n=15) and Grand Teton National Park (n=16) during Fall, 2004.

Figure 1 - Comparison of ANC and NO_3^- concentrations in Glacier National Park and Grand Teton National Park lakes (Reprinted with permission from Nanus et al. 2005).

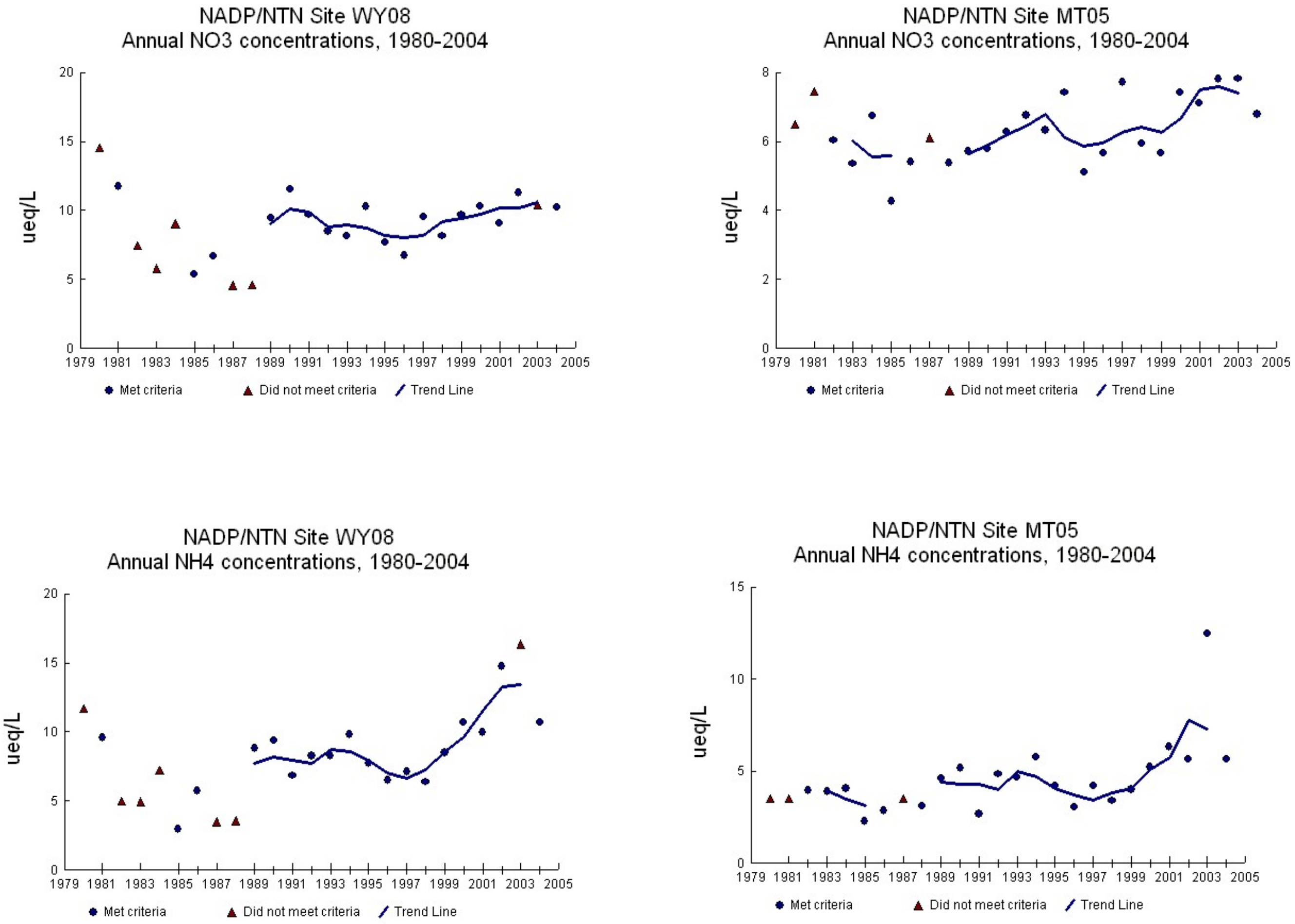


Figure 2 – National Atmospheric Deposition Program/National Trends Network (NADP/NTN) trend plots for NO_3^- and NH_4^+ in Yellowstone National Park (WY08) and Glacier National Park (MT05) (National Atmospheric Deposition Program 2005).

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Nanus, L., Williams, M.W., Campbell, D.H.,2005. Regional Assessment of the Relationship Between Landscape Attributes and Water Quality in Five National Parks of the Rocky Mountains. *Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract H23D-1458.*

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STUDENT FELLOWSHIP: Stream-groundwater interactions in a mountain to valley transition: impacts on watershed hydrologic response and stream water chemistry

Basic Information

Title:	STUDENT FELLOWSHIP: Stream-groundwater interactions in a mountain to valley transition: impacts on watershed hydrologic response and stream water chemistry
Project Number:	2005MT58B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Ground-water Flow and Transport
Focus Category:	Geomorphological Processes, Groundwater, None
Descriptors:	
Principal Investigators:	Brian Leonard McGlynn, Timothy Covino

Publication

1. Covino, Tim and Brian McGlynn, 2006, M.S. "Groundwater-stream interations in a mountain-valley transition: impacts on watershed hydrologic response and stream water chemistry," Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, 112 pages.

Results of the research conducted by this student fellow can be viewed earlier in this report in the McGlynn study.

STUDENT FELLOWSHIP: Movements of resident and non-resident anglers in Montana: implications for transferring whirling disease among drainages in the Greater Yellowstone Ecosystem

Basic Information

Title:	STUDENT FELLOWSHIP: Movements of resident and non-resident anglers in Montana: implications for transferring whirling disease among drainages in the Greater Yellowstone Ecosystem
Project Number:	2005MT59B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Social Sciences
Focus Category:	Ecology, Sediments, Management and Planning
Descriptors:	
Principal Investigators:	Christopher Guy, Kiza Gates

Publication

2005/2006 Water Center Fellowship Final Report

Movements of Resident and Non-Resident Anglers in Montana: Implications for Transferring Whirling Disease among Drainages in the Greater Yellowstone Ecosystem

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Abstract

Despite extensive research surrounding *Myxobolus cerebralis,* the causative agent of whirling disease, little is known about the parasite's transfer among drainages. Anglers represent a highly mobile group of individuals that travel among water access sites; however, it has not been established whether anglers are capable of transferring whirling disease. The myxospore phase of *M. cerebralis* is resistant to environmental stresses such as heat, cold, and desiccation. This makes it perceivable that spores could be transported on angling gear from one fishing site to another. To answer this question we plan to survey anglers and sample fishing equipment at popular fishing access sites on the, Beaverhead, Bighorn, Gallatin, Madison, Missouri, and Yellowstone rivers. The effectiveness of nested PCR testing at detecting small numbers of myxospores in water and sediment samples will also be evaluated. If PCR testing is successful, it will be used on samples collected from angling gear. Sediment and water samples will be cross-referenced with angler survey information to determine the origin of spores, if present, and the mobility of the angler carrying spores. In addition, survey data will document the movement of resident and non-resident anglers among basins within the Greater Yellowstone Ecosystem (GYE). Results from this study will be useful for developing management strategies aimed at reducing the spread of whirling disease and other invasive species.

Accomplishments

Goal 1: Assess the detectability of myxospores through PCR analyses in varying amounts of benthic sediment.

Test samples with known spore and sediment quantities were created in the Montana State University Trout Lab and sent to Biogenetics Laboratory in South Dakota for PCR analysis. The results were inconclusive; the lab was unable to detect even large numbers of spores when sediment was present in the sample. These results may have been caused by inhibitors present in the sediment. Another PCR lab (Pisces Molecular) was contacted and secondary test samples were sent to them in December of 2005. These samples also yielded inconclusive results possibly due to a fungal contaminant in the spore solution used to create the samples. Additional samples were sent with fresh myxospores and these yielded positive detection of myxospores in samples containing large quantities of myxospores (10,000 and 100,000) and small quantities of sediment (0.01g and 0.1g). Problems were encountered with inhibitors in the samples containing 1.0g of sediment that prevented PCR from detecting the presence of even large quantities of myxospores (100,000). Test samples with smaller quantities of myxospores (1,000 and 100) and the same quantities of sediment (less than 1.0g) are currently being prepared for PCR testing.

In addition to the PCR testing, in the fall of 2005 we developed a sediment texture centrifuge method for isolating spores from sediment by density separation. Although there is much information about the development of myxosporean spores, little is known about the movement of spores in water and their interactions with sediment. Varying quantities of sediment and stained myxospores were combined with aqueous sodium hexametaphosphate ($[NaPO_3]_6$). We were able to extract myxospores from all of the sediment and myxospore samples using a sediment texture centrifuge technique to separate particles by density. The mean percent myxospore recovery declined as the quantity of sediment added to each sample increased. These results support previous research indicating that even small quantities of sediment in a sample can negatively affect myxospore extraction. The sediment texture centrifuge technique used with aqueous $[NaPO_3]_6$ effectively isolated *M. cerebralis* myxospores from water samples with no sediment. This technique could be used to assess whirling disease infection levels in water samples without sediment.

Goal 2: Identify movement patterns of resident and non-resident anglers.

Humans play an influential role in the transport of aquatic nuisance species (ANS) throughout the world. Understanding the movement patterns of anglers in Montana will provide information regarding the potential transport of aquatic nuisance species among drainages, states, and globally. We surveyed anglers at access sites on the Beaverhead, Bighorn, Gallatin, Madison, Missouri, and Yellowstone rivers in Montana from June through August of 2005. Anglers were asked questions regarding their most recent prior fishing trip, fishing trips in the past month, planned fishing trips in the coming week, and their state or country of residence. Of the anglers surveyed, 40% were Montana residents whereas 60% where non-residents. Non-residents represented 39 states and 2 foreign countries. Over half of all non-residents surveyed had fished in at least one other state than Montana in the past month. The average distance traveled by Montana residents from their home was 59 miles (± 67, [95% CI], n=112). The average distance traveled by non-residents was 1,067 miles (± 769, [95% CI], n=162). Our results indicate that anglers in Montana are highly mobile.

Goal 3: Determine the amount of benthic sediment on waders, boats, and boat trailers from anglers.

A study design was completed for angler equipment sampling and was conducted for four months on the Beaverhead, Madison, Gallatin, Missouri, Yellowstone, and Bighorn Rivers. Logistical problems arose with sampling boats and boat trailers (we were unable to take samples from entire boats or boat trailers due to sample size restrictions and water source availability). We were not able to develop a precise method for subsampling varying types of boats and boat trailers either. As a result, samples were only obtained from angling boots and waders. Half of each sample was frozen and stored for future spore analysis while the other half of each sample was dried to determine dry sediment quantity carried by anglers. Dry sediment samples were sifted through to look for other possible aquatic hitchhikers such as New Zealand mud snails and noxious weed seeds. A New Zealand mud snail was found in one of the boot rinses however, it was determined that the snail was already deceased at the time of sampling. The average angler in the Greater Yellowstone Ecosystem is carrying 22.10 g (± 8.6, [95% CI], n= 42) of sediment on their boots and waders. Anglers in the Greater Yellowstone Ecosystem are capable of transporting detectable quantities of sediment between access sites. The potential for this sediment transport to move aquatic nuisance species that may be found in the sediment among drainages in Montana is of concern.

Goal 4: Test for the presence of myxospores in the benthic sediment from waders, boats, and boat trailers using polymerase chain reaction (PCR).

Awaiting results of Goal 1.

Goal 5: Experimentally test the accumulation of benthic sediment and the presence of myxospores on various wader and boot types.

Currently developing study design for spores adherence study to be conducted spring of 2006.

Conclusions

Polymerase Chain Reaction testing is not able to detect the presence of myxospores in samples containing greater than 1.0 g of sediment. Given the high average quantity of sediment carried by anglers on their boots and waders, we may need to sub-sample in order to keep the quantity of sediment below 1.0g when sending samples for PCR analysis this fall.

Preliminary results indicate that anglers in the Greater Yellowstone Ecosystem are moving between multiple drainages and multiple states within one-month periods. This coupled with the ability of anglers to transport significant quantities of sediment among sites on their boots and waders raises concern about the potential transport of nuisance species on angling equipment. Increased angler awareness campaigns and access site monitoring could be of value in preventing the spread of aquatic nuisance species among access sites. Providing angler wash stations at access sites may also be a way to encourage gear cleaning and raise awareness among anglers.

STUDENT FELLOWSHIP: The relationships between flood frequency, microhabitat variability, and riparian vegetation spacial pattern in montaine steams of western Montana

Basic Information

Title:	STUDENT FELLOWSHIP: The relationships between flood frequency, microhabitat variability, and riparian vegetation spacial pattern in montaine steams of western Montana
Project Number:	2005MT60B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Climate and Hydrologic Processes
Focus Category:	Floods, Sediments, Ecology
Descriptors:	
Principal Investigators:	Scott Woods, Motoshi Honda

Publication

The relationships between flood frequency, microhabitat variability, and riparian vegetation spatial pattern in montane streams of Western Montana

Motoshi Honda
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Abstract

Flooding plays an important role for spatial pattern of vegetation species in the riparian zone. However, its effects may not be clear due to presence of intermediate processes and spatial autocorrelations. I investigated relationships between environmental variables (flood frequency, soil, and light), spatial pattern of different vegetation measures (herb cover, shrub cover, tree density, and tree basal area) in three riparian zones of mountain streams from Western Montana. I used two methods, the boundary analysis and partial Mantel test, to quantify spatial relationships between environmental factors (flood frequency, soil, and light) and vegetation. The partial Mantel test can remove influence of a third variable, which may have confounding effect on the relationship of interest, and influence of spatial autocorrelation of vegetation. The boundary analysis computes the degree of spatial co-occurrence between two boundaries, defined as locations of high turnovers (species or variables).

The preliminary results (using standardized elevation instead of flood frequency) of partial Mantel tests from Mission Creek show minimum influence of spatial autocorrelation on all vegetation measures in spite of significant Moran's I values (a measure of spatial autocorrelation) in some vegetation measures. In the study area located at the north side of the creek, Mantel statistics between herb cover and light is considered as both statistically and ecologically significant while in the south side almost all the relationships between vegetation and variables are statistically and ecologically significant. The results based on the boundary analysis show higher co-occurrences of boundaries between vegetation and variables, and also among variables in the south side. These results suggest existence of a strong underlying driver affecting environmental variables in the south side. However, the major driving factor affecting herb species in Mission Creek site appears to be light because significantly strong relationships between herb and light remain even after removing space, elevation, and soil factors whereas the relationships become ecologically insignificant for elevation and soil after removing light. In Mission Creek, physical factors drive spatial pattern of vegetation species, but a major driver differs for different vegetation measures and different study areas.

Research Accomplishment

Vegetation, hydrological, and environmental data were gathered from three riparian zones along Kootenai and Bear Creeks from the Bitterroot Range and Mission Creek from the Flathead Indian Reservation in Western Montana during the 2005 field season. Each study site consisted of two to three study areas located on both sides of the stream. A size of each area ranged from 24 to 32m (along the stream) by 40 to 100m (across the valley). In 100 to 166 quadrats (plots) of 4 by 4 m, the basal area of all tree and shrub species more than 3.5cm in circumference at the breast height were measured, and their presence-absence were recorded. Each 4 by 4m plot was stratified into two 2 by 2m plots, and 2 by 2m plot was stratified into for 0.5 by 0.5m plots. The cover of shrub species (>30cm in height, <3.5cm in circumference) was estimated, and the presence-absence were recorded in all 2 by 2m plots. The cover of herbaceous species (<30cm) was estimated, and the presence-absence were recorded in one or two 0.5 by 0.5m plots randomly selected from each 2 by 2m plot. Understory plots (shrub and herb) within each 4 by 4m plot were combined to obtain average cover scores in order to compare different vegetation types and environmental variables at the same scale (4 by 4m). Ten to fifteen 2.54 by 10.16cm soil subsamples were taken from each 4 by 4m plot to form one representative sample of the plot. At each subsampled location, the depth of the organic horizon (O horizon) was measured. The soil samples have been analyzed for soil texture and pH. Hemispherical photos were taken at the center of the 4 by 4m plots to calculate the canopy openness by Gap Light Analyzer. A series of flow measurements were made in Kootenai Creek and Bear Creek while the flow data from the nearby USGS gauge were used for Mission Creek. The main and side channels were surveyed in the approximately 5m interval through the study areas. The study site topography was surveyed by a total station survey equipment. The boundary analysis and partial Mantel tests were performed on Mission Creek data using all vegetation types and all environmental data except flood frequency. Hydraulic modeling is underway using HEC-GeoRAS (combination of one dimensional flow model and TIN floodplain map) to estimate flood frequency for each plot. Instead, one elevation value for each 4 by 4m plot was assigned by averaging all the elevation points from the total station survey within the plot, and then the plot elevation value was standardized according to the valley slope for partial Mantel tests. Average elevation values were used for the boundary analysis.

Preliminary Conclusion

In Mission Creek, two study areas were placed in north and south side of the creek, and two areas show different floodplain topographies even though the dominant species remains western red cedar (*Thuja plicata*). In the south side, elevation increases monotonically from the channel where as the north side is dissected by side channels. Flooding is the ultimate driver of the system, but its influence varies temporally and spatially depending on vegetation types and topographic features. The preliminary results from Mission Creek show higher Mantel statistics and spatial boundary co-occurrences between vegetation and variables and among variables in monotonically changing topography. A major driver appears to be light for herb species in both study sites, and this may be attributable to conifer dominance of the study areas. Insignificant Mantel statistics in the north side and negative spatial co-occurrences of boundaries between tree basal areas and variables in both north and south sides suggest temporal variability of environmental factors and that the spatial patterns of tree basal area are not readily explicable by the current environmental conditions.

Spatial autocorrelation is often present in vegetation data as plots located closer in geological locations share similar vegetation composition and abundance (positive autocorrelation) than they are further apart. In spite of the fact that there are positive autocorrelation at short scale for most of the vegetation measures, the results from partial Mantel tests suggest spatial autocorrelation plays a minor role in vegetation spatial patterns in Mission Creek study areas. Spatial autocorrelation may become an important factor if a grain size (plot size) and extension of study site are changed.

STUDENT FELLOWSHIP: Environmental conditions associated with the extent and composition of woody riparian vegetation within the West Fork of the Gallatin River watershed

Basic Information

Title:	STUDENT FELLOWSHIP: Environmental conditions associated with the extent and composition of woody riparian vegetation within the West Fork of the Gallatin River watershed
Project Number:	2005MT62B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Climate and Hydrologic Processes
Focus Category:	Ecology, Geomorphological Processes, None
Descriptors:	
Principal Investigators:	Duncan T. Patten, Levia Shoutis

Publication

Levia Shoutis Montana Water Center June 2006 Progress Report

Abstract

Contact:
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Project Title: Environmental conditions associated with the extent and composition of woody riparian vegetation within the West Fork of the Gallatin River watershed

Riparian vegetation provides stability to banks and hillsides, influences biogeochemical processes, and interacts with both surface and groundwater to alter near-stream flow systems. It also provides a disproportionate amount of wildlife habitat relative to its area occupied on the landscape. This study focuses on woody riparian vegetation within the West Fork of the Gallatin River watershed. The primary objectives are to: (a) assess the significance of environmental factors as driving variables of riparian vegetation structure and composition and (b) assess the ability of remotely sensed topographic data to predict the vertical and lateral extent of riparian vegetation above the stream.

Research Accomplishments

The first objective was addressed during the 2005 field season. I sampled 80 plots across 30 sites within the main stem of the West Fork of the Gallatin River, and along two tributaries, the Middle Fork and Beehive Creek. Plots were located on one of three visually-determined landforms extending laterally from the stream channel (floodplain, terrace, and adjacent upland). Within each plot, percent cover of trees and shrubs was sampled, and the following environmental variables were collected: elevation, plot height above the stream, plot distance from the stream, floodplain width, valley confinement and stream gradient.

This initial data set was analyzed using multivariate methods. When data from all three landforms were included, species composition was related most strongly to elevation and plot height above the channel. When only floodplain and terrace data were used, species composition was related mostly to elevation and floodplain width. Additional sampling will occur within the West Fork watershed during the summer of 2006.

Conclusions

This study will provide valuable insights into riparian vegetation-environment relationships, as well as increase our understanding of the ability to use remotely sensed topographic data to predict the extent and composition of riparian vegetation in small mountain watersheds.

STUDENT FELLOWSHIP: Watershed carbon distribution and flux across environmental gradients

Basic Information

Title:	STUDENT FELLOWSHIP: Watershed carbon distribution and flux across environmental gradients
Project Number:	2005MT64B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Ground-water Flow and Transport
Focus Category:	Geochemical Processes, Solute Transport, Water Quality
Descriptors:	None
Principal Investigators:	Brian Leonard McGlynn, Vince Pacific

Publication

May 23, 2006

Susan Higgins, Communications Director
Montana Water Center
101 Huffman Hall
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Re: Montana Water Center Student Research Fellowship Final Report

Dear Ms. Higgins,

I am writing to give a final report on my research project "Watershed carbon distribution and flux across environmental gradients", which is supported in part by the Montana Water Center Student Research Fellowship Program. I am including my abstract with contact information, my research accomplishments, and conclusions.

Abstract:

The spatial and temporal controls on soil CO_2 production and efflux have been identified as an outstanding gap in our understanding of carbon cycling. We investigated the primary driving factors and their variability over space and time of soil CO_2 concentration and efflux across environmental gradients in the 550 ha Stringer Creek watershed, Little Belt Mountains, Montana. We collected measurements of soil temperature, soil moisture, C:N ratios, CO_2 efflux, and soil air CO_2 concentrations at two depths (20 cm and 50 cm) at 32 locations across riparian/hillslope transitions in a high elevation mountain watershed in the northern Rocky Mountains. We found that aspect exerted a large control on soil CO_2 concentrations and efflux as western aspects had larger CO_2 concentrations and efflux than eastern aspects. We also found that riparian landscape positions showed greater variability in soil CO_2 concentrations and efflux than hillslope landscape positions. In addition, we installed and collected hourly data from groundwater monitoring wells at over half of the sampling locations in order to determine the effect of groundwater fluctuations on soil CO_2 concentrations and efflux. We found a large increase in soil CO_2 concentrations and efflux as riparian landscape positions changed from saturated to unsaturated conditions. We also examined the diurnal variation in soil CO_2 concentrations and efflux and found that both CO_2 concentrations and efflux reached their maximum during the late afternoon. We conclude that environmental gradients related to catchment topography in soil moisture and soil temperature led to CO_2 concentration and efflux heterogeneity through space and time. We suggest that controlling variables such as riparian versus hillslope landscape position, aspect, differences in C:N ratios, and groundwater fluctuations are the primary controls on heterogeneity in CO_2 concentration and efflux across riparian/hillslope transitions.

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Collaborators that will be listed on poster and in pamphlet (in order of “importance”)

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Research Accomplishments:
For this project, I installed 120+ CO_2 monitoring wells, 60+ soil surface CO_2 efflux plots, and 60+ groundwater wells and piezometers. My experimental design was set up to determine differences in CO_2 production and efflux across different riparian/hillslope transitions throughout the Stringer Creek watershed in the Little Belt Mountains of central Montana.

Conclusions:
CO_2 concentrations and efflux were highly variable, both within and between dominant landscape elements. This heterogeneity was the result of a fluctuating groundwater table, differences in soil moisture, soil temperature, soil nutrient status, organic matter availability, CO_2 concentration gradients, and soil diffusional properties, all of which changed with landscape position. My most significant results are as follows:

1. **Excess soil moisture inhibited soil CO_2 production in riparian landscape positions**. Riparian zones showed greater variability in soil CO_2 concentrations than the hillslope zones along the same transect. Once the water table dropped in the riparian zone, soil saturation no longer inhibited respiration, and CO_2 concentrations quickly climbed up to two orders of magnitude.
2. **Soil CO_2 concentrations and efflux were controlled by soil temperature in hillslope landscape positions.** Soil CO_2 concentrations increased as soil temperatures increased and soil moisture levels remained nearly constant. There was also a small peak in hillslope soil CO_2 concentrations at the end of August, which was controlled by soil moisture as soil temperature remained nearly constant. Thus, **the relative control of soil temperature vs. soil moisture on soil respiration reversed on hillslopes during warm summer months when soil moisture limited respiration.**
3. **Soil CO_2 efflux diurnal fluctuation was controlled by variations in soil temperature**. Peak flux rates occurred late in the afternoon at levels 2-5 times as high as those measured late at night or early in the morning.
4. **Riparian zone soils showed much higher CO_2 concentrations than those soils located in hillslope landscape positions along the same transect.** This was attributed to the proximity of the water table in riparian landscape positions.
5. **The snowpack (1-2 m) exerted a strong influence on soil CO_2 concentrations and efflux as it insulated the ground and formed a poorly permeable layer.** This resulted in a large buildup of CO_2 underneath the snowpack and a decrease in CO_2 efflux.

These results were presented at the Montana Chapter of the American Water Resources Association meeting (October, 2005) in Bozeman, MT and the Fall Meeting of the American Geophysical Union (December, 2005) in San Francisco, CA. I acknowledged financial support from the Montana Water Center at both of these presentations.

Sincerely,

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STUDENT FELLOWSHIP: Clonal recruitment of Populus angustifolia along the Yellowstone River: extent and requirements

Basic Information

Title:	STUDENT FELLOWSHIP: Clonal recruitment of Populus angustifolia along the Yellowstone River: extent and requirements
Project Number:	2005MT67B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Biological Sciences
Focus Category:	Ecology, Surface Water, Management and Planning
Descriptors:	
Principal Investigators:	Donald Potts, Mary Louise Polzin

Publication

1. Polzin, Mary Louise, 2006, Ph.D. dissertation, "Temporal and Spatial Patterns of P. angustifolia along the Upper Yellowstone River and Clonal Recruitment: Extent and Requirements," College of Forestry and Conservation, Montana State University, Missoula, Montana.

Polzin December 12, 2006 mid-report:

Dear Susan Higgins:

I have been busy since the fellowship started with writing up the results of my research for my thesis. Presently I have just completed my thesis and will send it out to all of my committee members by Monday Dec. 19 at the latest. I have had two review processes of all of the chapters by Dr. Merigliano (chapters 1 and 2) and Dr. Fishman (chapters 3 and 4) with the last chapter (4) coming today (Dec. 16). Once all the committee has had a chance to read my thesis I will find out if it is ready to defend or if I need to work on some areas first. If it is ready to defend, I will set this up for some time in January after the 9th as expressed by one of my committee member. I then plan on working on a paper on the clonal process of *P. angustifolia* along the upper Yellowstone River with publication in 2006.

My discovery of the clonality of the upper Yellowstone River is the backbone of the organization of the thesis. My initial work was for the Governor's Task Force, which wanted to know what was happening along the flood plains of the river. My part was looking at and collecting data on the cottonwood trees and assessing the flood plain turnover period. During observation while collecting data and analysis of the data there was strong indications that root-suckering was making up a large portion of the mature stands. Because of this, I pursued the investigation in identifying clones by the use of DNA microsatellite analysis. Once I identified clones, I would apply the information gain from my initial study to see if any of the variables I measured affected the amount of clonality occurring.

Chapter 1 is an introduction with some of the background on cottonwood trees and a literature review of what is known so far.

Chapter 2 is the results from the cottonwood study, with flood plain turnover period, hydrological associations, and stand characteristics. The results suggested that clonal recruitment is occurring but it was only speculation at this point.

The population genetics and how well the selected microsatellite markers worked, was covered by chapter 3. It was found that the study reach was one population at the genetic level and that the markers were highly polymorphic with a high degree of confidence for identification of ramets that occurred within the fixed plots used.

The final chapter combines the results from chapter 2 and clone identification. Clonality plays a major role with 71% of the trees in mature stands originating from root suckering, branch fragment sprouting and or burial of flood-trained saplings. The amount of clonality increases following a 10-year or greater flood frequency event and the range in age within fixed plots was the result of multiple clonal recruitment events. Many of the recruitment events were correlated to very small frequent flood events indicating that while scour increases the amount of root suckering, any inundation will promote suckering even without any physical damage. Many of the variables measured did not have a significant affect on clonality but help to point at other areas to study and possibly set up some experiments in the field to see what variables do contribute to higher levels of clonality. As with most research, you are left with some questions answered and a completely new group of questions to ask now that it is known that clonal recruitment is an import part of the reproduction ecology of *P. angustifolia* along the upper Yellowstone River.

Polzin Final Report 3/20/2006

During my award year I was able to complete my dissertation and defend it successfully on January 27. The fellowship allowed me time to give my writing and searching for papers my full attention. Without this funding I would have had to find a job which would have restricted my time considerably so that I would not have been finished in January. I was also able to spend time in Missoula every month to consult with my genetic advisor Dr. Lila Fishman and Dr. Fred Allendorf for consultation on the population genetics portion of my research. Being able to go to Missoula when ever I needed personal help was essential and would not have been possible if I had a job that would have time demands attached to it. I found it very important to spend time every month at the University as it helped in the critical thinking aspect of the writing. Being able to bounce ideas off other colleges would result in many problems being resolved that I did not come up with the solution being at home writing. Even though I came up with the solutions myself having other colleges to discus things with seem to firm up ideas when spoken out loud. A couple of questions some one may ask that is not as familiar with the work as myself helped me to see what areas needed more explanation as I thought it was self explanatory but it was not. The fellowship was a very important aspect in helping me complete my dissertation and thus my PhD.

STUDENT FELLOWSHIP: Towards sustainable materials for drinking water infrastructure

Basic Information

Title:	STUDENT FELLOWSHIP: Towards sustainable materials for drinking water infrastructure
Project Number:	2005MT69B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Engineering
Focus Category:	Water Supply, Water Quality, Treatment
Descriptors:	
Principal Investigators:	Anne Camper, Mohammed Rahman

Publication

The Lead and Copper Rule (LCR) sets the action level for copper in the distribution system as 1.3 mg/L. Copper corrosion can cause not only health effects but also damages the water supply infrastructure. It is known that water quality factors having the greatest affect on lead and copper corrosion are pH, alkalinity or dissolved inorganic carbonate (DIC), orthophosphate concentration, and buffer intensity. Also, as the microbial community in the distribution system is influenced by nutrients, the nutrient concentration in water may play a significant role in microbial copper corrosion. Because of the DBP Rule, many water utilities have switched to monochloramine. When monochloramine decays it forms ammonia, which may influence copper corrosion and cause nitrification in the distribution system and plumbing systems. The objective of my research is to investigate the effect of total organic carbon and ammonia on copper corrosion under stagnant flow conditions and to discover the diversity of the biofilm in a simulated plumbing system.

A modified version of the commonly used CDC reactors was used in this project. In the first set of experiments two types of copper coupons (new and old, i.e. pre-exposed to 0.1N NaOH solution) were used. These reactors were fed with water with different carbon (2~4ppm) and ammonia (0.36~0.71ppm) concentrations. Biologically treated tap water was used to supply the homogenous bacterial population. Water in the reactor was stagnant for eight hours and then flowed for five minutes. At the low carbon concentration for both old and new copper, total copper concentration is lower than that for high carbon reactors. A similar trend was also found in the case of the dissolved copper. Heterotrophic plate counts also showed higher numbers for high carbon reactors. After three months of operation the biofilm was sampled from the reactors and DNA was collected. Molecular techniques such as PCR DGGE were used to analyze the microbial community profile of these samples. In the second set of experiments, pre aged copper and PVC coupons were used with high carbon (4 ppm) and ammonia feed. For each condition we used two duplicate reactors.

After three months of operation, the PVC reactors showed evidence of nitrification, while the copper reactors also expressed nitrification within five months. The nitrification in copper reactors may be delayed by copper toxicity. We are now investigating the population and processes of nitrification in these reactors. The microbial population in those reactors is being analyzed using PCR and DGGE. But preliminary results from duplicate reactor show the reproducibility of this experiment. So these modified CDC reactor can be used to investigate domestic plumbing system biofilm. Recently we raised the low ammonia feed (0.36ppm) reactor to high level (0.71ppm).The PVC reactors adjust to the change very quickly and nitrify the excess ammonia. But the copper reactors reacted slowly. So the biofilm in PVC reactors has more potential for nitrification. The corrosion in copper also increases as the nitrification starts. Also, a batch test is on going to estimate heterotrophic and autotrophic nitrification.

STUDENT FELLOWSHIP: On the dynamics and production of CO2 in a forested watershed

Basic Information

Title:	STUDENT FELLOWSHIP: On the dynamics and production of CO2 in a forested watershed
Project Number:	2005MT70B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Water Quality
Focus Category:	Geochemical Processes, Solute Transport, Water Quantity
Descriptors:	
Principal Investigators:	Brian Leonard McGlynn, Diego Riveros

Publication

June 7th, 2006

Susan Higgins, Assistant Director for Outreach
Montana Water Center
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Bozeman, MT 59717

Re: Final Fellowship Report.

Dear Ms. Higgins,

As requested in your recent email, I submit to you the final report of activities I have accomplished during the 2005-2006 year. My dissertation research is titled: "**On the dynamics and production of CO_2 in a forested watershed**." Feel free to contact me if you have further questions.

1. Abstract (to include your contact information).

The uncertainties embedded in current estimates of net ecosystem CO_2 exchange (NEE) are well acknowledged. More than two-thirds of total terrestrial C is stored below ground and exchanged to the atmosphere through plant and microbial activity, but the mechanisms of such exchange are not well understood. We investigated the variability of the environmental factors that control CO_2 production to understand the heterogeneity of soil CO_2 concentration and efflux at the watershed scale. We present measurements of CO_2 concentrations and flux over one year in mountainous, complex terrain of the 550-ha Stringer Creek watershed located in the Little Belt Mountains of Central Montana. Our results showed that the interaction of soil moisture and soil temperature plays a major role in controlling CO_2 production and efflux across topographic positions. High temporal resolution measurements showed two main trends in the variability of soil CO_2: short-term (daily) variability controlled mainly by soil temperature, and long-term variability controlled by soil moisture. Long-term soil CO_2 concentration showed similar trends at other sites across the watershed. At upland sites, soil CO_2 concentrations reached their maximum after snowmelt and decreased thereafter. At lowland sites, soil CO_2 concentrations did not peak until the late summer. Similarly, dry upland areas showed a greater relative increase in soil CO_2 concentrations after rewetting events than wet lowland areas. We seek to assess the role of topography in controlling soil temperature, soil moisture and soil nutrient status to measure and model CO_2 production and efflux at the watershed scale. Our results are the first to show watershed-scale concentrations and fluxes of CO_2 over time.

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Welsch, Daniel. Department of Geography. Frostburg State University, Frostburg, MD.

Epstein, Howard. Department of Environmental Sciences. University of Virginia,
Charlottesville, VA.

2. Research Accomplishments

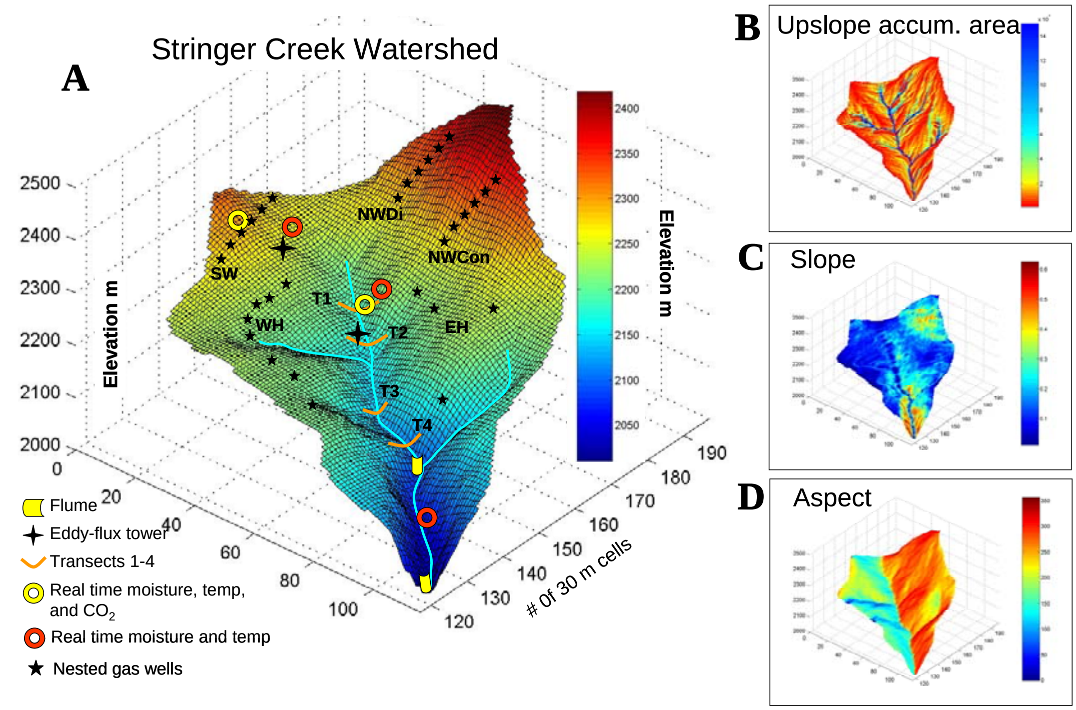

Figure 1. (**A**) Current instrumentation at the TCEF includes five real-time monitoring stations for soil moisture and temperature, >60 groundwater wells and piezometers, two eddy covariance towers and >120 gas wells. Calculations of accumulated area (**B**), slope **(C)** and aspect **(D)** demonstrate significant landscape heterogeneity at TCEF. **I seek to understand the effect of this heterogeneity on CO_2 distribution and flux at the watershed scale.**

Figure 1 summarizes the instrumentation that went into the Tenderfoot Creek Experimental Forest. I installed a network of 120+ gas wells at two different depths (20 and 50 cm) in the soil semi-distributed across the watershed. The purpose of this installation was to capture the range of variability in soil moisture, soil temperature, aspect, upslope accumulated area, and topographic index, across topographic gradients and see how those variables control CO_2 production and efflux from the soil. We are still performing long-term monitoring of CO_2 concentration in these gas wells across the watershed, as well as surface efflux.

3. Conclusions

Our results indicate that the effects of soil moisture and vegetation cover are responsible for differences in soil CO_2 evolution patterns. Soil CO_2 evolution in wetter low areas reflects photosynthetic activity better than in uplands. This means that there is a greater contribution by root respiration in riparian areas and that microbial activity is also more dependent on root exudate dynamics in the riparian areas of the watershed.

Short-term variability in soil CO_2 concentrations is controlled by soil temperature, whereas long-term variability is controlled by soil moisture. However, the interaction of both of these variables controls CO_2 production and efflux across topographic gradients. Once soil moisture is no longer a control, soil temperature becomes the dominant control.

Contrary to previous research, CO_2 diffusivity may not be significantly affected by increases of soil moisture in drier, upland areas. Therefore, generalizations from single point-scale measurements may be misleading. Instead such measurements should be conducted across the full range of environmental conditions. Our work shows that increases in soil moisture can increase CO_2 flux from soils in moisture-stressed soils. These findings have significant implications for model parameterization and modeling of soil respiration forcing factors at the watershed scale.

The integration of multiple point scale soil respiration studies is necessary to understand net ecosystem exchange of CO_2 at the catchment scale due to landscape heterogeneity. Our approach is unique as it directly addresses the variability in CO_2 generation and efflux at the catchment scale and focuses on the controls of soil respiration across environmental gradients.

STUDENT FELLOWSHIP: Factors that influence displacement of native cutthroat trout by nonnative brook trout

Basic Information

Title:	STUDENT FELLOWSHIP: Factors that influence displacement of native cutthroat trout by nonnative brook trout
Project Number:	2005MT71B
Start Date:	3/15/2005
End Date:	6/30/2006
Funding Source:	104B
Congressional District:	At-large
Research Category:	Biological Sciences
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Descriptors:	None
Principal Investigators:	Alexander Zale, Brad Shepard

Publication

Montana Water Center – Student Fellowship Award 2005

Factors that influence displacement of native cutthroat trout by nonnative brook trout

Final Report for 2005

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Abstract: Declines in the abundance, distribution, and genetic diversity of westslope and Yellowstone cutthroat trout (*Oncorhynchus clarkii lewisi*; *O. c. bouveri*; CT) throughout their native ranges have led to the need for fisheries managers to understand the mechanisms responsible for population declines so they can develop effective conservation and recovery programs. Factors associated with these declines include introductions of nonnative fishes, habitat changes, and over-exploitation. Many habitats previously occupied by CT in the Northern Rocky Mountains now contain populations of other nonnative trout, particularly brook trout *Salvelinus fontinalis*, indicating that brook trout may displace CT. However, little information exists detailing the mechanisms responsible for this displacement of cutthroat trout by brook trout. My research has focused on how watershed conditions influence the persistence of cutthroat trout, especially on how these conditions influence the displacement of cutthroat trout by nonnative brook trout. During 2005 I completed an extensive literature review, compiled four datasets for analyzing what habitat factors influence the presence and abundance of cutthroat trout and brook trout, analyzed one of these datasets, conducted a preliminary evaluation of the response of westslope cutthroat trout to removal of brook trout from several stream reaches within the upper Missouri River basin, evaluated food availability and use by cutthroat and brook trout in two streams, and conducted a preliminary experiment to assess competition between age-0 cutthroat trout and age-0 brook trout. My preliminary analyses of 144 sample sites within Montana indicated that stream size, latitude, riparian use, proportion of fine sediments in streambeds, water temperature, and pool features influence the presence or absence of both brook trout and cutthroat trout. Using these variables I was able to correctly classify the presence or absence of cutthroat trout in 85-95% and brook trout in 80-90% of the tested sample sites using various multivariate techniques. I found little difference in the food items used by age-2 and older brook and westslope cutthroat trout during the summer in two streams. The response of westslope cutthroat trout to the removal of brook trout indicated that displacement of cutthroat trout by brook trout likely occurs at an early age, probably age-0 to age-1, as abundances of age-0 cutthroat trout increased dramatically following brook trout removal. I begin further testing this preliminary conclusion in 2005 and will continue this experiment in 2006. Preliminary results suggest that age-0 cutthroat trout have little fat reserves going into the winter period and brook trout may limit the ability of age-0 cutthroat trout to build

up fat reserves prior to winter. These preliminary analyses and results will direct my future research.

Research Accomplishments: Completed an exhaustive literature review. Compiled four relatively large databases (144 to 4,000 sites in each) for evaluating influence of habitat on presence and abundance of cutthroat and brook trout. Completed preliminary analyses on one of these databases. Conducted two pilot experiments to evaluate effects of brook trout on cutthroat trout. Evaluated the response of cutthroat trout to brook trout removal in four different stream reaches to determine age where interactions between these two species may be most critical.

Conclusions (Preliminary):

1. Preliminary analyses indicate several habitat variables can be used to classify whether cutthroat trout or brook trout will be present or absent from a relatively high proportion of potential sites; however, further testing of these preliminary results is necessary.
2. Brook trout can displace cutthroat trout from some stream habitats.
3. Age-0 to age-1 cutthroat trout appear most susceptible to displacement by brook trout because this age class responded most dramatically to the removal of brook trout; however, the exact mechanism still remains unclear.
4. Preliminary results suggest that age-0 cutthroat trout have very low fat reserves going into their first winter and age-0 brook trout may influence fat reserves of age-0 cutthroat trout.
5. Competition for food by age-2 and older brook and cutthroat trout might be important as little difference was seen between food items used between these two species during the summer.

Hydrogeologic characterization of acid mine drainage (AMD) along Belt Creek near Belt, Montana

Basic Information

Title:	Hydrogeologic characterization of acid mine drainage (AMD) along Belt Creek near Belt, Montana
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Descriptors:	
Principal Investigators:	Jon C. Reiten

Publication

Hydrogeologic Characterization of Acid Mine Drainage (AMD) along Belt Creek near Belt, MT.

Final Technical Report

by Jon Reiten, Shawn Reddish, and Justin Brown

Montana Bureau of Mines and Geology

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EXECUTIVE SUMMARY

Decades of underground coal mining have resulted in acid mine drainage (AMD) that has contaminated ground-water and surface-water resources in Belt, Montana. The AMD has lowered the pH of Belt Creek and increased trace metals concentrations in the stream. The overall goal of work in the Belt area was to define the hydrogeologic regime in the vicinity of Belt so that recharge to old mine workings, the source of acid mine drainage, could then be delineated with a reasonable level of certainty. This project was funded by the Montana Department of Environmental Quality (MDEQ) 319 Program with supplemental funding from the MDEQ Remediation Division-Abandoned Mine Lands, Montana Water Resource Center, and the Montana Bureau of Mines and Geology (MBMG). Work is continuing under additional task orders through MDEQ Remediation Division-Abandoned Mine Lands.

This project consisted of a phased approach to define and mitigate water quality problems in Belt Creek near the town of Belt, which is 23 miles southeast of Great Falls. Phase 1 is a hydrogeologic investigation to determine contaminant sources and their relative contributions, and to identify and evaluate mitigation measures. Phase 2 will be based on a later proposal to apply specific measures to reduce recharge to the Anaconda Mine and monitor their success.

Shawn Reddish, under the supervision of Jon Reiten, conducted work documenting the hydrogeologic conditions surrounding the abandoned Anaconda Copper Mining Company Mine (Anaconda Mine) near Belt. Specific tasks included inventorying, sampling for water quality and collecting samples for age dating water from wells, springs, adits and seeps. These tasks were conducted to determine if the recharge to the mine workings was local or regional. The inventory process included collecting Geographic Positioning System (GPS) coordinates of pertinent locations, measuring specific conductivity (SC), pH, oxidation-reduction potential (ORP), dissolved oxygen (DO); and determining the geologic source of water in wells, springs, adits and seeps. These field data were then evaluated to screen for the most useful sampling sites; all information was entered into MBMG Ground Water Information Center (GWIC) a database accessible by the public.

Water levels at 28 wells and discharges at 2 springs were monitored. Some of these wells were measured monthly for about 2 years to monitor the fluctuations of local aquifers. Several of these wells and springs have been sampled for tritium, helium-3/tritium and

chlorofluorocarbons (CFC) to determine the average residence time of the water. All sampled wells have tritium concentrations greater than background pre-nuclear testing levels. This suggests a modern (post nuclear testing) age for ground water in the alluvial, Kootenai, Morrison, Swift, and Madison aquifers. CFC samples also indicated that all of the recharge is relatively recent. Several samples from the Madison aquifer were supersaturated with CFCs, but the cause of this supersaturation is unknown. The results of helium-3/tritium dating of two water samples also supports the relatively young age of water in aquifers near Belt.

Stream flows at 9 sites were also measured monthly in the study area. Differences in flows between measuring sites were used to evaluate gaining or losing reaches of the streams. Field parameters, including SC, pH, ORP, and DO were measured at each site. The AMD discharge, including flow and field parameters, was monitored at 5 sites on a monthly basis for approximately 2 years. In addition to monthly measurements, an H-flume installed by another project in the area was set up with a pressure transducer to record the AMD discharge from the mine adit. Based on this work and other ongoing MBMG research, the direct loading to Belt Creek from AMD was estimated to be 103,300 pounds of iron per year and 64,986 pounds of aluminum per year. Indirect loading to Belt Creek from other AMD sources moving through alluvial sediments was estimated to be 40,080 pounds of iron per year and 28,327 pounds of aluminum per year. The main source of AMD is the discharge from the Anaconda Mine, which averages about 132 gallons per minute (gpm) or about 213 acre feet per year. The primary purpose of this work has been to identify the source of water recharging the mine workings and recommend possible methods to reduce the recharge which would result in a decrease or possible elimination of AMD loading to Belt Creek.

Several possible sources of recharge were suggested when this project started; others developed as new information became available. Possible sources include: 1) recharge from regional aquifers such as the Madison aquifer, 2) upward seepage from deep aquifers along fault planes, 3) localized recharge from precipitation directly overlying the mines or up-gradient recharge areas, 4) water loss from Box Elder Creek, and 5) focused recharge through shallow depressions overlying the mines. Water-level data from wells completed in the Madison aquifer, below the mine workings and in areas surrounding the mine, indicate the static water-level in the Madison aquifer to be about 400 feet below the mine voids.

Therefore, the Madison aquifer is not hydrologically connected to the workings, nor is it a likely source of recharge to the mines. Other regional aquifers do not appear to be likely sources either, although these have not been completely ruled out. Upward seepage along fault planes does not appear to be a likely source of recharge; based on the downward hydraulic gradients. Box Elder Creek is at a higher elevation than the mine workings and therefore has a potential for losses to the mine. Flow data along Box Elder are currently inconclusive to document stream losses. The most likely source of recharge to the mines is infiltration of precipitation on the land surface overlying the mine workings; including up-gradient areas that recharge the localized Kootenai aquifer system.

A significant source of water to the Anaconda Mine (ACM) appears to be from the overlying Kootenai Formation; which is about 260 feet thick in the Belt area. A potentiometric-surface map of the Kootenai aquifer was constructed based on well inventory and monitoring measurements. This map was contoured using measurements from 48 wells and springs near the mine. The Kootenai potentiometric-surface map combines head data from aquifers in both the Sunburst and Cutbank Members of the Kootenai Formation. As a result, the map shows only general water-level conditions in the mapped area. Additional wells at critical locations will be needed to accurately depict ground-water flow. Ground water is interpreted to flow from a divide located about 3.5 miles south of the Anaconda Mine. The ground-water divide, south of the mine, appears to be both topographically and structurally controlled. The topographically high area forming the ground-water divide is located just north of a paired, anticline-syncline structure that trends north 45 degrees east. Only precipitation falling north of this divide has the potential to move towards the mine. Once recharge infiltrates vertically to the saturated zone, ground-water flow is generally to the north; perpendicular to the potentiometric contours illustrated in the predominant recharge area to the mine. The upland area between Belt Creek and Box Elder Creek is highly dissected by tributaries of the two streams. These tributaries, plus the main stems of the two streams, are discharge areas for ground water moving out of the Kootenai Formation. The potential recharge area covers about 2,100 acres overlying and up-gradient of the mine. The highly dissected nature of the upland appears to cause much of the precipitation to 1) recharge a shallow ground-water flow system, and 2) cause discharge to the surface-water drainages as seeps and springs in the valley walls. Several of the springs coincide with the contact of the Sunburst Sandstone Member (aquifer) and the underlying unnamed fine-grained unit (aquitard).

Based on the data collected, it appears that recharge to the Anaconda Mine is locally derived. The recharge appears to be relatively constant; as recorded in the discharges from the mine. Fluctuations in precipitation cause significant changes in discharge from the overlying Sunburst aquifer springs. However, the mine discharges remain stable. Apparently the head increase, caused by precipitation-derived recharge, is rapidly dissipated through leakage at contact springs. As a result of this localized flow system, the volume of AMD discharging from the mine could be reduced or possibly eliminated by changing land- use in the recharge area. Other possible remediation options would be diverting flow from overlying aquifers to prevent filling the mine voids or flooding the mine voids to reduce pyrite oxidation. Growing alfalfa or other water consumptive crops would have the potential to significantly reduce infiltration and possibly decrease the AMD discharges.

INTRODUCTION

In the vicinity of Belt, the water quality of Belt Creek is currently degraded by Acid Mine Drainage (AMD) from the abandoned Anaconda Mine, as well as, smaller acidic discharges from other abandoned coal mines along Belt Creek. The overall goal of all AMD work in the Belt area is to restore the water quality of Belt Creek by reducing or eliminating all sources of AMD pollution. This will improve stream habitat, restore native fish populations and improve ground-water quality of the alluvial aquifer. This project was designed to define hydrogeologic conditions in the vicinity of Belt so that recharge to old mine workings, the primary source of AMD, could be delineated with a reasonable level of certainty. Several possible sources of recharge were suggested when this project started and others developed as new information became available. The possible sources include: 1) recharge from regional aquifers such as the Madison aquifer, 2) upward seepage from deep aquifers along fault planes, 3) localized recharge from precipitation directly overlying the mines, or up-gradient recharge areas, 4) water loss from Box Elder Creek, and 5) focused recharge through shallow depressions overlying the mines. Hydrogeologic data and water-quality information were used to document the source of recharge and to estimate potential changes in recharge rates, ground-water flow rates, and acid mine drainage discharges under various scenarios including combinations of cropping, dewatering or other techniques that might have been found to be appropriate. Water samples from a variety of sources potentially associated with AMD was age-dated by testing for tritium, helium3/tritium and chlorofluorocarbons. With this combined hydrogeologic knowledge, best-management practices can be developed to reduce future generation of acidic discharges into Belt Creek.

Background

The town of Belt is located on the north flank of the Little Belt Mountains in central Montana (Figure 1). Decades of underground coal mining have resulted in acid mine drainage (AMD) that has contaminated ground-water and surface-water resources in Belt, Montana. The Anaconda Mine is the largest mine in the area and was developed in 1895 (Fischer, 1907). Coal was extracted from a 6-foot thick seam located in a stratigraphic position near the top of the Morrison Formation (Fischer, 1909). Although mining ended about 80 years ago, water with a pH of 2.94 is still flowing out of abandoned mine workings adjacent to, and near, the town of Belt. Acid mine drainage continues to add metals and lower the pH of Belt Creek. Belt Creek discharges acidic, metal-laden, water into the Missouri River. Belt Creek also can not support fish below the town of Belt. Previous mitigation efforts involved a development of a series of wetlands to remediate the AMD. These wetlands, however, were unsuccessful in reducing acidic discharges. Acid water recharging the alluvial aquifer along Belt Creek has rendered that aquifer unusable in some areas (Koerth, oral communication, 2002).

In 1978, the city of Belt drilled 2 public water wells. These wells were drilled through the alluvium aquifer and completed in the Madison Formation. The town of Belt is concerned that acid ground water, in the shallow alluvium along Belt Creek, might corrode the casings of the town's water wells. If corrosion to the city's well casings were to occur (including the direct damage to the city's infrastructure,) metal-laden, acidic water from the alluvium aquifer could drain down to the Madison Formation and consequently degrade that watersource.

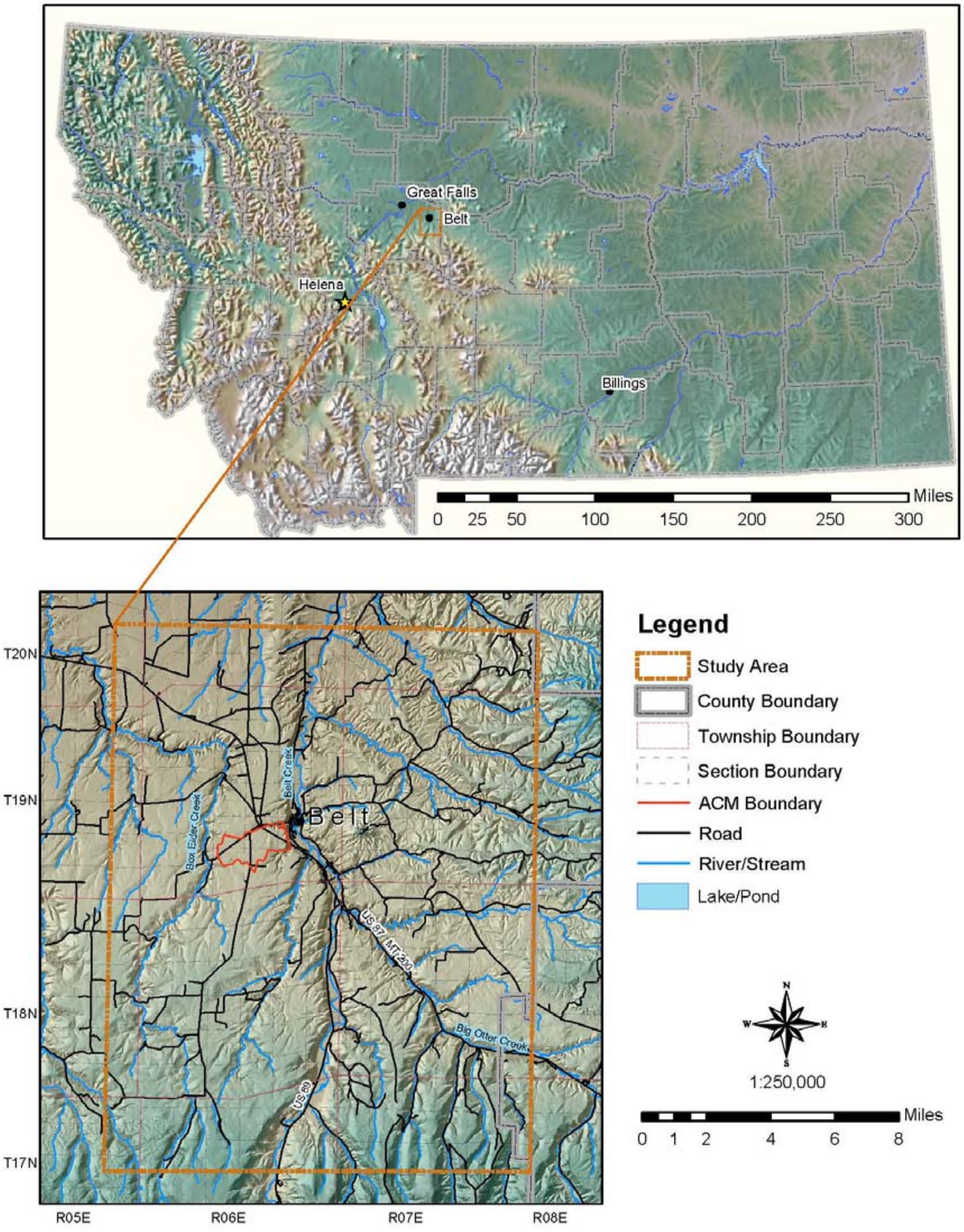


Figure 1. The town of Belt is located on the north flank of the Little Belt Mountains in central Montana.

Belt’s #2 well (GWIC ID 2315) is located near Belt Creek on “Coke Oven Flats”, where coal waste was stored during mining operations. This public well is located adjacent to reclaimed mine spoils and is only about 140 feet south east from monitor well #1(MW1-GWIC ID 214917). A water quality sample extracted from this monitor well indicated very corrosive water containing high concentrations of trace metals.

In the late 1980’s, the MDEQ began the reclamation of a large burning pile of coal waste located on “Coke Oven Flats” and closed several open mine portals. In 1994, the water main between the pump house and water tanks corroded and leaked. These leaks were caused by reactions of acidic ground-water and acidic soils with the metal pipe (Figure 2). The leaks were repaired when the metal water mains were replaced with plastic PVC pipe (DEQ, 2000).

Figure 2. Corroded municipal water line from the town of Belt.

Water-quality problems at Belt are caused by geochemical processes enhanced by the method of mine abandonment. Oxygen-rich meteoric waters recharging the ground-water system overlying the coal mines eventually infiltrates into mine workings that contain pyrite-rich waste coal and are often overlain by pyrite-rich sandstone immediately above the coal, thereby producing acid mine drainage (Wheaton and Brown, 1999). These acidic discharges flow into Belt Creek at an average rate of 132 gpm. These inflows, in addition to data for stream flow at Belt Creek, were collected as part of this project to help identify loading to Belt Creek. The AMD problem is continuous. Other studies show a direct relationship of AMD production with precipitation and infiltration (Wheaton and Brown, 1999; Osborne and others, 1987). Of particular concern is the increase in ground-water recharge brought about by the crop/fallow cropping system that overlies much of the recharge area to the mine.

Previous Investigations

In the 1980's, as part of a larger project covering the entire Great Falls coal field, the Montana Department of State Lands (currently MDEQ Remediation Division-Abandoned Mine Lands) identified a number of environmental problems associated with the historic coal mines and their ancillary facilities in the Belt area. As part of MDEQ's activities, the mine adit for the No.2 Anaconda Mine was closed. A pipe was installed to carry the acidic water, discharging from the mine, downhill where it combined with acidic water from another discharge. This combined AMD water forms a channel that flows adjacent to reclaimed mine spoils before discharging into Belt Creek.

MDEQ, along with the U.S. Bureau of Mines (USBM), installed a series of wetlands for passive treatment of acid-mine water originating from the French Coulee Mine, located in the next coulee south of the Anaconda Mine. This water is also very acidic. However, the flow is considerably less than that from the Anaconda Mine. A portion of this water was diverted into the wetlands for treatment and then discharged to Belt Creek. However, due to the high iron concentrations and harsh winter weather in the area, the wetlands were not able to achieve an acceptable level of treatment and were abandoned. Water from this location flows under the existing railroad beds, down a steep hill, and then discharges into the same channel that receives the Anaconda Mine drain water.

The United States Geologic Survey (Karper, 1998) conducted an intensive water-quality study of a number of sites in the Belt area as part of a study of acid mine drainage problems in the Stockett-Sand Coulee and Belt areas. They installed a flume and stilling well for continuous monitoring of the discharge from the Anaconda Mine and collected periodic water quality samples from various sites.

When the coal-waste area below the Anaconda Mine (and adjacent to the channel receiving acid mine water discharge) was reclaimed, a series of six, shallow, monitoring wells were installed by the MDEQ for ground-water monitoring (Tetra Tech, 1995). These wells were installed for monitoring of a proposed grouting project aimed at mitigating the discharge of contaminated ground-water into Belt Creek. However, this project was postponed and no additional data was collected from these wells.

One project (Osbourne and others, 1987) characterized hydrogeologic conditions at several abandoned mines in a similar geologic setting in the Stockett-Sand Coulee area and possible recommendations for cleanup at these sites were developed. One of the approaches discussed was to change current land uses in the recharge areas of the mines from a crop-fallow system to a more water consumptive cropping pattern. Another study done by Wheaton and Brown (1999) evaluated the hydrogeology and geochemistry of the Cottonwood Mine near Stockett-Sand Coulee. Local precipitation recharges the Cottonwood Mine workings. A previous land-use change from crop fallow to the Conservation Reserve Program (CRP) appears to have significantly reduced the recharge volume and, consequently, acidic discharges from the mine were also lowered.

A concurrent project, supervised by Ted Duaime of the MBMG and funded by the MDEQ, is focusing on the hydrogeology in the area immediately surrounding the Anaconda Mine. Work has included detailed geologic mapping, remote sensing mapping, AMD sampling, stream sampling, and surface flow monitoring of streams and other discharges. The construction of nested monitoring wells in significant aquifers in the Anaconda Mine area is nearly finished. Preliminary findings of this DEQ sponsored work has been published as a MBMG open file report (Duaime and others, 2004). This open file report also contains an excellent summary of the coal mining history in the Belt area.

Project Sponsor and Funding Sources

The city of Belt was the project sponsor. Funding sources came from MDEQ section 319 grant along with funds from the Montana Water Center, Task Orders through the MDEQ Remediation Division-Abandoned Mine Lands, and the Montana Bureau of Mines and Geology.

Methods

Data collected for this project include an inventory of ground-water and surface-water conditions, water-quality samples, stable-isotope samples, tritium samples and chlorofluorocarbon samples. All data are available on the Environmental Protection Agency (EPA) Storet data base. Ground-water, surface-water, and water-quality data are available on the Montana Bureau of Mines and the Geology Ground-Water Information Center (GWIC) at (www.mbmggwic.mtech.edu). GWIC ID numbers are attached to all wells used in this report.

During this project, 72 existing water wells, 6 AMD sites, 6 monitor wells, 2 ponds, 9 stream sites and 17 springs were inventoried in the vicinity of Belt (Figures 3 and 4). The locations of the inventory sites were determined using GPS, and surface elevations were estimated from 1:24,000 topographic maps or Digital Elevation Models (DEMs). As part of the well inventory, static-water level, pumping-water level, and well depth were measured when possible and water use was identified. At surface-water sites, stream flow and spring discharge were monitored as part of the inventory. Field water-quality parameters (pH, SC, Temperature, DO, Redox) were tested at all sites that water samples could be collected. All the inventory data are summarized in Appendix A.

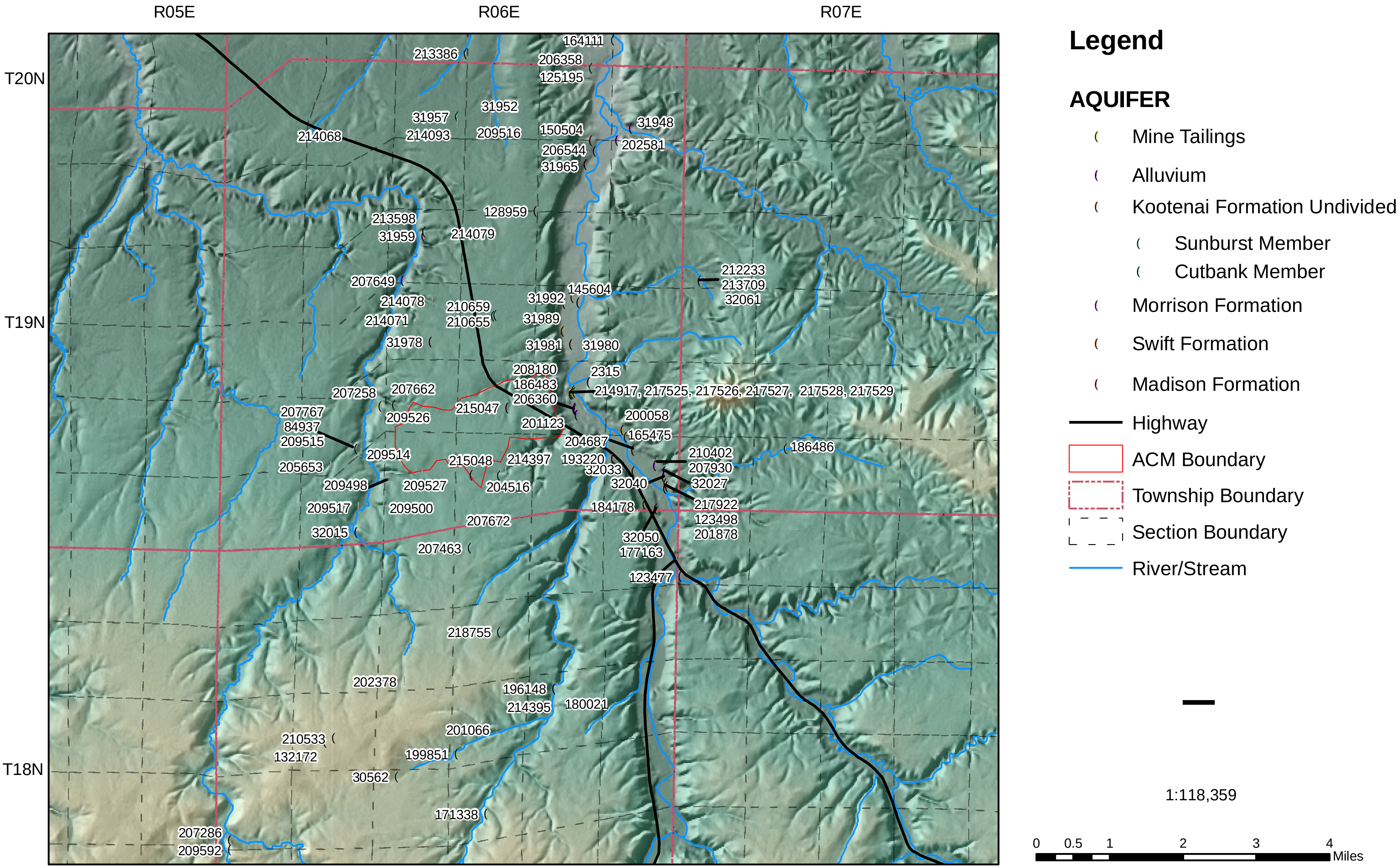


Figure 3. Map showing locations of wells and springs inventoried in the Belt area.

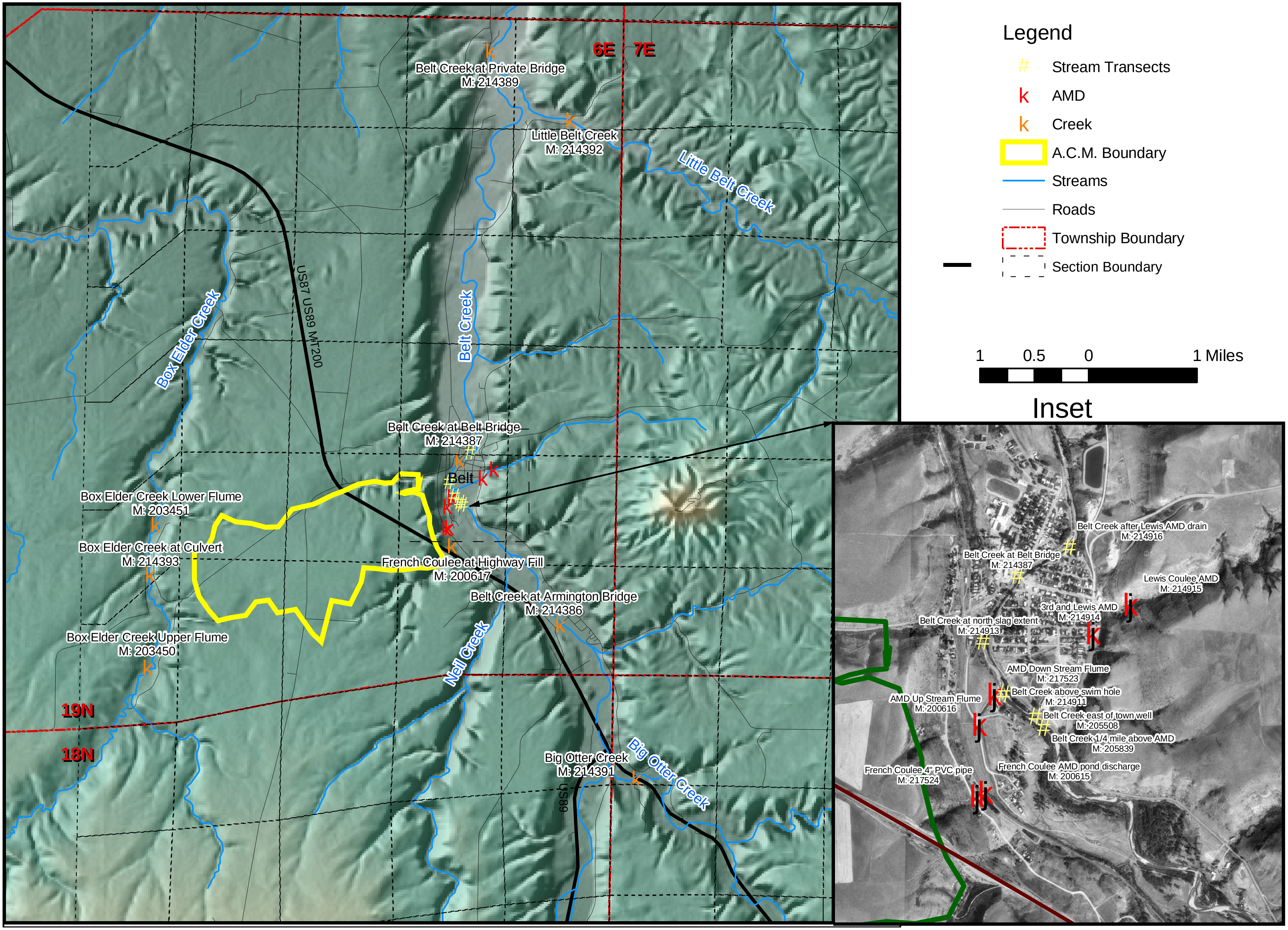


Figure 4. Map showing surface-water and AMD inventory and monitoring sites.

Between September, 2002 and October, 2004, ground-water and surface-water measurements were collected to document water-level fluctuations and changes in field water-quality parameters. Water-levels were measured monthly at 31 of the inventoried wells. Six wells, originally installed in 1995 by the Abandoned Mine Reclamation Bureau to monitor AMD, were included in the monitoring network. Two wells (GWIC ID #'s 2315 and 31992) were also measured quarterly by the MBMG ground-water characterization program. Ground-water level hydrographs were plotted with daily precipitation or stream flow and are compiled in Appendix B. Selected hydrographs are also shown in several figures within this report.

Stream flow, spring water flow rates and field water-quality parameters (pH, SC, Temperature, DO, Redox) were monitored monthly from 9 surface-water sites in the study area. During low-flow conditions, stream flow was calculated by measuring stream velocities while wading the creek at specific transect locations. During high-flow conditions, a bridge crane and weighted "fish" were used for transects when conditions were too dangerous to wade. Parshall flumes were used to measure flow in Box Elder Creek and at several AMD discharges. At some locations, flows were calibrated by gauge height or volumetric measurements (bucket and stop watch). Refer to Appendix C for field chemistry, flow measurement method, and flow rate chart data.

Acid mine drainage flow rates and field-water quality parameters were also measured monthly at five sites. Flow rates were obtained by either H-flume gauge height or volumetric measurements (bucket and stop watch). Refer to Appendix D for field chemistry, flow measurement method, and flow rate chart data.

Several ground-water samples were collected for tritium, stable isotopes, helium-3/tritium and Chlorofluorocarbons. These ground-water samples were collected after purging three casing volumes from the well (or until field water-quality parameters stabilized). Surface-water samples were collected directly from the stream or discharge. Samples were not preserved and were shipped to the appropriate laboratory for analyses as soon as possible.

The stable-isotopes of oxygen were analyzed on 15 samples to better delineate the source(s) of ground-water recharge. The samples were analyzed by the University of Waterloo in Ontario, Canada. Isotope contents are expressed in terms of the difference between the measured ratio of isotopes (i.e., sampled $^{18}O/^{16}O$) to a standard reference ratio of the isotopes (i.e. reference $^{18}O/^{16}O$) and are expressed in a delta notation (δ) in parts per thousand (permill). The formula for this expression (using ^{18}O as an example) is as follows:

$$\delta\, ^{18}O \text{ sample} = \frac{^{18}O/^{16}O \text{ sample-} \; ^{18}O/^{16}O \text{ VSMOW}}{^{18}O/^{16}O \text{ VSMOW}}$$

The standard reference ratios (Coplen and kendall, 2000) for the isotopes used in this investigation are as follows:

Hydrogen ($\delta\, ^{2}H$): VSMOW (Vienna Standard Mean Ocean Water)
Oxygen ($\delta^{18}O$): VSMOW

Tritium samples were collected to determine the age of ground-water, surface-water, and AMD-water in the study area. The tritium samples were collected from ground-water wells by purging wells and filling unpreserved bottles. Surface and AMD water were collected at the source. These tritium analyses were performed by The University of Waterloo in Ontario, Canada.

Chlorofluorocarbon (CFC) samples were also collected as another estimate of the average age of ground water. Samples were collected by attaching one end of low-permeability rubber viton tubing to an outside faucet, while placing the other end inside a small glass jar. The jars were then purged with water to avoid any atmospheric contamination. The samples were collected in bottles and sealed with tape and sent to the University of Miami for analysis.

Water samples were collected from 21 wells, 14 surface-water sites, and 4 AMD sites for common-ion and trace constituent analyses. Ground-water samples were collected after purging the well approximately three casing volumes. Stream-water samples were collected at individual flow measurement sites along stream transects and combined into a composite sample. Field parameters of pH, SC, ^{0}C, DO, and ORP were also recorded at time of sample collection. The samples were collected in accordance with standard field and laboratory protocols. The analyses for the water-quality samples were conducted by the MBMG analytical laboratory in Butte, Montana. Refer to Appendix E for lab analyses.

PROJECT SETTING

Climate, Physiography and Land Use

Belt has a semiarid climate with warm summers, cold winters and moderate amounts of precipitation. Because of the location near the boundary between the Great Plains and the Rocky Mountains, the climate is influenced by characteristics of both regions. This climate summary is based on records from the closest long-term climatic station about 25 miles northwest of Belt at the Great Falls Airport (http://www.wrcc.dri.edu). The average annual precipitation for the period of record (July, 1948-December, 2004) is 14.77 inches. The average snowfall is 60.6 inches. Much of the precipitation falls during the growing season. The average monthly maximum temperature is 56.4 degrees F. and the average monthly minimum is 33.2 degrees F. Winter is cold, but temperatures are often moderated by extended periods of mild temperatures brought on by strong, southwesterly, Chinook winds. Spring is usually cloudy and cool with frequent episodes of rain or snow. Summer characteristically has warm days and cool nights with frequent afternoon and evening thunderstorms. Fall months cycle between cool, moist and warm, dry conditions.

Climatic conditions during the study period (2002-2004) were drier than normal (Figure 5). A local climate station was established in April, 2003, located approximately three miles southwest of Belt at the Reddish Ranch (T 18N R 6E NW1/4 Section 14). Data from this site, and the long-term monthly averages at the Great Falls Airport, are compared in Figure 6. During the 21 month period from April, 2003 through December, 2004, precipitation at Belt was 6 inches less than the average at the Great Falls Airport. Much of the deficit in precipitation was during the typically wet growing season months; especially in 2003.

The reclaimed main access to the Anaconda Mine is located within the city limits of Belt with the main haulage opening on the west side of the Belt Creek valley. The Anaconda Mine underlies the drainage divide between the Belt Creek watershed and the Box Elder Creek watershed (part of the Upper Missouri-Dearborn River watershed). The land surface rises to the southwest from an elevation at Belt, about 3,500 feet above sea level, towards the Little Belt Mountains. The highest elevation in the study area is about 5,000 feet. Many springs exist in the area; especially in the Box Elder Creek drainage. These springs flow year round with pronounced seasonal fluctuations.

Several of the main streams in the area, including Belt Creek and Box Elder Creek, are intermittent. Most of the flow in Belt Creek is from snowmelt in the Little Belt Mountains. Stream flow in Belt Creek typically peaks in the late spring.

Farming and ranching are the main land uses in the Belt area (Figure 7). Small grain crops and hay meadows account for about 30,564 acres. Rangeland accounts for about 46,197 acres. Urban and commercial development account for about 303 acres. Other land uses make up the remaining 62 acres. Coal mining was historically important, but hasn't been a significant part of the economy for over 80 years. Recently, Belt has become a bedroom community for Great Falls and it appears associated housing development is likely to increase.

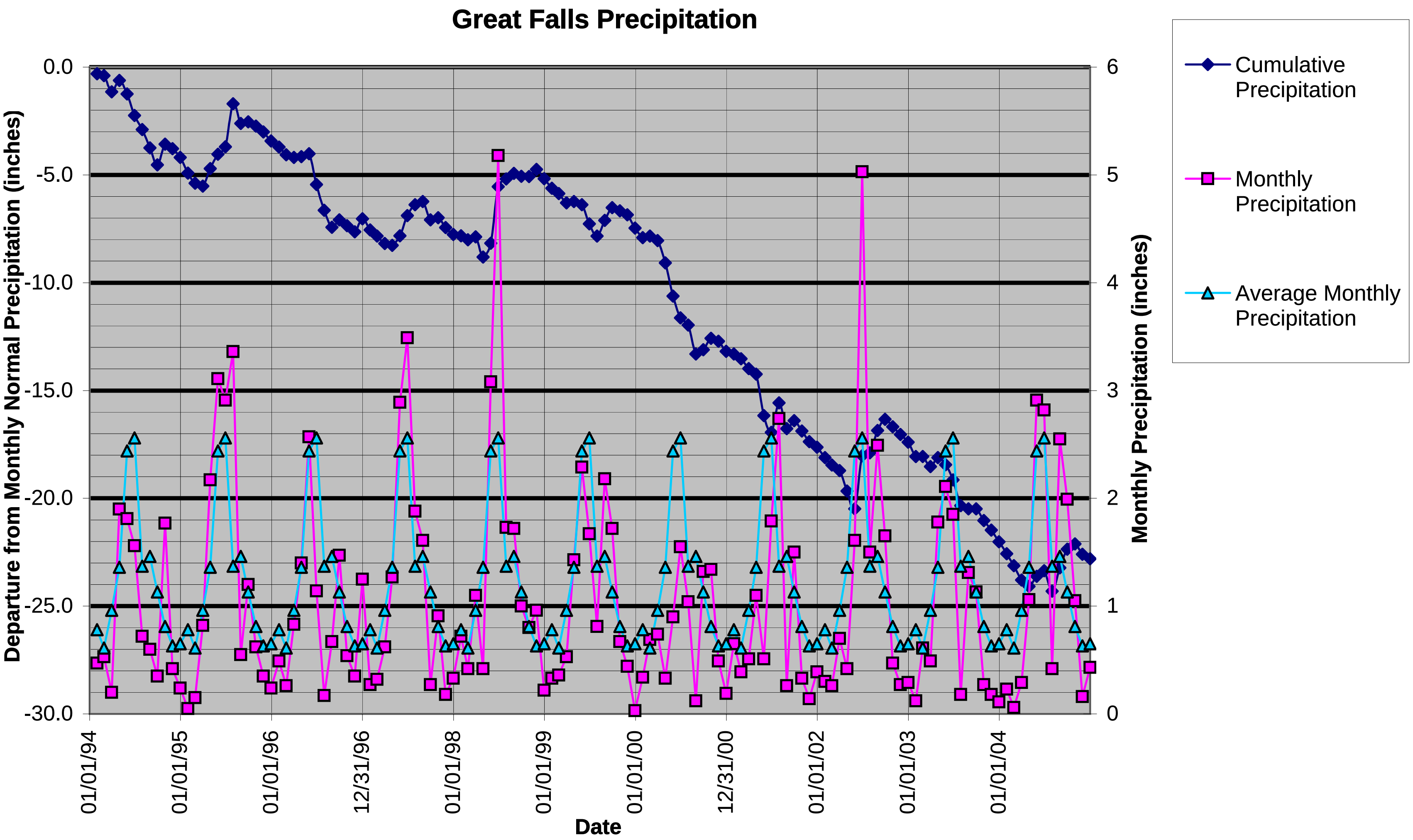


Figure 5. Comparison of Great Falls precipitation as cumulative departure from monthly normal to recorded monthly precipitation and average long-term monthly precipitation.

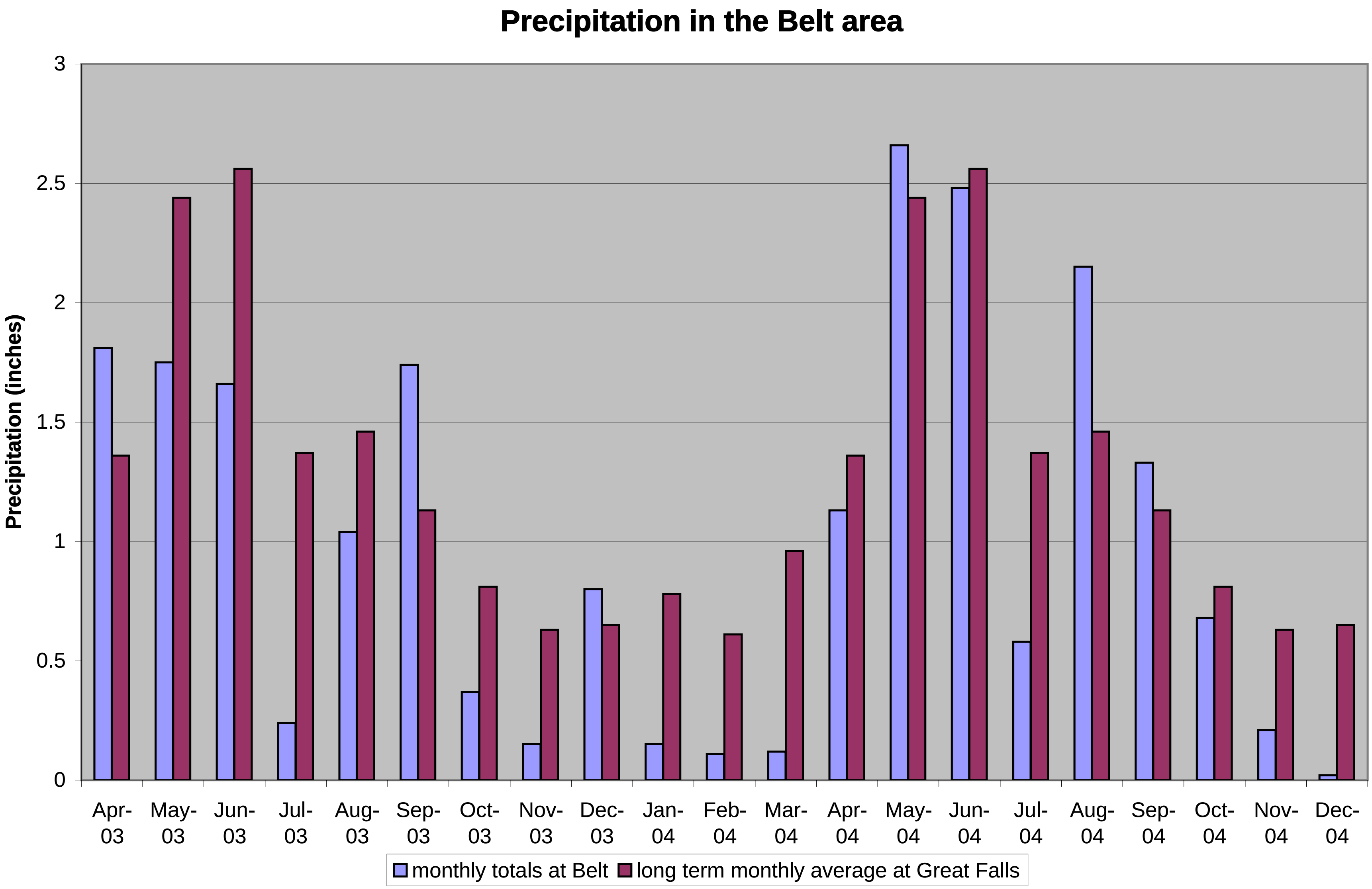


Figure 6. Comparison of precipitation from the Reddish Weather Station near Belt to long-term average precipitation at Great Falls.

Land Use	Acres	%
Other	61.60	0.07%
Urban	302.94	0.36%
Forest	6021.35	7.24%
Range/Pasture	46197.24	55.56%
Cropland	30564.46	36.76%
Total	83147.59	100.00%

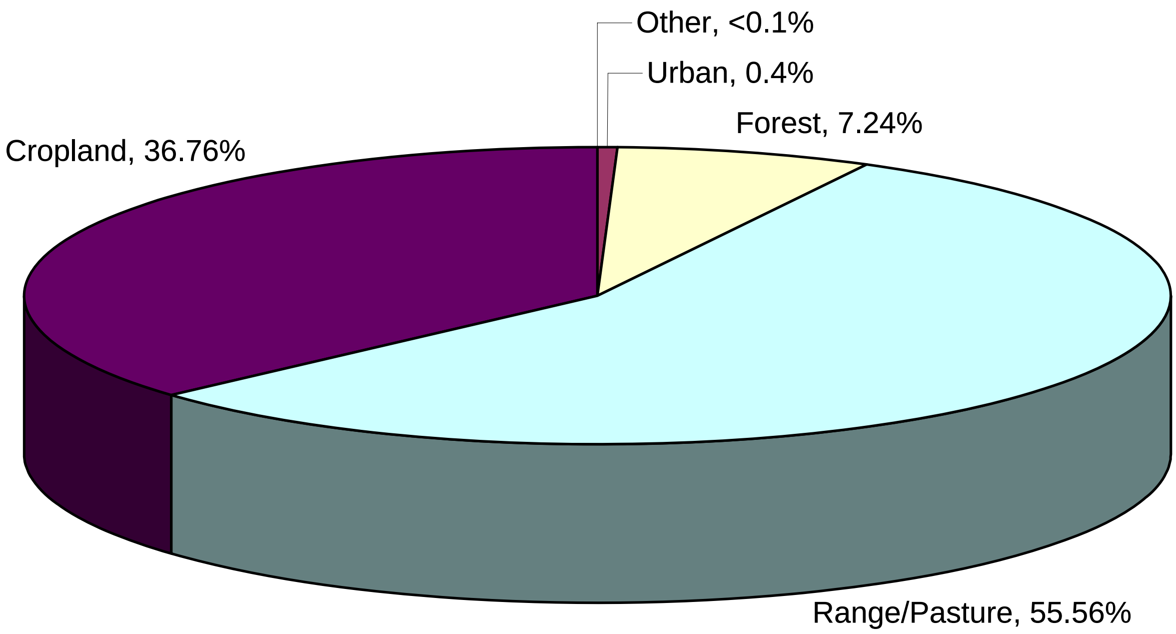


Figure 7. Land use in the Belt area (USGS, 2000).

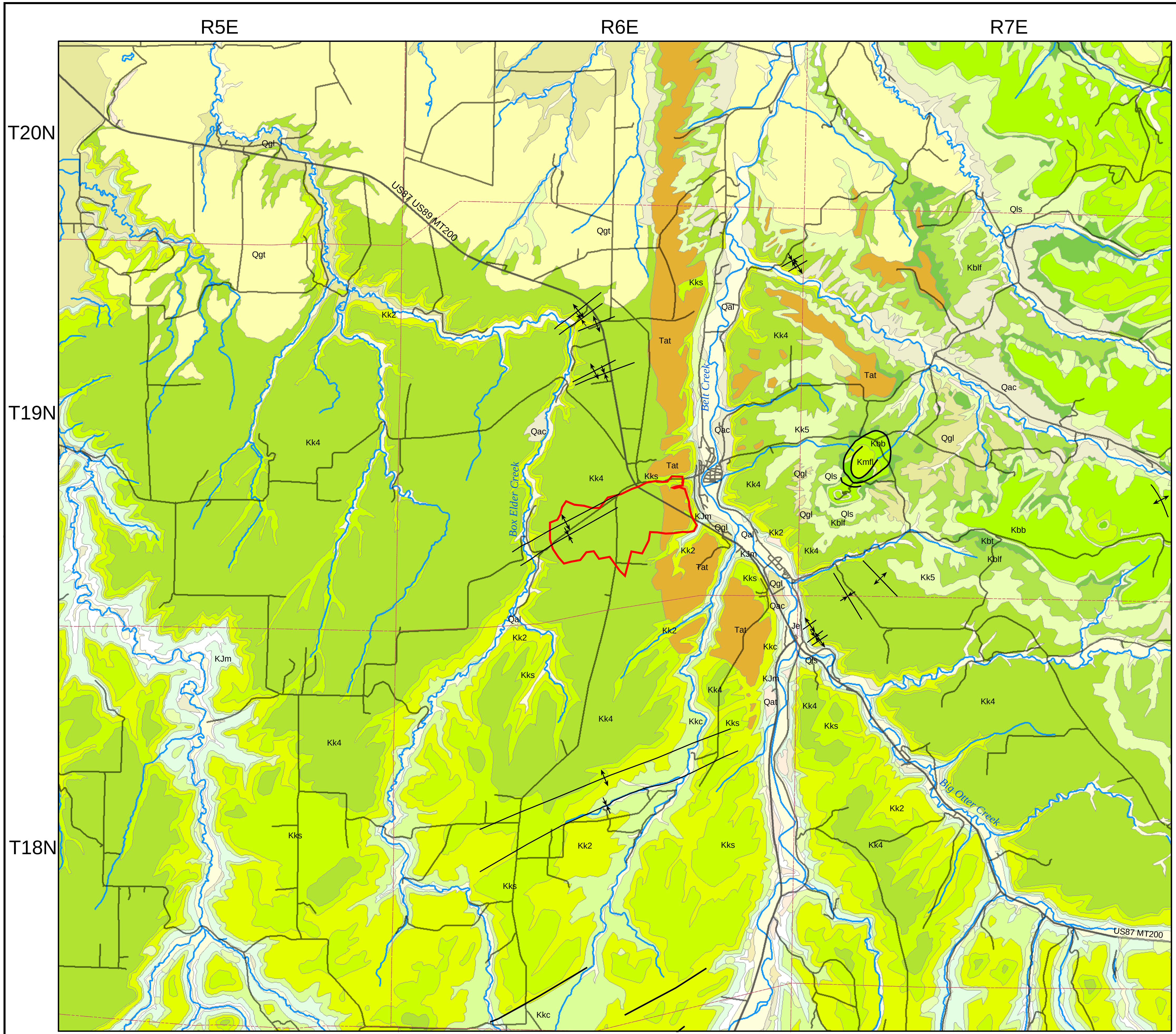
Geology

A geologic map of the Belt area (Vuke and others, 2002) showing the extent of surficial geologic units is illustrated in Figure 8. The topographic divide overlying the Anaconda Mine consists of weathered mudstone and sandstone of the Kootenai Formation. Thin soils are developed on the fractured sandstone beds. These soils contain abundant cobble and boulder-sized tabular slabs of weathered sandstone. The flood plain and alluvial deposits underlying the Belt Creek valley are up to 40 feet thick. The alluvium is composed of yellowish-brown to gray gravel, sand, silt, and clay. Coal was mined from the upper part of the Morrison Formation which is overlain by the lower Kootenai Formation. A few miles north of Belt, the upper Kootenai and overlying Blackleaf Formation are also exposed and are overlain by glacial and Tertiary terrace gravels. In the mine area, the Morrison Formation is underlain by the Swift Formation and the Madison Group. However, within a few miles south of Belt; other units of the Big Snowy Group appear between the Swift Formation and the Madison Group: the Sawtooth Formation, Otter Formation, and Kibbey Formation. Age, lithology, thickness, and depositional environments of these stratigraphic units are summarized in Table 1.

Several wells were constructed in and around the Anaconda Mine as part of an ongoing DEQ funded project. Based on lithologic logs of wells drilled in fall 2004, an average of about 256 feet of the Kootenai Formation overlies the Anaconda Mine (Duaime and others, 2004). The Kootenai Formation is comprised of five distinct members composed of interlayered beds of siltstone, mudstone, and sandstone; two of which are relatively clean and thick sandstone water-bearing units. The uppermost unit (Kk5) is predominantly red mudstone and sandstone, but is not present overlying the mine. The Fourth member (Kk4) is predominantly thin-bedded layers of sandstone at the land surface overlying the mine and averages about 80 feet thick. The Third member (Kk3) is the uppermost sandstone unit and is also referred to as the Sunburst Sandstone Member. This unit is about 45 feet thick at the mine and is composed of light-yellowish-brown, well sorted, resistant, quartzose sandstone. The Second member (Kk2) is about 115 feet thick at the mine and is predominantly red mudstone with limestone lenses. The basal unit is the Cutbank Sandstone Member (JKk1). The Cutbank Sandstone is resistant, well sorted, quartz sandstone up to 100 ft thick in some locations (Vuke and others, 2002). The Cutbank Sandstone immediately overlies the Morrison coal bed above the old mine workings.

Table 1. Stratigraphic units in the mine area (Duaime and others, 2004)

Stratigraphic Unit	Period	Lithology	Thickness	Depositional Environment
Quaternary Alluvium	Quaternary	Interbedded clay, silt, sand, and gravel	Up to 40 feet thick in the Belt Creek valley	Stream channel and floodplain
Blackleaf Formation	Cretaceous	Black shale and sandstone beds	Not present at mine; 600' thick to north	Mostly marine
Kootenai Formation	Cretaceous			
Fifth member		Red mudstone and sandstone	Not present at mine; 120' thick to north	Alluvial plain
Fourth member		Fine-grained, thin-bedded red or brown sandstone	45' thick at mine	Deltaic and fluvial
Sunburst Sandstone		Clean, porous quartz sandstone	45' thick at mine	Marginal marine
Second member		Red mudstone with limestone lenses	115' thick at mine	Alluvial plain
Cutbank Sandstone		"Salt and pepper" sandstone, may be conglomeratic	20' thick at mine	Fluvial
Morrison Formation	Cretaceous and Jurassic			Alluvial plain
ELLIS GROUP	Jurassic			Marine
Swift Formation		Orange-brown sandstone, conglomeratic, fossiliferous	50' thick at mine	
Sawtooth (Piper) Formation		Oolitic limestone, shale and siltstone	Not present at mine; 30' thick to south	
BIG SNOWY GROUP	Mississippian			Marine
Otter Formation		Green shale, limestone and gypsum	Not present at mine; 300' thick to south	
Kibbey Formation		Red mudstone, siltstone and fine-grained sandstone	Not present at mine; 100' thick to south of mine	
MADISON GROUP	Mississippian			Marine
Mission Canyon Formation		Gray, thick-bedded limestone	800' thick to south of mine	
Lodgepole Formation		Gray, thin-bedded limestone and shale	700' thick to south of mine	



Qac	Alluvium-colluvium	*(Holocene) Grayish-orange to brownish-gray, poorly sorted to moderately well sorted, locally derived sediment deposited on slopes; particle size ranges from clay and silt to gravel depending on source. Colluvium generally present only on slopes steeper than 8 percent. Contains a significant component of glacial-lake and loess deposits near glaciated areas. Thickness as much as 200 ft.*
Qat	Alluvium of terrace deposit	*(Holocene and Pleistocee): Light brown to light gray, unconsolidated crudely to well-stratified and moderately to well-sorted sand and gravel in alluvial terraces adjacent to and higher than modern meandering streams. Thickness as much as 29 ft.*
Qgt	Glacial Till	*(Pleistocene, Illinoian): Reddish-brown, brownish-gray, and gray, unstratified, compact, unsorted clay, silt, sand, and gravel with sparse matrix-supported granules, pebbles, cobbles, and boulders. Deposits mark approximate limit of Illinoian continental glaciation. Matrix dominantly calcareous clay loam, silty clay loam, and loam. Glacial erratics are chiefly limestone, dolostone, orthoquartzite, and igneous and metamorphic rocks. Thickness as much as 50 ft, but generally 30 to 15 ft thick.*
Qal	Alluvium of modern channels and flood plains	*(Holocene): Yellowish-brown to gray gravel, sand, silt, and clay beneath flood plains and in valleys of active streams. Deposits are well to poorly stratified and moderately well sorted. Maximum clast diameter 12 ft. Thickness as much as 15 ft.*
Qls	Landslide deposit	*(Holocene and Pleistocene): Mass-wasting deposit that consists of stable to unstable, unsorted mixtures of clay- to boulder-size particles or rotated blocks of bedrock. Includes bloc-glide masses of bedrock, slumped blocks of bedrock and surficial sediment, earthflow deposits, and mudflow deposits. Color and lithology reflect parent rock and transported surficial materials. Thickness as much as 200 ft, but generally less than 100 ft.*
Qaf	Alluvial fan deposit	*(Holocene): Yellowish-brown to gray, poorly stratified and poorly sorted clay, silt, sand, and sandy gravel in small fans at mouths of tributary streams. Thickness as much as 15 ft.*
Qgl	Glacial Lake Great Falls deposit	*Dark-gray to reddish-brown, massive, clay, silt, and fine sand with scattered boulders, cobbles, pebbles, and granules. Thickenss as much as 20 ft.*
Tat	Alluvium of alluvial terrace deposit	*(Pliocene): Light-brown to light-gray, crudely to well sorted, coarse sand and gravel. Upper part locally cemented by calcium carbonate. Thickness as much as 40 ft, but generally about 20 ft.*
Marias River Shale		
Kmc	Cone Member of Marias River Shale	*(Upper Cretaceous): Lower part consists of dark-gray-weathered, calcareous shale that contains a basal zone of gray septarian concretions and a thick persistent bentonite bed. Upper part consists of thin beds of platy, medium-gray- or grayish-orange-weathered petroliferous limestone with blue fish scales, Inoceramid, and oyster fragments. Thickness about 60 ft.*
Kmfl	Floweree Member of Marias River Shale	*(Upper Cretaceous): Dark-gray-weathered, fissile shale that contains several thin beds of grayish-orange-weathered siltstone, fine-grained sandstone, and also lightyellowish-gray, low-swelling, thin bentonite beds. Locally contains septarian concretions and ferruginous dolostone concretions that weather to small chips similar to those in the Ferdig Member. Thickness about 60 ft.*
Kmf	Ferdig Member of Marias River Shale	*(Upper Cretaceous): Noncalcareous, dark-gray-weathered, fissile shale that contains lenticular-bedded siltstone, fine-grained sandstone, and distinctive reddish-orange ferruginous dolostone concretions that weather into small chips. Thin beds of fine-grained, planar-bedded sandstone or siltstone are present in upper part. Thickness about 200 ft.*
Mowry Formation		
Kac	Arrow Creek Bed of Mowry and Blackleaf Formations	*(Upper and Lower Cretaceous): Very light-gray and yellowish-gray-weathered porcellanite, locally zeolitized tuff, and bentonite. Some porcellanite contains contorted bedding produced by soft-sediment deformation. Unit occurs at base of the Mowry Formation where Mowry is present, or is within the Bootlegger Member of the Blackleaf Formation. Thickness ranges from 5 inches to 65 ft.*
Blackleaf Formation		
Kbv	Vaughn Member of Blackleaf Formation	*(Lower Cretaceous): Poorly exposed, very bentonitic, silty, gray-weathered shale with thin bentonite beds. Thickness about 100 ft.*
Kbt	Taft Hill Member of Blackleaf Formation	*(Lower Cretaceous): Medium-dark-gray- to medium-lightgray-weathered, bentonitic silty shale with several thin, glauconitic sandstone beds. Member grades laterally into the Thermopolis Shale. Thickness about 120 ft.*
Kbb	Bootlegger Member of Blackleaf Formation	*(Upper and Lower Cretaceous): Dark-gray-weathered, fissile shale that contains 2 to 6 prominent sandstone beds, each 10 to 40 ft thick, separated by 50 to 100 ft of shale. Tops of sandstone beds locally contain black chert pebbles. A well-cemented chert-pebble conglomerate or coarsegrained sandstone is present at top of member.Thickness ranges from 60 to 330 ft.*
Kblf	Flood Member of Blackleaf Formation	*(Lower Cretaceous): Black- to dark-gray-weathered fissile shale that contains pods and lenses of bioturbated sandstone at its base. Lacks two prominent sandstone beds that are present west of the quadrangle. Member grades laterally into the Thermopolis Shale. Thickness ranges from 100 to 130 ft.*
Kootenai Formation		
Kk5	Fifth member of Kootenai Formation	*(Lower Cretaceous): Red-weathered mudstone that contains lenses of sandstone and limestone. Uppermost part of member consists of massive, color-banded, greenish-gray, grayish-red-purple, moderate-red and very dark red mudstone with lenses of fine- to medium-grained, trough-cross-bedded, greenish-gray-weathered sandstone. Thickness about 120 ft.*
Kk4	Fourth member of Kootenai Formation	*(Lower Cretaceous): Dusky-red to pale-reddishbrown-weathered, fine- to medium-grained, thin- to medium-bedded, ripple-laminated, argillaceous, platybedded sandstone interbedded with very-dark-red-weathered mudstone. Thickness about 100 ft.*
Kks	Sunburst Sandstone Member of Kootenai Formation	*(Lower Cretaceous): Light-yellowish-brownweathered, well-sorted, resistant quartzose sandstone with interspersed limonite specks. Scour base with rip-up clasts and chert pebbles cuts into second member and locally into Cutbank Sandstone Member. As much as 20 percent interstitial dark chert at base, but dark chert is almost completely lacking higher in the section. Member pinches out east of Raynesford. Thickness from 0 to 80 ft.*
Kk2	Second member of Kootenai Formation	*(Lower Cretaceous): Red-weathered, poorly resistant mudstone that contains dense, medium-gray micrite and argillaceous, light-brownish-gray micritic concretions that laterally become lenticular, irregular beds. Thin, lenticular, chert-rich quartzose sandstone beds are present locally. A bed of intraformational, micrite-clast conglomerate is present near top of member. Thickness about 110 ft.*
Kkc	Cutbank Sandstone Member of Kootenai Formation	*(Lower Cretaceous): Basal, resistant, festooncross-bedded, moderately well sorted quartz sandstone with 20 to 50 percent black, dark-gray, and lightgray chert; appears to be depositionally related to underlying Morrison Formation coal bed. Coarse-grained sandstone, chert-granule conglomerate, or chert-pebble conglomerate present at scour base of member, typically with rip-up clasts of coal, plant fragments, and plant impressions. Becomes finer-grained upward, and in some areas upper part of sandstone contains very little chert. Thickness ranges from 20 to 100 ft.*
Morrison Formation		
KJm	Morrison Formation	*(Lower Cretaceous and Jurassic): Light-greenish-gray mudstone or locally light-red weathered-sandstone with interbedded lenses of medium-gray micrite, and fine- to medium-grained, calcareous, thin-bedded, yellowish-brown-weathered sandstone. Subbituminous coal bed as much as 12 ft thick at or near top of formation. Gradational contact with underlying Swift Formation and overlying Kootenai Formation, but contains a significant unconformity below the dark shale and coal of the upper Morrison. Thickness ranges from 100 to 200 ft.*

✛	Anticline
✛	Syncline
—	Fault
▭	Township Boundary
—	Road
—	River/Stream
🟥	ACM Boundary

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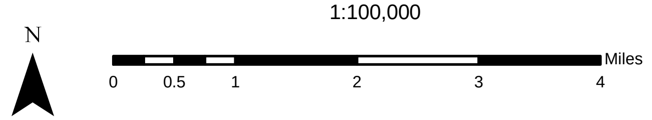


Figure 8. Geologic Map of the Belt Area, Central Montana. (Geology adapted from Vuke and others, 2002, and Vuke, 2000.)

The Jurassic Morrison Formation is about 100 feet to 300 feet thick in this area. The Morrison Formation is light-greenish- grey mudstone with lenses of yellowish-brown-weathering sandstone. A subituminous coal bed as thick as 12 feet is located at or near the top of the Morrison Formation (Vuke and others, 2002). The recent DEQ drilling project encountered voids where the coal had been mined out in this interval at several locations (Duaime, oral communications, 2004).

The Ellis Group contains the Swift Formation and is predominantly sandstone that ranges from 50-120 feet thick in the area. The Swift weathers grayish-orange and is composed of fine- to coarse-grained sandstone (Vuke and others, 2002).

Rocks of the Big Snowy Group do not appear to underlie the Anaconda Mine. These units thicken rapidly towards the Little Belt Mountains and make a significant difference in estimating depths to the Madison aquifer in the area south of Belt.

Limestone of the Mission Canyon Formation, which is up to 800 feet thick in the area, forms the upper unit of the Madison Group. The Madison Group is light-grey to dark-grey weathering, resistant, massive limestone (Vuke and others, 2002). Drill holes into the Mission Canyon Formation frequently encounter solution cavities. Sinkholes, caves, and other karst features are common in the Mission Canyon Formation.

Structure

The overall dip of surficial sedimentary rocks near the Anaconda Mine is about 4 degrees to the northeast (Vuke and others, 2002). The overall structural grain is shown by the strike of several small faults and folds (mapped in Figure 8) and trends northeast in the Belt area. The geologic structure controls deposition, erosion and exposure of geologic units in the Belt area. Tectonic forces that form faults, folds and other structures typically control development of secondary porosity such as cleat in coal beds and fractures in other rocks. This secondary porosity typically forms hydraulic connections between pore spaces and voids in the rocks to form aquifers. Several episodes of structural movement and deformation are summarized in the study done by Duaime and others (2004). Pre-Jurrassic uplift tilted the sedimentary units to the south that were subsequently eroded. Recurrent movement has been documented along the Great Falls Tectonic Zone; a northeast trending basement suture that may be responsible for much of the fracturing and folding in the Belt area (O'Neill and Lopez, 1985). The Anaconda Mine is located on the southeast flank of the Sweetgrass Arch; another recurrent basement structure that appears to have influenced the distribution of the Sunburst Sandstone and also the development of fractures and folds. Faults and folds appear to coincide with hydrologic features such as ground-water divides and may control saturated versus dry regions in the abandoned mine workings.

Underground mining commonly causes collapse of the overlying roof rocks which can project to the surface. No obvious signs of roof collapse have been observed overlying the ACM mine near Belt. However, there is also a strong potential for fractures to develop over the mine workings. These fractures could provide conduits for infiltration of recharge through the overlying sediments. This has not been verified at Belt but may potentially enhance the development of AMD in the mine workings.

HYDROGEOLOGY

Aquifers/Aquitards

Several of the geologic units in the Belt area form aquifers of either regional or local extent. The Mission Canyon Formation of the Madison Group is probably the most prolific regional aquifer in the Belt area and is commonly referred to as the Madison aquifer. This aquifer supplies discharges of about 300 cubic feet per second (cfs) at Giant Springs in Great Falls (Patton, oral communications, 2004). The town of Belt has two production wells completed in the Madison aquifer. During the recent drought, many farmers and ranchers in the Belt area have either deepened their shallow wells or directly targeted the Madison aquifer. The Swift Formation of the Ellis Group forms an important local aquifer along many reaches of Belt Creek. Sandstone beds in the Morrison Formation (the coal bed located at the top of the Morrison) and the Cutbank Sandstone of the Kootenai Formation combine to form an important aquifer system of both local and regional extent in central Montana. The Sunburst Member of the Kootenai Formation is another significant aquifer and appears to be the source of numerous springs along Belt Creek and Box Elder Creek. Quaternary sand and gravel deposits along Belt Creek and Box Elder Creek are also important local aquifers. They are typically directly connected to the streams and therefore sensitive to surface flows.

Ground-Water Flow

Ground water moves through the primary porosity of sand, gravel and sandstone, secondary fractures in the sandstone, cleat in the coal, secondary fractures and solution cavities in limestone. Regional ground-water flow is both down-dip and down-slope to the north. Locally, the ground-water flow appears to be directed towards Belt Creek.

Ground-water flow in the Belt area can be characterized by individual aquifers. The primary question regarding ground-water flow for this project is: What primary source of water enters the Anaconda Mine and forms the acidic discharges? Significant differences in flow conditions are dependant on the depth and continuity of geologic units making up the aquifers. The deepest and most laterally continuous aquifer in the area is the Madison aquifer. Recharge to this aquifer is from snowmelt in the Little Belt Mountains, where the Mission Canyon Formation is at the land surface, and from infiltration of precipitation through overlying deposits down-slope from the outcrop area. The Madison aquifer receives recharge from overlying units until somewhere between Belt and the Missouri River. The potentiometric surface of the Madison aquifer ranges from 3,275 feet (above mean sea level) where it underlies the Anaconda Mine to 3,290 feet (above mean sea level) underlying the town of Belt. The potentiometric surface underlying the Anaconda Mine ranges from about 344 feet to 412 feet below the mined out coal horizon.

The Swift aquifer is typically only developed in stream valleys in the Belt area. Not enough data points are available to construct a ground-water flow map of this aquifer; but the potentiometric surface appears to be controlled by stream stage.

The well inventory and monitoring focused on identifying aquifers up-slope from and overlying the Anaconda Mine in areas that would potentially recharge the mines. The Kootenai aquifer system is the predominant water-bearing unit underlying this recharge area. Several layers of fine-grained mudstones, siltstones and clay beds form aquitards generally restricting the vertical flow of infiltrating recharge water and forming confining beds both above and underlying many of the aquifers in the Belt area. The vertical flow is restricted enough in places to allow perched aquifers to form and contact springs to flow at the lower contact of this aquifer. The Sunburst aquifer is perched on the Second member (Kk2) of the Kootenai Formation overlying the Anaconda Mine. Several springs issue from the base of the Sunburst aquifer along Box Elder Creek and Belt Creek. Other springs in the Belt area appear to issue from the Cutbank sandstone which underlies the Second Member of the Kootenai Formation (Kk2). Although vertical flow is restricted, some water infiltrates through the aquitards recharging underlying aquifers and the mine workings. Much of this infiltration is through fractures in the sedimentary rocks. Unfortunately, only a few wells are located in this area making it difficult to verify our hydrogeologic interpretations. Supplemental drilling by the MDEQ has greatly enhanced our understanding of the hydrogeology directly overlying the Anaconda Mine. The hydrogeology is currently being interpreted through another MBMG project.

A potentiometric-surface map of the Kootenai aquifer was constructed based on well inventory and monitoring measurements. This map was contoured using measurements from 48 wells and springs near the mine (Figure 9). The Kootenai potentiometric surface map combines head data, collected in July, 2004, from aquifers in both the Sunburst and Cutbank Members of the Kootenai Formation. As a result, this map shows only general water-level conditions in the mapped area. Additional wells at critical locations will be needed to accurately depict ground-water flow. Ground water is interpreted to flow from a divide located about 3.5 miles south of the Anaconda Mine. The ground-water divide south of the mine appears to be both topographically and structurally controlled. The topographically high area forming the ground-water divide is located just north of a paired, anticline-syncline, structure that trends north 45 degrees east. Only precipitation falling north of this divide has the potential to move towards the mine. Once recharge infiltrates vertically to the saturated zone, ground-water flow is generally to the north, perpendicular to the potentiometric contours depicted in Figure 9. The upland area between Belt Creek and Box Elder Creek is highly dissected by tributaries of the two streams. These tributaries, plus the main stems of the two streams, are discharge areas for ground water moving out of the Kootenai Formation. The potential recharge area covers about 2,100 acres overlying and up-gradient of the mine. The highly dissected nature of the upland appears to 1) cause much of the precipitation falling on the upland to recharge a shallow ground-water flow system, and 2) cause discharge to the surface-water drainages as seeps and springs in the valley walls. Several of the springs coincide with the contact of the Sunburst Sandstone Member aquifer and the underlying unnamed fine-grained unit (aquitard). North of the Anaconda Mine, the flow gradient in the Kootenai aquifer decreases. This may be in response to drainage into the mine voids through secondary fractures. A more detailed well network could potentially indicate the southern ground-water flow in areas just north of the mine.

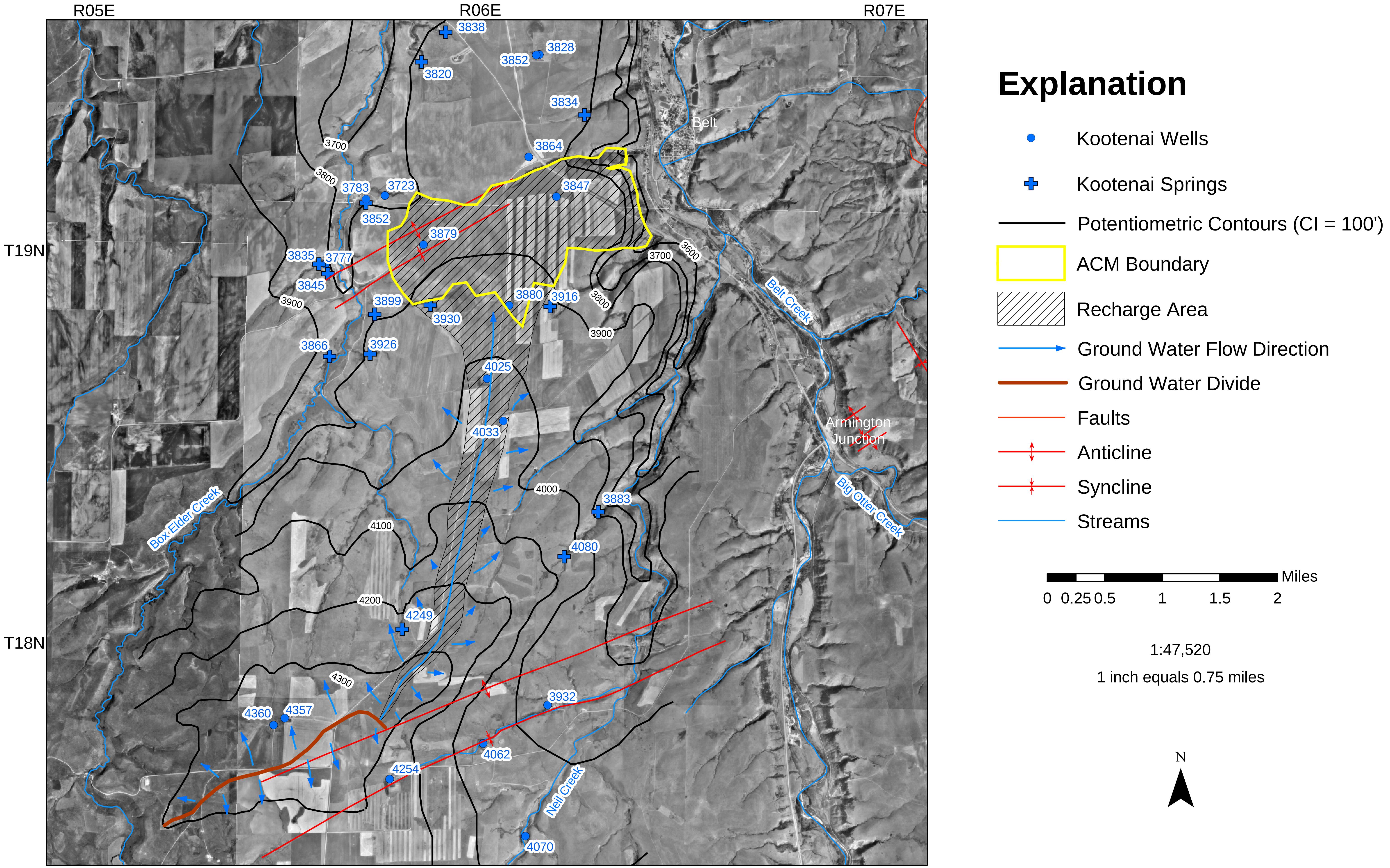


Figure 9. Potentiometric surface and ground water divide of the Kootenai aquifer system near the ACM mine based on elevations of inventoried springs, ground-water elevations measured in July 2004, and water levels from wells drilled.

Based on these interpretations, a significant source of water to the Anaconda Mine appears to be from the overlying Kootenai Formation. The Kootenai Formation is about 260 feet thick in the Belt area. The lower sandstone unit (Cutbank Sandstone Member) forms an aquifer directly overlying the targeted coal bed. The Cutbank Sandstone Member is overlain by an unnamed fine-grained unit that forms an aquitard. The Sunburst Sandstone Member forms another aquifer overlying this aquitard. The upper unit of the Kootenai Formation is another unnamed fine-grained aquitard. The Kootenai Formation is highly fractured causing some degree of vertical hydraulic connection from the surface down to the underlying coal bed and mine voids.

Water in the alluvial aquifer adjacent to and underlying the Belt Creek valley is hydraulically connected to the stream channel. Flow is towards the stream during low stages, while flood waters reverse the ground-water flow and recharge the aquifers during high stages.

Water-Level Fluctuations

The observed water-level fluctuations in monitoring wells responded to several variables. These include the geologic source of each well, the precipitation, and the position of each well in the landscape. Hydrographs of all wells measured are shown in Appendix B. Hydrographs of selected wells that are good examples of documenting responses to specific hydrologic events are shown in Figures 10-12.

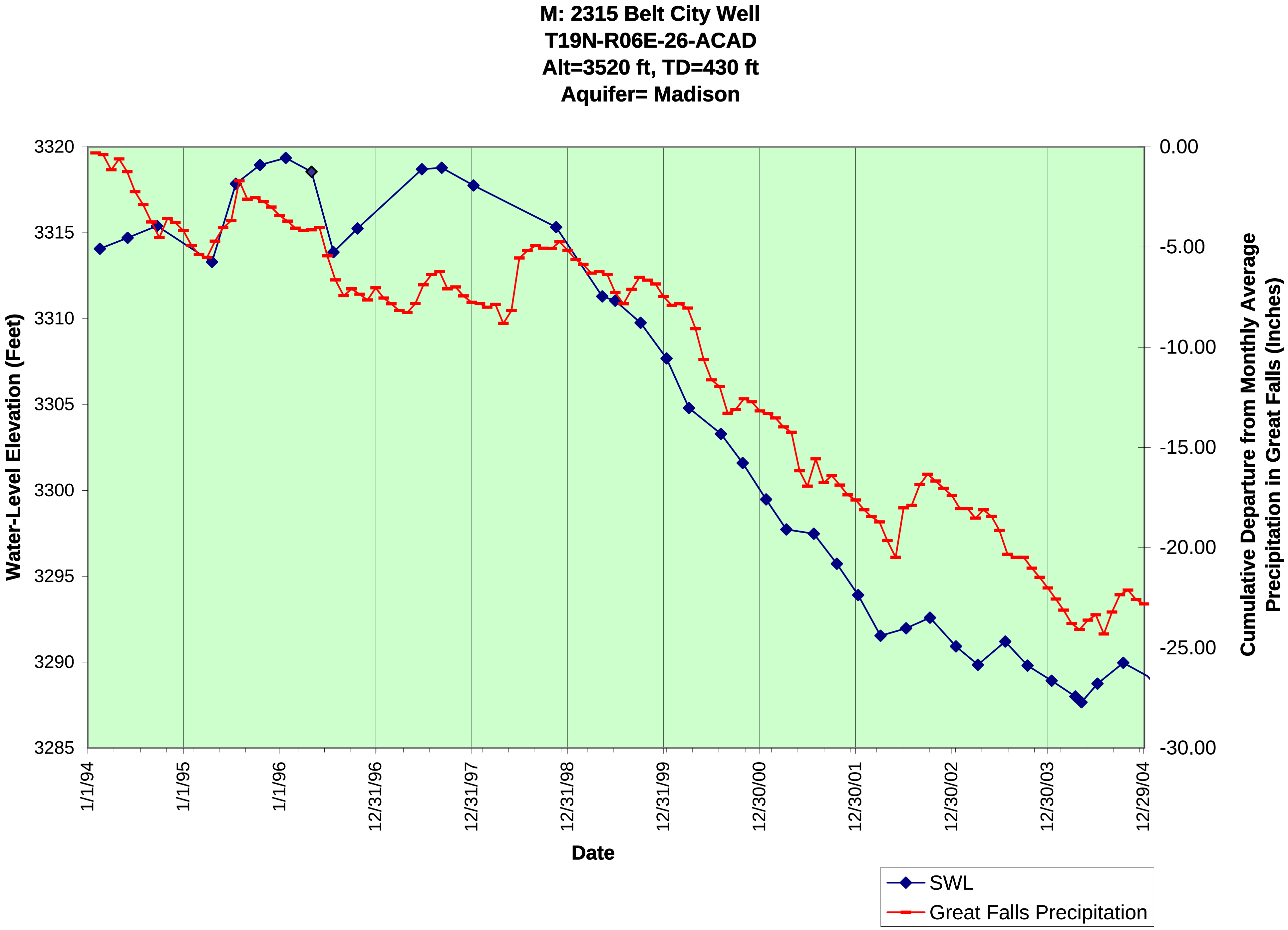


Figure 10. Hydrograph of water-level fluctuations in the Madison aquifer at Belt compared to Great Falls precipitation.

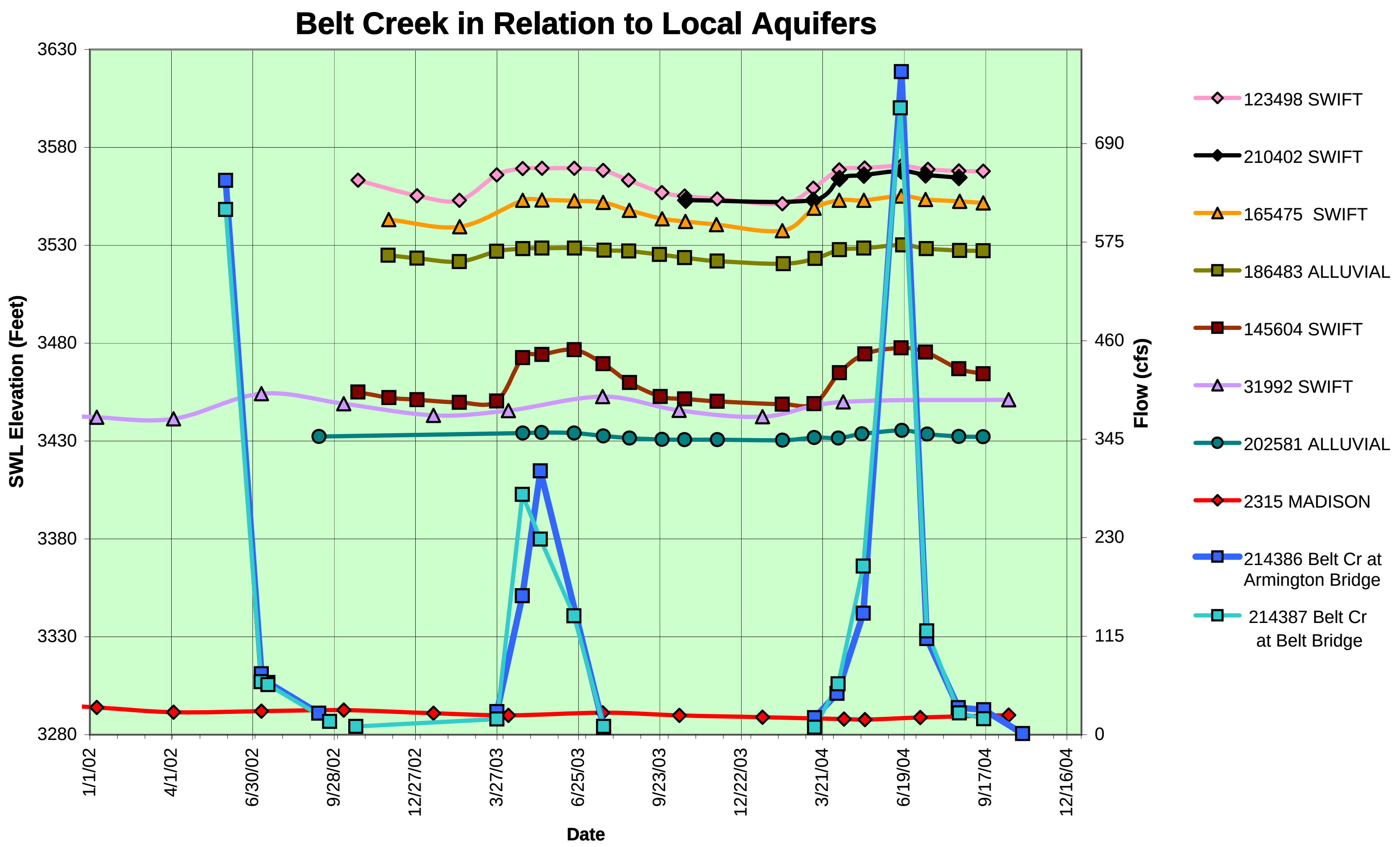
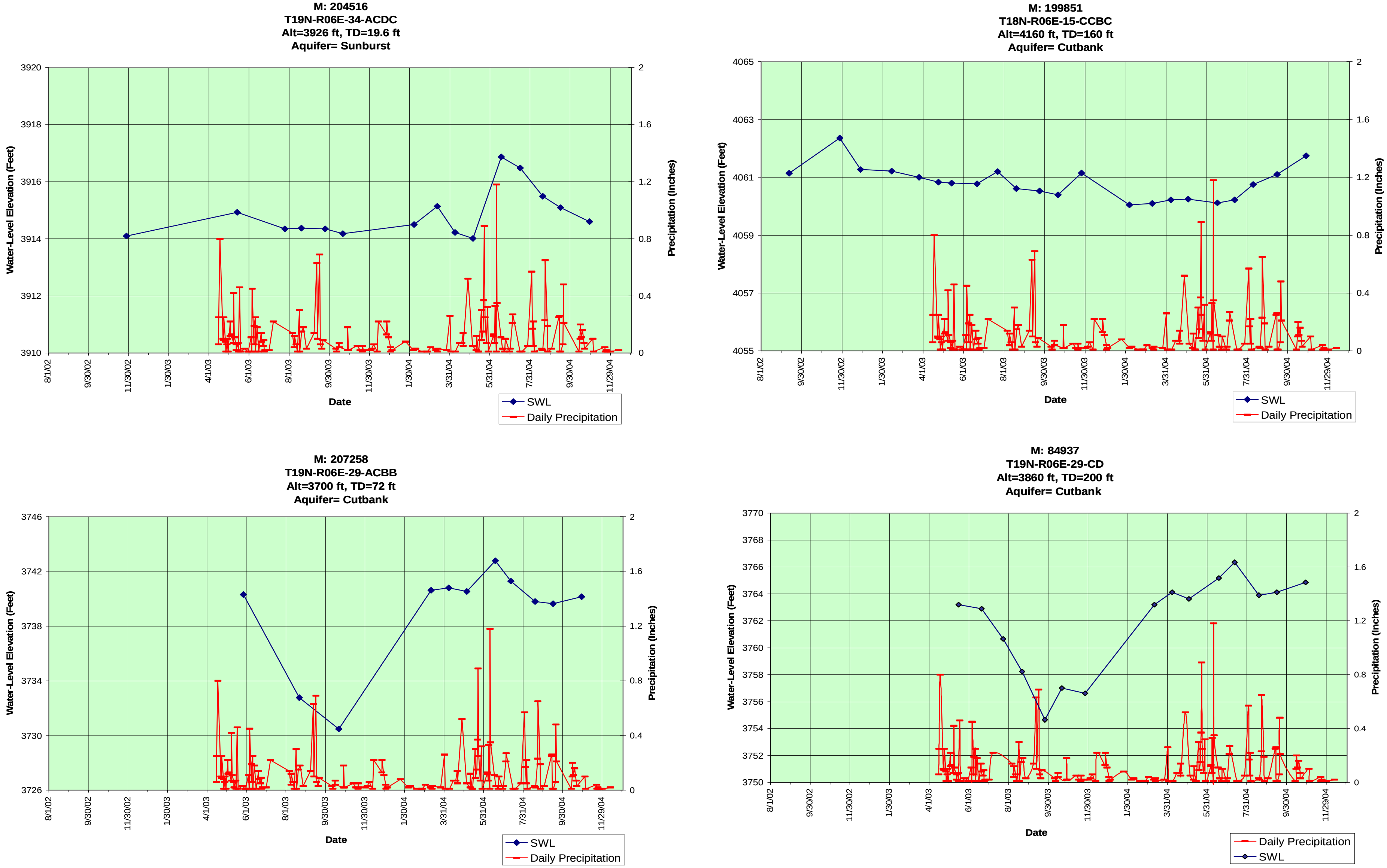


Figure 11. Hydrographs comparing water-level fluctuations in the Swift, alluvial, and Madison aquifers with Belt Creek stream flow.



M: 204516
T19N-R06E-34-ACDC
Alt=3926 ft, TD=19.6 ft
Aquifer= Sunburst

M: 199851
T18N-R06E-15-CCBC
Alt=4160 ft, TD=160 ft
Aquifer= Cutbank

M: 207258
T19N-R06E-29-ACBB
Alt=3700 ft, TD=72 ft
Aquifer= Cutbank

M: 84937
T19N-R06E-29-CD
Alt=3860 ft, TD=200 ft
Aquifer= Cutbank

Figure 12. Hydrographs showing magnitude and pattern of water-level fluctuations in the Kootenai aquifer system close to the Anaconda Mine. The upper two charts are from wells in uplands, up-gradient of the mine and depict low magnitude annual responses (2-3 feet). The lower two charts are from wells near slope breaks along tributaries and depict higher magnitude annual responses (11 - 13 feet).

Hydrographs from wells completed in the Madison aquifers show the response of the extended drought in the Belt area. Figure 10 is a relatively long-term hydrograph for one of the Belt city wells (GWIC ID 2315). Water levels in deeper wells completed in the Madison aquifer rise slightly in early spring, but the overall trends are declining water levels. Water levels have steadily declined since about 1998. This closely corresponds to the extended drought in this area.

Hydrographs from wells completed in the Swift aquifer show annual responses to stream stage along Belt Creek (Figure 11). Most of these wells are located very close to Belt Creek. Water levels in these wells appear to rise during periods of high stream flow and fall as snow-melt derived runoff declines.

Kootenai aquifer wells completed in the uplands, up-gradient of the mine, demonstrated minor water-level fluctuations trending flat to a slight decline responding to the recent drought (Figure 12). However water levels in the Kootenai aquifer wells completed near the break-in slope, towards small tributaries, showed a greater magnitude of water-level fluctuations in response to the recent drought. Most upland Kootenai wells have a rapid water level increase after large precipitation events. Water-level responses in the Kootenai appear to be more dependent on the geographic setting than the specific aquifer; as can be observed in the two upper hydrographs in Figure 12. Both wells are located in an upland setting, but at different depths. The shallow well (GWIC ID 204516) is completed in the Sunburst aquifer at a depth of about 20 feet. In contrast, the deeper well (GWIC ID 199851) is completed in the Cutbank aquifer at a depth of about 160 feet.

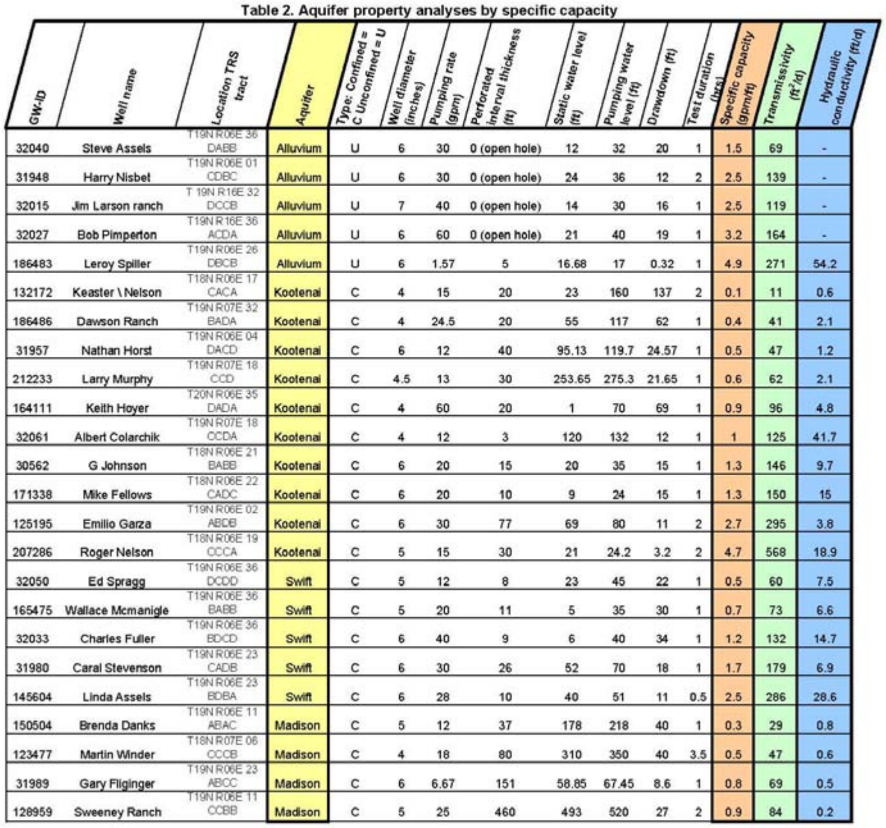
Water levels in wells completed in the alluvial aquifer near Belt Creek tend to rise and decline with Belt Creek's seasonal variation; similar to the Swift water levels (Figure 11).

Aquifer Properties

Specific Capacity Evaluation

By accessing well drill logs in the study area, specific capacity (gpm/ft) values were calculated to estimate the aquifer properties (Table 2).

Table 2. Aquifer property analyses by specific capacity



GW-ID	Well name	Location TRS tract	Aquifer	Type: Confined = C Unconfined = U	Well diameter (inches)	Pumping rate (gpm)	Perforated interval thickness (ft)	Static water level (ft)	Pumping water level (ft)	Drawdown (ft)	Test duration (hrs)	Specific capacity (gpm/ft)	Transmissivity (ft²/d)	Hydraulic conductivity (ft/d)
32040	Steve Assels	T19N R06E 36 DABB	Alluvium	U	6	30	0 (open hole)	12	32	20	1	1.5	69	-
31948	Harry Nisbet	T19N R06E 01 CDBC	Alluvium	U	6	30	0 (open hole)	24	36	12	2	2.5	139	-
32015	Jim Larson ranch	T 19N R16E 32 DCCB	Alluvium	U	7	40	0 (open hole)	14	30	16	1	2.5	119	-
32027	Bob Pimperton	T19N R16E 36 ACDA	Alluvium	U	6	60	0 (open hole)	21	40	19	1	3.2	164	-
186483	Leroy Spiller	T19N R06E 26 DBCB	Alluvium	U	6	1.57	5	16.68	17	0.32	1	4.9	271	54.2
132172	Keaster \ Nelson	T18N R06E 17 CACA	Kootenai	C	4	15	20	23	160	137	2	0.1	11	0.6
186486	Dawson Ranch	T19N R07E 32 BADA	Kootenai	C	4	24.5	20	55	117	62	1	0.4	41	2.1
31957	Nathan Horst	T19N R06E 04 DACD	Kootenai	C	6	12	40	95.13	119.7	24.57	1	0.5	47	1.2
212233	Larry Murphy	T19N R07E 18 CCD	Kootenai	C	4.5	13	30	253.65	275.3	21.65	1	0.6	62	2.1
164111	Keith Hoyer	T20N R06E 35 DADA	Kootenai	C	4	60	20	1	70	69	1	0.9	96	4.8
32061	Albert Colarchik	T19N R07E 18 CCDA	Kootenai	C	4	12	3	120	132	12	1	1	125	41.7
30562	G Johnson	T18N R06E 21 BABB	Kootenai	C	6	20	15	20	35	15	1	1.3	146	9.7
171338	Mike Fellows	T18N R06E 22 CADC	Kootenai	C	6	20	10	9	24	15	1	1.3	150	15
125195	Emilio Garza	T19N R06E 02 ABDB	Kootenai	C	6	30	77	69	80	11	2	2.7	295	3.8
207286	Roger Nelson	T18N R06E 19 CCCA	Kootenai	C	5	15	30	21	24.2	3.2	2	4.7	568	18.9
32050	Ed Spragg	T19N R06E 36 DCDD	Swift	C	5	12	8	23	45	22	1	0.5	60	7.5
165475	Wallace Mcmanigle	T19N R06E 36 BABB	Swift	C	5	20	11	5	35	30	1	0.7	73	6.6
32033	Charles Fuller	T19N R06E 36 BDCD	Swift	C	6	40	9	6	40	34	1	1.2	132	14.7
31980	Caral Stevenson	T19N R06E 23 CADB	Swift	C	6	30	26	52	70	18	1	1.7	179	6.9
145604	Linda Assels	T19N R06E 23 BDBA	Swift	C	6	28	10	40	51	11	0.5	2.5	286	28.6
150504	Brenda Danks	T19N R06E 11 ABAC	Madison	C	5	12	37	178	218	40	1	0.3	29	0.8
123477	Martin Winder	T18N R07E 06 CCCB	Madison	C	4	18	80	310	350	40	3.5	0.5	47	0.6
31989	Gary Fliginger	T19N R06E 23 ABCC	Madison	C	6	6.67	151	58.85	67.45	8.6	1	0.8	69	0.5
128959	Sweeney Ranch	T19N R06E 11 CCBB	Madison	C	5	25	460	493	520	27	2	0.9	84	0.2

Using the median specific capacity, the transmissivity (ft^2d) and hydraulic conductivity (ft/d) were also estimated for each aquifer and are shown in Table 3 (Lohman, 1979).

Table 3. Aquifer properties estimated from median specific capacity values for each aquifer.

Aquifer property analyses by specific capacity			
Aquifer	**Specific capacity (gpm/ft)**	**Transmissivity (ft^2/d)**	**Hydraulic conductivity (ft/d)**
Alluvium	2.5	139	-
Kootenai	0.95	110.5	4.3
Swift	1.2	132	7.5
Madison	0.65	58	0.55

Slug Tests

Slug tests were performed in the fall of 2004 on 5 of the 6 monitoring wells (MW) located on the reclaimed slag area on Coke Oven Flats. MW-3 (GWIC ID 217526) and MW-4 (GWIC ID 217527) had sufficient casing volume for the slug test to work properly. Slug-test data from these two wells were evaluated using the Hvorslev method (Hvorslev, 1951). The results of these analyses indicated the ground-water hydraulic conductivity ranged from about 0.6 to 32.5 feet per day. MW-4 represents an alluvial well with the hydraulic conductivity between 20 and 32 feet per day. Most wells were completed at a depth where hard, cemented gravel was encountered that could not be penetrated by the auger. Unlike the other five wells drilled in this area, MW-5 (GWIC ID 217528) was different because cemented gravel was not encountered during drilling. MW-2 (GWIC ID 217525) penetrated about 15 feet of reclaimed slag consisting of a mixture of scoria and river gravel. Based on the Hvorslev model, the hydraulic conductivity of the reclaimed waste site ranged from 0.6 to 3 feet per day.

Surface Water

Surface-water monitoring locations are shown in Figure 4. AMD discharges were monitored at 5 locations. Stream flows were periodically monitored at 3 tributaries to Belt Creek, 3 locations along Belt Creek, and 3 locations on Box Elder Creek. Flow data is summarized in Appendix C.

Acid Mine Discharges

AMD were identified at 5 sites in the Belt Creek Valley (figure 4). All sites were monitored and sampled for water-quality at least once for this project. Later, several flumes were added to collect more accurate flow measurements (Duaime and others, 2004).

In 1986, the Anaconda Mine’s main entrance was sealed and the AMD was piped beneath the county road and Burlington Northern Sante Fe Railroad (BNSF RR) tracks to a ditch which drained into a local swimming hole at Belt Creek (Figure 13). On the east side of the railroad tracks, the area known as “Coke Oven Flats”, 27 acres of waste was reclaimed in 1987. After decades of smoldering, the coal waste was extinguished and removed or buried on site (DEQ, 2000). The USGS flume recorded an average flow rate of 99 gpm from July 1994 through July 1996 (Karper, 1998). The MBMG recorded flow readings from the same flume (GWIC ID 200616) from May, 2002 to December, 2004 with an average flow rate of 132 gpm.

The French Coulee Mine Drain (GWIC ID 200615) originates from several reclaimed mines buried on the north and south side of French Coulee adjacent to the US 87 highway fill (DEQ, 2000). AMD is collected and piped under the county road to a drainage ditch (Figure 14) that was designed to mix with the Anaconda Mine discharges flowing into Belt Creek (DEQ, 2000). The AMD from the French Coulee Mine, however, seeps into the ground and does not make it directly to Belt Creek. An average flow rate of 9 gpm was measured on the east side of the railroad tracks. Flows could not be compared from USGS data due to different flow collection points.

The Lewis Coulee Mine area was reclaimed in 1985 (DEQ, 2000). The two mine openings were plugged and spoil piles were graded. A large storm drain was also constructed to carry the Lewis Coulee water and AMD (GWIC ID 214915) directly to Belt Creek (Figure 15). The average flow rate of the Lewis Coulee AMD, recorded by the MBMG during 2002-2004, was 3 gpm. Following a large precipitation event in June, the runoff flow increased to 30 gpm. Stream-flow monitoring, done by the USGS in 1994 through 1996, revealed similar flow conditions of an average flow rate of 3 gpm (Karper, 1998). The USGS data also showed large precipitation events causing peak flows over 100 gpm.

Brodie, Meisted and Millard Mines were reclaimed on the east side of Belt Creek in 1986 (DEQ, 2000). The AMD discharging from these mines (GWIC ID 214914) has been referred to as "Lewis Coulee above Castner Park" in previous reports and is continued in this report (Figure 16). This AMD does not typically discharge directly into Belt Creek, but is discharged to an unlined drainage ditch where it seeps into the alluvial aquifer before entering Belt Creek (Figure 17). The MBMG estimated average flow rates to be about 2 gpm. Flow monitoring from the USGS in 1994 through 1996 averaged 5 gpm (Karper, 1998). A list of AMD sites including flow rate and field parameters are listed in Appendix D.

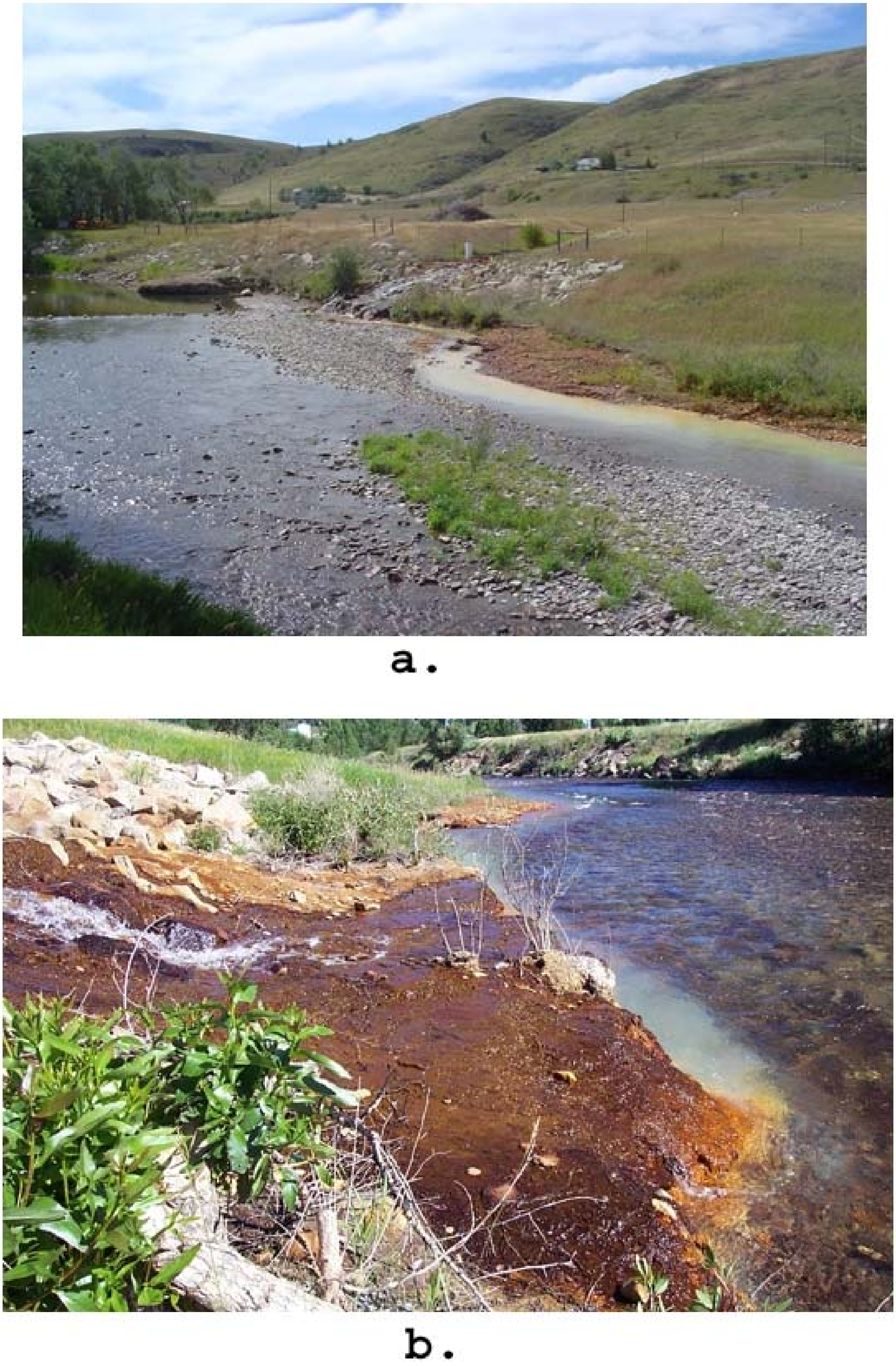


Figure 13. Anaconda Mine AMD discharges into Belt Creek at the local "swimming hole".
a. View to the south. b. View to the north.

Figure 14. The French Coulee Mine Drain collects AMD from several reclaimed mines.

Figure 15. Outlet of the Lewis Coulee Storm Drain where it enters Belt Creek.

Figure 16. Collection area for AMD from "Lewis Coulee above Castner Park".

Figure 17. AMD from "Lewis Coulee above Castner Park" seeps into an unlined ditch.

Belt Creek

Belt Creek starts near the top of the Little Belt Mountains flowing generally in a northward direction through the town of Belt and empties into the Missouri River about 15 miles north of Belt. Belt Creek is an intermittent stream with flows ranging from no-flow in late summer to nearly 800 cfs in the spring (Figure 18). The annual average flow of Belt Creek is 154 cfs; based on two years of monitoring. The main recharge to Belt creek is snow melt from the Little Belt Mountains located about 20 miles south of Belt. Belt Creek has segments that are influent (losing water to the channel) and effluent (gaining water from the channel). The Belt alluvial valley is underlain by the Swift Formation of the Ellis Group. The Swift Formation is a fine to course grained sandstone with interbeds of shale fragments with a thickness of 50 to 120 feet (Vuke and others, 2002). The Swift and alluvial aquifers located along Belt Creek are being directly recharged by the spring run off delivered by Belt Creek.

Belt Creek looses water in the reach from the Armington Bridge (GWIC ID 214386) to the bridge in downtown Belt (Figure 18). A gaining reach of Belt Creek starts just below the Belt Bridge; based on higher flows and cooler average water temperatures which suggest the influence of ground water. Gains in flow are also evident between the Belt Bridge (GWIC ID 214387) and the downstream private bridge (GWIC ID 214389). Other minor gaining and losing reaches of Belt Creek have been observed, but were less significant than those identified in the above section. During periods of low flow, AMD discharges from the Anaconda Mine provide all the water to Belt Creek.

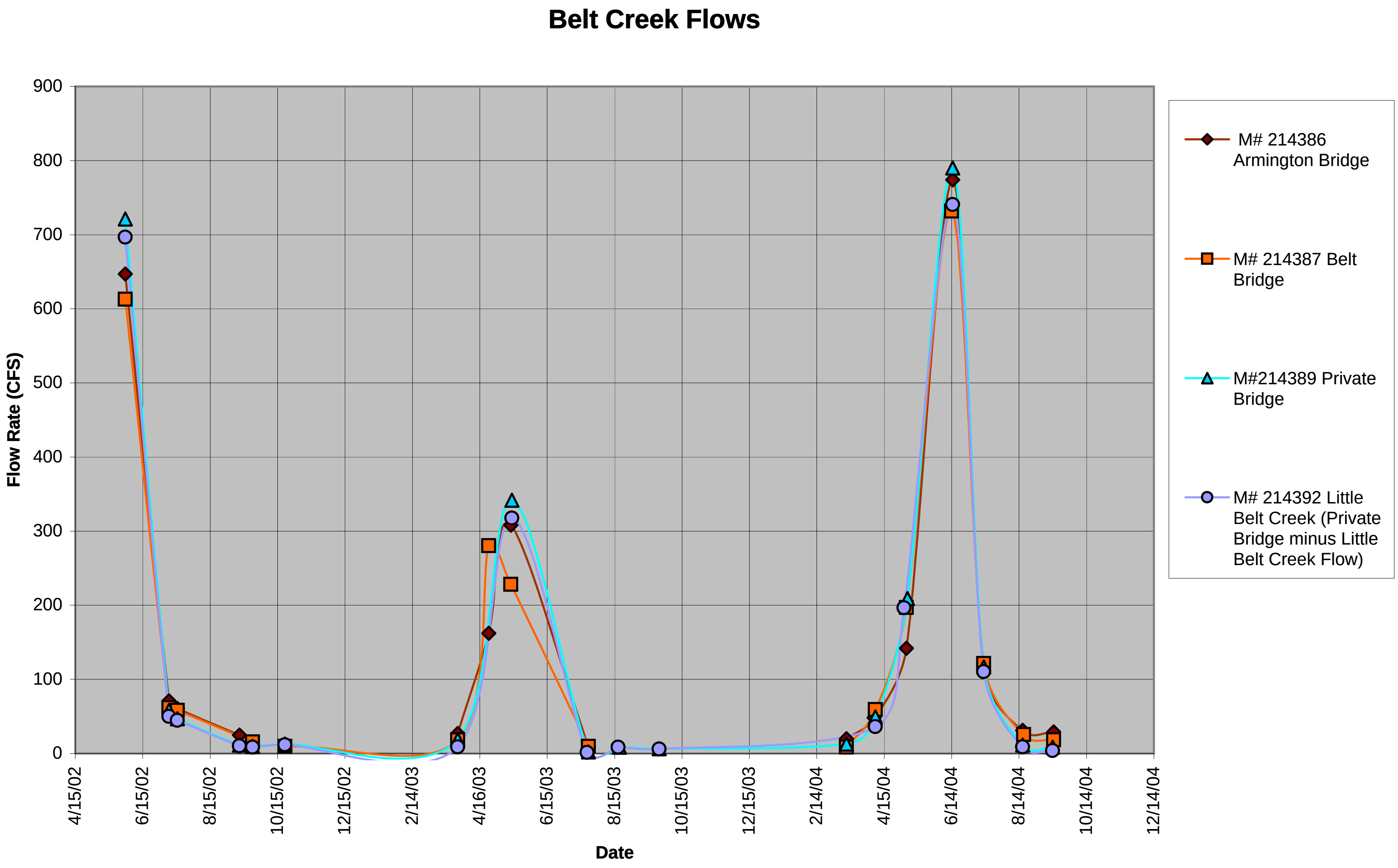


Figure 18. Stream flows along Belt Creek.

Small Streams and Springs

Within the study area, four tributary streams were monitored. Big Otter Creek, French Coulee Highway Drain and Little Belt Creek are all tributary streams that flow into Belt Creek. Box Elder Creek is a tributary of the Missouri River. Stream flow and field water-quality parameters were periodically monitored at these streams (Figure 19).

Big Otter Creek (GWIC ID 214391) is located about 3.5 miles south of the town of Belt. Big Otter Creek is an intermittent stream which occasionally goes dry in late summer. The flows range from no-flow to 28 cfs with an average of 7 cfs flowing into Belt Creek.

French Coulee Highway Drain (GWIC ID 200617) is located about one mile south of Belt, near the main Anaconda Mine adit. The creek is piped under the highway fill, draining both the French Coulee and runoff from the highway. This drain is a perennial stream with flows ranging from 1 gpm to 171 gpm with an average flow of 27 gpm emptying into Belt Creek. The stream is of good water quality, but AMD appears to be seeping out of the hillside on the north embankment. On the south embankment, there is a 2-inch PVC pipe draining water from a small seep associated with the highway fill that is referred to as the Highway Drain Seep (GWIC ID 204710).

Little Belt Creek (GWIC ID 214392) is located about 3.5 miles north of the town of Belt. Little Belt Creek is a perennial stream with flows ranging from 0.1 cfs to 49 cfs with an average of 9 cfs emptying into Belt Creek.

Box Elder Creek is located about three miles to the west of Belt. This creek was monitored in three locations. The first monitoring site was a Parshall flume installed upstream, up-gradient from any possible mine workings. The flows ranged from no-flow to 145 gpm, with a mean flow of 18 gpm. The second monitoring site (GWIC ID 214393) was located down stream, about one mile where the stream is piped under the county road. The flows at this location ranged from no-flow to 709 gpm, with a mean flow of 81 gpm. The third monitoring site was a Parshall flume located about a half mile further downstream. The flows ranged from no-flow to 908 gpm, with a mean flow rate of 75 gpm. It has been speculated that water losses from Box Elder Creek may provide recharge to the Anaconda Mine. The hydraulic head is about 130 to 140 feet higher in Box Elder Creek than the elevation of the mine voids. This provides a potential head difference for flow from Box Elder Creek to the mine. Fractures in the Kootenai Formation could produce conduits allowing flow from Box Elder Creek to the mine. Numerous springs enter into Box Elder Creek, between the upper and lower, flume making it difficult to assess gaining or losing conditions through this reach.

Several springs (GWIC ID's 213598, 205653, 207767, and 204516) were initially inventoried in our study area, but only a few were monitored on a regular basis. Most of the springs identified were contact springs discharging from the base of the Sunburst Formation. These springs flow all season with increased discharges corresponding to large precipitation events. Refer to Appendix C for flow rates and water-quality parameters on springs in this area.

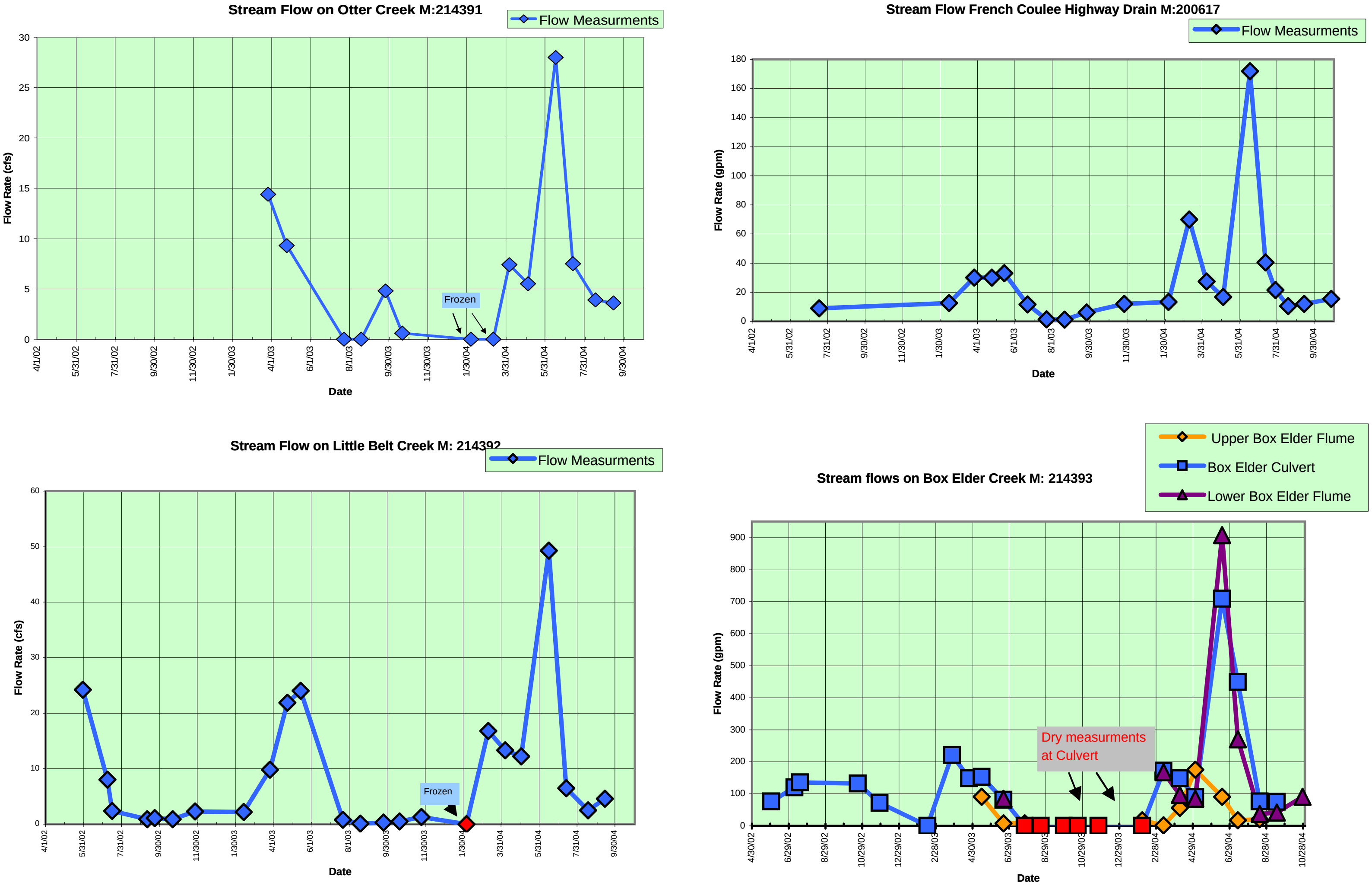


Figure 19. Hydrographs of small streams in the Belt area.

WATER-QUALITY ASSESSMENT

Field water-quality parameters measured as part of the well inventory and water-quality monitoring are shown in Appendix E. The range of dissolved minerals concentrations, oxidizing–reducing conditions, Dissolved Oxygen concentrations, temperature and pH of each water source were determined by evaluating these data. Variability of these parameters was also used to help determine seasonal fluctuations and the best time to collect representative samples.

Water-quality samples collected as part of this project are summarized in Appendix E. Source information and concentration data used for constructing the modified Schoeller plots are listed in Table 4. Modified Schoeller diagrams of major cations and anions were constructed to compare and contrast water quality of several water sources in the Belt area by plotting the dominant ions (Figure 20). The results of water analyses were grouped by water source (plotting lines using the same color) and were distinguished from similar sources (using solid and dashed lines).

The standard Schoeller plots were modified by adding Iron (Fe) and Aluminum (Al) to the list of dominant ions. Average concentrations for each constituent were calculated and converted from milligrams per liter (mg/L) to milliequivilants per liter (meq/L). When concentrations of a particular ion were below detection limits, a concentration value on half of the listed detection limit was used. In acidic waters, a low concentration value (0.0001) for the bicarbonate ion was used to allow construction of logarithmic plots.

Table 4. The average concentrations of major cations and anions (meq/L) from each source and the type of water based on dominant ions.

Source	Ca	Mg	Na	Fe	Al	HCO_3	SO_4	Cl	TYPE
AMD	10.674	8.283	0.571	28.863	31.488	0.000	86.880	0.381	Al-Fe-SO_4
Sunburst springs	3.813	4.270	0.435	0.020	0.010	5.426	2.532	0.150	Mg-Ca-HCO_3
All Creeks	3.724	2.620	0.383	0.414	0.006	4.532	1.703	0.141	Ca-HCO_3
Madison wells	4.232	2.353	0.205	0.001	0.002	3.850	2.955	0.048	Ca-HCO_3-SO_4
Alluvial wells	3.797	2.674	0.466	0.001	0.002	5.455	1.477	0.120	Ca-HCO_3
Till well	1.282	5.374	1.583	0.001	0.002	6.231	1.230	0.231	Mg-HCO_3
Mine tailings well	23.603	52.912	1.157	0.172	41.481	0.000	119.424	0.353	Mg-Al-SO_4
Sunburst wells	3.395	4.573	1.534	0.006	0.002	7.124	1.981	0.210	Mg-Ca-HCO_3
Cutbank wells	3.480	2.540	0.360	0.026	0.002	4.848	1.418	0.086	Ca-Mg-HCO_3
Coal well	4.990	3.925	0.966	0.005	0.002	6.826	2.394	0.080	Ca-Mg-HCO_3
Swift well	4.291	2.000	0.347	0.001	0.002	3.663	2.519	0.169	Ca-HCO_3-SO_4

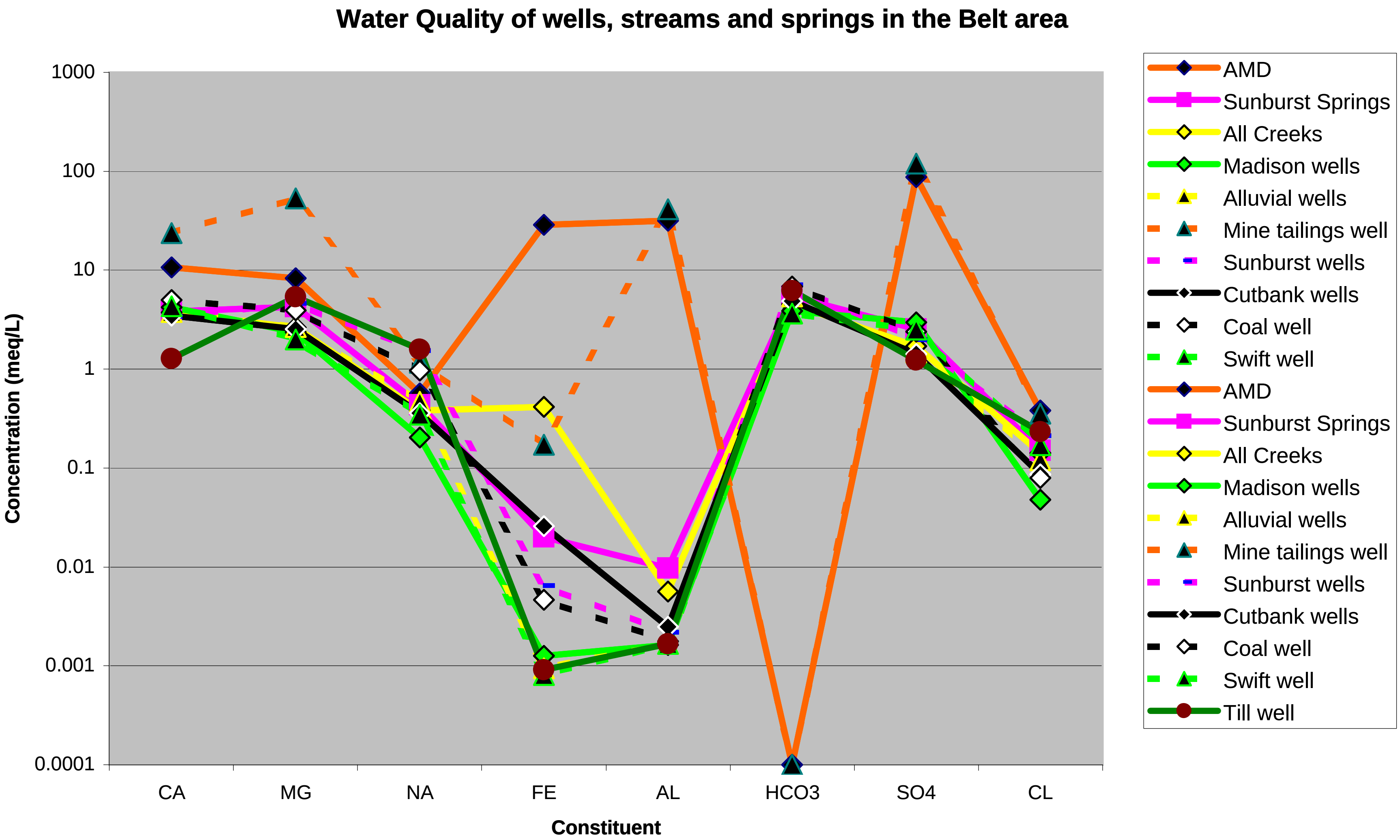


Figure 20. Schoeller diagram depicting average major ion concentrations from water sources in the Belt area.

Acid Mine Drainage (AMD) Water

Distinct characteristics of AMD discharges are visually, physically and chemically obvious. High iron concentrations form reddish-orange precipitates of iron-oxide minerals when exposed to oxygen in the atmosphere. These iron-oxide minerals frequently cement alluvial sand and gravel along streams impacted by AMD discharges. White to light gray colloidal discharges are common where high concentrations of aluminum hydroxide in ground water discharge into relatively fresh surface water; similar to what is found at the Belt "city swimming hole"(Figure 21). Field parameters of AMD discharges include pH values ranging from 1.75 to 3.99 and an average SC of 3,585 µmhos/cm. Sources of the iron, sulfate, and acidity are pyrite deposits commonly associated with coal deposits. Previous work in the Sand Coulee area identified high concentrations of acid-producing material in the Cutbank sandstone roof rock immediately above the coal (Wheaton and Brown, 1999). Since the same coal bed was mined in the Anaconda Mine at Belt, it appears that the source of acid is likely to be similar. No cores were collected in the Belt area, but pyrite deposits overlying or within the coal appear to be primary source of AMD.

AMD samples near Belt were collected from the Anaconda Mine (GWIC ID 200616 average discharge 132 gpm), French Coulee Mine (GWIC ID 200615 average discharge 9 gpm), and Lewis Coulee area mines (GWIC ID 214914 and GWIC ID 214915~average discharge 5 gpm). Samples of AMD discharges are dominated by ions of Aluminum (Al), Iron (Fe) and Sulfate (SO_4), (Al-Fe-SO_4 type water). The pH of the AMD ranged from 2.4 to 4.1. The average calculated dissolved solids (CDS) of the AMD discharges were 5,378 mg/L, average dissolved iron concentrations 537 mg/L, average dissolved aluminum concentrations 283 mg/L and average dissolved manganese (Mn) concentrations 0.682 mg/L. Piper plots (Figure 22) of AMD show a mixed dominance of Calcium (Ca) and Magnesium (Mg) cations and a strong dominance of Sulfate (SO_4) anions. These dominant cations are misleading however, since Al and Fe are the dominant cations; yet neither was included in the construction of the piper plots. The Schoeller diagram (Figure 20) more accurately depicts the dominant ions. The quality of AMD water was not uniform from the different sources. The Anaconda Mine had the freshest water with calculated dissolved solids (CDS) averaging 2,346 mg/L, average dissolved iron concentrations 152 mg/L, average dissolved aluminum concentrations 104 mg/L and average dissolved manganese concentrations 0.417 mg/L. AMD water from the Lewis Coulee Mine and "Lewis Coulee above Castner Park" were similar at intermediate concentrations with an average CDS of 5,800 mg/L, average dissolved iron concentrations 615 mg/L, average dissolved aluminum concentrations 336 mg/L and average dissolved manganese concentrations 1.15 mg/L. The French Coulee Mine drainage had the most concentrated water with calculated dissolved solids (CDS) averaging 8,566 mg/L, average dissolved iron concentrations 939 mg/L, average dissolved aluminum concentrations 468 mg/L and average dissolved manganese concentrations 0.900 mg/L.

A sample of water extracted from a well completed in mine tailings near the Coke Oven Flats also shows impacts of AMD. Water from this well is dominated by ions of magnesium (Mg), aluminum (Al), and sulfate (SO_4), (Mg-Al-SO_4 type water). The mine tailings water was similar to AMD on the Schoeller diagram. In the mine tailings water, there were lower concentrations of dissolved iron and higher concentrations of dissolved magnesium. The pH and the CDS of the water in the mine tailings are 4.48 and 7,286 mg/L respectively. The concentrations of other significant constituents were the average dissolved iron concentrations 3.21 mg/L, average dissolved aluminum concentrations 373 mg/L, and average dissolved manganese concentrations 5.98 mg/L. Iron concentrations are significantly lower and manganese concentrations significantly higher than measured in any of the AMD discharges. These chemical differences suggest that dissolved iron may be depleted in the mine tailings, while dissolved magnesium and manganese are enriched. Water discharging into Belt Creek from the mine tailings appears related to the aluminum hydroxide discharges visible at the Belt "city swimming hole".

Figure 21. Aluminum hydroxide discharging into Belt Creek at the Belt "city swimming hole"

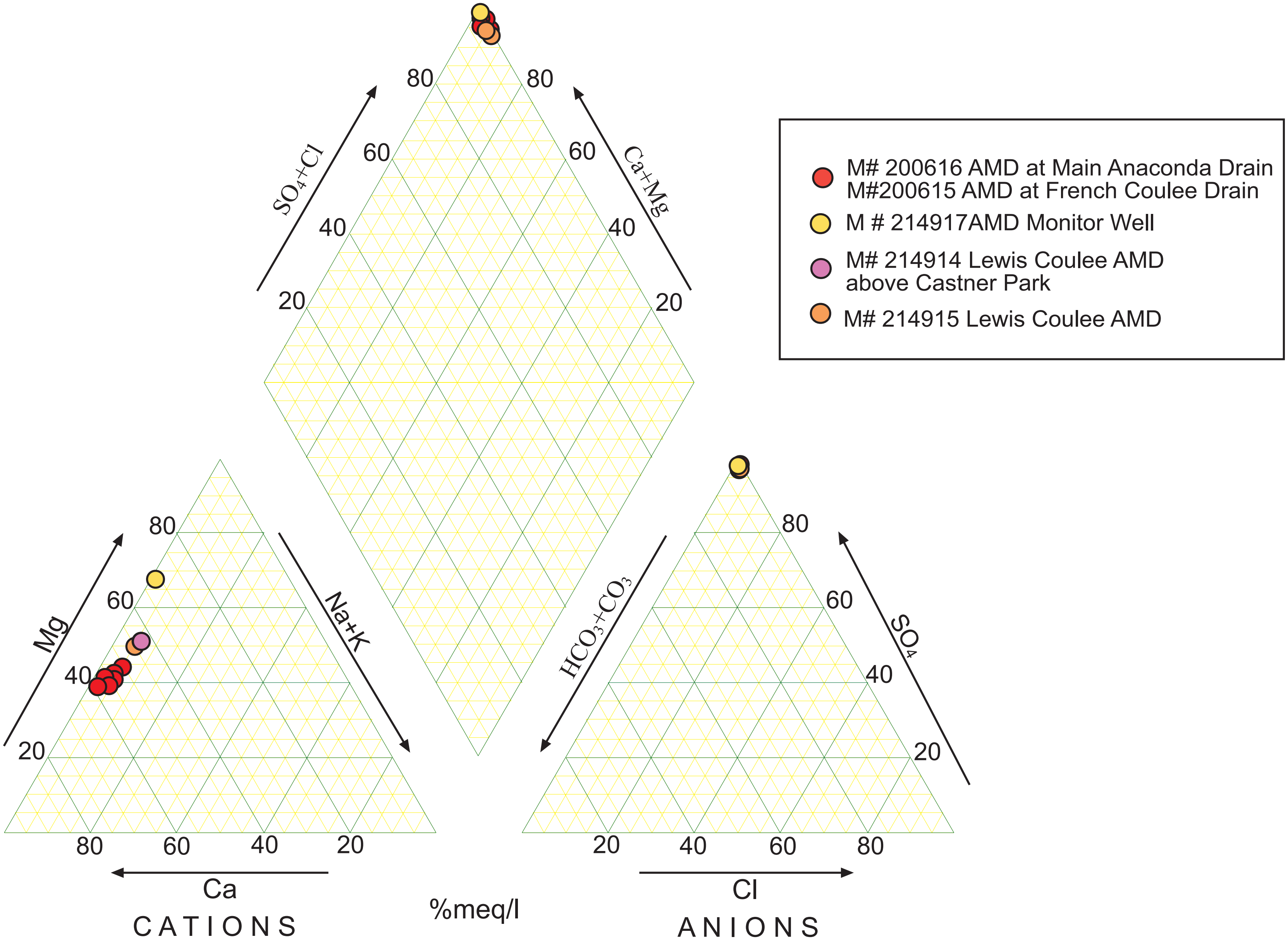


Figure 22. Piper plot of Acid Mine Drainage water in the Belt area.

Surface Water

Belt Creek and Box Elder Creek

The two main streams (Belt Creek and Box Elder Creek) in the vicinity of the Anaconda Mine contain relatively good quality water; where not impacted by AMD. Piper plot (Figure 23) of Belt and Box Elder Creek samples were dominated by ions of calcium (CA) and bicarbonate (HCO_3), (CA- HCO_3 type water). The laboratory pH of all samples from these Creeks ranged from 5.83 to 8.12 and the average CDS was 353 mg/L. Schoeller diagrams of major ions from Box Elder and Belt Creeks were very similar to the diagrams constructed using average concentrations in samples from alluvial wells (figure 20). This demonstrates the close hydrologic relationship between these sources. The two plots are virtually identical with the exception of elevated concentrations of dissolved iron and aluminum ions in the stream samples. The anomalies in the average concentrations of these ions were caused by elevated concentrations in Belt Creek that are clearly associated with AMD.

Water samples from Belt Creek were collected at several locations, including the following locations: Armington Bridge (GWIC ID 214386); Belt (GWIC ID 205836); Belt (GWIC ID 205838); Belt (GWIC ID 205839); near city well (GWIC ID 205508); below Lewis Coulee discharges (GWIC ID 214916); above swimming hole (GWIC ID 214911); and at the north extent of mine tailings (GWIC ID 214913). The pH of Belt Creek ranged from 5.83 to 7.83. The average calculated dissolved solids concentrations (CDS) of Belt Creek were 326 mg/L, average dissolved iron concentrations 1.03 mg/L, average dissolved aluminum concentrations 73 micrograms/L (µg/L), and average dissolved manganese concentrations 0.08 mg/L. The quality of water along Belt Creek showed impacts of AMD with elevated concentrations of metals associated with areas of surface and ground water acidic discharges. Metals loading to Belt Creek will be discussed in a later section of this report.

Water samples from Box Elder Creek were collected at the upper flume (GWIC ID 203450) and the lower flume (GWIC ID 203451). The pH of Box Elder Creek ranged from 6.44 to 8.26. The average calculated dissolved solids concentrations (CDS) of Box Elder Creek were 371 mg/L. The average dissolved iron concentrations were 0.03 mg/L. Average dissolved aluminum concentrations 84.4 µg/L and average dissolved manganese concentrations 0.08 mg/L. The quality of water along Box Elder Creek does not appear to be impacted by AMD and no known AMD discharges have been identified along this creek.

Other small streams, including Little Belt Creek and Otter Creek, were not sampled. Based on field values, these streams are relatively fresh and have not been impacted by AMD.

Sunburst springs

Several springs discharging from the Sunburst aquifer were sampled. These include the French Coulee Highway Drain (GWIC ID 200617), a small seep referred to as the Highway Drain seep (GWIC ID 204710), and four relatively fresh springs along upper French Coulee and Box Elder Creek (GWIC ID's 213598, 205653, 207767, and 204516). Sunburst aquifer spring samples are dominated by ions of magnesium (Mg), calcium (Ca) and bicarbonate (HCO_3), (Mg-Ca- HCO_3 type water) as shown in the Piper Plot (Figure 24) and the Schoeller diagram (Figure 20). The laboratory pH of all samples from these sources ranged from 7.08 to 8.36 and the average CDS was 830 mg/L. Nitrate concentrations of the Sunburst springs range from less than 0.05 to 25.6 mg/L and nearly all of the samples had concentrations greater than 1 mg/L. The elevated nitrate concentrations appear to be associated with fertilizer applications on the small grain cropland that makes up most of the recharge areas to these springs.

The four fresh Sunburst springs had an average CDS concentration of 298 mg/L. These springs had very low average sulfate concentrations (29 mg/L) and chloride concentrations (3 mg/L). Nitrate concentrations were variable, but typically relatively high. The CDS of spring discharges in the French Coulee Highway Drain averaged 516 mg/L. This drain had intermediate average sulfate concentrations (164 mg/L) and low to intermediate chloride concentrations (6 mg/L). Nitrate concentrations were variable, but typically relatively high. The small seep in the Highway Drain has significantly different water quality than the other Sunburst springs. The average CDS of this water is 3,255 mg/L; nearly 3 times as concentrated as the fresh Sunburst springs. The average sulfate concentration is 2,109 mg/L, which is more than one order-of-magnitude greater than the Highway Drain and nearly two orders-of-magnitude greater than the fresh Sunburst springs. Water from this seep contains anomalously high concentrations of chloride ions.

Water qualities of the French Coulee Highway Drain and the small seep associated with the drain have relatively neutral pH and appear to have been degraded by a source other than AMD. The water appears to be associated with construction of the highway grade that these springs drain. The fill material may contain higher concentrations of salts than the typical Sunburst aquifer. In addition, pulses of calcium chloride appear to be cyclical and may relate to wintertime applications of road salt.

The water quality of samples from Sunburst springs is very similar to samples from Sunburst aquifer wells (Figure 20). The average dissolved concentration of most ions from the spring samples are higher than ions from well samples. Salts may be more available for leaching in the highway fill. In addition, elevated concentrations of dissolved iron and aluminum ions may indicate an additional source of AMD.

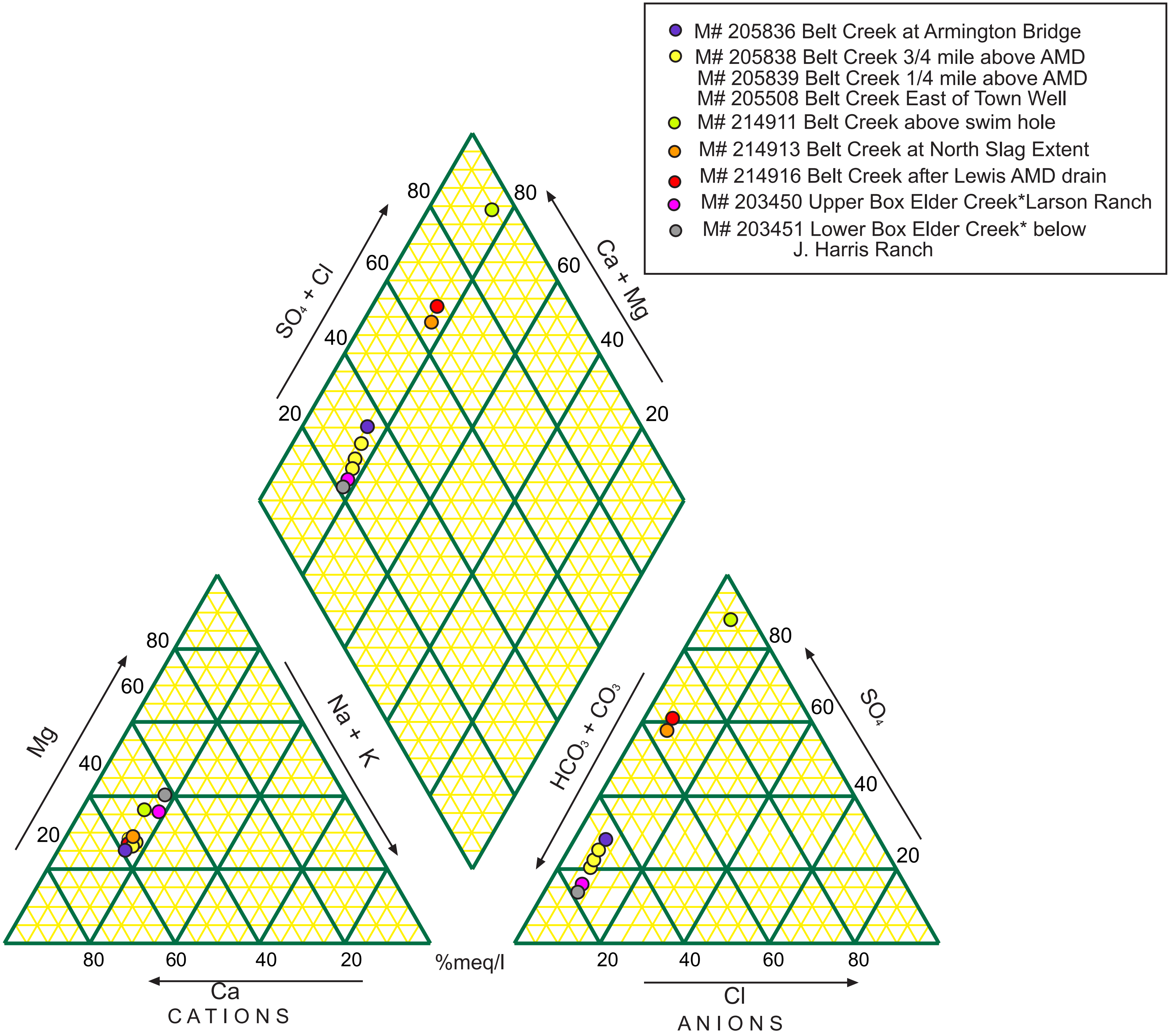


Figure 23. Piper plot of water samples from Belt Creek and Box Elder Creek. Table lists wells from upstream to downstream.

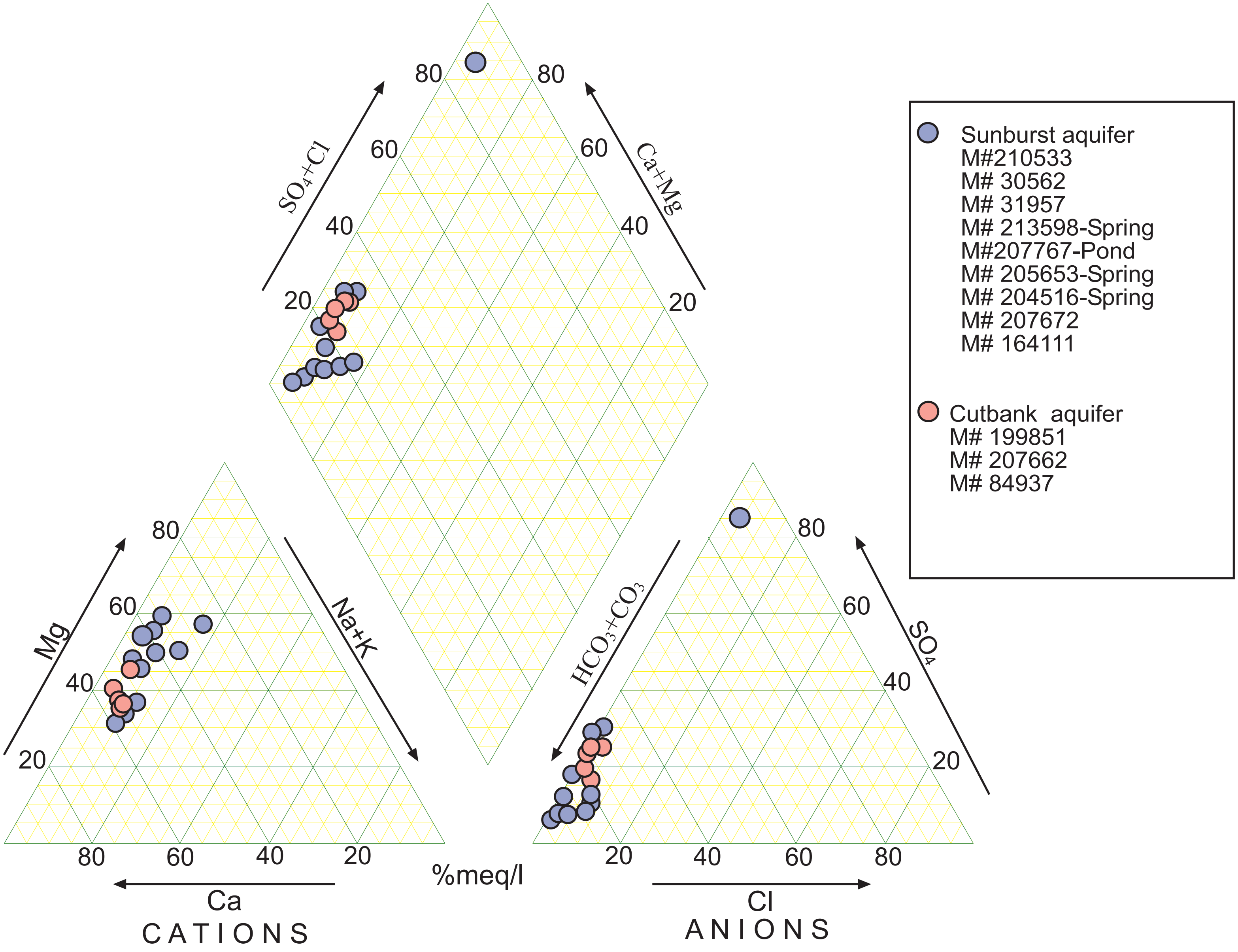


Figure 24. Piper plots of water samples from wells and springs in the Sunburst aquifer and wells in the Cutbank aquifer. Both aquifers are developed in sandstone of the Kootenai Formation.

Ground Water

Several aquifers were sampled and water-quality data compiled from the Belt area. These include the alluvial aquifer along Belt Creek and Box Elder Creek, the Kootenai aquifer system (including the Sunburst aquifer and the Cutbank aquifer), the Morrison aquifer (represented by one well into the coal bed), the Swift aquifer, and the Madison aquifer.

Alluvial aquifer

Three samples collected from two wells completed in the alluvial aquifer were analyzed for dissolved constituents. A well along Box Elder Creek (GWIC ID 32015) was sampled twice and a well along Belt Creek (GWIC ID 186483) was sampled once. The alluvial aquifer samples are very similar to each other and are dominated by ions of dissolved calcium (Ca) and bicarbonate (HCO_3), (Ca- HCO_3 type water) as shown in the Piper Plot (Figure 25) and the Schoeller diagram (Figure 20). The laboratory pH of all samples from these wells ranged from 7.66 to 7.68 and the average CDS was 372 mg/L. Dissolved nitrate concentrations from the alluvial well along Belt creek was 0.66mg/L and concentrations from the well along Box Elder Creek averaged 1.04 mg/L. The slightly elevated nitrate concentrations in the Box Elder Creek alluvium are associated with discharge of Sunburst springs that appear to be impacted by fertilizer applications. The average concentration of dissolved iron was 0.018 mg/L and ranged from 0.012 to 0.023. Neither of these wells appears to be impacted by AMD. As previously discussed, the water quality of alluvial aquifer water samples is very similar to the stream samples.

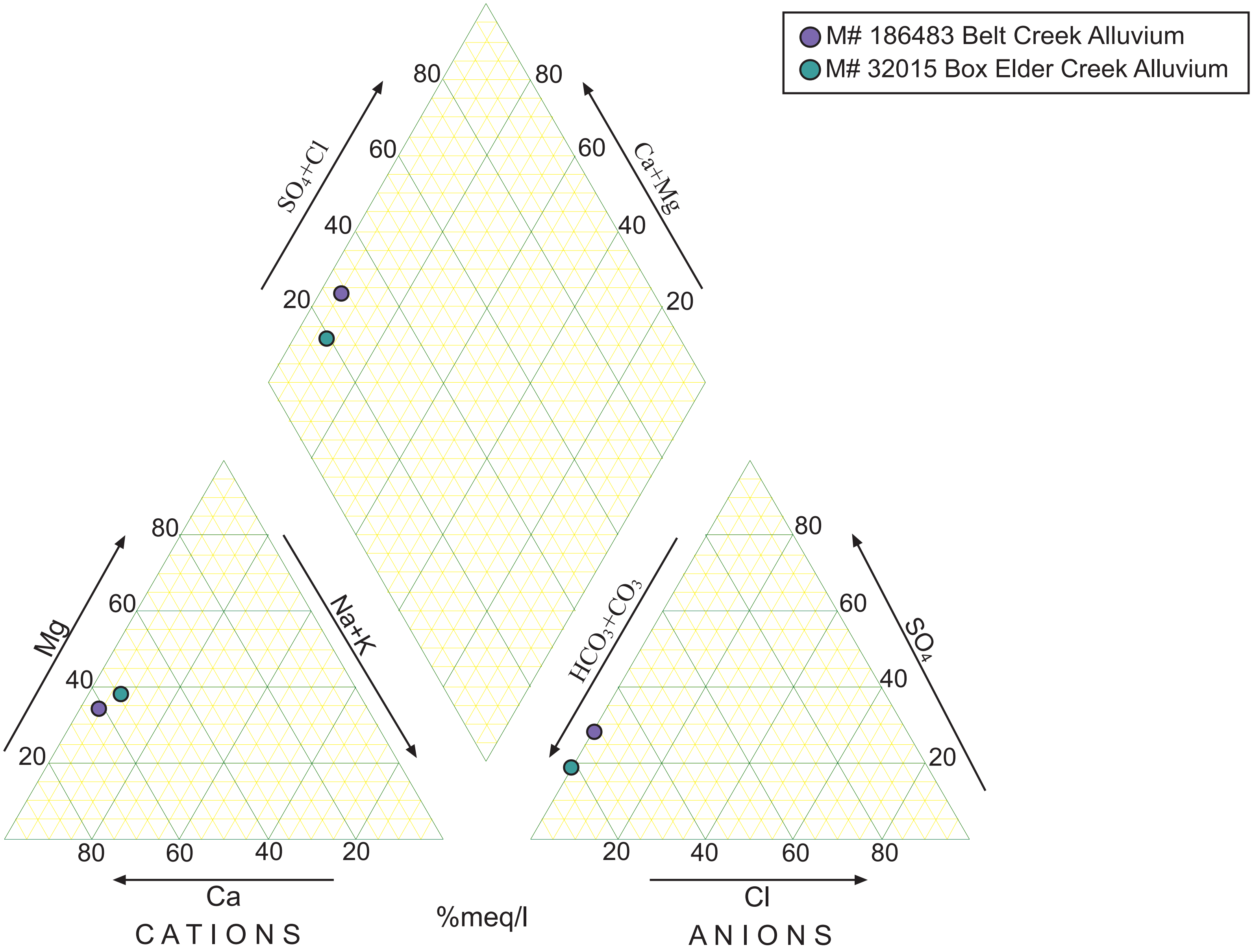


Figure 25. Piper plot of water samples from well completed in alluvium of Belt Creek (GWIC ID 186483) and Box Elder Creek Alluvium (GWIC ID 32015).

Sunburst aquifer

Nine wells completed in the Sunburst aquifer were sampled (GWIC ID's 210533, 30562, 31957, 213598, 207767, 205653, 204516, 207672, and 164111). Sunburst aquifer samples are dominated by ions of magnesium (Mg), calcium (Cg) and bicarbonate (HCO_3), (Mg-Ca- HCO_3 type water) as shown in the Piper Plot (Figure 24) and the Schoeller diagram (Figure 20). The laboratory pH of all samples from these sources ranged from 7.26 to 8.00 and the average CDS was 491 mg/L. Nitrate concentrations of the Sunburst aquifer ranged from less than 0.05 to 11.8 mg/L. Nearly all of the samples had concentrations greater than 1 mg/L. The elevated nitrate concentrations appear to be associated with fertilizer applications on the small grain cropland that makes up most of the recharge areas to these wells. Orthophosphate (OPO_4) concentrations ranging from 0.1 to 0.2 mg/L were identified in samples from two recently drilled wells located above or adjacent to the Anaconda Mine. No other Sunburst aquifer samples had detectable concentrations of this constituent and it is plausible that these observations are the result of fertilizer impacts with infiltration enhanced by fractures developed over the abandoned mine workings. As previously discussed, the water quality of Sunburst aquifer water samples is very similar to the Sunburst spring samples. The Sunburst wells have an overall lower CDS than the Sunburst springs. This observation is a result of the springs being impacted by AMD, whereas water quality of the wells is not impacted.

Cutbank aquifer

Three wells completed in the Cutbank aquifer were sampled (GWIC ID's 199851, 84937 and 207662). The average concentration of Cutbank aquifer samples are dominated by ions of calcium (Ca) magnesium (Mg), and bicarbonate (HCO_3), (Ca-Mg-HCO_3 type water) as shown in the Piper Plot (Figure 24) and the Schoeller diagram (Figure 20). The laboratory pH of all samples from these sources ranged from 7.26 to 7.58 and the average CDS was 339 mg/L. Nitrate concentrations of the Cutbank aquifer ranged from less than 0.05 to 2.17 mg/L. Orthophosphate concentrations of 0.054 mg/L were identified in one Cutbank aquifer well that is located adjacent to the Anaconda Mine. It is plausible that this observation is the result of fertilizer impacts with infiltration enhanced by fractures developed over the abandoned mine workings. Schoeller diagrams of major ions from the Cutbank aquifer were very similar to the diagrams constructed using average concentrations in samples from a well completed in the coal bed at the top of the Morrison Formation (GWIC ID 215048). This demonstrates the close hydrologic relationship between these sources and supports well-log data indicating these units are part of a single aquifer.

Madison aquifer

Six wells completed in the Madison aquifer were sampled (GWIC ID's 196148, 150504, 31978, 2315, 215047 and 177163). Madison aquifer samples are dominated by ions of calcium (Ca), bicarbonate (HCO_3), and sulfate (SO_4) (Ca-Mg-HCO_3-SO_4 type water) as shown in the Piper Plot (Figure 26) and the Schoeller diagram (Figure 20). The laboratory pH of all samples from these sources ranged from 7.46 to 8.05 and the average CDS was 390 mg/L. Nitrate concentrations of the Madison aquifer were very low. AMD impacts were not evident in any of these samples. Sulfate ions are the second dominant anion in Madison water samples. Since no other metals have elevated concentrations, it appears that the Madison aquifer in the Belt area has relatively high concentrations of sulfate anions in comparison to other aquifers. Schoeller diagrams of major ions from the Madison aquifer were very similar to the diagrams constructed using average concentrations in samples from a well completed in the Swift aquifer (GWIC ID 145604). These aquifers are hydrologically connected in some areas and are likely to have similar water quality.

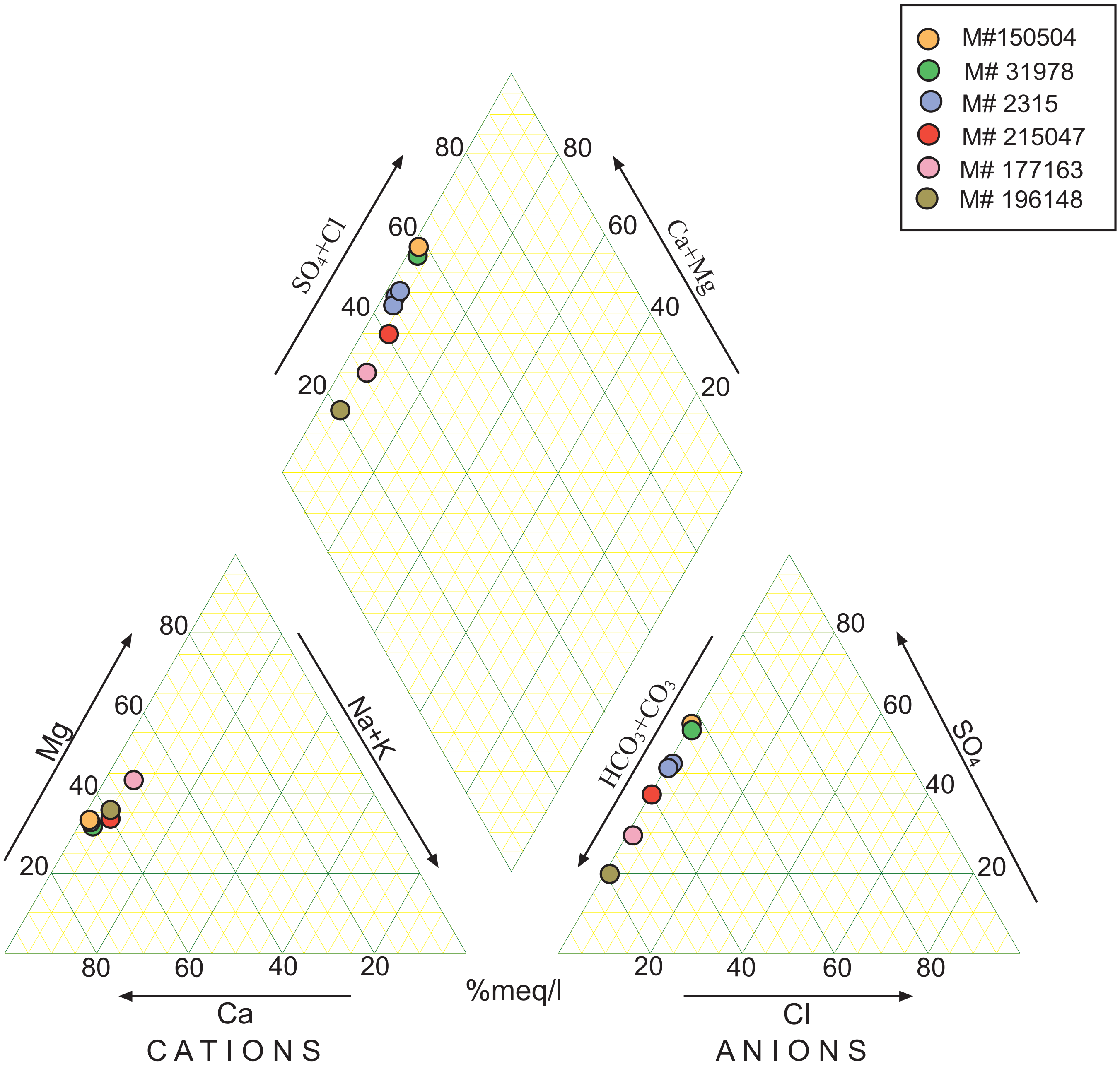


Figure 26. Piper plots of water samples from the Madison aquifer in the Belt area.

Other aquifers

Piper plots of water-quality data from other aquifers are shown in Figure 27 and the Schoeller diagram in Figure 20. These aquifers include a well completed in a glacial till aquifer (GWIC ID 231952), a well completed in the Morrison Coal (GWIC ID 215048), and a well completed in the Swift aquifer (GWIC ID 145604). All of these wells, except for the glacial till aquifer, have been covered in previous discussions. The glacial till well is located several miles north of the Anaconda Mine. The main interest in discussing the water quality from this well is to show the variability of water quality in the Belt area. Water in the till aquifer is dominated by ions of magnesium (Mg) and bicarbonate ($HC0_3$) ($Mg\text{-}HC0_3$ type water). The pH of the till well was 7.97 and CDS was 413 mg/L. Nitrate concentrations were 10.77 mg/L; which is above the drinking water standard. Water in this well appears to be impacted by an agricultural source; possibly fertilizer or animal waste. AMD impacts have not affected water in this well.

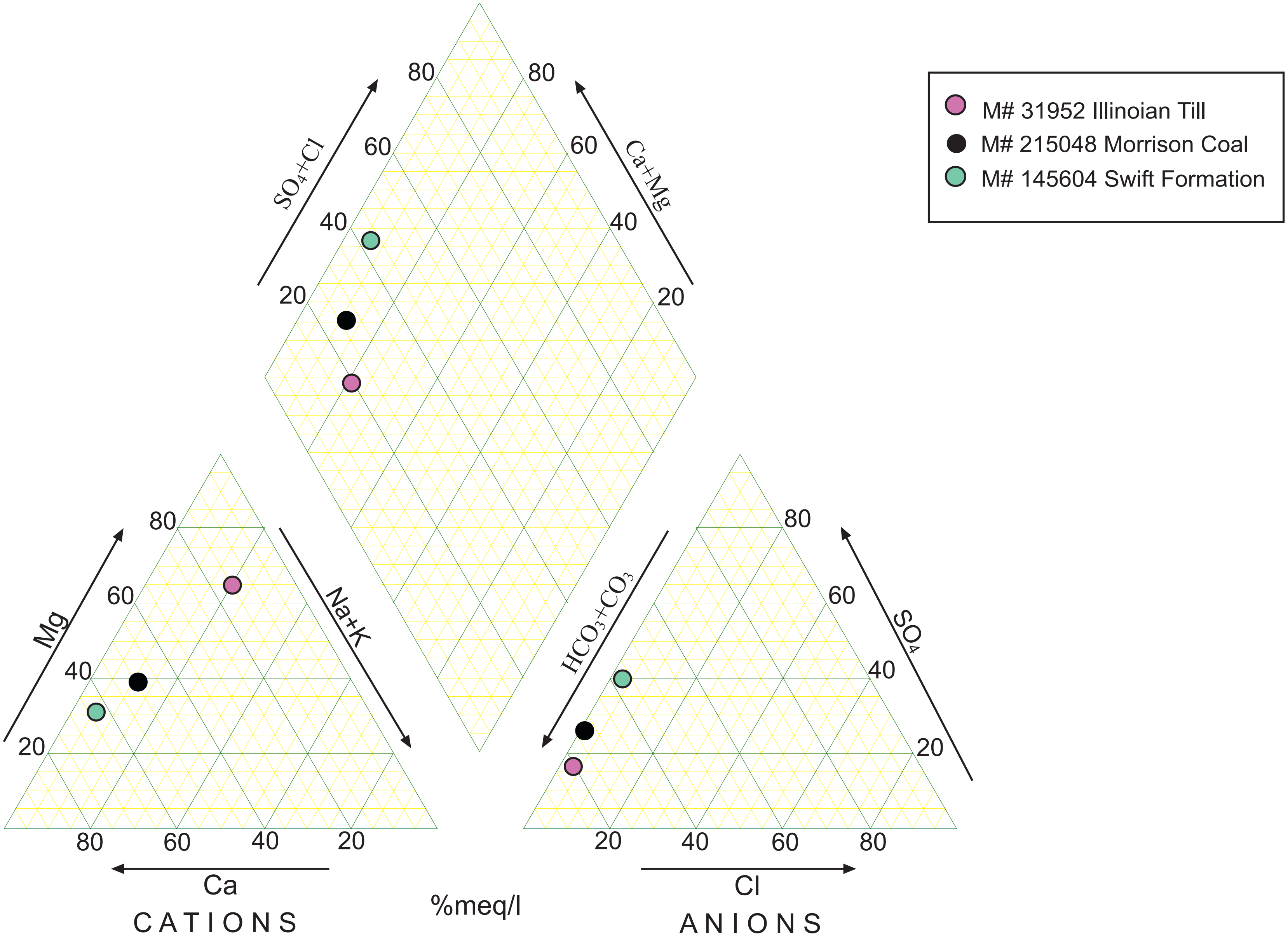


Figure 27. Piper plot of water samples from other aquifers in the Belt area.

ISOTOPE ASSESSMENT

Stable Isotopes

The stable isotope of oxygen-18 (^{18}O) was analyzed in ground-water to determine recharge sources. The value of $\delta\ ^{18}O$ in precipitation is influenced by meteorological processes and particularly by the temperature, elevation, and latitude of the rain or snowfall event (Clark and Fritz, 1997). Precipitation occurring over warmer climates, low elevations, and low latitudes has higher (less depleted) $\delta\ ^{18}O$ values than precipitation occurring over colder climates, higher elevations, and higher latitudes (Olson and Reiten, 2002).

Values of $\delta\ ^{18}O$ from 35 samples range from -19.79 to -15.34 per mill (Figure 28). Samples from the Madison aquifer have relativity low values ranging from -19.64 to -18.67 per mill. They also have a narrow value range, suggesting the recharge is likely from snowfall. The Kootenai aquifer has a wide value range from -19.79 to -15.34 per mill, implying the recharge is by snowfall mixing with rain events. AMD water plots near the midpoint of the range of Kootenai aquifer waters possibly suggesting this aquifer is the source of the AMD. Surface water, Swift Formation water, and alluvial water samples have a similar range; indicating a mixture of snowmelt and rainfall and possible mixing between these sources. A sample taken from the Missouri River, at Toston in May, 1986, indicated snow melt was the dominant recharge source, later mixing with rain fall (Coplan and Kendall, 2000). The map view of $\delta\ ^{18}O$ values shows no obvious trend over the study area.

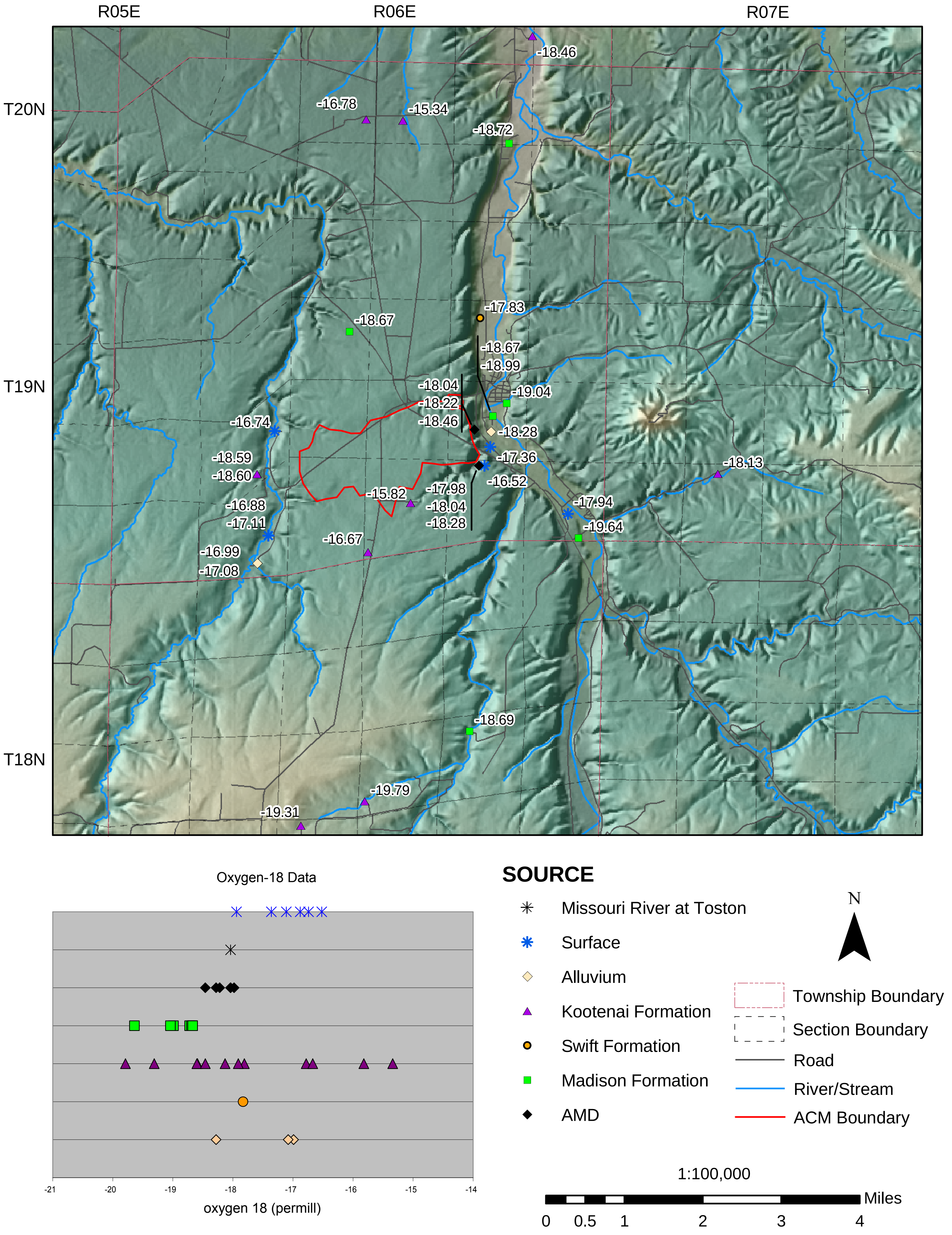


Figure 28. Map and chart showing Oxygen 18 isotopes by water source.

Average Residence Time of Ground Water

Tritium (^3H) is a radioactive isotope of hydrogen that decays with a half-life of 12.43 years and is contained at ambient levels in precipitation as it falls to the earth. Tritium is produced naturally in the atmosphere by interaction of cosmic rays with nitrogen and oxygen; but nuclear bombs, tested between 1952 and 1969, released large quantities of tritium into the atmosphere. Therefore, precipitation during times of nuclear testing contained very high concentrations of tritium. According to the decay equation (Clark and Fritz, 1997), as the precipitation infiltrates into the ground, recharging the aquifers, the radioactive tritium decays to helium-3 (^3He). The age of the water sample is determined by the ratio of the parent (^3H) to the daughter (^3He). The relative age can be estimated using the tritium concentration alone. Table 5 lists tritium concentration and age of water based upon a linear interpretation of data (Hendry and Schwartz, 1990).

Table 5. Age date of ground water estimated from tritium concentration.

Tritium Concentration (Tu)	Age Interpretation (modified from Hendry, 1988)
>38	Average ground-water likely recharged during peak of thermo-nuclear testing between 1960-1965
4-38	Average ground-water less than 50 years old
1-4	Average ground-water less than 35 years old
<1,>0.1	Average ground-water older than 45 years old
< 0.1	Average ground-water older than 65 years old

Most of the samples collected in Belt had tritium concentrations ranging from 4-38 Tritium Units (TU). This implies the average residence time of ground water is less than 50 years old. Some samples ranged between 1-4 TU. This implies the recharge is less than 35 years old. Figure 29 displays how tritium concentrations vary across each aquifer. There was no obvious trend of tritium concentrations or ages either within specific hydrogeologic sources or by map locations of the sample sites. A few general similarities within and between groups were noted. A similar range of tritium concentrations are shown in the surface-water samples, AMD water samples, the Swift Formation water samples, and alluvial water samples. Tritium concentrations from Madison aquifer wells demonstrated the tightest grouping with TU values ranging from 11-14 for all but one sample. The Kootenai Formation water samples displayed the widest spread with TU values ranging from about 1 to greater than 20. The range of tritium concentrations in the AMD water samples tended to concentrate near the midpoint of Kootenai aquifer water samples. One possible explanation of the large range in the Kootenai samples is that many parts of the aquifer have poor hydraulic connections.

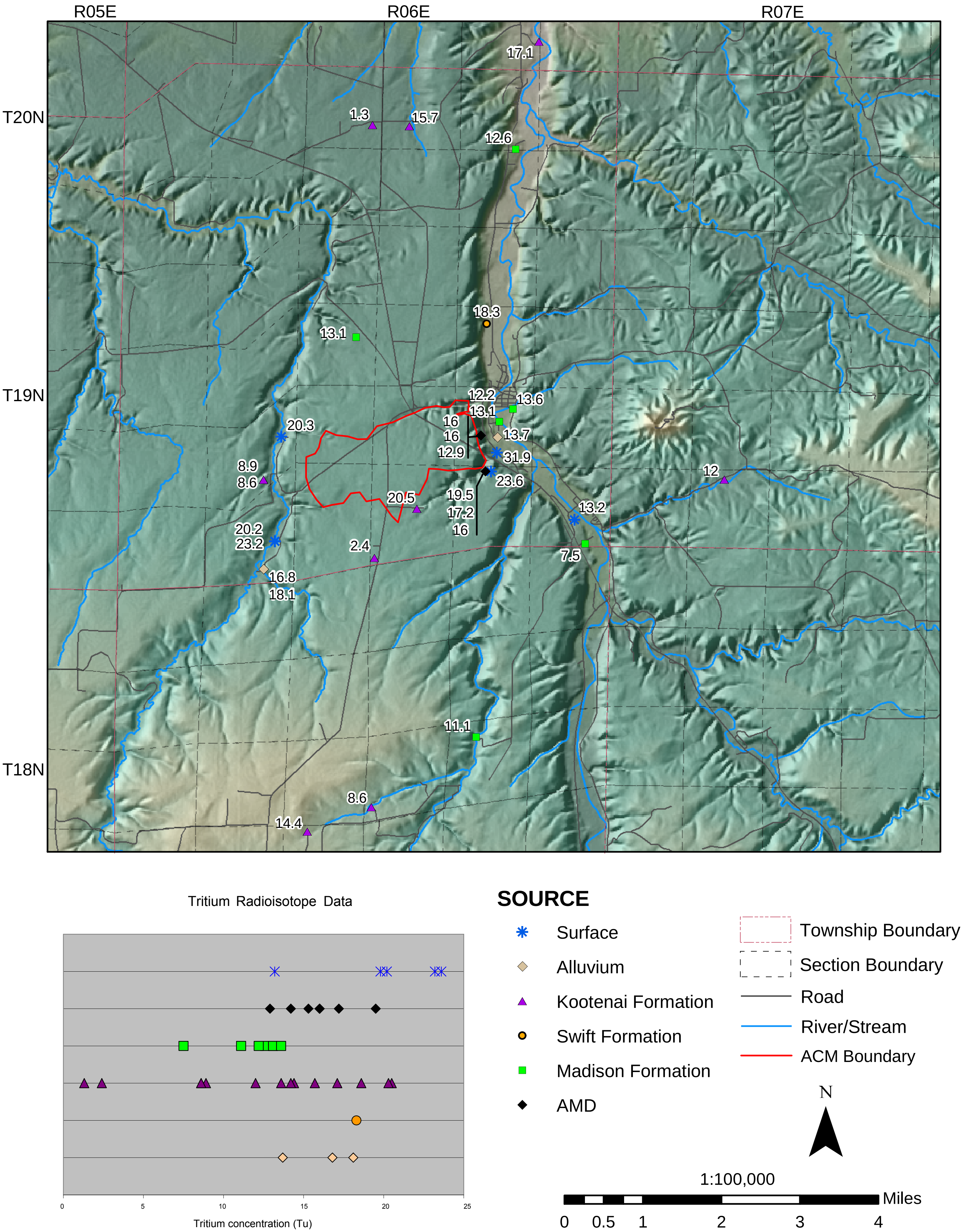


Figure 29. Map and chart showing tritium concentration by water source.

The more specific apparent ages of ground water can be estimated using the helium-3/tritium method and the chlorofluorocarbon method. Helium-3/tritium ages were estimated from two samples. A Madison aquifer sample (GWIC ID 177163) was dated at 8 years and a Kootenai aquifer sample (GWIC ID 193220) was dated at 22 years (Figure 30).

Chlorofluorocarbons (CFC) are anthropogenic components of the atmosphere that have increased in concentrations from the 1940's to the 1990's. Chlorofluorocarbon samples were also collected as another method of age-dating ground-water from the Belt area. Concentrations of three different CFC compounds (CFC-11, CFC-12, and CFC-13) can be used to estimate the average residence time of ground water (Warner and Weiss, 1985; Bu and Warner, 1995; and Prinn and others, 2000). The best recharge age estimates are typically determined by measuring CFC-12 compounds because the concentration levels are still rising and they appear to exhibit the most conservative behavior (Cook and others, 1995). Both CFC-11 and CFC-13 have leveled off since the 1990's, making two recharge ages possible on either side of the curve (younger or older). If the CFC concentrations results are supersaturated, it indicates the atmosphere is not the sole source of CFCs to the aquifer. The sample could be contaminated by industrial or urban CFC sources. Other complications involve determining the temperature of the water, as it recharged the aquifer, and the elevation of the recharge area. Varying these factors can significantly change the estimated average residence time of ground water. CFC age estimates ranged from very recent to as old as 42 years (Table 6).

The CFC age estimates and the helium-3/tritium age estimates confirmed the modern ages of water indicated by the tritium concentrations. All valid samples confirmed that the age of water in these aquifers is less than 50 years old. The cause of the high rate of supersaturated CFC results is unknown.

Both CFC and helium-3/tritium age estimates were determined at two sample sites. At well (GWIC ID 193220), the relatively close agreement between the CFC age (17 years) and the helium-3/tritium age (22 years) suggest that the Kootenai aquifer water is about 20 years old. The water in the Madison aquifer at well (GWIC ID 177163) is about 8 years old based on the helium-3/tritium method, but cannot be determined based on the CFC method.

The relatively young age of the stratigraphically deeper Madison water suggests a higher rate of ground-water flux through the Madison aquifer than through the Kootenai aquifer.

It is difficult to have a great deal of confidence in apparent age dates from the various methods described above. The most significant observation from this assessment is that the water tested from all significant aquifers contained modern recharge.

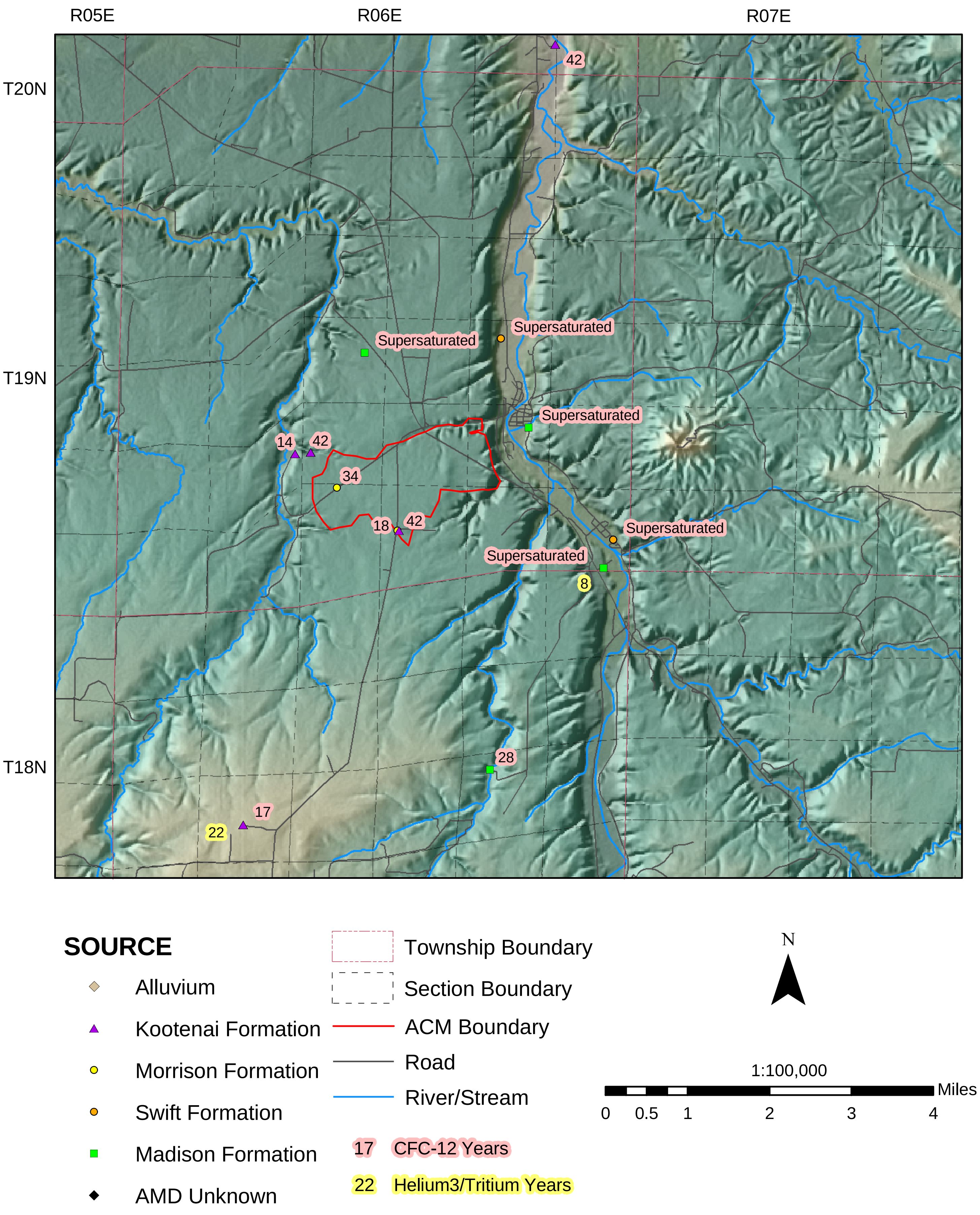


Figure 30. Map showing average residence time of ground water.

GWIC	Sample	Recharge	Recharge	Aquifer	CFC12	error	CFC11	error
ID	Date	Elev. (m)	Temp °C		years	years	years	years
207258	5/5/2004	1152	10.66	Kootenai	14	2	26	2
207258	5/5/2004	1152	10.66	Kootenai	13	2	26	2
207258	5/5/2004	1152	10.66	Kootenai	13	2	26	2
164111	5/6/2004	1039	10.37	Kootenai	Obscured by H_2S		47	2
164111	5/6/2004	1039	10.37	Kootenai	42	2	47	2
164111	5/7/2004	1039	10.37	Kootenai	42	2	47	2
207662	5/7/2004	1177	10.02	Kootenai	41	2	39	2
207662	5/7/2004	1177	10.02	Kootenai	42	2	39	2
207662	5/6/2004	1177	10.02	Kootenai	43	2	39	2
210533	5/6/2004	1338	8.17	Kootenai	18	2	21	2
210533	5/6/2004	1338	8.17	Kootenai	17	2	21	2
210533	5/6/2004	1338	8.17	Kootenai	17	2	21	2
217056	10/28/2004	1213	8.88	Kootenai	Obscured by H_2S	2	41	2
217056	10/28/2004	1213	8.88	Kootenai	40	2	39	2
217056	10/28/2004	1213	8.88	Kootenai	40	2	38	2
215048	10/27/2004	1213	8.83	Morrison	17	2	29	2
215048	10/27/2004	1213	8.83	Morrison	Obscured by H_2S	2	31	2
215048	10/27/2004	1213	8.83	Morrison	19	2	30	2
217052	12/30/2004	1201	8.82	Morrison	34	2	38	2
217052	12/31/2004	1201	8.82	Morrison	35	2	39	2
217052	1/1/2005	1201	8.82	Morrison	34	2	37	2
145604	5/6/2004	1067	9.11	Swift	1Supersaturated		1Supersaturated	
145604	5/6/2004	1067	9.11	Swift	1Supersaturated		1Supersaturated	
145604	5/6/2004	1067	9.11	Swift	1Supersaturated		1Supersaturated	
217922	7/14/2004	1085	9.5	Swift	1Supersaturated		1Supersaturated	
217922	7/14/2004	1085	9.5	Swift	1Supersaturated		1Supersaturated	
217922	7/14/2004	1085	9.5	Swift	1Supersaturated		1Supersaturated	
196148	5/3/2004	1676	10	Madison	28	2	30	2
196148	5/3/2004	1676	10	Madison	27	2	29	2
196148	5/3/2004	1676	10	Madison	28	2	29	2
2315	5/6/2004	1676	11.1	Madison	1Supersaturated		22	2
2315	5/6/2004	1676	11.1	Madison	1Supersaturated		22	2
2315	5/6/2004	1676	11.1	Madison	1Supersaturated		23	2
177163	7/29/2004	1676	9.63	Madison	1Supersaturated		1Supersaturated	
177163	7/29/2004	1676	9.63	Madison	1Supersaturated		1Supersaturated	
177163	7/29/2004	1676	9.63	Madison	1Supersaturated		1Supersaturated	
31978	7/29/2004	1676	11.39	Madison	1Supersaturated		1Supersaturated	
31978	7/29/2004	1676	11.39	Madison	1Supersaturated		1Supersaturated	
31978	7/29/2004	1676	11.39	Madison	1Supersaturated		1Supersaturated	

Table 6. Summary of CFC results.

ACID MINE DRAINAGE IMPACTS

Loading From AMD Discharge

Five sources of AMD discharges were identified in the Belt area. Two are direct discharges to Belt Creek: the main Anaconda Mine Drain and the Lewis Coulee Mine Drain. In addition, indirect discharges were identified from the French Coulee Main Drain and the Lewis Coulee Drain above Castner Park. Another source of indirect AMD discharge is not from a mine drain, but from seepage from Coke Oven Flats; a 27 acre area of reclaimed coal waste located near the Anaconda Mine Drain (DEQ, 2000).

Based on this work and other ongoing MBMG research, the direct loading to Belt Creek from AMD is estimated to be 103,300 pounds of iron per year and 64,986 pounds of aluminum per year (Figure 31). Indirect loading to Belt Creek, from other AMD drains moving through alluvial sediments, is estimated to be 40,080 pounds of iron per year and 28,327 pounds of aluminum per year. This indicates indirect loading from Coke Oven Flats estimated at about 80 pounds of iron per year and 8,780 pounds of aluminum per year (Table 7). The main direct source of AMD is the discharge from the Anaconda Mine; which averages about 132 gpm, or about 213 acre feet per year. The Lewis Coulee Mine Drain discharges an average of 3 gpm, or about 4.8 acre feet per year. The indirect sources discharge about 9 gpm, or 14.5 acre feet per year from the French Coulee Main Drain, and about 2 gpm, or 3.2 acre feet per year from the Lewis Coulee Drain above Castner Park. At both of these indirect sources, the AMD discharges seep into alluvial deposits prior to discharging into the creek. Indirect discharges from the Coke Oven Flats reclamation is through seeps along Belt Creek. The discharge volumes at this site were estimated based on a range of 1 to 3 percent of the year's annual precipitation recharging the 27 acre area of reclaimed waste coal that flows into Belt Creek. Using the high estimate (3 percent of precipitation), about 1 acre foot of this water discharges into Belt Creek annually. The metal loading from all known sources of AMD discharging into Belt Creek near Belt is estimated to be 143,380 pounds of iron per year and 93,313 pounds of aluminum per year.

Mnumber	Site Name	Average Flow Rate (gpm)	Iron (Fe) lbs/year	Aluminum (Al) lbs/year	Loading to Belt Creek
200616	Main Anaconda Mine Drain	132	94,500	59,279	Direct
214915	Lewis Coulee Mine Drain	3	8,800	5,707	Direct
200615	French Coulee Mine Drain	9	35,100	17,484	Indirect
214914	Lewis Coulee above Castner Park	2	4,900	2,063	Indirect
214917	Coke Oven Flats	0.62	80	8,780	Indirect
Subtotal from Direct Loading			**103300**	**64,986**	
Subtotal from Indirect Loading			**40,080**	**28,327**	
Total			**143,380**	**93,313**	

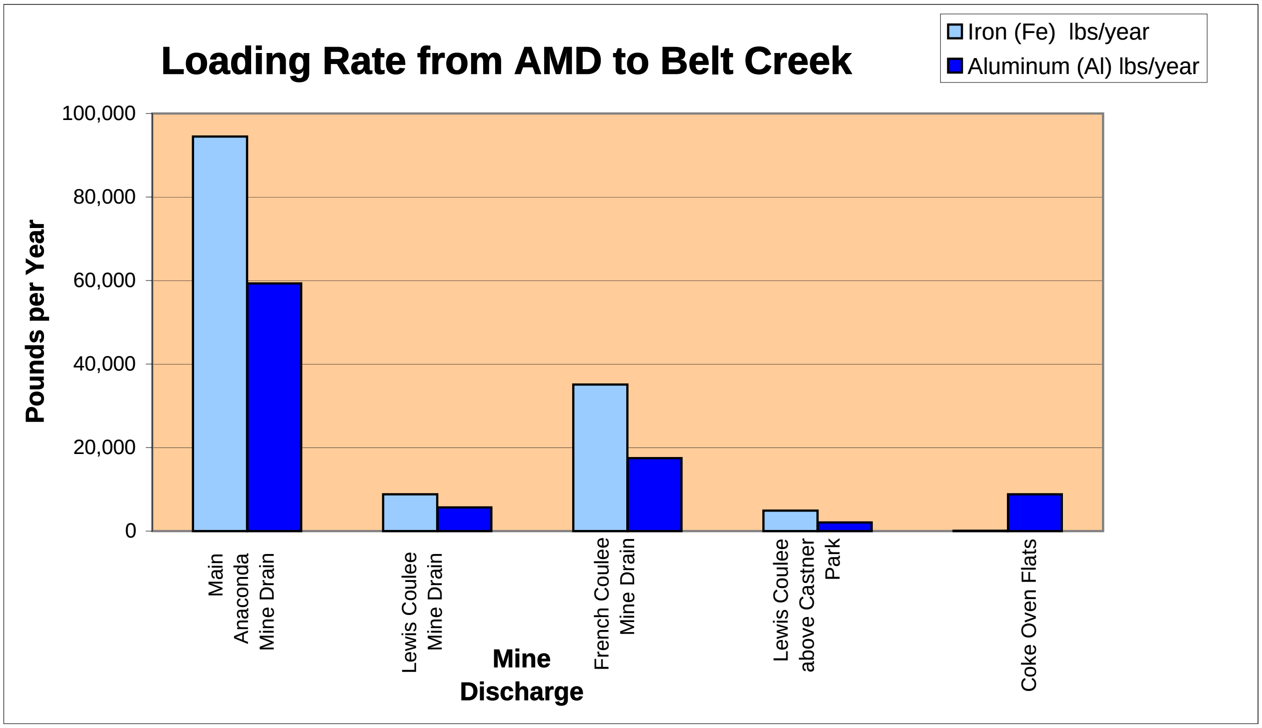


Figure 31. Loading to Belt Creek calculated from water quality samples taken from 1-2003 to 10-2004.

Table 7. Data used for loading calculations.

Mnumber	Site Name	Percent of Precipitation Infiltrated on 27 Acres	Flow Rate on Belt Creek at Time of Sample	Iron (Fe) mg/L	Fe Pounds/Year	Aluminum (Al) mg/L	Al Pounds/Year
214917	MW1, A Well Located Within 27 Acres of Reclaimed Coal waste on "Coke Oven Flats"	1%	*	3.210	30	373.061	2,930
		2%	*	3.210	50	373.061	5,850
		3%	*	3.210	80	373.061	8,780
214911	Belt Creek Al Above Swim Hole	*	900	0.169	700	0.568	2,230
214913	Belt Creek at North Extent of Spoil Piles	*	848	6.010	22,200	0.017	100
200616	Anaconda Mine Drain	*	132	171.000	94,500	102.846	59,280

Loading from Ground Water

Transects Across Belt Creek

The impacts of AMD discharges on Belt Creek are shown on Figure 32. This figure is based on data from eight stream transects that were conducted on October 24, 2004 along Belt Creek; from immediately above the first obvious source of AMD discharges to a point about ½ mile downstream. Field parameters pH, temperature, and specific conductance were collected as a composite sample at each transect. In addition, stream flow was measured at three of the transects. The overall flow decreased from about 2 cfs to about 1.3 cfs along this ½ mile reach of Belt Creek. Background conditions are assumed at mile point 0 (Belt Creek behind the city well). At this point, the specific conductance was less than 500 µmhos/cm, pH was about 7.8 S.U., and the water temperature was about 10.5 ^{0}C. For at least ½ mile downstream, AMD discharges were clearly evident by distinctive field parameter measurements from Belt Creek water; with lower pH and higher specific conductance values. The water temperature increased slightly from about mile point 0 to mile point 0.17. Near mile point 0.47, the water temperature had dropped by about 3 ^{0}C. This drop in temperature probably relates to a change from a losing to a gaining reach between mile points 0.17 and 0.47. The AMD impacts to Belt Creek are likely to extend further downstream and consequences on aquatic life are more of a problem during periods of low flow.

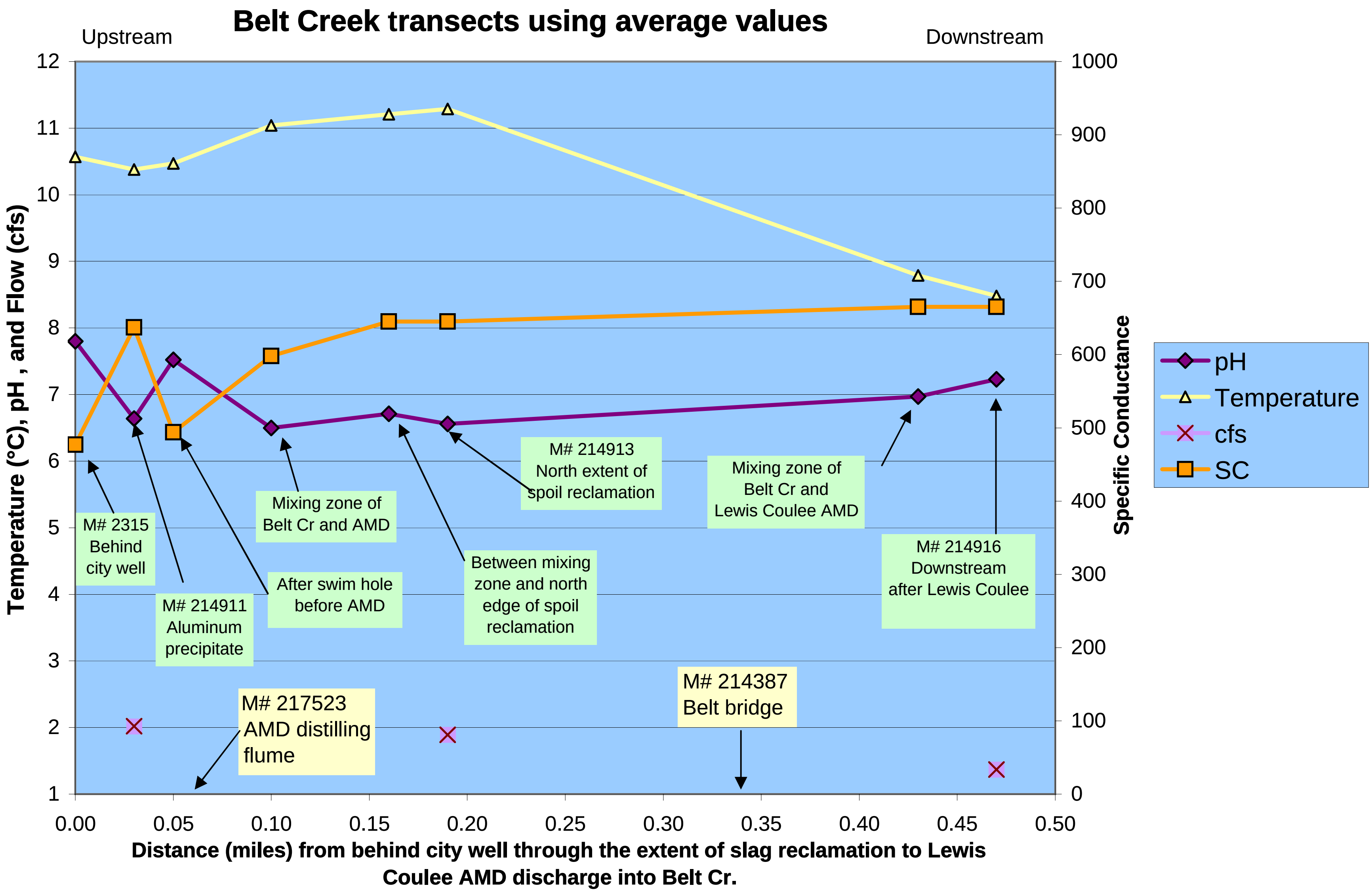


Figure 32. Field measurements collected at 8 transects along Belt Creek show AMD impacts.

Public Well

The Belt Public water supply well #2 (GWIC ID 2315) is located on “Coke Oven Flats”, adjacent to Belt Creek. It produces water from the Madison aquifer from a depth of 430 feet. In 1994, the water main line between the pump house and water tanks corroded and leaked. This public well is located only about 140 feet southeast from monitor well #1(MW1) on the reclaimed spoil area. A water-quality sample was extracted from MW1 (GWIC ID 214917). This water appears to be AMD that is very corrosive and high in trace elements. The corrosion in the main line appears to be directly caused due to action of contaminated shallow ground-water and acidic soils. To mitigate the problem, the main line was replaced with plastic pipe (DEQ, 2000). MBMG attempted to inspect the public water supply well for corrosion but we could not access the well casing with the down-hole camera. According to Ground-Water Information Center (GWIC), city well #2 is completed with an 8 inch steel casing. Public water supply rules require that the well be properly grouted. It is likely that cement grout is protecting the well casing from the corrosive shallow ground water. Our recommendation would be to periodically inspect the city well for corrosion, be aware of the corrosion potential, and to develop a plan to repair the casing in case of a leak.

REMEDIATION

Based on the data collected, it appears that recharge to the Anaconda Mine is locally derived. The key to reducing AMD discharges is to slow down, or stop, the infiltration of moisture into the abandoned mine. This recharge appears to be relatively constant as recorded in the discharges from the mine. Fluctuations in precipitation cause significant changes in discharge from the overlying Sunburst aquifer springs. However, the mine discharges remain stable. Apparently the head increase, caused by precipitation-derived recharge, is rapidly dissipated through leakage at contact springs. As a result of this localized flow system, the volume of AMD discharging from the mine could be reduced, or possibly eliminated, by changing land use in the recharge area. Figure 33 is a pie chart of land use in the recharge area towards the Anaconda Mine. Crop-fallow farming covers about 73 percent of the recharge area to the mine. This type of cropping allows significant amounts of water to move below the root zone, recharging underlying ground-water systems. By changing the land use to permanent vegetation, more water consumption would be possible; preventing excess water from recharging the mine voids.

Land Use	Acres	%
Transportation	14.13	0.70%
Range/Pasture	486.10	24.00%
Forest	37.72	1.86%
Cropland	1,487.09	73.43%
Total	2,025.04	100.00%

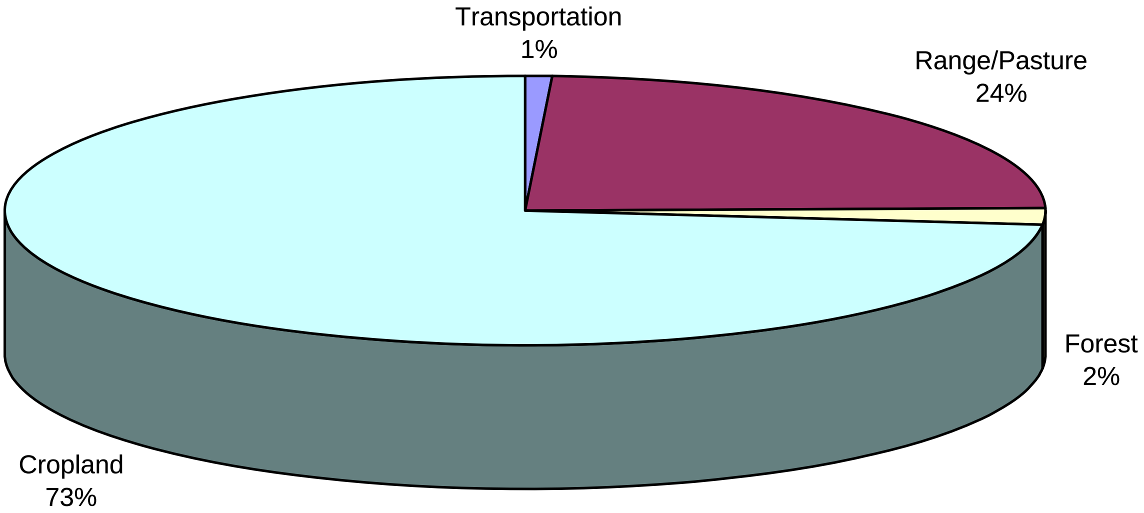


Figure 33. Land use in ground water recharge area.

It is recommended to initially focus cropping changes to areas directly over the mine voids. The region over the mine workings are likely to be highly fractured as a result of collapse or settling of overlying rocks into the mine void. Reducing recharge in this area is likely to have a good potential to limit the movement of water into the mine voids. Land-use changes in other parts of the recharge area could be developed in the future. Long-term monitoring of the AMD discharges, and selected wells in and near the mine workings, should be conducted to document any change in the hydrogeologic system. Other possible remediation options including diverting flow from overlying aquifers to prevent water from filling the mine voids. This could be accomplished by constructing horizontal wells to drain overlying aquifers laterally, or by designing vertical wells to bypass the mine workings and recharge lower aquifer zones. Flooding the mine voids to reduce pyrite oxidation could conceivably reduce AMD, but may result in other unwanted discharges. It appears likely that the least engineered solution has the best potential for mitigating the AMD problem at Belt. Growing alfalfa or other water consumptive crops would have the potential to significantly reduce infiltration and possibly decrease or eliminate the AMD discharges.

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APPENDIX A

Inventory Data

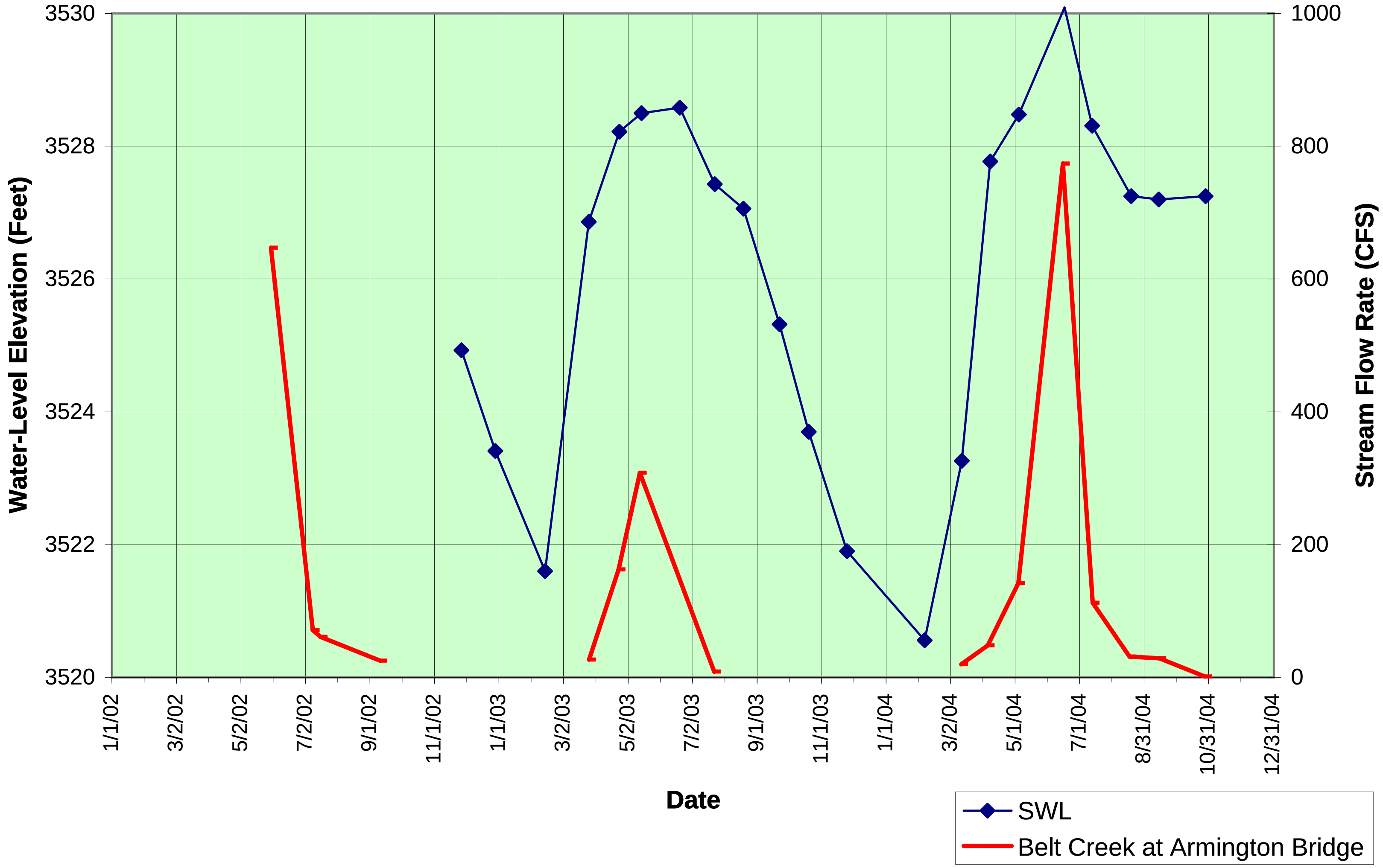
	Site Name	Latitude	Longitude	Township	Range	Section	Tract	Ground Elevation (ft)	Total depth (ft)	Date (mm/dd/yy)	Static water level from mp (ft)	Pumping water level (ft)	Water temperature (°C)	Field SC (umhos/cm)	Field pH	ORP (mV)	Field test nitrate (mg/L N)	Dissolved Oxygen (mg/L)
2315	TOWN OF BELT WELL 2	47.3838	-110.9228	19N	06E	26	ACAD	3520	430	6/5/03			12.2	600	7.06	258		5.8
30562	JOHNSON GERALD	47.3052	-110.9765	18N	06E	21	BABB	4280	35	9/12/02	19.18	19.34	8.9	512	7.42	276	5	
30562	JOHNSON GERALD	47.3052	-110.9765	18N	06E	21	BABB	4280	35	9/23/03	20.15	20.43	9.26	682	6.89	209	10	7.86
31948	NISBET HARRY	47.4342	-110.9119	19N	06E	1	CDBC	3450	56	7/25/03	23.92	28.8	10	672	7.28	-108	0	
31952	GOO EDWARD	47.4305	-110.9547	19N	06E	3	CDBA	3700	12	5/30/03	1.2		12.11	763	7.78	102.3		9.1
31957	HORST NATHAN	47.4298	-110.9655	19N	06E	4	DACD	3715	140	5/29/03	96		15	1123	7.07	14.6		
31957	HORST NATHAN	47.4298	-110.9655	19N	06E	4	DACD	3715	140	9/23/03	95.13	119.7	9.87					
31959	RIMROCK VALLY RANCH INC *BUMGARNER J. EVERETT	47.4122	-110.9718	19N	06E	9	DCC	3730	660	5/29/03			14.8					
31965	BELT COMMUNITY CHURCH	47.4269	-110.9249	19N	06E	11	ABDB	3510	250	7/25/03	216.91		12.2	634	6.94	315	0	
31978	DAWSON JIM AND DELORES	47.3913	-110.9691	19N	06E	21	ACDB	3855	670	5/28/03	427.5		13.3	737	7.32	139.5		5.7
31978	DAWSON JIM AND DELORES	47.3913	-110.9691	19N	06E	21	ACDB	3855	670	11/25/03			9.71					
31980	STEVENSON CARAL AND TERRY	47.3939	-110.9306	19N	06E	23	CADB	3500	74	9/11/02	58.76	60.5	11.3	983	7.36	195	2	
31981	BELT SCHOOL	47.3913	-110.9282	19N	06E	23	CDAD	3500	300	5/3/04	214.81							
31989	FLIGINGER GARY AND MICHELE	47.3996	-110.9263	19N	06E	23	ABCC	3490	200	10/22/03	58.85	67.45	11.4	552	7.04	213	2	9.13
32015	JIM LARSON RANCH	47.3534	-110.9897	19N	06E	32	DCCB	3865	32	6/5/03			10.2	645	7.27	222		5.81
32015	JIM LARSON RANCH	47.3534	-110.9897	19N	06E	32	DCCB	3865	32	10/23/03			10.5	630	7.34	68		5.59
32027	PIMPERTON BOB	47.3666	-110.9003	19N	06E	36	ACDA	3580	44	10/22/03	30.5			460	7	148	2	6.7
32033	FULLER CHARLES H	47.3665	-110.9093	19N	06E	36	BDCD	3570	45	10/24/02	16.85		10.4	641	7.25	-53.2	0	0.24
32040	ASSELS STEVE D.	47.3654	-110.9005	19N	06E	36	DABB	3570	41	10/24/02	18.65		9.7	475	7.49	225	0	6.87
32050	SPRAGG ED	47.3592	-110.9026	19N	06E	36	DCDD	3620	47	9/10/02	45.42							
32061	COLARCHIK ALBERT AND PATRICIA	47.4041	-110.8903	19N	07E	18	CCDA	3765	135	8/19/04	124		9.74	3152	7.03	-4		5.29
84937	HARRIS JOHN JR.	47.3699	-110.9902	19N	06E	29	DD	3860	200	5/16/03	77.8		9.1	815	7.21	180.1	0	5.6
84937	HARRIS JOHN JR.	47.3699	-110.9902	19N	06E	29	DD	3860	200	8/19/03			9.9	740	6.86	186		4.24
84937	HARRIS JOHN JR.	47.3699	-110.9902	19N	06E	29	DD	3860	200	10/23/03			9	730	7.1	36		3.3
123477	WINDER MARTIN AND BARBARA	47.3458	-110.8951	18N	07E	6	CCCB	3600	403	11/26/02	158		10.3	929	7.51	131.4	0	8.7
123498	ARNDT DENNIS	47.3632	-110.9001	19N	06E	36	DACC	3575	53	10/24/02	13.5	21	11.5	458	7.53	15.6	0	5.3
125195	GARZA EMILIO H. AND GERALDINE	47.446	-110.9238	19N	06E	2	ABDB	3480	100	7/24/03	71.9	74.1	13.8	907	6.27	244	0	
128959	SWEENEY RANCH INC.	47.4175	-110.9393	19N	06E	11	CCBB	3805	990	5/29/03	522.5		14.7	625	7.61	48		2.6
132172	KEASTER BRUCE AND NELSON ROGER	47.3118	-110.9975	18N	06E	17	CACA	4380	200	4/9/04	22.03		7.98	736	7.43	128	10	10.7
145604	ASSELS STEVEN D. AND LINDA L.	47.3994	-110.9304	19N	06E	23	BDBA	3500	66	10/24/02	47.3	50.54	12.4	652	7.27	288	0	7.91
145604	ASSELS STEVEN D. AND LINDA L.	47.3994	-110.9304	19N	06E	23	BDBA	3500	66	9/23/03		52.8	11.69	637	7.29			
150504	DANKS BRENDA	47.4317	-110.9234	19N	06E	11	ABAC	3510	300	9/11/02	211.1		12.6	656	7.66	80	0.5	
150504	DANKS BRENDA	47.4317	-110.9234	19N	06E	11	ABAC	3510	300	11/25/03	213.22		11.27	657	7.17	224		6.09
164111	HOYER KEITH AND HEATHER	47.4516	-110.9176	20N	06E	35	DADA	3410	90	8/21/03	3.7	8.48	11.3	617	7.06	8	0	0.32
164111	HOYER KEITH AND HEATHER	47.4516	-110.9176	20N	06E	35	DADA	3410	90	9/23/03	3.71	8.9	11.57	597	7.38			
165475	MCMANIGLE WALLACE	47.3732	-110.9117	19N	06E	36	BABB	3560	50	11/27/02	17.75	26.1	9.6	683	7.44	68.2	0	3.9
171338	FELLOWS MIKE	47.2982	-110.9503	18N	06E	22	CADC	4050	40	4/8/04	10.85	16.2	9.15	442	7.46	-28	2	0.87
177163	SPRAGG ED	47.3592	-110.9026	19N	06E	36	DCDD	3620	490	9/10/02	146.03		10	463	7.46	176.9	0	
177163	SPRAGG ED	47.3592	-110.9026	19N	06E	36	DCDD	3620	490	8/22/03	339.8	339.8	10.4	542	7.53	151	0	10.8
177163	SPRAGG ED	47.3592	-110.9026	19N	06E	36	DCDD	3620	490	11/26/03	340.85		9.08	608	7.36			
180021	REDDISH GARY	47.3232	-110.9302	18N	06E	14	BDBA	3890	200	11/25/00	97.65		9.8	356	7		1	
184178	HEILIG BILL	47.36	-110.906	19N	06E	36	CDAD	3640	262	11/26/03	241.1	250	9.74	813	7.25	194	0	6.22
186483	SPILLER LEROY AND FAYE	47.3785	-110.9269	19N	06E	26	DBCB	3540	24	11/26/02	17.07	17.15	10.6	639	7.32	267.4	0	7.65
186483	SPILLER LEROY AND FAYE	47.3785	-110.9269	19N	06E	26	DBCB	3540	24	9/22/03		16.69	11.19	619	7.19	245.8		6.82
186486	DAWSON RANCH	47.3715	-110.8651	19N	07E	32	BADA	3790	200	9/10/02	57.2	78.2	9.7	1585	7.23	81.8	0	
186486	DAWSON RANCH	47.3715	-110.8651	19N	07E	32	BADA	3790	200	9/23/03	57.55	94.6	9.15	2086	7	179.4		0.36
186802	BELT CR *ABOVE BELT	47.3797	-110.9285	19N	06E	26	BDDA			8/20/03			23.2	1250	3.73	477		5.74
193220	EVANS DAN AND MARY	47.3689	-110.9154	19N	06E	36	BCBD	3560	500	5/13/03	261							
196148	REDDISH GARY	47.3232	-110.9312	18N	06E	14	BDBA	3890	800	9/10/02			10	367	7.79	84	0	
196148	REDDISH GARY	47.3232	-110.9312	18N	06E	14	BDBA	3890	800	9/23/03			10.09	530	7.32	126.9		4.35
199851	ERIC JOHNSON	47.3099	-110.9593	18N	06E	15	CCBC	4160	160	9/12/02	100.06		10.2	485	7.53	55.5	0	
199851	ERIC JOHNSON	47.3099	-110.9593	18N	06E	15	CCBC	4160	160	9/23/03		100.87	10.22	482	6.84	174.5		0.34
200058	IKE HAGGESON	47.3746	-110.9127	19N	06E	25	CCDA	3560	100	11/26/02	36.65	40.47	10.5	879	7.25		0	3.65
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		1/29/03			7	5620	2.7	628		4.73
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		3/15/03			7.2	5030	2.68	650		3.75
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		4/22/03			9.7	4660	2.68	659		3.12
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		5/28/03			12.2	4410	2.62	655		3.54
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		6/18/03			12.2	2820	2.63	653		4.42
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		7/17/03								
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		8/19/03			14.3	5180	2.36	639		3.15
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		9/18/03			11.3	5690	2.41	636		5.97
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		10/23/03			10.3	5800	2.73	288		3.72
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		4/24/04			10.2	4080	2.57	573		6.63
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		6/24/04			12.23	4090	1.75	546		
200615	FRENCH COULEE MINE	47.3722	-110.93	19N	06E	26	CDDB	3550		8/12/04			12.2	6230	3.99	626		8.8
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		1/30/03			9.8	2290	2.99	627		2.91
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		3/15/03			10.7	2220	3.01	626		2.75
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		4/22/03			7.5	2260	2.89	639		2.6
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		5/28/03			11.3	2350	2.84	623		1.8
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		6/18/03			9.9	1425	2.51	631		2.51
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		7/17/03								
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		8/19/03			9.9	2355	2.58	607		2.1
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		9/18/03			9.94	2390	2.7	623		1.54
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		10/23/03			9.91	2300	2.99	264		1.83
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		4/24/04			9.8	2275	2.8	460		3.78
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		6/24/04			11.91	2120	2.75	495		
200616	ANACONDA MINE DRAIN AT CULVERT	47.3788	-110.9314	19N	06E	26	BDCD	3540		8/12/04			9.9	2465	2.68	630		1.61
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		1/30/03			3.5	610	7.79	82		11.09
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		3/15/03			4.1	440	8.17	144		10.9

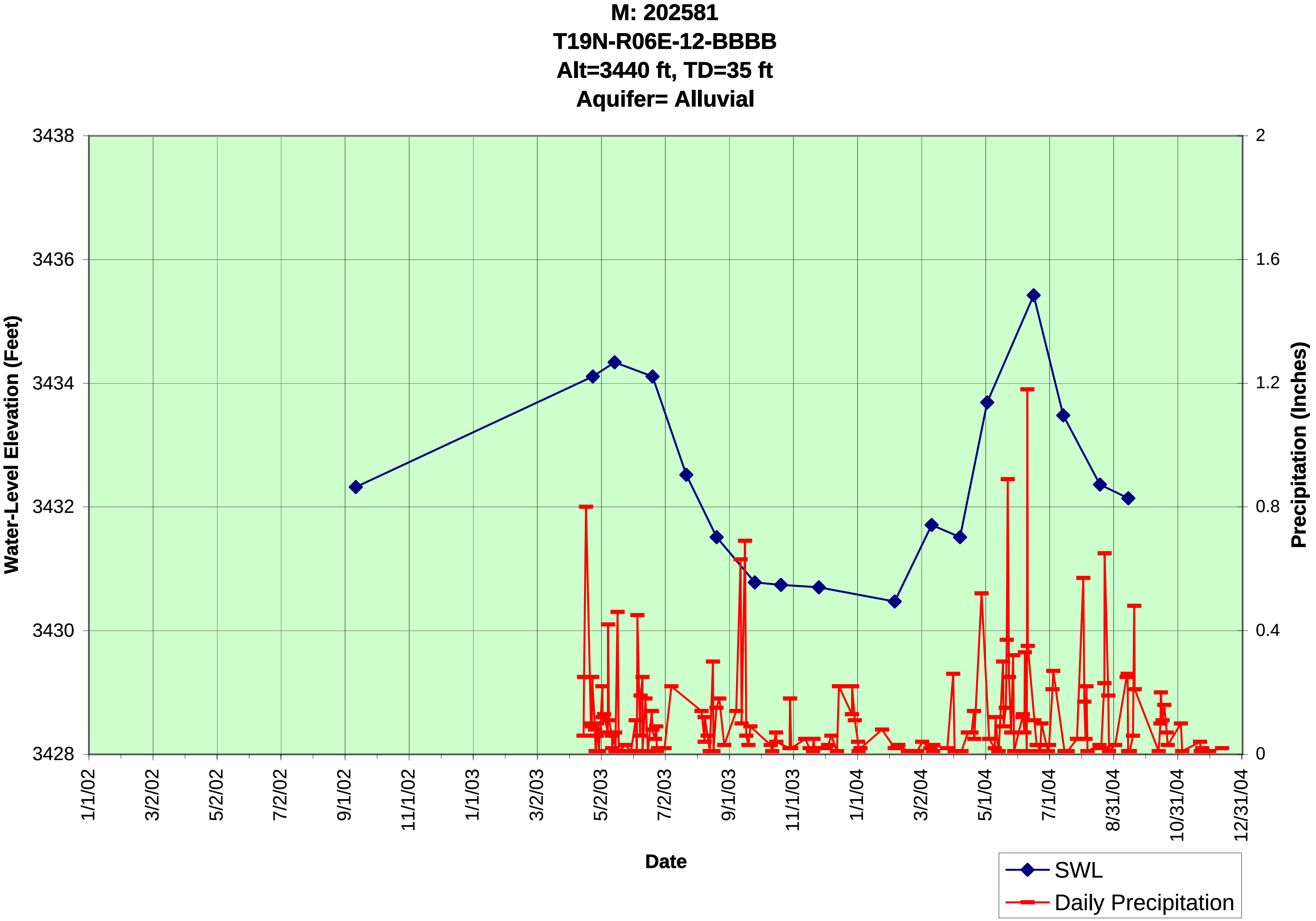
	Site Name	Latitude	Longitude	Township	Range	Section	Tract	Ground Elevation (ft)	Total depth (ft)	Date (mm/dd/yy)	Static water level from mp (ft)	Pumping water level (ft)	Water temperature (°C)	Field SC (umhos/cm)	Field pH	ORP (mV)	Field test nitrate (mg/L N)	Dissolved Oxygen (mg/L)
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		4/22/03			8.6	605	7.78	114		10.8
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		5/28/03			13.6	740	8.13	50		9.05
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		6/17/03			15.1	460	8.07	42		11.05
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		7/17/03								
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		8/19/03			10.6	790	7.66	304		9.6
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		9/19/03			9.34	860	7.74	116		9.57
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		4/24/04			8.3	620	8.16	322		12.1
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		6/24/04			12.18	586	7.3	372		
200617	FRENCH COULEE * HIGHWAY DRAIN	47.3722	-110.9285	19N	06E	26	CDDA	3560		8/12/04			12	765	9.72			10.4
201066	RAY OGLE	47.3149	-110.9475	18N	06E	15	DBAC	4060		9/12/02	131.92		13.2	553	7.32	171	0	
201069	DAVE FETTER	47.2573	-110.916	17N	06E	1	CCCC	3830	11	9/12/02	9.18	10.61	14.6	417	7.81	147	0	
201123	GLEN MCCLELAND	47.3774	-110.9262	19N	06E	26	DCBA	3540		9/10/02	20.6	22.15	9.8	634	7.41	-143.9	0	
201878	PONDEROSA CAMPGROUND	47.3636	-110.8996	19N	06E	36	DACC	3580	505	8/19/03	206.55							
202378	DANNY HARDINGER	47.3241	-110.9747	18N	06E	9	CDCA	4240	0	5/16/03	3.4		7.6	601	6.86	300.9	2	6.49
202581	GENE ERBETTA	47.4318	-110.9159	19N	06E	12	BBBB	3440	35	9/11/02	9.28		13.4	446	7.69	163.9	0	
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		5/28/03			19	675	8.1	240		7.32
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		6/17/03			18.2	400	7.89	299		7.81
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		7/17/03								
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		8/19/03			15.6	620	7.85	253		7.93
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		9/18/03			8.7	620	7.58	245		9.13
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		10/23/03			9.3	660	7.71	66		6.95
203450	UPPER BOX ELDER CREEK * LARSON RANCH	47.3586	-110.9868	19N	06E	32		3840		4/25/04			13	635	8.48	296		12.8
203451	LOWER BOX ELDER CREEK * BELOW J HARRIS RANCH	47.3779	-110.9856	19N	06E	29		3745		5/28/03			24.5	680	8.2	236		5.73
203451	LOWER BOX ELDER CREEK * BELOW J HARRIS RANCH	47.3779	-110.9856	19N	06E	29		3745		6/17/03			23.3	395	8.15	286		7.88
203451	LOWER BOX ELDER CREEK * BELOW J HARRIS RANCH	47.3779	-110.9856	19N	06E	29		3745		4/25/04			17	570	8.67	288		14.3
204516	JIM LARSON	47.3651	-110.9484	19N	06E	34	ACDC	3926	19.6	11/27/02	12.9		8.1					
204516	JIM LARSON	47.3651	-110.9484	19N	06E	34	ACDC	3926	19.6	9/24/03	12.65		11.31	526	7.46	233.6		8.57
204687	OSTERMAN DARIN AND NOEL	47.3706	-110.9095	19N	06E	36	BACD	3570	381	11/26/02	278.85	279.53	10					
204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN * BELT MT	47.3757	-110.927	19N	06E	26		3600		7/17/03								
204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN * BELT MT	47.3757	-110.927	19N	06E	26		3600		8/19/03								
204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN * BELT MT	47.3757	-110.927	19N	06E	26		3600		9/19/03			10.4	3510	7.4	210		9.11
205508	BELT CREEK * E OF TOWN WELL #2	47.3812	-110.9257	19N	06E	26		3520		8/20/03			20.9	460	7.48	253		8.28
205653	JOHN HARRIS RANCH * SPRING	47.3663	-110.9974	19N	06E	29		3920		8/19/03			10	560	7.02	234		4.29
205653	JOHN HARRIS RANCH * SPRING	47.3663	-110.9974	19N	06E	29		3920		10/23/03			9.5	560	7.42	62		3.9
205836	BELT CREEK	47.3636	-110.9056	18N	06E	12	ABDA			8/27/03			17.9	297	7.79	510		
205838	BELT CREEK	47.3753	-110.9183	18N	06E	26	DDDA			8/27/03			18.4	371	7.22	512		
205839	BELT CREEK	47.3808	-110.9253	18N	06E	26	DBBA			8/27/03			19.2	372	7.48	513		
206358	BONNIE ZANTO	47.4478	-110.924	20N	06E	35	DCDB	3490	202	8/20/03	97.2		13.1	789	6.82	190	0	14.6
206360	FRANK BALITOR	47.3788	-110.9268	19N	06E	26	DBCB	3530		11/27/02								
206544	HOYER JERRY T.	47.4296	-110.9223	19N	06E	11	ABDD		265	8/22/03	175.55							
207258	PLEASENT VALLEY COLONY	47.3784	-110.9834	19N	06E	29	ACBB	3770	72	5/27/03	30.59		10		7.21	85.8		
207258	PLEASENT VALLEY COLONY	47.3784	-110.9834	19N	06E	29	ACBB	3770	72	8/21/03	38.13	38.3	10.7	137	7.55	137	1.5	8.03
207286	NELSON ROGER	47.292	-111.0247	18N	06E	19	CCCA	4150	60	4/9/04	14.72		7.99	487	7.99	-18	0	0.52
207463	IRVINE	47.3507	-110.9566	18N	06E	3	BCAD	4060	56.3	9/24/03	25.69							
207649	BRUCE KEASTER	47.4033	-110.9775	19N	06E	16	CCB	3635	30	5/28/03	4.11		19.8	892	7.02	75.5		3.9
207662	BURGE EXPLORATION ACM WELL	47.3787	-110.9794	19N	06E	29	DAAA	3860	186	8/20/03	125.4							
207662	BURGE EXPLORATION ACM WELL	47.3787	-110.9794	19N	06E	29	DAAA	3860	186	4/25/04	118.58		11.1	220	7.21	310		4.9
207662	BURGE EXPLORATION ACM WELL	47.3787	-110.9794	19N	06E	29	DAAA	3860	186	5/7/04	118.3		10.02	606	6.92	76		2.82
207672	IRVINE	47.3559	-110.9597	19N	06E	34	CCCC	4022		9/24/03			10.51	558	7.18	178	0	10.91
207767	HARRIS JOHN * POND	47.37	-110.9918	19N	06E	29		3760		9/19/03			9.9	500	7.34	192		7.73
207930	GARY CROWDER	47.3676	-110.9031	19N	06E	36	ACAA	3560	40	10/21/03	28	29.9	10.3	476	7.27	237	0	7.92
209498	JIM LARSON SPRING 3	47.3637	-110.9809	19N	06E	32	AAD	3860		5/27/03			20.7		8.19	74.6		5.4
209500	JIM LARSON SPRING 2	47.3587	-110.9816	19N	06E	32	DAA	4020		5/27/03			18.8	800	8.22	105.5		6.9
209514	JOHN HARRIS S-9	47.369	-110.9886	19N	06E	29	C	3840		5/29/03			14.4	835	7.9	76		8.3
209515	JOHN HARRIS S-8	47.3699	-110.9914	19N	06E	29	C	3820		5/29/03			14.6	775	8.01	103		9
209516	EDWARD GOO POND	47.4348	-110.9527	19N	06E	3	CDCB	3700		5/30/03			18.7	512	7.91	40.3		
209517	JIM LARSON S-1	47.3583	-110.9891	19N	06E	32	DBB	3840		5/27/03			21.5	799	8.22	82.3		7.5
209526	PLEASANT VALLEY COLONY SPRING	47.3777	-110.9829	19N	06E	29	DCAA	3800		5/27/03			16	878	7.65	106		
209527	PLEASANT VALLEY COLLONY S-4	47.365	-110.9706	19N	06E	33	BD	3910		5/27/03			18.1	574	8.58	141		6
209592	ROGER NELSON	47.2901	-111.0247	18N	06E	19	CCCD	4160		4/9/04			8.63	484	7.02	224	0	2.22
210402	BRUCE KEASTER	47.3683	-110.9024	19N	06E	36	ACAD	3580	27.5	10/21/03								
210533	MARRY EVANS	47.3126	-110.9951	18N	06E	17	CAAD	4390	90	5/6/04	29.57	32.4	8.17	1019	7.51	90.8	10	9.03
210533	MARRY EVANS	47.3126	-110.9951	18N	06E	17	CAAD	4390	90	7/29/04	25.77		8.61	886	7.26	107		8.14
210655	JIM SNIDER	47.3966	-110.951	19N	06E	22	BDDB	3860	76	5/7/04	34.65		9.83	801	7.43	173	5	6.1
212233	MURPHY, LARRY	47.4043	-110.8911	19N	07E	18	CCD	3765	380	8/19/04	253.65	275.3	10.9	1689	6.66	64		0.42
213386	JIM SNIDER	47.4484	-110.9604	20N	06E	33	DDDB	3635	29	5/7/04	12.5		8.93	1085	7.73	234	20	7.8
213598	PLEASANT VALLEY SPRING * OLD HARRIS HOMESTEAD	47.4131	-110.9716	19N	06E	16		3670		8/12/04			12.8	650	9.71	381		9.36
214068	RICK BECKER	47.4318	-110.9939	19N	06E	5	C	3730		5/30/04			10.8					
214071	JIM DAWSON	47.3956	-110.9731	19N	06E	21	BDC	3800		5/28/03			10.2	745	7.9	37.5		10.6
214078	JIM DAWSON	47.3994	-110.9687	19N	06E	21	BAD	3790		5/28/03			20.5	810	7.82	109		14.9
214079	RICK BECKER	47.413	-110.9486	19N	06E	5	C	3730		5/30/03	4.28		11.7	819	7.58	98		9.1
214093	DOUG ZIMMERMAN	47.4345	-110.9623	19N	06E	4	CADC	3720		5/29/03	94.19		12.9	1398	6.87	14.6		1.6
214395	GARY REDDISH LOWER SPRING	47.3196	-110.9298	18N	06E	14	CABA	3940		9/26/03			12.9	500	7.85	230		8.65

Appendix B

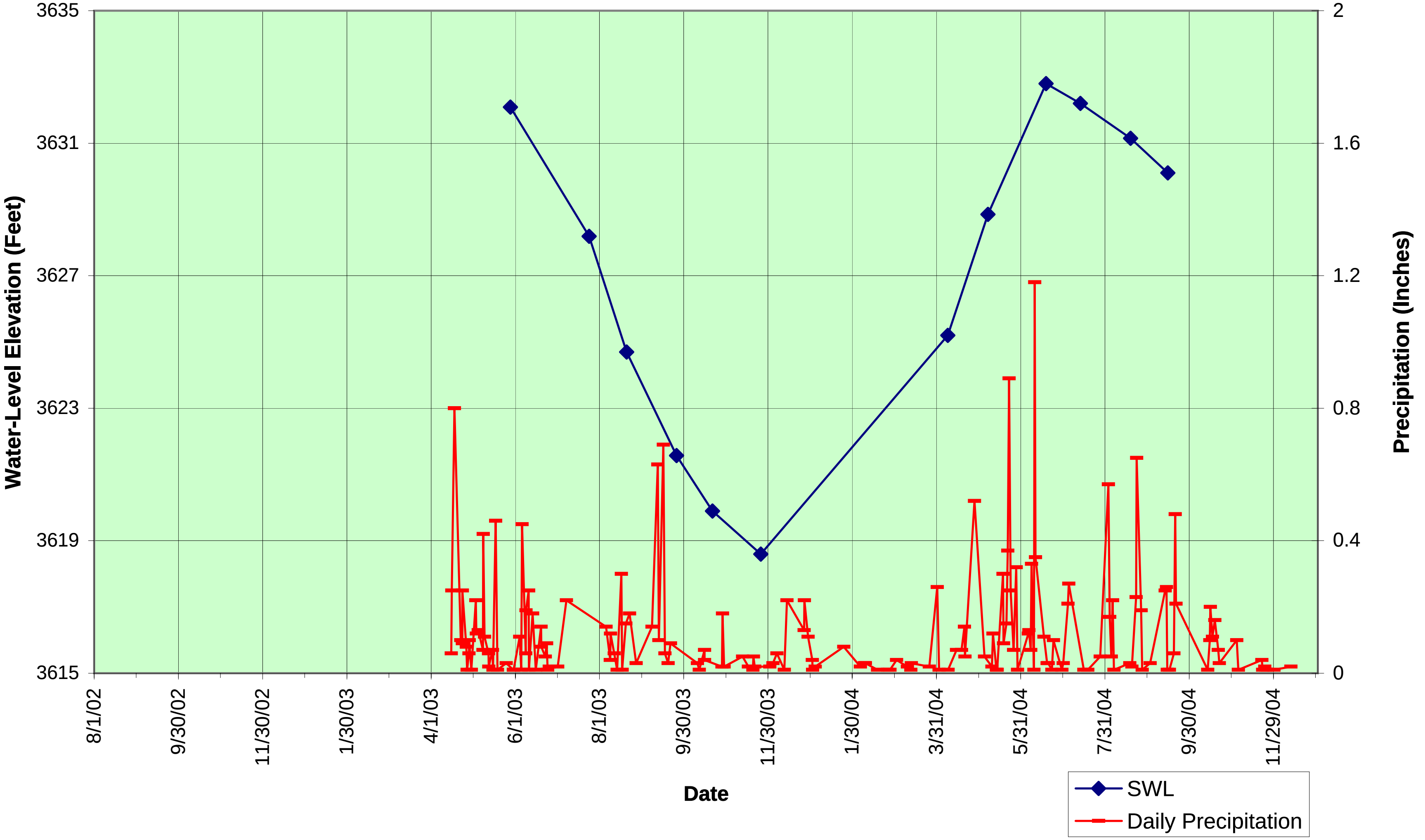
Ground-Water Hydrographs

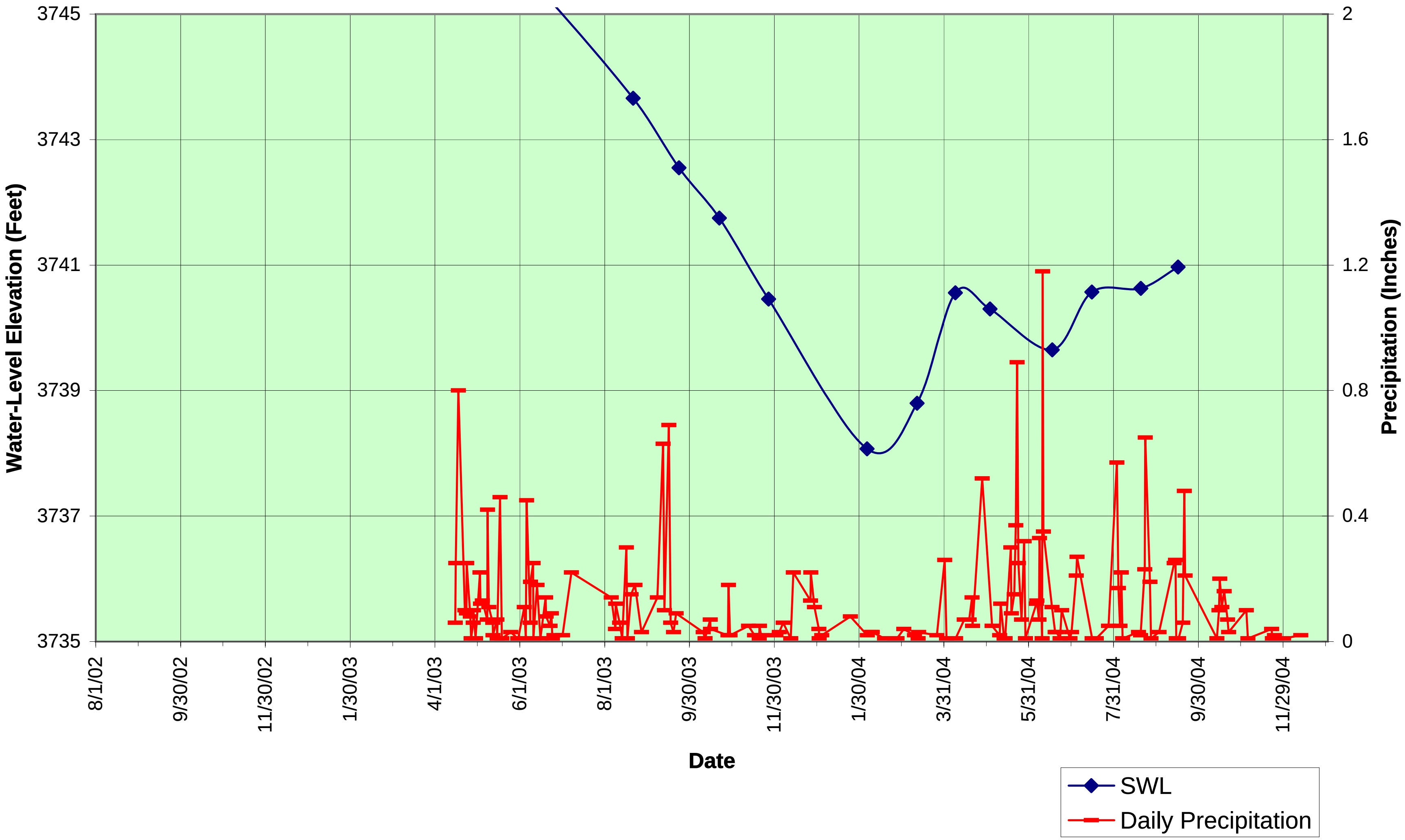
M: 186483
T19N-R06E-26-DBCB
Alt=3540 ft, TD=24 ft
Aquifer= Alluvial




M: 202581
T19N-R06E-12-BBBB
Alt=3440 ft, TD=35 ft
Aquifer= Alluvial
Water-Level Elevation (Feet)
3438
3436
3434
3432
3430
3428
Precipitation (Inches)
2
1.6
1.2
0.8
0.4
0
1/1/02
3/2/02
5/2/02
7/2/02
9/1/02
11/1/02
1/1/03
3/2/03
5/2/03
7/2/03
9/1/03
11/1/03
1/1/04
3/2/04
5/1/04
7/1/04
8/31/04
10/31/04
12/31/04
Date
SWL
Daily Precipitation

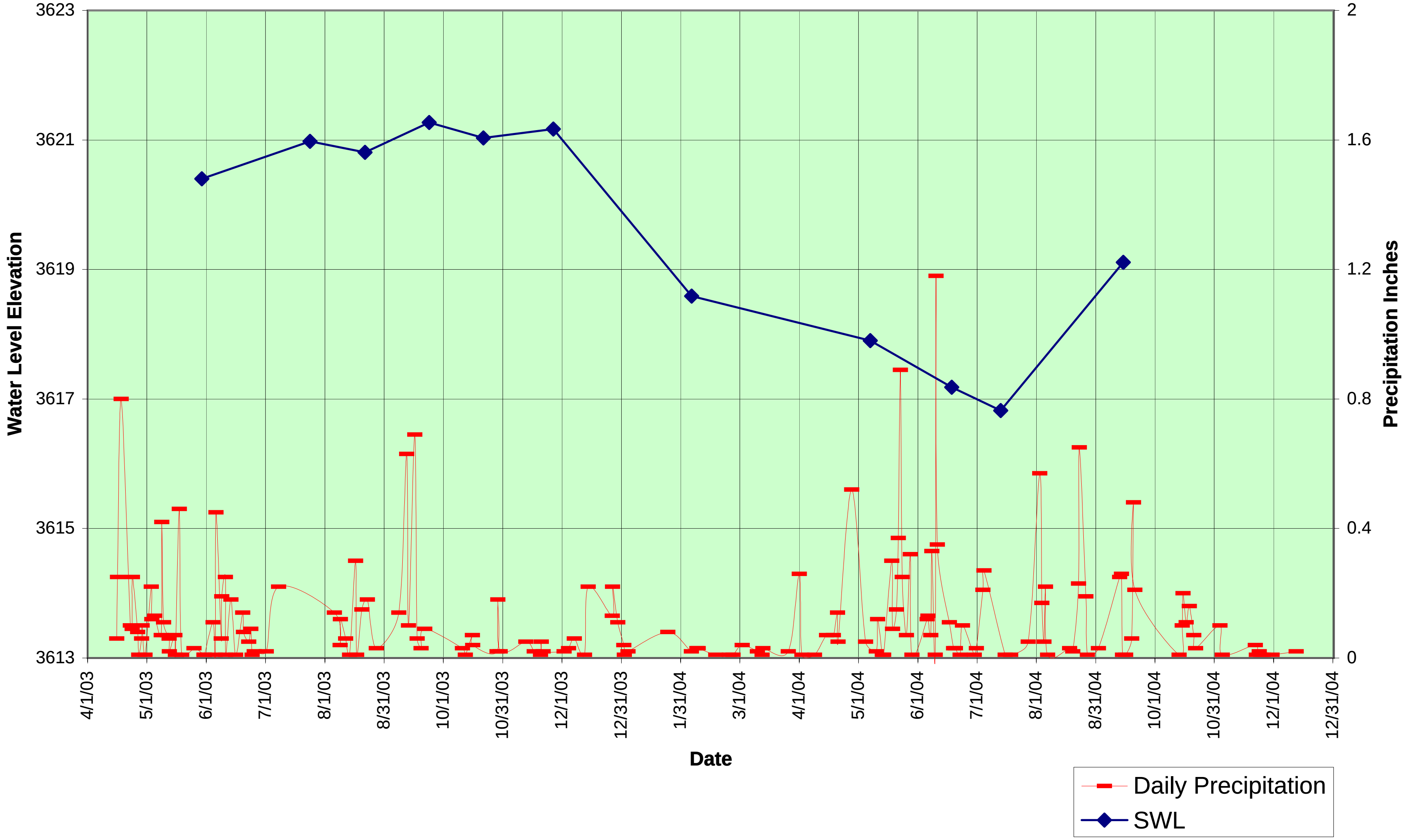
M: 207649
T19N-R06E-16-CCB
Alt=3635 ft, TD=30 ft
Aquifer= Alluvial



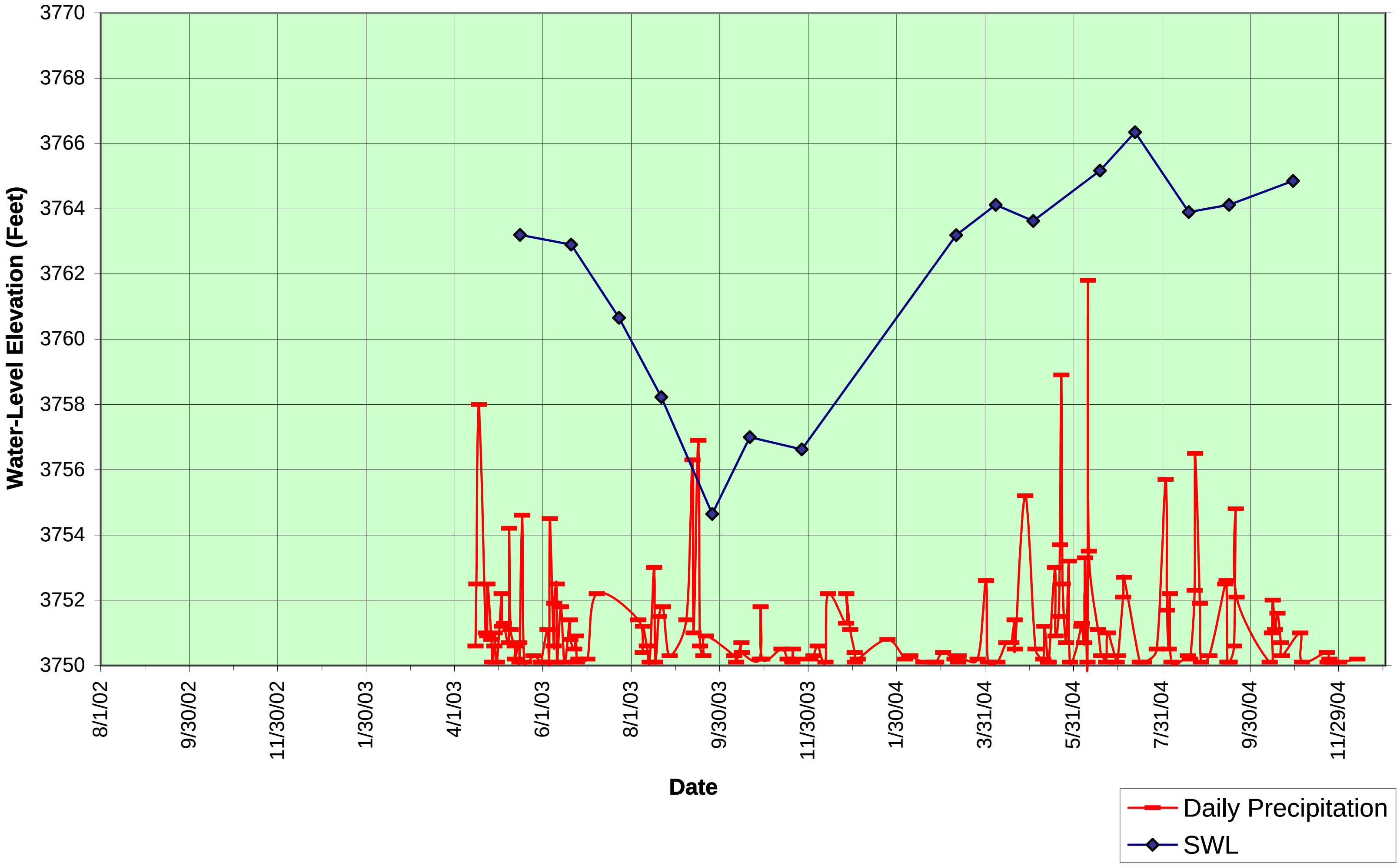


M: 180021
T18N-R06E-14-BDBA
Alt=3890 ft, TD=200 ft
Aquifer= Kootenai

M: 31957
T19N-R06E-4-DDBA
Alt=3715 ft,TD=140 ft
Aquifer= Kootenai

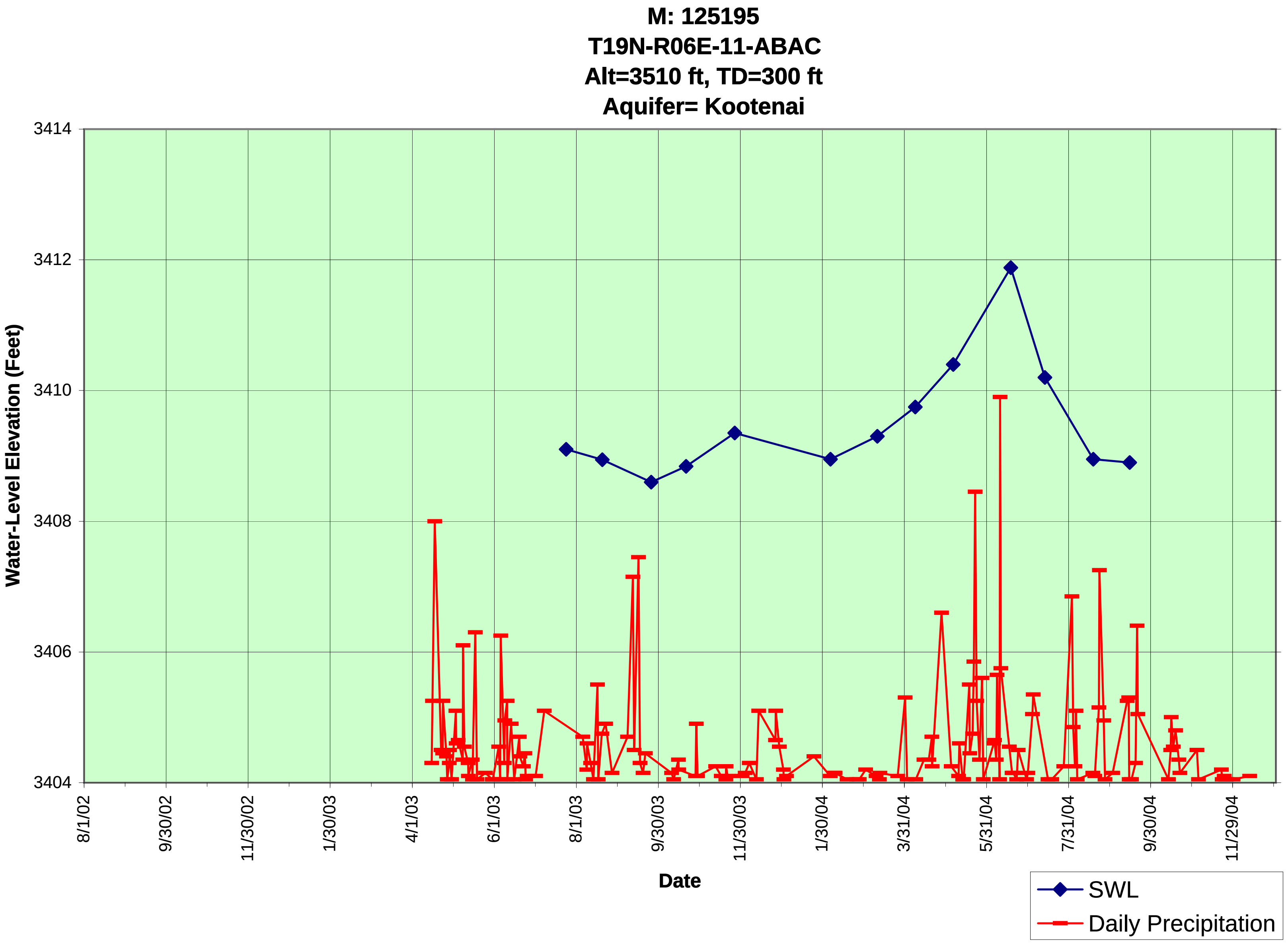


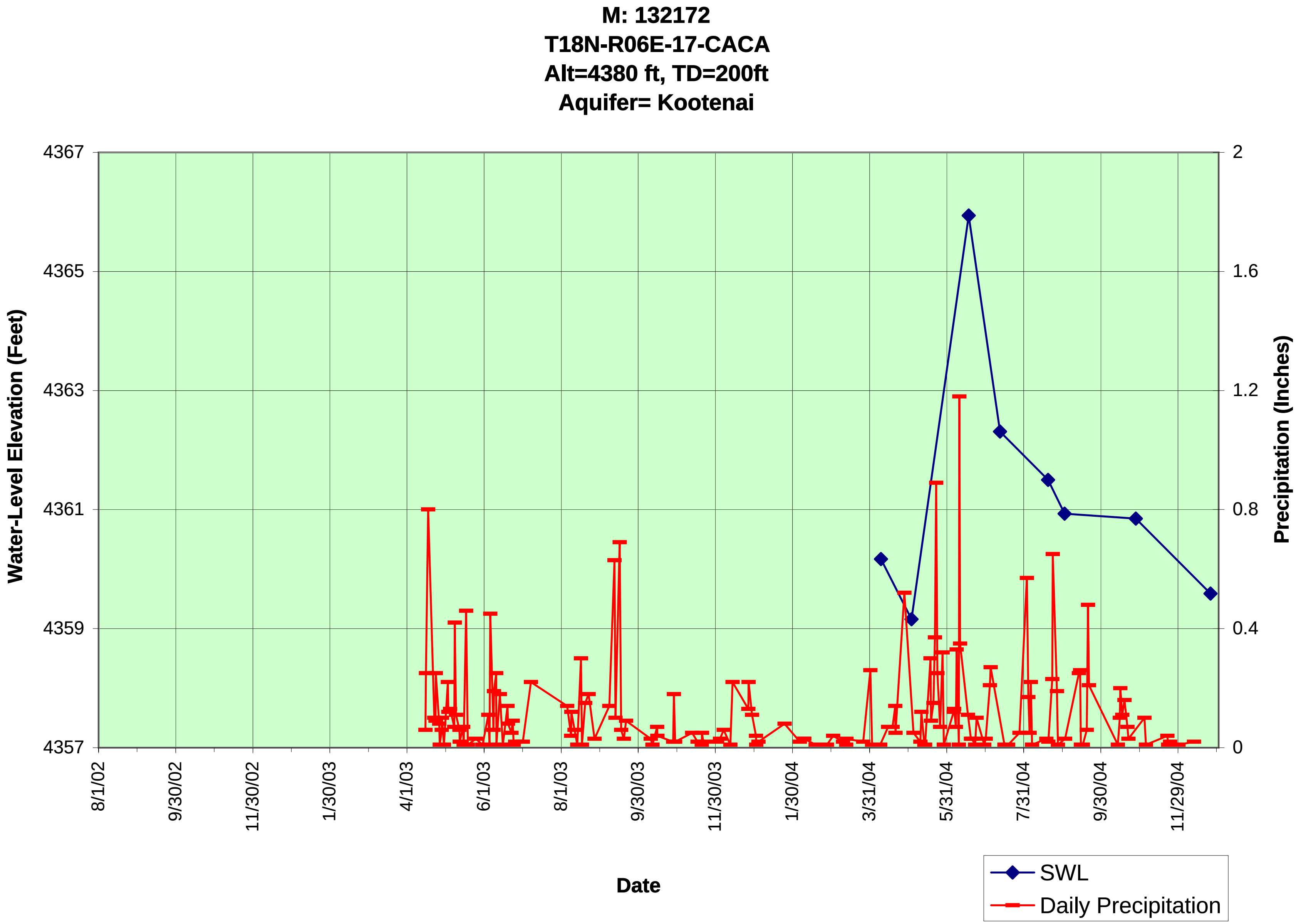
M: 84937
T19N-R06E-29-CD
Alt=3860 ft, TD=200 ft
Aquifer=Kootenai/ Cutbank



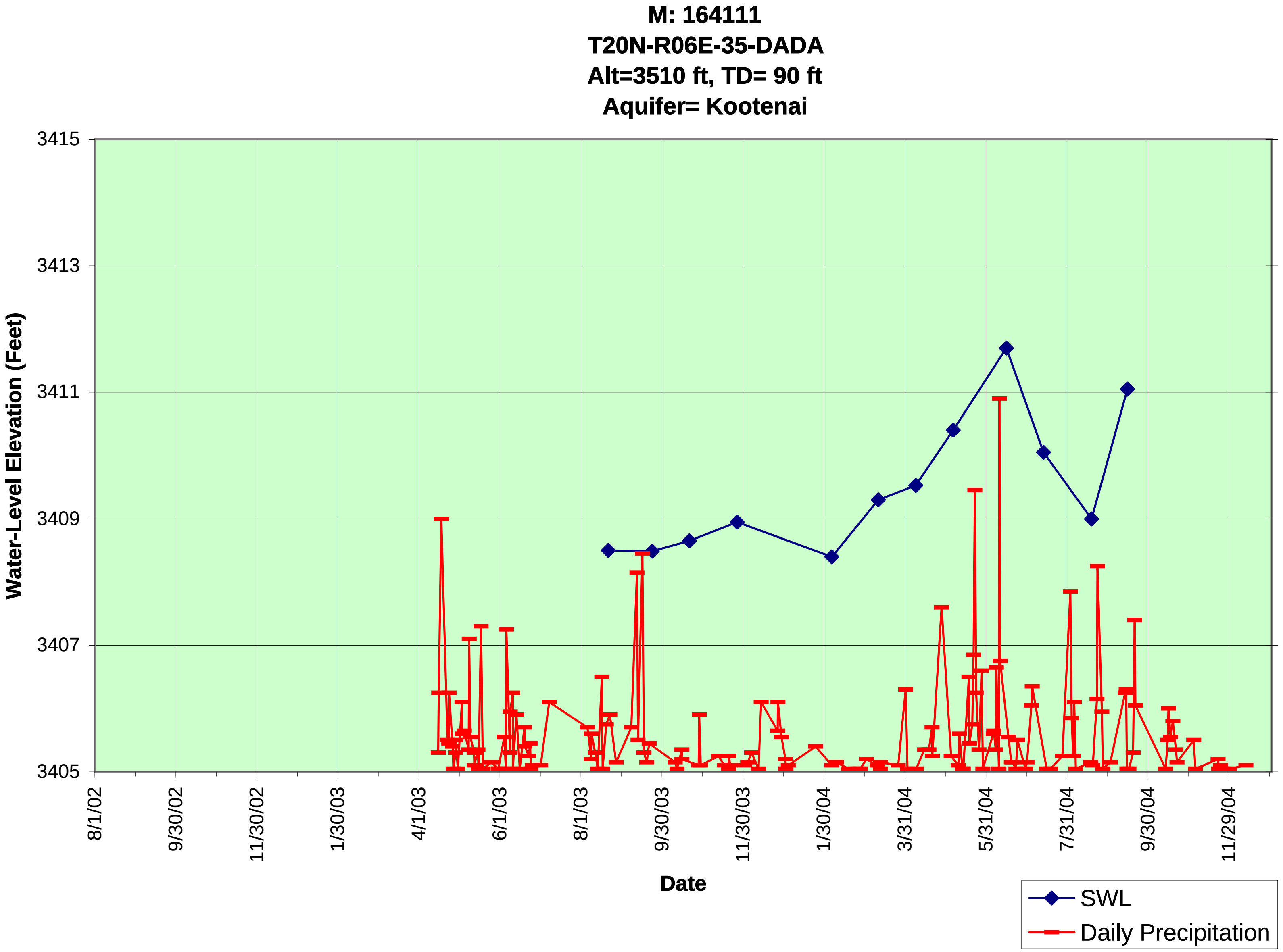
B6

B7

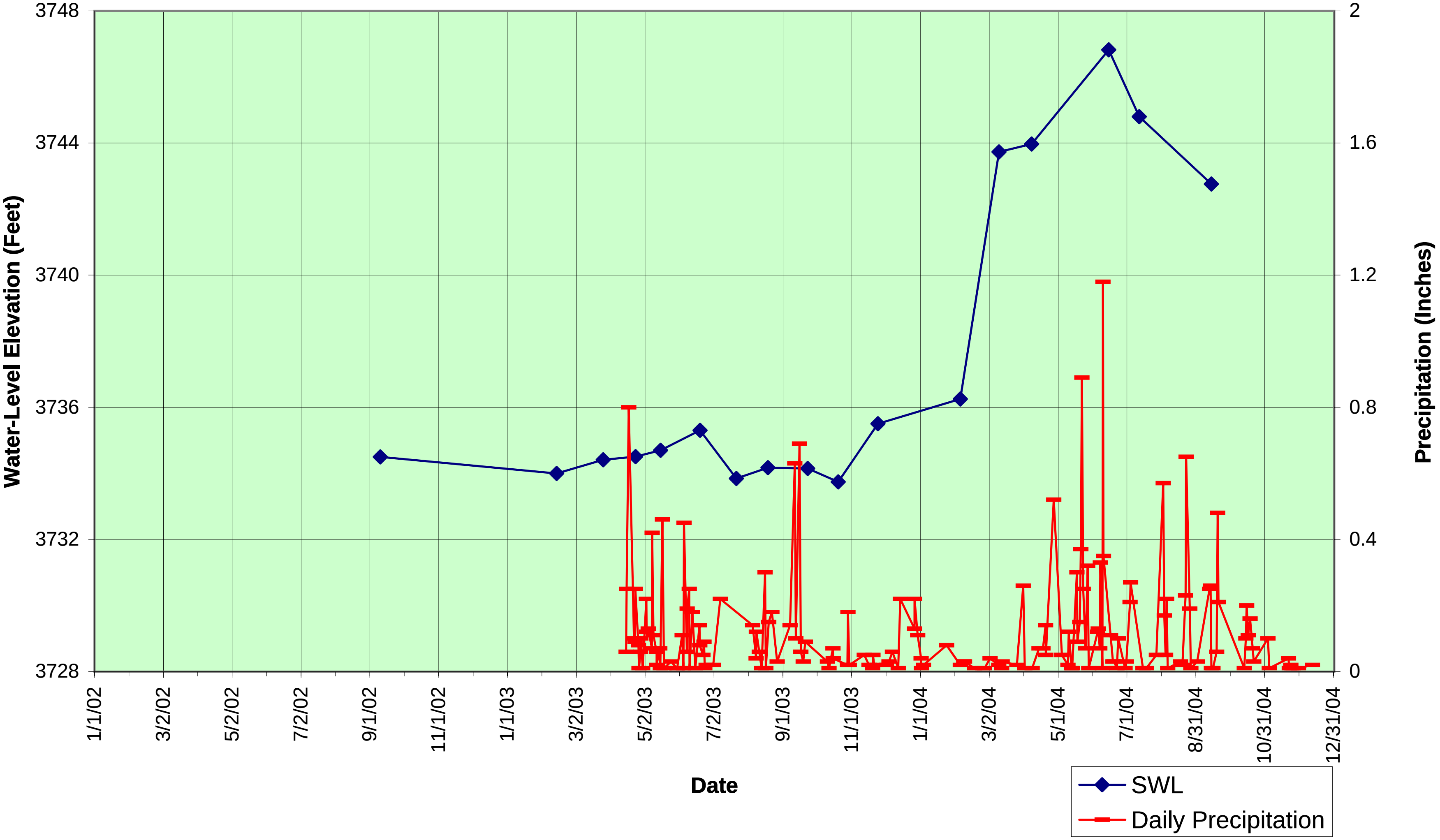

M: 125195
T19N-R06E-11-ABAC
Alt=3510 ft, TD=300 ft
Aquifer= Kootenai
Water-Level Elevation (Feet)
3414
3412
3410
3408
3406
3404
Precipitation (Inches)
2
1.6
1.2
0.8
0.4
0
8/1/02
9/30/02
11/30/02
1/30/03
4/1/03
6/1/03
8/1/03
9/30/03
11/30/03
1/30/04
3/31/04
5/31/04
7/31/04
9/30/04
11/29/04
Date
SWL
Daily Precipitation


M: 132172
T18N-R06E-17-CACA
Alt=4380 ft, TD=200ft
Aquifer= Kootenai
Water-Level Elevation (Feet)
4367
4365
4363
4361
4359
4357
Precipitation (Inches)
2
1.6
1.2
0.8
0.4
0
8/1/02
9/30/02
11/30/02
1/30/03
4/1/03
6/1/03
8/1/03
9/30/03
11/30/03
1/30/04
3/31/04
5/31/04
7/31/04
9/30/04
11/29/04
Date
SWL
Daily Precipitation

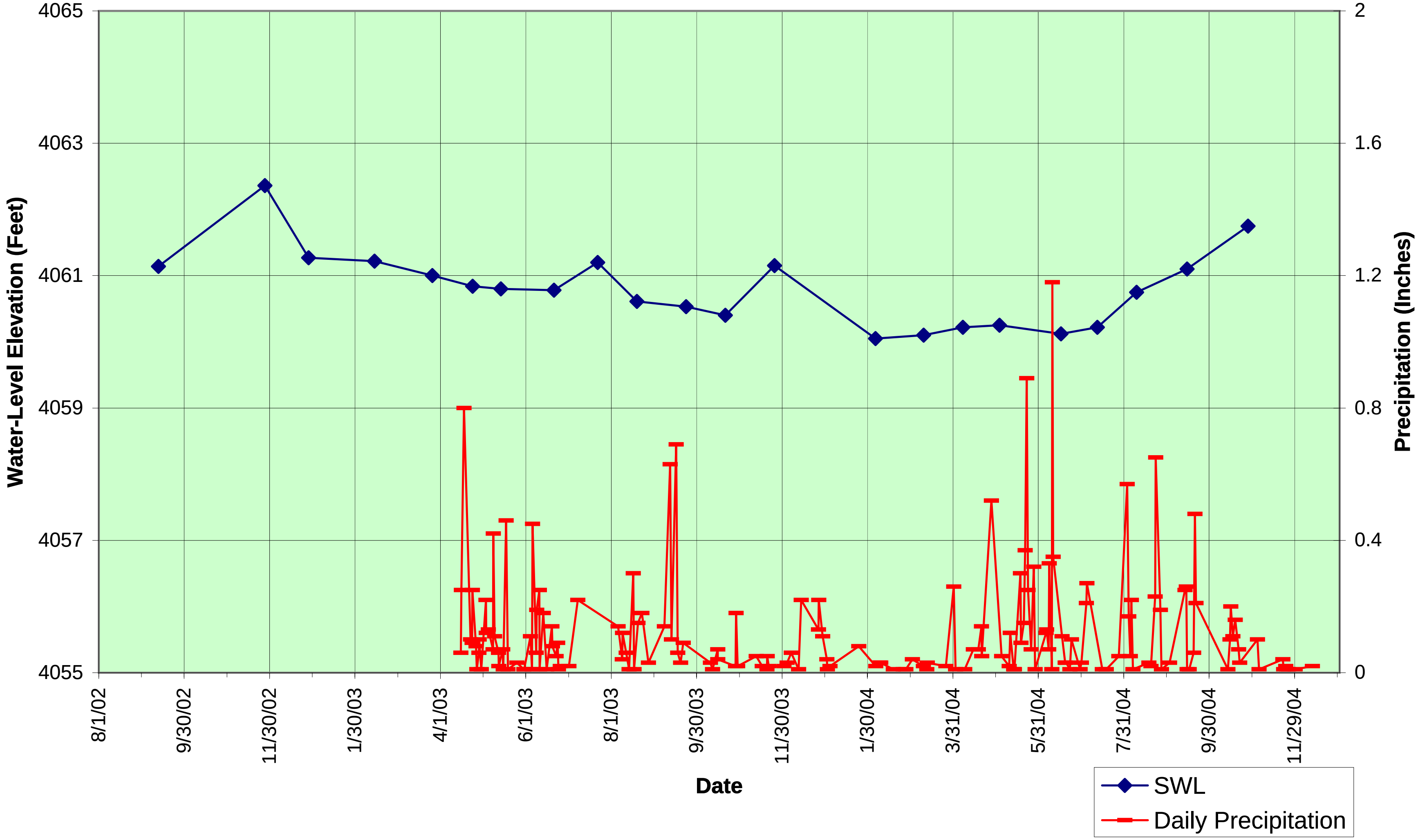
B9


M: 164111
T20N-R06E-35-DADA
Alt=3510 ft, TD= 90 ft
Aquifer= Kootenai
Water-Level Elevation (Feet)
3415
3413
3411
3409
3407
3405
Precipitation (Inches)
2
1.6
1.2
0.8
0.4
0
8/1/02
9/30/02
11/30/02
1/30/03
4/1/03
6/1/03
8/1/03
9/30/03
11/30/03
1/30/04
3/31/04
5/31/04
7/31/04
9/30/04
11/29/04
Date
SWL
Daily Precipitation

M: 186486
T19N-R07E-32-BADA
Alt=3790 ft, TD=200 ft
Aquifer= Kootenai

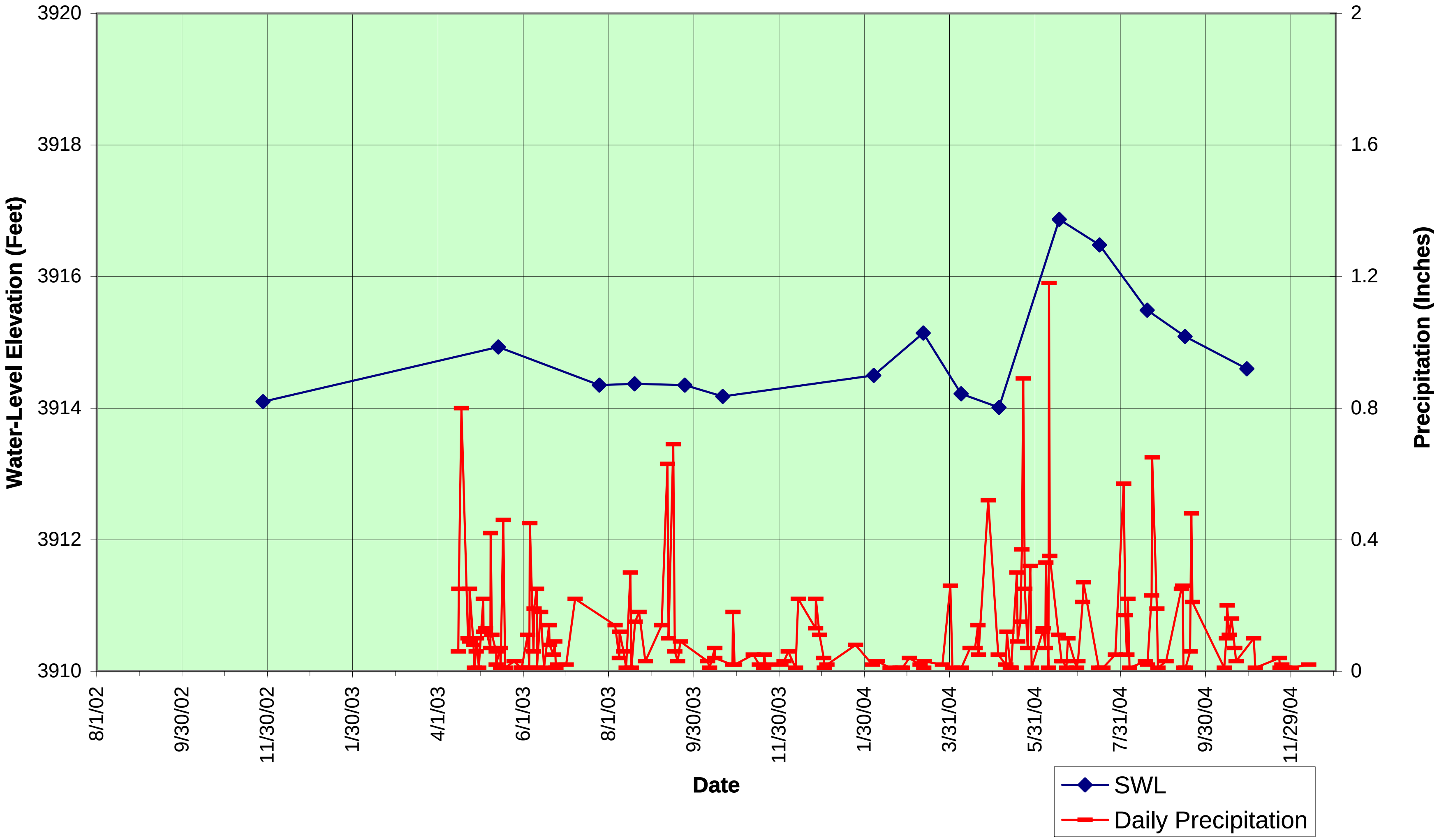


M: 199851
T18N-R06E-15-CCBC
Alt=4160 ft, TD=160 ft
Aquifer= Kootenai/ Cutbank

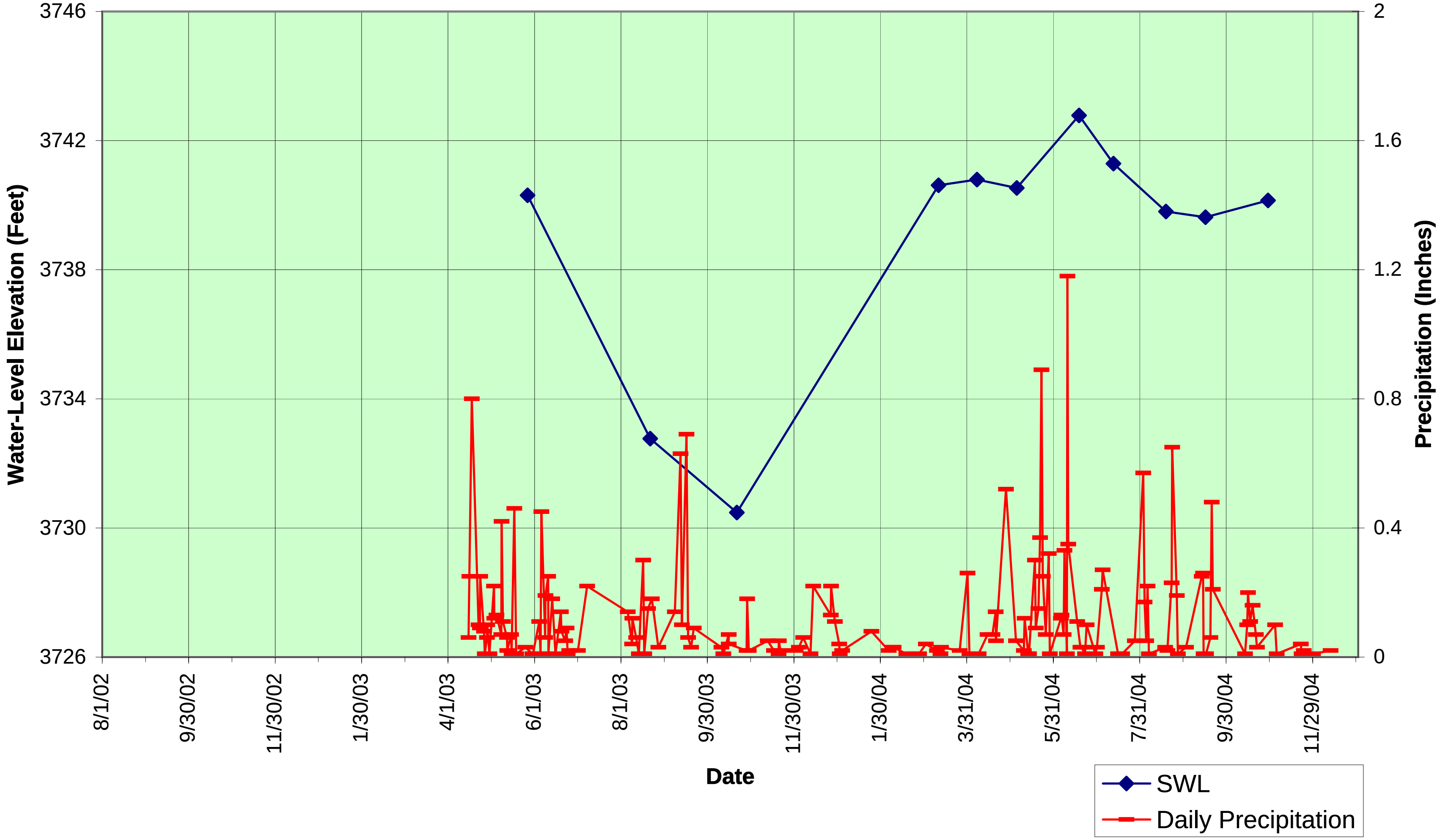


M: 204516
T19N-R06E-34-ACDC
Alt=3926 ft, TD=19.6 ft
Aquifer= Kootenai/ Sunburst

B12



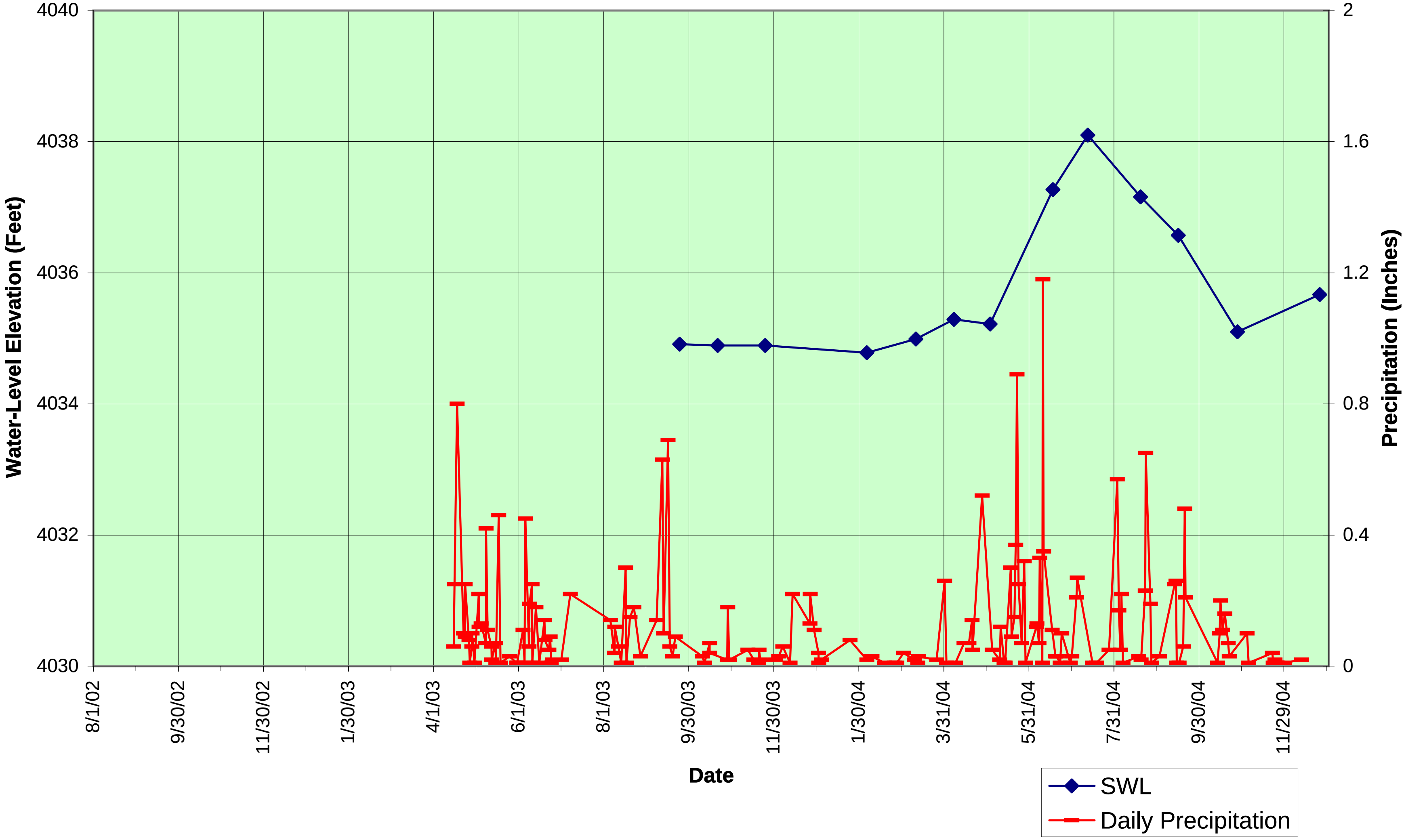
M: 207258
T19N-R06E-29-ACBB
Alt=3700 ft, TD=72 ft
Aquifer= Kootenai/ Cutbank

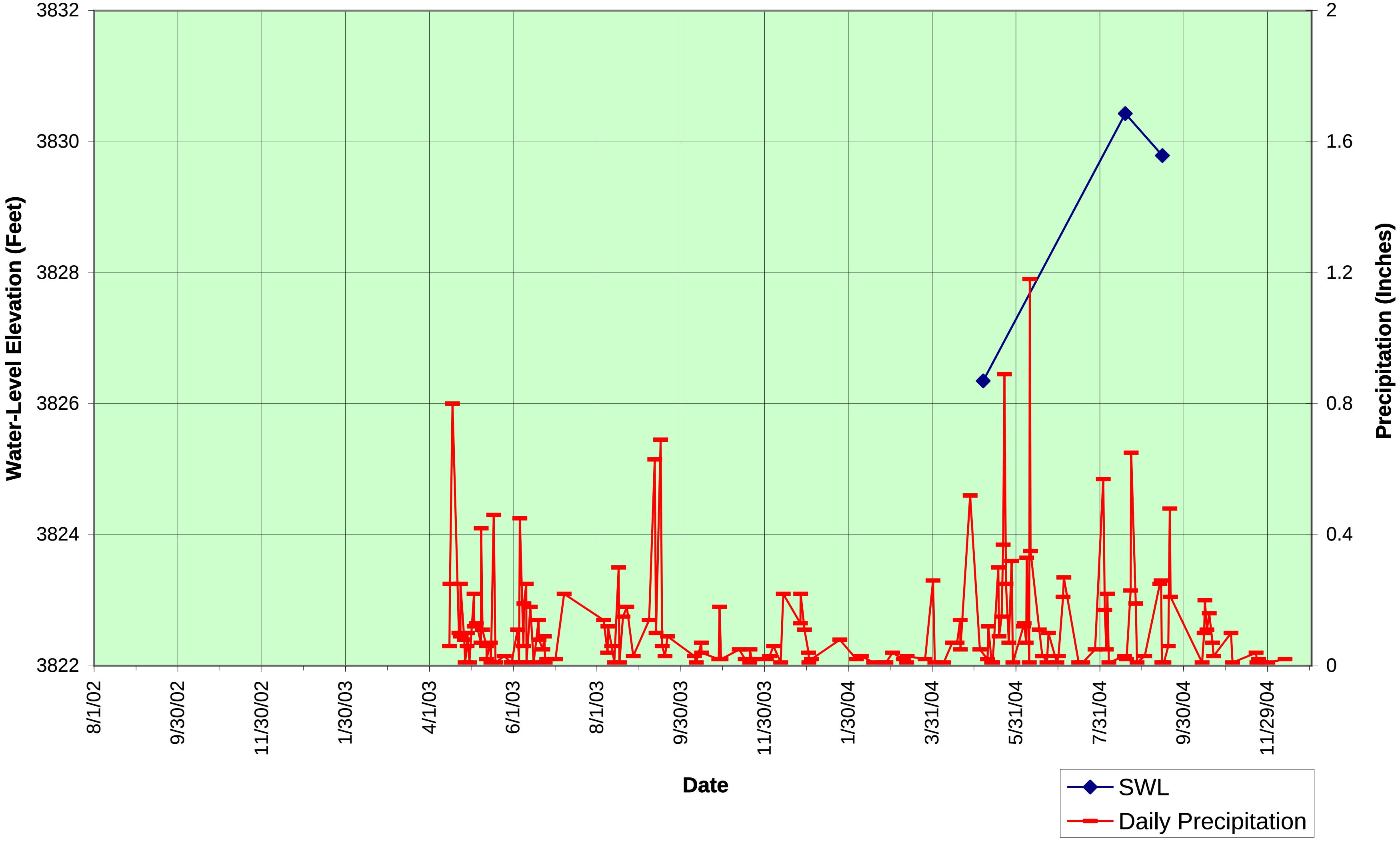


B13

B14

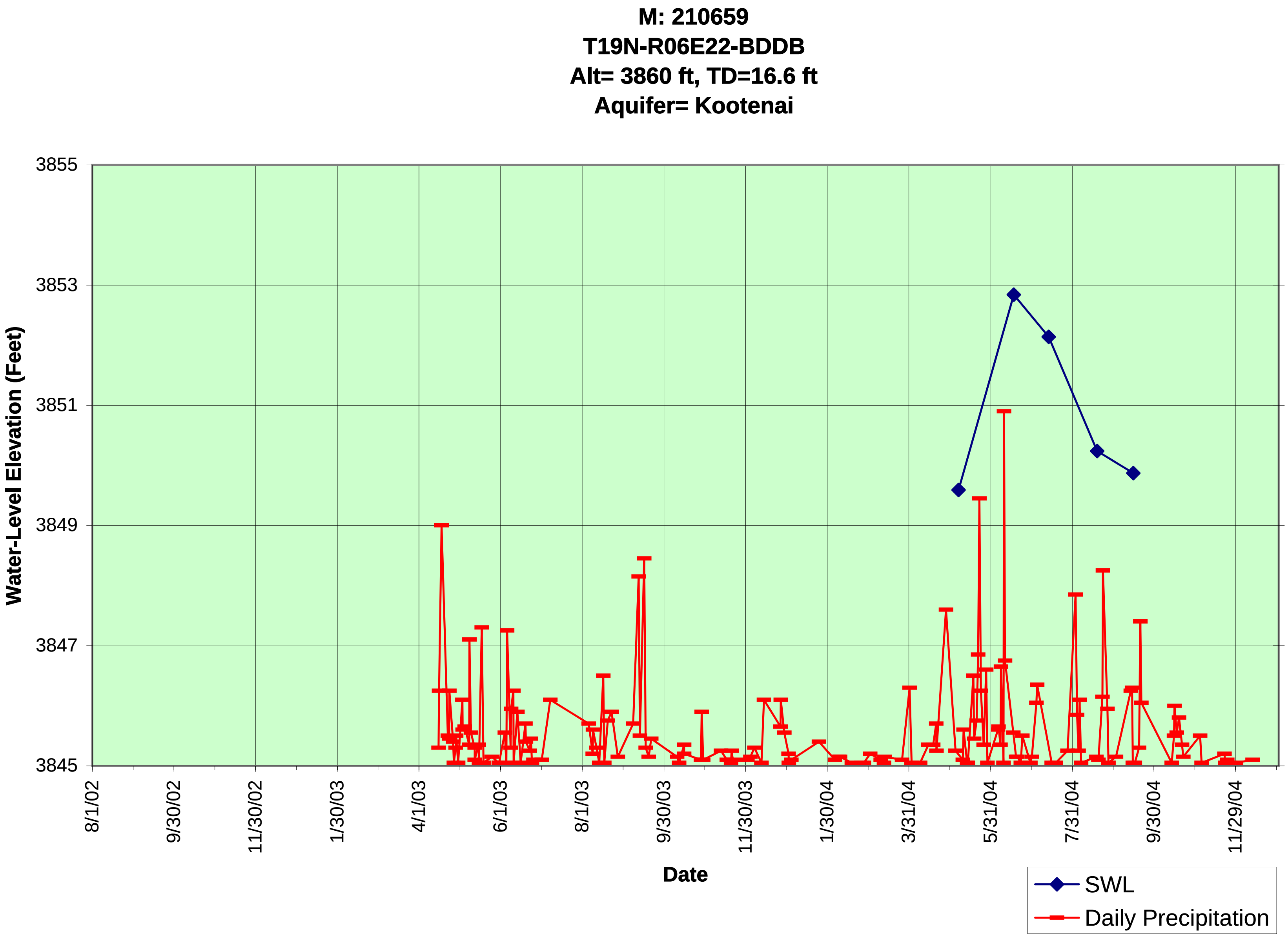
M: 207463
T18N-R06E-3-BCAD
Alt=4060 ft, TD=53.6 ft
Aquifer= Kootenai



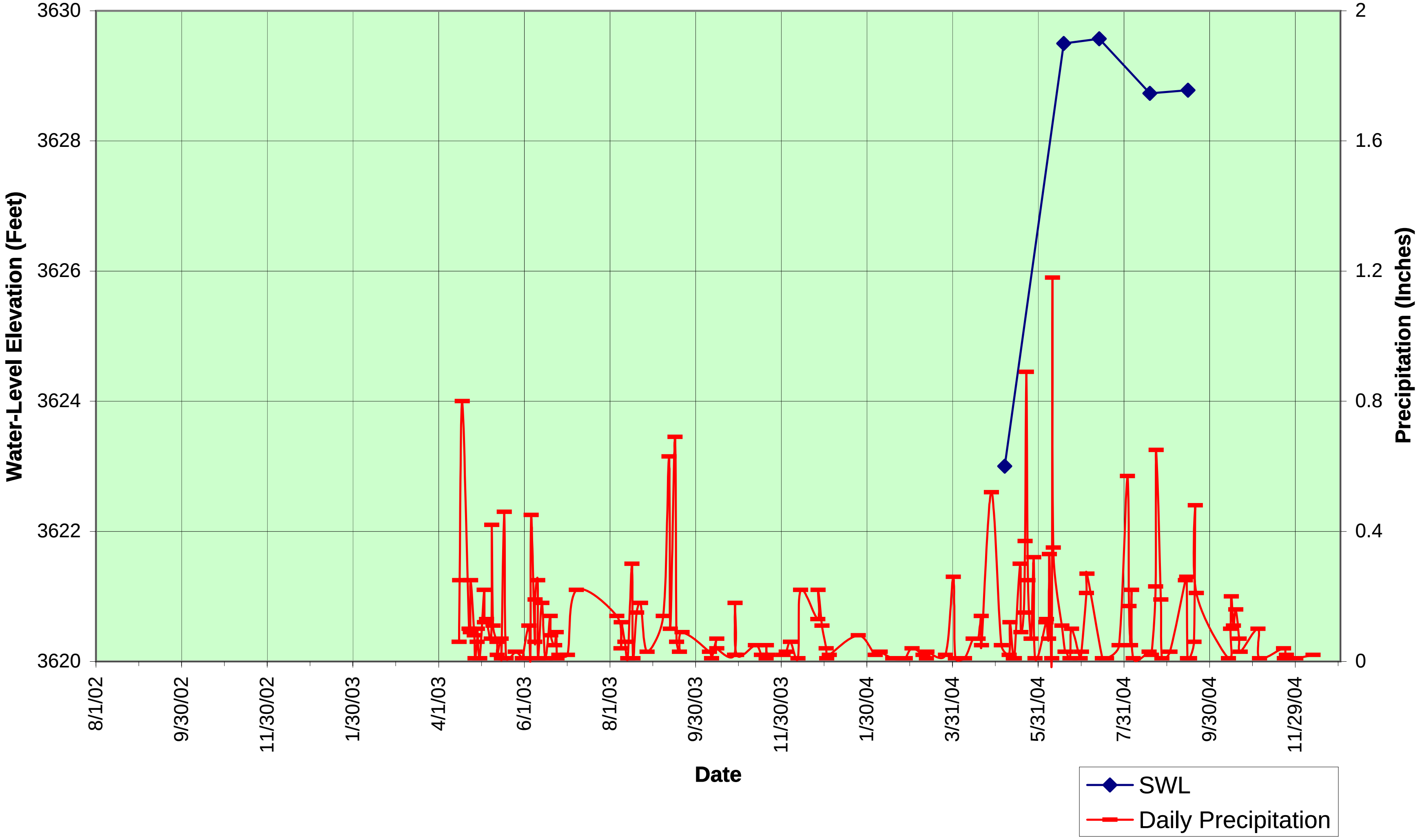


M: 210655
T19N-06E-22-BDDB
Alt=3860 ft, TD=80 ft
Aquifer= Kootenai

B16

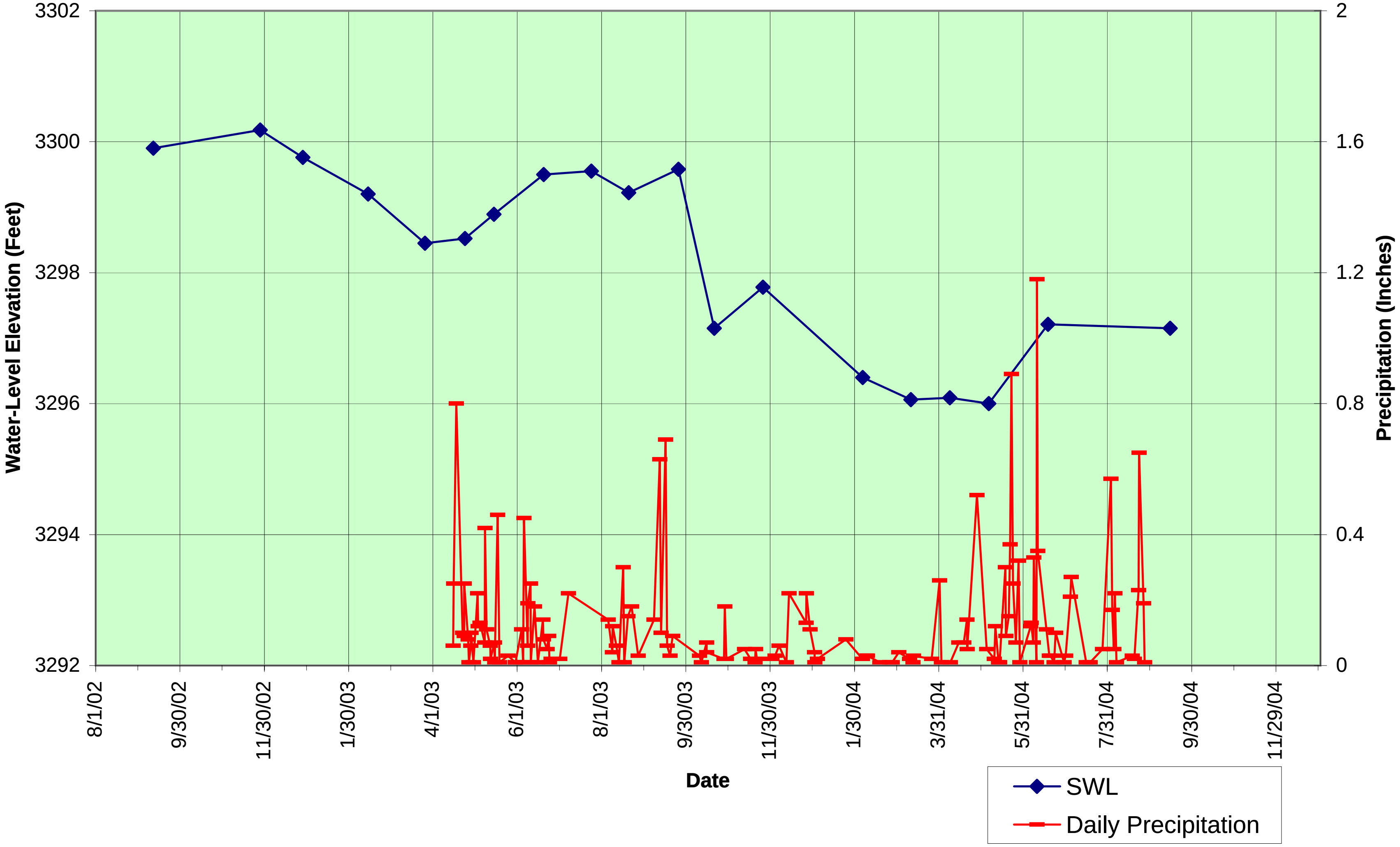

M: 210659
T19N-R06E22-BDDB
Alt= 3860 ft, TD=16.6 ft
Aquifer= Kootenai
Water-Level Elevation (Feet)
3855
3853
3851
3849
3847
3845
Precipitation (Inches)
2
1.6
1.2
0.8
0.4
0
8/1/02
9/30/02
11/30/02
1/30/03
4/1/03
6/1/03
8/1/03
9/30/03
11/30/03
1/30/04
3/31/04
5/31/04
7/31/04
9/30/04
11/29/04
Date
SWL
Daily Precipitation

M: 213386
T20N-R06E-33-DDDB
Alt=3635 ft, TD=29 ft
Aquifer= Kootenai



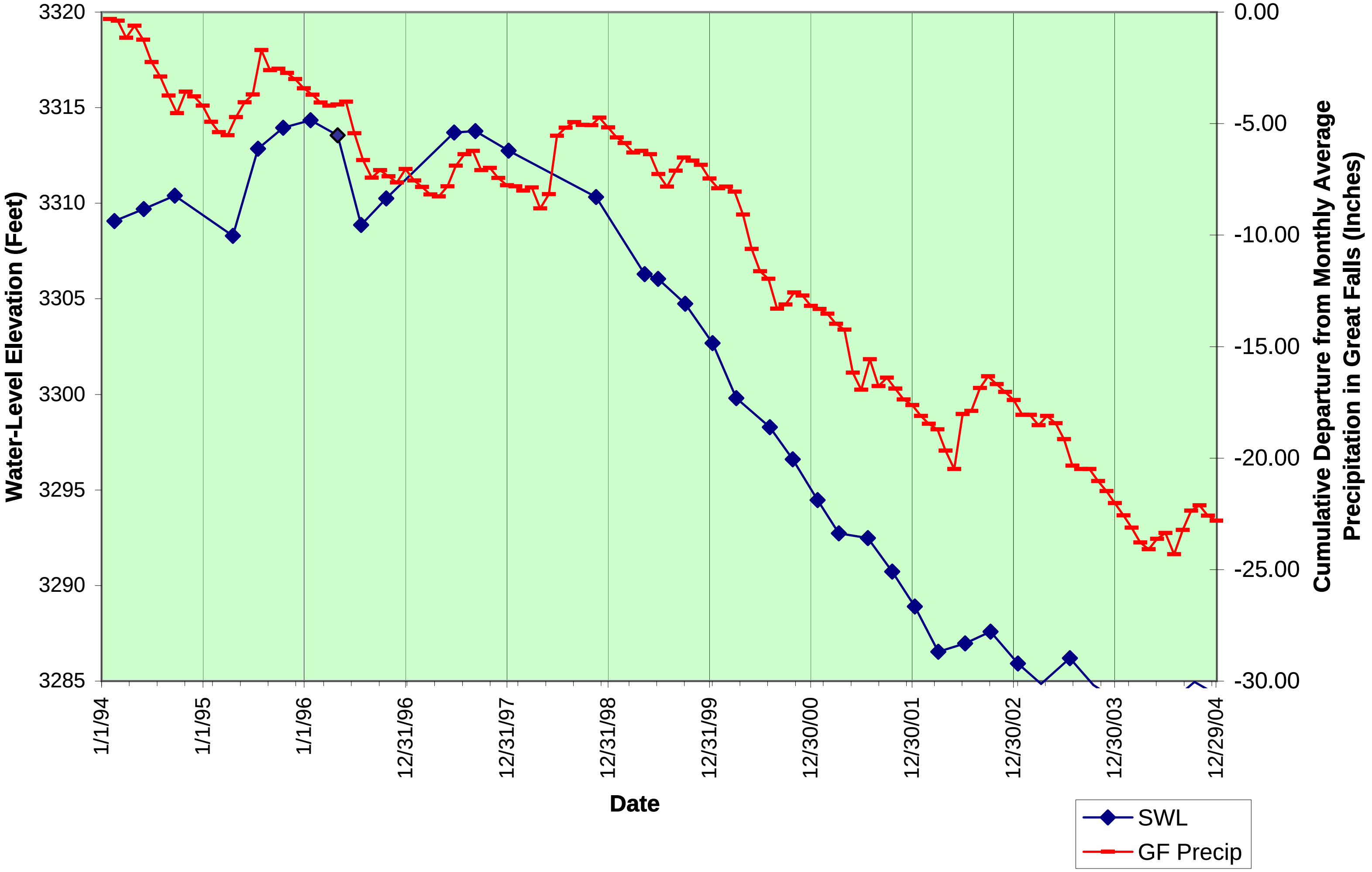
B18

M: 150504
T19N-R06E-11-ABAC
Alt=3510 ft, TD=300 ft
Aquifer= Madison

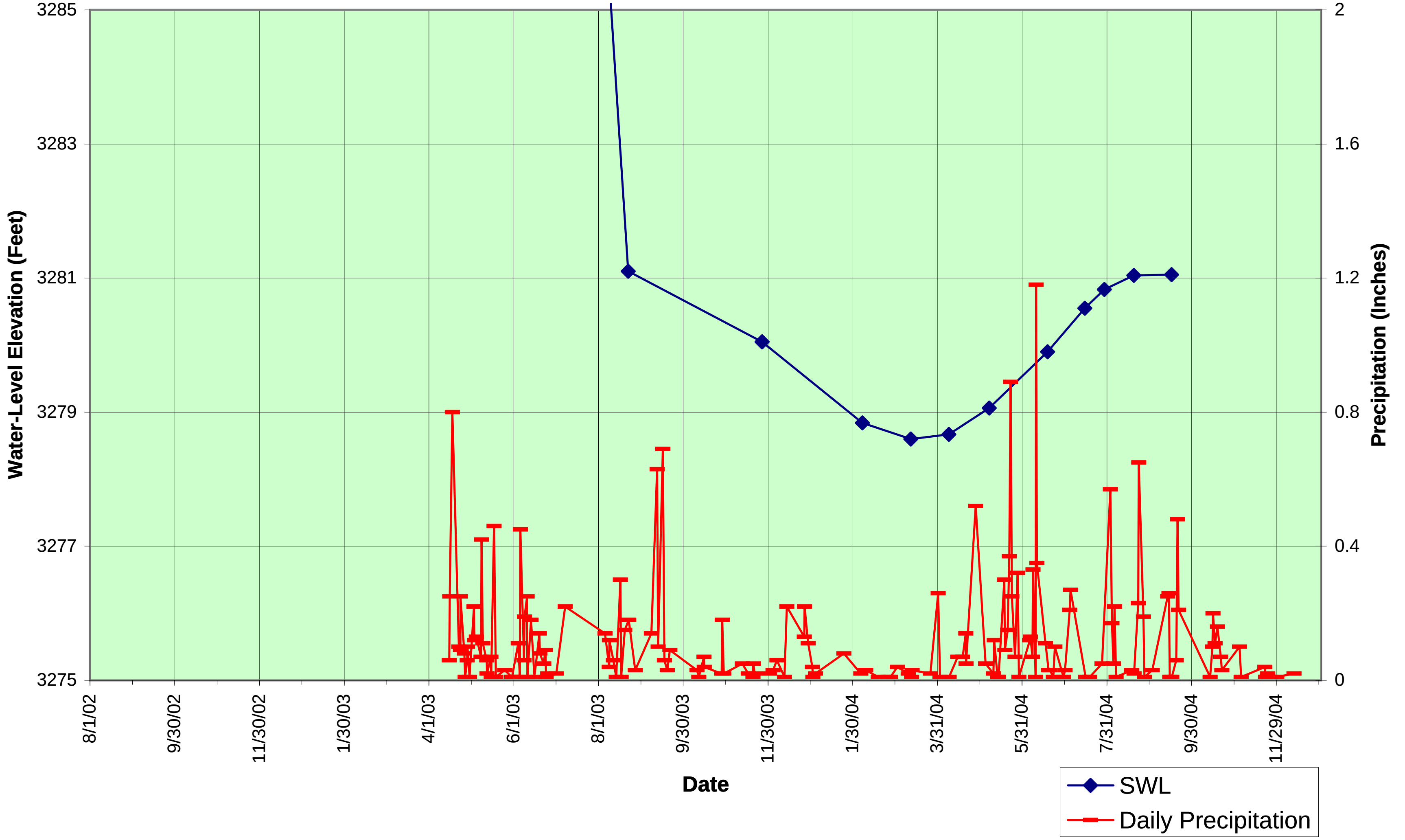


M: 2315 Belt City Well
T19N-R06E-26-ACAD
Alt=3520 ft, TD=430 ft
Aquifer= Madison

B19

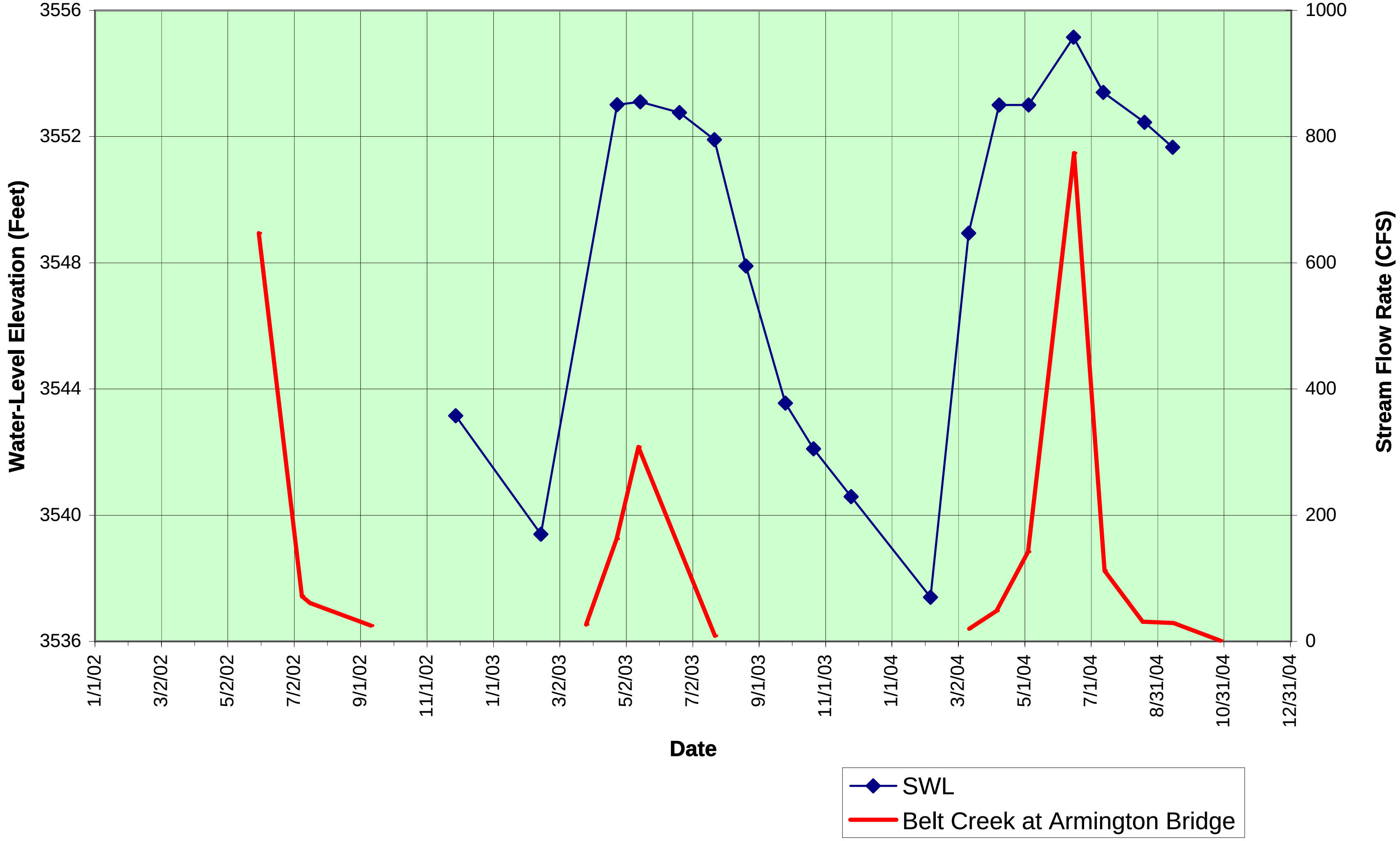


M: 177163
T19N-R06E-36-DCDD
Alt=3620 ft, TD=490 ft
Aquifer= Madison

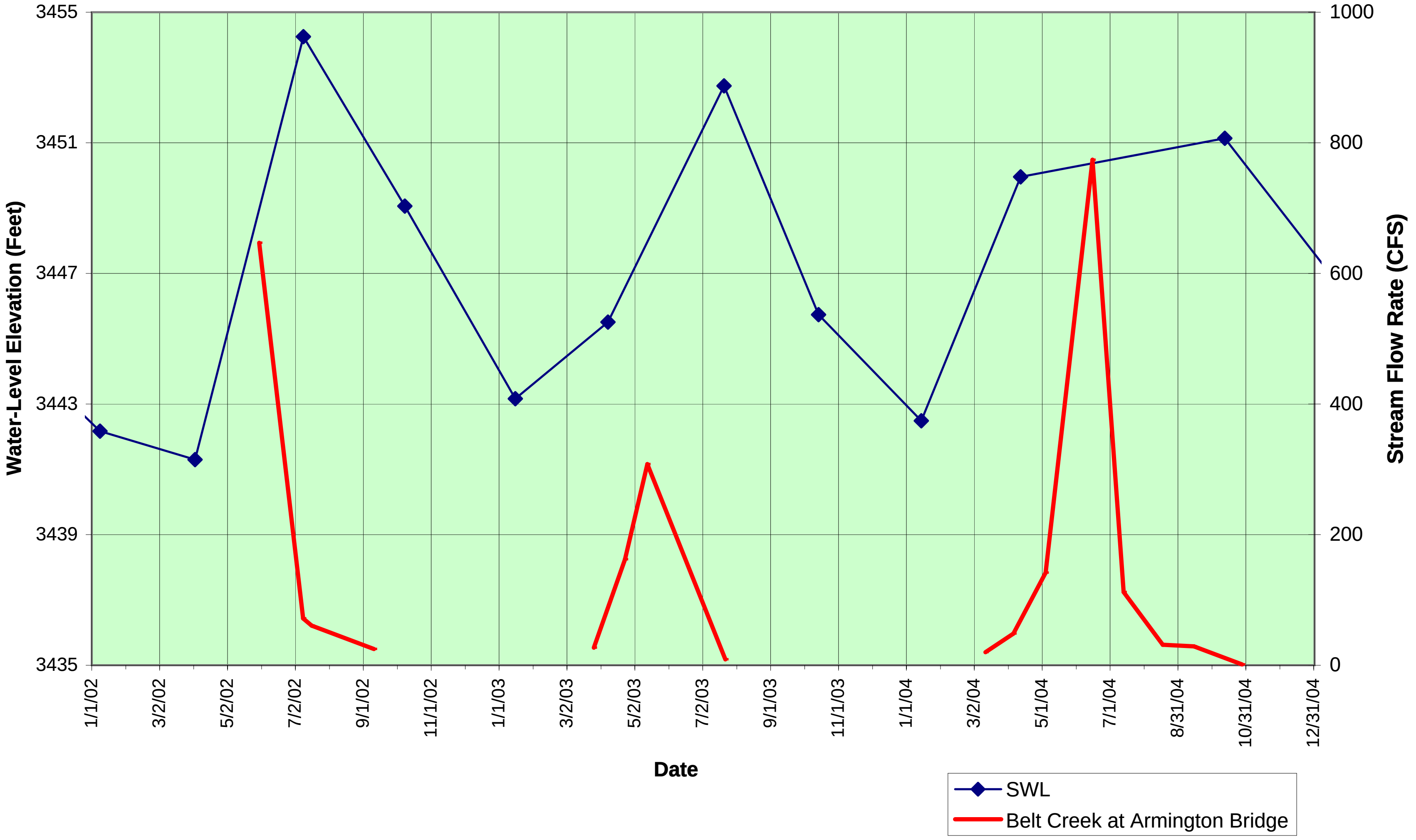


B21

M: 165475
T19N-R06E-36-BABB
Alt=3560 ft, TD=50 ft
Aquifer: Swift

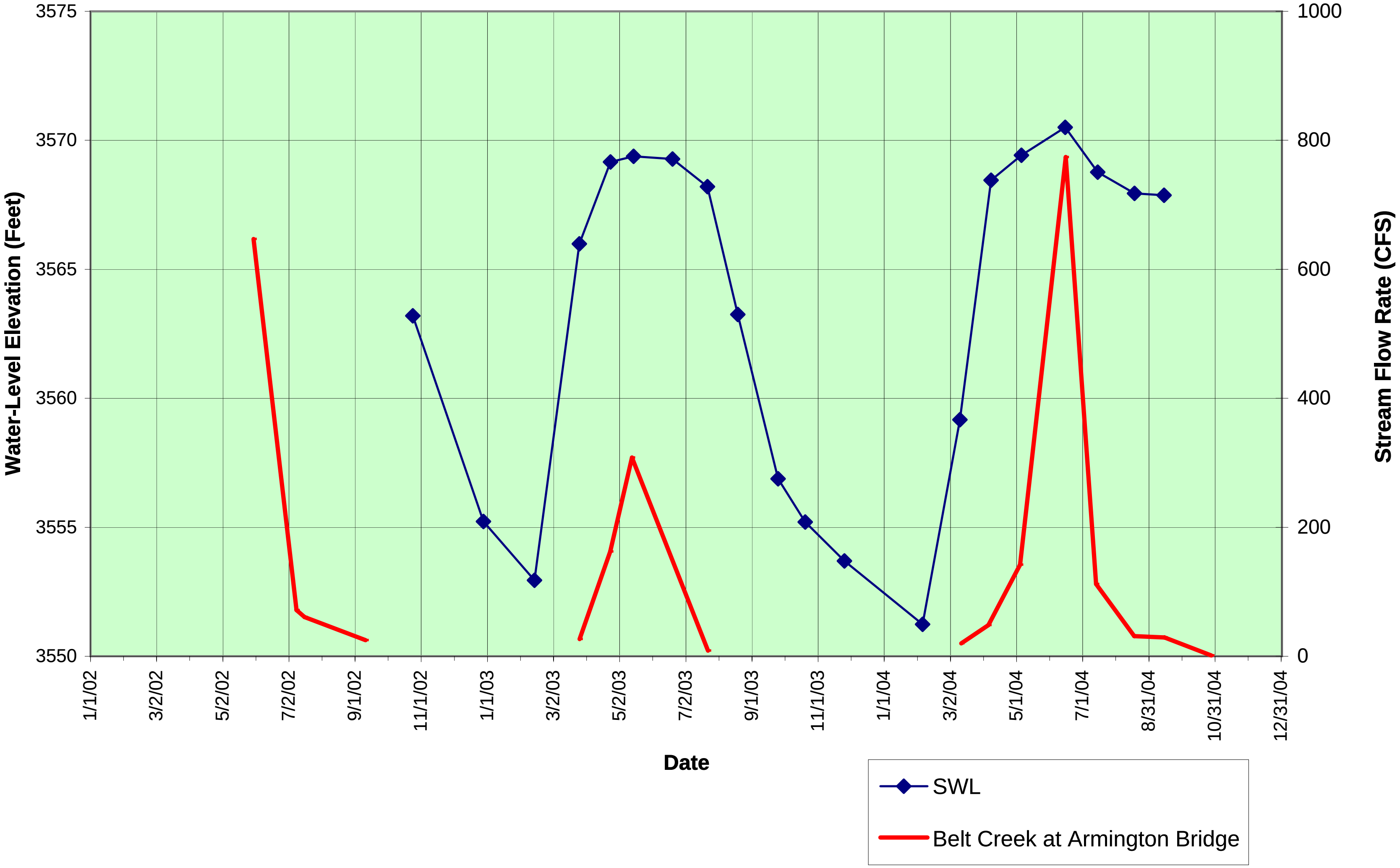


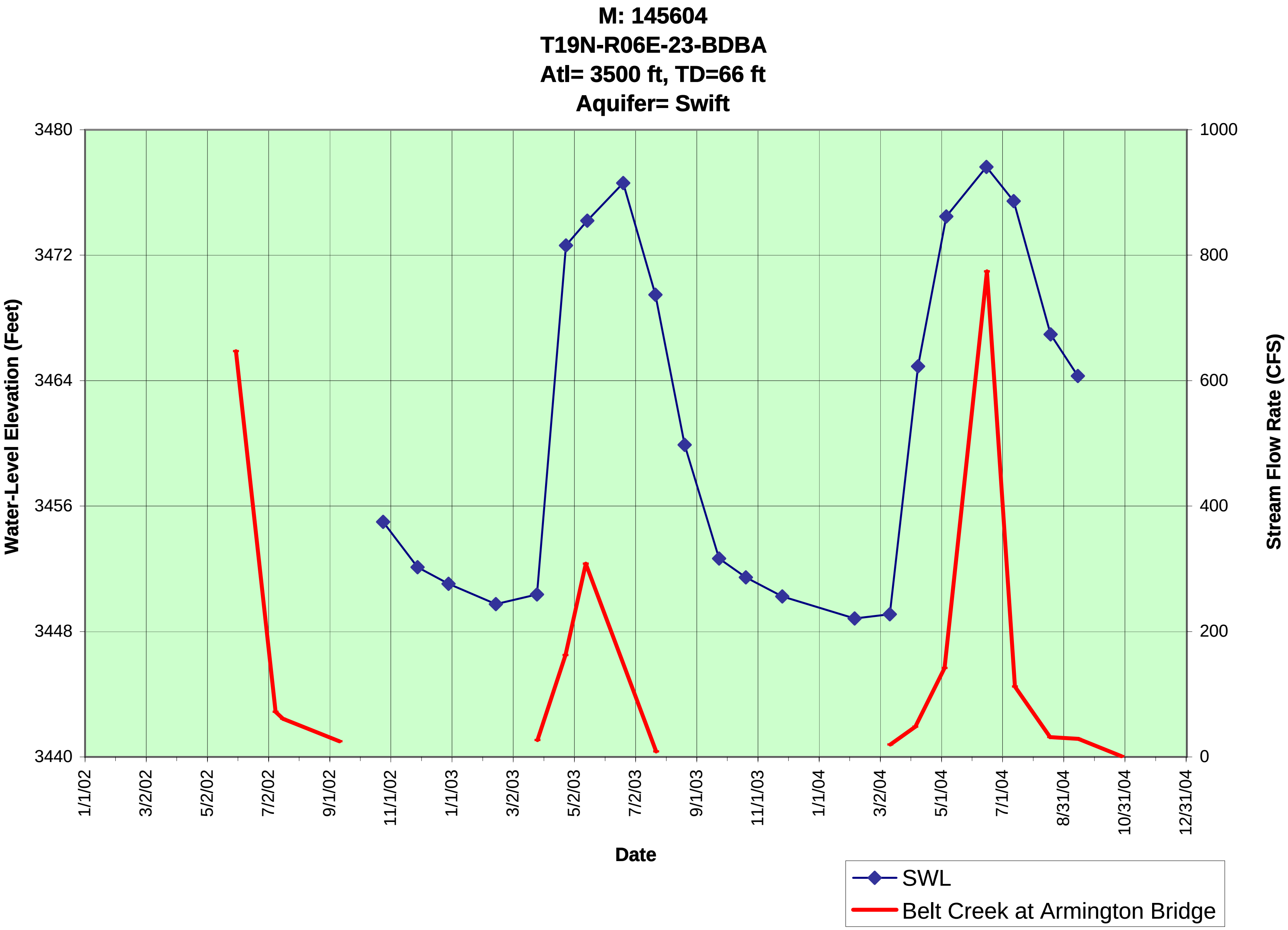
M: 31992
19N-06E-23-BADA
Alt=3494 ft, TD=75 ft
Aquifer= Swift



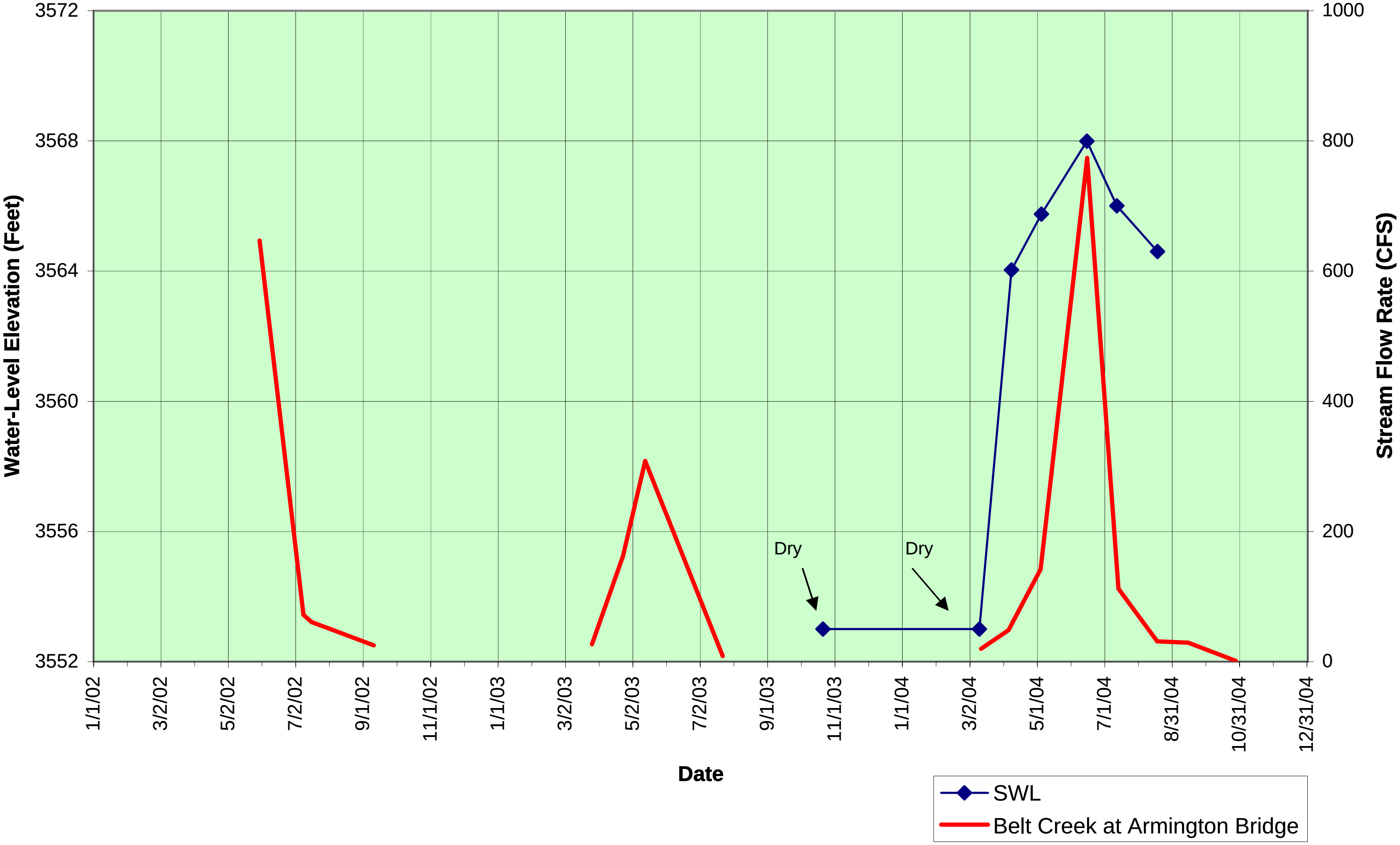
B22

M: 123498
T19N-R06E-36-DACC
Alt=3575 ft, TD=53 ft
Aquifer= Swift

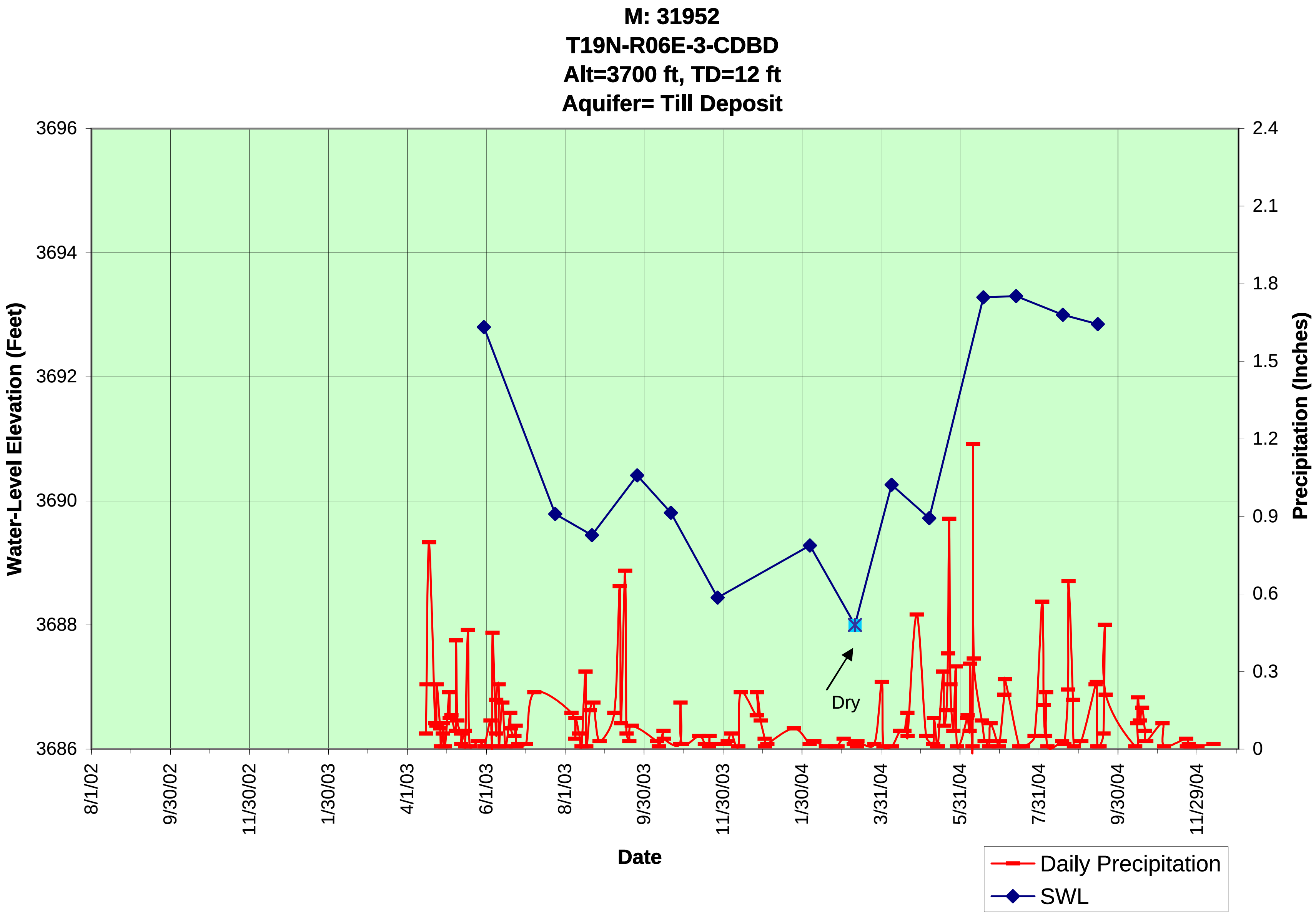



M: 145604
T19N-R06E-23-BDBA
Atl= 3500 ft, TD=66 ft
Aquifer= Swift
Water-Level Elevation (Feet)
3480
3472
3464
3456
3448
3440
Stream Flow Rate (CFS)
1000
800
600
400
200
0
1/1/02
3/2/02
5/2/02
7/2/02
9/1/02
11/1/02
1/1/03
3/2/03
5/2/03
7/2/03
9/1/03
11/1/03
1/1/04
3/2/04
5/1/04
7/1/04
8/31/04
10/31/04
12/31/04
Date
SWL
Belt Creek at Armington Bridge

M 210402
T19N-R06E-36-ACAD
Alt=3580 ft, TD=27.5 ft
Aquifer= Swift



B25


M: 31952
T19N-R06E-3-CDBD
Alt=3700 ft, TD=12 ft
Aquifer= Till Deposit
Water-Level Elevation (Feet)
3696
3694
3692
3690
3688
3686
Precipitation (Inches)
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
Date
8/1/02
9/30/02
11/30/02
1/30/03
4/1/03
6/1/03
8/1/03
9/30/03
11/30/03
1/30/04
3/31/04
5/31/04
7/31/04
9/30/04
11/29/04
Dry
Daily Precipitation
SWL

Appendix C

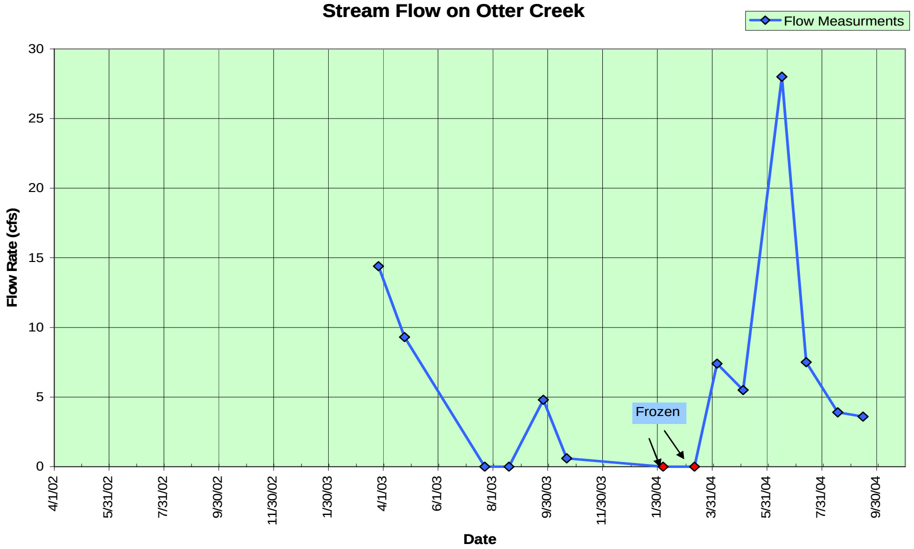
Surface and Spring Field Parameters and Flow Charts

C1

Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (cfs)	Flow Mesurment Method	Stream Conditions
214391	Otter Creek	Bridge Discharging into Belt Creek	T18N R07E 06 CCCB	47.346	-110.8957	3600	3/27/03	16.1	9.52	653	3.3	13	138.7	14.4	Staff and Wade	
							4/25/03	15.5	8.2	813	13.5		250	9.3	Staff and Wade	
							7/23/03							0		Dry
							8/19/03							0		Dry
							9/26/03	16.5						(4.8)	E	
							10/22/03	16.8	8.32	1053	13.8	13.1	239	0.6	Staff and Wade	
							2/6/04							0		Frozen
							3/12/04		7.1	634	7.02	11.27	272	0		Frozen
							4/6/04	16.6	8.15	848	14.55	13.56	283	7.4	Staff and Wade	
							5/5/04	15.6	8.16	947	14.41	12.12	123	5.5	Staff and Wade	
							6/17/04	14.8	8.37	663	12.57	10.14	224	28	Staff and Wade	
							7/14/04	16.6	8.21	892	19.23	9.26	144	7.5	Staff and Wade	
							8/18/04	16.7	7.98	1015	17.72	8.07	124	(3.9)	E	
							9/15/04	16.6	7.22	1021	11.46	12.4	107	(3.6)	E	

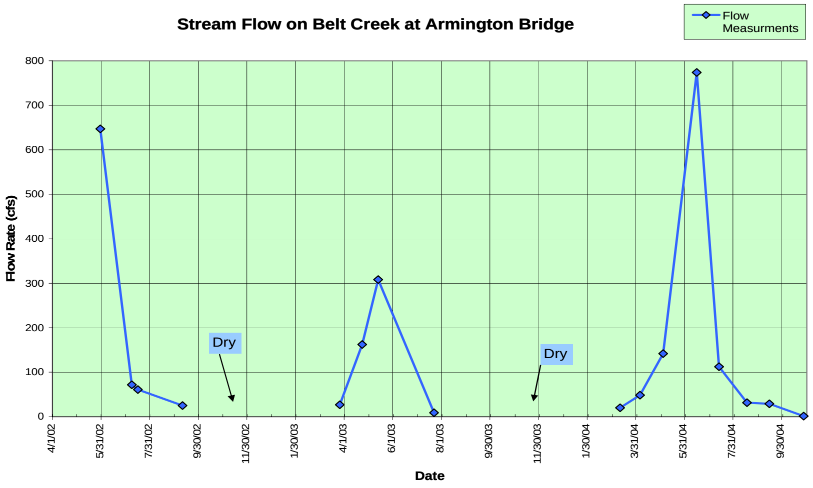
Flow measurements denoting E were calculated by using a Depth to Water method.

Stream Flow on Otter Creek



Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mgl)	ORP (mv)	Flow (cfs)	Flow Mesurment Method	Stream Conditions
214386	Belt Creek	Armington Bridge	T19N R06E 36 DBBB	47.3654	-110.9066	3560	5/31/02	12.32	8.04	153	12.3		130.8	647	Fish and Crane	
							7/9/02	15.6	8.57	250	16			(71.7)	E	
							7/17/02	16.1	8.38	270	24	96.2	72.5	60.7	Staff and Wade	
							9/11/02	16.89						(25.)	E	
							9/17/02									Dry
							9/23/02									Dry
							10/22/02									Dry
							11/27/02									Dry
							3/27/03	16.8						(26.8)	E	Water From Otter Cr
							4/24/03	14.65						(162.3)	E	
							5/14/03	14.9	8.06	216	14.3	11	219	308.1	Fish and Crane	
							7/23/03	16.6	8.3	not working	25			8.77	Staff and Wade	
							8/19/03									Dry
							9/26/03									Dry
							10/21/03									Dry
							11/25/03									Dry
							2/6/04									Dry
							3/12/04	16.5	7.17	623	8.43	22.5	271	19.9	Staff and Wade	
							4/6/04	16.25	8.48	336	14.21	10.94	234	48.3		
							5/5/04	14.8	8.33	153	10.69	12.56	133	(141.9)	E	To Fast To Wade
							6/16/04	13.7	8.67	172	9.64	11.15	141	773.9	Fish and Crane	
							7/14/04	15.9	6.01	259	21.8	8.65	162	112.1	Staff and Wade	
							8/18/04	16.6	8.37	323	17.57	7.74	253	(31.4)	E	
							9/15/04	16.7	6.7	370	11.85	11.05	101	(29.)	E	
							10/28/04	17.5	7.27	487	3.68	9.67	186	1.27	Staff and Wade	

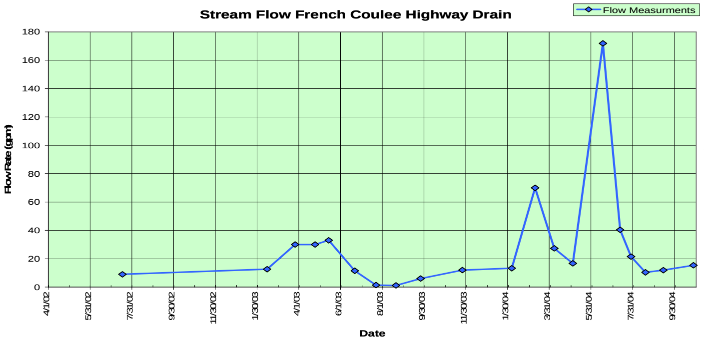
Flow measurements denoting E were calculated by using a Depth to Water method.



Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method	Nitrate	Flume size is .5 " H flume	Stream Conditions
200617	French Coulee Highway Drain	East side of Fill	T19N R06E 26 CDDA	47.3754	-110.9286	3560	7/18/02	6.26	8.41	540	15.2	9.45	22.4	9	Staff and Wade			
							2/14/03	6.3	7.8	570	2.3	12.27	109	12.6	Staff and Wade			
							3/27/03	6.3	8.45	507	4.6	13.1	199.9	30	Bucket Stop Watch			
							4/25/03		8.45	616	9.1		-15	30	Bucket Stop Watch			
							5/15/03		8.29	627	12	11.7	56.3	33	Bucket Stop Watch			
							6/22/03		8.26	745	11.9	11.14	101.3	11.5	Bucket Stop Watch			
							7/23/03		7.48	1548	15.1		22	1.40	Bucket Stop Watch			
							8/21/03		5.62	880	14.5	16.65	54	1.2	Bucket Stop Watch			
							9/26/03		7.3	971	10.93	11.16	143	6	Bucket Stop Watch			
							11/26/03		8.16	843	3.57	13.91	-113.9	12	Bucket Stop Watch			
							2/6/04		5.7	683	1.48	13.71	0.3	13.3	Bucket Stop Watch			
							3/11/04		8.18	601	5.46	19.7	65	70	Bucket Stop Watch			
							4/8/04		7.02	649	6.21	11.97	-39	27.3	Bucket Stop Watch			
							5/5/04		6.84	645	8.8	11.3	-92	16.7	Bucket Stop Watch			was .4 now .5 inch h flume
							6/18/04		6.26	667	8.95	10.3	137	171.9	Staff and Wade			Overflowing
							7/13/04		6.7	661	11.8	10.14	50	40.4	Staff and Wade	10		Overflowing
							7/29/04							21.5	Flume Guage		0.21	
							8/19/04		6.54	763	12.56	7.66	69	10.4	Flume Guage		0.15	
							9/14/04		6.82	712	10.6	10.16	8.2	11.93	Flume Guage		0.16	
							10/28/04							15.38	Flume Guage		0.18	

Flow measurements denoting E were calculated by using a Depth to Water method.

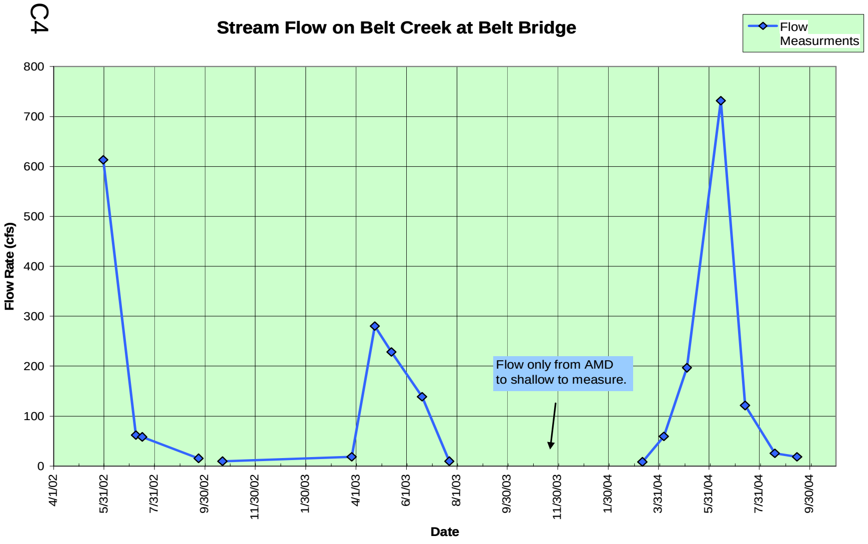
C3



Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (cfs)	Flow Mesurment Method	Stream Conditions
214387	Belt Creek	Belt Bridge	T19N R06E 26 ABBC	47.387	-110.9269	3510	5/31/02	18.57	8.04	144	13.2		170	613	Fish and Crane	
							7/9/02	19.77	8.24	270	14.2			(61.8)	E	
							7/17/02	20.1	8.14	300	24.4	7.96	60.1	58.3	Staff and Wade	
							9/23/02	20.6		615	11			(15.5)	E	
							10/7/02		7.21	768	15					
							10/22/02	20.9	6.4	979	4.6	12	181	(9.6)	E	Creek is to spread out to get proper flow.
							3/27/03	20.5						(18.3)	E	
							4/24/03	18.9	8.08	174	11.3		202	(280.4)	E	
							5/14/03	19.32	7.67	213	14.2	10.74	220	228.3	Fish and Crane	
							6/20/03	19.3	8.28	231	14.3	10.55	168.5	(138.7)	E	
							7/23/03	20.4	7.9		25		220	9.6	Staff and Wade	
							8/19/03									Creek is to spread out to get proper flow.
							9/23/03									Dry except for AMD Discharge
							10/21/03									Dry except for AMD Discharge
							11/25/03									Dry except for AMD Discharge
							3/12/04	20.5	6.28	587	4.52	13.24	148	8.5	Staff and Wade	
							4/7/04	20	7.4	348	6.47	13.4	18.6	59.4	Fish and Crane	
							5/5/04	19.1	7.76	163	11.08	11.22	185	(196.9)	E	Leaves keep stopping meter.
							6/15/04	18	8.33	176	8.09	10.4	168	731.7	Fish and Crane	
							7/14/04	19.8	7.41	278	21.87	8.32	244	121.2	Staff and Wade	
							8/19/04	20.3	8.05	439	18.88	7.64	196	(25.4)	E	
							9/15/04	20.5	7.95	572	11.57	8.93	-115	(18.5)	E	

Flow measurements denoting E were calculated by using a Depth to Water method.

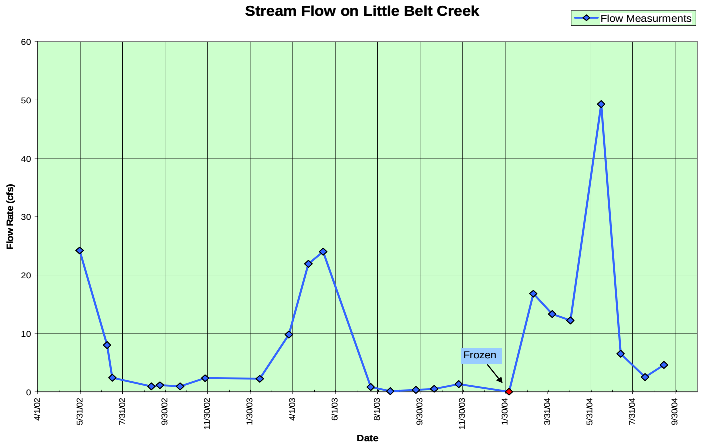
C4



C5

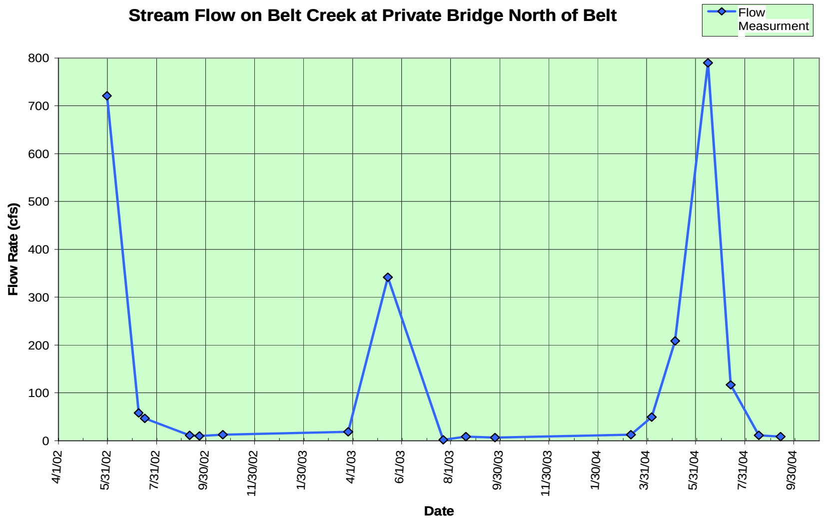
Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (cfs)	Flow Mesurment Method	Stream Conditions
214392	Little Belt Creek	First Bridge	T19N R06E 1 CDDD	47.433	-110.9065	3450	5/31/02	11.75	8.36	247	20	214.8		24.2	Staff and Wade	
							7/9/02	11.92	8.77	330	15.7			(8.)	E	
							7/17/02	12.13	9.13	370	26	34.7	7.92	2.4	Staff and Wade	
							9/11/02	12.26						(.9)	E	
							9/23/02	12.23		401	11			(1.1)	E	
							10/22/02	12.26						(.9)		
							11/27/02	12.1	8.12	377	5.8	257.1	12.23	2.3	Staff and Wade	
							2/13/03	12.12						(2.2)	E	
							3/27/03	11.9	8.5	265	3.3	211.8	14.14	9.8	Staff and Wade	
							4/24/03	11.8	8.01	268	16.5	300		21.9	Staff and Wade	
							5/15/03	11.75						(24.)	E	
							7/22/03	12.4	8.66	380	25	25		0.8	Staff and Wade	
							8/19/03	12.37	8.4	380	27	180	157	0.1	Staff and Wade	
							9/25/03	12.45						(.3)	E	
							10/21/03	12.27	8.53	384	14.65	129.8	10.93	0.5	Staff and Wade	
							11/25/03	12.2	6.9	355	2.15	210	14.9	(1.3)	E	
							2/5/04							0		Frozen
							3/11/04	11.85	8.4	349	7.82	144	14	16.8	Staff and Wade	
							4/7/04	11.9	8.42	281	7.29	186	15.35	13.3	Staff and Wade	
							5/3/04	12	7.13	296	12.2	170	10.8	12.2	Staff and Wade	
							6/16/04	11.5	8.28	253	14.86	159.5	9.15	49.3	Staff and Wade	
							7/14/04	11.9	8.06	247	24.7	220	8.37	6.5	Staff and Wade	
							8/18/04	12.1	8.66	370	18.57	196	8.49	(2.5)	E	
							9/14/04	12	8.77	365	14.45	11.07	7.5	(4.6)	E	

Flow measurements denoting E were calculated by using a Depth to Water method.



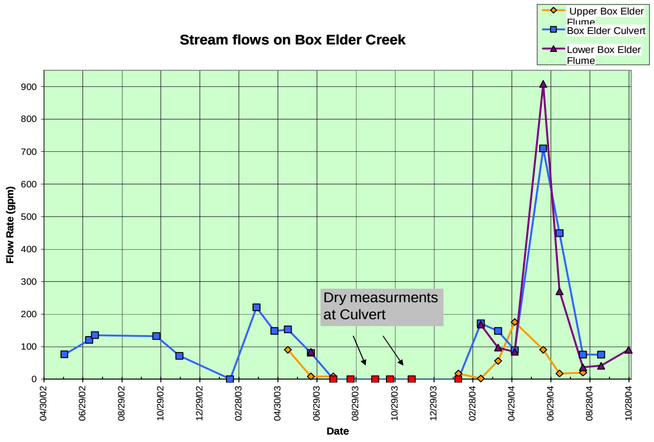
Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (cfs)	Flow Mesurment Method	Stream Conditions
214389	Belt Creek	Private Bridge	T19N R06E 2 ACAD	47.4414	-110.9225	3440	5/31/02	12.32	8.04	153	12.3		130.8	721	Fish and Crane	
							7/9/02	13.69	8.44	290	15.9			(58.1)	E	
							7/17/02	14.14	8.51	350	25.7	8.17	73.6	47	Staff and Wade	
							9/11/02	14.8						(11.3)	E	
							9/23/02	14.91		484	14.4			(9.7)	E	
							10/22/02	14.72						(12.7)	E	
							3/27/03	14.45						(18.7)	E	
							5/15/03	12.8	8.21	214	11	11.24	247.9	341.6	Fish and Crane	
							7/23/03	14.8	8.34	430	22.7		220	2.1	Staff and Wade	
							8/20/03	15						(8.5)	E	
							9/25/03	15.2						(6.5)	E	
							3/12/04	14.7	7.86	354	4.19	14.19	134	12.9	Staff and Wade	
							4/7/04	14.2	8.38	367	9.76	13	237	49.4	Staff and Wade	
							5/6/04	12.7						(208.9)	E	
							6/16/04	11.6	8.42	188	11.15	10.47	150	789.9	Fish and Crane	
							7/14/04	13.8	8.51	264	23.2	8.6	184	116.7	Staff and Wade	
							8/18/04	14.8						(11.3)	E	
							9/14/04	15	8.22	442	15.38	9	162	(8.5)	E	

Flow measurements denoting E were calculated by using a Depth to Water method.



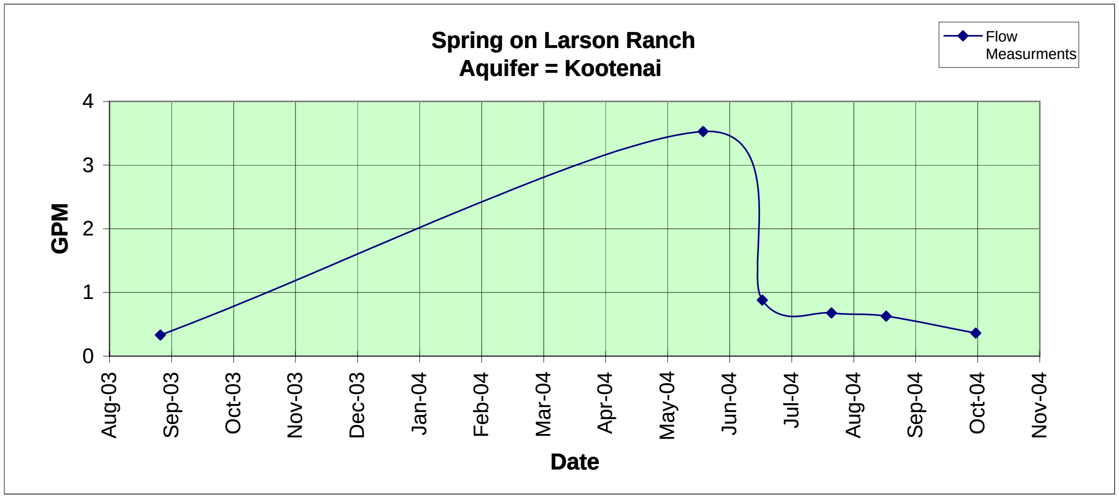
Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method	Other conditions	Nitrate	Upper Flume 6-inch Parshall Flumes	Upper Flume Flow (gpm)	Lower Flume 6-inch Parshall Flume	Lower Flume Flow (gpm)
214393	Box Elder Creek	Road Culvert	T19N R06E 29 DCBB	47.371	-110.9875	3790	5/31/02	7	7.02	657	20.5		-71	76.33	Staff and Wade						
							7/9/02	6.9	8.27	750	8.27			(120.1)	E						
							7/18/02	6.85						(135.2)	E	Not enough flow to measure.					
							10/22/02	6.86	7.02	720	1.5	13.38	222	(132.)	E	Not enough flow to measure.					
							11/27/02	6.81	8.05	650	0.08	14.33	276	71.84	Staff and Wade						
							2/14/03							0	E	Frozen					
							3/27/03	6.85	8.54	586	2.9	16.14	188	221	Staff and Wade						
							4/24/03	6.8	7.18	694	16		268	148.2	Staff and Wade						
							5/15/03	6.75	8.29	693	18.2	10.08	205	152.7	Staff and Wade						
							6/20/03	6.8	7.51	632	16.6	7.98	135	80.8	Staff and Wade			0.23	90.51	0.22	84.37
							7/25/03							0		Dry		0.05	8.12	0	
							8/21/03							0		Dry		0.05	8.12	0	
							9/29/03							0		Dry		0		0	
							10/21/03							0		Dry		0		0	
							11/25/03							0		Dry		0		0	
							2/5/04							0		Frozen		0		0	
							3/11/04	6.75	8.09	600	7.35	18.97	108	(171.5)	E			0.08	17.06	0.34	167.83
							4/7/04	6.8	8.21	685	14.67	7.6	255	148.2	Staff and Wade			0.02	1.91	0.24	96.8
							5/3/04	7.1	8.54	658	17.76	8.02	214	89.8	Staff and Wade			0.17	56.14	0.22	84.37
							6/16/04	6.2	8.25	706	14.79	9.26	155	709.4			10	0.35	175.7	1.11	908
							7/12/04	6.8	8.3	678	19.64	6.71	190	449	Staff and Wade			0.23	90.51	0.46	270.58
							8/18/04	7.1	7.84	698	16.06	7.03	250	(75.6)	E	Water is flowing under culvert.		0.08	17.06	0.13	36.74
							9/15/04	7.1						(75.2)	E			0.095	20.55	0.14	41.31
							10/28/04											0.13	36.74	0.23	90.51

Flow measurements denoting E were calculated by using a Depth to Water method.

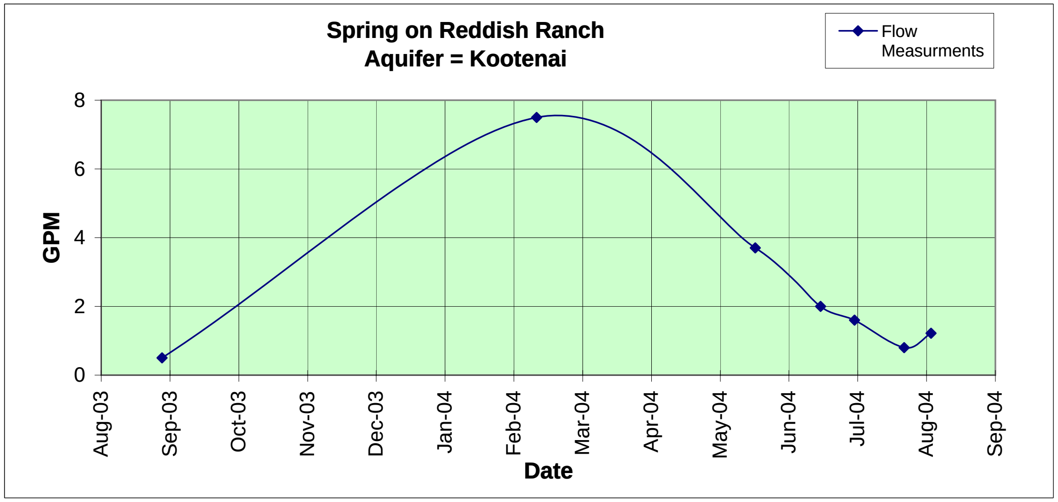


Mnumber	Spring	Station	Location (TRSt)	Latitude	Longitude	Aquifer	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method	Nitrate	Spring Conditions
214397	Larson Spring	Overflow Pipe	T19N R06E 34 ACDB	47.3658	-110.9463	217SNRS	3880	9/24/03	7.46	526	11.31	8.57	234	0.33	Bucket Stop Watch		
								6/17/04	5.3	583	8.73	7.1	281	3.53	Bucket Stop Watch	20	Overflow running everywhere
								7/16/04	6.02	512	10.22	6.56	255	0.88	Bucket Stop Watch	10 to 20	
								8/19/04	7.9	514	10.73	7.47	261	0.68	Bucket Stop Watch		
								9/15/04						0.63	Bucket Stop Watch		
								10/29/04						0.36	Bucket Stop Watch		

C8



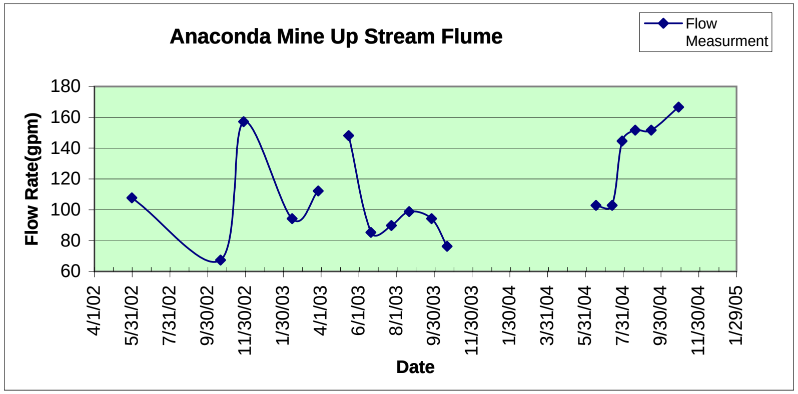
Mnumber	Stream	Station	Location (TRSt)	Latitude	Longitude	Aquifer	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method	Nitrate	Stream Conditions
214395	Reddish Spring	Lower	18N R06E 14 CABA	47.3196	-110.9298	217CBNK	3940	9/26/03	7.85	500	12.93	8.65	230	0.5	Bucket Stop Watch		
								3/10/04	6.18	396	6.2	14.65	302.1	7.5	Bucket Stop Watch		
								6/15/04	6.79	440	10.11	9.29	305	3.7	Bucket Stop Watch		
								7/14/04						2	Bucket Stop Watch		
								7/29/04						1.6	Bucket Stop Watch		
								8/20/04						0.8	Bucket Stop Watch	2	
								9/1/04						1.22	Bucket Stop Watch		



Appendix D

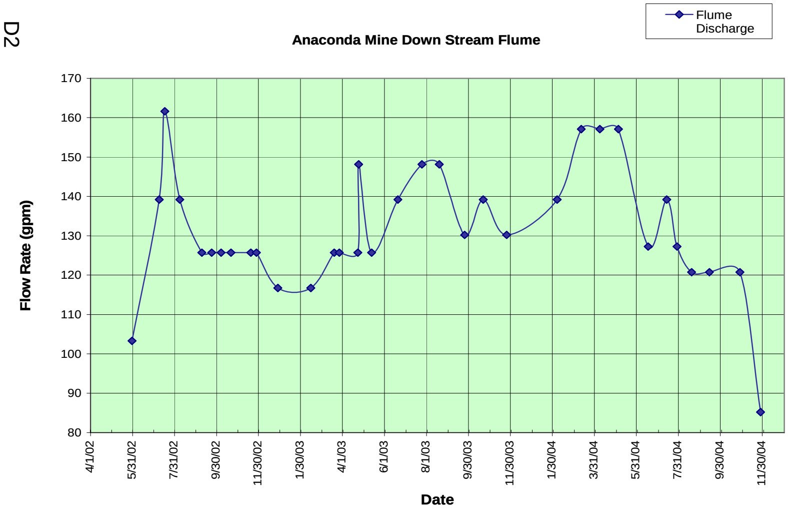
AMD Hydrographs & Field Measurements

Mnumber	AMD	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	Depth to Water (feet)	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	was .5 now .75 H flume	Flow Mesurment Method	Other Conditions
200616	Anaconda Mine Drain At Culvert	AMD Up Stream Flume	T19N R06E 26 CAAA	47.381	-110.9292	3540	5/31/02	0.9	2.55	2000	11.5			107.76		Staff and Wade	
							10/21/02	0.86	2.76	2440	11	2.39	406	67.35		Staff and Wade	
							11/27/02	0.9	2.65	2260	10	1.6	407	157.15		Staff and Wade	
							2/13/03	0.82	2.87	2400	10.4	1.91	415	94.29		Staff and Wade	
							3/27/03	0.8	2.63	2220	10.3	1.6	409	112.25		Staff and Wade	
							4/24/03		2.97	2119	10.5		415			Staff and Wade	
							5/15/03	0.82	2.95	2260	10.9	1.7	415	148.17		Staff and Wade	
							6/20/03	0.9	3.24	2360	10.5	1.87	411	85.31		Staff and Wade	
							7/23/03	0.86	2.7		10.02		413	89.8		Staff and Wade	
							8/21/03	0.9	2.7	2070	10.9	2.09	408	98.78		Staff and Wade	
							9/26/03	0.9	2.85	2485	10	1.79	438.2	94.29		Staff and Wade	
							10/21/03	0.87	3.01	2471	9.99	1.75	432	76.33		Staff and Wade	
							11/25/03	0.85	2.86	2436	9.85	1	440				Did not measure
							2/6/04	0.81	2.95	2348	9.91	3.3	439				Did not measure
							3/12/04		2.6	2407	9.78	0.94	438				Did not measure
							4/8/04		2.79	2364	9.81	0.99	443				Did not measure
							5/5/04		2.86	2442	9.86	1.07	434				Did not measure
							6/17/04		2.91	2343	9.74	0.9	432	102.86	0.42	Flume	
							7/13/04		2.73	2369	9.85	1	433	102.86	0.42	Flume	
							7/29/04		2.98	2378	9.88	1.08	428	144.6	0.47	Flume	
							8/19/04		2.74	2413	9.94	2.49	426	151.7	0.48	Flume	
							9/14/04		2.98	2455	9.97	1.73	440	151.7	0.48	Flume	
							10/28/04		2.83	2470	9.94	1.44	415	166.6	0.5	Flume	Sampled



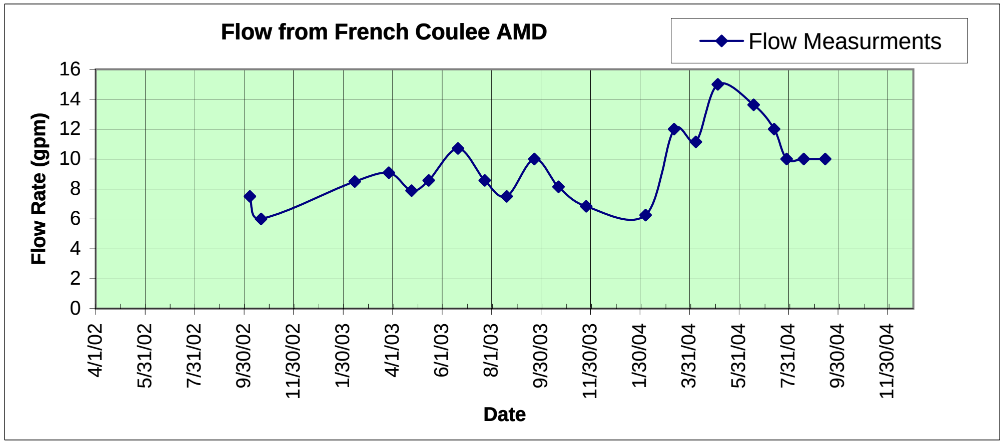
Mnumber	AMD	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Staff Guage Readings	Flow Mesurment Method	Other Conditions
217523	Anaconda Mine Drain at Down Stream Flume	AMD Down Stream Flume	T19N R06E 26 BDDD	47.3823	-110.9281	3530	5/31/02	2.58	2000	18.7		452	103.27		Staff and Wade	
							7/9/02	2.61	2680	14.7			139.19	0.42	Guage	
							7/17/02	2.55	2000	15.9	10.62	472	161.64	0.45	Guage	
							8/8/02						139.19	0.42	Guage	
							9/9/02						125.72	0.4	Guage	
							9/23/02		2340	16.7			125.72	0.4	Guage	
							10/7/02	2.64	1655	12.8			125.72	0.4	Guage	
							10/21/02	2.71	2430	12.2	2.5	442	125.72	0.4	Guage	
							11/19/02						125.72	0.4	Guage	
							11/27/02	2.73	2270	9.4	9.57	444	125.72	0.4	Guage	
							12/28/02						116.74	0.38	Guage	
							2/14/03						116.74	0.38	Guage	culver is plugged, not all water is flowing to flume
							3/20/03						125.72	0.4	Guage	
							3/27/03						125.72	0.4	Guage	
							4/23/03						125.72	0.4	Guage	
							4/24/03						148.17	0.43	Guage	Just rained hard
							5/13/03	2.98	2060	17.9	9.79	452	125.72	0.4	Guage	
							6/20/03	3.04	2290	13	9.48	441	139.19	0.42	Guage	
							7/25/03						148.17	0.43	Guage	
							8/19/03						148.17	0.43	Guage	AM Install of data logger
							9/25/03						130.21	0.41	Guage	
							10/22/03	3.02	2365	11.92	10.48	470	139.19	0.42	Guage	
							11/25/03	2.85	2382	6.04	10.94	466	130.21	0.41	Guage	logger frozen
							2/6/04	2.94	2391	10.73	10.24	464	139.19	0.42	Guage	
							3/12/04	2.77	2347	11.31	10.41	464	157.09	0.44	Guage	
							4/8/04	2.83	2294	11.08	11.17	468	157.09	0.44	Guage	
							5/5/04	2.91	2389	11.78	10.74	453	157.09	0.44	Guage	
							6/17/04	2.84	2288	13.28	9.6	458	127.28	0.4	Guage	
							7/14/04	2.85	2285	17.45	10.65	452	139.19	0.42	Guage	
							7/29/04						127.28	0.4	Guage	
							8/19/04	2.76	2331	19.23	6.46	464	120.75	0.39	Guage	Rocks jammed staff was 0.53
							9/14/04	3.28	2467	12.74	10.31	465	120.75	0.4	Guage	
							10/28/04	2.89	2312	11.71	8.65	458	120.75	0.4	Guage	
							11/27/04						85.21	0.36	Guage	

D2



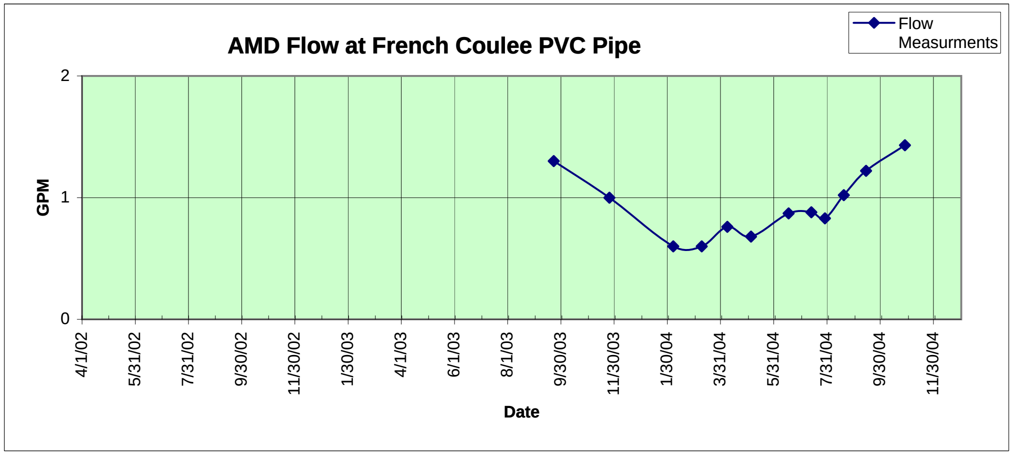
Mnumber	AMD	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method
200615	French Coulee Discharge	Below Pond East side of RR tracks	T19N R16E 26 CADD	47.3782	-110.9278	3550	10/7/02	2.39	4400	12.8				Bucket Stop Watch
							10/21/02	2.53	4180	10.5	3.93	442	7.5	Bucket Stop Watch
							2/13/03	2.43	4400	7.2	3.5	426	6	Bucket Stop Watch
							3/27/03	2.67	4320	7.9	4.2	426	8.5	Bucket Stop Watch
							4/24/03	3.12	3520	10.5		415	9.09	Bucket Stop Watch
							5/15/03	2.68	4150	11.3	4.99	443	7.89	Bucket Stop Watch
							6/20/03	2.69	3160	12.1	4.54	438	8.57	Bucket Stop Watch
							7/23/03	2.64		14		444	10.71	Bucket Stop Watch
							8/19/03	2.91	4600	15.2		442	8.57	Bucket Stop Watch
							9/22/03	2.58	5764	12.31	4.7	457.4	7.5	Bucket Stop Watch
							10/22/03	2.76	4197	10.59	3.46	455	10	Bucket Stop Watch
							11/25/03	2.43	5875	7.28	4.52	472	8.14	Bucket Stop Watch
							2/6/04	2.68	6000	6.77	4.84	440	6.84	Bucket Stop Watch
							3/12/04	2.6	5365	7.42	3.52	445	6.25	Bucket Stop Watch
							4/8/04	2.57	4148	9.12	3.91	469	12	Bucket Stop Watch
							5/5/04	2.7	4813	9.78	4.12	465	11.15	Bucket Stop Watch
							6/18/04	2.59	3645	10.71	3.94	480	15	Bucket Stop Watch
							7/13/04	2.54	5071	12.09	2.61	451	13.63	Bucket Stop Watch
							7/29/04	2.96	5138	12.69	2.4	444	12	Bucket Stop Watch
							8/19/04	2.6	5818	13.09	1.99	441	10	Bucket Stop Watch
							9/14/04	2.67	5898	11.98	2.67	461	10	Bucket Stop Watch
							10/28/04	3.21	5935	9.69	3.06	434	10	Bucket Stop Watch

D3



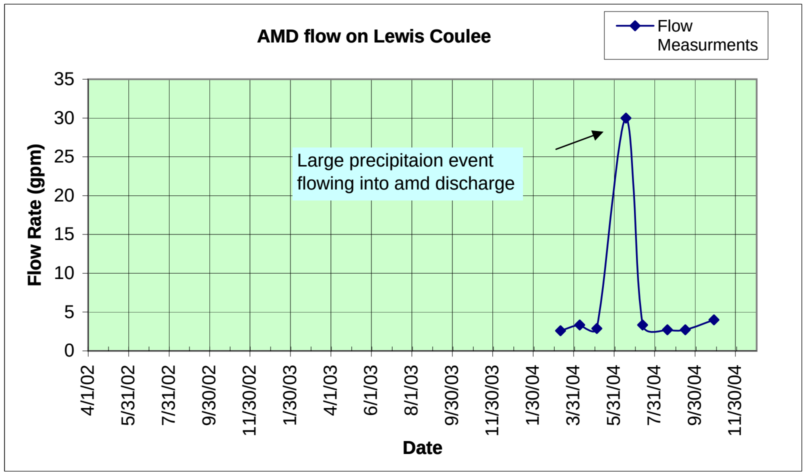
D4

Mnumber	AMD	Station	Location (TRSt)	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Flow Mesurment Method	Other Conditions	Nitrate	Nitrite
217524	French Coulee Discharge	French coulee 4" pvc pipe AMD	T19N R16E 26 CADC	3560	9/22/03	2.11	7322	12.05	7.31	507.8	1.3	Bucket Stop Watch			
					11/25/03	2.28	7438	8.47	7	494	1	Bucket Stop Watch			
					2/6/04	1.88	7397	7.51	9.2	509	0.6	Bucket Stop Watch			
					3/10/04	2.12	7215	8.3	8.85	499	0.6	Bucket Stop Watch			
					4/8/04	2.4	7203	9.45	8.5	491	0.76	Bucket Stop Watch			
					5/5/04	2.32	7216	10.22	7.73	486	0.68	Bucket Stop Watch			
					6/17/04	2.59	6941	10.81	9.5	479	0.87	Bucket Stop Watch		2	1.5 to 3.0
					7/13/04	2.41	6888	11.93	6.3	475	0.88	Bucket Stop Watch		1.5-3.0	
					7/29/04	2.43	6838	12.54	6.56	475	0.83	Bucket Stop Watch			
					8/19/04	2.24	7087	12.18	5.59	473	1.02	Bucket Stop Watch			
					9/14/04	2.61	7085	11.39	7.22	477	1.22	Bucket Stop Watch			
					10/28/04	2.2	7066	10.22	8.79	463	1.43	Bucket Stop Watch			



Mnumber	AMD	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Nitrate	Flow Mesurment Method	Other Conditions
214915	Lewis Coulee	Lewis Coulee at first AMD flow	T19N R06E 26 AACD	47.386	-110.9193	3540	3/11/04	3.6	3806	9.54	9.06	334	2.6		Bucket Stop Watch	
							4/9/04	3.54	3735	12.5	6.08	304	3.33		Bucket Stop Watch	
							5/5/04	3.8	3575	9.85	5.2	284	2.89		Bucket Stop Watch	
							6/18/04	7.03	1132	9.41	10.09	-46	30	5	Bucket Stop Watch	30 gpm runnoff water feeding into mine
							7/13/04	3.62	3201	14.47	4.9	325	3.33		Bucket Stop Watch	
							8/19/04	3.05	3741	17.44	5.25	396	2.72		Bucket Stop Watch	
							9/15/04	3.85	3423	11.62	7.64	380	2.72		Bucket Stop Watch	
							10/28/04	3.78	3791	9.25	5.22	367	4		Bucket Stop Watch	Sampled

D5



Mnumber	AMD	Station	Location (TRSt)	Latitude	Longitude	Elevation (feet)	Date	pH	Conductivity (umhos/cm)	Temp (C°)	DO (mg/l)	ORP (mv)	Flow (gpm)	Other Conditions
214914	AMD at Lewis Coulee above Castner Park	AMD at 3rd and Lewis street in Belt	T19N R06E 26 ACAA	47.3848	-110.9223	3520	10/28/04	2.77	5319	9.04	2.67	427.7	2 estimate	sampled

Appendix E

Water-Quality Data

	Gwic Id	Site Name	Water Source	Latitude	Longitude	Geomethod	Datum	Location (TRS)	County	State	Site Type	Depth (ft)	Agency	Sample Date	Water Temp	Field pH	Lab pH	Field SC	Lab SC	CDS (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Fe (mg/l)	Mn (mg/l)	SiO2 (mg/l)	HCO3 (mg/l)	CO3 (mg/l)	SO4 (mg/l)
2005Q0283	214915	AMD AT LEWIS COULEE	AMD	47.386	-110.92	NAV-GPS	NAD83	19N06E26AACD	CASCADE	MT	MINE DRAINAGE		MBMG	10/28/2004 16:00	9.25	3.78	3.01	3,791.00	4300	6,728	226	152	27.6	0.523	672	1.07	105	0	0	5100
2005Q0287	214914	AMD 3RD AND LEWIS STREET IN BELT	AMD	47.3848	-110.922	UNKNOWN	NAD83	19N06E26ACAA	CASCADE	MT	MINE DRAINAGE		MBMG	10/28/2004 17:30	9.04	2.77	3.1	5319	3660	4873	203	147	25.1	6.97	558	1.23	69.9	0	0	3618
2003Q0848	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	1/30/2003 11:30	9.8	2.99	3.01	2290	2285	2471	148	68.6	10.3	3.24	166	0.403	52.6	0	0	1920
2003Q0866	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	3/15/2003 11:15	10.7	3.01	2.97	2220	2279	2521	164	70.4	10.5	3.3	173	0.5	52.5	0	0	1934
2003Q1018	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	4/22/2003 15:45	7.5	2.89	2.95	2260	2265	2430	153	69.7	10.9	2.83	150	0.363	49.9	0	0	1900
2003Q1079	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	5/28/2003 18:30	11.3	2.84	3.03	2350	2120	2043	140	67.5	10.8	2.8	143	0.375	52.5	0	0	1523
2003Q1163	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	6/18/2003 11:50	9.9	2.51	2.88	1425	2080	2184	156	72.5	10.7	2.92	168	0.426	53.2	0	0	1606
2004Q0029	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	7/17/2003 17:45			2.79		2090	2180	162	73.3	10.5	2.98	155	0.426	53	0	0	1610
2004Q0103	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	8/19/2003 16:30	9.9	2.58	2.8	2355	2290	2434	150	72	10.5	3.15	169	0.435	53.8	0	0	1851
2004Q0147	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	9/18/2003 18:45	9.94	2.7	2.93	2390	2350	2496	155	69.3	10.2	3.16	174	0.412	57.3	0	0	1905
2004Q0241	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	10/23/2003 16:20	9.91	2.99	3.01	2300	2290	2620	168	71.2	9.9	3.14	173	0.411	58.5	0	0	2025
2004Q0470	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	4/24/2004 15:20	9.8	2.8	3.19	2275	2280	2475	163	73.5	11	2.93	120	0.406	54.9	0	0	1916
2004Q0574	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	6/24/2004 16:50	11.91	2.75	3.34	2120	2230	2003	154	72.3	10.5	2.85	83.1	0.406	56.3	0	0	1510
2005Q0075	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	8/12/2004 14:30	9.9	2.68	2.8	2465	2280	2094	163	72.3	11	3.28	103	0.428	58.5	0	0	1580
2005Q0288	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	10/28/2004 11:30	9.94	2.83	3.09	2470	2390	2264	177	72.9	10.8	3.21	171	0.433	59.1	0	0	1663
2005Q0358	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	2/3/2005 16:25			3.13		2340	2514	167	72.6	10.8	3.08	174	0.44	56.9	0	0	1921
2005Q0419	200616	ANACONDA MINE DRAIN AT CULVERT	AMD	47.3788	-110.931	TRS-TWN	NAD27	19N06E26BDCD	CASCADE	MT	MINE DRAINAGE		MBMG	4/8/2005 12:45			3.16		2220	2456	150	68.3	10.1	2.88	156	0.395	54	0	0	2099
2003Q0846	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	1/29/2003 14:00	7	2.7	2.75	5620	5625	10057	271	117	11.7	5.4	1050	0.963	101	0	0	7990
2003Q0865	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	3/15/2003 10:45	7.2	2.68	2.71	5030	5150	8960	284	122	12.2	5.37	989	0.988	97.6	0	0	6975
2003Q1020	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	4/22/2003 14:55	9.7	2.68	2.7	4660	4800	7877	246	111	13.5	4.2	808	0.703	90	0	0	6198
2003Q1081	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	5/28/2003 18:00	12.2	2.62	2.78	4410	3960	5814	208	103	17.6	3.38	665	0.531	85.2	0	0	4400
2003Q1164	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	6/18/2003			2.66		4030	6824	241	114	16.6	3.34	761	0.65	89.8	0	0	5226
2004Q0031	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	7/17/2003 17:10			2.4		4400	7523	275	126	14.4	2.82	821	0.833	103	0	0	5750
2004Q0095	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	8/19/2003 16:00	14.3	2.36	2.54	5180	4810	8770	277	122	13.8	4.15	843	0.888	106	0	0	6891
2004Q0149	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	9/18/2003 19:05	11.3	2.41	2.76	5690	5080	9072	279	126	13.2	<5.0	929	0.902	105.4	0	0	7133
2004Q0235	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	10/23/2003 15:50	10.3	2.73	2.71	5800	5600	10491	293	127	10.8	3.65	1185	1.03	109	0	0	8152
2004Q0472	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	4/24/2004 15:45	10.2	2.57	2.95	4080	4070	6190	198	108	19.3	3.28	673	0.528	83.2	0	0	4799
2004Q0572	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	6/24/2004 16:00	12.23	1.75	3.14	4090	5510	9697	436	177	12.9	<0.50	950	1.52	160	0	0	7350
2005Q0077	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	8/12/2004 15:15	12.2	3.99	4.1	6230	5180	8373	262	129	14.7	3.75	1078	0.959	108	0	0	6244
2005Q0356	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	2/3/2005 16:45			2.9		5760	10198	292	138	12.5	4.47	1169	1.08	117	0	0	7878
2005Q0417	200615	FRENCH COULEE MINE	AMD	47.3722	-110.93	TRS-TWN	NAD27	19N06E26CDDB	CASCADE	MT	MINE DRAINAGE		MBMG	4/8/2005 15:15			2.84		5400	10082	270	135	12.6	5.59	1227	1.02	105	0	0	8694
2005Q0081	213598	PLEASANT VALLEY SPRING * OLD HARRI	217SBRS	47.4131	-110.972	NAV-GPS	NAD27	19N06E16	CASCADE	MT	SPRING		MBMG	8/12/2004 18:40	12.8	9.71	8.36	650	668	311	48.1	49.6	8.37	1.56	0.008	<0.001	8.09	285.48	0.867	20
2005Q0352	213598	PLEASANT VALLEY SPRING * OLD HARRI	217SBRS	47.4131	-110.972	NAV-GPS	NAD27	19N06E16	CASCADE	MT	SPRING		MBMG	2/4/2005 13:10			8.36		637	301	44.3	49.6	9.34	1.94	0.011	0.002	7.62	309.6	6	26.3
2004Q0025	204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN	217SBRS	47.3757	-110.927	NAV-GPS	NAD27	19N06E26	CASCADE	MT	OTHER		MBMG	7/17/2003 14:15			7.05		3340	3236	445	364	41.7	11	0.889	0.035	10.9	334.3	0	2116
2004Q0090	204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN	217SBRS	47.3757	-110.927	NAV-GPS	NAD27	19N06E26	CASCADE	MT	OTHER		MBMG	8/19/2003 18:10			7.62		3350	3271	428	352	43.9	11.5	0.534	0.033	10.7	494.1	0	2105
2004Q0153	204710	SEEP ON LEFT SIDE OF HIGHWAY DRAIN	217SBRS	47.3757	-110.927	NAV-GPS	NAD27	19N06E26	CASCADE	MT	OTHER		MBMG	9/19/2003 10:30	10.4	7.4	7.68	3510	3520	3258	443	354	43.2	11.2	0.44	0.042	10	407.5	0	2105
2003Q0850	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	1/30/2003 14:10	3.5	7.79	7.93	610	659	376	65.3	39.8	9.65	1.72	0.384	0.068	9	344.7	0	72.7
2003Q0863	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	3/15/2003 13:15	4.1	7.88	7.88	440	494	276	53.8	29	7.17	2.74	0.646	0.042	8.6	258.9	0	39.5
2003Q1024	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	4/22/2003 14:00	8.6	7.78	7.82	605	607	349	61.7	37.1	9.1	1.76	0.156	0.066	8.21	322.5	0	64.9
2003Q1083	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	5/28/2003 17:25	13.6	8.13	7.71	740	784	431	74.1	46.4	11	2.39	0.047	0.083	9.56	356.2	0	105
2003Q1165	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	6/17/2003 17:45	15.1	7.78	7.78	460	699	459	78.8	53.2	11	2.96	0.039	0.093	10.6	379.4	0	108.4
2004Q0027	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	7/17/2003 14:50			7.8		1412	967	152	103	16.5	4.59	0.698	0.147	13.3	411.5	0	457
2004Q0099	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	8/19/2003 17:45	10.6	7.66	7.69	790	1508	12634	181	134	20.1	5.82	2.12	0.196	12.4	351.4	0	706
2004Q0151	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	9/19/2003 10:05	9.34	7.74	8.13	860	1022	586	92.5	64.8	13.6	2.32	0.035	0.108	12.4	393.3	0	198
2004Q0474	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	4/24/2004 18:00	8.3	8.16	8.05	620	618	417	72	51	12	2.33	0.026	0.067	9.8	348.6	0	91.1
2004Q0570	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	6/24/2004 15:00	12.18	7.3	8.2	586	619	387	76.1	46.2	7.87	2.58	0.024	0.034	10.7	317.2	0	68.1
2005Q0079	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	8/12/2004 16:00	12	9.7	7.78	765	916	439	84.6	50	9.38	2.36	0.007	0.041	12.8	351.36	0	86
2005Q0354	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	2/4/2005 9:55			8.06		653	402	76.1	44.2	9.25	2.16	2.59	0.066	12.1	338.3	0	81.2
2005Q0415	200617	FRENCH COULEE * HIGHWAY DRAIN	217SBRS	47.3722	-110.929	TRS-TWN	NAD27	19N06E26CDDA	CASCADE	MT	OTHER		MBMG	4/8/2005 15:40			8.27		639	361	65.9	41.1	8.86	1.8	0.178	0.027	8.98	341.9	0	59.2
2004Q0101	205653	JOHN HARRIS RANCH * SPRING	217SBRS	47.3663	-110.997	NAV-GPS	NAD27	19N06E29	CASCADE	MT	SPRING		MBMG	8/19/2003 14:10	1	7.02	7.54	560	576	315	56.7	40.4	7.96	2.31	0.019	<0.001	8.35	314.8	0	36.2
2004Q0157	207767	HARRIS JOHN * POND	217SBRS	47.37	-110.992	NAV-GPS	NAD27	19N06E29	CASCADE	MT	POND		MBMG	9/19/2003 12:15	9.9	7.34	7.97	500	523	294	51.9	38.5	7.66	2.36	0.056	0.01	11.7	278.5	0	39
2004Q0233	205653	JOHN HARRIS RANCH * SPRING	217SBRS	47.3663	-110.997	NAV-GPS	NAD27	19N06E29	CASCADE	MT	SPRING		MBMG	10/23/2003 13:50	9.5	7.4	7.74	560	607	318	59.4	42.7	6.4	1.56	0.021	0.001	7.6	316.5	0	37.1
2004Q0159	204516	JIM LARSON	217SBRS	47.3651	-110.948	NAV-GPS	NAD27	19N06E34ACDC	CASCADE	MT	SPRING	19.6	MBMG	9/24/2003 15:00	11.31	7.46	7.8	526	506	248	57.5	25.3	4.69	0.84	0.011	<0.001	10.7	270.1	0	14.7
2004Q0110	205836	BELT CREEK	BELT CREEK	47.3636	-110.906	NAV-GPS	NAD27	18N06E12ABDA	CASCADE	MT	STREAM		MBMG	8/27/2003 10:50	17.9	7.79	7.83	297	428	213	51.8	14.6	4.4	1.61	0.027	0.095	7.07	157.4	0	54.7
2004Q0114	205839	BELT CREEK	BELT CREEK	47.3808	-110.925	NAV-GPS	NAD27	18N06E26DBBA	CASCADE	MT	STREAM		MBMG	8/27/2003 15:15	19.2	7.48	7.82	372	403	248	60.5	15.1	4.97	1.67	0.028	0.006	9.52	212.6	0	49.9
2004Q0112	205838	BELT CREEK	BELT CREEK	47.3753	-110.918	NAV-GPS	NAD27	18N06E26DDDA	CASCADE	MT	STREAM		MBMG	8/27/2003	18.4	7.22	7.67	371	415	242	56.3	15	5.27	1.85	0.04	0.003	8.39	217.9	0	46.5
2004Q0091	205508	BELT CREEK * E OF TOWN WELL #2	BELT CRK @CITY WELL	47.3812	-110.926	NAV-GPS	NAD27	19N06E26	CASCADE	MT	STREAM		MBMG	8/20/2003 12:30	20.9	7.48	7.83	460	552	281	69.1	17.1	5.15	1.79	0.036	0.005	9.27	227.2	0	64.8
2005Q0285	214916	BELT CREEK AFTER LEWIS AMD DRAIN	BELT CRK @LEWIS	47.3884	-110.924	NAV-GPS	NAD83	19N06E26ABAB	CASCADE	MT	STREAM		MBMG	10/29/2004 13:45	8.47	7.23	7.28	665	674	415	97	27.2	6.77	2.45	1.93	0.075	9.49	134.8	0	201
2005Q0284	214911	BELT CREEK AL ABOVE SWIM HOLE	BELT CRK @SWIM	47.382	-110.928	NAV-GPS	NAD83	19N06E26ACCC	CASCADE	MT	STREAM		MBMG	10/28/2004 14:00	10.38	6.64	5.83	637	737	506	90.4	35.8	6.04	1.78	0.169	0.375	8.35	32.9	0	344
2005Q0282	214913	BELT CREEK AT NORTH SLAG EXTENT	BELT CRK @NSLAG	47.3843	-110.929	NAV-GPS	NAD83	19N06E26BDAC	CASCADE	MT	STREAM		MBMG	10/28/2004 16:00	11.29	6.55	7.31	645	639	413	92.5	25.8	6.47	1.88	6.01	0.074	11.9	148.7	0	193
2003Q1087	203451	LOWER BOX ELDER CREEK * BELOW J H	LOWER BOXELDER	47.3779	-110.986	NAV-GPS	NAD27	19N06E29	CASCADE	MT	STREAM		MBMG	5/28/2003 16:45	24.5	8.2	8.02	680	645	371	74.8	37.6	10.4	2.7	0.061	0.065	12.8	355.4	0	49.3
2003Q1162	203451	LOWER BOX ELDER CREEK * BELOW J H	LOWER BOXELDER	47.3779	-110.986	NAV-GPS	NAD27	19N06E29	CASCADE	MT	STREAM		MBMG	6/17/2003 16:05	23.3	8.15	8.21	395	592	375	75.7	40.9	10.1	2.29	0.042	0.035	16.7	358.7	0	45.6
2004Q0478	203451	LOWER BOX ELDER CREEK * BELOW J H	LOWER BOXELDER	47.3779	-110.986	NAV-GPS	NAD27	19N06E29	CASCADE	MT	STREAM		MBMG	4/25/2004 14:10	17	8.67	8.26	570	562	344	66.7	39	10.7	3.08	0.035	0.008	3.14	315.1	0	56.6
2005Q0411	203451	LOWER BOX ELDER CREEK * BELOW J H	LOWER BOXELDER	47.3779	-110.986	NAV-GPS	NAD27	19N06E29	CASCADE	MT	STREAM		MBMG	4/8/2005 11:15	8.3	6.78	8.14	655	669	377	76.6	40.1	9.88	2.4	0.013	0.022	8.48	370.4	0	44.2
2003Q1085	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	5/28/2003 15:50	19	8.1	8.13	675	678	379	78.2	34.2	11.2	2.93	0.039	0.052	9.17	351	0	59.2
2003Q1166	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	6/17/2003 17:15	18.2	7.89		400			84.4	38.1	11.3	2.62	0.046	0.032	12.8			
2004Q0033	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	7/17/2003 12:20			6.44		834	340	68.2	36.8	11.9	2.37	0.032	0.024	11.8	287.3	0	53.5
2004Q0097	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	8/19/2003 11:20	15.6	7.85	8.09	620	625	344	68.6	36.6	9.91	2.18	0.037	0.023	12.1	330.01	0	40.6
2004Q0155	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	9/18/2003 18:05	8.7	7.58	7.88	620	697	342	69.9	37.2	9.68	2.47	0.028	0.046	11.7	328.6	0	40.4
2004Q0237	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	10/23/2003 11:15	9.3	7.71	7.89	660	732	387	78.4	38.9	10.3	2.3	0.033	0.042	11.8	357.5	0	51.2
2004Q0476	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	4/25/2004 14:40	13	8.48	8.19	635	639	430	85.9	47.3	14.6	4.06	0.021	0.019	6.13	389.6	0	66.7
2005Q0350	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	2/4/2005 13:35			8.15		683	404	77.8	38.7	11.5	2.86	0.032	0.023	11.8	401.1	0	50.1
2005Q0413	203450	UPPER BOX ELDER CREEK * LARSON RA	UPPER BOXELDER	47.3586	-110.987	NAV-GPS	NAD27	19N06E32	CASCADE	MT	STREAM		MBMG	4/8/2005 11:50			8.13		662	355	68.5	34.8	10	2.21	0.015	0.027	10	335.5	0	49.8
2005Q0286	214386	BELT CREEK AT ARMINGTON BRIDGE IN	BELT CRK @ARMING	47.3654	-110.907	NAV-GPS	NAD83	19N06E36DBBB	CASCADE	MT	STREAM		MBMG	10/28/2004 10:00	3.68	7.27	8.12	487	497	292	75.8	17.9	4.5	1.39	0.012	0.004	8.96	219.1	0	74.6
2004Q0166	196148	REDDISH GARY	330MDSN	47.3232	-110.931	NAV-GPS	NAD27	18N06E14BDBA	CASCADE	MT	WELL	800	MBMG	9/23/2003 9:00	10.09	7.32	7.68	530	542	299	65.9	23.5	5.32	1.79	0.043	0.004	8.46	277.6	0	53.1

	Gwic Id	Site Name	Water Source	Latitude	Longitude	Geomethod	Datum	Location (TRS)	County	State	Site Type	Depth (ft)	Agency	Sample Date	Water Temp	Field pH	Lab pH	Field SC	Lab SC	CDS (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Fe (mg/l)	Mn (mg/l)	SiO2 (mg/l)	HCO3 (mg/l)	CO3 (mg/l)	SO4 (mg/l)
2004Q0330	150504	DANKS BRENDA	330MDSN	47.4317	-110.923	NAV-GPS	NAD27	19N06E11ABAC	CASCADE	MT	WELL	300	MBMG	11/25/2003 14:15	11.27	7.17	7.46	657	655	425	93.4	28.6	2.4	0.916	0.013	<0.001	7.1	187.9	0	198
2004Q0329	31978	DAWSON JIM AND DELORES	330MDSN	47.3913	-110.969	NAV-GPS	NAD27	19N06E21ACDB	CASCADE	MT	WELL	670	MBMG	11/25/2003 15:35	9.71		7.54		676	445	96.5	29.3	3.49	1.13	0.024	0.004	7.8	203.1	0	205
1982Q0356	2315	TOWN OF BELT WELL 2	330MDSN	47.3838	-110.923	NAV-GPS	NAD27	19N06E26ACAD	CASCADE	MT	WELL	430	MBMG	1/6/1982 19:11	9.8	7.49	7.58	529	535.1	345	78.3	23	2.4	0.7	0.015	0.001	9	190.8	0	135
2001Q0358	2315	TOWN OF BELT WELL 2	330MDSN	47.3838	-110.923	NAV-GPS	NAD27	19N06E26ACAD	CASCADE	MT	WELL	430	MBMG	8/4/2000 11:18	10.2	7.77	8.05	574	565	346	80.4	23.4	2.5	1.1	0.006	<.001	7.85	197.2	0	132
2003Q1129	2315	TOWN OF BELT WELL 2	330MDSN	47.3838	-110.923	NAV-GPS	NAD27	19N06E26ACAD	CASCADE	MT	WELL	430	MBMG	6/5/2003 15:15	12.2	7.06	7.78	600	583	377	86.6	24.7	3.78	1.35	0.014	<0.001	7.92	208.3	0	150
2005Q0195	215047	BELT WELL 2A * MADISON WELL * LARSE	330MDSN	47.3786	-110.946	NAV-GPS	NAD27	19N06E27	CASCADE	MT	WELL	734	MBMG	9/22/2004 12:50	12.8	7.99	7.73	950	823	509	97.5	50.3	11.8	3.13	0.06	0.177	16	317.5	0	163
2004Q0328	177163	SPRAGG ED	330MDSN	47.3592	-110.903	NAV-GPS	NAD27	19N06E36DCDD	CASCADE	MT	WELL	490	MBMG	11/26/2003 14:30	9.08	7.36	7.46	608	599	373	79.9	26	5.96	5.26	0.013	0.005	7	296.7	0	99.3
2004Q0160	186483	SPILLER LEROY AND FAYE	110ALVM	47.3785	-110.927	NAV-GPS	NAD27	19N06E26DBCB	CASCADE	MT	WELL	24	MBMG	9/22/2003 16:45	11.19	7.19	7.66	619	604	360	79.1	27.5	7.64	2.75	0.018	<0.001	9.38	282.1	0	89.2
2003Q1131	32015	JIM LARSON RANCH	110ALVM	47.3534	-110.99	NAV-GPS	NAD27	19N06E32DCCB	CASCADE	MT	WELL	32	MBMG	6/5/2003 13:40	10.2	7.27	7.67	645	622	377	74.3	35.4	12.6	2.45	0.023	<0.001	9.71	349.5	0	64.6
2004Q0239	32015	JIM LARSON RANCH	110ALVM	47.3534	-110.99	NAV-GPS	NAD27	19N06E32DCCB	CASCADE	MT	WELL	32	MBMG	10/23/2003 12:20	10.5	7.34	7.68	630	655	380	74.9	34.6	11.9	2.47	0.012	<0.001	11	366.9	0	59
2004Q0163	31952	GOO EDWARD	112TILL	47.4357	-110.953	NAV-GPS	NAD27	19N06E03CDBA	CASCADE	MT	WELL	12	MBMG	9/25/2003 14:15		6.62	7.97	752	758	413	25.7	65.3	36.4	3.67	0.017	<0.001	15.3	380.2	0	59.1
2005Q0289	214917	DEQ RECLAIMED SITE MONITOR WELL 1	111MTLG	47.3815	-110.928	NAV-GPS	NAD83	19N06E26BDDD	CASCADE	MT	WELL	13.3	MBMG	10/29/2004 15:15	10.58	4.48	4.45	5462	5230	7286	473	643	26.6	9.53	3.21	5.98	4.22	0	0	5736
2005Q0043	210533	MARRY EVANS	217SBRS	47.3126	-110.995	NAV-GPS	NAD27	18N06E17CAAD	CASCADE	MT	WELL	90	MBMG	7/29/2004 15:30	8.61	7.26	8	886	896	473	71.3	63	31	1.77	0.041	<0.001	9.1	454.5	0	46.6
2004Q0168	30562	JOHNSON GERALD	217SBRS	47.3052	-110.977	NAV-GPS	NAD27	18N06E21BABB	CASCADE	MT	WELL	35	MBMG	9/23/2003 11:00	9.26	6.89	7.48	682	666	357	77.6	28.9	14.1	5.01	0.012	<0.001	10.2	316.8	0	26.9
2004Q0169	31957	HORST NATHAN	217SBRS	47.4359	-110.963	NAV-GPS	NAD27	19N06E04DACD	CASCADE	MT	WELL	140	MBMG	9/23/2003 16:35		6.92	7.29	1077	1056	642	69.8	93.7	46.1	5.72	0.12	0.05	6.37	588.8	0	121
2005Q0348	217048	BELT WELL 1C	217SBRS	47.3839	-110.953	NAV-GPS	NAD83	19N06E27BACC	CASCADE	MT	WELL	90	MBMG	2/3/2005 15:40			7.91		913	517	86.4	75.3	11.1	4.03	0.178	0.097	6.82	566.1	0	51.1
2005Q0425	217048	BELT WELL 1C	217SBRS	47.3839	-110.953	NAV-GPS	NAD83	19N06E27BACC	CASCADE	MT	WELL	90	MBMG	4/8/2005 14:30			7.31		904	510	85	75.7	11.5	3.95	0.199	0.065	6.77	553.1	0	51.5
2005Q0346	217050	BELT WELL 2C	217SBRS	47.3789	-110.947	NAV-GPS	NAD83	19N06E27CBBC	CASCADE	MT	WELL	80	MBMG	2/3/2005 17:30			7.67		615	304	37.5	46.2	6.58	1.67	0.008	0.015	7.25	357.2	0	20.1
2005Q0423	217050	BELT WELL 2C	217SBRS	47.3789	-110.947	NAV-GPS	NAD83	19N06E27CBBC	CASCADE	MT	WELL	80	MBMG	4/8/2005 18:40			7.43		654	329	43.5	55.6	8.62	2.09	0.009	0.019	7.77	348	0	25.9
2005Q0344	217053	BELT WELL 3C	217SBRS	47.3726	-110.972	NAV-GPS	NAD83	19N06E28CDC	CASCADE	MT	WELL	159	MBMG	2/4/2005 10:40			7.56		628	353	50.6	44.7	16	4.94	0.217	0.104	6.33	411.4	0	23.6
2005Q0421	217053	BELT WELL 3C	217SBRS	47.3726	-110.972	NAV-GPS	NAD83	19N06E28CDC	CASCADE	MT	WELL	159	MBMG	4/8/2005 16:50			7.51		679	367	53.5	47.4	16.9	4.86	0.283	0.097	6.24	416	0	28.9
2004Q0161	207672	IRVINE	217SBRS	47.3559	-110.96	NAV-GPS	NAD27	19N06E34CCCC	CASCADE	MT	WELL		MBMG	9/24/2003			7.74		576	318	50.3	44.9	7.42	1.78	0.03	0.002	6.9	346.2	0	24.3
2004Q0165	186486	DAWSON RANCH	217SBRS	47.3715	-110.865	NAV-GPS	NAD27	19N07E32BADA	CASCADE	MT	WELL	200	MBMG	9/23/2003 13:30	9.15	7	7.58	2086	1990	1418	119	69.4	260	6.45	0.027	0.14	7.85	512.4	0	684
2004Q0162	164111	HOYER, KEITH AND HEATHER	217SBRS	47.4516	-110.918	NAV-GPS	NAD27	20N06E35DADA	CASCADE	MT	WELL	90	MBMG	9/23/2003 15:35	11.57	7.38	7.79	597	602	359	74.9	26.4	9.16	2.56	0.102	0.213	10	274.5	0	97
2005Q0342	217056	BELT WELL 4C	217SBRS	47.3651	-110.956	NAV-GPS	NAD83		CASCADE	MT	WELL		MBMG	2/3/2005 13:50	9.6	6.83	7.37	735	761	438	65.1	51.2	20.1	6.1	0.324	0.051	6.02	505.5	0	35.9
2004Q0167	199851	ERIC JOHNSON	217CBNK	47.3099	-110.959	NAV-GPS	NAD27	18N06E15CCBC	CASCADE	MT	WELL	160	MBMG	9/23/2003 10:25	10.22	6.84	7.26	482	484	265	51.2	28.3	5.45	2.35	0.017	0.004	7.05	272.4	0	31.6
2004Q0093	84937	HARRIS JOHN JR.	217CBNK	47.3699	-110.99	NAV-GPS	NAD27	19N06E29CD	CASCADE	MT	WELL	200	MBMG	8/19/2003 13:20	9.9	6.86	7.28	740	730	444	94.5	41.3	11.9	4.06	1.31	0.09	6.35	350.4	0	107
2004Q0231	84937	HARRIS JOHN JR.	217CBNK	47.3699	-110.99	NAV-GPS	NAD27	19N06E29CD	CASCADE	MT	WELL	200	MBMG	10/23/2003 13:20	9	7.1	7.54	730	736	467	97	38.9	11.9	4.08	1.16	0.081	6.24	411.5	0	101
2004Q0468	207662	BURGE EXPLORATION ACM WELL	217CBNK	47.3787	-110.979	NAV-GPS	NAD27	19N06E29DAAA	CASCADE	MT	WELL	186	MBMG	4/25/2004 13:00	11.1	7.21	7.28	220	295	133	24	10.7	3.86	3.19	0.23	0.184	6.57	109.6	0	15.7
2004Q0513	207662	BURGE EXPLORATION ACM WELL	217CBNK	47.3787	-110.979	NAV-GPS	NAD27	19N06E29DAAA	CASCADE	MT	WELL	186	MBMG	5/7/2004 11:00			7.58		577	354	75.2	34.1	7.84	2.89	0.034	0.015	6.3	303.8	0	73.8
2005Q0340	207662	BURGE EXPLORATION ACM WELL	217CBNK	47.3787	-110.979	NAV-GPS	NAD27	19N06E29DAAA	CASCADE	MT	WELL	186	MBMG	2/4/2005 12:40			7.32		612	371	76.5	31.9	8.71	2.69	0.13	0.021	6.14	327	0	79.6
2005Q0290	215048	BELT WELL 4B COAL	221MRSN	47.3625	-110.95	TRS-TWN	NAD27	19N06E34	CASCADE	MT	WELL		MBMG	10/29/2004 10:00	8.83	6.59	7.37	877	921	507	100	47.7	22.2	5.88	0.087	0.376	7.48	416.5	0	115
2004Q0164	145604	ASSELS STEVEN D. AND LINDA L.	221SWFT	47.3994	-110.93	NAV-GPS	NAD27	19N06E23BDBA	CASCADE	MT	WELL	66	MBMG	9/23/2003 15:00	11.69	7.29	7.67	637	623	367	86	24.3	7.98	2	0.015	0.008	8.29	223.5	0	121

	Gwic Id	Cl (mg/l)	NO3 (mg/l)	F (mg/l)	OPO4 (mg/l)	Ag (ug/l)	Al (ug/l)	As (ug/l)	B (ug/l)	Ba (ug/l)	Be (ug/l)	Br (ug/l)	Cd (ug/l)	Co (ug/l)	Cr (ug/l)	Cu (ug/l)	Li (ug/l)	Mo (ug/l)	Ni (ug/l)	Pb (ug/l)	Sb (ug/l)	Se (ug/l)	Sr (ug/l)	Ti (ug/l)	Tl (ug/l)	U (ug/l)	V (ug/l)	Zn (ug/l)	Zr (ug/l)
2005Q0283	214915	<12.5	<2.50 P	<1.25	<2.50	<5	436295	<5	<150	<10	16	<1250	77.4	661	143	98.6	701	<50	2975	<10	<10	<5	2227	<10	<25	127	<25	7823	<10
2005Q0287	214914	<25.0	<2 50 P	2.91	<2.50	<10	236600	<10	<300	<20	<20	<2500	<10	517	33.8	48.1	495	<100	1377	<20	<20	<10	1888	<10	<50	24.2	<50	4376	<20
2003Q0848	200616	<10	<1.0	<1.0	<1.0	<5	99000	<5	<150	<10	16.6	<1000	6.59	265	28.3	<50	208	<10	618	<10	<10	<5	1630	1.84	<25	2.79	<25	3280	<2
2003Q0866	200616	5.8	<0.5	1.83	<0.5	<10	102000	<10	111	<20	18.8	<500	<10	292	31.5	15.7	219	<10	777	<20	<20	<10	1780	<5	<50		<50	2800	2.4
2003Q1018	200616	<10.0	<1.0	<1.0	<1.0	<5	90700	<5	118	<10	16.3	<1000	3.96	222	23.3	<10	192	<50	398	<10	<10	<5	1510	<1	<25	<2.5	<25	2790	4.49
2003Q1079	200616	7.51	<0.50	1.87	<0.50	<5	90850	<5	95	<10	11	<500	3.52	245	27	11.4	190	<50	416	<10	<10	<5	1598	<1	<25	2.94	17.3	2817	2.82
2003Q1163	200616	4.65	<0.25	0.549	<0.25	<5	106252	<2	102	2.86	20.3	<250	26	250	27.7	10.9	206	<10	450	<10	<10	<5	1930	<1	<25	3.01	<25	3121	2.66
2004Q0029	200616	<12.5	<1.25	2.18	<1.25	<5	107767	<5	96.6	<2	19	<1250	4.13	255	27.7	<10	210	<10	438	<10	<10	<5	1700	<1	<25	2.73	22.7	3171	3.01
2004Q0103	200616	8.6	<0.5	3.71	<0.5	<5	108575	<5	105	2.27	19.7	<500	4.68	264	30	<10	212	<10	485	<10	<10	<5	1876	<1	<25	2.74	26.6	3249	3.39
2004Q0147	200616	<5.0	<0.5	2.15	<0.5	<5	116063	<5	109	3.01	15.2	<500	5.33	260	38.4	<10	217	<10	454	<10	<10	<5	1806	<1	<20	2.9	18.6	3283	3.1
2004Q0241	200616	<5.0	<0.5	1.78	<0.5	<5	105949	<5	<150	2.2	14.9	<500	4.39	265	29.5	<10	217	<10	430	<10	<10	<5	1873	<1	<25	2.64	16.3	3229	3.32
2004Q0470	200616	<10.0	<1.0	4.23	<1.0	<10	126252	<5	82.5	<2	15.4	<1000	5.57	254	24.1	<10	198	<10	456	<10	<10	<5	1864	<1	<25	2.67	<25	3100	<10
2004Q0574	200616	6.7	<2.5 P	1.92	<0.50	<5	101577	<5	102	<2	18.9	<500	3.97	247	22.3	10.9	210	<10	452	<10	<10	<5	1773	<1	<20	3.13	<25	3261	<10
2005Q0075	200616	<5.0	<0.25	<0.25	<0.25	<5	98934	<5	116	2.45	12.7	<250	5.05	253	27.8	<10	218	<10	487	<10	<10	<5	1743	1.5	<20	3.46	<10	3339	4.11
2005Q0288	200616	<5.0	<1 25 P	<0.50	<0.50	<5	102846	<5	<150	4.27	19.5	<500	5.26	250	26.6	<10	216	<10	760	<10	<10	<5	1969	<1	<25	<3	21.2	3299	<2
2005Q0358	200616	<50.0	<5.0	<5.0	<5.0	<5	105027	<5	<150	<10	15.1	<5000	6.25	239	26.3	<10	212	<10	445	<10	<10	<5	1832	2.08	<20	<3.0	<25	3333	3.16
2005Q0419	200616	<10.0	<1.0	<1.0	<1.0	<5	95278	<5	109	4.59	<10	<1000	5.8	240	18.2	<10	207	<10	473	<10	<10	<5	1633	<1	<20	<3	16.5	2715	<2
2003Q0846	200615	<50	<5.0	<5.0	<5.0	<10	505000	65.6	<300	<20	45	<5000	16.8	368	131	<200	684	<100	974	<20	<20	<10	2720	<10	<50	16	<50	5120	<20
2003Q0865	200615	<50.0	<5.0	<5.0	<5.0	<10	470000	51.8	178	<20	56.5	<5000	10.7	363	130	97.5	659	<50	1080	<20	<20	<10	2880	<25	<50		<50	4090	<10
2003Q1020	200615	<125.0	<12.5	<12.5	<12.5	<10	402000	29.5	<<300	<20	<20	<12500	<10	287	95.4	93.9	547	<100	819	<20	<20	<10	2520	<10	<50	12.2	<50	3820	<20
2003Q1081	200615	16.3	<1.0	5.84	<1.0	<10	305844	24.1	<300	<20	20.7	<1000	<10	240	80.3	42.9	415	<100	356	<20	<20	<10	2119	<10	<50	14	<50	2845	21.8
2003Q1164	200615	<50.0	<5.0	<5.0	<5.0	<5	368398	27.5	<150	<10	25.9	<5000	33.7	227	80.7	31.3	488	<50	778	<10	<10	<5	2592	<5	<25	15.5	<25	3446	10.5
2004Q0031	200615	<25.0	<2.50	3.46	<2.50	<10	422685	28.3	<300	<20	34.2	<250	<10	240	92	31	589	<100	344	<20	<20	<10	2974	<10	<50	16.3	<100	4245	28.3
2004Q0095	200615	29.6	<2.5 P	9.91	<2.5	<10	467327	31.7	<300	<20	42.5	<2500	54.5	330	123	41.6	640	<100	1074	<20	<20	<10	3035	<10	<50	15.9	<50	4819	<20
2004Q0149	200615	<25.0	<2.5	6.79	<2.5	<10	473245	27.7	<300	<20	45.8	<2500	55	339	125	41.2	667	<100	539	<20	<20	<10	3154	<100	<50	16.4	<50	5082	<20
2004Q0235	200615	<25.0	<2.5	7.94	<2.5	<10	595625	45.1	<300	<20	40.8	<2500	<10	406	152	26.7	714	<100	556	<20	<20	<10	3410	<10	<50	19.5	<50	5787	<20
2004Q0472	200615	<63.0	<6.3	<6.3	<6.3	<10	304001	<10	<300	<20	28.6	<6300	<10	239	47.7	38.8	436	<100	399	<20	<20	<10	1962	<10	<50	16	<100	1835	<20
2004Q0572	200615	<25.0	<2.5	<2.5	<2.5	<10	600602	<10	<300	<20	51.4	<2500	<100	401	182	85.3	967	<100	781	<20	<20	<10	5420	<10	<50	26.6	<50	8401	<20
2005Q0077	200615	17.3	<1.25	2.57	<1.25	<10	506913	35.9	<300	<20	38.1	<1250	<10	337	128	38.8	692	<100	589	<20	<20	<10	2926	<10	<50	21.1	<50	5275	<20
2005Q0356	200615	<12.5	<12.5	13.3	<12.5	<10	566482	46.1	<300	<20	43.9	<12500	11.8	339	132	35.4	796	<100	588	<20	<20	<10	3600	<10	<50	15.6	<50	5982	<20
2005Q0417	200615	<25.0	<2.5	<2.5	<2.5	<10	560947	48.5	<300	<20	44.7	<2500	10	362	118	24.6	751	<100	600	<20	<20	<20		3058	<10	<50	13.8	4568	<20
2005Q0081	213598	7.25	25.6	1.25	<0.05	<1	51.7	<1	84.2	216	<2	<50	<1	<2	2.24	<2	24.8	<10	5.81	<2	<2	2.31	581	<1	<5	4.77	<5	<2	<2
2005Q0352	213598	2.94	<0.05	0.573	<0.05	<1	<30	<1	47.1	197	<2	<50	<1	<2	<2	<2	28.3	<10	3.77	<2	<2	2.54	577	<1	<55	3.64	<5	<2	<2
2004Q0025	204710	79.2	1.91	<0.25	<0.25	<5	<150	<5	<150	11.1	<10	<250	<5	<10	<10	<10	69.3	<50	<10	<10	<10	<5	2224	<5	<25	22	<25	254	<10
2004Q0090	204710	74.8					322	<50	<150	10.3	<10		<5	<10	<50	<25	80.4	<50	<10	<50	<50	<75	2174	<5	<100		<50	337	12.1
2004Q0153	204710	83.8	1.95	4.63	<0.5	<10	<300	<10	<300	<20	<20	<500	<10	<20	<20	<20	73.1	<100	<20	<20	<20	<10	2355	<10	<50	23.3	<50	161	<20
2003Q0850	200617	2.47	4.09	0.52	<0.05	<1	68.3	<1	31.5	173	<2	<50	1.17	<2	<2	<2	20.9	<10	3.73	<2	<2	2.43	442	<1	<5	4.57	<2	3.66	<2
2003Q0863	200617	2.6	3.78	0.56	<0.05	<1	136	<1	<30	158	<2	<50	<1	<2	<2	<2	18.2	<10	2.77	<2	<2	2.02	342	<5	<5		<5	5.27	<2
2003Q1024	200617	2.53	3.7	0.669	<0.05	<1	86.8	<1	<30	168	<2	<50	<1	<2	<2	<2	19.2	<10	2.28	<2	<2	1.82	436	<1	<5	4.06	<5	2.29	2.1
2003Q1083	200617	3.97	2.41	0.628	<0.05	<1	113	<1	<30	203	<2	<50	<1	<2	2.03	<2	24.5	<10	3.22	<2	<2	1.25	547	<1	<5	4.81	<5	3.89	<2
2003Q1165	200617	4.8	1.882	0.612	<0.05	<1	137	<1	45.3	207	<2	<50	<1	<2	<2	<2	26.6	<10	3.35	<2	<2	1.35	586	<1	<5	4.86	<5	3.45	<2
2004Q0027	200617	14.8	1.22	0.517	<0.25	<5	<30	<5	33.4	192	<2	<250	<1	<2	<10	<5	39.8	<10	4.12	<10	<10	<5	852	<1	<25	6.21	<10	33.7	2.42
2004Q0099	200617	26.1	1.04	1.87	<0.5	<1	<30	<1	59.5	113	<2	<500	<1	3.15	<2	<2	47.4	<10	10.42	<2	<2	3.8	1041	<1	<5	8.4	<5	65.7	<2
2004Q0151	200617	7.13	1.16	0.445	<0.10	<1	45.8	<1	51.7	208	<2	<100	<1	<2	<2	<2	29.9	<10	4.72	<2	<2	2.1	621	<1	<5	5.45	<5	4.83	<2
2004Q0474	200617	3.28	2.94	0.579	<0.10	<1	101	<1	51	258	<2	<100	<1	<2	<2	<2	27.9	<10	3.4	<2	<2	1.93	522	2.06	<5	6.31	<5	<2	<2
2004Q0570	200617	4.61	14.1	0.533	<0.05	<1	11.1	<1	52.8	243	<2	<50	<1	4.08	5.35	3.29	28.1	<10	4.43	<2	<2	1.28	638	<1	<5	5.67	<5	19.9	<2
2005Q0079	200617	4.36	15.6	0.49	<0.05	<1	51.6	<1	60.5	227	<2	<50	<1	<2	3.05	<2	26.6	<10	9.64	<2	<2	1.84	572	1.1	<5	7.06	<5	<2	<2
2005Q0354	200617	3.08	3.64	0.422	<0.05	<1	631	<1	<30	185	<2	<50	<1	<2	<2	<2	25.9	<10	7.94	<2	<2	2.69	599	<1	<5	4.8	<5	11.7	<2
2005Q0415	200617	2.68	3.74	0.46	<0.05	<1	127	<1	<30	186	<2	<50	<1	<2	<2	<2	20.1	<10	3.05	<2	<2	2.33	470	<1	<5	4.64	<5	2.32	<2
2004Q0101	205653	3.52	3.72	0.618	<0.05	<1	<30	<1	45.1	122	<2	127	<1	<2	<2	<2	19.1	<10	<2	<2	<2	1.89	446	<1	<5	2.4	<5	<2	<2
2004Q0157	207767	2.28	2.92	0.495	<0.05	<1	<30	1.92	39.7	150	<2	<50	<1	<2	<2	<2	19.5	<10	<2	<2	<2	1.28	385	<1	<5	<1	<5	<2	<2
2004Q0233	205653	1.8	4.4	0.672	<0.05	<1	<30	<1	40.1	133	<2	<50	<1	<2	<2	<2	18.3	<10	3.74	<2	<2	1.77	443	<1	<5	2.71	<5	4.35	<2
2004Q0159	204516	0.85	<0.5 P	0.392	<0.05	<1	<30	<1	<30	471	<2	<50	<1	<2	<2	<2	15.8	<10	<2	<2	<2	1.35	425	<1	<5	2.81	<5	3.83	<2
2004Q0110	205836	0.823	0.092	0.077	<0.05	<1	40.7	<1	<30	74.1	<2	<50	1.45	<2	<2	6.26	8.14	17.4	<2	<2	<2	<1	639	<1	<5	3.05	<5	29	<2
2004Q0114	205839	1.46	0.075	0.07	<0.05	<1	71.2	<1	<30	77.5	<2	<50	<1	<2	<2	<2	10.4	<10	<2	<2	<2	<1	673	<1	<5	1.07	<5	10.4	<2
2004Q0112	205838	1.45	<0.05	0.159	<0.05	<1	36.5	<1	<30	66.1	<2	<50	<1	<2	<2	<2	10.7	<10	<2	<2	<2	<1	644	<1	<5	1.13	<5	10.3	<2
2004Q0091	205508	1.85	0.112 P	0.161	<0.05	<1	<30	<1	<30	77.7	<2	<50	<1	<2	<2	<2	11	<10	<2	<2	<2	<1	714	<1	<5	1.17	<5	7.75	<2
2005Q0285	214916	2.11	<0.25 P	0.242	<0.05	<1	16.1	<1	31.4	59.9	<2	<50	<1	25.1	<2	<2	35	<10	61.5	<2	<2	<1	799	<1	<5	<1	<5	104	<2
2005Q0284	214911	1.75	0.532	0.14	<0.05	<1	568	<1	47.4	71.3	<2	<50	1.36	45.1	<2	<2	85.2	<10	74.5	<2	<2	<1	734	<1	<5	<1	<5	145	<2
2005Q0282	214913	1.69	<0.25 P	0.195	<0.05	<1	16.5	<1	<30	63.6	<2	<50	<1	28.2	<2	<2	34.9	<10	77.1	<2	<2	<1	814	<1	<5	<1	<5	212	<2
2003Q1087	203451	6.07	1.22	0.464	<0.05	<1	40	1.86	<30	244	<2	<50	<1	<2	3.24	3.343	16.7	<10	2.05	<2	<2	<1	436	<1	<5	2.56	<5	12	<2
2003Q1162	203451	5.5	0.991	0.461	<0.05	<1	39.1	2.07	37.7	294	<2	<50	<1	<2	<2	<2	17.7	<10	2.01	<2	<2	<1	444	<1	<5	2.74	<5	2.14	<2
2004Q0478	203451	6.8	1.81	0.434	<0.10	<1	<30	<1	40.7	213	<2	<100	1.41	<2	<2	<2	25.3	<10	3.39	<2	<2	1.04	555	<1	<5	3.67	<5	7.79	<2
2005Q0411	203451	5.81	6.95	0.348	<0.05	<1	<30	<1	<30	220	<2	<50	<1	<2	<2	<2	17.2	<10	2.79	<2	<2	<1	430	<1	<5	3.06	<5	<2	<2
2003Q1085	203450	7.91	2.51	0.401	<0.05	<1	<30	1.04	<30	213	<2	<50	<1	<2	2.82	<2	15	<10	2.08	<2	<2	<1	394	<1	<5	2.19	<5	<2	<2
2003Q1166	203450					<1	32	1.08	<30	235	<2		<1	<2	<2	<2	15.8	<10	<2	<2	<2	<1	453	<1	<5	2.29	<5	<2	<2
2004Q0033	203450	8.76	4.59	0.371	<0.05	<1	<30	<1	<30	253	<2	<50	<1	<2	<2	<2	16.9	<10	<2	<2	<2	<1	438	<1	<5	2.62	<5	<2	<2
2004Q0097	203450	7.09	3.41	0.512	<0.05	<1	<30	<1	39.8	286	<2	<50	<1	<2	<2	<2	18.1	<10	<2	<2	<2	1.14	442	<1	<5	2.71	<5	2.58	<2
2004Q0155	203450	6.96	1.33	0.43	<0.05	<1	<30	<1	35.7	338	<2	<50	<1	<2	<2	<2	17.9	<10	2.49	<2	<2	1.4	450	<1	<5	3.01	<5	<2	<2
2004Q0237	203450	7.11	9.98	0.584	<0.05	<1	35.4	<1	<30	303	<2	<50	<1	<2	<2	<2	19.7	<10	4.67	<2	<2	<1	470	<1	<5	3.84	<5	10.6	<2
2004Q0476	203450	9.85	3.48	0.39	<0.10	<1	<30	<1	42	265	<2	<100	<1	<2	<2	<2	22.2	<10	3.65	<2	<2	1.01	533	<1	<5	5.48	<5	<2	<2
2005Q0350	203450	8.2	4.75	0.264	<0.05	<1	<30	<1	<30	232	<2	<50	<1	<2	<2	<2	18	<10	6.62	<2	<2	1.08	432	1.57	<5	3.02	<5	<2	<2
2005Q0413	203450	8.04	5.81	0.328	<0.05	<1	32.4	<1	<30	203	<2	<50	<1	<2	<2	<2	15.1	<10	2.45	<2	<2	<1	354	<1	<5	2.53	<5	<2	<2
2005Q0286	214386	0.938	<0.25 P	0.061	<0.05	<1	<10	<1	<30	77.5	<2	<50	<1	<2	<2	<2	8.4	<10	2.84	<2	<2	<1	950	<1	<5	1.26	<5	17	<2
2004Q0166	196148	2.28	1.25	0.277	<0.05	<1	<30	<1	<30	69.4	<2	<50	<1	<2	<2	<2	8.42	<10	2.65	<2	<2	<1	441	<1	<5	1.28	<5	292	<2

	Gwic Id	Cl (mg/l)	NO3 (mg/l)	F (mg/l)	OPO4 (mg/l)	Ag (ug/l)	Al (ug/l)	As (ug/l)	B (ug/l)	Ba (ug/l)	Be (ug/l)	Br (ug/l)	Cd (ug/l)	Co (ug/l)	Cr (ug/l)	Cu (ug/l)	Li (ug/l)	Mo (ug/l)	Ni (ug/l)	Pb (ug/l)	Sb (ug/l)	Se (ug/l)	Sr (ug/l)	Ti (ug/l)	Tl (ug/l)	U (ug/l)	V (ug/l)	Zn (ug/l)	Zr (ug/l)
2004Q0330	150504	1.09	<0.5 P	0.802	<0.05	<1	<30	<1	<30	18.3	<2	<50	<1	<2	<2	3.8	6.35	12.9	3.46	<2	<2	1.88	995	<1	<5	2.95	<5	19.6	2.06
2004Q0329	31978	0.98	<0.5 P	0.462	<0.05	<1	<30	<1	<30	20	<2		1.52	<2	<2	<2	7.49	<10	2.61	<2	<2	<1	1738	<1	<5	2.69	<5	503	<2
1982Q0356	2315	1.6	0.34	0.43		<2.	<30.		140				<2.		<2.	9	2	30	<10.	70			1090	31			2	120	8
2001Q0358	2315	0.751	<.5 P	0.41	<.05	<1	<30	<1	<30	35.1	<2	<50	<2	<2	<2	<2	6.11	<10	2.17	<2	<2	<1	1190	<1	<5		<5	<2	<2
2003Q1129	2315	<5.0	<0.5	<0.5	<0.5	<1	<30	<1	<30	39.5	<2		<1	<2	<2	2.31	8.35	<10	<2	<2	<2	<1	1465	<1	<5	1.71	<5	4.78	<2
2005Q0195	215047	1.78	7.94	0.912	<0.10	<1	12.3	1.25	60.6	45.1	<2	<100	<1	<2	5.6	<2	38.7	18.1	11.5	<2	<2	5.08	1109	<1	<5	4.89	<5	<2	<2
2004Q0328	177163	2.6	<0.5 P	0.579	<0.05	<1	<30	<1	93.1	29.2	<2	<50	<1	<2	<2	2.89	27.8	<10	2.16	<2	<2	<1	1593	<1	<5	0.5	<5	4	2.98
2004Q0160	186483	4.26	0.664	0.37	<0.05	<1	<30	<1	32.5	51.9	<2	<50	<1	<2	<2	<2	15.7	<10	2.35	<2	<2	1.52	423	<1	<5	1.65	<5	8.5	<2
2003Q1131	32015	4.38	1.05	0.379	<0.05	<1	<30	<1	<30	241	<2		<1	<2	<2	<2	15.7	<10	<2	<2	<2	<1	356	<1	<5	<2	2.37	<5	50
2004Q0239	32015	4.14	1.04	0.36	<0.05	<1	<30	<1	36.2	254	<2	<50	<1	<2	<2	3.98	16	<10	<2	<2	<2	<1	351	<1	<5	2.72	<5	128	<2
2004Q0163	31952	8.2	10.77 P	1.18	<0.05	<1	<30	<1	132	88.2	<2	<50	<1	<2	<2	<2	50.8	<10	<2	<2	<2	3.03	544	<1	<5	9.12	<5	11.4	<2
2005Q0289	214917	<25.0	7.84 P	2.62	<2.50	<10	373061	<10	628	24.2	21	<2500	<10	309	<20	<20	946	<100	753	<20	<20	<10	1621	<10	<50	39.6	<50	1196	<20
2005Q0043	210533	25.5	<0.25 P	0.9	<0.05	<1	<10	<1	59.2	115	<2	<50	1.99	<2	<2	<2	27.9	<10	5.6	<2	<2	<1	558	<1	<5	10.7	<5	2.69	<2
2004Q0168	30562	23.9	14.35	0.107	<0.05	<1	<30	<1	<30	916	<2	<50	<1	<2	<2	<2	8.3	<10	2.96	<2	<2	<1	346	<1	<5	4.92	<5	2.36	<2
2004Q0169	31957	7.79	<0.5	0.966	<0.1	<1	<30	<1	118	23	<2	<100	<1	<2	<2	<2	105	<10	<2	<2	<2	<1	1233	<1	<5	1.36	<5	4.08	2.3
2005Q0348	217048	2.98	<0.05	0.233	0.098	<1	<30	<1	48.6	74.9	<2	<50	<1	<2	2.28	<2	36.5	<10	7.38	<2	<2	<1	640	1.54	<5	6.99	<5	<2	<2
2005Q0425	217048	2.74	<0.05	0.359	0.167	<1	42.3	<1	45.7	75.4	<2	<50	<1	<2	3.83	<2	35.4	<10	4.13	<2	<2	<1	629	<1	<5	6.76	<5	<2	<2
2005Q0346	217050	1.46	5.95	0.906	<0.05	<1	34.7	<1	48.4	108	<2	<50	<1	<2	<2	<2	28.9	<10	3.86	<2	<2	4.06	467	<1	<5	3.59	<5	5.92	<2
2005Q0423	217050	1.37	11.8	0.842	<0.05	<1	<10	<1	42.2	124	<2	<50	<1	<2	<2	<2	35.7	<10	2.23	<2	<2	3.58	545	<1	<5	3.53	<5	4.73	<2
2005Q0344	217053	2.11	0.06	1.55	0.125	<1	<30	5.41	115	94.1	<2	<50	<1	5.07	2.03	<2	65.5	<10	23.3	<2	<2	<1	915	<1	<5	<1	<5	<2	<2
2005Q0421	217053	1.92	<0.05	1.34	0.108	<1	47.2	5.3	104	95.6	<2	<50	<1	3.74	<2	<2	61.6	<10	20.5	<2	<2	<1	909	<1	<5	<1	<5	<2	<2
2004Q0161	207672	3.53	7.96	0.778	<0.05	<1	<30	<1	34.7	88.1	<2	<50	<1	<2	<2	2.7	31.2	<10	<2	<2	<2	4.17	418	<1	<5	2.64	<5	40.6	<2
2004Q0165	186486	17.9	1.2	<1.0	<1.0	<5	<30	<5	162	15.7	<2	<1000	<1	3.57	<10	<5	195.8	<10	7.87	<10	<10	<5	1876	<1	<25	7.92	<10	40.7	<2
2004Q0162	164111	3.26	<0.5 P	0.221	<0.05	<1	<30	<1	<30	58.6	<2	<50	<1	<2	<2	<2	15.2	<10	3.34	<2	<2	<1	760	<1	<5	1.77	<5	32.7	<2
2005Q0342	217056	2.51	<0.05	1.35	<0.05	<1	<30	1.14	175	59.7	<2	<50	<1	<2	2.1	<2	106	<10	4.7	<2	<2	<1	1211	<1	<5	<1	<5	<2	<2
2004Q0167	199851	2.57	1.12	1.07	<0.05	<1	<30	<1	57.3	93	<2	100	<1	<2	<2	2.39	21.9	<10	3.45	<2	<2	2.33	371	<1	<5	3.04	<5	21.3	<2
2004Q0093	84937	3.08	<0.05	1.41	<0.05	<1	<30	<1	114	21	<2	76	<1	<2	<2	<2	52.4	<10	4.32	<2	<2	<1	889	<1	<5	1.13	<5	19.3	<2
2004Q0231	84937	2.75	<0.05	1.49	<0.05	<1	<30	<1	107	22.5	<2	62	<1	<2	2.58	<2	54.3	<10	7.71	<2	<2	<1	914	<1	<5	1.41	<5	19.7	<2
2004Q0468	207662	3.89	2.17	0.255	<0.05	<1	58.4	<1	<30	71.9	<2	<50	1.85	4.42	<2	92.8	8.89	<10	7.09	<2	<2	<1	215	<1	<5	0.592	<5	8249	2
2004Q0513	207662	2.9	<0.5	0.702	<0.05	<1	<30	<1	55.7	67.6	<2	<50	<1	<2	8.83	<2	25.1	23.1	7.99	<2	<2	<1	536	1.26	<5	0.509	<5	57.3	<2
2005Q0340	207662	3.07	0.195	0.721	0.054	<1	<30	<1	39.8	64.3	<2	109	<1	<2	<2	<2	27.1	17.5	15.7	<2	<2	<1	609	<1	<5	0.908	<5	312	<2
2005Q0290	215048	2.83	<0.25	0.609	<0.10	<1	16	1.26	89	64.1	<2	128	<1	3.38	<2	<2	61.5	<10	12	<2	<2	<1	1037	<1	<5	3.05	<5	13	<2
2004Q0164	145604	6	0.79 P	0.133	<0.05	<1	<30	<1	<30	73.9	<2	<50	<1	<2	<2	<2	14.6	<10	3.22	<2	<2	<1	761	<1	<5	1.72	<5	28.9	<2

Appendix F

Isotope Data

Isotope Data						
mnumber	Sample Name	Date	Lab #	Tritium TU E3H	Oxygen 18O	Previously collected data
200616	Anaconda Mine Drain	1/30/03	57350	14.2		X
200616	Anaconda Mine Drain	5/28/03	67115	16	-18.04	X
200616	Anaconda Mine Drain	7/17/03	67123	16	-18.22	X
200616	Anaconda Mine Drain	10/23/03	72794	12.9	-18.46	X
205838	Belt Creek#2 above AMD	7/17/03	67122	13.2	-17.94	X
*	Box Elder Creek, Harris Ranch	1/29/03	57353	18.6		X
150504	Brenda Danks	11/25/03	73725	12.6	-18.72	
31978	Jim Dawson	11/24/03	73724	13.1	-18.67	
177163	Ed Spragg	11/26/03	73726	7.5	-19.64	
199851	Eric Johnson	9/23/03	73716	8.6	-19.79	
200615	French Coulee Drain	1/29/03	57351	15.3		X
200615	French Coulee Drain	5/28/03	67116	19.5	-17.98	X
200615	French Coulee Drain	7/17/03	67124	17.2	-18.04	X
200615	French Coulee Drain	10/23/03	72793	16	-18.28	X
186483	Fye Spiller	9/22/03	73713	13.7	-18.28	
196148	Gary Reddish	9/23/03	73719	11.1	-18.69	
31952	Edward Goo	9/25/03	73723	15.7	-15.34	
200617	Highway Drain	1/30/03	57352	26		X
200617	Highway Drain	5/28/03	67117	23.6	-16.52	X
204710	HWD-Seep	7/17/03	67125	31.9	-17.36	X
207672	Irvine	9/24/03	73721	2.4	-16.67	
186486	Jeff Dawson	9/23/03	73718	12	-18.13	
30562	Jerry Johnson	9/23/03	73714	14.4	-19.31	
32015	Jim Larson Well	6/5/03	67120	18.1	-16.99	X
32015	Jim Larson Well	10/23/03	72791	16.8	-17.08	X
84937	John Harris	8/19/03	68103	8.9	-18.59	X
84937	John Harris	10/23/03	72789	8.6	-18.6	X
205653	John Harris Spring	8/19/03	68104	14.2	-17.81	X
205653	John Harris Spring	10/23/03	72790	13.6	-17.91	X
164111	Keath Hoyer	9/23/03	73720	17.1	-18.46	
204516	Larson Well (Windmill)	9/24/03	73722	20.5	-15.82	
145604	Linda Assels	9/23/03	73715	18.3	-17.83	
203451	Lower Box Elder Creek	5/28/03	67118	20.3	-16.74	X
31957	Nathanial Horst	9/23/03	73717	1.3	-16.78	
2316	Town of Belt Well #1 Creek Well	6/5/03	67121	13.1	-18.67	X
2316	Town of Belt Well #1 Creek Well	11/23/03	72795	12.2	-18.99	X
2315	Town of Belt Well #2 Park Well	11/23/03	72796	13.6	-19.04	X
203450	Upper Box Elder Creek, Larson Ranch	5/28/03	67119	20.2	-17.11	X
203450	Upper Box Elder Creek	7/17/03	67126	19.8		X
203450	Upper Box Elder Creek	10/23/03	72792	23.2	-16.88	X

X = Open File Report No. 504

Beaver effects on landscape patterns of lentic habitat and the population structure of Columbia spotted frogs (Rana luteiventris) in western Montana watersheds

Basic Information

Title:	Beaver effects on landscape patterns of lentic habitat and the population structure of Columbia spotted frogs (Rana luteiventris) in western Montana watersheds
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Beaver effects on landscape patterns of lentic habitat and the population structure of Columbia spotted frogs (*Rana luteiventris*) in western Montana watersheds

Stephen J. Amish and Lisa A. Eby

Abstract

Examining dispersal across different landscapes is essential for understanding population connectivity as well as how humans are altering it. Even though beaver (*Castor canadensis)* are considered ecosystem engineers, their effects on the spatial pattern of lentic habitat and subsequent effects on populations using those habitats has not been evaluated. We used a landscape database of randomly selected watersheds in western Montana to examine the composition and configuration of different lentic habitat types and occupancy by Columbia spotted frogs (*Rana luteiventris*) across the region and to compare beaver and non-beaver watersheds. Overall, median distances between breeding sites for all of the watersheds were within the range of known Columbia spotted frog (CSF) dispersal distances of 3 to 5 km. The distribution of breeding sites showed higher spatial autocorrelation over distances of 3 to 7 km than lentic sites implying that active breeding sites are more clustered than available habitat at these distances. When beaver and non-beaver watersheds were compared, there were large differences in lentic site composition and distribution. Four times as many lentic, permanent lentic and breeding sites were found in beaver watersheds. In addition to more overwintering and breeding habitat, beaver activity produced more evenly dispersed habitat configurations. Finally, the longer distances observed between frog breeding sites in beaver watersheds exceeded estimates of dispersal ability.

To investigate the effects of habitat and breeding site distribution on Columbia spotted frog population structure gene flow, we estimated from allele frequencies at eight microsatellite markers. CSF breeding sites displayed fine scale population structure with limited gene flow and isolation by distance patterns in 4 of 6 watersheds. Population structure within watersheds agreed with the scale implied by capture-recapture data from the literature. Based on Mantel's correlograms and median F_{ST} values, statistically and biologically significant genetic divergence began at distances between 5 and 7.5 km depending on whether an overland or riparian travel route was assumed. In addition, watersheds with shorter average distances (< 5km) between breeding sites or where beaver presence was detected showed higher levels of population connectivity over distances up to 7.5 km. Thus, factors that influence the spatial patterns of lentic sites alter population structure of Columbia spotted frogs. Watershed patterns and beaver ecology are intertwined with population processes of Columbia spotted frogs and play an important role in their persistence, especially on arid landscapes.

Introduction

Over the past two decades amphibians have been the focus of increasing concern because of potential population declines (Houlahan et al. 2000). Although amphibian populations naturally undergo wide fluctuations in number (e.g., Pechmann et al. 1991) and many factors negatively affect amphibian populations, habitat loss and fragmentation are often cited as key factors behind population declines and decreasing overall diversity (e.g., Blaustein et al. 1994). Although the importance of current land use practices in recent losses around the world is still unknown (Collins & Storfer 2003), effects from the historic loss of habitat through both changing land use and management activities in temperate regions of North America have been demonstrated (Hecnar & M'Closkey 1996; Knapp & Matthews 2000). Losses in amphibian diversity have been tied to the historic draining of wetlands and clearing of forests (Hecnar & M'Closkey 1996), while the introduction of fish in historically fishless lakes led to population declines of the mountain yellow-legged frog (*Rana muscosa*) (Knapp & Matthews 2000).

Historically, large areas of lentic habitat in North America were created by beaver activity. In the upper Mississippi and Missouri river basins, Hey and Philippi (1995) estimated a pre-trapping population of 40 million beaver existed and would have created 207,000 km^2 of beaver ponds (an area roughly half the size of Montana). The dramatic decrease in beaver numbers due to overexploitation resulted in a large change in the landscape, converting a considerable portion of the U.S wetlands to dry land (Naiman et al. 1986). For example, in the upper Mississippi and Missouri river basins, approximately 2,070 km^2 of those beaver ponds (1%) remain today (Hey & Phillippi 1995). Although this habitat was lost rapidly after beaver removal, its rate of creation where beaver have returned has been slow (Johnston & Naiman 1990; Naiman et al. 1986; Snodgrass 1997).

Beaver wetlands have important effects on water storage and water table levels, biogeochemical cycling such as nitrogen flow and carbon storage, biotic productivity of invertebrate communities, plant and bird biodiversity, and aquatic vertebrate communities in several regions of North America (for reviews see Collen & Gibson 2001; Hammerson 1994; Naiman et al. 1986). In the intermountain west, alterations to the hydrology and nutrient flow of subalpine and midelevation valleys by beaver have been shown to be important for maintaining the characteristics of aquatic and riparian systems (Dahm & Sedell 1986; Jonas 1955; Maret & Fanin 1987; Munther 1982; Neff 1957; Parker et al. 1985). In addition, beaver wetlands can act as over-wintering and breeding habitat for many species of lentic breeding amphibians. Disruption of the temporal and spatial distribution of these critical habitats may fragment amphibian populations dependent on a landscape shaped by a history of beaver disturbance. Especially in arid regions, rapid pond drying can result in a decline and the eventual extinction of a local amphibian population (Semlitsch 2002). In southwestern Montana limited lentic habitat, small population sizes, and high variability in recruitment may make dispersal of individuals critical for overcoming the effects of habitat fragmentation and for long-term population persistence given the ephemeral nature of the majority (69%; Maxell, unpub. data) of ponds.

Metapopulation theory is often invoked in discussions about the conservation biology or management of populations at the landscape and regional scale because of its ability to link population and landscape processes like habitat fragmentation (McCullough 1996). The theory implies that the size, number, and distribution of habitat patches affects the dynamics and long-term persistence of a population (Rieman & Dunham 2000). Even with the current concerns about habitat fragmentation and the intuitive appeal of metapopulation theory, it is rare to find data that compare movement behavior among landscapes that differ in the amount and configuration of suitable habitat for a species (Wiens 1997). Consequently, little is known about the mechanisms that link changes in habitat patterns with potential short and long-term ecological consequences (McGarigal & Cushman 2002).

The loss of beaver and associated standing water bodies and wetlands they create may be an important source of habitat loss and fragmentation for lentic breeding amphibians. We investigated how beaver activity may be altering the quantity and distribution of breeding habitat for amphibians within watersheds and examine the genetic population structure of one amphibian species, the Columbia spotted frog (*Rana luteiventris*). We focused on Columbia spotted frogs because they are distributed widely across western Montana (ensuring an adequate sample size to address these questions) and their ecology links them tightly to aquatic habitat.

Columbia spotted frogs (*Rana luteiventris*) have the smooth skin, long legs, and jumping ability typical of a member of the family *Ranidae*, or True frogs. They are highly aquatic and are usually not found far from the edge of lentic or riparian habitat used for foraging. Adults generally overwinter in larger permanent water bodies or in springs (Pilliod et al. 2002; Turner 1960). Breeding typically occurs after snow melt or pond ice out. Females deposit eggs in shallow water among emergent vegetation. Vagility does not appear to be as limited as has been seen in some other *Ranid* species. Data currently available for *R. luteiventris* from mark recapture and telemetry studies of dispersal and seasonal migrations reveal most movements cover short distances (< 2 km; see Funk et al. 2005b; Pilliod et al. 2002; < 2 km; see Turner 1960). Mark recapture work on Keeler and Marten Creeks by Funk et al. (2005b) shows most juvenile dispersals covered distances of one kilometer or less, with low frequency dispersals of up to six kilometers. Almost all adults in the same area moved distances of less than one kilometer, with one or two dispersals of up to three kilometers being recorded. However, both mark recapture and telemetry data may be biased low due to the rarity of long distance dispersal events (Koenig et al. 1996).

Because of current and historic anthropogenic activities, questions about the conservation status of widespread species like the Columbia spotted frog exist. Even in Montana, within the center of its range, the species is suffering habitat loss due to a host of mechanisms commonly cited for amphibian declines in temperate regions including the stocking of historically fishless lakes, loss of habitat due to exotic species like the bullfrog, changing land use (e.g., the draining and filling of wetlands due to development and agricultural uses), the extirpation of beaver, pollution, and the spread of disease (Maxell 2000). Some of these same mechanisms, specifically changing land use and beaver extirpation, have been implicated in historic declines which led to the protection of two populations at the southern periphery of the species' range (USFWS 2002).

Although the extent and probable sources of regional population differentiation have been well described, the level and importance of current gene flow for local population persistence is still unknown (USFWS 2002). Both local population dynamics and ecological connectivity of subpopulations need to be investigated if current threats from fragmentation to long-term population persistence are going to be addressed (Semlitsch 2002). Studies of local genetic variation using high-resolution microsatellite markers will be important for understanding the temporal and spatial scales over which fragmentation is operating and for defining appropriate management units.

We evaluated two main objectives involving how landscape influences populations of *R. luteiventris* in western Montana watersheds. First, we examined the landscape in terms of lentic habitat and Columbia spotted frog detection to address two questions; (1) how do *R. luteiventris* detection patterns compare to the distribution of lentic habitat and estimated dispersal distances, and (2) does the structure of lentic habitat and patterns of Columbia spotted frog detection differ between beaver and non-beaver watersheds? Second, we compared the population structure of Columbia spotted frogs in six Montana watersheds and evaluated the importance of regional and watershed processes in defining population structure, examined whether estimates of dispersal distance based on patterns of genetic divergence are similar to estimates of dispersal distances from capture-recapture data, and assessed whether the population structure of Columbia spotted frogs reflects beaver presence in the watershed.

Materials and Methods

Database

We used an existing database developed for monitoring lentic amphibian presence in Montana. The database consists of approximately 155 sixth hydrological unit code (HUC) watersheds that were randomly selected in southwestern Montana or chosen as focal watersheds (Fig. 1). A 6th field HUC is a headwater watershed or subwatershed of 4,047 -16,188 hectares (federal standards for the delineation of hydrologic unit boundaries). The database was created by Bryce Maxell collaboratively with state and federal agencies (Department of Enivronmental Quality, National Heritage Program, Montana Fish Wildlife and Parks, United States Forest Service) and is now overseen by the Montana Natural Heritage program. The majority (92%) of the 6th field HUCs were selected using a stratified random cluster sampling design. Western Montana was stratified by level three ecoregions resulting in separate bioregions with similar abiotic conditions (Nesser et al. 1997). Watersheds (6th field HUCs) within each ecoregion containing at least 25% federal or state land were randomly selected. The total area of the watersheds chosen within each stratum (ecoregion) was proportional to the area of a stratum relative to all strata (Maxell 2005).

Within each watershed, field crews surveyed all standing water bodies (lentic sites) identified from topographic maps or aerial photos on public lands (and some private lands). Breeding sites were defined by the presence of Columbia spotted frog amplexed pairs, egg masses, or tadpoles. The physical characteristics required for a site to be classified as a potential breeding site included shallow water and emergent vegetation (for details on survey methods see Maxell 2004a; for details on survey methods see Maxell 2004b).

We projected survey data in ArcMap and collected additional data on watershed geomorphology and composition from this map to create a database of lentic habitat distribution and CSF detection for southwestern Montana. Digital USGS 7.5’ maps of the study area and detailed Montana Fish Wildlife and Parks (MFWP) stream and lake layers were added to the database. We noted elevations for the lowest and highest sites, as well as the intersection of the main drainage with the lower watershed boundary. In addition, we measured the shortest route between pairs of CSF breeding sites and pairs of potential CSF breeding sites along riparian corridors. Creeks and rivers present on USGS maps or the MFWP stream layer were used to define riparian corridors. In areas where water was not indicated, we followed depressions suggesting the presence of riparian corridors. In areas with little or no topographic relief and no riparian corridors, we measured the shortest straight-line path.

Database analyses

We identified variables from the new database describing the composition and configuration of lentic habitat and *R. luteiventris* detection within watersheds. We ran a multivariate ordination on variables describing watershed characteristics, land ownership and survey characteristics, quantity of lentic habitat within a watershed, and the distribution of lentic habitat within a watershed (for details see Amish 2006) to examine whether there were any biases in the data set that would influence the results. Differences associated with ecoregions would suggest they should be analyzed separately. Binary variables such as beaver detection and ecoregion were projected within the ordination space to identify possible groupings or trends correlated with ordination axes (for details see Amish 2006).

We used SPSS for summary statistics, as well as univariate and non-parametric analyses to examine differences in the number of sites and distances between sites in beaver and non-beaver watersheds and between ecoregions. Specifically, we used a Mann-Whitney U and Kolmogorov-Smirnov tests to determine whether beaver and ecoregion comparisons had significantly different medians or distributions for variables describing the composition or configuration of lentic habitat within watersheds and to examine whether beaver watersheds had significantly different gradients or areas than non-beaver watersheds.

To investigate whether beaver altered the patterning (clustering) of sites, we ran spatial statistics in R version 1.13 (R Development Core Team 2005) using a combination of packages that allow mapped point pattern data to be projected and analyzed. Pair correlation functions were run on point data using SPATSTAT version 1.8-5 (Baddeley & Turner 2005), SPSPATSTAT version 0.1-1, and SP version 0.8-9. Within watershed patterns were aggregated across all watersheds after testing for regional differences. For a stationary Poisson process the pair correlation function is equal to 1, with values $g(r) < 1$ suggesting inhibition between points and values greater than 1 suggesting clustering. The pair-correlation function represents the cumulative frequency distribution of observations at a given point-to-point distance and captures the spatial structure of the variable (for details see Amish 2006). We evaluated the intensity and pattern of pair correlation functions to investigate differences among lentic site, potential breeding site, and known breeding site configurations.

Genetic study design and sample collection

We selected one pair of headwater watersheds (6th code HUCs) from three mountain ranges in two eco-regions of western Montana: the northern Bitterroots, the Pioneers, and the Pintlers (Fig. 1). These watersheds were less than 30 km apart, similar in geomorphology, climate and size and were paired based on differences in average distance between breeding sites (short < 5 km, long > 5 km) (Table 1, Fig. 2). Within these six watersheds, we sampled all potential CSF breeding sites identified from topographic maps, aerial photos, and previous amphibian surveys. Whenever possible, thirty samples were collected from each breeding site by removing 1 cm of tissue from the tip of each tadpole's tail. Overall 1267 tissue samples from 48 breeding sites in western Montana were successfully analyzed (Table 2). Tadpole tail-clips were used for tissue samples instead of adult toes to facilitate obtaining samples across a large area. Collecting tadpoles may lead to samples representing the reproduction of only a few adults (e.g., Allendorf & Phelps 1981; Hansen et al. 1997). To avoid this problem, we collected tadpoles from the entire breeding site. We also gathered general survey information on the number of egg masses, tadpoles, juveniles and adults repeatedly during the field season to establish relative population sizes (for details see Amish 2006).

Genetic data analyses

Allele frequencies, observed and expected heterozygosities, average number of alleles, Nei's genetic distance (Nei 1978), and F_{IS} were calculated using GENALEX version 6 (Peakall & Smouse 2006). We estimated exact probabilities for Hardy-Weinberg proportions (Guo & Thompson 1992), exact probabilities for genotypic disequilibrium, and pair-wise F_{ST} (Weir & Cockerham 1984) using GENEPOP version 3.4 (Raymond & Rousset 1995). PHYLIP version 3.6 (Felsenstein 2005) was used to generate an unweighted pair group method with arithmetic mean (UPGMA) tree based on Nei's genetic distance between breeding sites. All watersheds had sites separated by a range of Euclidian distances ranging from 0.5 kilometer to 14 kilometers and across a range of riparian distances from 0.5 kilometer to 22 kilometers. We calculated Euclidian distances between sites from UTM coordinates and measured riparian distances in a GIS database on digital USGS 7.5 minute maps.

Differences in the genetic structure of watersheds may be a result of regional differences in a species' landscape history. In order to investigate large-scale patterns which might be present in the genetic variation of watersheds, the hierarchical structure of genetic variation in the data was investigated and isolation by distance plots from different mountain ranges and eco-regions were compared. Hierarchical levels of genetic variation based on eco-region, mountain range, watershed, breeding site and individual were examined and tested for significance using the package HIERFSTAT version 0.04-2 (Goudet 2005) in the program R. Differences in the genetic variation between eco-regions, mountain ranges, watersheds, and breeding sites were tested by permutation with 1000 iterations to determine the significance of ecological groupings and whether watersheds could be aggregated. We plotted genetic distance between sites (F_{ST} / 1 – F_{ST}) against geographic distance to check for patterns of isolation by distance (IBD). Plots examining the correlation of pairwise genetic and geographic distance measures assume a stepping stone model of dispersal and compare the relative effects of random genetic drift and gene flow between pairs of sampling points (Hutchinson & Templeton 1999). If sampling points in the study area are in migration-drift equilibrium a linear relationship between genetic and geographic distance is expected and suggests limited gene flow at that scale. We used FSTAT version 2.9.3 (Goudet 1995) for Mantel's tests of global correlation between genetic and geographic distance matrices with significance based on 2000 randomizations.

To establish whether allele frequency data supported previous capture-recapture data suggesting 2 and 7 kilometers were biologically significant distances for CSF population structure, we compared pair-wise F_{ST} across three distance categories (0 – 2.5 km; 2.5- 7.5 km; > 7.5 km) within watersheds. We used Mantel's tests of correlation between genetic and geographic distance matrices to determine the distance class at which statistically significant genetic divergence began within watersheds. Starting with 0 – 1.5 km and 0 – 2.5 km, and increasing in intervals of 2.5 km until 15 km, individual distance classes were tested. A correlogram was created based on the correlation coefficients for each distance class, with significance tested using 2000 randomizations.

Lastly, we investigated watershed characteristics describing the pattern of breeding or lentic sites (e.g. average distance between breeding sites, beaver presence) to look for differences in the type of Columbia spotted frog population structure they exhibited. We compared average F_{ST} to geographic distance between beaver and non-beaver watersheds (Table 1). We also used Mantel's tests and plots of the correlation between genetic and geographic distance to compare levels of genetic divergence between these watershed pairs.

Results and Discussion

How do CSF detection patterns compare to lentic habitat distribution and known CSF dispersal distances?

The landscape structure of CSF breeding sites was more aggregated than the underlying pattern of lentic habitat over distances up to 13 km (Amish 2006). Since the composition and configuration of lentic sites and potential lentic sites were similar, the availability of breeding habitat does not appear to limit the distribution of CSF breeding sites (Amish 2006). Between distances of 2 to 6 km and 9 to 14 km frog breeding sites were more spatially autocorrelated than lentic sites (Fig. 3). At these shorter distances (2 to 6 km), increased spatial autocorrelation was likely produced by CSF dispersal. Both mark recapture and genetic data suggest that dispersal over distances less than 2 km is common, and that movements up to 7 km do occur (Amish 2006; Funk et al. 2005a; Funk et al. 2005b). At longer distances (9 to 14 km) within watershed or between watershed processes may explain the clustering of breeding sites. For example, since watersheds are of a similar size, clusters of lentic sites at the top and bottom of watersheds could have created a second cluster at distances of 9 – 14 km. In addition, their configuration could have also produced this second peak in breeding site configuration.

How do lentic habitat and CSF detection patterns in beaver and non-beaver watersheds differ?

To evaluate how beaver may influence the composition of lentic sites on the landscape, we examined the number of lentic sites, potential breeding sites, and known breeding sites in beaver and non-beaver watersheds. The number of lentic sites with Columbia spotted frog presence and breeding were higher in beaver watersheds than non-beaver watersheds. In beaver watersheds, frogs were almost always detected breeding at multiple sites, while non-beaver watersheds had much lower presence and breeding detection rates. Beaver watersheds have four times the median number of lentic sites, potential breeding sites, and known breeding sites than non-beaver watersheds (Table 3).

To investigate whether the larger number of breeding sites detected in beaver watersheds was simply a product of increased number of lentic sites, we examined the proportions of different site types (potential breeding, breeding) versus total lentic sites in beaver versus non-beaver watersheds. Beaver watersheds had a higher proportion of lentic habitat important to the breeding and overwintering of CSF (permanent and potential CSF breeding sites per lentic site), and a higher proportion of frogs detected per lentic site. Only breeding occupancy rate (proportion of CSF breeding per lentic and per potential breeding site) was not different (for details see Amish 2006).

There was no evidence of differences between the distribution of lentic habitat between beaver and non-beaver watersheds, but beaver watersheds had more dispersed frog breeding sites than non-beaver watersheds (Figure 4). Distances between watershed size, different habitat types (lentic sites, potential and breeding sites), as well as the longest nearest-neighbor distance were significantly longer in beaver watersheds including many nearest-neighbor distances that are beyond the typical dispersal distances of CSF (Table 4). This suggests that in beaver watersheds, occupancy was not closely tied to dispersal or distance among sites. Three hypothetical mechanisms that could produce these patterns include: (1) historic movement of beaver (and frogs) throughout the watershed, (2) conditions that create greater dispersal distances (such as riparian corridors that may be easier to move through), or (3) much larger population sizes (and subsequently more successful longer dispersal distances). In non-beaver watersheds, median distances between all habitat types are shorter (2 to 4 km) and rarely exceed typical dispersal distances (Table 4).

Overall genetic structure across western MT

Overall levels of genetic variation found using tadpoles was in accordance with earlier work done using adult Columbia spotted frogs (Amish 2006). Genetic structure within watersheds was characterized by high genetic differentiation between breeding sites with moderate levels of within population genetic diversity. The level of genetic structure seen (F_{ST} = 0.01 – 0.232) in this study across scales of 1 to 25 km was similar to recent work done on *R. luteiventris* (Funk et al. 2005a) and *R. cascadae* (Monsen & Blouin 2004). Lower values for the same scale (F_{ST} = 0.04 – 0.09) were seen for *R. temporaria* (Johansson et al. 2006) across a landscape with less physical relief and a more hospitable matrix. Estimated levels of expected heterozygosity were within the range seen in other anuran studies (reviewed Hoffman et al. 2004; Monsen & Blouin 2004).

Across the study area, watersheds appear to structure CSF populations. Similar to results in Funk et al. (2005a), basin or watershed groupings of breeding sites explained the highest portion of loci variation (here 18.1%) after the variation associated with breeding site (23.9%). Landscape structures associated with watersheds boundaries (like ridges) have been seen to be important for structuring populations of *R. luteiventris* (Funk et al. 2005a) and is well supported in the literature for other amphibians (García-Paris et al. 2000; Monsen & Blouin 2004; Shaffer et al. 2000; Tallmon et al. 2000). The strong genetic subdivisions seen in two montane frog species (Funk et al. 2005a, this study; Monsen & Blouin 2004) and known impacts from ridges suggest headwater watersheds are well suited for use as conservation and management units for Columbia spotted frogs.

Do watershed patterns of genetic variation match expected dispersal distances from capture – recapture data?

General agreement was seen between indirect estimates of dispersal distance and direct estimates of dispersal distances from the literature. We determined indirect estimates of dispersal from average F_{ST} values across distance classes and from a Mantel's correlogram. Mantel's correlogram results demonstrated isolation by distance patterns present across Euclidian distances of 0 - 5 km and riparian distances of 0 - 7.5 km (Fig. 5). Average F_{ST} values across three distance categories (0 - 2.5km, 2.5 - 7.5km, and > 7.5km) showed corresponding statistically significant breaks (Fig. 6). Together these data suggest that dispersal distances of up to 2 - 7.5 km distances from direct measures (Funk et al. 2005b; Pilliod et al. 2002; Turner 1960) are also reflected in genetic data.

Landscape analysis of genetic data suggests the arrangement and connection (dry land vs. riparian) of breeding sites will impact population connectivity. A lower average pair-wise F_{ST} between breeding sites when grouped by riparian versus Euclidian distance implies that although CSF are effective dispersers for short over land (Euclidian) distances they are more successful along riparian corridors over longer distances (Fig. 6).

These results have several implications for conservation and management units of Columbia spotted frogs. First, breeding sites or populations separated by distances greater than 5 - 7.5 km may be isolated from each other. IBD patterns suggest that in some areas, a stepping stone model of gene flow is appropriate when addressing population connectivity, while its absence suggests another model may be more appropriate depending on the landscape and population history. Second, terrestrial habitat surrounding ponds is known to be important for the conservation of most amphibian species (Semlitsch 2002). In watersheds with groups of breeding sites separated by distances of less than 5 km, maintenance of landscape characteristics conducive to over land dispersal may be important to their connectivity, while in watersheds with longer distances among ponds, riparian corridors are likely critical for maintaining populations.

How does beaver presence in the watershed characteristics affect frog population structure?

The composition and configuration of breeding sites within watersheds was reflected in the population structure of CSF. Watersheds classified by beaver presence showed sharp contrasts in the distribution of average F_{ST} values across distance classes (0 - 2.5, 2.5 - 7.5, > 7.5 km) (Fig. 7). For example, within non-beaver watersheds the level of genetic differentiation exhibited over short and medium distance classes suggested population subdivision, while beaver watersheds exhibited substantially lower average pair-wise F_{ST} values implying low population subdivision and connected populations over the same distances (Fig. 7). Beaver watersheds showed an IBD pattern, indicative of a stepping stone model of gene flow, and a high correlation between genetic and geographic distance. In contrast, nonbeaver watersheds showed no correlation between distance measures (Fig. 8).

Conclusions

Examining dispersal across different landscapes is essential for understanding population connectivity as well as how humans are altering it. Even though beaver (*Castor canadensis)* are considered ecosystem engineers, their effects on the spatial pattern of lentic habitat and subsequent effects on populations using those habitats has not been evaluated. We used a landscape database of watersheds in western Montana to examine the composition and configuration of different lentic habitat types and occupancy by Columbia spotted frogs (*Rana luteiventris*) and to compare beaver and non-beaver watersheds. Columbia spotted frogs displayed fine population structure within watersheds over distances of less than 20 km, thus factors influencing the spatial patterns of lentic sites at this scale likely affect population structure.

When beaver and non-beaver watersheds were compared large differences in lentic site composition and distribution were observed. Of primary importance, more lentic sites and more breeding sites were detected in beaver watersheds. An increase in four fold of breeding habitat is important for maintaining populations and reducing stochastic threats to their persistence. In addition to more overwintering and breeding habitat, beaver activity produced more evenly dispersed habitat configurations. Unlike nonbeaver watersheds, the longest distances observed between frog breeding sites in beaver watersheds exceeded estimates of dispersal ability. Beaver appear to alter the distribution of frogs on the landscape by facilitating either longer dispersal distances or the persistence of more isolated breeding sites.

The distribution of lentic sites, potential breeding sites, and known Columbia spotted frog breeding sites all displayed clustering within watersheds (Amish 2006). Clustering intensity showed little change when the distribution of potential breeding sites was compared to all lentic sites (Amish 2006). However, breeding sites were more clustered over distances of 2.5 – 6 km than the underlying pattern of available habitat. Mark-recapture studies and landscape genetics work suggest dispersal of CSF is common at distances less than 2 km and rare over distances of 5 to 7.5 km (Amish 2006; Funk et al. 2005b). However, it is not possible to distinguish from the data whether spatial dependence (sites are too dispersed at longer distances) or an ecological spatial processes (physical limit to dispersal ability) has resulted in the observed pattern of CSF breeding sites.

To investigate the effects of habitat and breeding site distribution on Columbia spotted frog population structure gene flow was estimated from allele frequencies at eight microsatellite markers. CSF breeding sites displayed fine scale population structure with limited gene flow and isolation by distance patterns in 4 of 6 watersheds (Amish 2006). Population structure within watersheds agreed with the scale implied by capture-recapture data from the literature. Based on Mantel's correlograms and median F_{ST} values, statistically and biologically significant genetic divergence began at distances between 5 and 7.5 km depending on whether an overland or riparian travel route was assumed. Watersheds where beaver presence was detected showed higher levels of population connectivity over distances up to 7.5km. Specifically, although beaver watersheds had longer distances between breeding sites, genetic differentiation was lower than in nonbeaver watersheds. Beaver appeared to alter the distribution of CSF on the landscape by creating watersheds where populations were separated by distances longer than direct or indirect estimates of dispersal support and showed less isolation than expected.

As ecosystem engineers, beaver physically alter their environment changing the pattern of lentic habitat on the landscape (Power et al. 1996). Because Columbia spotted frogs have limited vagility and stochastic recruitment (Amish 2006, Maxell unpub. data; Funk et al. 2005a; Funk et al. 2005b), connectivity is important for maintaining populations over time. By creating habitat, beaver redistribute frogs across the landscape and modify watershed structure. Watershed patterns and beaver ecology are intertwined with population processes of Columbia spotted frogs and play an important role in their persistence, especially on arid landscapes. It is likely changes to the distribution of lentic habitat in watersheds are also important for other lentic breeding amphibians.

Table 1. Watershed classification: watershed name; watershed type based on average distance between breeding sites (S = short, L = long), and beaver detection; watershed area in hectares; number of breeding sites within watershed; total riparian distance between all breeding sites in meters; number of confluences between breeding sites.

	Type		Area	Breeding	Riparian	
Watershed	**Distances**	**Beaver**	(hectares)	**sites**	**distance** (m)	**Confluences**
Seymour Crk	S	Y	7473	14	47020	5
Pintler Crk	L	N	8470	9	33346	4
Squaw Crk	S	Y	5265	4	16731	3
Alder Crk	L	N	5615	7	24929	7
N. Fork Fish Crk	S	N	6791	6	22689	5
Cache Crk	L	Y	11657	5	30353	4

Table 2. Sampled breeding sites organized by eco-region, mountain range, and watershed: Site number; number of complete genotypes (N); average number of alleles (N_a); expected heterozygosity (H_e); number of egg masses detected; site elevation (meters); Universal Transverse Mercator coordinates (UTME & UTMN).

Location & Site Number	N	N_a	H_e	Egg Masses	Elevation	UTM Zone	UTME	UTMN
West-central Montana Ecoregion								
Northern Bitterroot Mountains								
Cache Creek								
C1	25	5.500	0.628	-	3920	11	677396	5184482
C2	25	3.625	0.531	-	4200	11	678066	5183416
C3	32	4.000	0.524	-	6230	11	670567	5186025
C4	32	2.000	0.286	-	6300	11	669314	5183148
C5	32	2.875	0.424	-	6321	11	670643	5178585
North Fork Fish Creek								
NF1	33	3.750	0.519	-	6230	11	658511	5203903
NF2	32	4.250	0.616	-	6000	11	659861	5199601
NF3	16	3.500	0.522	-	6263	11	656897	5199001
NF4	31	4.375	0.645	-	6480	11	658304	5197711
NF5	34	4.875	0.634	-	5763	11	656302	5197843
NF6	20	4.000	0.594	-	6280	11	655038	5200819
Southwestern Montana Ecoregion								
Pioneer Range								
Alder Creek								
A1	18	4.125	0.543	-	7162	12	336002	5074716
A2	31	3.625	0.532	-	2626	12	333746	5072359
A3	29	3.875	0.438	16	2621	12	333581	5072493
A4	25	3.375	0.418	-	2631	12	333950	5071851
A5	13	2.625	0.465	2	2808	12	333333	5025469
A6	10	1.750	0.259	1	2863	12	331887	5068054
A7	25	4.125	0.436	4	2760	12	334274	5067413
Squaw Creek								
SQ1	10	3.125	0.507	-	2161	12	323919	5070170
SQ2	15	3.875	0.468	-	2174	12	324156	5070337
SQ3	24	3.625	0.510	-	2471	12	325837	5067442
SQ4	23	3.875	0.476	-	2403	12	326050	5067875
SQ5	14	3.750	0.452	-	2386	12	327346	5069299
Pintler Range								
Pintler Creek								
P1	39	4.625	0.508	-	2147	12	309924	5076789
P2	30	4.000	0.526	-	2156	12	311048	5078736
P3	31	4.125	0.456	-	2147	12		
P4	31	4.375	0.396	9	2198	12	308580	5083413
P5	16	2.625	0.351	-	2829	12	304679	5087382
P6	32	4.125	0.496	-	2737	12	303806	5086491
P7	15	2.750	0.368	-	2856	12		
P8	29	3.500	0.474	-	2917	12	304239	5088054
P9	32	3.875	0.505	-	2733	12		
PX	15	2.125	0.370	-	2706	12	303523	5085827
Seymour Creek								
S1	32	3.875	0.502	-	2042	12	330416	5088038
S2	34	4.125	0.515	5	2181	12	332365	5090859
S3	18	4.125	0.497	-	2174	12	331977	5091255
S4	32	4.000	0.529	-	2236	12	332929	5092162
S5	33	4.375	0.572	-	2413	12	330247	5093579
S6	36	4.500	0.547	-	2454	12	330224	5094284
S7	31	4.375	0.580	-	2467	12	330129	5094520
S8	30	4.000	0.520	-	2311	12	330781	5094870
S9	30	4.375	0.546	-	2324	12	330883	5095427
S10	28	4.000	0.546	-	2372	12	330883	5095724
S11	30	4.125	0.566	20	2348	12	330799	5095724
S12	28	3.625	0.484	-	2377	12	330130	5096333
S13	32	3.375	0.511	-	2617	12	325691	5100797
S14	31	3.000	0.471	111	2863	12	323931	5099542

Table 3. Summary of watershed detection rates (number of watersheds with activity detected) for beaver and Columbia spotted frogs (CSF) and median number of lentic habitat types observed or detected between two ecoregions and beaver and nonbeaver watersheds. Variables include lentic sites holding water at time of survey (wet), permanent hydroperiod (perm), potential CSF breeding sites, and CSF breeding detected at one or more site.

	Watershed detection rate				**Median number of sites within watersheds**			
	Beaver	CSF presence	CSF breeding	>1 CSF breeding site	Wet lentic	Perm lentic	Potential CSF breeding	CSF breeding
West-central	27%	83%	74%	45%	6.5	2.5	3.0	1.5
Southwestern	53%	83%	71%	60%	11.0	3.0	5.0	2.0
Non-beaver	NA	70%	57%	65%	4	1	2	1
Beaver	NA	98%	92%	80%	16	6	8	4

Table 4. A comparison of watershed characteristics and lentic habitat configurations for beaver and non-beaver watersheds. Gradient and median watershed area were investigated as possible sources of bias in the data set. Distances were measured along riparian corridors. Median values and Mann-Whitney U (M-W) and Kolmogorov-Smirnov (K-S) test p-values are reported.

	All	**Beaver**	**Non-beaver**	**p-value**	
				M-W	K-S
Gradient (m/km)	46	41.3	49.6	0.158	0.142
Watershed area (hectares)	7111	8346	7067	0.040	0.212
Distance between lowest to highest lentic site (km)	12.1	15.1	9.8	0.005	0.008
Distance between lowest to highest potential CSF breeding sites (km)	7.0	9.2	5.1	0.032	0.041
Distance between lowest to highest CSF breeding sites (km)	7.7	8.6	5.1	0.002	0.013
Longest nearest-neighbor distance between breeding sites (km)	7.1	8.3	5.7	0.017	0.077
Distance between all CSF breeding sites (km)	1.6	1.9	1.2	0.586	0.978

Figure 1. Map of study area: Inset map shows the nine eco-regions of western Montana with the two involved in this study in gold and orange; map detail shows watersheds in the two southwestern eco-regions used in the landscape analysis in corresponding gold and orange; watershed pairs for genetics analysis are shown in solid grey and are labeled by mountain range.

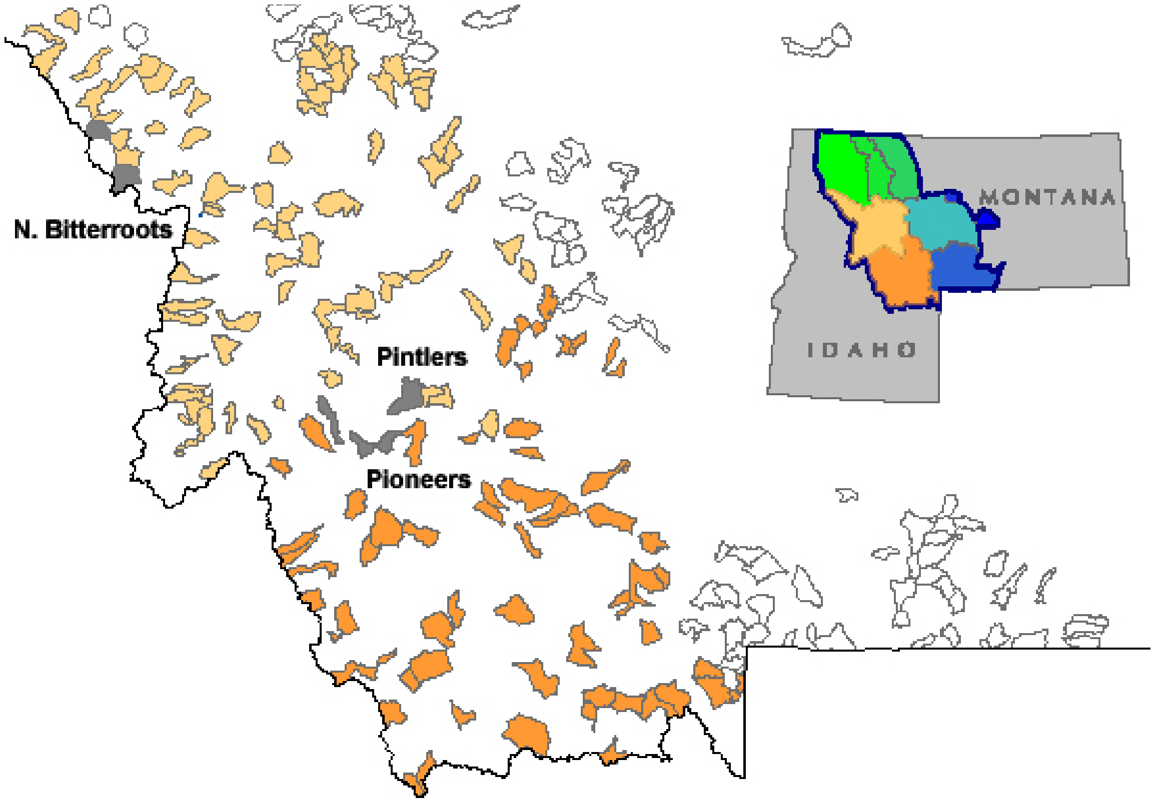


Figure 2. Detail of watershed pairs: northern Bitterroot watersheds are the North Fork Fish Creek and Cache Creek; Pintler watersheds are Pintler Creek and Seymour Creek; Pioneer watersheds are Alder Creek and Squaw Creek; breeding sites are numbered from the bottom to the top of the watershed; site number shading reflect groupings from UPGMA tree; red sites were not grouped with other sites within their watershed; circled sites were most closely grouped with sites in watersheds across the Big Hole River; sites with squares around them are most closely associated with sites within contrasting watershed.

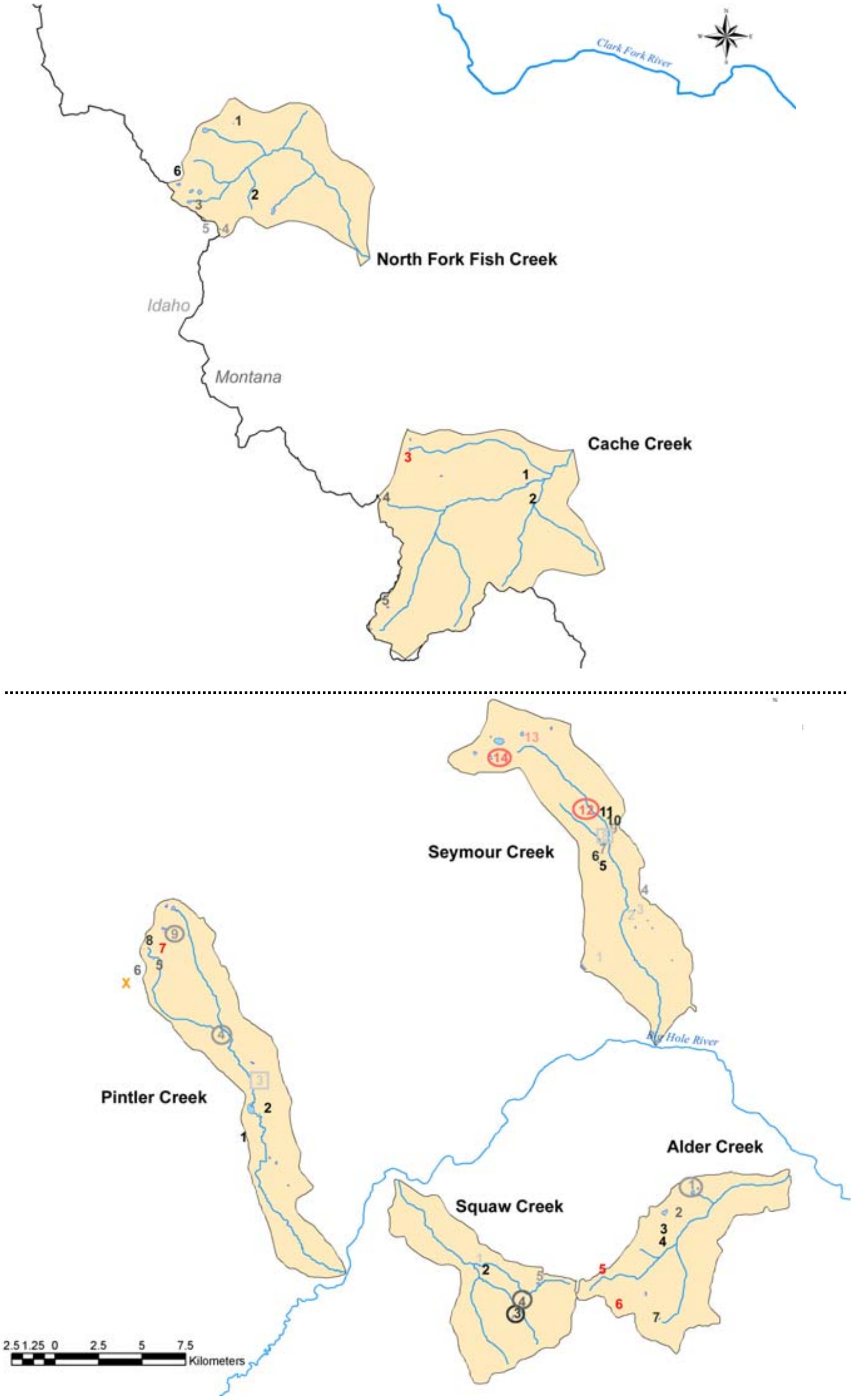


Figure 3. Pair correlation function showing the clustering and dispersion of CSF breeding sites within all watersheds. The x-axis represents the distance in meters between sites. Points above the dashed line at pcf(r) = 1 represent clustering and points below represent dispersion compared to a stationary Poisson process. The distribution of all lentic sites is shown with dotted line and CSF breeding sites is shown with solid line.

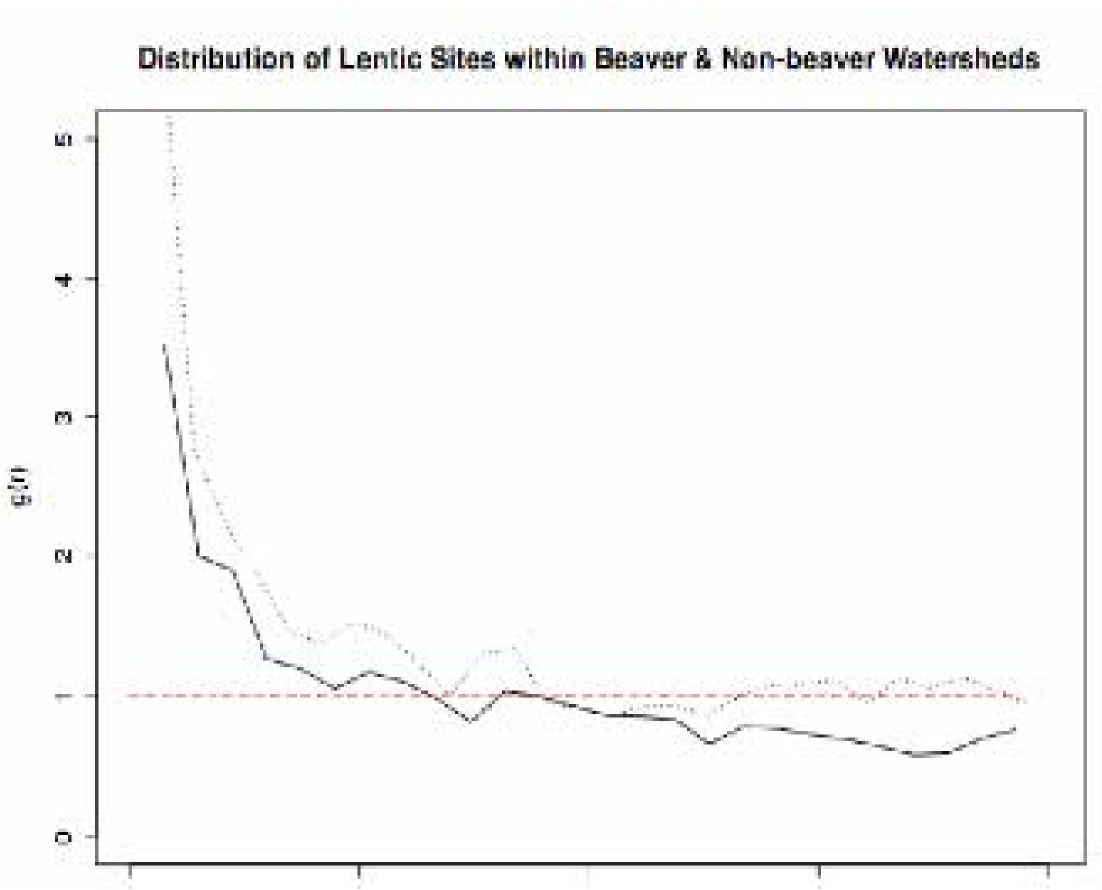
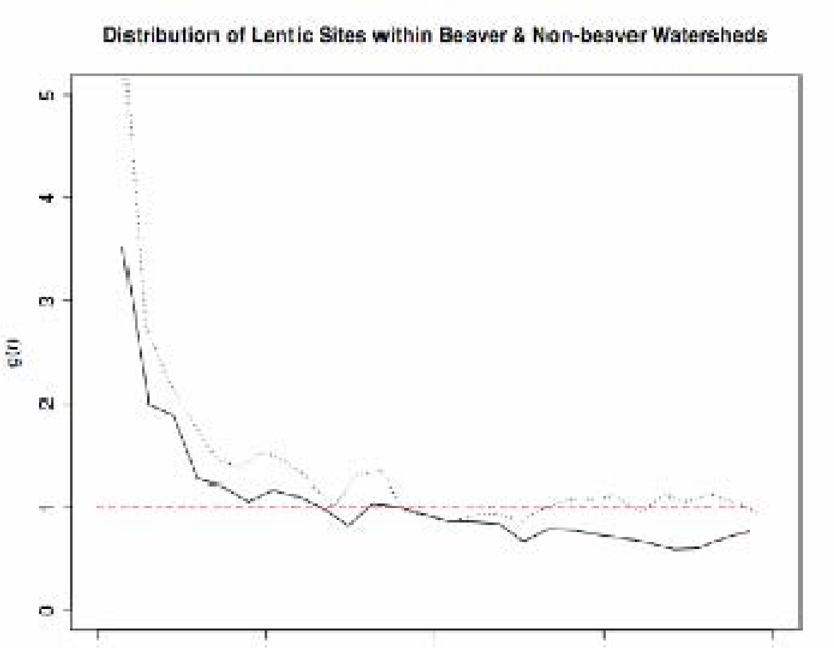


Figure 4. Pair correlation function showing the clustering and dispersion of CSF lentic sites within beaver and non-beaver watersheds. The x-axis represents the distance in meters between sites. Points above the dashed line at pcf(r) = 1 represent clustering and points below represent dispersion compared to a stationary Poisson process. Lentic site distribution in non-beaver watersheds is represented with dotted line and the distribution of lentic sites in beaver watersheds is shown with solid line. The distribution of CSF breeding sites in non-beaver watersheds is shown with dotted line and CSF breeding site distribution in beaver watersheds is represented with solid line.

(4a)



(4b)

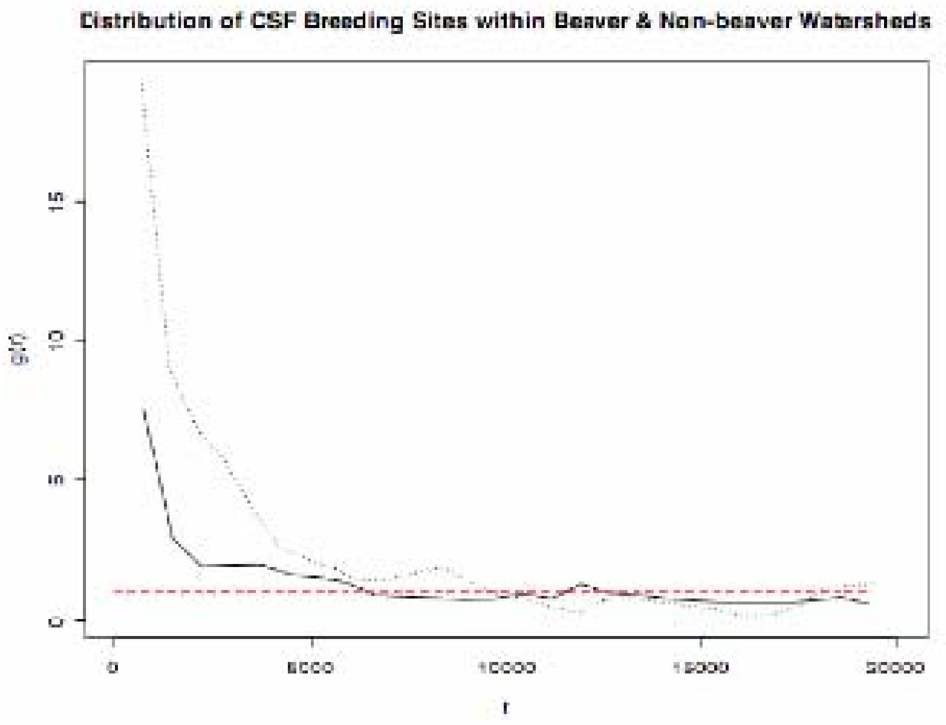


Figure 5. Mantel's correlogram across increasing distance classes: correlation (r) of geographic distance with genetic distance plotted with circles for Euclidian distance and triangles for riparian distance. Significance at the $p < 0.05$ level for the coefficient is represented by solid fill.

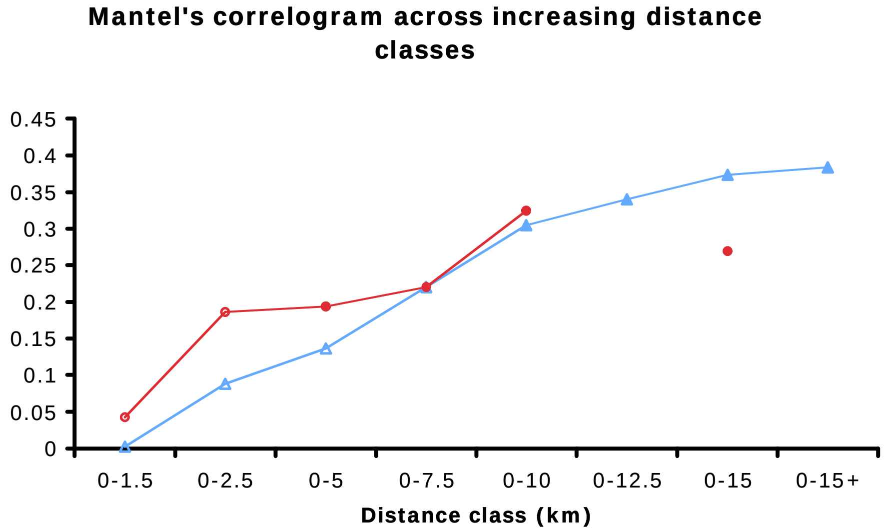


Figure 6. Within Watershed Genetic Variation Across Three Distance Categories: Average pair-wise F_{ST} values compared across distance classes using Euclidian and riparian geographic distance measures. The 95% CI's do not overlap between the starred and next smallest distance class.

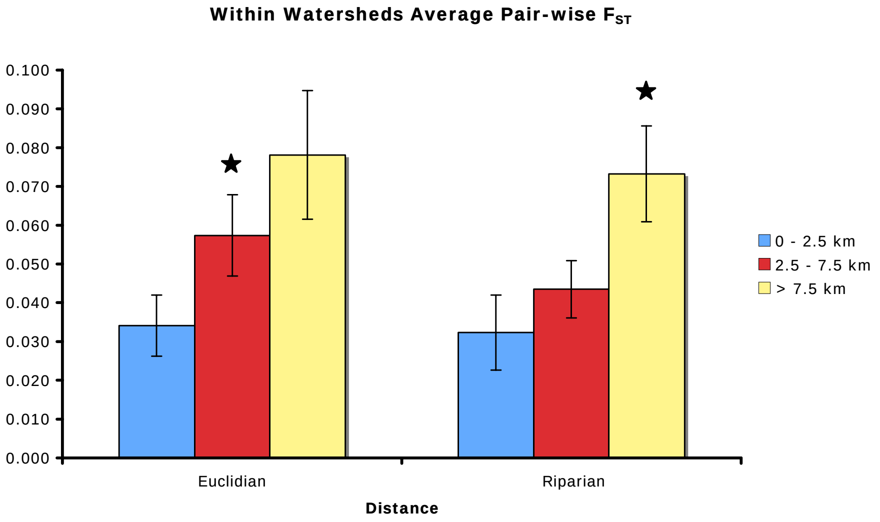
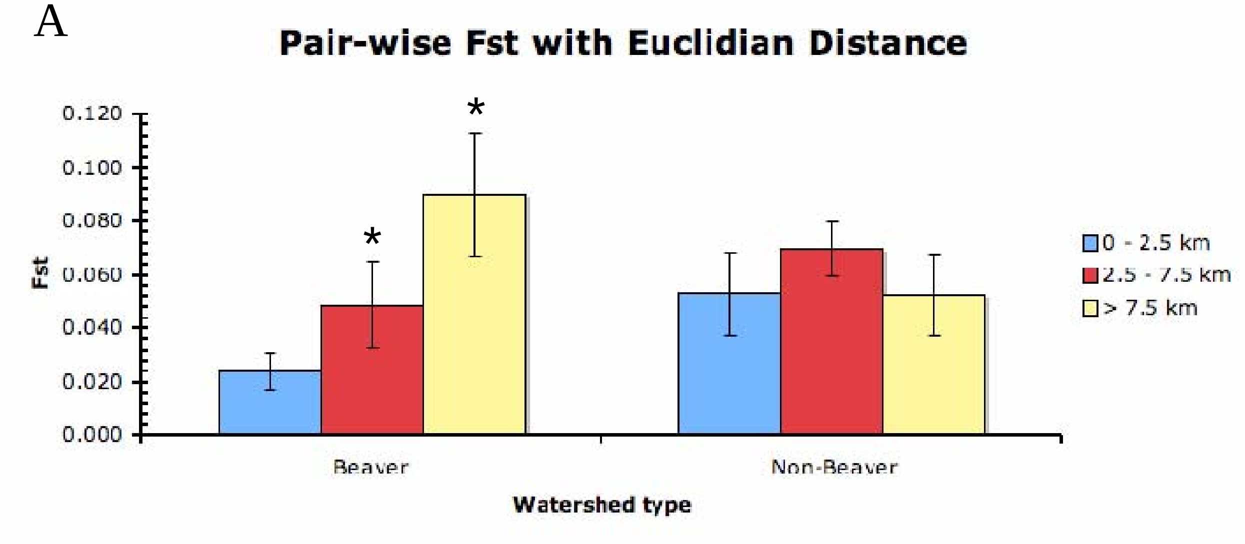


Figure 7. Genetic variation and geographic distance when watersheds are partitioned by type: Three beaver and non-beaver watershed pairs were originally selected for study, but a measure of watershed complexity was used after sampling was completed to investigate the effects of partitioning watersheds based on the distribution of lentic sites. The 95% CI's do not overlap between the starred and next smallest distance class.

A



B

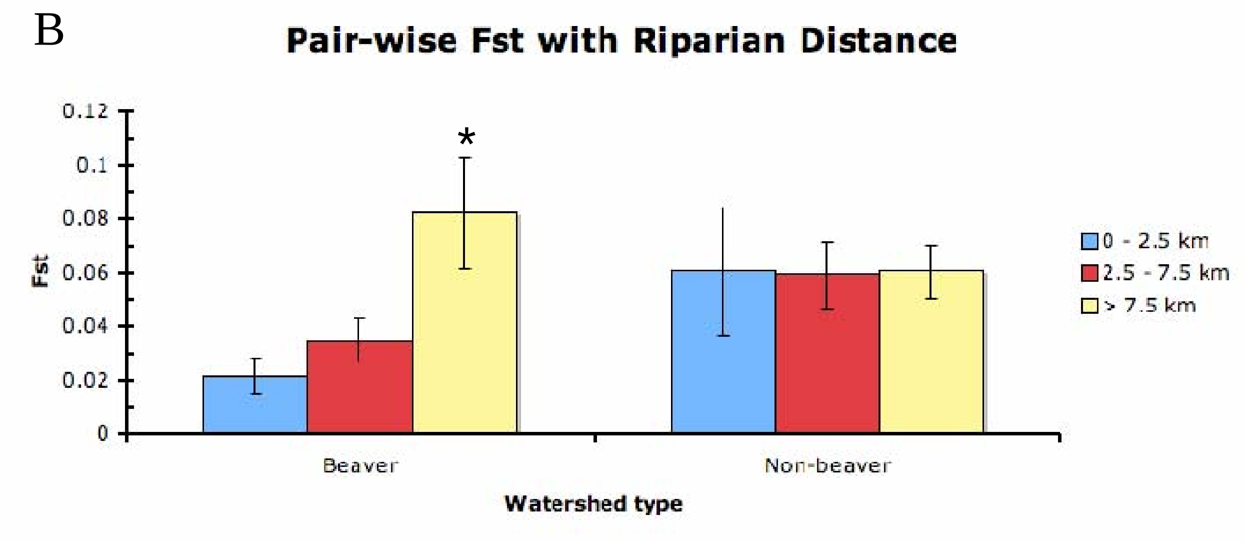
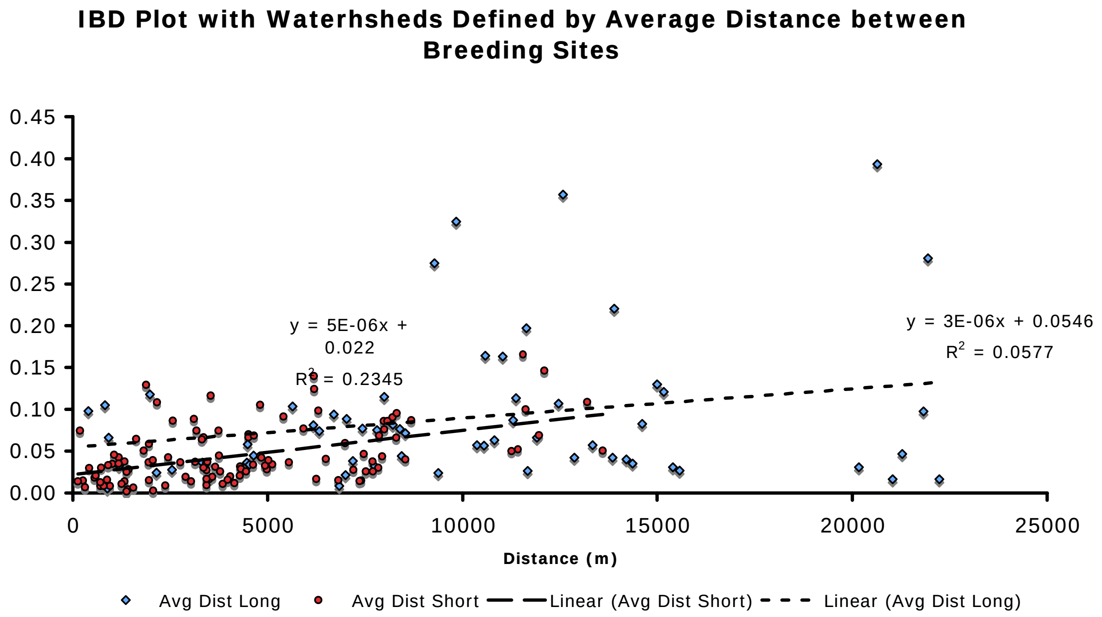
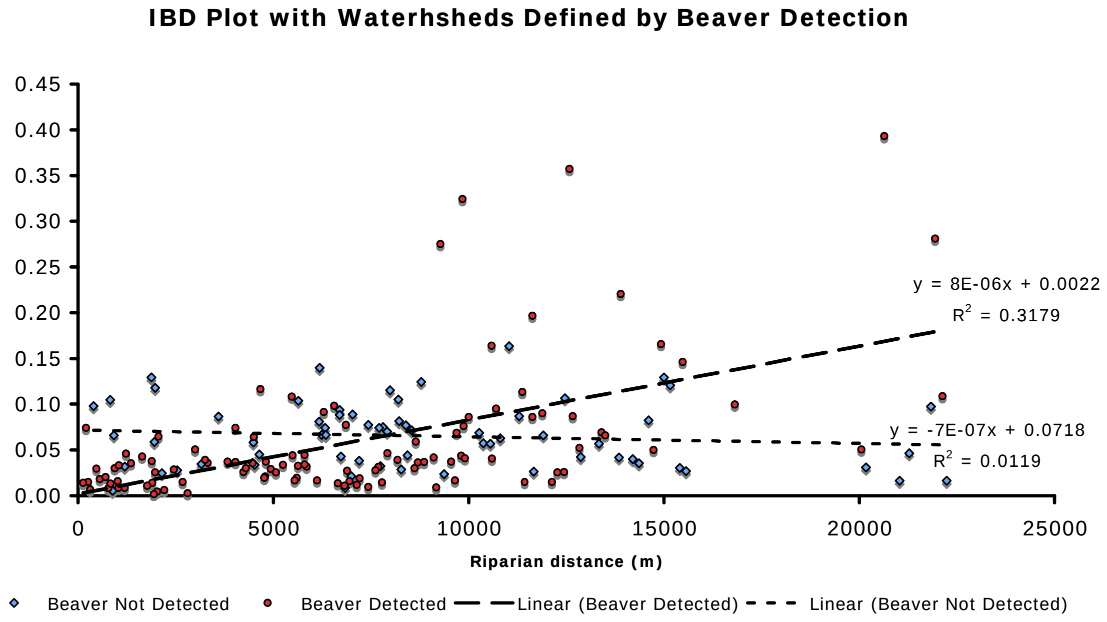


Figure 8. Isolation by distance graphs for two watershed characteristics: A) Watersheds are identified by the average distance between breeding sites (short and long), with short watersheds showing Euclidian distance plotted against genetic distance while long watersheds show riparian distance plotted against genetic distance. B) Watersheds are identified by beaver presence and riparian distance is plotted against genetic distance.

A)



B)



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Investigation of microbial ecology, structure, and function in coalbed aquifers: Powder River Basin, Montana

Basic Information

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Montana Water Center
Montana State University
Bozeman, Montana

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Abstract

In southeastern Montana, coal beds supply coal for energy; water for domestic and agricultural uses, and are being developed for coalbed methane (CBM). A comprehensive understanding of the relationships between the hydrogeologic systems and the total microbial community at depth will help establish best management practices for methane production.

The origin of CBM in the Powder River Basin (PRB) is the result of microbial processes (biogenic methanogenesis). The purpose of this research is to begin the process of identifying the structure, diversity and presumptive function of the total microbial community and ecology within a specific methane-bearing coalbed aquifer in the PRB and conduct culture-based investigations that will help delineate the kinetic rates and pathways for methanogenesis.

Samples of coal and coal-aquifer water were collected and analyzed. The coalbed water-quality sample is typical of CBM production water in the PRB, with a total dissolved solids concentration of 2,056 mg/L, specific conductivity of 3,275 umhos/cm^2, a sulfate concentration of less than 2.5 mg/L, and a sodium adsorption ratio of 25.5.

Results of total microbial community analyses from the aqueous phase indicate a relatively low diversity of the total community. Sequencing of several prevalent bands indicated that all presumptive identities, based on known sequences in the Ribosomal Database (RDP II), had relevant metabolic capabilities consistent for their presumed role in coal formations that generate methane.

The methanogen sequences, also derived from the aqueous phase, were closely associated with the genus *Methanolobus* within the order *Methanosarcinales*. In addition, all five organisms were most closely related to the species *M. taylorii* or *M. oregonensis* (averaging 93% homology). Interestingly and unexpectedly, this group is typically linked with marine environments, which may indicate that they thrive in a high sodium environment. However, the geological formation and shallow depth where this sample was taken have not been associated with ancient marine origins.

In addition, seven sequences were produced from a coal sample, and all are related to members of the *Methanosarcinales* or *Methanobacteriales* orders. Six appear to be unique from each other and their closest matches are to environmental clones from various methane-related origins.

In addition to the molecular data, coal samples were incubated in an anaerobic growth media used to specifically culture methanogens. To date this has proven to be unproductive. However, growth is typically very slow and may take a period of time well beyond the time frame of this study.

This initial investigation proved to be an excellent starting point for continuing efforts toward unraveling the complexity of the microbial community responsible for biogenic methane production.

Introduction and background

Coal beds supply three critical resources in southeastern Montana: 1) coal for energy; 2) water for domestic and agricultural uses; and 3) coalbed methane. Currently, coalbed aquifers are being impacted by conventional coalbed methane (CBM) development. As concerns of global warming increase, speculation that these aquifers may serve as repositories for industrial CO_2 suggests that additional impacts are likely in the future. A comprehensive understanding of the relationships between the hydrogeologic systems and the total microbial community at depth will help establish best management practices for methane production and potential CO_2 sequestration. Minimizing waste of the methane and the production water is key to preserving the aquifers yet allowing for long-term methane production, and may help remediate the atmospheric CO_2.

Methane is held on cleat faces and micropore surfaces in coal by a combination of physical sorption and hydrostatic pressure from ground water in the coal (Law and others, 1991; Rightmire, 1984), and is released when the water pressure is reduced. To reduce hydrostatic pressure and capture released gas, water is pumped from wells drilled and completed in coalbeds.

The origin of CBM in the Powder River Basin (PRB) is the result of biogenic methanogenesis, a microbial process (Law and others, 1991). The success of CO_2 sequestration strategies may be a function of microbial activities as well. The purpose of this research is to begin the process of identifying the structure, diversity and presumptive function of the total microbial community and ecology within a specific methane-bearing coalbed aquifer in the PRB and conduct culture-based investigations that will help delineate the kinetic rates and pathways for methanogenesis. We foresee the value of data collected during this project as a means of moving toward a philosophy of harvesting CBM over long periods of time.

There are two distinct types of ground-water flow systems in the Powder River Basin, a deep regional system and a series of local flow systems. Ground water flows generally from the south to the north, with flow in the local systems reflecting topographic control. Ground-water recharge occurs at outcrop areas around the edges of the Basin in Wyoming and in high clinker-capped ridges such as the Wolf Mountains in Montana (Wheaton and Donato, 2004). Coal seams are the most continuous water-bearing geologic units and have hydraulic conductivity values equal to or slightly greater than those in sandstone aquifers.

Due to the geologic structure of the Powder River Basin, and the topographic relationship between generally higher elevations in Wyoming and lower elevations in Montana, coal seams crop out along valley walls in Montana and ground-water discharge areas are reflected in the springs that occur in these outcrop areas. Additional ground-water discharge occurs as baseflow to streams and rivers in Montana.

The quality of ground water in the Powder River Basin reflects chemical and biological reactions that occur along flow paths. In deep coal beds, such as those that contain coalbed methane, chemical reactions have greatly reduced the amounts of sulfate, calcium, and magnesium, and the water quality is dominated by moderate concentrations of sodium and bicarbonate. Coalbed methane can only exist in the sulfate-depleted, anoxic conditions which occur in deeper coals. All CBM production water is rich in sodium and much of it has a high SAR value and moderate concentrations of total dissolved solids (Van Voast, 2003).

It is understood that biogenic methane is produced as an end-product of a complex set of metabolic pathways represented by a consortium of microorganisms, including members of the domains *Eubacteria* and *Archaea*. This intricate and closely associated assemblage resides in anoxic zones depleted of typical electron acceptors (sulfate, nitrate, ferrous iron) found in many subsurface environments. Four groups of functionally diverse prokaryotes have been identified, as being necessary for the formation of methane under these conditions: 1) hydrolytic bacteria, 2) fermentative bacteria, 3) acetogenic bacteria and 4) methanogens (Whiticar, 1999). Each of these groups of microorganisms is responsible for an important function in the methanogenic pathway.

The hydrolysis of higher molecular weight substrates, such as cellulose, high molecular weight proteins and mixed composition polysaccharides by hydrolytic and cellulolytic competent bacteria is a necessary first step in the decomposition of organic materials (Figure 1). It has been postulated that this process is the rate limiting step in the formation of methane in anoxic environments. Following their breakdown into monomeric subunits such as short-chain fatty acids, sugars, amino acids and additional substrates (e.g. ammonia and hydrogen sulfide), fermentation proceeds, mediated by assorted fermentative bacteria.

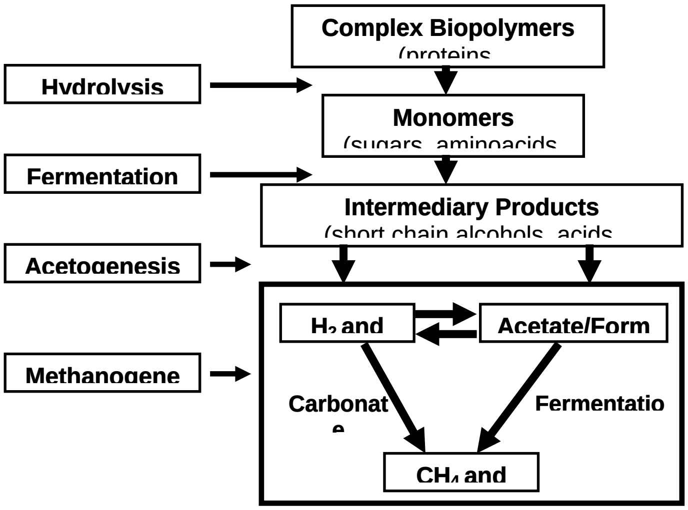


Figure 1. Anaerobic degradation of organic

The fermentation process produces a number of byproducts, including additional short-chain alcohols and acids (propionate and butyrate are common), as well as, acetate, formate and carbon dioxide (CO_2). Because methanogens metabolize a narrow range of compounds and are restricted to anoxic environments with redox potentials of Eh < -200 mV (Budwill, 2003), some further degradation is assumed to be required. Syntrophic acetogenic bacteria play an important role in consuming many of the short-chain acids that accumulate in the pathway, and the end products, predominately acetate and CO_2, become viable substrates for methanogenesis.

The final step prior to conversion to methane is to convert any remaining alcohols and acids into acetate, carbon dioxide (methanol and methylamines may also be substrates for methanogenesis), hydrogen (H_2) and in some cases formate. This general scheme of anaerobic degradation of organic compounds to methane is diagrammed in figure 1.

Although the reduction of carbon dioxide by hydrogen (equation 1) is thought to be the most commonly used method for the production of methane in anoxic environments (Scott, 1999), the reduction of acetate, or a very limited methyl group containing hydrocarbon (equation 2) provides a greater change in free energy and therefore is more favorable for energy conservation. This situation remains unclear, as the opposite is thought to be true in certain environments such as marine or open freshwater settings (Whiticar and others, 1986). The two pathways may operate simultaneously under some circumstances and at differing stages of sedimentation of organic materials (Kotelnikova, 2002). While each of the two reductive processes produces methane, the two separate pathways may be active. The former by the (hydrogen mediated reduction of carbon dioxide) carbonate reduction pathway and the latter by the fermentation pathway. The general chemical equations for the respective pathways are illustrated below.

Equation 1:

Carbonate reduction pathway: $4\ H_2 + HCO_3^- + H^+ = CH_4 + 3H_2O$
(µG° -3.2 KJ)*

Equation 2:

Fermentation (methyl-group) pathway: $CH_3COO^- + H_2O = CH_4 + HCO_3^-$
(µG° -24.7 KJ)*

*Reported free energy values vary from source to source.

Evidence supporting the notion that the two pathways operate at various times was reported by Chin and others, (2003). They described temporal changes in methanogen production in flooded rice paddies. Their findings indicate that structural changes in the methanogenic community lead to functional changes in methane production with time. Similarly Scheid and others (2003) using rice roots as a community model for methanogenesis were able to show methanogenic community shifts when nitrate and sulfate were introduced. Apparently, the addition of alternative electron acceptors leads to changes in community substrate usage and may have broad effects on community structure and activity. Likely, competition between methanogens and sulfate- and nitrate-reducing bacteria led to these changes.

The use of culture-independent molecular techniques for our investigation is crucial. It is generally accepted that classic culturing techniques may under represent microbial diversity in typical environments by two to three orders of magnitude (Torsvik and others, 1990a; Torsvik and others, 1990b). It is apparent that microbial communities and their associated populations play important roles in biogeochemical and physicochemical processes including methanogenesis and carbon cycling. Functional guilds of bacteria that have been associated with biogenic methane production include hydrolytic and cellulolytic bacteria, fermentative and acetogenic bacteria, as well as methanogens (Whiticar, 1999). However; Polman and others (1993) reported that there were no viable microorganisms in three different ranked coals. Their observations were based on results of experiments attempting to grow bacteria in cultures. Vorres (1990) reported that anaerobically preserved coals produced methane in sealed ampoules. Also these samples contained cultivable Clostridium species. In 1994, work by both Johnson and others (1994), and Volkwein and others (1994), noted that higher-rank coals produced low-molecular-weight organic acids when they were inoculated with presumptive anaerobic consortiums from various sources. Based on additional work completed by these groups, they concluded that the microorganisms collected from those environments (that were likely to contain methanogens and other consortium members) were responsible for the production of the methane. In Volkwein and others, (1994), cultures remained viable and continued to produce methane through five successive transfers, however they were unsuccessful at identifying any of the microorganisms.

The purpose of this research was to elucidate the diversity, composition, activity and function of the methane producing microbial community in coalbeds. The findings will have broader impacts than simply exploring the microbial ecology of a novel subsurface environment. Understanding the nature of the microbial ecology of coal beds will contribute knowledge toward management of enhanced microbial methane production and recovery, and possibly contribute to CO_2 sequestration efforts thereby impacting greenhouse gas mitigation strategies.

Methods

Sample collection

Two microbial samples were collected in Wyoming from the Tongue River Member, Big George coal seam. The sites are in the Powder River watershed in east central Johnson County, Wyoming. The coal samples were collected during under reaming, using forward air rotary, of an already cased CBM well. The samples were gathered from the diverter pipe on the drill rig with a sample screen. In less than one minute the coal was inserted into an anaerobic chamber with an oxygen-consuming package and sealed. The coal samples were held in cold storage until they arrived at the laboratory at the University of Montana. A water-quality sample was collected at a nearby CBM discharge point from wells completed in the same coal seam, but different from the well where the coal samples were collected. The water-sample was submitted to the Montana Bureau of Mines and Geology analytical laboratory for analysis.

The upper coal sample was collected while reaming from 1,525 feet to 1,530 feet below ground surface. The second coal sample was collected just after reaching the base of coal (1,596 feet) while cleaning the borehole. Because the well was cased, neither coal sample contained material from farther up the bore hole, and appeared clean and in good condition.

Molecular Analysis

Nucleic Acid extraction

Aqueous phase: To increase the biomass for molecular analysis, cells were collected by filtration onto three separate 142-mm Supor (Pall Corporation, Ann Arbor, MI) 0.2 um membrane filters. Each filter received an approximate equal volume of groundwater (approximately 13 liters). Filters were placed in sterile Whirl-Pak bags (Nasco, Fort Atkinson, WI) and frozen at -80° C. Prior to genomic DNA extraction, the frozen filter was crushed thoroughly within the collection bag. Processing of total community DNA from the filter was carried out by the direct lysis method of Holben (1997) with minor modifications. Briefly, 20 ml of autoclaved extraction buffer (200 mM sodium phosphate buffer (NaPO4), 100 mM ethylenediamine tetra-acetate (EDTA) and 1.5% sodium dodecyl sulfate (SDS), pH 8.0) was added to sterile Oak Ridge tubes containing sterile glass beads (5 g of 0.2 mm and 5 g of 1 mm diameter) (Sigma Chemical Co., St. Louis, MO.). To this tube, one macerated filter was added, placed in a 70° C water bath for 30 minutes with frequent vortexing (5 minute intervals). Tubes were then placed on a reciprocal platform shaker and shaken on high (approximately 100 oscillations/minute) for 30 minutes at room temperature. Filter, particulate and cell debris were removed by centrifugation (Sovall RC 5B Plus with SS34 rotor) at 10,000 RPM (7,796 x g) for 10 minutes at 10° C. Supernatant was transferred to clean Oak Ridge tubes and incubated on ice for 30 minutes to precipitate the SDS, then centrifuged as above to pellet SDS. Liquid was transferred to new 50 ml tubes with addition of 10% volume 3 M sodium acetate (pH

5.2) and 2.5 volumes 100% cold ethanol. After overnight incubation at -20° C, nucleic acids were collected by centrifugation, as described above. Nucleic acid pellets were resuspended in approximately 1 ml of sterile deionized water and precipitated by addition of 2.5 volumes 100% cold ethanol and placed at -20° overnight. After centrifugation (as above) the resulting nucleic acid pellet was air dried and suspended in approximately 500 ul TE buffer (10 mM Tris, 1 mM EDTA, pH 8.0).

Solid phase: Anaerobic coal samples were subjected to direct nucleic acid extraction, as well as used as inocula in both groundwater and growth media. Direct nucleic acid extractions were performed using Power Soil DNA Extraction Kits (Mo Bio, Solano Beach, CA) as per manufacture's suggestion. In addition to standard extractions, coal samples were subjected to further DNA purification which included the addition of chaotropic salts (6M guanidine HCl) with ethanol washes in combination with silicon binding matrices. This method has proven to be beneficial when attempting to amplify various environmental samples.

PCR amplification

Resulting DNA from both solid and aqueous phases was subsequently subjected to DNA amplification by the Polymerase Chain Reaction (PCR) using both generally conserved primers and methanogen specific primer sets 16S rDNA primers (536fc and 907r) as well as the methanogen-specific primer pair 23fc and 440r). Both of these primer sets provided sufficient amplification to generate adequate PCR product for Denaturing Gradient Gel Electrophoresis (DGGE) analysis. More recently, the genomic DNA was amplified with a additional primer sets (ME1 and ME2), which are specific for the *mcr* (methyl coenzyme M reductase) gene (alpha subunit). The expected product is approximately 750 kb. The result of this amplification gave correct size products, which were gel purified and are to be used to align with groups of other amplicons derived from Powder River Basin coal samples and associated aquifers. From these alignments "coal specific" methanogen primers will be constructed, which will be used to amplify any samples that are coal related.

Denaturing Gradient Gel Electrophoresis (DGGE)

As mentioned above, the first two sets of primers (ME1 and ME2) generated amplicons from PCR amplification that were subjected to further analysis by DGGE. This method of analysis separates double stranded DNA amplicons run in an acrylamide gel matrix based on sequence differences. The gel matrix also contains a linear gradient of urea and formamide which act in concert to induce denaturing of the DNA strand. In figure 2, (below) each individual band theoretically represents an individual organism.

Sequence analysis

Sequence analysis is the process of identifying an organism based on it genomic nucleotide content. Bands of PCR amplified DNA were selected from the DGGE analysis (figure 2), excised and used directly for cloning and DNA sequence analysis. PCR products obtained using the ME1 and ME2 primer sets were used to generate direct clone libraries. All PCR products, whether cut from gels or derived directly from amplification, were subject to a blunt-end cloning procedure, in which the pT7Blue-3 plasmid vector was used with the Perfectly Blunt Cloning Kit (Novagen, Madison, WI), as per manufacture's suggestion. Putative plasmid clones were identified based on blue-white screening. Plasmid DNA was subsequently purified using Qiagen mini-prep kits (Qiagen, Valencia, CA) according to the manufacturer's specifications. Insert size of individual clones was confirmed by restriction fragment analysis using *Eco*RI. All confirmed clones were subjected to unidirectional DNA sequence analysis and sequence comparison to determine the best match to known sequences using the either the Ribosomal Database Project II website at http://www.cme.msu.edu/RDP/html/index.html. or a Blast search on the NCBI website.

Culturing methods

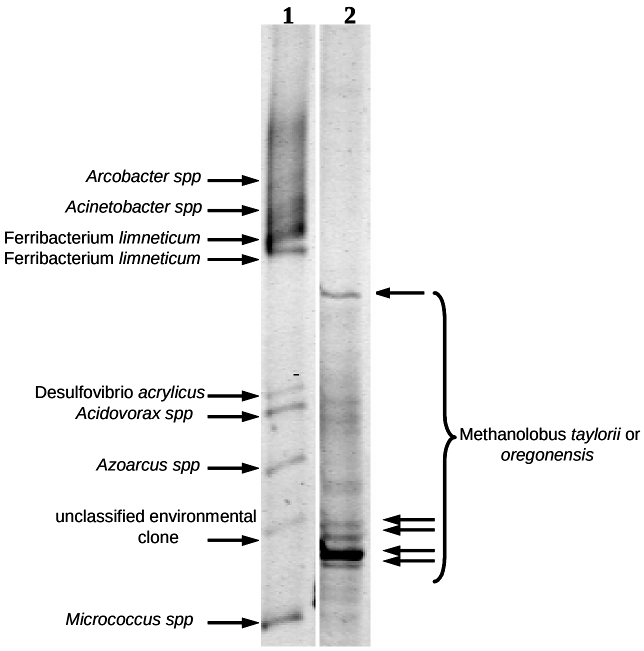
Coal samples were also used as inocula. Reduced ground water and growth media were allowed to incubate in the dark at room temperature. The growth medium for culturing core samples and for growing anaerobic consortia consisted of a modified mineral salts solution (Fedorak and Hrudey, 1984). Cultures were incubated in a headspace gas of 20% CO_2 and 80% N_2. Bottles were sealed with butyl rubber stoppers and crimped down with aluminum seals and received 0.35 g $NaHCO_3$/100 ml. All anaerobic work was completed in an oxygen free atmosphere to ensure anaerobic conditions prevailed.

Results

Coal-aquifer water quality

Analytical results of the coalbed water-quality sample indicated the total dissolved solids concentration was 2,056 mg/L, specific conductivity was 3,275 umhos/cm^2, and the pH was 7.63. The water temperature was 21.4 C. The sodium concentration was 779 mg/L, bicarbonate concentration was 2,216.8 mg/L, the sulfate concentration was not detectable (less than 2.5 mg/L), iron concentration was 0.043 mg/L and nitrate (as N) was 0.146 mg/L. The sodium adsorption ratio was 25.5. The water quality is typical of CBM production water in the PRB.

Molecular-based analysis



Lane 1 – Powder River Basin Sample 536fc and 907r
Lane 2 - Powder River Basin Sample 23fc and 440r

Figure 2. DGGE analysis of the microbial community of PRB coal associated aquifer water.

The results indicate relatively low diversity of the total microbial community (see lane 1) compared to that of a typical subsurface or soil environment. Sequencing of several prevalent bands (indicated by arrows) indicated that all presumptive identities, based on known sequences in the Ribosomal Database (RDP II), had relevant metabolic capabilities consistent for their presumed role in coal formations that generate methane. The diversity of the methanogen community (as indicated by the number of bands in lane 2) appeared quite high, but the five bands sequenced all had similar phylogenetic affiliations. Each sequence was closely associated with the genus *Methanolobus* within the order *Methanosarcinales*. In addition, all five were most closely related to the species *M. taylorii* or *M. oregonensis* (averaging 93% homology). Interestingly and unexpectedly, this group is typically linked with marine environments, which may indicate that they thrive in a high sodium environment. However, the geological formation and shallow depth where this sample was taken have not been associated with ancient marine origins. This evidence supports the concept that this environment may sustain novel members of the methanogen group.

More recently, an additional survey of coal methanogens (using ME1 and ME2) produced seven sequences all related to members of the *Methanosarcinales* or *Methanobacteriales* orders. Six appear to be unique and their closest matches are to environmental clones from various origins (Table 1). This information will aid in development of primers specific for amplification of the methyl coenzyme M reductase gene from methanogens found in coal environments.

Many of the important members of the consortia may be underrepresented in terms of numbers, but may be dominant in terms of activity. If this is the case, it suggests that there are a number of minority microbial populations present in coalbeds, and that to more fully understand the community ecology an extensive and intensive investigation must be undertaken.

Table 1. Closest matched organism produced from the total microbial community extract and amplified using generally conserved 16S rDNA primers.

Clone	**Group Affiliation**	**Best Match Species**	**SAB Score**	**Functional in Environment**
Meth 1	Proteo -Epsil	Arcobacter	0.075	oxidize sulfur in aqueous environments
Meth 2	Proteo-Gam	Acinetobacter	0.92	Environmental GW clone
Meth 3	Proteo-Beta	Ferribacterium limneticum	0.88	Iron reducer
Meth 4	Proteo-Beta	Ferribacterium limneticum	0.91	Iron reducer
Meth 5	Proteo-Delta	Desulfovibrio acrylicus	0.63	SRB anoxic enviroments
Meth 6	Proteo-Beta	Acidovorax	0.89	Denitrifying Iron - oxidizing bacteria
Meth 7	Proteo-Beta	Azoarcus	0.76	N2-fixing plant- and fungus-associated
Meth 8	Proteo-Epsil	unclassified clone	0.78	Environmental clone from activated sludge
Meth 9	Proteo-Epsil	Arcobacter	0.77	isolated from a coculture capable of sulfate reduction
Meth 10	Gram+ High GC	Micrococcus	0.85	Isolated from deep subsurface environment

Culture based analysis

In addition to the molecular data, coal samples were incubated in an anaerobic growth media used to specifically culture methanogens. To date, this has proven to be unproductive, with no apparent evidence of growth, based on turbidity and direct observations. This is not a complete surprise as methanogen growth is typically very slow and may indeed take a period of time well beyond the time frame of this study. However these culture attempts will continue and a molecular analysis of these samples will be undertaken. Data from this experiment may aid in future studies.

Direct counts

Initial direct cell counts were completed on the coal samples by acridine orange (AOD) staining and were inconclusive. This was likely due to the fact that the coal contained an abundance of material that interfered with the staining of cells. Therefore differentiating cells from background material was very difficult. To improve on this, specific probes may be used in a fluorescent *in situ* hybridization (FISH) technique.

Conclusions and recommendations

This initial investigation proved to be an excellent starting point for continuing efforts toward unraveling the complexity of the microbial community responsible for biogenic methane production. In this study we found a lower-than-expected total microbial community diversity. All of these identified community members were presumptively capable of metabolic processes leading to the formation of methane. In regards to methanogens, the organisms grouped fairly coherently into two orders (*Methanosarcinales* and *Methanobacteriales*). Because so little is known about methanogens in coal beds we can not yet identify their specific role in methane production, other then to say that, indeed methanogens are prevalent in our coal and associated samples.

To fully underpin the microbial community in this environment a more comprehensive study must be undertaken which would include the following:

- Continue with sequencing efforts on the total microbial community within coal samples (not limited to methanogens).
- Develop conceptual models of the microbial community present based on molecular analysis.
- Design primers appropriate for real-time PCR for measuring abundance of particular functional groups associated with coal.
- Conduct culturing experiments and isolate pure cultures to confirm the presence of novel organisms (methanogens as well as other major groups)
- Design amendment/perturbation experiments for laboratory (later for *in situ*?)
- Develop activity studies aimed at determining active microbial populations responsible for methane production (future stable isotope experiment)

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Stream-groundwater interactions in a mountain to valley transition

Basic Information

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3. Covino, T., and B.L. McGlynn, 2006, Master's Thesis, Groundwater-Stream Interactions in a Mountain Valley Transition: Impacts on Watershed Hydrologic Response and Stream Water Chemistry. Land Resources and Environmental Sciences Department, Montana State University, Bozeman, Montana, 112 pp.
4. Covino, T., B.L. McGlynn, and R. Sojda, 2005, Groundwater-Stream Interactions in a Mountain Valley Transition: Impacts on Catchment Hydrologic Response and Stream Water Chemistry, in American Geophysical Union Fall Meeting. OUTSTANDING STUDENT PAPER AWARD
5. Covino, T., B.L. McGlynn, and R. Sojda, 2005, Groundwater-Stream Interactions in a Mountain Valley Transition: Impacts on Catchment Hydrologic Response and Stream Water Chemistry. Montana Chapter of the American Water Resources Association Annual Meeting. THIRD PLACE IN STUDENT PRESENTATION COMPETITION.

STREAM-GROUNDWATER INTERACTIONS IN A MOUNTAIN TO VALLEY TRANSITION: IMPACTS ON WATERSHED HYDROLOGIC RESPONSE AND STREAM WATER CHEMISTRY

Introduction

The realization that streams and surrounding groundwater (GW) exist as a connected resource has helped to advance the fields of hydrology, biogeochemistry, and aquatic ecology. Stream-GW exchange plays an important role in the processes that affect watershed hydrologic response, water quality, and subsequent impacts on aquatic biota. The exchange of water between streams and GW has been noted as an important mechanism involved in solute and contaminant transport (Ren and Packman, 2005); dissolved organic carbon (DOC) cycling (Wagner and Beisser, 2005); lotic ecosystem functioning (Wroblicky et al., 1998); and water resource management (Oxtobee and Novakowski, 2002). Although these studies have increased understanding of these processes, many have focused on small spatial and temporal scale interactions. Furthermore, a watershed scale conceptual model that incorporates the impact of larger scale stream-GW exchange on hydrologic response, source water contributions, and stream water chemistry is lacking.

Hydrologists, biogeochemists, and ecologists have become interested in the stream-GW exchanges that occur in the hyporheic zone (HZ), and considerable improvements in understanding have been made in this area. The HZ has been defined as the interstitial areas of saturation located beneath and beside the channel that contain a proportion of stream water (White, 1993). Advances in the study of the HZ have been crucial to developing the link between streams and GW and the HZ is now viewed as an integral part of the stream itself (Malard et al., 2002). HZ interactions occur at small scales, which exist embedded within a larger framework of stream-GW exchanges. Harvey et al. (1996) define smaller scale exchanges as those that occur at centimeter-long flow paths, and timescales of minutes; and, larger scale exchanges as those that occur over hundreds of meters and timescales of years. At the larger scale, stream reaches can be defined as losing water to GW, or gaining water from GW. Whether a stream reach is losing (GW recharge) or gaining (GW discharge) will be spatially and temporally dynamic, and will have substantial impacts on the hydrologic and chemical characteristics of stream flow.

Limited stream-GW exchange research at larger spatial and temporal scales has focused on mountain front GW recharge. The term mountain front recharge (MFR) refers to the contributions from mountain regions to the GW recharge of adjacent basins (Wilson and Guan, 2004). Efforts to understand and model MFR in arid to semi-arid regions have increased as growing populations demand adequate and sustainable water supplies, particularly in the southwestern United States (Hogan et al., 2004). Significant GW withdrawals in the southwestern United States over the past several decades have led to GW depletion, land subsidence, decreased in-stream flows, and loss of riparian habitat (Hogan et al., 2004). MFR has been noted as being a major component of GW recharge in semiarid regions (Manning and Solomon, 2003). MFR can either occur as percolation through the mountain block or as seepage losses from streams that exit the mountains. Maurer and Berger (1997) compared the surface and subsurface flow from eight catchments in western Nevada and estimated that 30-90% of the total annual flow across the mountain front was stream flow. Niswonger et al. (2005) noted that numerous intermittent and ephemeral streams that discharge from mountainous catchments of the western United States lose most of their total discharge as seepage to GW as they flow across alluvial fans and piedmont alluvial plains; highlighting the importance of stream seepage in MFR. Although MFR has been noted as being an important source of GW recharge to valley aquifers in arid to semi-arid regions, it remains poorly understood and quantified (Wilson and Guan, 2004).

Exchanges of water between the stream and GW vary across different landscape elements within a watershed. These hydrologic systems will affect streams and the degree that streams will either gain or lose water to/from the local GW table. If we break a watershed into three distinct landscape elements such as a mountain collection zone, a mountain front recharge (MFR) zone, and a valley bottom zone we could begin to determine the dominant hydrological features of each landscape element. We can define the mountain collection zone as the headwaters of the watershed where channels originate; the MFR zone as the piedmont zone between points A and B on Figure 1 (Wilson and Guan, 2004), and the valley bottom zone as the basin floor downstream of the MFR zone (Fig. 1). Mountain collection zones typically have higher precipitation, lower evapotranspiration (ET), and less soil development than downslope landscape elements (Wilson and

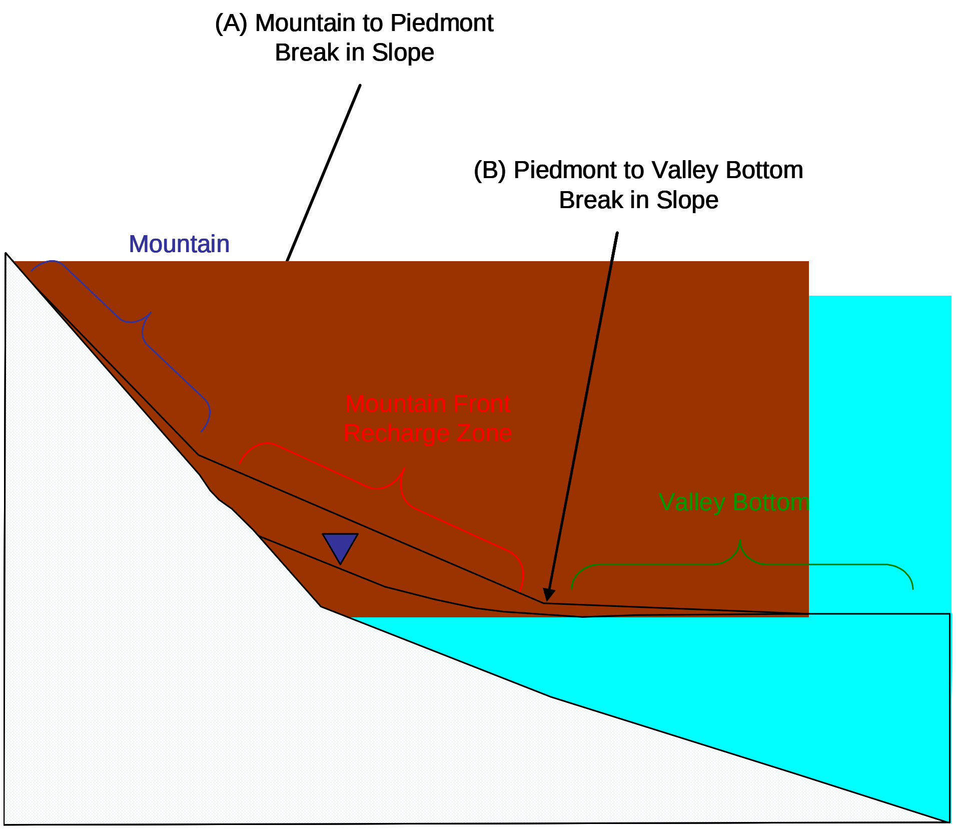

Figure 1. Conceptual diagram illustrating the mountain front recharge (MFR) zone, and the valley bottom. The MFR zone is the region between points A and B. (Adapted from Wilson and Guan (2004).

Guan, 2004). Recent studies suggest that MFR is responsible for one third to nearly all of the GW recharge to inter-mountain basin fill aquifers (Anderson and Freethey, 1996; Prudic and Herman, 1996; and Mason, 1998). However, few studies have connected MFR to valley bottom hydrology. Investigating the hydrology and geochemistry of the stream and GW in both the MFR zone and the valley bottom zone allows determination of how stream-GW exchanges can change from one landscape element to the next, and the impact these exchanges can have on watershed hydrologic response, source water mixing, and stream chemistry.

Large scale stream-GW exchanges and the impact they have on MFR and valley bottom hydrology are poorly understood. We used GW monitoring wells, in stream piezometers, stream gauging stations, and geochemical hydrograph separations in the Humphrey Creek watershed in southwestern Montana to investigate the following questions:

(1) How do alpine to valley bottom transitions impact stream discharge magnitude and timing?
(2) How does stream-GW exchange change over alpine to valley bottom transition zones?
(3) What are the relative proportions of alpine and groundwater inputs to stream discharge in Humphrey Creek from the MFR zone to the valley bottom?

We hypothesize that mountain-valley transitions function as hydrologic and biogeochemical buffers via groundwater recharge and subsequent groundwater discharge. More specifically, that streams recharge groundwater near the mountain front, and that stored groundwater discharges to the stream in the valley bottom. The spatial and temporal dynamics of these interactions impact stream hydrograph response and chemistry. Implications are that MFR magnitudes can control valley aquifer storage state which combined with alpine runoff magnitude and valley bottom groundwater discharge controls stream water quantity and geochemical composition downstream.

Study Area

The Humphrey Creek watershed is located in the Centennial Mountains and Red Rock Lakes National Wildlife Refuge in southwestern Montana at 111.82778 degrees west longitude, and 44.61778 degrees north latitude (Fig. 2). The continental divide forms the southern boundary of the watershed and Humphrey Creek flows from south to north. Humphrey Creek flows into Lower Red Rock Lake (LRRL), and drains a 351 hectare (ha) watershed. The Humphrey Creek watershed elevation ranges from 2,012 to 2,969 meters (m). The headwaters of the creek begin above tree line in the alpine region of the watershed. Humphrey Creek then flows through sub-alpine mixed coniferous forest, exits the forest and flows through upland grasses, willows, and shrubs and enters the valley bottom where the vegetation consists of sedges, rushes, grasses and willows.

The area of instrumentation begins where Humphrey Creek exits the coniferous forest and continues to the lake edge (Fig. 3A). Instrumentation covers the mountain front recharge (MFR) zone (where Humphrey Creek exits the coniferous forest) to the valley bottom zone (where Humphrey Creek enters the lake). We define the MFR zone as the piedmont zone between points A and B on Figure 1 (Wilson and Guan, 2004

Average annual precipitation data was obtained from the Lakeview Ridge SNOTEL site, which is located 1.5 kilometers (km) southeast of the Humphrey Creek watershed at an elevation of 2,256 m. The thirty year average annual precipitation is 782 millimeters (mm).

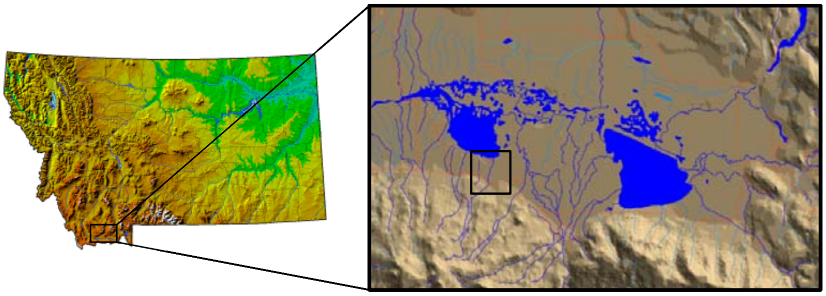

Figure 2. Location of the Humphrey Creek watershed in southwestern Montana.

Methods

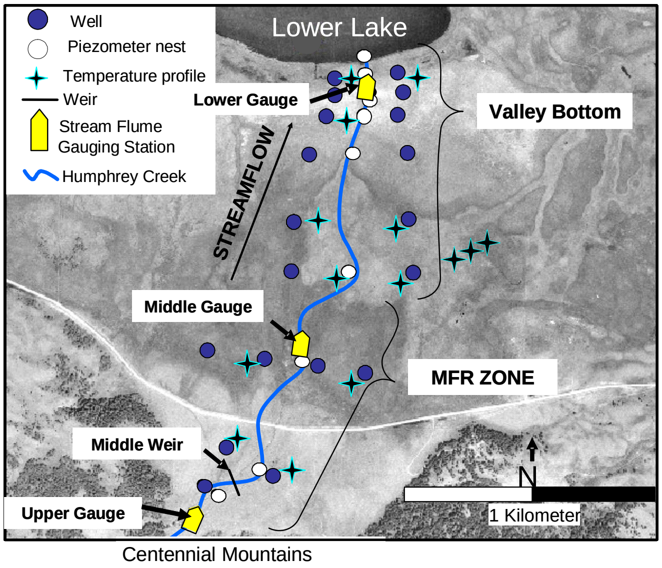

Figure 3A. Instrument layout in the Humphrey Creek watershed. Ten transects perpendicular to the stream channel, alternatively viewed as three to four transects parallel to the stream channel. Instrumentation includes: nine piezometer nests (two piezometers per nest), nineteen wells,fourteen temperature profile nests (ten depths in each nest), and four stream gauging stations. Plan view of mountain front recharge (MFR) zone and valley bottom shown on map.

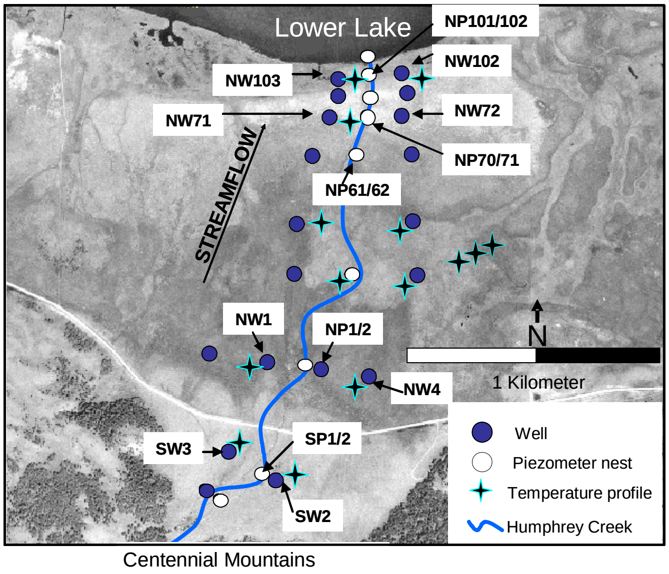

Figure 3B. Instrument layout in the Humphrey Creek watershed showing location and names of wells and piezomerters. Nested piezometers are in-stream piezometers.

Groundwater Measurements

We installed nine transects of wells perpendicular to Humphrey Creek from the upstream edge of the MFR zone to the lake edge to measure the shape and dynamics of the local groundwater (GW) table surrounding the stream (Fig. 3B). Wells were 2 inch diameter, schedule 40, 0.010 inch slot, poly vinyl chloride (PVC). Well screening extended from well completion depths to approximately 10 centimeters (cm) below the ground surface. Most wells were instrumented with TruTrack, Inc. recording capacitance rods that recorded GW height and temperature at ten minute intervals. We manually measured GW wells for depth to GW, GW specific conductance (SC), and GW temperature at variable intervals depending on season (daily to weekly intervals).

At the middle of each perpendicular to the stream well transect we installed two nested piezometers in the streambed to determine the vertical GW gradients (Fig. 3B). Piezometers were 1.5 inch diameter PVC pipe, and were open only at completion depths (no screening). Piezometers were installed by driving them into the ground with a removable solid piezometer driver that occupied the volume of the PVC in order to keep them from filling with sediment. TruTrack, Inc. recording capacitance rods were installed in most piezometers and recorded GW height (total potential) and temperature at ten minute intervals. We manually measured GW total potential, SC, and temperature at variable intervals depending on season (daily to weekly intervals). Well and piezometer measurements began in March, 2004 and continued through September, 2004.

Stream, Soil, and Meteorological Measurements

We installed three Parshall flumes (three-inch constriction) in Humphrey Creek during the spring of 2004: one in the upper reach of the study area, referred to as the upper gauge, a second in the middle reach of the study area, referred to as the middle gauge, and a third in the downstream reach of the study area, referred to as the lower gauge (Fig. 3A). The upper gauge was located at the upstream edge of the MFR zone, the middle gauge was located at the downstream edge of the MFR zone, and the lower gauge was located in the valley bottom zone near the lake edge. We instrumented each flume with stage recording data loggers (either Druck pressure transducers connected to Campbell CR10X data loggers, or TruTrack, Inc. recording capacitance rods) installed in stilling wells recording at ten minute intervals. Discharge was then calculated from developed stage-discharge rating curves. Gauge measurements began at the end of April, 2004 and continued until the end of September, 2004.

A rectangular weir existed in Humphrey Creek prior to the project, and was utilized for stream gauging. This weir was located between the upper gauge and the middle gauge in the middle of the MFR zone and is referred to as the middle weir (Fig. 3A). We widened and deepened a section of stream behind the middle weir to create a stilling pool, and constructed a stilling well on the upstream side of the weir which was instrumented with a TruTrack, Inc. recording capacitance rod. Stage measurements were recorded at ten minute intervals, and were taken from the end of April, 2004 to the end of September, 2004. Again, we developed a stage-discharge rating curve to calculate discharge.

We recorded stream SC, stream temperature, and local soil moisture status at the upper gauge, the middle gauge, and the lower gauge. Stream SC and temperature were measured with Campbell CS547A conductivity and temperature probes at ten minute intervals. Local soil moisture status was measured with Campbell CS616 water content reflectometers at ten minute intervals. We installed a Campbell TE525 tipping bucket rain gauge at the middle gauge to collect rain data, and a Thermocron I-Button to record air temperature. The rain gauge recorded each 0.1 millimeter (mm) of rain and air temperature was recorded at ten minute intervals. Snow water equivalent (SWE) data was obtained from the Lakeview Ridge SNOTEL site. The SNOTEL site was located 1.5 kilometers (km) southeast of the Humphrey Creek watershed at an elevation of 2,256 m.

Water Sampling

GWsamples were collected from wells, piezometers, and springs for chemical analysis. We used a hand held peristaltic pump and pumped and purged lines before sample was collected in 250 milliliter (mL) HDPE bottles and refrigerated at 4°C until filtering. Stream samples were collected from gauging locations either as grab samples or with ISCO auto samplers. Stream grab samples were collected in 250 mL HDPE bottles and refrigerated at 4°C until filtering. We filtered all water samples through 0.45 µm polypropylene filters and stored them in the dark at 4°C until analysis.

Chemical Analysis

Water samples were analyzed for major ions with a Metrohm-Peak compact ion chromatograph on Montana State University campus. Sodium (Na), ammonium (NH_4), potassium (K), calcium (Ca), and magnesium (Mg) were measured on a Metrosep C-2-250 cation column. Nitrate (NO_3), chloride (Cl), phosphate (PO_4), and sulphate (SO_4) were measured on a Metrosep C-2-250 anion column. And silica (Si) was measured as silicate (SiO_2) on a Hamilton PRP-X100 anion column. IC analysis protocol was developed following manufacturer instructions. Standards and blanks were analyzed at the beginning of each sample run, were inserted between every ten field water samples, and were analyzed at the back end of each sample run for quality assurance/quality control (QA/QC).

Hydrograph Separation and Uncertainty

Hydrograph separations are powerful tools for determining contributions to stream flow from various sources (e.g. alpine zone surface water and valley bottom GW) (McGlynn and McDonnell, 2003). If two sources contributing to stream flow are unique, and their signatures are known, a two component separation can be performed. We developed real-time separations for the middle gauge and the lower gauge using specific conductance (SC), under the assumption that SC was conservative over the time and space of the study. Substitution of SC for ion concentrations has been previously established by Gooseff and McGlynn (2005). GW SC was measured in wells and piezometers at daily to weekly intervals (dependent on season). Alpine stream SC, the middle gauge stream SC, and the lower gauge stream SC were measured at ten minute intervals. We defined alpine SC as the SC of water exiting the mountains and entering the MFR zone as channel flow. Chemical analysis of samples and regression of ion concentration versus SC was used to corroborate this separation. Further validation was obtained by plotting snap-shot separations using geochemistry of GW and surface water grab samples and comparing them to SC separations.

A two-component separation can be solved by simultaneously solving equations one (1), two (2), and three (3) (Pinder and Jones, 1969).

$$Q_{AL} = \left[\frac{C_{ST} - C_{GW}}{C_{AL} - C_{GW}}\right] Q_{ST} \quad \textbf{(1);}$$

$$Q_{GW} = \left[\frac{C_{ST} - C_{AL}}{C_{GW} - C_{AL}}\right] Q_{ST} \quad \textbf{(2);}$$

$$Q_{ST} = Q_{GW} + Q_{AL} \quad \textbf{(3)}$$

Where Q_{AL} is the contribution to discharge from the alpine zone, Q_{GW} is the contribution to discharge from valley bottom GW, Q_{ST} is stream discharge, and C_{AL}, C_{GW}, and C_{ST} are the concentration of tracer (either SC or a solute) from alpine sources, GW sources, and resultant stream concentration, respectively. We applied uncertainty analyses to the hydrograph separations following the methods of Genereux (1998) using equations four (4) and five (5).

$$W_{f_{AL}} = \left\{ \left[\frac{C_{GW} - C_{ST}}{\left(C_{GW} - C_{AL}\right)^2} W_{C_{AL}}\right]^2 + \left[\frac{C_{ST} - C_{AL}}{\left(C_{GW} - C_{AL}\right)^2} W_{C_{GW}}\right]^2 + \left[\frac{-1}{C_{GW} - C_{AL}} W_{C_{ST}}\right]^2 \right\}^{1/2} \quad \textbf{(4);}$$

$$W_{f_{GW}} = \left\{ \left[\frac{C_{AL} - C_{ST}}{\left(C_{AL} - C_{GW}\right)^2} W_{C_{GW}}\right]^2 + \left[\frac{C_{ST} - C_{AL}}{\left(C_{AL} - C_{GW}\right)^2} W_{C_{AL}}\right]^2 + \left[\frac{-1}{C_{AL} - C_{GW}} W_{C_{ST}}\right]^2 \right\}^{1/2} \quad \textbf{(5)}$$

Where $W_{f_{AL}}$ is the uncertainty in the alpine component, $W_{f_{GW}}$ is the uncertainty in the GW component, $W_{C_{AL}}$, $W_{C_{GW}}$, and $W_{C_{ST}}$ are the analytical errors in alpine, GW, and stream concentration measurements, and C_{AL}, C_{GW}, and C_{ST} are alpine, GW, and stream concentrations (SC or a solute). Stream SC measurements were accurate to +/- 5% over a 0.44 to 7 mS cm^{-1} range, and +/- 10% over a 0.005 to 0.44 mS cm^{-1} range; and GW SC measurements were accurate to +/- 0.5% of full scale of the measurement.

Results

Stream Discharge

Stream discharge was greatest at the upper gauge where water exited the mountains and entered the mountain front recharge (MFR) zone (Fig. 4). The annual hydrograph at the upper gauge was driven primarily by mountain snow-melt, and responded to rain events with pulsed increases in discharge. Discharge was consistently greater at the upper gauge than the middle gauge, however, the magnitude of the differences in discharge varied over the duration of study. Five day total discharges at the upper gauge were 66 m^3 to 7,504 m^3 greater than five day total discharges at the middle gauge over the course of study. The middle gauge five day total discharges ranged from 43-97% of the upper gauge five day total discharges. The upper gauge and the middle gauge bracketed the MFR zone, with the upper gauge at the upstream end of the MFR zone and the middle gauge at the downstream end of the MFR zone. The discharge differences between the upper gauge and the middle gauge show that a significant amount of water exiting the mountains as channel flow was lost from Humphrey Creek. These losses were likely due to stream seepage losses to groundwater recharge as Humphrey Creek flowed through the MFR zone.

The shapes of the upper gauge and middle gauge hydrographs were similar, as was the onset and cessation of channel flow (Fig. 4 B & C). Both the upper gauge and the middle gauge showed peaks in stream discharge driven by a rain event on 28 May, 2004. Annual peak discharge occurred on 9 June at both of these gauges. Rain events on 22 July and 22 August caused similar peaks in the hydrographs for both the upper gauge and the middle gauge.

The hydrograph for the lower gauge, located in the valley bottom ~ 80 m upstream of Lower Red Rock Lake (LRRL), had a different hydrograph shape and duration than those for the upper gauge and the middle gauge (Fig. 4 D). Channel flow at the lower gauge began two weeks before flow commenced at the upper gauge or the middle gauge. Discharge magnitude was consistently less at the lower gauge compared to discharge in the MFR zone. Differences in discharge magnitude between the upper gauge and the lower gauge varied over the duration of study. The five day total discharge deficits for the lower gauge compared to the upper gauge ranged from 1,624 m^3 to 15,099 m^3. Five day total discharges at the lower gauge were between 0-73% of five day total discharges at the upper gauge (0% indicating no flow at the lower gauge). Discharge at the lower gauge was typically lower than discharge at the middle gauge, except for the fourth five day period on record, when total discharge was greater at the lower gauge than the middle gauge. During the fourth five day discharge period a 1,778 m^3 greater discharge total at the lower gauge than the middle gauge was recorded. The middle gauge total discharge was 68% of total discharge at the lower gauge during this period. For all other five day discharge totals on record, the middle gauge had greater discharge than the lower gauge, and these differences varied between 293 m^3 and 10,873 m^3. The lower gauge five day total discharges ranged between 0-94% of the middle gauge five day total discharges during these time periods (0% indicating no flow at the lower gauge).

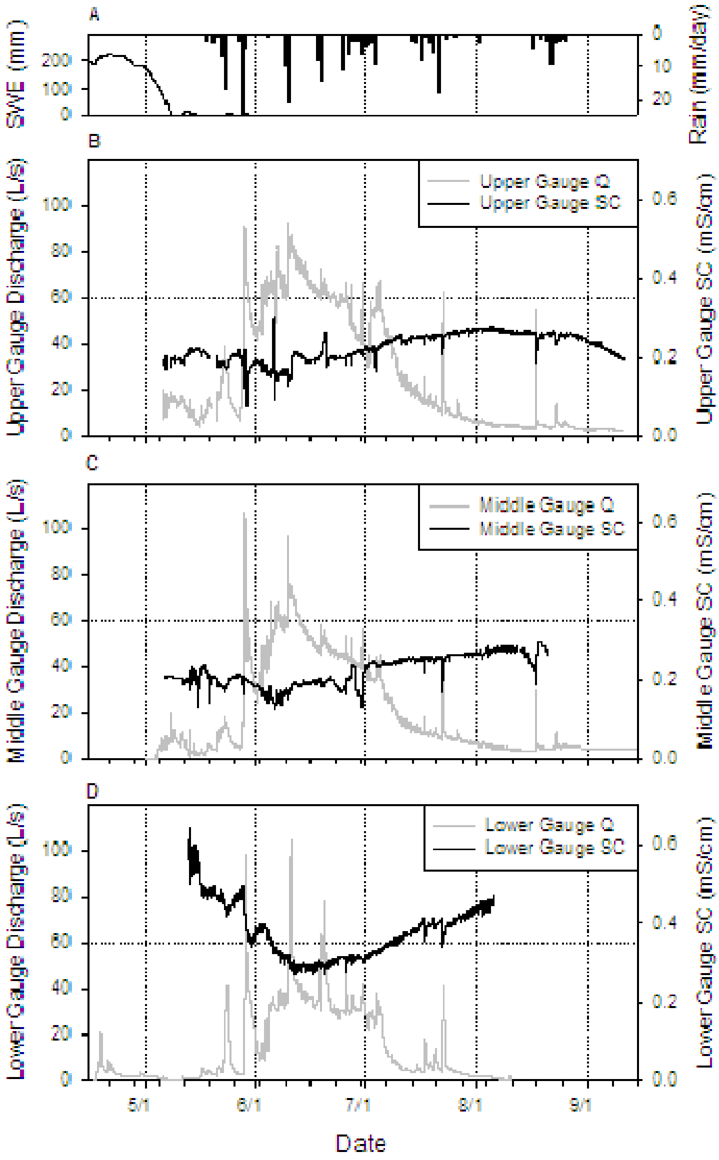

Figure 4. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 16 April, 2004 through 16 September, 2004. Time series stream hydrographs and stream specific conductance (SC) for: (B) the upper gauge located at the upstream edge of the mountain front recharge zone; (C) the middle gauge located at the downstream edge of the mountain front recharge zone; and (D) the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

The hydrograph for the lower gauge was flashier than the hydrographs for the upper gauge or the middle gauge (Fig. 4D). Rain events caused large departures from baseflow in the valley bottom; much more so than in the MFR zone. In particular, rain events that occurred on 19 June, and 25 June caused sizeable peaks in the hydrograph for the lower gauge, whereas rain induced peaks in discharge at the upper gauge and the middle gauge during this time period did not diverge substantially from baseflow (Fig. 4). Peak discharge at the lower gauge occurred one day later than it did in the MFR zone (June 10 for the lower gauge, June 9 for the upper gauge and the middle gauge). Discharge at the lower gauge ceased roughly three weeks prior to cessation of channel flow at the upper gauge and the middle gauge, and did not respond to a 22 August rain event, although the upper gauge and the middle gauge did.

Three time periods were chosen for closer evaluation of discharge dynamics. These were 20 May to 30 May which included two rain induced peaks (Fig. 5), 8 June to 15 June which included peak discharge (Fig. 6), and 15 July to 31 July where ten days of rain caused two peaks at the upper gauge and the middle gauge and three peaks in discharge at the lower gauge (Fig. 7).

A rain event on 21 May caused a hydrograph response at all three gauges. The largest hydrograph response was measured at the lower gauge, followed by the upper gauge, then the middle gauge (Fig. 5). The

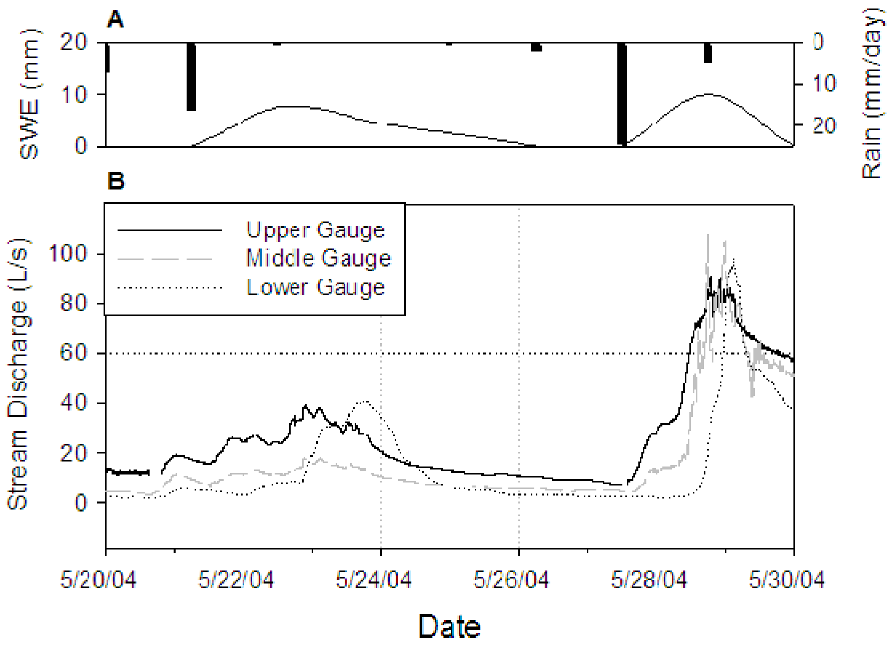

Figure 5. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 20 May, 2004 through 30 May, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

lower gauge discharge rose from 5 to 40 L s^{-1}, the upper gauge discharge rose from 15 to 40 L s^{-1}, and the middle gauge discharge rose from 5 to 18 L s^{-1} (Fig. 5). The peak at the lower gauge was a greater departure from baseflow than those for the upper gauge or the middle gauge, and was delayed by one day compared to the upper gauge and the middle gauge (Fig. 5). The timing of the rain induced peak on 29 May was similar for all three gauges (Fig. 5). However, the hydrographs at the upper gauge and the middle gauge began to rise before any response at the lower gauge. The middle gauge had the highest peak at 104 L s^{-1}, followed by the lower gauge at 98 L s^{-1}, and the upper gauge at 90 L s^{-1} (Fig. 5). Although the middle gauge had the highest peak, the upper gauge had the greatest total discharge over the course of the event, followed by the middle gauge, then the lower gauge. The 29 May hydrograph response for the middle gauge had numerous peaks, whereas the hydrograph responses for the upper gauge and the lower gauge were single peaks (Fig. 5).

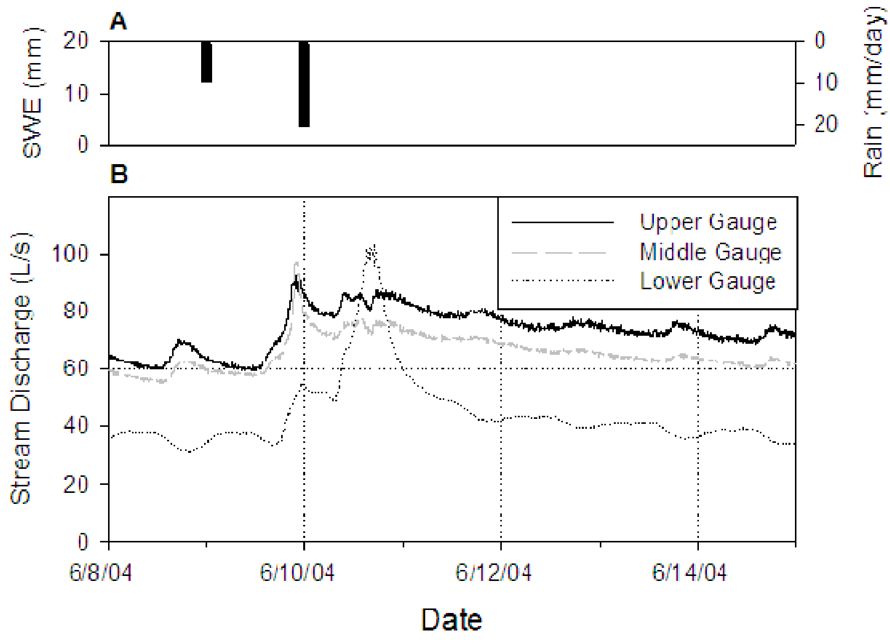

Figure 6. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 8 June, 2004 through 15 June, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

Peak seasonal discharge occurred on 9 June at the upper and middle gauges and on 10 June at the lower gauge. The upper gauge and the middle gauge hydrographs began rising from ~ 60 L s^{-1} near mid-day 9 June to peaks of ~ 95 L s^{-1} near midnight on 9 June (Fig. 6). The rise to peak for the middle gauge was more abrupt than that for the upper gauge. The upper gauge discharge decreased to ~ 70 L s^{-1} by 15 June, while the middle gauge discharge decreased to ~ 60 L s^{-1}. The lower gauge hydrograph rose from ~ 40 L s^{-1} with similar timing to the upper gauge and the middle gauge hydrographs, however the rising limb for the lower gauge stalled ~ 55 L s^{-1} for 8 hours on 10, June (Fig. 6). The lower gauge hydrograph began rising again and reached a peak discharge ~ 100 L s^{-1} on 10 June (Fig. 6). The lower gauge discharge then decreased to ~ 40 L s^{-1} by 12 June and leveled off. Again, the peak for the lower gauge was a large departure from baseflow, yet total discharge was low due to the low baseflow discharge (~ 40 L s^{-1}), compared to higher baseflow discharge at the upper gauge and the middle gauge.

A rain induced peak occurred on 17 July at all three gauges (Fig. 7). Fine time scale resolution shows that the timing of these three peaks was staggered. The upper gauge peak occurred first, followed by the middle gauge, then the lower gauge. The lower gauge peak induced by this rain event was substantially larger than those for the upper gauge or the middle gauge despite little additional watershed area added between the MFR zone and the lower gauge (Fig. 7). The upper gauge and the middle gauge peaks were narrower, and the lower gauge peak was broader. Higher baseflow discharge at the upper gauge and the middle gauge accounted for higher total discharge compared to the lower gauge. Three days later on 20 July a rain induced peak was measured at the lower gauge, however no peaks were observed at the upper gauge or the middle gauge (Fig. 7). A third rain driven peak over this time period occurred on 23 July, and was observed at all three gauges (Fig. 7). The upper gauge had the highest peak ~ 62 L s^{-1}, and the middle gauge and the lower gauge had peaks ~ 40 L s^{-1} (Fig. 7). The lower gauge peak was broader compared to the upper gauge and the middle gauge peaks, and all three peaks were substantial departures from baseflow (Fig. 7).

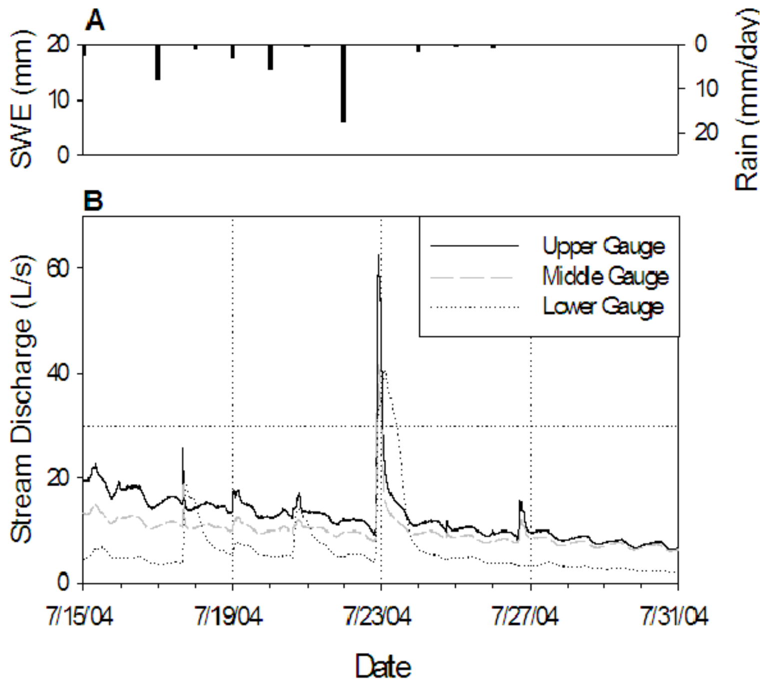

Figure 7. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 15 July, 2004 through 31 July, 2004; and (B) time series stream hydrographs for the upper gauge located at the upstream edge of the mountain front recharge zone, the middle gauge located at the downstream edge of the mountain front recharge zone, and the lower gauge located in the valley bottom near the Lower Red Rock Lake edge.

In summary: discharge decreased moving downstream, hydrograph responses at the upper gauge and middle gauge were tightly coupled but hydrograph responses at the lower gauge were more disconnected from hydrograph responses at the upper gauge and the middle gauge, and rain events cause larger departures from baseflow at the lower gauge than at the upper gauge or the middle gauge.

Groundwater Well Hydrometric Data

Depths to groundwater were typically greater than instrument completion depths in the mountain front recharge (MFR) zone. Figure 8B shows groundwater time series for south wells 2 (SW2) and 3 (SW3) along with local stream hydrograph time series. These wells were located in the middle of the MFR zone on a transect north (downstream) of the middle weir (Fig. 3B). SW2 was completed to 1.64 meters (m), and SW3 was completed to 0.98 m. Rocky soils limited completion depths. Due to shallow completion depths and significant depth to groundwater, there was rarely groundwater in these wells. The saturated zone began at some depth greater than 1.64 m on this transect. Groundwater levels in SW2 and SW3 were generally greater than the depth of the channel bed, resulting in a disconnected groundwater-stream system, ie. no saturated connection between the stream and the groundwater table. There was a small rise in groundwater levels in SW2 and SW3 during the last week of March/first week of April, 2004 which was likely driven by local snowmelt in the MFR zone. It is possible that infiltration was impeded by ice lenses or frozen soils which led to a perched water table. Soil temperature data shows that soils were frozen to depths approaching 1.2 meters during the winter and these soils rapidly thawed in early April (Fig. 9).

Figure 8C displays north well 1 (NW1) and north well 4 (NW4) groundwater time series along with local stream hydrograph time series. NW1 and NW4 were installed at the down stream end of the MFR zone (Fig. 3B) and completed to depths of 2 m and 2.76 m, respectively. Groundwater levels in these wells began to rise on 28 May. This rise in groundwater levels was coincident with a peak in local stream discharge, and

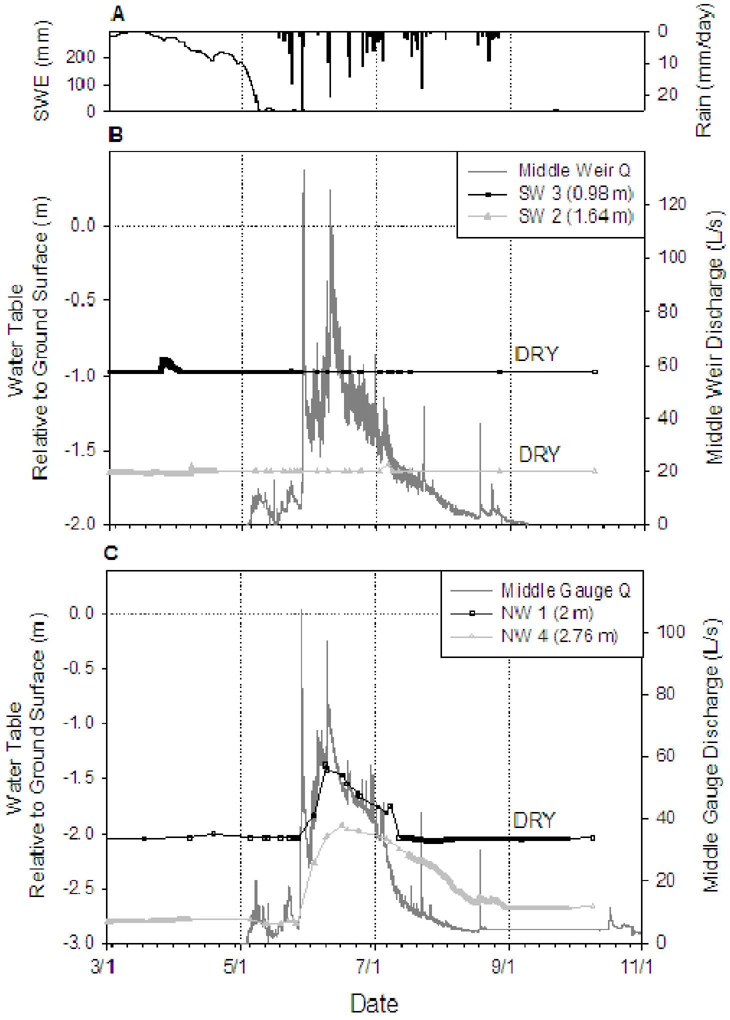

Figure 8. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 1 November, 2004; (B) time series water table dynamics for south well 2 (SW2) and SW3 (located in the middle of the mountain front recharge zone) along with the local stream hydrograph; and (C) water table dynamics for north well 1 (NW1) and NW4 (located at the down stream edge of the mountain front recharge zone) along with the local stream hydrograph.

appears to have been initiated by a rain event on 28 May. Subsequently, groundwater levels in NW1 and NW4 rose and fell with the stream hydrograph, which suggests stream seepage losses over this reach. Groundwater levels in NW4 receded more slowly than in NW1, however due to the shallow completion of NW1 a complete analysis of the falling limb of groundwater levels in this well was not possible.

Depths to groundwater in the valley bottom were shallow, and groundwater was typically at or near the ground surface in this zone. Figure 10 shows groundwater time series and local hydrograph time series for north wells 71 (NW71), NW72, NW102, and NW103. The completion depths for NW71, NW72, NW102, and NW103 were 2.4 m, 2.09 m, 2.5 m, and 2.12 m, respectively. A sharp rise in groundwater levels was measured in these wells on 20 March (Fig. 10). This increase in groundwater levels was likely driven by local snowmelt. This event contributed significantly to local groundwater recharge, and also initiated Humphrey Creek channel flow in the valley bottom at the lower gauge. Once channel flow was initiated, groundwater levels in this zone remained fairly constant throughout the season. A small rise in groundwater levels in NW72 was measured between 28 May and 7 June, and peaked on 5 June (Fig. 10B). A rain event on 28 May likely drove this increase in groundwater levels. Increased groundwater levels were not measured in NW71, NW102, or NW103. Groundwater levels in the valley bottom zone were relatively unresponsive to rain events and were particularly unresponsive to local stream discharge. Inputs to the groundwater table in this area appeared to be from local snowmelt, and deeper groundwater dynamics not affected by surface processes or stream discharge. As groundwater levels in NW71 and NW72 began to decrease in early August, channel flow at the lower gauge in the valley bottom decreased abruptly.

Piezometeric Data

Completion depths of piezometers in the MFR zone were limited by rocky soils, and these piezometers were typically dry, despite being completed in the streambed. Piezometers in the MFR zone included south piezometer 1 (SP1), south piezometer 2 (SP2), north piezometer 1 (NP1), and north piezometer 2 (NP2) which were completed to 0.87 m, 1.76 m, 0.8 m, and 1.75 m, respectively. SP1 and SP2 were located in the middle of the MFR zone, and NP1 and NP2 were located at the downstream end of the MFR zone (Fig. 3B). Groundwater was not observed in SP1 or NP1 over the duration of the study (Fig. 11). A small increase in groundwater total potential in SP2 was measured during the first week of May, but SP2 was dry at all other times during the study (Fig. 11). The rise in groundwater total potential in SP2 was coincident with declining snow water equivalent (SWE) in the mountain snow pack. Total potential in NP2 began to rise on 28 May and

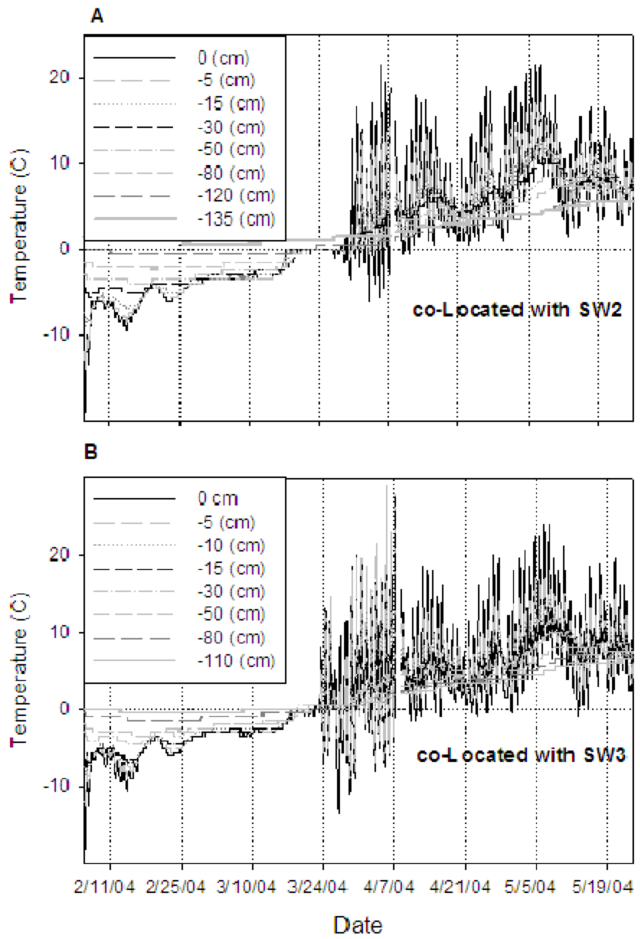

Figure 9. Soil temperature time series dynamics in the mountain front recharge zone during spring snowmelt. (A) Soil temperature nest co-located with south well 2 (SW2) in the middle of the mountain front recharge zone (MFR); and, (B) soil temperature nest co-located with south well 3 (SW3) in the middle of the MFR zone. Legends indicate the depth below ground surface of the temperature recording.

subsequently rose and fell with the local stream hydrograph suggesting groundwater recharge from stream seepage in this reach, along with inputs from snowmelt. Groundwater levels in the MFR zone were typically deeper than the channel bed, indicating hydraulic gradients out of the stream (stream water losses to groundwater).

Upward vertical groundwater gradients were observed in the valley bottom zone. North piezometer 61 (NP 61) and north piezometer 62 (NP 62) were installed as a nest in the valley bottom zone and were completed to 1.29 m, and 0.66 m, respectively. These piezometers were located half way between the downstream edge of the MFR zone and Lower Red Rock Lake (LRRL) (Fig. 3B). Time series of groundwater total potential for NP61 and NP62 along with local stream hydrograph are shown in Figure 12B. Total potentials in NP61 and NP62 were above ground surface during periods of channel flow in the valley bottom, and upward vertical gradients were measured during this period (Fig. 12). Groundwater total potentials in these piezometers peaked before local stream discharge, suggesting groundwater controls on stream discharge. Further, upward groundwater gradients were strongest during peak discharge in the valley bottom zone. Upward gradients resulted in significant groundwater contributions to channel flow in the valley bottom reach of Humphrey Creek. As groundwater total potentials in NP61 and NP62 fell below the ground surface during the middle of August, channel flow ceased in the valley bottom. An increase in groundwater total potential was measured in NP62 between 18 August and 11 September, and peaked on 28 August (Fig. 12B). Rain events during this time frame may have initiated the increase in total potential measured in NP62 (rain data was not available after 1 September) (Fig. 12A). A much smaller increase in groundwater total potential was measured in NP61, which was not only a considerably smaller response than the response measured in NP62 but also was delayed by 10 days (Fig. 12B). A sharp increase in total potential began at NP62 on 12 September and at NP61 on 20 September (Fig. 12B). None of the increases in groundwater total potentials measured in NP61 and NP62 during this time frame led to re-initiation of valley bottom channel flow.

Farther downstream toward LRRL, groundwater gradients were predominantly lateral during the period of study (Fig. 13B & C). North piezometer 70 (NP70) and north piezometer 71 (NP71) were located three-quarters of the way from the MFR zone to the LRRL edge (Fig. 3B), and were completed to 1.18 m, and 1.91 m, respectively. A sharp rise in groundwater total potentials was measured in NP70 and NP71 on March, 20 (Fig. 13B). Lateral groundwater gradients persisted at this location from March through August of 2004 (Fig. 13B). Groundwater total potentials in NP70 and NP71 were consistently at or above ground surface during times of channel flow in the valley bottom. Total potentials in these piezometers rose before local stream discharge, suggesting groundwater controls on local stream discharge. As groundwater total potentials in NP70 and 71 dropped below the ground surface in mid-August, channel flow in the valley bottom ceased. North piezometer 101 (NP101) and north piezometer 102 (NP102) were located about 50 m from the LRRL edge in the valley bottom zone, and were completed to 0.95 m and 1.95 m, respectively (Fig. 3B). The dynamics of total potentials measured in these piezometers were very similar to the dynamics measured in NP70 and NP71.

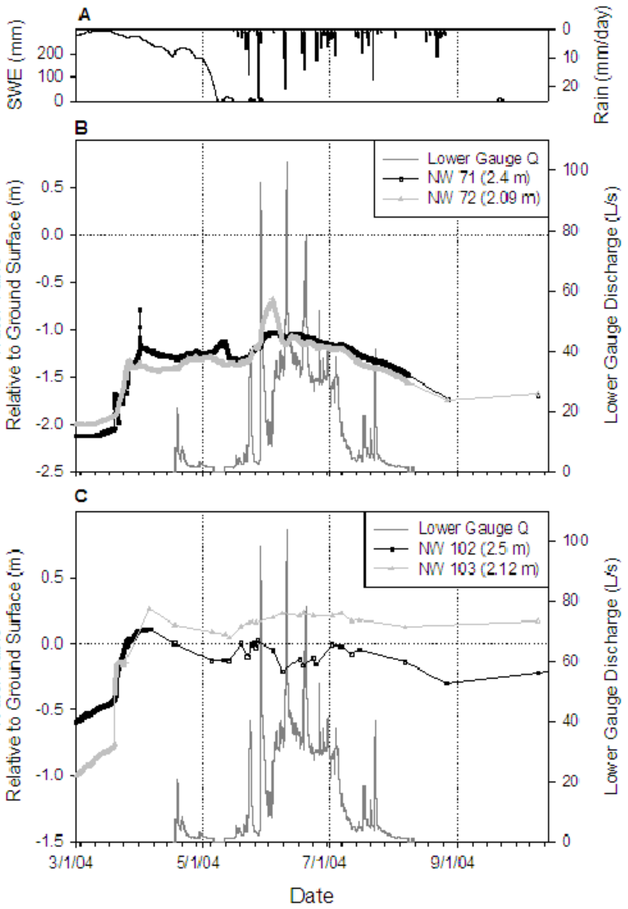

Figure 10. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 November, 2004; (B) time series water table dynamics for north well 71 (NW71) and NW72 (located in the valley bottom) along with the local stream hydrograph; and, (C) water table dynamics for north well 102 (NW102) and NW103 (located at the Lower Red Rock Lake Edge) along with the ocal stream hydrograph.

An abrupt rise in total potentials was measured on 23 March in NP101 and NP102 (Fig. 13C). Subsequently, total potentials remained fairly constant and lateral gradients persisted during the duration of local channel flow. Groundwater total potentials began to fall in NP101 and NP102 on 24 July, and local channel flow ceased on 10 August (Fig. 13C). A rise in groundwater total potential was measured in NP102 between 22 August and 17 September, and peaked on 29 August (Fig. 13C). This rise in groundwater total potential coincided with a 22 August rain event but did not re-initiate local channel flow (Fig. 2.13A).

In summary: groundwater levels were deep in the MFR zone, shallow in the valley bottom; gradients were out from the stream in the MFR zone, and into the stream or lateral in the valley bottom; and groundwater had a substantial impact on stream discharge in the valley bottom, but not in the MFR zone.

Stream Discharge and Local Groundwater Affect on Lake Stage

LRRL stage did not control local stream discharge or near shore groundwater levels in the study area. Near shore groundwater levels rose before local stream discharge or LRRL stage (Fig. 14). The lower gauge discharge and LRRL stage began to increase near the same time, however stream discharge peaked 6 weeks prior to LRRL peak stage (Fig. 14). Local groundwater levels rose abruptly ~ 20 March, remained relatively constant through June, and began to decline in July. The timing of the near shore hydrology measured was groundwater levels peaked first, followed by stream discharge, then LRRL stage (Fig. 14). Local groundwater was at peak levels from March through June, local stream discharge peaked on 10 June, and LRRL stage peaked on 25 July (Fig. 14). Local groundwater levels and local stream discharge had declined significantly, and continued to decline, by the time LRRL stage peaked (Fig. 14).

Stream Water Conductivity

Stream water specific conductance (SC) was measured at the upper gauge, the middle gauge, and the lower gauge. SC at the upper gauge and the middle gauge was similar (Fig. 4). The SC was ~ 0.2 mS cm^{-1} during the rising limb and peak of the hydrographs for both of these gauges (Fig. 4). The SC at the upper gauge and the middle gauge rose slightly during late season base flow (Fig. 4). Rain events caused sharp decreases in SC, due to increased contributions of low SC water to stream flow. The lower gauge early season SC was much higher compared to the upper gauge and the middle gauge (Fig. 4). SC was near 0.6 mS cm^{-1} when channel flow began in May at the lower gauge (Fig. 4). SC at the lower gauge was similar to groundwater SC. Valley bottom groundwater conductivity was ~ 0.6 mS cm^{-1} +/- 0.05 mS cm^{-1}. Stream SC at the lower gauge was ~ 0.6 mS cm^{-1} during early season (May) channel flow, decreased to ~ 0.3 mS cm^{-1} during peak discharge (June), and rose to ~ 0.5 mS cm^{-1} during late season baseflow (July) (Fig. 4).

Chemistry Data

Geochemical analysis of water samples was used to corroborate hydrograph separations based on SC (next section). Regression of milli-equivalents versus SC for calcium (Ca), and magnesium (Mg) showed

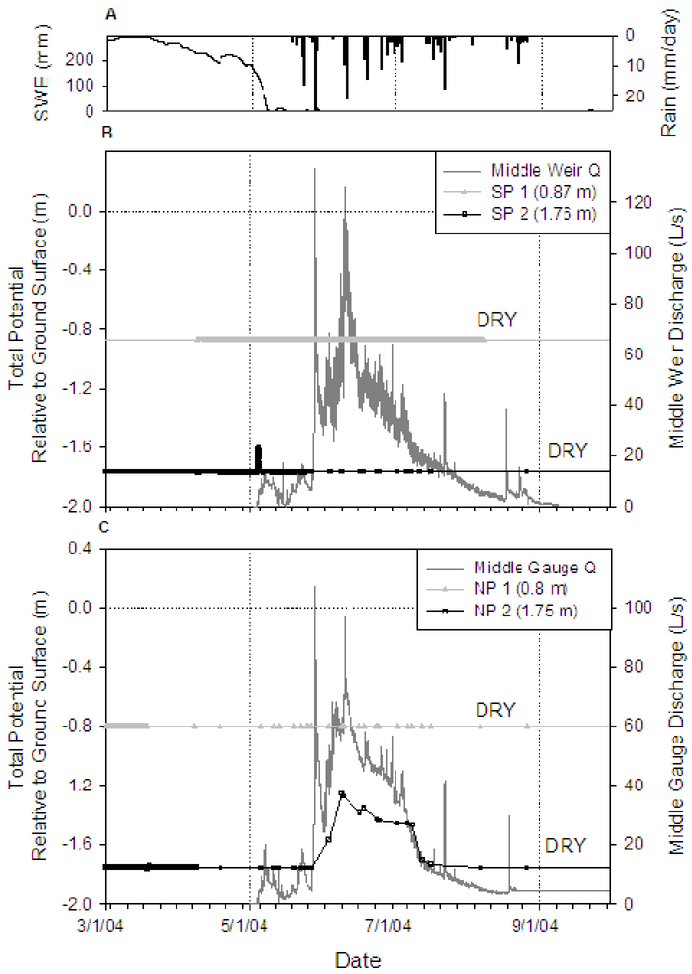

Figure 11. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 1 October, 2004; (B) time series groundwater total potential dynamics for south piezometer 1 (SP1) and SP2 (located in the middle of the mountain front recharge (MFR) zone), along with the local stream hydrograph; and, (C) time series groundwater total potential dynamics for north piezometer 1 (NP1) and NP2 (located at the downstream edge of the MFR zone), along with the local stream hydrograph.

strong linear relationships; the R^2 for Ca was 0.949, and 0.932 for Mg (Fig. 15). Comparable results would have been obtained had hydrograph separations been based on any of these ion concentrations, however this would not have allowed real-time separations (10 minute intervals). Snap-shot-in-time separations were made using geochemical concentrations of groundwater and stream water samples, and were plotted with corresponding SC separations (Fig. 16). The geochemical snap-shot separations further validated hydrograph separations based on SC.

Hydrograph Separations and Uncertainty Analysis

Hydrograph separations allowed determination of the relative contributions of alpine and groundwater sources to stream discharge at the middle gauge and the lower gauge. We defined alpine water as water exiting the mountains as channel flow at the upper gauge. Real-time (10 minute interval) measurements of stream SC at the upper gauge were used to determine the signature of alpine water. The signature of groundwater was determined by averaging SC from ~ 100 groundwater samples, and was determined to be relatively constant at 0.6 mS cm^{-1} +/- 0.05 mS cm^{-1}. This value was chosen as the groundwater end-member because it represented an average signature of shallow valley bottom groundwater, particularly where vertical groundwater gradients were upward. Resultant SC of stream discharge at the middle gauge and the lower gauge was measured real-time (10 minute intervals). This approach was developed following the methods of Gooseff and McGlynn (2005), and enabled real-time hydrograph separations from May, 2004 through August.

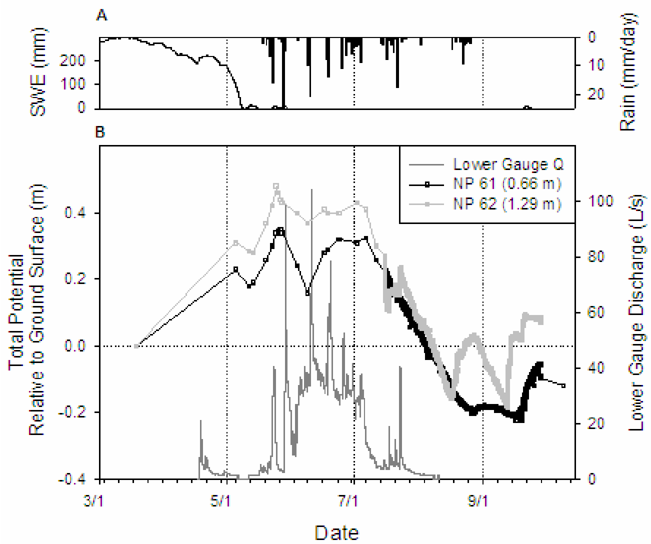

Figure 12. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 October, 2004; and, (B) time series groundwater total potential dynamics for north piezometer 61 (NP61) and NP62 (located in the valley bottom), along with the local stream hydrograph.

Uncertainty is displayed as error bars on the hydrograph separation time series (Fig. 17). Uncertainty was determined for each ten minute time step, but was plotted once daily at noon on the hydrograph separation time series. Error bars show that uncertainty in the separations is not confounding and does not affect interpretation.

Marked shifts in stream water composition (source water) were apparent between the middle gauge and the lower gauge (Fig. 17). Four month stream discharge totals at the middle gauge were composed predominantly of alpine water, whereas, stream flow at the lower gauge was comprised of ~ 50% groundwater (Fig. 17).

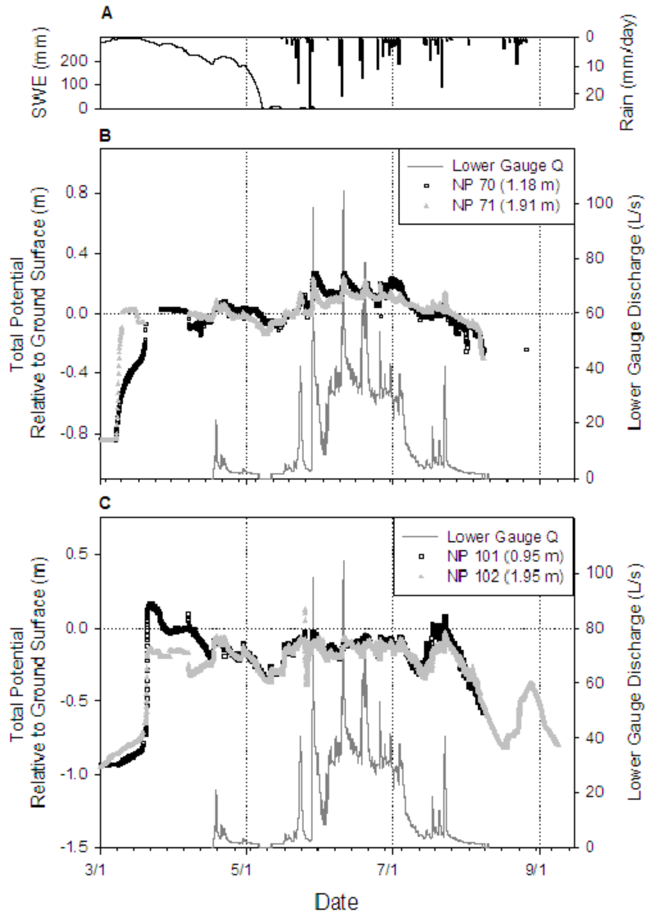

Figure 13. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 March, 2004 through 15 September, 2004; (B) time series groundwater total potential dynamics for north piezometer 70 (NP70) and NP71 (located in the valley bottom), along with the local stream hydrograph; and, (C) time series groundwater total potential dynamics for north piezometer 101 (NP101) and NP102 (located at the Lower Red Rock Lake edge), along with the local stream hydrograph.

Greatest groundwater contributions were measured at the middle gauge during the rain induced hydrograph peak on 28 May (Fig. 17B). From this time onward, including peak stream discharge, flow at the middle gauge was composed primarily of alpine water. In contrast, stream discharge at the lower gauge had substantial contributions from groundwater sources throughout the study period (Fig. 17C). During early season flow, groundwater sources dominated stream discharge contributions at the lower gauge. Rain induced peaks in discharge for the lower gauge occurring on 23 May, and 29 May were composed nearly entirely of groundwater. From 1 June, to 5 July, groundwater contributions were responsible for ~ 50% of stream discharge at the lower gauge (Fig. 17C). From 5 July, to 8 August, groundwater comprised nearly all of the water flowing in the channel at the lower gauge. This was in strong contrast to the hydrograph separation for the middle gauge where alpine contributions dominated throughout the season.

Over the period of stream flow at the middle gauge, groundwater contributions accounted for ~ 3% of total discharge, while alpine water contributions comprised ~ 97% of total discharge (Fig. 17B pie-chart). Conversely, groundwater contributions over the period of stream flow at the lower gauge were responsible for ~ 52% of the total discharge, while alpine water contributions comprised ~ 48% of the total stream discharge (Fig. 17C pie-chart). The shift in source water contributions to channel flow between the middle gauge and the lower gauge substantially altered the geochemistry of stream water, increased total discharge and lengthened the duration of valley bottom channel flow. Conversely, stream seepage losses in the MFR zone decreased total discharge at the middle gauge while contributing to groundwater recharge.

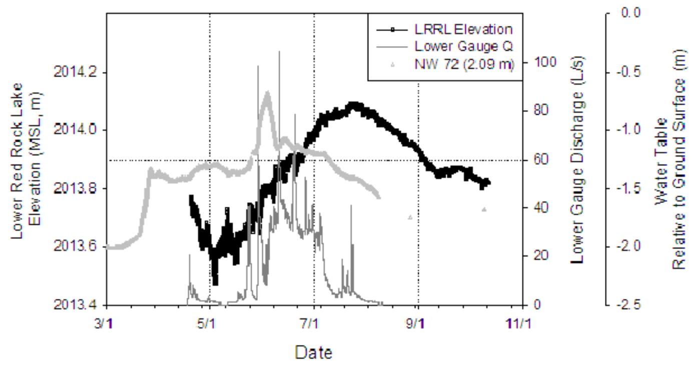

Figure 14. Time series of Lower Red Rock Lake (LRRL) elevation, lower gauge stream discharge (located ~80 meters upstream of the LRRL edge), and groundwater table dynamics for north well 72 (located ~200 meters upstream of the LRRL edge).

Two week discharge totals for the three gauges were determined and separated into groundwater and alpine water components for each two week period from the beginning of May to the end of August. The upper gauge had the highest total discharge for all two week periods except the last two weeks of August, (Fig. 18). The upper gauge discharge was composed completely of alpine water as the gauge was located at the mouth of the mountain watershed, and we defined stream water exiting the mountains as alpine water. The middle gauge discharge totals were typically less than the upper gauge discharge totals, and greater than the lower gauge discharge totals. Groundwater contributions to channel flow at the middle gauge were minor. Weeks 3-4 had the greatest relative groundwater contributions to stream discharge at the middle gauge (Fig. 18). Early and late season base flow at the middle gauge was comprised almost entirely of alpine water, and minor groundwater contributions were measured during rain events.

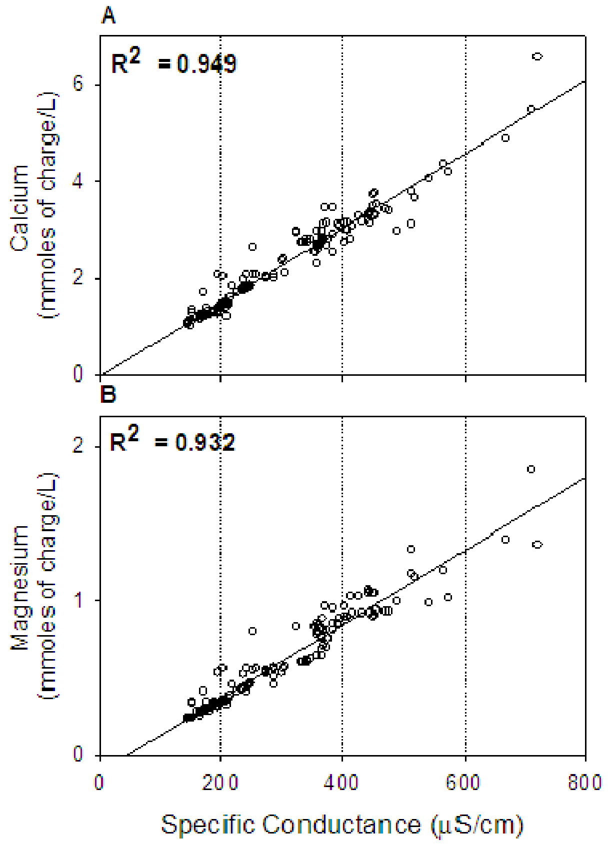

Figure 15. (A) Regression analysis of calcium milli-equivalents (mmole of charge/L) vs. specific conductance (µS/cm); and, (B) regression analysis of magnesium milli-equivalents (mmole of charge/L) vs. specific conductance (µS/cm).

The lower gauge stream discharge was comprised almost entirely of groundwater during weeks 1-2 (Fig. 18). A slightly higher alpine water contribution was evident during weeks 3-4 at the lower gauge, yet discharge was still primarily driven by groundwater contributions (Fig. 18). Groundwater and alpine water contributions to the lower gauge stream discharge during weeks 5-6 were nearly equal (Fig. 18). Alpine water contributions were greater than 50% during weeks 7-8. Weeks 9-10 showed nearly equal contributions from alpine water and groundwater. Late season flow was comprised primarily of groundwater; the lower gauge stream discharge during weeks 11-12 was ~ 80% groundwater and 100 % groundwater during weeks 13-14 (Fig. 18). There was no channel flow at the lower gauge during weeks 15-16.

Groundwater was a major component of valley bottom stream discharge but not MFR zone discharge. Groundwater contributed to MFR zone discharge during rain events, and baseflow was dominated by alpine water contributions. Alpine water contributions to valley bottom discharge were increased during peak annual discharge, and baseflow was dominated by groundwater contributions.

Discussion

How do Alpine to Valley Bottom Transitions Impact Stream Discharge Magnitude and Timing?

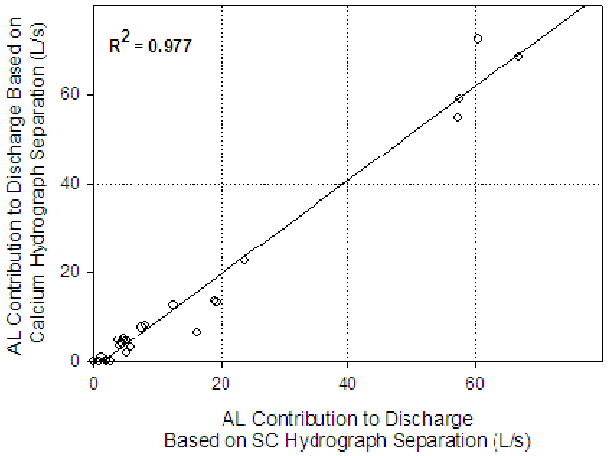

Figure 16. (A) Regression analysis of the calculated alpine runoff (AL) contribution to stream discharge using calcium milli-equivalents from stream and groundwater grab samples vs. the calculated alpine runoff (AL) contribution to stream discharge using specific conductance of the grab samples.

As Humphrey Creek flowed through the mountain front recharge (MFR) zone and across the valley bottom, stream discharge decreased. Stream discharge was greatest at the mountain watershed outlet and least in the valley bottom. Discharge at the upper gauge was 10% of the annual average precipitation. Between 7 May, 2004 and 23 August, stream discharge was 63,005 m^3 greater at the upper gauge than the middle gauge, and 129,551 m^3 greater at the upper gauge than the lower gauge. Total discharge at the middle gauge was 77% of total discharge at the upper gauge, and total discharge at the lower gauge was 50% of total discharge at the upper gauge. Stream seepage losses contributed to evapotranspiration (ET), and soil moisture and groundwater recharge across the transition from alpine to valley bottom.

Stream losses in the MFR zone were partly driven by the physical disconnection between the stream and groundwater system (ie. no continuous zone of saturation between the stream and groundwater).

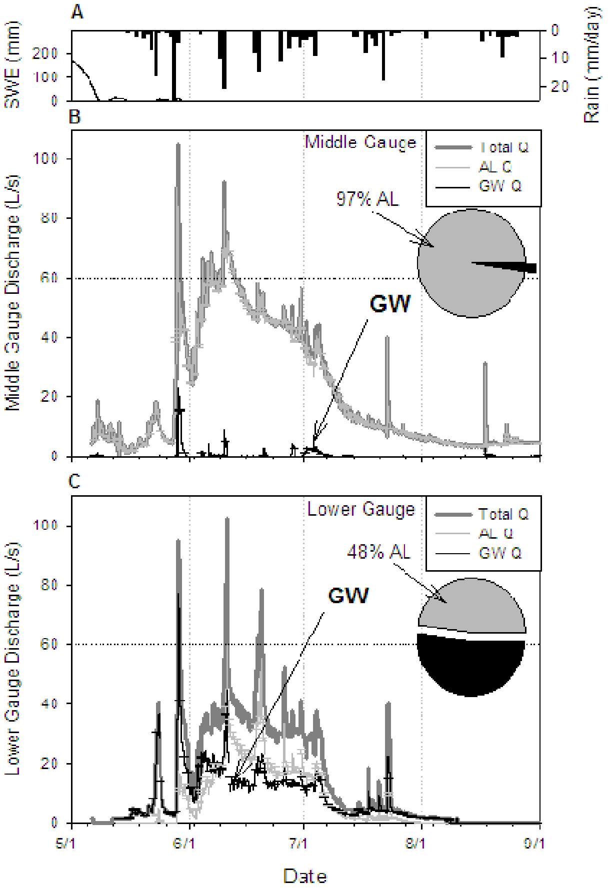

Figure 17. (A) Snow water equivalent (line) and rainfall hyetograph (hanging bars) for 1 May, 2004 through 1 September, 2004. (B) Ten minute interval time series hydrograph separation for the middle gauge (located at the downstream edge of the mountain front recharge zone) into alpine runoff (AL) and groundwater (GW) contributions to stream discharge. Pie-chart represents the alpine runoff and groundwater contributions to total discharge over the four months. (C) Ten minute interval time series hydrograph separation for the lower gauge (located in the valley bottom at the upstream edge of Lower Red Rock Lake) into alpine runoff and groundwater contributions to stream discharge. Pie-chart represents the alpine runoff and groundwater contributions to total discharge over the four months.

When a discontinuity between the stream and groundwater exists, stream seepage will occur and the rate of loss will be a function of stream stage, wetted perimeter, hydraulic conductivity, and bed armoring (Niswonger et al., 2005). Stream seepage losses have been noted as an important source of groundwater recharge in the Basin and Range Province of the Western United States, where streams exiting the mountains can lose the majority of their water as seepage (Niswonger et al., 2005). In the Humphrey Creek watershed, stream discharge at the downstream edge of the MFR zone was 77% of the stream discharge at the upstream edge of the MFR zone. Since there were minimal groundwater inputs to channel flow in this zone, we conclude that ~ 23% of stream water was lost as seepage across the MFR zone. The stream gauges in the MFR zone were separated by ~ 0.5 km, therefore, ~ 23% of the stream water exiting the mountain watershed was lost from the stream in the first 0.5 km. If we assume constant seepage losses across the MFR zone, ~ 126 m^3 of water per m of stream length (m^3/m) would have been lost from the stream between 7 May and 23 August. This is equal to 1.2 m^3/m/day of stream seepage losses contributing to groundwater recharge.

A significant amount of water was lost from the stream at the break in slope where the MFR zone met the valley bottom. This break in slope, where two distinct landscape elements met, was an important location for stream seepage losses and groundwater recharge. Channel slope decreased and fine sediment deposition was evident. In this area Humphrey Creek becomes a multiple thread channel that flows through sedges, rushes, grasses and willows. Occasionally surface flow was not observed in the area where the MFR zone and the valley bottom zone met. In this area surface water had four possible fates: 1) it continued to flow across the surface to where Humphrey Creek was again a single channel; 2) it infiltrated and contributed to soil moisture and groundwater recharge; 3) it was transpired by marsh plants; and, 4) it evaporated from the surface. The wetland-marsh area decreased the velocity of Humphrey Creek stream water, which increased the time available for interaction between stream water and the surrounding soil environment. This was a function of decreased slope and increased surface roughness. Such a situation provides increased opportunity for surface water infiltration to the subsurface, even with low hydraulic conductivities that may be expected in fine sediment depositional areas. The MFR zone stream gauging, groundwater levels, and hydrograph separation support the possibility that MFR zone stream seepage losses are an important source of groundwater recharge to basin aquifers adjacent to mountain watersheds.

Short time-scale hydrograph response to rain events was similar for both the valley bottom and the MFR zone. Although initial hydrograph responses were nearly synchronous, the rain induced hydrograph peaks in the valley bottom were broader than those in the MFR zone. This is likely due to the large groundwater reservoir connected to the stream in the valley bottom and greater upstream contributions. During rain induced discharge peaks, rain, groundwater, and upstream channel flow could contribute to increased stream discharge in the valley bottom. However, in the MFR zone groundwater could not contribute to increased stream

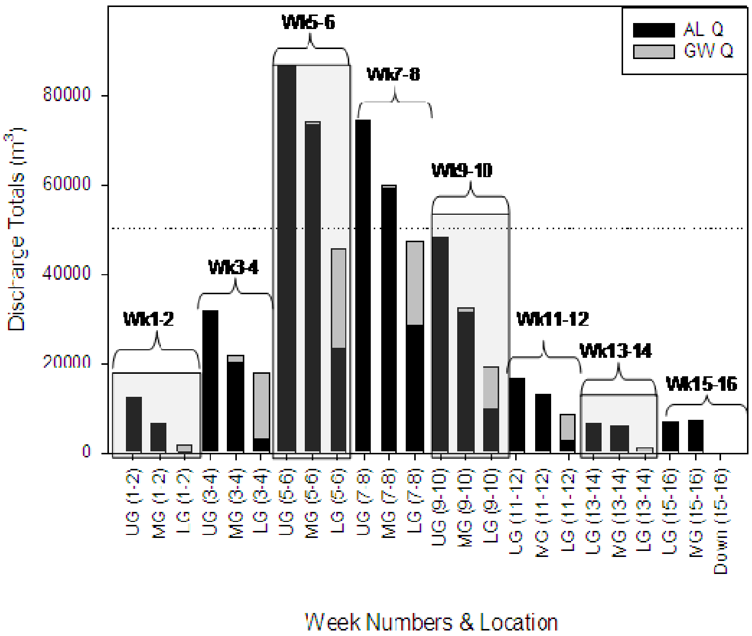

Figure 18. Two week discharge totals separated into alpine runoff (AL) and groundwater (GW) contributions to stream discharge for the upper gauge middle gauge, and lower gauge. The upper gauge was located at the upstream edge of the mountain front recharge (MFR) zone and upper gauge stream discharge was defined as alpine runoff. The middle gauge was located at the downstream edge of the MFR zone, and the lower gauge was located in the valley bottom near the Lower Red Rock Lake edge. All measurements were made at ten minute intervals from 12 May, 2004 through 23 August, 2004.

discharge due to the disconnected stream-groundwater system. Valley bottom groundwater contributions to stream discharge combined with in-channel travel time of upstream storm runoff, would cause broader hydrograph peaks in the valley bottom than in the MFR zone.

Peak annual discharge was snowmelt driven in the MFR zone and the valley bottom of the Humphrey Creek watershed. However, peak annual discharge occurred one day later in the valley bottom than in the MFR zone. This was likely due to in-channel travel time from the MFR zone to the valley bottom. The valley bottom annual discharge peak was broader than the MFR zone peaks. This was likely due to the connected stream-groundwater system in the valley as opposed to the disconnected stream-groundwater system in the MFR zone. We suggest a similar mechanism broadens the snowmelt driven peak and the rain driven hydrograph peaks.

These data suggest that in-channel travel times delay snowmelt driven hydrograph responses from the MFR zone to the valley bottom, and stream-groundwater exchanges and in-channel travel times broaden hydrograph responses to snow and rain driven hydrograph peaks in systems where the stream and groundwater are connected.

How does Stream-Groundwater Exchange Change Over Alpine to Valley Bottom Transition Zones?

Exchange between stream water and local groundwater are dynamic both spatially and temporally. Stream-groundwater exchanges occur at both small and large scales. Small scale exchanges occur along centimeter-long flowpaths, and timescales of seconds to minutes; while, larger scale exchanges occur over hundreds of meters and timescales of days to years (Harvey et al., 1996). At meso-scales, stream-groundwater exchange is impacted by a range of factors including channel sinuosity, width, slope, and aquifer penetration (Sharp, 1977; Larkin and Sharp, 1992); stream water flow through point bars; (Vervier et al., 1993; Wroblicky et al., 1998); temporal variations in groundwater height and stream stage (Pinder and Sauer, 1971); the geometry of the surrounding aquifer, water balance, and hydraulic properties (Freeze and Witherspoon, 1967, 1968; Winter, 1995); and channel changes from constrained to unconstrained (Stanford and Ward, 1993; Fernald et al., 2001). Constrained reaches of the stream channel are often groundwater discharge zones, whereas unconstrained reaches are often groundwater recharge zones (Gregory et al., 1991; Stanford and Ward, 1993).

This research investigated larger scale stream-groundwater exchange and identified groundwater recharge and groundwater discharge zones. Groundwater recharge and discharge zones were associated with specific landscape elements. Groundwater recharge was most pronounced in the upper reaches of the study area (the MFR zone), while groundwater discharge was associated with the valley bottom zone. Although recharge consistently occurred in the MFR zone, and groundwater discharge occurred consistently in the valley bottom, the rates of recharge/discharge were temporally variable.

The area from the outlet of the mountain watershed to the beginning of the valley bottom was a groundwater recharge zone and was defined as the MFR zone. Recharge rates in the MFR zone were highest during early season flow through peak discharge. We suggest that this was due to higher stream stage, lower soil moisture, and deeper groundwater levels during early season flow. Since the stream in the MFR zone was losing water between the upper gauge and the middle gauge, the stream water chemistry remained relatively constant between these two gauges. Consistent stream water chemistry across the MFR zone corroborates the stream hydrograph, groundwater level, and piezometric data that indicated stream seepage. Losing streams which do not have input of groundwater do not have mixing of multiple source waters that would lead to changing chemistry across a reach. The stream water flowing across the MFR zone was from the same source, the alpine zone of the watershed.

The valley bottom zone, the area between the MFR zone and the Lower Red Rock Lake (LRRL) edge, was a groundwater discharge zone. Upward and lateral groundwater gradients were observed, and groundwater levels in the valley bottom zone constrained the stream channel. The hydrology in the valley bottom was distinct from the hydrology in the MFR zone. Specifically, instead of the stream supplying water to the groundwater system, as in the MFR zone, the opposite occurred in the valley bottom. Groundwater inputs to the stream channel drove stream discharge and a critical groundwater level was necessary to sustain channel flow. While alpine runoff was the major input to channel flow in the MFR zone, groundwater was the major input to annual channel flow in the valley bottom. Since substantial amounts of water were lost from Humphrey Creek before the stream reached the valley bottom, another source of water was necessary for channel flow. When groundwater levels decreased below a threshold value, stream discharge in the valley bottom ended abruptly. This suggests that water exiting the mountains was not adequate to sustain valley bottom channel flow.

Groundwater inputs to the stream channel led to mixing of alpine water inputs and groundwater inputs to valley bottom stream discharge. This altered the chemistry of stream water flowing downstream across the valley bottom zone. Stream water in the valley bottom had a chemical signature closer to that of groundwater than alpine water, particularly during baseflow. Harvey et al. (1996) noted timescales of years for stream-groundwater exchange on larger spatial scales. This coupled with the small mixing volume of alpine water compared to the large mixing volume of valley bottom groundwater suggests that the bulk of alpine water that exits the stream will have obtained a groundwater signature by the time it re-enters the stream channel. This caused stream water chemistry to be substantially different over a relatively a short distance of 1.5 km from MFR zone to the valley bottom. Distinct hydrologic systems from the MFR zone to the valley bottom impacted stream hydrograph response, stream-groundwater exchange, and stream water chemistry.

<u>What are the Relative Proportions of Alpine and Groundwater Inputs to Stream Discharge in Humphrey Creek from the MFR Zone to the Valley Bottom?</u>

Geochemical tracers are powerful tools for determining the proportions of various source water contributions to stream flow and have been applied worldwide across a full range of environmental conditions (Pinder and Jones, 1969; Sklash and Farvolden, 1979; McDonnell et al., 1990; Bonnell, 1993; Mullholland, 1993; Harris et al., 1995; McGlynn et al., 1999).

Gooseff and McGlynn (2005) demonstrated that specific conductance (SC) can be substituted for geochemical tracers in hydrograph separations. We used SC to develop real-time hydrograph separations and were able to determine the relative proportions of alpine water and groundwater contributions to stream discharge at the middle gauge and the lower gauge at 10 minute intervals.

Stream discharge in the MFR zone was dominated by alpine water in 2004. Alpine water was responsible for ~ 97% of the total discharge at the middle gauge. This corroborates hydrometric data which suggested that Humphrey Creek was losing over this reach. Groundwater inputs to stream discharge occurred during rain events at the middle gauge. This suggests that rain events displaced groundwater into the stream channel. More specifically that rain increased groundwater levels and groundwater gradients toward the stream. After rain ended, groundwater contributions to channel flow decreased to ~ 0% of total discharge. Due to the lack of groundwater inputs to stream flow in the MFR zone, the difference in discharge between the upper gauge and the middle gauge was ~ equal to the stream losses that occurred over this reach. Furthermore, the chemistry of stream water across the MFR zone was relatively constant due to the lack of groundwater source water contributions to stream discharge.

In contrast to the hydrology in the MFR zone, groundwater contributed ~ 52% of the total discharge at the lower gauge in 2004. This corroborated hydrometric data (wells, and piezometers) which suggested that Humphrey Creek was gaining over this reach. Hydrograph separations allowed us to determine how much of the alpine water that exited the mountains reached the valley bottom as channel flow. For instance, the upper gauge total discharge was 129,551 m^3 more than the lower gauge total discharge in 2004. However, by separating the lower gauge total discharge into alpine water and groundwater components, we find that alpine discharge at the upper gauge was 202,214 m^3 greater than the alpine discharge at the lower gauge. Although the lower gauge total discharge equaled ~ 50% of the total discharge at the upper gauge, in terms of the alpine water component the lower gauge discharge equaled only ~ 24% of the upper gauge discharge. Groundwater contributions to valley bottom stream discharge not only increased the amount of discharge but also substantially altered the chemistry of the stream water in the valley bottom compared to MFR zone stream water. Valley bottom stream water was similar in geochemical signature to valley bottom groundwater, while MFR zone stream water was similar to alpine water. This suggests that stream-groundwater exchange and groundwater inputs to stream discharge are an important mechanism in valley bottom stream flow generation and that local groundwater chemistry largely dictates the chemistry of stream water in gaining valley bottom streams.

Conclusions

Stream and groundwater hydrometric data coupled with geochemical hydrograph separations in the Humphrey Creek watershed of southwestern Montana suggest that:

(1) Humphrey Creek recharged groundwater in the mountain front recharge (MFR) zone, and stream seepage losses were an important mechanism for valley bottom groundwater recharge,

(2) Valley bottom groundwater was the predominant source of valley bottom stream discharge, and sustained channel flow,

(3) Stream-groundwater exchange in the valley bottom attenuated stream hydrograph response and altered stream water chemical composition,

(4) Spatially and temporally dynamic stream-groundwater exchange is important for valley bottom aquifer status, hydrograph response to snow and rain inputs, and can determine stream water chemistry.

A better understanding of large scale stream-groundwater exchange is important to hydrologists, biogeochemists, and ecologists. This research provides insight into the impacts that large scale stream-groundwater exchanges can have on watershed hydrologic responses and their potential impact on the timing, quantity, and chemistry of water moving through a watershed; which has implications for biogeochemical cycling and ecosystem functioning. To continue to improve the understanding of stream-groundwater exchange and their impact on watershed hydrology, biogeochemistry and ecosystem processes it is imperative that further studies of large scale stream-groundwater exchange be undertaken. The results presented in this paper highlight the necessity of a combined approach to the study of dynamic stream-groundwater exchange.

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Information Transfer Program

During FY 2005 (March 1, 2005 through February 28, 2006), the Montana Water Center developed and sponsored many programs and tools to carry out its 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. Because of support from the USGS, the Center was actively involved in the following water information transfer activities:

-- Coordinated all water research and information transfer activities in collaboration with the Center's Director at Montana State University (Gretchen Rupp), and Associate Directors at the University of Montana (Dr. Donald Potts) and Montana Tech (Dr. Marvin Miller) campuses;

--Administered the 104b research grants, and promoted interest in the 104g research grant program, all with assistance from and formal communications with the Center's Water Research Advisory Committee (see Introduction for list);

--Developed and circulated an RFP for the competitive student fellowship program, and ultimately offered research awards to 12 undergraduate and graduate students from three Montana institutions of higher education;

--Trained and mentored two student interns who helped track research findings and develop outreach materials for the Montana Water Center's monthly e-newsletter;

--On this note, published twelve monthly Montana Water e-newsletters distributed to a database of over 1,500 people. E-news archives are posted at http://water.montana.edu/newsletter/archives/default.asp;

--Coordinated and facilitated the Montana Water Summit: A Conversation about Research Education and Outreach at Montana State University on Friday, August 19, 2005. Thirty-five faculty, research and outreach staff members attended the Summit to engage in a facilitated discussion concerning MSU's efforts in water research, education and outreach. Summit background information and a summary of recommendations that arose from these deliberations may be found at http://water.montana.edu/summit;

--Hosted a February 7, 2006 presentation entitled: After the Tsunami: Protecting Public Health in a Devastated Province presented by Dr. Paul Byleveld, Manager of the Water Unit in the New South Wales Department of Health, Australia. A member of the Australian Army Reserve, Major Byleveld shared his experience of helping to establish and monitor emergency water and sanitation systems after the tsunami in Indonesia where he was a team leader for six weeks;

--Assisted in regional planning for the Workshop on Energy and Water How Can We Get Both for the Price of One? offered in Fort Collins, Colorado to explore potential uses for the waters produced from fossil fuel development, including coal bed methane extraction. Workshop speakers and panelists examined policy challenges involved in converting produced waters to beneficial use. It was hosted by the Colorado Water Resources Research Institute. Complete workshop information is available at www.cwrri.colostate.edu;

--With the Inland Northwest Research Alliance, began planning for a 2006 Northwest Water Policy and Law Symposium to be held in Bozeman, Montana on September 18-20, 2006. Although the workshop was not conducted in the reporting period, significant outreach effort went into developing the meeting agenda and the meeting web site at http://water.montana.edu/policy;

--Continued to maintain and expand MONTANA WATER, the Montana Water Center's web information network at http://water.montana.edu. This website includes an events page, news updates, an online library, water-resource forums, a Montana watersheds projects database, an expertise directory, water facts and more;

--Maintained the web site of the Montana Watersheds Coordination Council at http://water.montana.edu/watersheds/default.asp; and the Montana Water Center's Outreach Director served as co-chair for the Council;

--Produced the Montana Water Center's Annual Report, Fiscal Year 2005 covering all of the programs accomplished through the Center's $2.3M budget, posted at http://watercenter.montana.edu/publication/reports.htm;

--Coordinated two live teleconferences sponsored by the American Water Works Association. Water-system professionals attended at downlink sites in Missoula, Havre, Great Falls, Billings, Helena, Butte and Bozeman (at the Water Center offices). The March 10, 2005 teleconference focused on Excellence in Water Quality Distribution and the November 3, 2005 teleconference was titled The Shrinking Workforce: Hype or Crisis?;

--Conducted the state-wide water research meeting on October 27 and 28, 2005 in Bozeman, Montana. The theme of this 22nd annual meeting, held in conjunction with the Montana Section of the American Water Resources Association, was "Surface Water/Ground Water: One Resource." A pre-meeting field trip examined surface water/ground water problems of the Gallatin Valley. With record attendance, the meeting attracted over 200 Montana hydrologists and policy makers who took in stimulating plenary presentations by Robert Glennon, Bill Woessner and Jack Ward Thomas. Nearly 60 technical papers were presented. Two of the six students awarded for excellence in scientific presentation were funded by the USGS base grant. The web-based archive of this meeting is found at http://awra.org/state/montana/events/conf_archives.htm;

--Served as a liaison among the university community, water professionals, and decisionmakers in local, state, and tribal and federal governments, including attendance at all Montana Legislative Environmental Quality Council meetings and Montana University System research outreach coordination meetings;

--Invested time in partnering with other groups with similar goals of translating scientific information for effective problem-solving;

--Participated in the 72nd Annual Water School on October 3-6, 2005 at Montana State University. Designed for water and wastewater managers and operators, this training provided information on treatment plant chemical safety, emergency response, developing quality assurance programs, and more. At the close of the training, operators may sit for the water/wastewater certification exam administered by the Montana Department of Environmental Quality (DEQ). Along with DEQ, this program is conducted by the Montana Environmental Training Center, the Montana Water Center, and the MSU Department of Civil Engineering; and

--Created the second annual black-and-white water facts and photos calendar for general circulation entitled Montana Water 2006. Each month was dedicated to a different Montana water topic. A copy of this is located at http://watercenter.montana.edu/publications/other.htm

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	0	0	0	6
Masters	9	0	0	0	9
Ph.D.	4	0	0	0	4
Post-Doc.	0	0	0	0	0
Total	19	0	0	0	19

Notable Awards and Achievements

The Montana Water Center's Annual Water Conference organized in Bozeman in October 2005 claimed record attendance on a key topic. Entitled Surface and Ground Water: One Resource, the conference attracted well over 200 Montana hydrologists and policy makers who took in stimulating plenary presentations by Robert Glennon, Bill Woessner and Jack Ward Thomas. The panelists inspired in-depth discussion about the future of Montana's ground water resources in a time of population expansion and climate change. Those assembled also presented nearly 60 technical papers on the subject. Two of the six students awarded for excellence in scientific presentation were funded by the USGS base grant.

Because of the foundation offered by the annual USGS base grant, the Montana Water Center is also able to achieve funding for other research initiatives. This year it unveiled the Virtual System Explorer 2006. This widely-distributed DVD simulates an untreated ground water system, a treated ground water system, and a surface water system. Using this software, users learn how to operate a water system, perform a security risk assessment, and improve the financial capacity of a system.

Publications from Prior Projects