Aquifers and Streams of the Stillwater–Rosebud Watersheds

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ABSTRACT

The local population of the Stillwater and Rosebud valleys in south-central Montana depends entirely upon groundwater for potable water. Most homes are beyond municipal services and obtain their water from individual domestic wells that are concentrated in the center of the thin alluvial valley fill. Because the demand for water is increasing and land use is changing, there is potential for groundwater resources in the valleys to become stressed and over utilized in some locations, which could limit availability of groundwater and reduce in-stream flows. The primary threat to the alluvial aquifer is land-use change from agricultural to residential. This type of change could impact the alluvial aquifer by reducing recharge during the irrigation season, possibly resulting in dry wells. In-stream flow rates of the Stillwater and Rosebud rivers could also be impacted by reduced groundwater discharge during summer base flow conditions.

The alluvial aquifers in the study area consist of thin, highly conductive sand and gravel layers confined below by shale and semi-confined above (in some areas) by soft clay. Irrigation dominates the hydrology of the alluvial valleys and unlined ditches convey water across the valley floors. Aquifer pumping tests and calculated specific capacity values were used to estimate the hydrologic properties of the alluvial and bedrock aquifers. A transmissivity range of 653 to 3,800 ft2 / day and hydraulic conductivity range of 48 to 120 ft / day were determined for the Stillwater alluvial aquifer. A specific yield of 0.16 was calculated using the Neuman method. The Tertiary and Cretaceous bedrock aquifers consist of alternating beds of fractured shale and sandstone. Groundwater flow through the bedrock aquifers is probably fracture dominated. The bedrock aquifers have a range of transmissivity of 62 to 190 ft2 /day and a hydraulic conductivity of 6 to 13 ft /day, with a calculated storativity value of 0.02.

Many different field methods were used to examine the interaction between groundwater and surface water in the study area. Evidence from stable isotopes of water indicates the bedrock aquifer is recharged from low altitude rain, or snow that has been partially evaporated. In contrast, the alluvial groundwater and the river water have experienced little evaporation and the isotopic compositions suggest these waters are sourced from precipitation at higher elevations along the Beartooth Plateau. Isotopic similarities imply that river water, diverted onto the fields during irrigation, is the dominant source of groundwater in the alluvium. Salinity (specific conductance) measurements were used as a groundwater tracer and indicated flow of groundwater from the alluvial and bedrock aquifers into the surface water systems. Water levels in the alluvial aquifer responded rapidly to changes in ditch flow, indicating a close connection between surface water and groundwater. Water-level data also showed that the alluvial and bedrock aquifer are in hydrologic connection. Based on synoptic flow-rate surveys, the Stillwater River gains water from the alluvial and bedrock aquifers through the central and lower portions of the field area.

Steady state and transient groundwater flow models were created with Groundwater Modeling System software using MODFLOW to simulate the flow of groundwater through the alluvial aquifer. Projective simulations were used to determine if adequate groundwater would be available if the valley was no longer irrigated. The model predicts a water-level-head drop of up to 18 feet in the alluvial aquifer if irrigation is discontinued in the Stillwater valley. The Stillwater River base flow would also be impacted by a reduced groundwater discharge of about 6 cfs. Less fresh, cool groundwater discharging to the river during summer low-flow periods could have adverse effects on aquatic life. Because of the close connection between irrigation water, shallow groundwater, and river water, the alluvial aquifer in the study area is very sensitive to changes in land use. This also implies that the aquifer is highly vulnerable to surface contamination, which needs to be taken into consideration as future development is considered.

INTRODUCTION

Background

Between 1990 and 2000 the population in Stillwater County grew by over 25 percent (Montana Department of Commerce, 1990, 2000). The majority of the population in this area depends entirely upon groundwater for potable water. Most homes are beyond municipal services and obtain their water from individual domestic wells that are concentrated in the alluvial valleys. Because of the population growth, there is potential for groundwater resources to become stressed and over-utilized in some locations. With new development expected to continue into the future, there was a need to determine the sustainable level of use of the major alluvial and bedrock groundwater systems in the Stillwater and Rosebud watersheds (fig. 1).

A primary reason the region is experiencing such rapid growth is the numerous high-quality streams and fisheries available for recreation and other uses. However, the very rivers that are drawing people to the region may be impacted by the increased population. The interaction between the groundwater used for homes, lawns, and gardens and the surface water used for irrigation and recreation has not previously been defined for the Stillwater and Rosebud watersheds. It was suspected, however, that baseflows for the rivers are supported by groundwater. Therefore, it was important to determine how much effect an increasing population will have on river flow rates. River flow could be impacted by the increased number of wells in the area by either intercepting groundwater flow that would have discharged to a river or by capturing river flow directly (river depletion) through riverbed infiltration. Land-use changes from agricultural to domestic and changes to irrigation practices and irrigation ditches may also affect groundwater and surface-water flows.

Purpose and Scope

The purpose of this project was to determine if the aquifers in the Stillwater and Rosebud watersheds can support increased population demand. This was accomplished through methods consisting of compiling existing data, monitoring groundwater levels and field parameters, measuring streamflows, collecting water quality and stable isotope samples, performing aquifer pumping tests, and constructing a computer model of a representative section of the Stillwater alluvial valley (outlined in red on fig. 1).

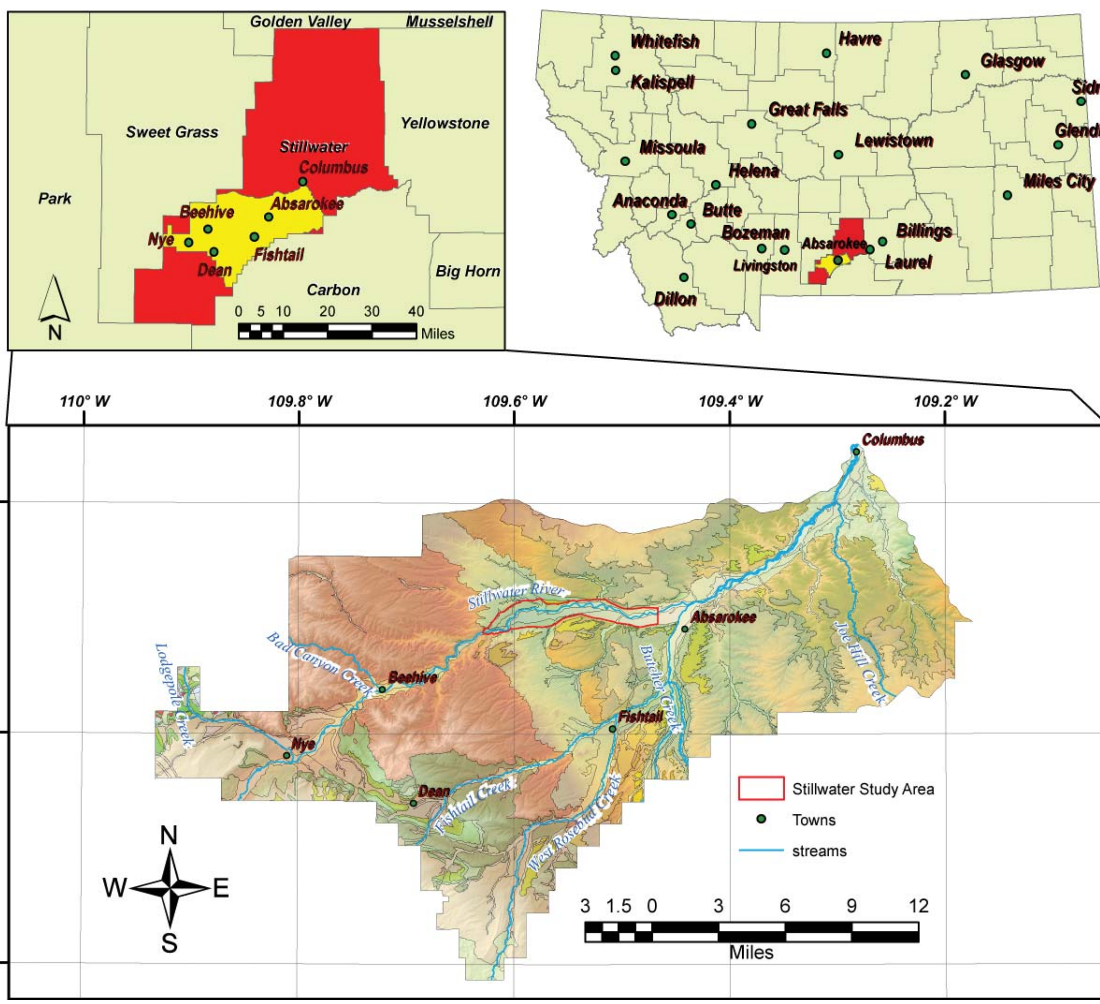


Figure 1. Location map of the project area within Stillwater County, Montana.

Overview of the Project Area

Physiography

From its headwaters in the Beartooth Mountains to Columbus, Montana, where it drains into the Yellowstone River, the Stillwater River and Rosebud Creek area transitions from rather narrow, deep glaciated canyons to wide valleys with floodplains and terraces on the plains (Feltis and Litke, 1987). The river is about 65 miles long and is fed by numerous tributary streams. Several of the largest tributaries, East and West Rosebud Creeks and Fishtail Creek, also have narrow, deep glaciated canyons with headwaters in the Beartooth Mountains that have incised into Tertiary and Cretaceous age geologic bedrock units.

The United States Geological Survey (USGS) has a stream-flow gauging station located on the Stillwater River north of Absarokee, after the confluence of the East and West Rosebud Creeks enter the Stillwater River. The USGS gauging station has recorded streamflow readings from this location since 1910.

Of the numerous tributary streams that enter the project area, the larger perennial streams have flow rates that are high during spring runoff and decrease to baseflows of 1 to 2 cubic feet per second (cfs) the rest of the year. Other small, ephemeral streams were not measured, but, outside of high flows in the spring, have an estimated flow rate of 1 cfs or less and can be dry at baseflow conditions.

Irrigation effects dominate the hydrology in most of the alluvial valleys. The irrigation ditches convey water out of the rivers by way of rock-constructed weirs. The water is then transported across fields through unlined canals and ditches, maintaining the highest elevation possible. Flood irrigation is the main form of irrigation; however, a couple of center pivots and sprinkler systems are also supplied by ditch water.

Geology Overview

The geology of the project area is summarized in figure 2 (next page). The main hydrostratigraphic units are Quaternary alluvium and Tertiary, Cretaceous, and Jurassic bedrock formations. The area's structure is dominated by the Reed Point Syncline, Beartooth Uplift, and the Stillwater Complex, a layered igneous intrusion.

The following geologic descriptions are taken from Lopez (2000). The modern Holocene alluvium consists of gravel, sand, silt, and clay along the modern riverbed and tributary channels. Igneous and metamorphic boulders, cobbles, and pebbles make up the beds of the Stillwater River and Rosebud Creeks.

Several different Pleistocene alluvial terrace deposits are present in the project area. Some of the oldest terrace gravels are exposed from 200 to 600 ft above the current river level. They occur as erosional remnants up to 20 ft thick on top of the Tertiary and Cretaceous bedrock and contain mainly igneous and metamorphic clasts that range in size from cobbles to gravel. The younger alluvial gravel terraces occupy the river valleys at elevations that range from 10 to 20 ft above the current river channel. These gravels are about 10 to 40 ft thick and, like the modern alluvium, are dominated by igneous and metamorphic clasts that range in size from cobbles to pebbles with minor sand and silt.

Near the Reed Point Syncline, Tertiary rocks crop out along the fold axis and are flanked on either side by the Cretaceous Hell Creek Formation (fig. 2). The Hell Creek Formation consists mainly of light brownish-grey, fine-grained, ledge-forming, thick-bedded sandstone. The unit is interbedded with mudstones of varying color. The total thickness of the formation is about 900 to 1,100 ft. The Hell Creek Formation is conformably overlain by the Tertiary Fort Union Formation, which is subdivided into the Tongue River, Lebo, and Tullock Members. Both the Tongue River and Tullock Members contain fine- to medium-grained, ledge-forming sandstones that are gray to yellow in color. The Tongue River Member is interbedded with carbonaceous shale and siltstone and minor coalbeds. The unit can be up to 400 ft thick. The Lebo Member consists mostly of gray to olive-green shale, with some thin interbeds of sandstone and siltstone. The Lebo Member is 200 to 250 ft thick. The Tullock Member is interbedded with claystone, siltstone, and minor carbonaceous shale, and is about 400 to 600 ft thick.

Many other Cretaceous and Jurassic Formations are also present in the southwestern boundary of the project. The formations have numerous faults and have tilting associated with tectonic events. These sedimentary units alternate between shale and sandstone and have varying thicknesses. Outcrops in the northwest boundary of the project consist of the Cretaceous Sliderock

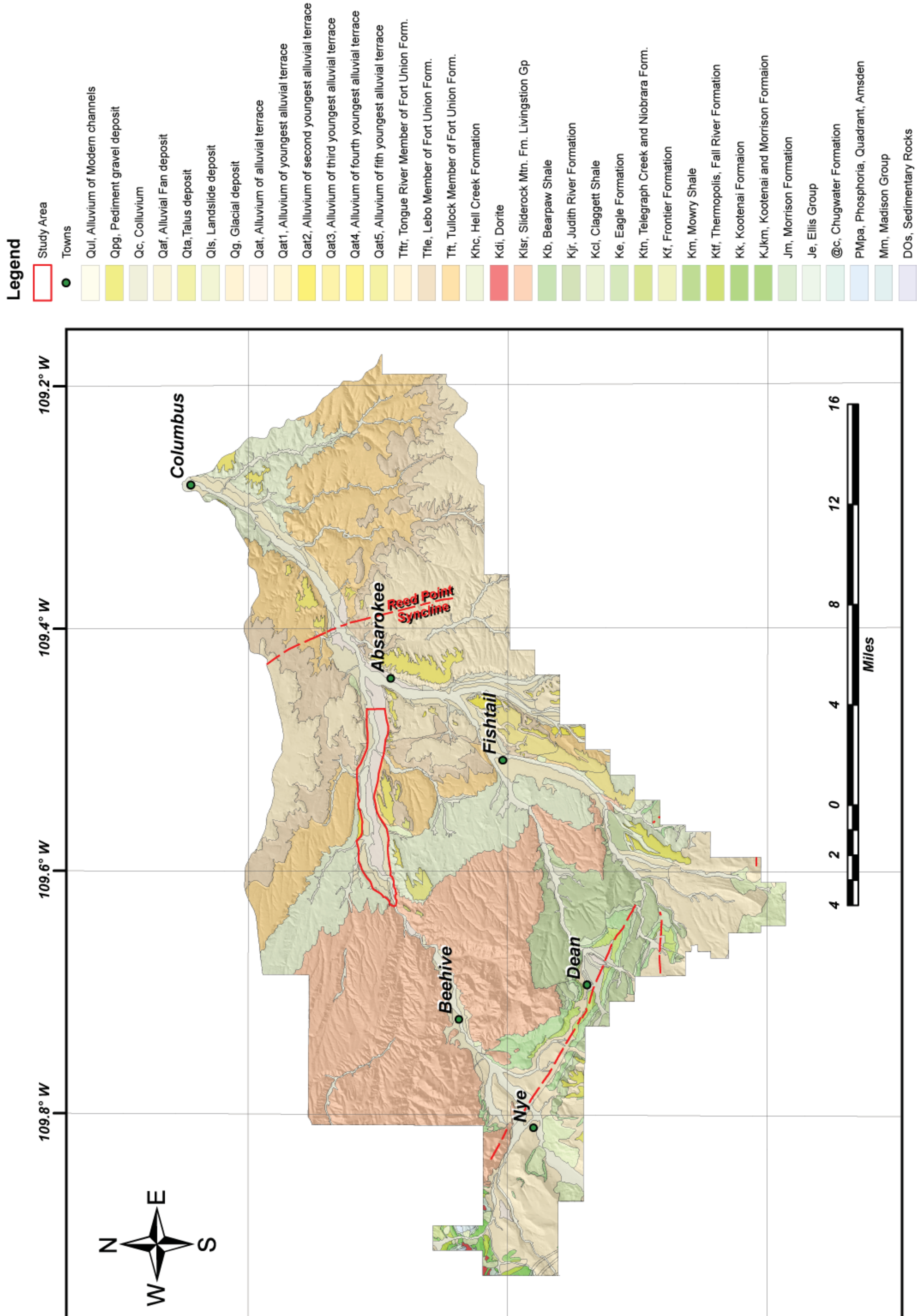


Figure 2. Geology of the project area (modified from Lopez, 2000).

Mountain Formation. This formation is up to 1,000 ft thick and consists mostly of gray, purple, and green andesite breccia derived from rocks erupted from the Sliderock stratovolcano (Du Bray and Harlan, 1994; Lopez, 2000).

If more information is desired, Feltis and Litke (1987) and Lopez (2000, 2001) give a more detailed survey of the local and regional geology of the area.

Climate

The project area has a semi-arid climate in the lower elevations and an alpine climate in the higher elevations. A semi-arid climate is defined by precipitation levels that fall just below the potential evapotranspiration and has areas with major temperature changes between day and night, while alpine climates have a mean temperature below 50 degrees Fahrenheit. Climate data used during this study were recorded at the Fishtail RAWS meteorological station located approximately 4 miles south of the project area and north of the town of Fishtail at T. 4 S., R. 17 E., sec. 25 at an elevation of 4550 ft (Western Regional Climate Center, 2010). The average annual precipitation is 17.96 in, using 56 years of precipitation data. Most of the precipitation for the area occurs during spring and early summer, with little in late summer and winter. May is the wettest month, with an average total precipitation of 3.54 in, while December and January are the driest, with an average total precipitation of 0.6 in. Thunderstorms primarily bring the spring precipitation, while snow events bring winter precipitation. Large amounts of snow are stored in the adjacent Beartooth Mountains. This snow slowly melts each spring and supplies the rivers and streams with large amounts of water.

Land Use

Land use in the valleys mainly consists of irrigated agricultural practices. Although the growing season is relatively short in this region, the alfalfa and grassland hay typically receive two cuttings. Area ranches are typically small to moderate in size (generally less than 500 acres), family operated, and primarily raise cattle and/or sheep. Based on personal communication with landowners, many of the farm/ranch properties in the area have stayed within the same families for generations. Land use in the uplands above the valleys is mainly reserved for pastures and dry-land farming practices. In recent years, patchwork pieces of the valleys and uplands have been converted from irrigated rural lands to residential subdivisions.

Previous Hydrogeological Investigations

Several hydrogeologic studies have been done in and near Stillwater County and in south-central Montana. Some of the studies used aquifer pumping tests to determine aquifer properties of the alluvial and bedrock aquifers in the region. In other studies, water chemistry has been used to distinguish the different aquifer types and to determine groundwater recharge sources.

Feltis and Litke (1987) studied the hydrology of groundwater and surface water in the Boulder and Stillwater River basins. They determined that the Stillwater River is actively down-cutting its own alluvial valley. Because of this down-cutting, the river does not naturally recharge the alluvial aquifers in the area. Transmissivity values determined by pumping tests in the thicker outwash and alluvial fan deposits ranged from 18,000 to 53,000 ft^2/day. These pumping tests were located at T. 4 S., R. 16 E., sec. 29. Water-quality samples were collected from both groundwater and surface water. The surface-water quality was classified as mainly dilute calcium bicarbonate type. The groundwater quality varied according to the source rock and the length of time the water was in contact with the aquifer.

Olson and Reiten (2002) evaluated the hydrogeology and impacts of land-use changes in the west Billings area where land is being converted from irrigated farmland to residential homes. In west Billings, the primary irrigation type is flood irrigation and, for over a century, flood irrigation has created an artificially recharged alluvial aquifer. Olson and Reiten (2002) performed aquifer pumping tests to estimate the transmissivity of the Yellowstone River alluvial aquifer and determined the range was between 140 and 15,600 ft^2/day. It was also documented that wells located near major irrigation ditches had rising water levels as soon as irrigation ditches were turned on and falling water levels directly after ditches were turned off. Olson and Reiten (2002) determined that large ditches (10–30 ft wide) leak 2–6 ft^3/day/ft of ditch. It was concluded that conversion of agricultural land to subdivisions could lead to a reduction in recharge by ditch leakage if the ditches were rerouted or shut off, which could have an adverse effect on the alluvial aquifer system. Olson and Reiten (2002) used stable isotopes of hydrogen and oxygen in water to help determine sources of groundwater recharge. Precipitation in the form of colder, high-altitude snow has distinct isotope ratios compared to warmer, lower-altitude rain. Irrigation water comes from the river, which is primarily direct snowmelt or groundwater that was recharged during snowmelt. Based on the isotope signatures it was determined that recharge of the shallow alluvial aquifer in the west Billings area was primarily from irrigation water. Chloride, a non-reactive conservative ion, was used to calculate the percentage of evapotranspiration loss for irrigated fields, which ranged from 70 to 80 percent of applied irrigation water.

The Montana Bureau of Mines and Geology's (MBMG) Ground-Water Assessment Program performed a groundwater characterization of Carbon and Stillwater Counties from 2002 to 2005 (Carstarphen and Smith, 2007). The purpose of the project was to collect baseline groundwater conditions for alluvial and bedrock aquifers, which will help the public to understand the groundwater quantity and quality. The data collected included static water levels, pH, temperature, and specific conductance (Carstarphen and Smith, 2007). Water-quality samples were also collected at numerous sites. At several of the well sites, water levels were measured monthly and are at present monitored quarterly by the statewide program.

The Montana Department of Natural Resources and Conservation (DNRC, 2009) has created a draft report for the Horse Creek Temporary Controlled Ground Water Area (CGWA) in Stillwater County. This controlled area was developed because landowners were worried about groundwater impacts from a new 65-lot subdivision (fig. 3). Wells and springs were monitored for several years in the CGWA. In July 2008, two aquifer tests were performed: one by a local well driller for an 8-hour period and a second by DNRC for a 47-hour period. The 8-hour and 47-hour tests provided estimates of Tullock bedrock aquifer transmissivity of 840 and 1,050 ft^2/day. It was concluded by the DNRC that groundwater drawdown by pumping wells would affect springs in the Horse Creek CGWA and surface water such as Rosebud Creek and Stillwater River.

Meredith and others (2009) evaluated the hydrogeology of the northern Bighorn River Valley to evaluate potential effects of land-use change. Currently, a majority of the valley's residents live outside city limits and depend on the alluvial aquifer for their drinking water source. Similar to the project area, the alluvial aquifer is recharged by irrigation ditch leakage and direct field application. Meredith and others (2009) performed two 24-hour aquifer pumping tests, and transmissivity was estimated to be between 1,054 and 2,080 ft^2/day in the alluvial aquifer. Hydrogen and oxygen isotopes of water were used as tracers to help determine the recharge source in the alluvial aquifer. Isotope samples were collected from the Bighorn River, from ditches fed by the Bighorn River, and from alluvial wells. It was determined that most of the groundwater isotope ratios were very similar to those in the river and the ditches, indicating nearly all shallow groundwater is recharged from surface water.

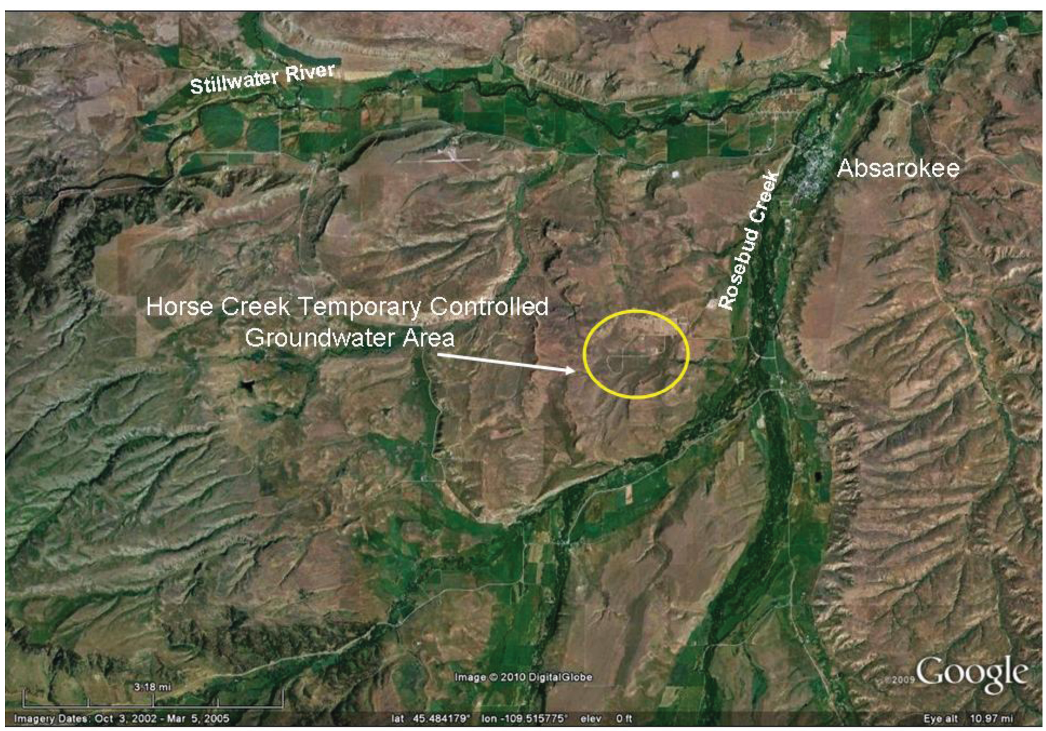


Figure 3. Location of Horse Creek Temporary Controlled Ground Water Area.

METHODS

Field Methods

Field methods used in this project area include: well inventory and monthly water-level measurements, stream and irrigation-ditch flow measurements, pressure transducer data logger recording, field water-quality measurements, water-quality sampling, stable-isotope sampling, altitude surveying, well installation, aquifer pumping tests, and evaporation pan measurements.

Well Inventory and Monthly Water Levels

The inventory data include: static water level, total depth of well (TD), field pH, field specific conductance (SC), water temperature, and a GPS location. The wells were located within the alluvial valleys of the project area or on the uplands above the valley floor. Lithologic well logs were retrieved from the MBMG website Groundwater Information Center (GWIC) and were used to help determine geologic units and aquifer thickness (MBMG, 2009). All well logs in the GWIC database are assigned an identification number (GWIC ID). This number is used by the GWIC database to retrieve information about specific wells. The GWIC ID number will be used throughout this paper to refer to specific wells.

Water levels in several of the inventoried wells were monitored monthly, and additional wells for monthly monitoring were identified throughout the duration of the project to fill data gaps. By the end of the project, 51 wells were monitored monthly.

Flow Measurements

Streamflows were measured using standard USGS methods (Rantz and others, 1982). To measure streamflow rates, the width, depth, and time-integrated velocity of the stream must be measured. To measure the width of the river, a field measuring tape was stretched across the river and securely tied on each end. The total width from bank to bank was then divided into 20 equal portions to minimize flow error and obtain a representative cross section. The water depth was recorded by using the depth rod scale engraved onto a Swoffer 2100 current-velocity meter. The flows were then gauged at 6/10 of the stream depth from the surface of the stream using the Swoffer 2100. This meter uses a horizontal-axis, propeller-driven photo-fiber optic sensor to determine a time-integrated stream velocity. The time-integrated stream velocity (ft/s), multiplied by the cross-sectional area (ft^2), is the streamflow in cubic feet per second (cfs).

The accuracy of the Swoffer velocity meter was checked on February 13, 2009 by comparing the measured streamflow of the Stillwater River as described above to the reported streamflow from a USGS real-time gauging station at the same location. The Swoffer result was 5 percent lower than the USGS result (249 versus 262 cfs); therefore, the two values are well within the combined measurement error. At high-flow times in the spring, the Swoffer velocity meter was attached to a bridge-mounted crane.

Pressure Transducer Installation

Several real-time, water-level data loggers (In-Situ Level Troll 100s) were installed to measure and record changes in water level and temperature. The device is non-vented (records both barometric and water-level pressure changes), so a separate barometer logger was used to adjust for barometric changes in the atmosphere. To measure groundwater head, the loggers were suspended inside well casings within the water column on a cable. For surface-water applications, the loggers were inserted inside 2-in PVC pipes that were attached to bridge pylons. All loggers were set to record depth-to-water and temperature once every hour.

Field Water-Quality Measurements

Field water-quality measurements were taken for both surface and groundwater samples. In order to ensure a well-mixed surface-water sample, a bucket was lowered from a bridge at the fastest moving point in a stream to collect the sample. Field water-quality measurements for groundwater were only recorded after pumping the well a sufficient time for the parameters to stabilize, usually a volume of water approximately equal to three times the water column.

Field water-quality measurements included: pH, SC, and temperature. Parameters were measured on surface water seasonally and on groundwater when wells were initially visited. A handheld Geotech WTW meter was used to measure pH and a YSI conductivity meter was used to measure SC values in µS/cm. The water temperature was displayed by both instruments but was always recorded from the pH probe for consistency. A two-point calibration method was performed every field day with the pH meter. The two standardized calibration buffers used were pH 7.0 and pH 10.00. All calibrations were performed according to the manufacturer's instructions.

Specific conductivity was calibrated monthly in the laboratory to a known standard of 1413 µS/cm. All SC values were automatically temperature-corrected to 25°C by the meter. During some of the winter trips, the surface-water temperature was too cold (below 2°C) for the meter to automatically apply this correction. The uncorrected SC value and water temperature were then recorded and corrected later using the meter's correction factor.

Water-Quality Sampling

Water-quality samples were collected from surface water and groundwater within the project area. The surface-water samples were collected at baseflow conditions in January. Groundwater samples were collected from wells in various aquifers throughout the year. The common ion and trace constituents were analyzed.

Samples were collected according to the MBMG standard sampling procedures. Groundwater samples were collected after purging approximately three well-casing volumes. The samples were contained, preserved, and stored in accordance with standard laboratory protocol. Nitric (1 percent) and sulfuric (0.5 percent) acid were added to preserve the samples. A 0.45 µm filter was used for the filtered samples. Distilled water was used to rinse the sampling tube between each sample. Nitrile powderless gloves were worn to prevent sample contamination.

Isotope Sampling

Isotopic analyses of water were used to help determine the source of groundwater recharge. To collect these samples, approximately three well casing volumes of water were purged or field parameters were stable for 15 minutes. The well water was purged into a clean 1 gallon bucket. To minimize exposure to the atmosphere, a 50 ml glass vial was submerged and capped within the overflowing bucket. The vial was sealed with no head space or air bubbles and was then wrapped with Parafilm to prevent leakage or air exposure. Surface-water samples followed the same procedure, but vials were submerged within the water body itself. Isotope samples for oxygen-18 and hydrogen-2 analysis were shipped to the University of Wyoming's Stable Isotope Facility in Laramie, Wyoming.

Tritium (^3H) isotopes were used to help constrain the residence time of the groundwater since it last had contact with the atmosphere. The tritium samples were also collected after three casing volumes of water were purged from the well. A 500 ml bottle was submerged and capped in a flowing water bucket to prevent atmosphere exposure. The samples were then shipped to the University of Miami's Tritium Laboratory in Miami, Florida.

Elevation Surveys

Elevations for wells were determined by plotting well locations on a topographic map with an accuracy of +/- 10 ft. For wells used in constructing cross sections that are within a line of sight, a relative-elevation survey was performed. The relative elevations of top of water in the ditch, ground surface next to the well, and the water-level measuring point on top of the well casing were measured with an accuracy of +/- 0.10 ft using a level and surveying rod.

Well Installation

Most of the wells used for this project were private domestic or stock wells. However, nine monitor wells were installed in the alluvial, Tullock, and Hell Creek aquifers. Four of the five sites had paired wells. The fifth site encountered a dry hole, so it was abandoned, leaving only one well on site. The wells were installed to perform aquifer pumping tests and for monitoring purposes. Hourly data loggers were installed in five of the new wells. The well locations were chosen to represent the alluvial valleys and two of the major bedrock aquifers in the region.

Aquifer Pumping Tests

The hydraulic properties of the aquifers were evaluated by performing 7- to 24-hour pumping tests at four of the installed well sites. During the tests, water was pumped at a constant rate and water levels were measured in the pumping and observation wells. The water levels were measured by data loggers and by hand measurements, using a sounder, for the duration of the aquifer pumping test including during drawdown and recovery.

Evaporation Pan Installation

To have a better understanding of direct evaporation from free-water surfaces in the local area, a class A-type evaporation pan was installed on a pond near the eastern edge of the study area (fig. 4). To measure the hourly evaporation rate, a data logger was installed in the 50 gallon reservoir tank on the pond bank. Evaporation out of the pan drove water from the reservoir tank to the floating pan. The rate of water leaving the reservoir tank was proportional to the evaporation rate. A tipping bucket rain gauge was also installed near the pond. An accurate rain total is important because rain also fills the floating pan, and this additional water has to evaporate before the reservoir tank water will be consumed again.

Figure 4. The evaporation type-A pan was located on a private pond south of Absarokee.

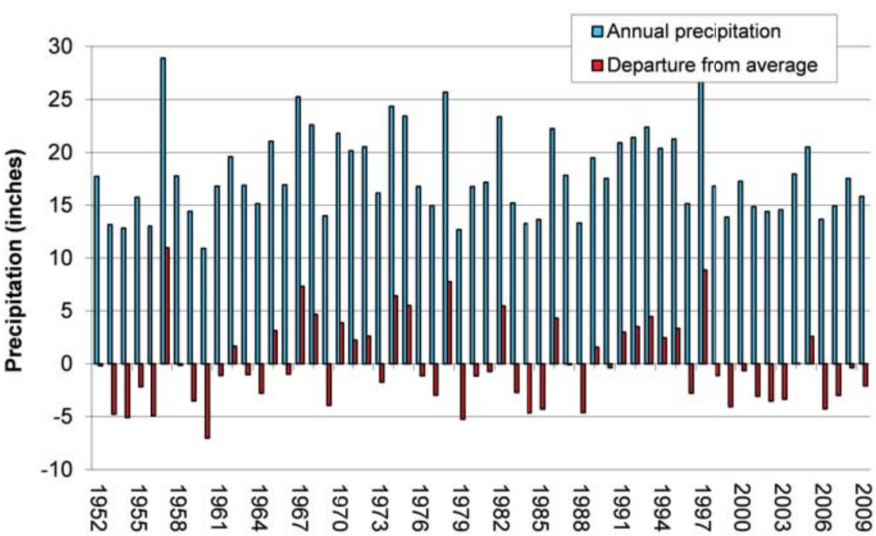


Figure 5. Annual precipitation (blue) and departure from average precipitation (red) recorded at the Fishtail meteorological station.

HYDROGEOLOGY

Precipitation

The Fishtail area has an average annual precipitation of 17.92 in (Western Regional Climate Center, 2009). During the period this project was undertaken, from 2008 to 2010, the area experienced slight drought conditions, with precipitation totals 2 to 12 percent below normal average (fig. 5). Recent years, such as 2006, show more significant drought conditions, with precipitation totals 24 percent below average.

Evaporation

The evaporation rate from May to October 2009 (fig. 6) was measured using a class A evaporation pan and a water-level data logger. The total water loss from the pan was approximately 20 in during these months. Accounting for the 5.7 in of rain that fell during this time results in a total evaporative water loss of approximately 26 in over 6 months. These results are consistent with a USGS report that summarized the estimated net annual evaporation from several reservoirs in Montana; the closest to the study area was Cooney Reservoir in Carbon County (Cannon and Johnson, 2004). The estimated average annual evaporation from Cooney Reservoir is 30 in, which is in reasonable agreement with the results of this study.

Surface Water

Stillwater River

The Stillwater River is 65 miles long from the headwaters in the Beartooth Mountains to the mouth near Columbus (Feltis and Litke, 1987). The riverbed is filled with igneous and metamorphic cobbles to large boulders carried down from the mountains. The rocks are generally rounded to well-rounded in shape. Very fine sand and silt are minor constituents in the active river bed strata.

The USGS has a gauging station located on the Stillwater River just north of Absarokee, which includes flow from the Rosebud Creeks, Fishtail Creek, Butcher Creek, and smaller tributary streams. The USGS has been recording river flow rates at

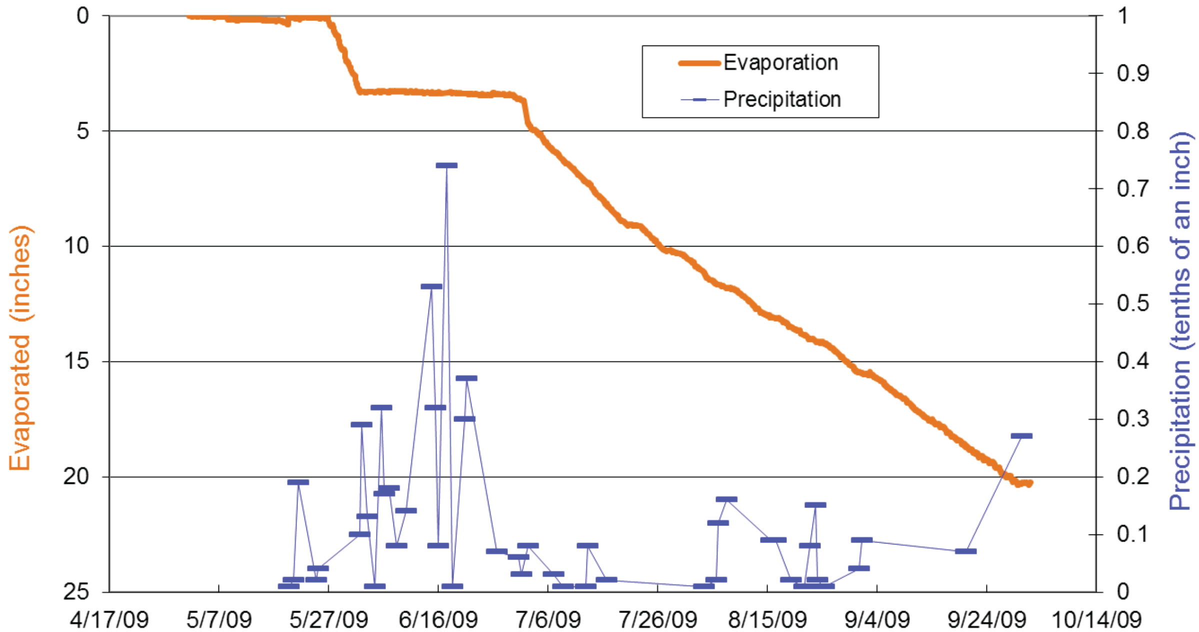


Figure 6. Evaporation and precipitation recorded from May to October 2009 from the evaporation pan.

this site since 1910 with real-time data available since 2000. The mean monthly low flow rate is 264 cfs in February and the mean monthly high flow rate is 3,395 cfs in July when spring snowmelt is occurring. The hydrograph in figure 7 illustrates the seasonal patterns of the Stillwater River.

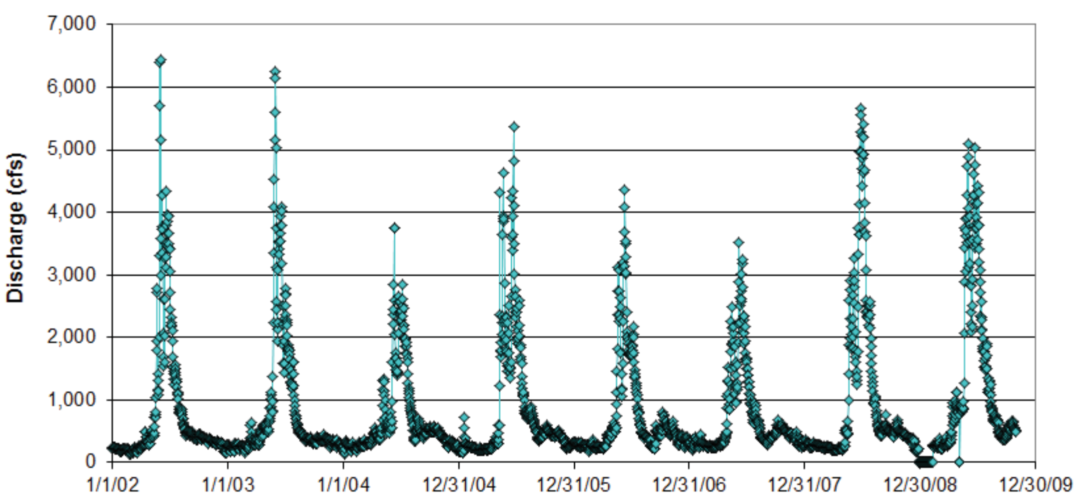


Figure 7. Eight-year hydrograph of the Stillwater River.

Synoptic Flow Measurements

Synoptic flow-rate surveys provide a detailed evaluation of gains or losses within a stretch of river at the same time (Weight, 2008). Synoptic surface-water flow rates were measured five times during this study to determine if specific reaches along the Stillwater River were gaining or losing water. Flows were all measured in a single day on the Stillwater River from the upper end at Cox Bridge to the lower end at Johnson Bridge, including measurements on all ditches that were flowing, and all tributary streams. The total gain in flow of the Stillwater River due to groundwater contributions (Qgain) was then calculated using equation 1:

$$Qgain = Qout - (Qin + Qtribs - Qditch), \quad (1)$$

where Qin and Qout are the measured flows at Cox Bridge and Johnson Bridge, respectively. Qditch represents the amount of water diverted out of the study reach of the river from irrigation ditches, and Qtribs is the total amount of water entering the river from tributary streams.

Synoptic flow rates were measured in September and October of 2008 and in August of 2009 when irrigation ditches were active, and in February and March 2009 when the river was considered to be at or near baseflow conditions.

Data from all five synoptic flow sets indicate the Stillwater River gains water across the entire study area (table 1). About 94 cfs was gained between Cox and Johnson Bridge in August 2009 as compared with a

Table 1. Synoptic flow rates measured on a 9-mile stretch of the Stillwater River from Cox Bridge to Johnson Bridge from September 2008 to August 2009.

Date	QStillwater River into Study Area (Cox Bridge) (cfs)	QStillwater River out of Study Area (Johnson Bridge) (cfs)	Qtributary Flow (cfs)	Qdiversion Ditch Flow (cfs)	Total Groundwater Return Flow (cfs)
9/6/2008	224	237	14	49	48
10/9/2008	175	203	8	8	28
2/11/2009	58	85	5	0	22
3/5/2009	105	121	6	0	10
8/18/2009	330	359	10	75	94

gain of about 10 cfs in March 2009. The gain measured at Johnson Bridge can be at least partially explained by the stored alluvial groundwater discharging back into the surface-water system. The stored groundwater in the alluvium discharges until it reaches winter equilibrium. It is hypothesized that the gain of 10 cfs in March, during baseflow conditions, is groundwater discharging from the bedrock aquifer. The river was floated during the height of irrigation season and surface irrigation-return flow was observed to be minimal.

Synoptic flows rates were also measured on February 13, 2009 on a 28-mile stretch of the Stillwater River from Beehive to just south of Columbus (fig. 8). The synoptic data were collected at baseflow conditions near bedrock contacts to determine the relative groundwater contribution of the different formations (table 2). The data indicate that sites D, E, and G have the greatest gains. These sites do not seem to be related to the different geologic units but rather to underflow from shallow alluvium of tributary streams. The contributory streams are Grove Creek, Rosebud Creek, and Joe Hill Creek from sections D, E, and G, respectively.

A decreased flux rate (a losing stretch) was measured between sites A and B and between D and E. Groundwater wells located near site A (159730, 101153, and 101154) indicate that the average alluvial thickness in

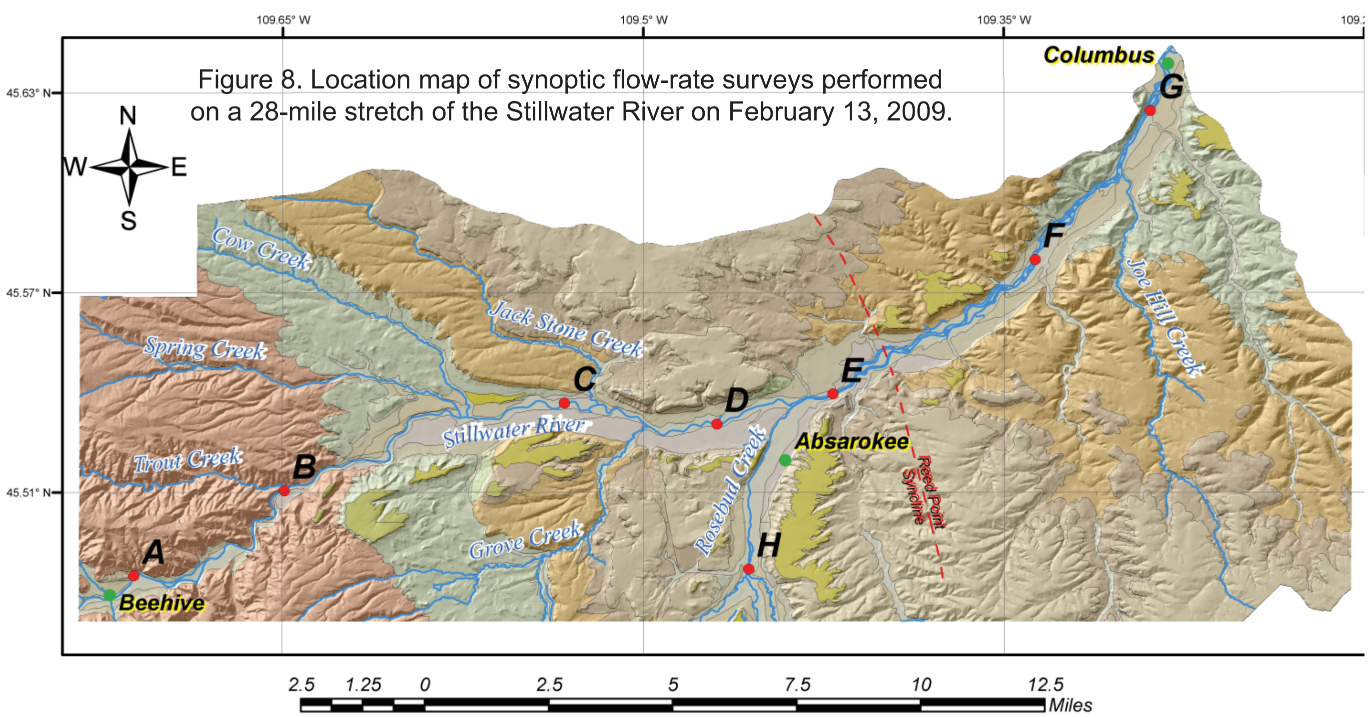


Figure 8. Location map of synoptic flow-rate surveys performed on a 28-mile stretch of the Stillwater River on February 13, 2009.

Table 2. Stillwater River synoptic flow rates and associated geologic units.

Site Name	Measured Flow at each Site (cfs)	Distance between each Site (mile)	Change in Flow per lineal foot of River (ft^3/day/ft (length))	Associated Geologic Unit
A	140	0.0	0	Livingston Group
B[1]	79	4.7	273	Livingston Group
C	106	6.9	251	Tullock
D	110	3.8	468	Lebo
E[1,2]	80	2.6	511	Lebo
F[2]	94	5.4	284	Tullock
G[2]	108	4.2	421	Hell Creek

[1]Decreased flux rate.
[2]Reported flow rates do not include Rosebud Creek measured rate of 169 cfs.

this area is 22 ft. Well logs near site B (161202, 187945, and 7522) indicate an average alluvial thickness of 79 ft. The thickening of the alluvial deposit allows surface water to move as subsurface flow, resulting in less measured surface flow. The decrease in flow rate observed from site D to E is probably due to, in addition to the thickening of the alluvium, the widening of the alluvial valley. In order to compare flows only on the Stillwater River after site D, the contributions from Rosebud Creek had to be accounted for. A flow rate of 169 cfs was measured on February 13, 2009 at Smith Bridge (site H) on Rosebud Creek. The rate was then subtracted from the total measured flow rates at sites E through G.

Rosebud Creeks

The Rosebud Creeks begin their journey with headwaters in the Beartooth Mountains, then join the Stillwater River near Absarokee. The creeks are at youthful stages and are actively down-cutting into the bedrock. The active riverbed is filled with igneous and metamorphic cobbles to large boulders carried down from the mountains.

The USGS has a gauging station located on the West Rosebud Creek near Roscoe (USGS 06204050). The USGS has been recording river flows at this site continuously since 1965. The gauging station is at an elevation of 6,535.6 ft above sea level and drains 52.1 mi^2. The mean monthly low-flow rate from 2005 to 2009 is 39 cfs in May and 334 cfs in August when summer snowmelt is occurring. The gauging station is located down drainage from Mystic Lake power station; therefore, the flows are partially regulated by the power station. Figure 9 is a hydrograph of West Rosebud Creek's seasonal pattern.

The MBMG collected creek flow rates four times at two locations on West Rosebud Creek using the bridge crane and staff-wading methods. The flow rates at the upgradient site on West Rosebud Road below the dam ranged from 58 cfs at baseflow to 660 cfs in spring, and at the downgradient site on Sleepy Hollow Road ranged from 73 cfs at baseflow to 502 cfs in spring.

Flow rates were also measured four times at two locations on East Rosebud Creek. The upgradient site above Roscoe had flow rates ranging from 38 cfs at baseflow to 804 cfs in spring, and the downgradient site at Tuttle road ranged from 42 cfs at baseflow to 1,253 cfs in spring. A set of synoptic flow rates were measured on East Rosebud Creek in April 2009 during baseflow conditions (fig. 10). The measured 15-mile stretch of river was a gaining reach and gained about 19 cfs from groundwater. The groundwater source could be either or both bedrock and alluvial-aquifer discharge.

Minor Streams

Many minor streams exist within the project area. Some of the larger perennial tributary streams include Fishtail Creek, Grove Creek, Trout Creek, and Butcher Creek. Many of the small streams are likely to flow only during spring snowmelt and during large storm events.

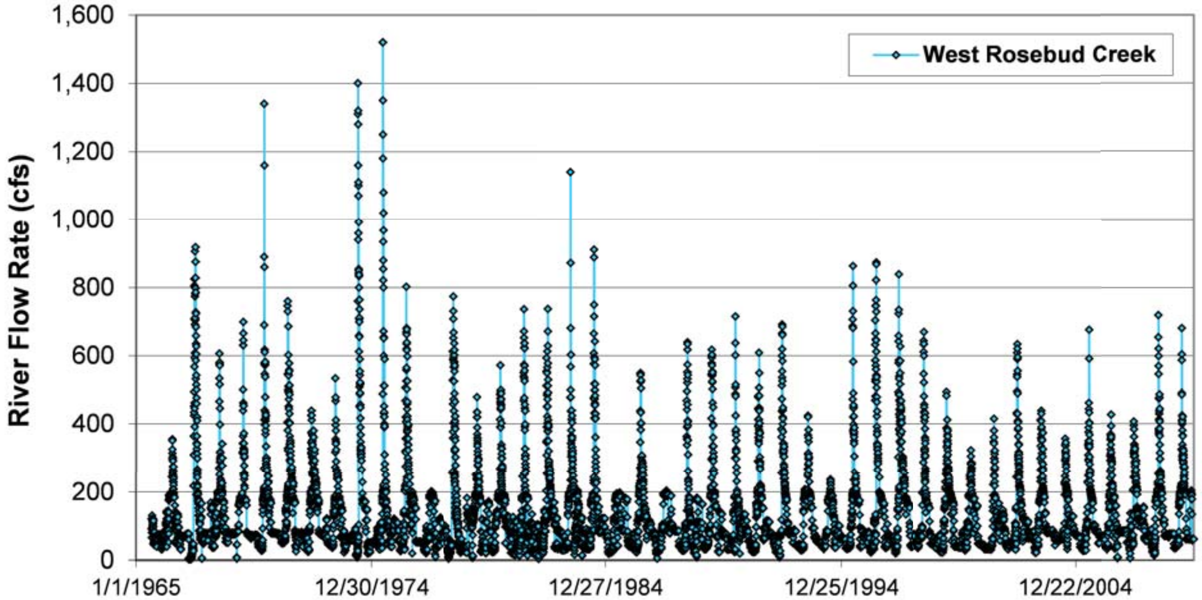


Figure 9. Hydrograph of West Rosebud Creek seasonal fluctuations.

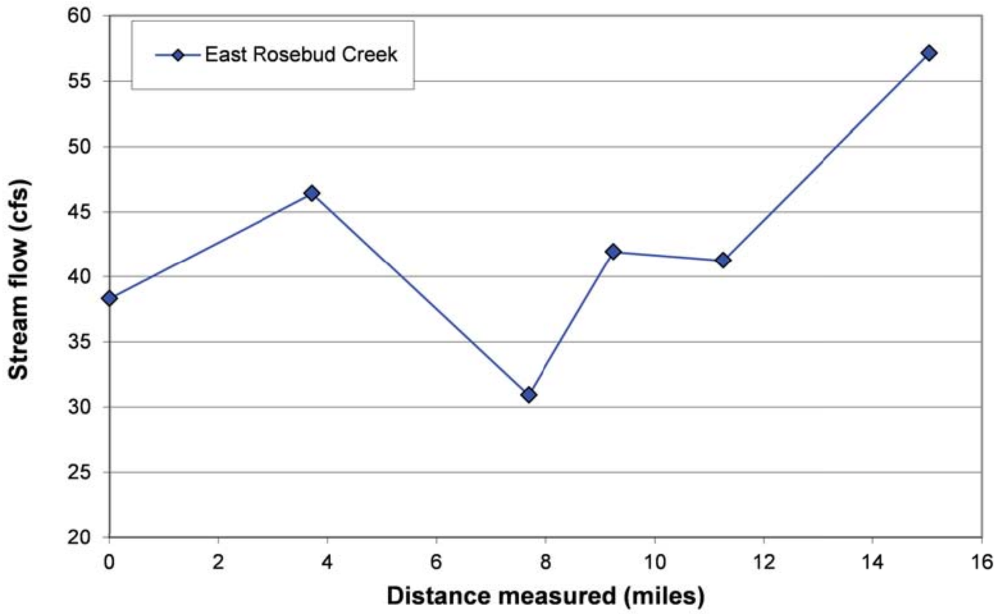


Figure 10. Synoptic flow measured on East Rosebud Creek in April 2009.

Surface-water flow rates and field water-quality parameters were measured on some of the tributary creeks and are listed in appendix A1,A2.

Fishtail Creek is diverted to many ditches to irrigate parts of the valley. At baseflow in April 2009, a synoptic flow set was performed on Fishtail Creek (fig. 11). The data indicate it was a gaining stream for the entire reach measured. Recharge to the alluvial aquifer during irrigation and bedrock aquifer contact to the valley supply the groundwater that discharges to the creek throughout the year.

Synoptic flows were also performed on Grove Creek in April 2009 (fig. 11). The measured flow rates indicate a gaining reach for the first 3 miles measured and losing between the 3rd and 5th mile. The first 3 miles of creek gain flow as it crosses the Hell Creek and Tullock bedrock formations. The stream loses surface flow when it crosses into the Stillwater River Valley alluvium, where it loses flow into the alluvial gravel below.

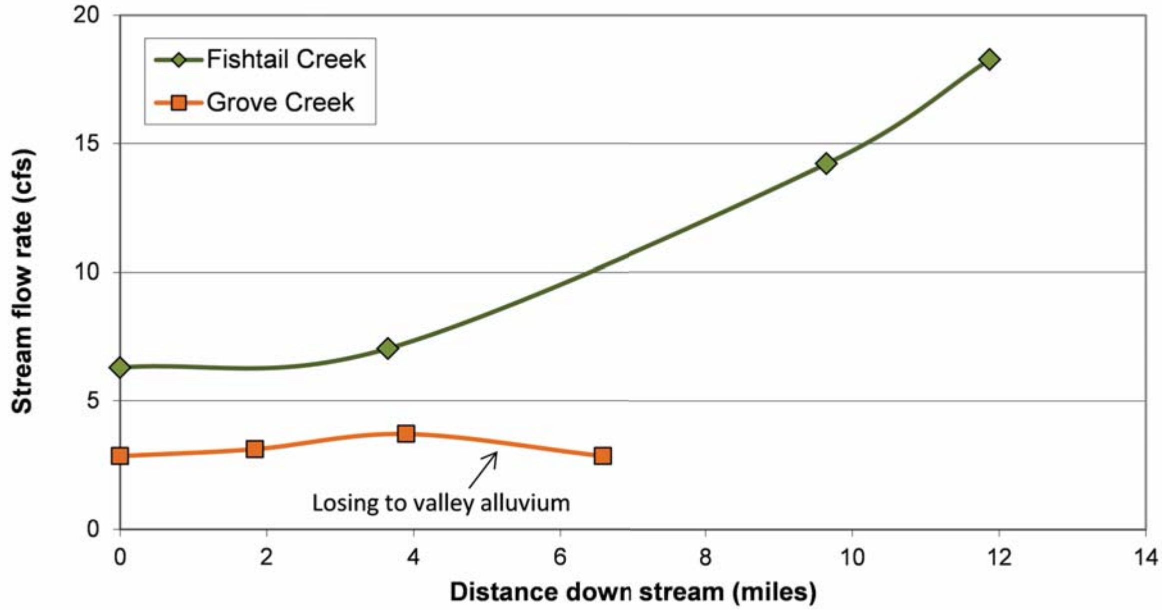


Figure 11. Synoptic flows performed on Fishtail and Grove Creeks in April 2009.

Ditch Leakage and Irrigation Withdrawals

Within the project area, the Stillwater River, Rosebud Creeks, Fishtail Creek, and Butcher Creek are all large suppliers of irrigation water. The streams originate in the Beartooth Mountains, where they are supplied in the spring and summer by slow-melting snow. The river/creek water is then diverted to the irrigation ditches, which transfer the water miles down the alluvial valleys. The majority of irrigation ditches in the area are unlined and therefore allow water to leak through the bottom and sides. Irrigation provides groundwater recharge through leakage by ditches or by infiltration of flood-irrigation-applied water.

To determine how much irrigation water leaks directly from the unlined ditches, synoptic flows measurements were performed on Mendenhall, Brey Riddle, and Butcher Creek ditches (fig. 12). The measurements were all performed in August and September 2009 to ensure the ditches were saturated.

Brey Riddle and Mendenhall ditches are both located in the Stillwater valley west of Absarokee. They both are constructed in porous alluvial material. Flow measurements determined that they were leaking 1.1 to 1.8 ft^3/sec/mile (18 to 29 ft^3/day/ft). Butcher Creek ditch is located adjacent to Butcher Creek and East Rosebud Creek. This ditch is constructed on the hillside of the valley in the Lebo shale. Flow measurements determined that the ditch was leaking 0.5 ft^3/sec/mile (8 ft^3/day/ft) of ditch. The ditch leakage is similar to what Olson and Reiten (2002) found in west Billings. The loss from the ditch constructed in shale is less than the loss from ditches constructed in the alluvial valley, indicating that ditch leakage rates are site-dependent. Direct evaporation from the surface water and transpiration from the plants that line the ditch also result in

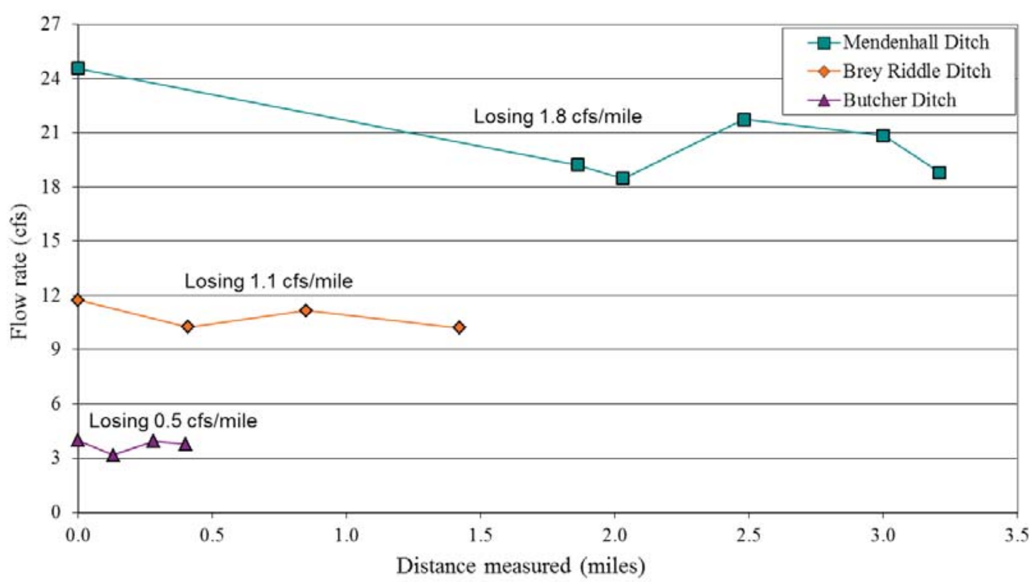


Figure 12. Synoptic flow measurements performed in summer 2009.

some water loss out of the ditch. While there were no visible contributories, there were some measured gains in the ditches that were either from subsurface flow into the ditches or complications during measurement, such as upgradient precipitation or changes in ditch usage during the synoptic measurements.

Flood irrigation typically applies water in excess of the evapotranspiration demand, thereby providing recharge to the near-surface aquifers. Cannon and Johnson (2004) compiled two irrigation and crop surveys and determined that in the year 2000, Stillwater County had 23,590 acres of irrigated crop land, withdrew 187.87 million gallons per day (Mgal/d) of surface water, and had 37.06 Mgal/d consumptive use from plants. This suggests that the plants consumed about 20 percent of the applied water. The Natural Resources Conservation Service (NRCS) uses a computer program called Irrigation Water Requirements that uses the Blaney and Criddle (1950) method to calculate evapotranspiration for different crops. Alfalfa hay in Stillwater County has a potential ET rate of 23 in. (May to September) in the growing season.

Alluvial Aquifer System

During this and other groundwater projects (Carstarphen and Smith, 2007), numerous wells were inventoried in Stillwater County. From inventoried well logs with coded completions in the alluvial aquifer, it is estimated that the average alluvial thickness in the project area is about 40 ft. The average saturated thickness of the aquifer ranges between 21 ft at baseflow and 26 ft during irrigation season. However, the saturated thickness was measured to be less than 10 ft in some wells located near the valley margins where irrigation effects are limited. In the alluvial valleys, most wells are completed in the alluvial aquifer. However, a few wells have been drilled through the alluvium and completed in the bedrock unit below. Beneath the alluvium, alternating shale or sandstone layers are encountered depending upon the location within the valley. Figure 13 is a cross section of three wells drilled into the alluvial aquifer near the lower end of the study area.

Groundwater moves from an area of higher pressure to lower pressure. The difference between these pressures can be expressed as the local hydraulic gra-

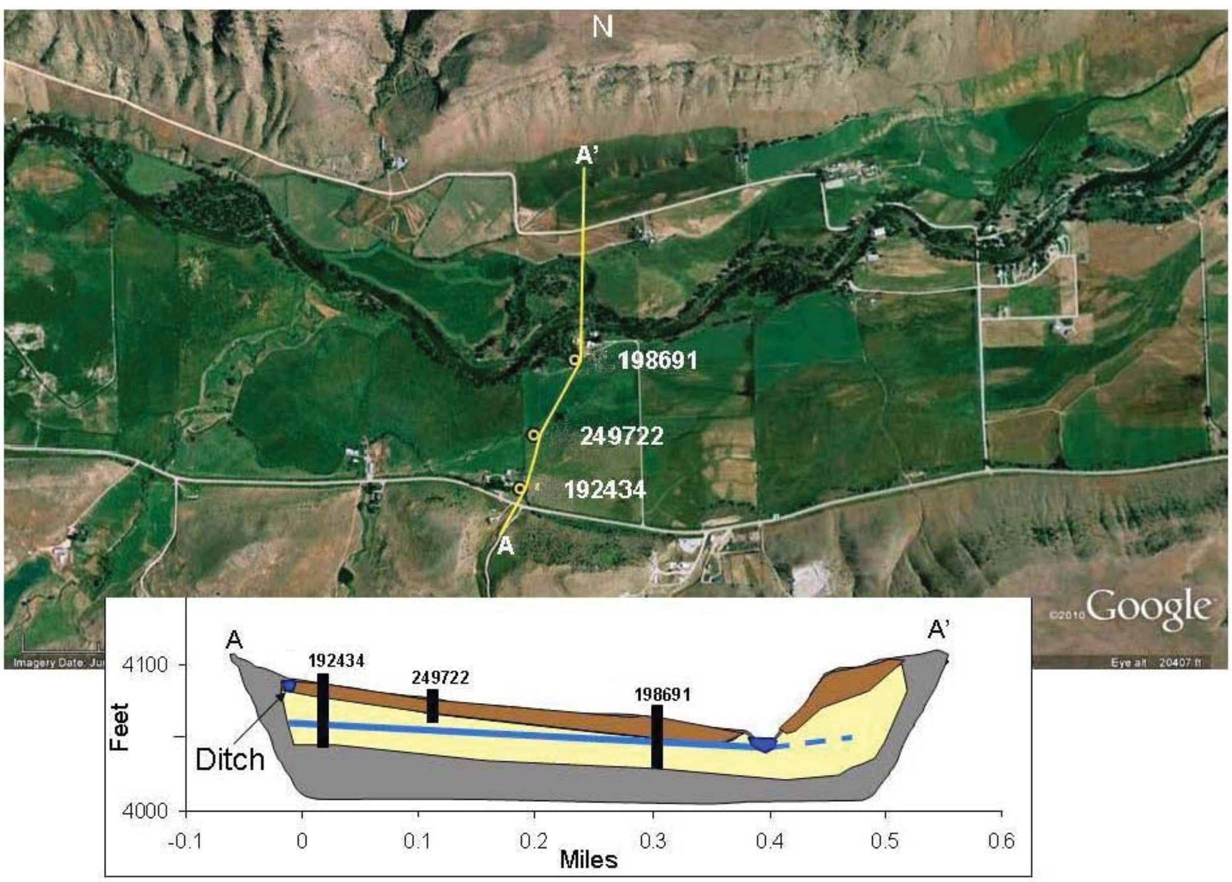


Figure 13. Cross section of the wells in the alluvial aquifer.

dient. Groundwater travels at a velocity that is proportional to this hydraulic gradient. Rates of the movement can vary from less than a foot per day to over a hundred feet per day depending on the permeability of the aquifer and the hydraulic head.

In parts of the project area that have closely spaced data, the longitudinal gradient was calculated for the groundwater table, ground surface, and river elevation. Along the Stillwater River Valley the longitudinal gradients were 41 ft/mile (0.008 ft/ft).

A water table elevation map of the Stillwater River Valley, where there is a high density of wells, was hand contoured using baseflow water levels collected on March 4, 2009 (fig. 14); the rest of the Stillwater Valley and Rosebud Creek valleys are expected to behave similarly. Groundwater flow direction is perpendicular to the water table lines (black lines in fig. 14). Overall, groundwater is moving parallel to the river in a west to east direction. However, near the edges of the valley the flow is directed toward the river. The non-uniform spacing of the lines indicates variability in the hydraulic conductivity or saturated thickness of the alluvial aquifer material. Water levels collected in peak irrigation season on August 18, 2009 plotted within the same gradients as the baseflow water levels (March 4, 2009). The bedrock aquifer water levels (purple squares in fig. 14) fall close to the alluvial potentiometric surface, indicating the bedrock aquifer is probably hydraulically connected to the alluvial groundwater system. The bedrock aquifer appears to discharge evenly to the alluvial aquifer on both sides of the valley.

Aquifer Tests and Estimation of Transmissivity, Hydraulic Conductivity, and Storage

The transmissivity, hydraulic conductivity, and storage values were established through analysis of aquifer pumping tests, well log information, published tables, and monitored water-level changes.

To achieve a better understanding of the aquifer properties in the area, three alluvial monitoring well pairs were installed in the proj-

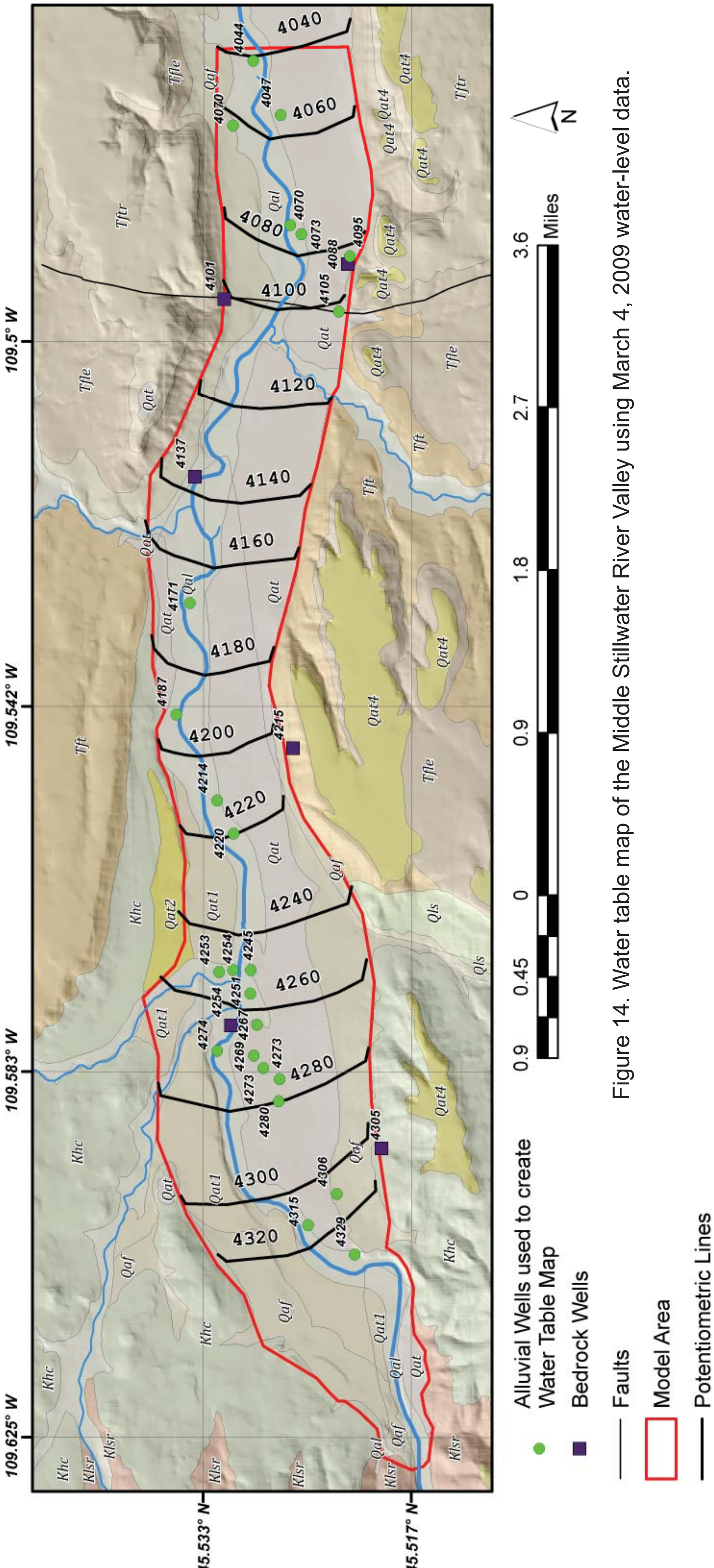


Figure 14. Water table map of the Middle Stillwater River Valley using March 4, 2009 water-level data.

ect area in the summer of 2009. Aquifer pumping tests were performed on two of sites. One well set was located in T. 3 S., R. 18 E., sec. 35. Well 252301 was installed in the study area in the summer of 2009 next to an existing alluvial stock well (99949). The well was completed with a 6-in steel casing and had a total depth below ground surface of 38.5 ft with an open-hole completion 1 ft above the bedrock (fig. 15). The alluvial stock well (99949) was used for the observation well. The stock well has a total depth of 42 ft and a screened interval at 37 to 41 ft.

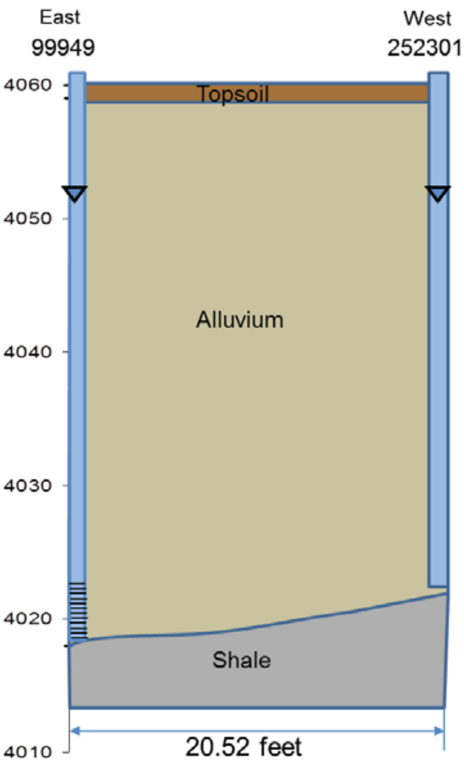


Figure 15. Well completion diagram for observation well 99949 and pumping well 252301. Water levels used for the diagram were measured on 8-25-09.

On September 2, 2009, the MBMG performed a 24-hour aquifer pumping test on well 252301. The well was pumped at a constant rate of 100 gallons per minute (gpm). The saturated thickness at the beginning of the pumping test was 31.81 ft. During the test the pumping well had a maximum drawdown of 3.95 ft while the observation well had a maximum drawdown of 2.62 ft. Figure 16 shows the location of the wells and the distance to the Stillwater River.

The aquifer was monitored before the pumping test and the water levels show a declining trend (fig. 17). Before analyzing the data, a straight line correction factor was added to the pumping test water levels to compensate for the declining trend.

During a pumping test the first several minutes usually include pumping rate adjustments. During this test, 100 gpm was achieved within the first few minutes. However, after 7 minutes the rate was bumped up to 111 gpm to attempt further aquifer stress. The higher rate exceeded the limit of the discharge hose and the pumping rate was reduced back to 100 gpm. When the rate was checked again at minute 35 and minute 90, the rate had dropped slightly below 100 gpm. The rates were always adjusted to 100 gpm and after 90 minutes the rate remained fairly constant for the duration of the test. Minutes 300 to 700, the water level flattened, suggesting a recharge boundary condition response (fig. 18). After 700 minutes the water level trend began to decrease again, but on a steeper slope.

The time-drawdown data collected from the aquifer pumping test was hand calculated and also entered into AQTESOLV 4.0 (HydroSolve, Inc., http://www.aqtesolv.com). The Cooper–Jacob straight line method (Cooper and Jacob, 1946) was used to calculate transmissivity value of about 2,900 ft^2/day (fig. 18).

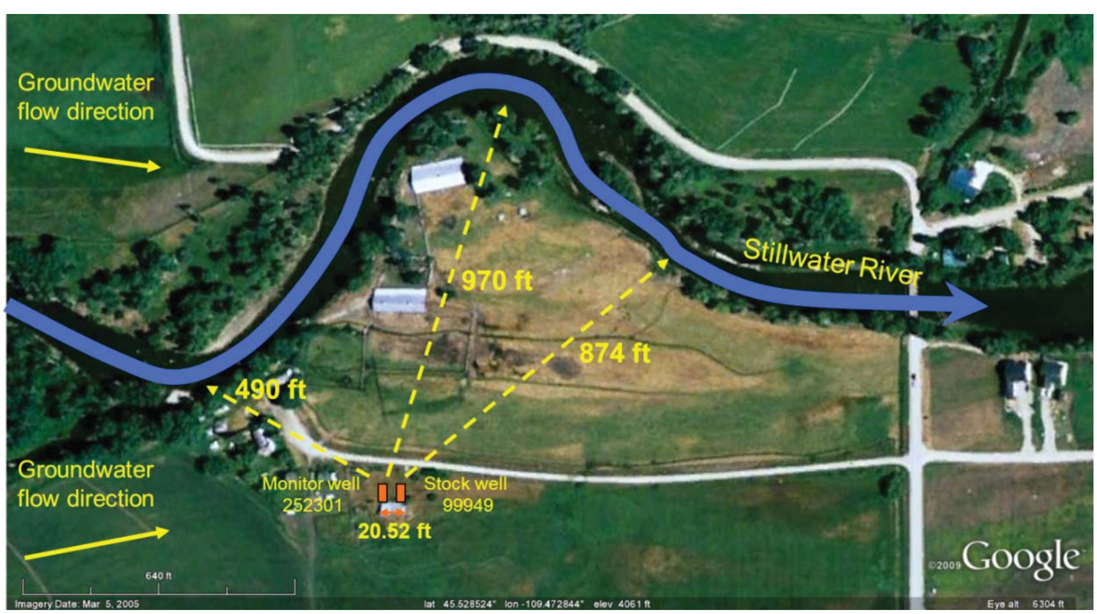


Figure 16. Google image showing location of wells used in pumping test at Johnson Lane site.

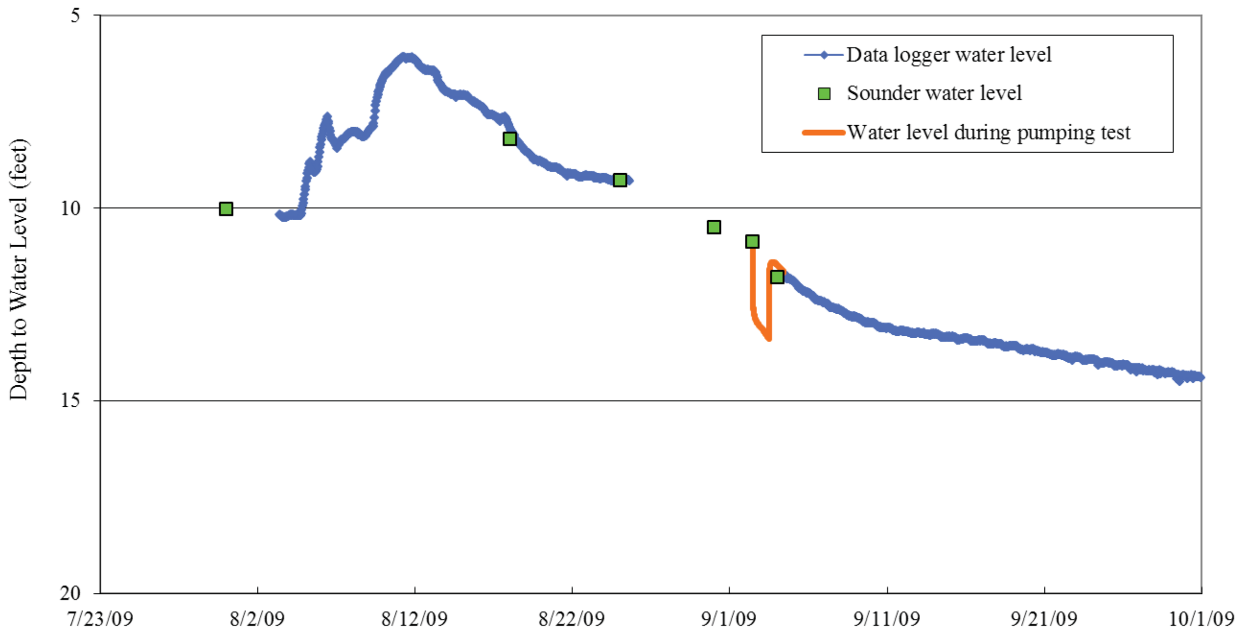


Figure 17. Falling water levels in well 252301.

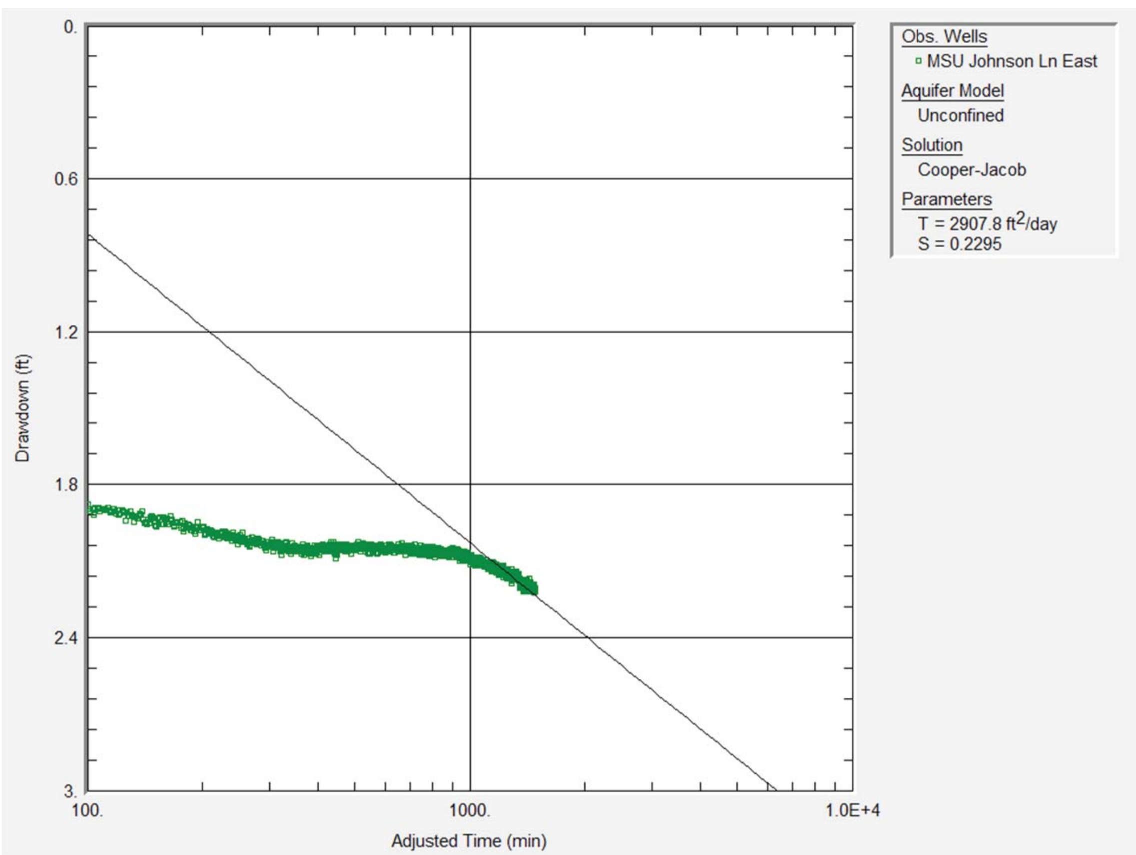


Figure 18. Cooper–Jacob plot of the alluvial aquifer pumping test at the Johnson Lane site from observation well 99949.

The Neuman (1974) method was used to determine a transmissivity value of 3,800 ft^2/day and specific yield of 0.16 (fig. 19). Additionally, the recovery data was plotted using the residual drawdown versus time, which resulted in a calculated transmissivity value of 11,800ft2/day (fig. 20). Table 3 is the tabulated aquifer pumping test results.

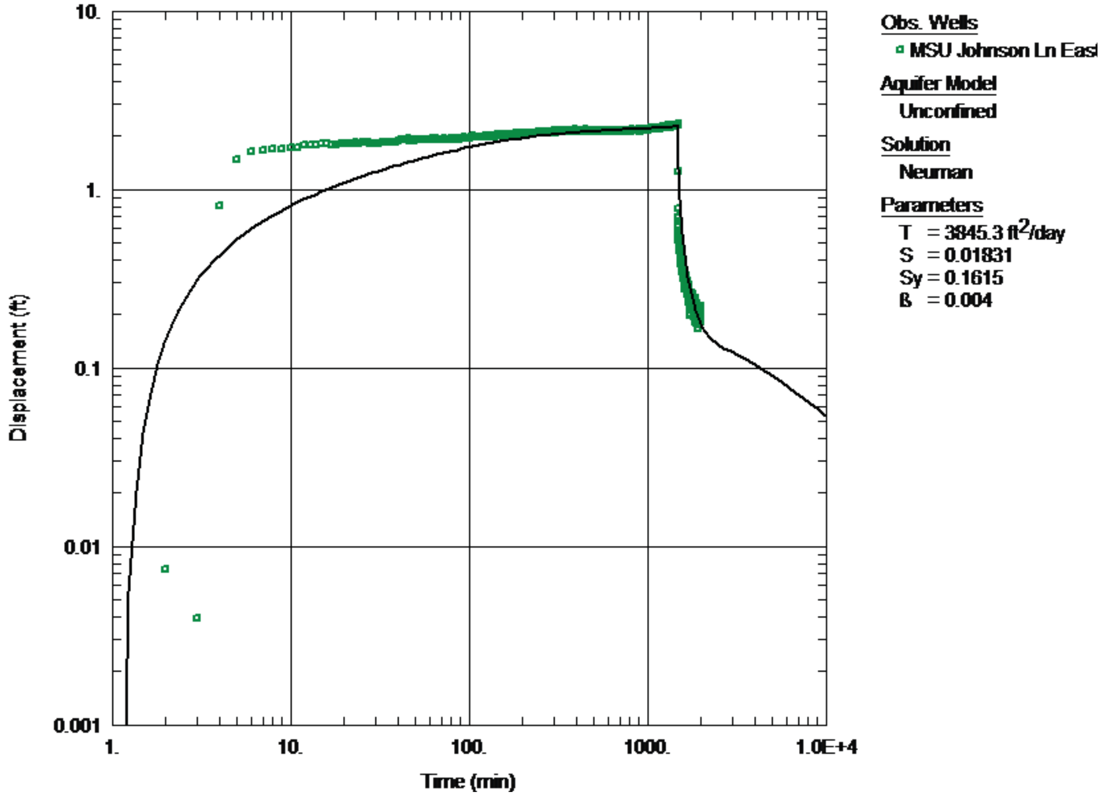


Figure 19. Neuman plot of the alluvial aquifer pumping test at the Johnson Lane site from observation well 99949.

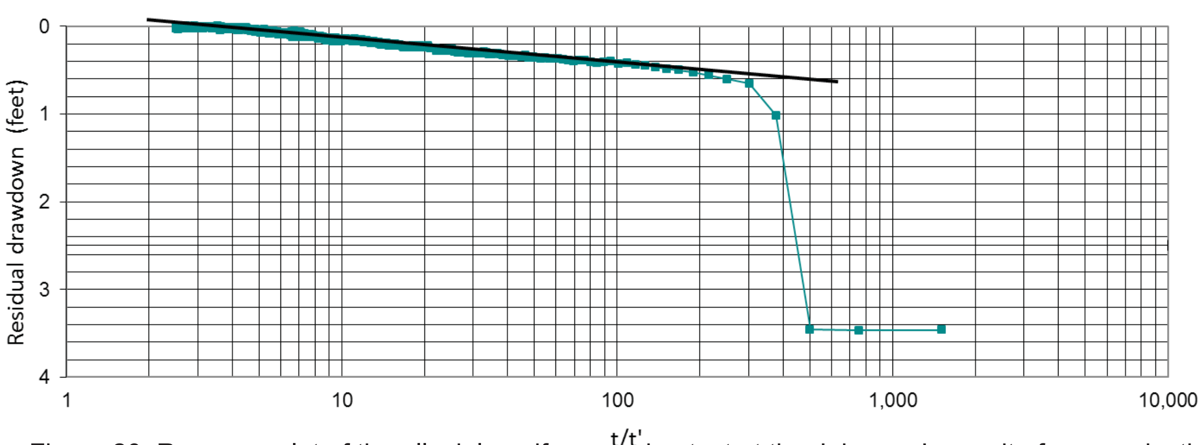


Figure 20. Recovery plot of the alluvial aquifer pumping test at the Johnson Lane site from production well 252301.

Table 3. Alluvial aquifer test results at the Johnson Lane site.

Method	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)
Cooper–Jacob	2,900	90
Neuman	3,800	120
Recovery (residual drawdown vs. t/t')	11,750	370

The hydraulic conductivity can be calculated using the transmissivity value and the saturated aquifer thickness using equation 2:

$$K = \frac{T}{b}, \tag{2}$$

where K is hydraulic conductivity (length per time), T is transmissivity (length^2 per time), and b is saturated aquifer thickness (length).

Assuming a saturated thickness of 31.8 ft, a hydraulic conductivity of 90 to120 ft/day was calculated from the Cooper-Jacob and Neuman methods.

The Cooper-Jacob (1946) time-drawdown and Jacob (1950) distance-drawdown relationships can be used to determine the extent of the cone of depression at any given time. The estimate can be made with only one observation well using equation 3:

$$r_0 = \sqrt{\frac{2.25 \times T \times t}{S}}, \tag{3}$$

where r_o is range of influence, straight-line projection of the distance drawdown curve up to where it intersects the zero drawdown axis (length); T is transmissivity (length^2 per time); t is time (time); and S is storativity (dimensionless).

For transmissivity, the value of 3,800 ft^2/day from the Neuman solution was used, and 24 hours was used for the duration of the pumping test. The specific yield value of 0.16 was used. Assuming the cone of depression is symmetrical, the maximum extent of the cone of depression extended about 230 ft at 24 hours of pumping at 100 gpm. As shown in figure 16, this is considerably less than the distance to the Stillwater River, meaning that the river should not have influenced the test.

The second alluvial well set that was used for an aquifer pumping test is located at T. 4 S., R. 18 E., sec. 24 (252303, 252302). Both wells had a total depth of 37 ft with open hole completions 1 ft above the bedrock. The two wells are located 19.94 ft apart (fig. 21).

In August 2009, a 24-hour aquifer pumping test was performed at this site. The west well (252303) was used as the pumping well and the east well (252302) was used as the observation well (fig. 22). The well was pumped at a constant rate of 75 gpm. The saturated thickness at the beginning of the pumping test was 25 ft. During the test, the pumping well had a maximum drawdown of 11.15 ft while the observation well had a maximum drawdown of 3.36 ft. During the second half of the pumping test, flood irrigation was applied to the field where the test was being performed. The effects of the surface recharge are visible near the end of the pumping test (fig. 23)

The Cooper–Jacob method calculated a transmissivity value of 2,846 ft2/day (fig. 23). The hydraulic conductivity was calculated to be 113 ft/day. The extent of the cone of depression was calculated to have traveled 207 ft at 24 hours.

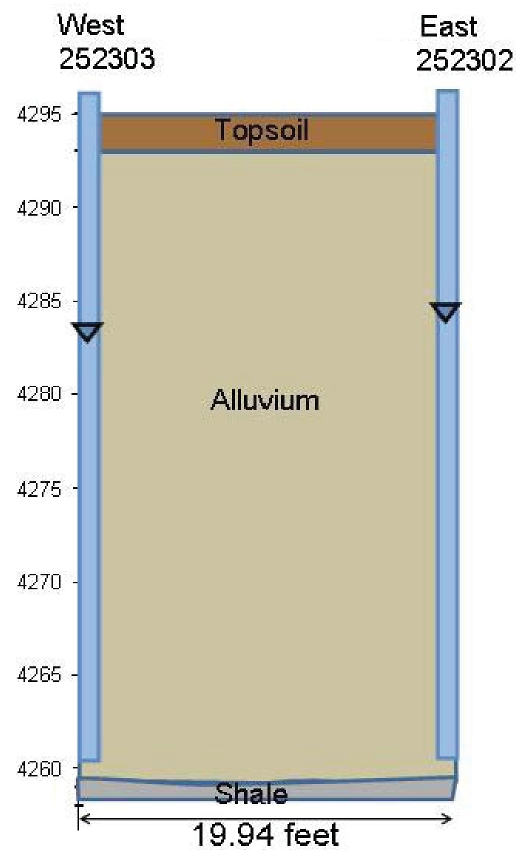


Figure 21. Well completion diagram for observation well 252303 and pumping well 252302. Water levels used for the diagram were measured on 8-25-09.

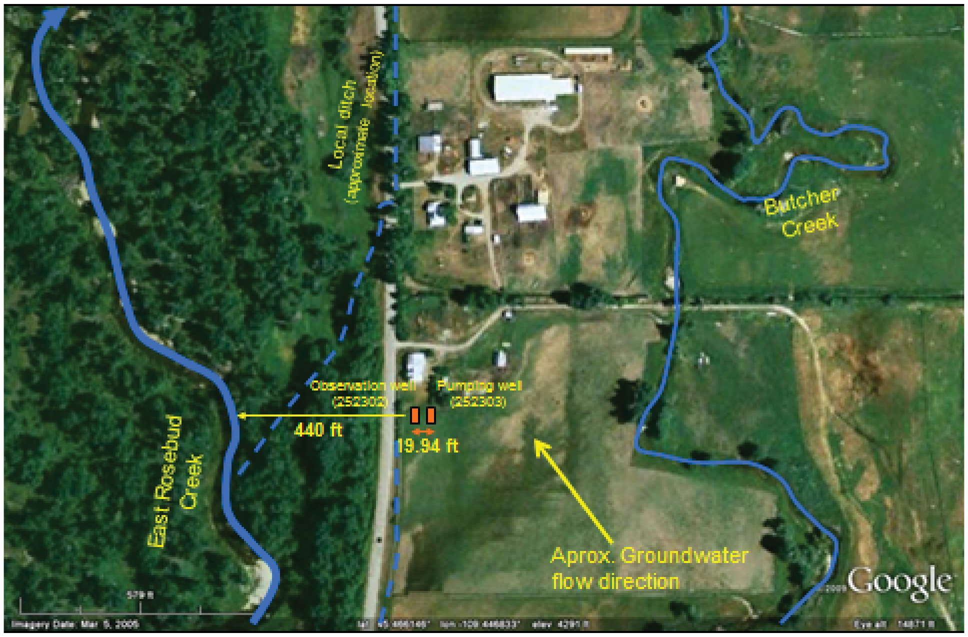


Figure 22. Google Earth© image showing location of wells used in pumping test at the second test site (T. 4 S., R. 18 E., sec. 24).

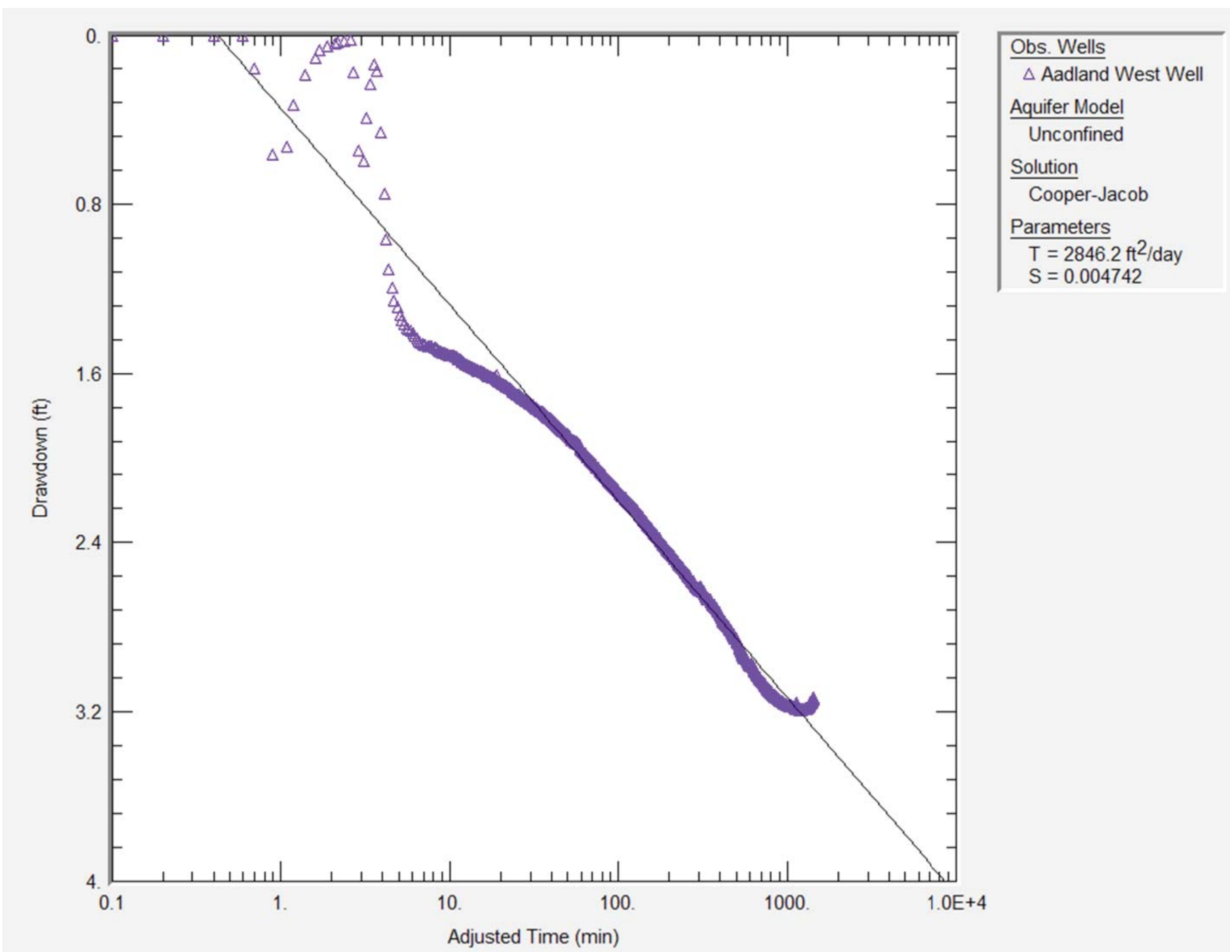


Figure 23. Cooper–Jacob plot of the alluvial aquifer pumping test at the Aadland site.

Freeze and Cherry (1979) have tables of ranges of hydraulic conductivity for different geologic materials. They suggest the hydraulic conductivity for fine-to-coarse sand and gravel ranges from 10 to 1,000 ft/day. On March 4, 2009, water levels taken from 21 alluvial wells in the study area indicated the average saturated thickness was 21 ft. The transmissivity estimated using the published hydraulic conductivity values and average saturated thickness (equation 2) are not well constrained and range from 210 ft^2/day to 21,000 ft^2/day.

The storativity for an unconfined aquifer can also be estimated by using the volume of water drained from the aquifer as the head is lowered. This can be calculated using equation 4:

$$S = \frac{Vw}{A\Delta h}, \tag{4}$$

where S is storativity (dimensionless), Vw is volume of water drained (cubic length), A is surface area overlying the drained aquifer (square length), and Δh is average decline in head (length; Fetter, 2001).

The irrigated alluvial area outlined by the model boundary (fig. 11) provides the information necessary to calculate an estimate of the storativity using the equation above. According to land-use shape files provided by NRIS (1992), irrigated land from the top of the boundary to the bottom near Johnson Bridge is approximately 4.9 mi^2 (3,200 acres or 139,000,000 ft^2). Eleven alluvial wells located randomly throughout the study area had an average water-level drop of 1.3 ft from September 19th/20th to October 10th, 2008, a period of 21 days. Measured groundwater inflows (Qgain) on the Stillwater River on September 6th, 2008 between Beehive and Johnson Bridge were 75 cfs over the reach and a month later, on October 9th, 2008, only 51 cfs. This represents a difference of 24 cfs, or a linear flow decrease of 0.7 cfs per day. No precipitation events occurred and tributary flows were factored out. All gains were presumably from groundwater discharge to the Stillwater River as baseflow. Using these observations in relation to equation 6, a storativity value of 0.15 was calculated for the alluvial aquifer within the boundary.

Seasonal Changes in Groundwater Levels

Recharge and discharge rates control the magnitude and timing of groundwater-level fluctuations in the alluvial aquifer. Water levels will rise when recharge rates exceed discharge rates and when discharge rates are greater, the water level will fall. Within the project area the groundwater levels fluctuate seasonally by as much as 20 ft. The hydrograph depicted in figure 24 illustrates this effect. The well is located south of Columbus (143942) and is located in the alluvial valley. The hydrograph demonstrates the same seasonal trends of rising water levels in the spring followed by falling water levels in the fall. The water levels reach their peak in July or August and then begin to fall steadily until the irrigation process repeats itself in the next year. The rapid groundwater response time indicates a very sensitive alluvial aquifer. The aquifer will be vulnerable to changes in water quantity and quality.

Groundwater Response near Ditches

In wells with continuous data loggers, a water-level rise can be seen both in April due to precipitation events and then again rapidly in late May when the irrigation ditches are filled and begin to leak. Data loggers located in Mendenhall ditch and three wells (192434, 249722,

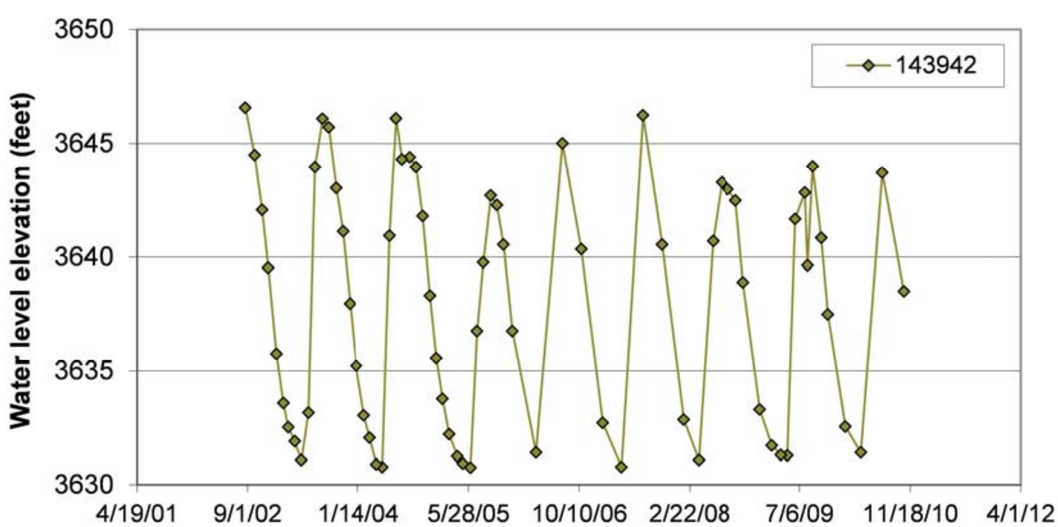


Figure 24. Hydrograph of a well completed in the alluvial aquifer demonstrating the seasonal water-level patterns.

198691) captured the timing of ditch activation and groundwater-level response. Figure 25 is a topographic map showing the location of the ditch and three wells. Well 192434 is located about 50 ft from Mendenhall ditch, while 249722 and 198691 are located about 780 and 1,800 ft away from the ditch, respectively.

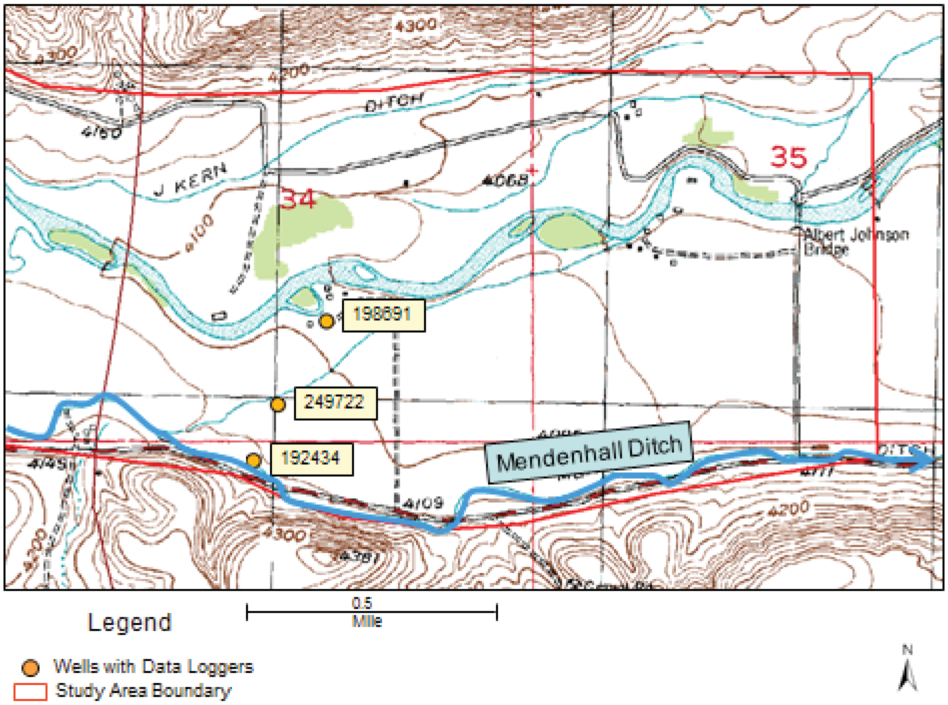


Figure 25. Topographic map showing location of wells with data loggers installed.

Hydrographs of the wells demonstrate the timing and magnitude of the water-level response (fig. 26). According to the hourly measurements from the data logger, the ditch first carried water at this site on 5-24-2009, and a water-level response was detected at 192434 4 days later.

Groundwater Gradient, Darcian Flux

Within the Stillwater Valley, a private alluvial well (192434) located near the south flank of the valley and downgradient from Mendenhall ditch was monitored frequently for water-level changes. The hydrograph demonstrates that it took 4 days for the water level in the well to respond after water in Mendenhall ditch was filled (fig. 26). A similar response was seen in a well further downgradient from Mendenhall ditch (198691; fig. 26). Using these wells and an additional well (252301), the longitudinal and lateral groundwater gradients for this part of the valley were estimated using water levels measured on August 18, 2009 (fig. 27). The longitudinal gradient from well 198691 to 252301 was 37 ft/mile (0.007 ft/ft; table 4). The lateral gradient from well 192434, located near the south flank of the valley, to well 198691, located near the center of the valley, was 79 ft/mile (0.015 ft/ft; table 4). The differences in the longitudinal and lateral gradients may be attributed to asymmetric hydraulic conductivity of the alluvial aquifer. Fluvial depositional valleys are dynamic, and usually the higher hydraulic conductivity follows the main axis of the valley (Winter and others,1998; Woessner, 1998).

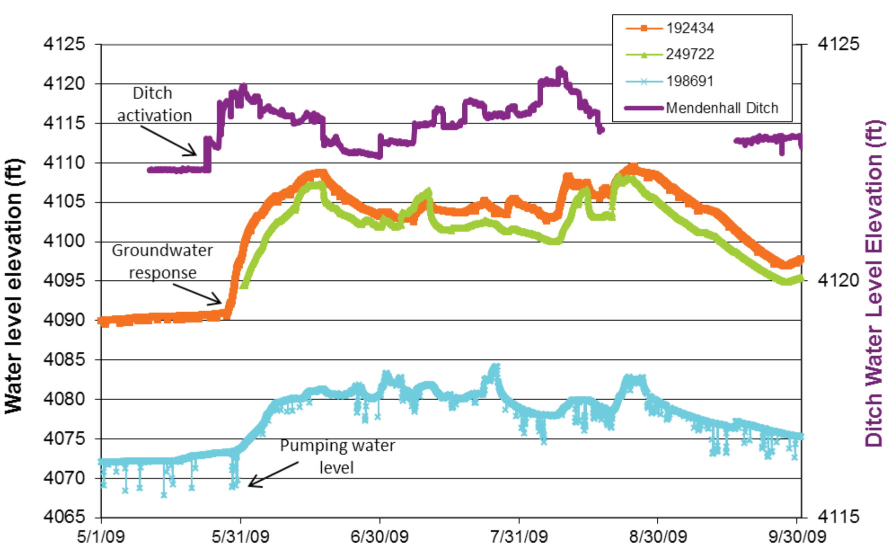


Figure 26. Hydrograph for water-level trends when irrigation season begins.

The return of irrigation water to streams is represented by surface-water gains after the irrigation season is complete. Darcy's law can be used as a simple relationship to calculate the flux of groundwater in the longitudinal and lateral direction of the study area using equation 5:

$$Q = -K \ x \ A \ x \ i, \qquad (5)$$

where Q is discharge (cubic length per time), K is hydraulic conductivity

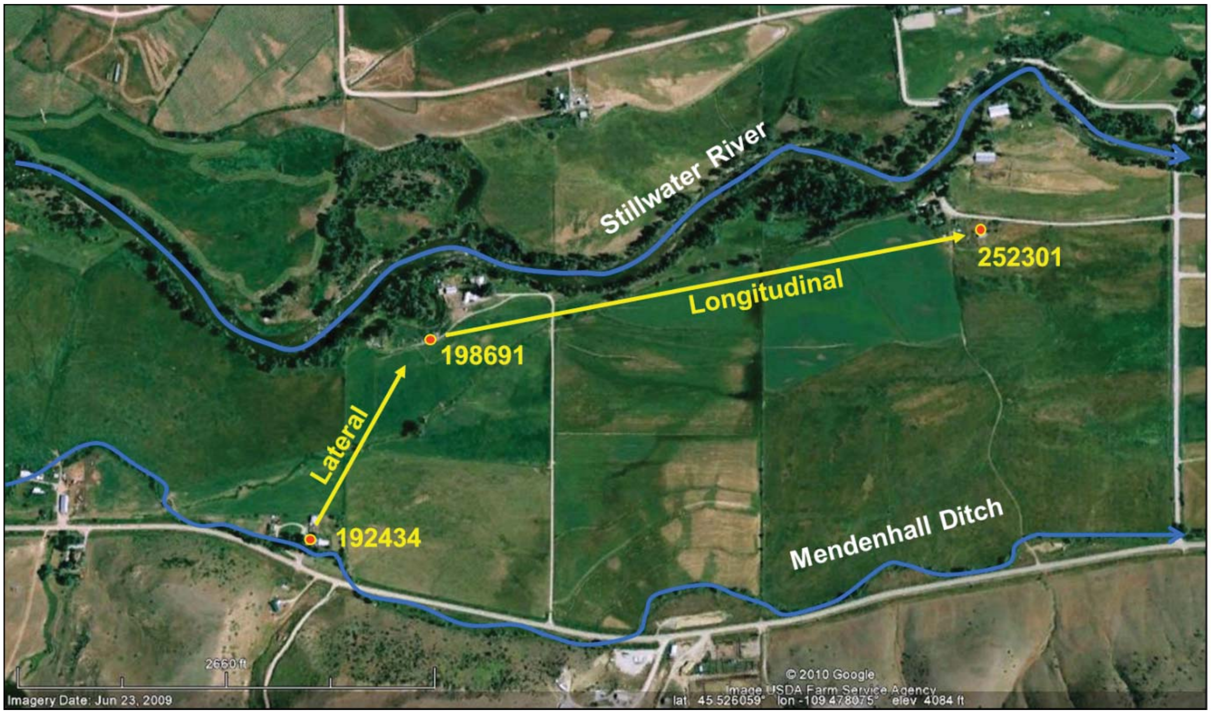


Figure 27. Google image of wells used to compare longitudinal and lateral gradients (192434, 198691, and 252301).

Table 4. Longitudinal and lateral calculated groundwater gradients for August 2009 and March 2010.

GWIC ID	Date	Water-Level Elevation (ft)	Water-Level Elevation Difference (ft)	Distance between Wells (ft)	Groundwater Gradient (ft/ft)	Groundwater Gradient (ft/mile)
Longitudinal groundwater gradient						
198691	8/18/2009	4079	26	3500	0.007	37
252301	8/18/2009	4053				
Lateral groundwater gradient						
192434	8/18/2009	4102	23	1500	0.015	79
198691	8/18/2009	4079				

(length per time), A is area (length^2), and i is hydraulic gradient (length per length). The minus sign indicates groundwater flow is from higher head to lower head.

Figure 28 shows the location (yellow circle) of the wells used to calculate the longitudinal groundwater flux. Well 174838 was chosen to represent the upgradient end of the study area. Well 198691 was chosen to represent the downgradient end of the study area.

To apply Darcy's law, the following parameters were used: pumping test yielded hydraulic conductivity of 120 ft/day and specific capacity from well inventories gave 48 to 102 ft/day, and the cross-sectional area was determined using the average width of the valley, 4,488 ft (0.85 miles), multiplied by the average saturated thickness (24 to 30 ft) of the aquifer. The hydraulic gradient was determined by using the change in water level between the upgradient and downgradient wells (244 to 237 ft) divided by the distance between the wells, which is approximately 30,300 ft (5.7 miles).

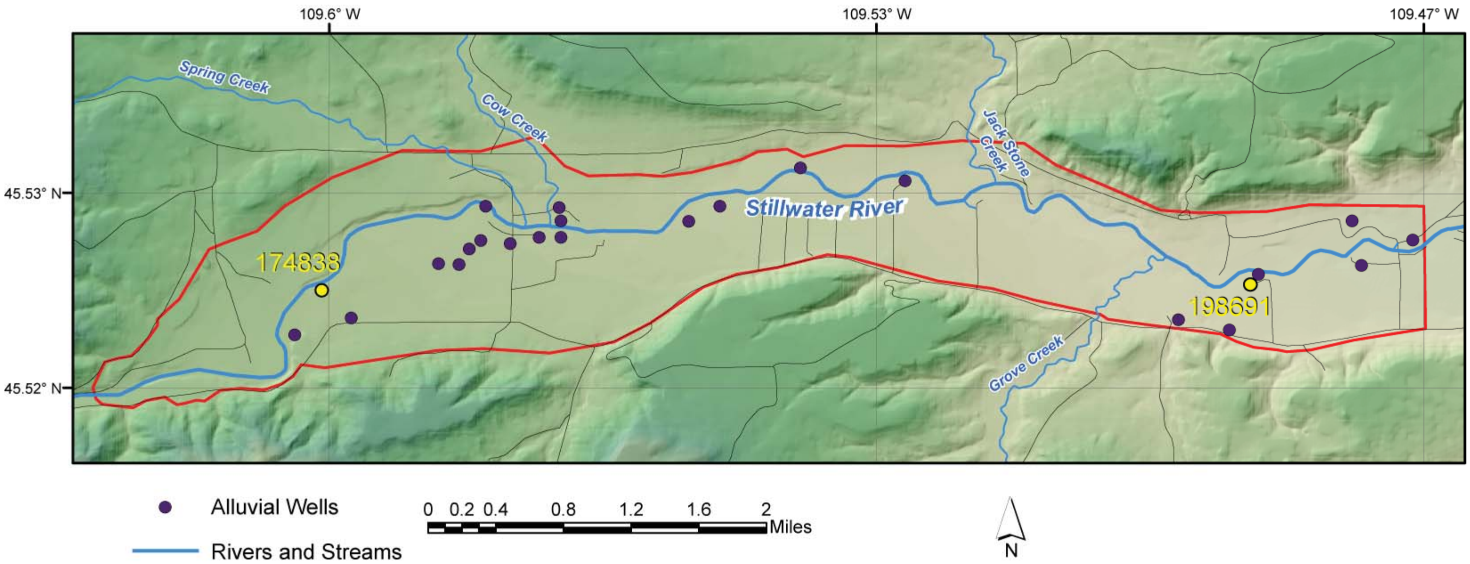


Figure 28. Location map of wells used to calculate the longitudinal groundwater flux.

Figure 29 shows the seasonal pattern for the groundwater flux (Q). The increased amount of groundwater flux in April and May is due to early spring precipitation. As flood irrigation begins, it increases the recharge rate, causing excess groundwater to discharge into the surface water in June and July. As the irrigation rate decreases, the groundwater leaving storage also decreases until groundwater drops to baseflow conditions in March. The 20 percent increase in average saturated thickness that occurs from irrigation increases the flow estimate [the cross-sectional area (A)] slightly. However, since the entire valley's groundwater levels rise over the entire length of the study area, there is little difference in the overall groundwater gradient. The range of hydraulic conductivity values, (48 to 102 and 120 ft/day) illustrated in figure 29 shows the variability of the alluvial aquifer system. The flux [ft^3/day/ft (length)] was normalized by dividing the total flux by the width of the flux boundary (fig. 29).

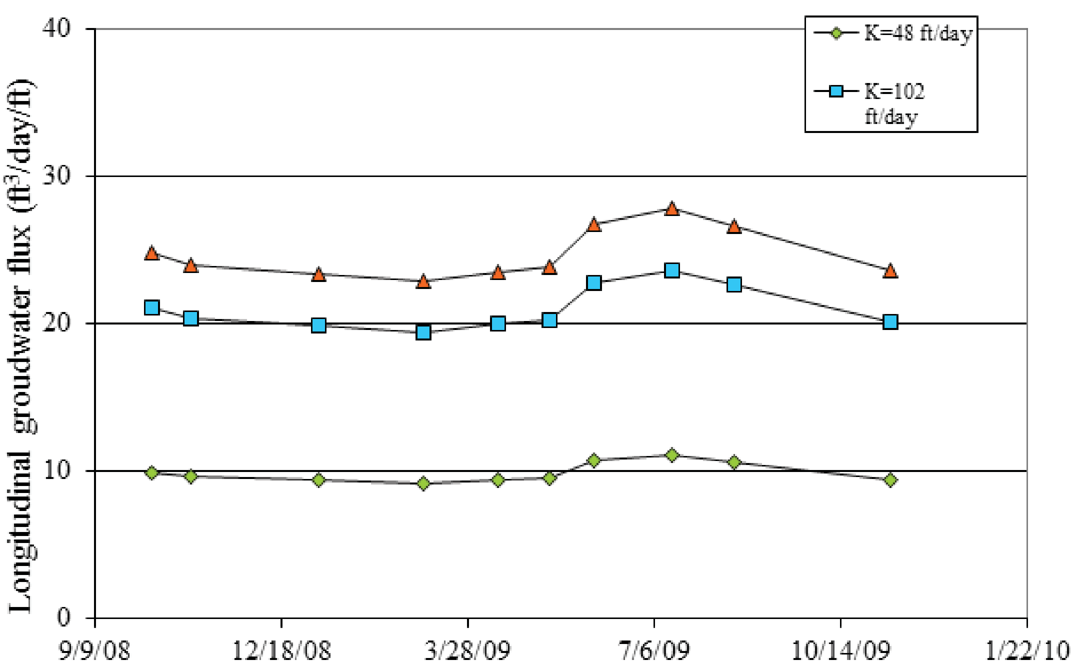


Figure 29. Estimated longitudinal groundwater flux in ft^3/day/ft (width) through the alluvial aquifer with varying hydraulic conductivities at different times of the year.

Darcy's law was also used to calculate the groundwater flux that travels laterally from Mendenhall ditch toward the center of the valley using water-level data from 192434 to 198691 (fig. 27). The flux calculation is sensitive to the hydraulic conductivity parameter, so a range of 48, 102, and 120 ft/day was used from calculated specific capacity and alluvial pumping test data. The area was determined using the length of the entire valley, 31,900 ft, multiplied by the average saturated thickness (12 to 25 ft) of the aquifer. The hydraulic gradient was determined using the change in hydraulic head divided by a distance of 1,570 ft between the two wells (192434 to 198691). The distances are approximations using the online mapping software GoogleEarth™. During the irrigation season (June to September), the lateral flux toward the river could be as high as 21 cfs through the shallow alluvial system, assuming a hydraulic conductivity of 120 ft/day (fig. 30). The flux [ft^3/day/ft (length)] was normalized by dividing the total flux by the width of the flux boundary (fig. 30).

These flux rates were assumed to be similar for the entire study area; however, the density of wells was sufficient in only one area to make these calculations. To test this assumption, it would be necessary to have a higher density of observation wells on the edges of the valley.

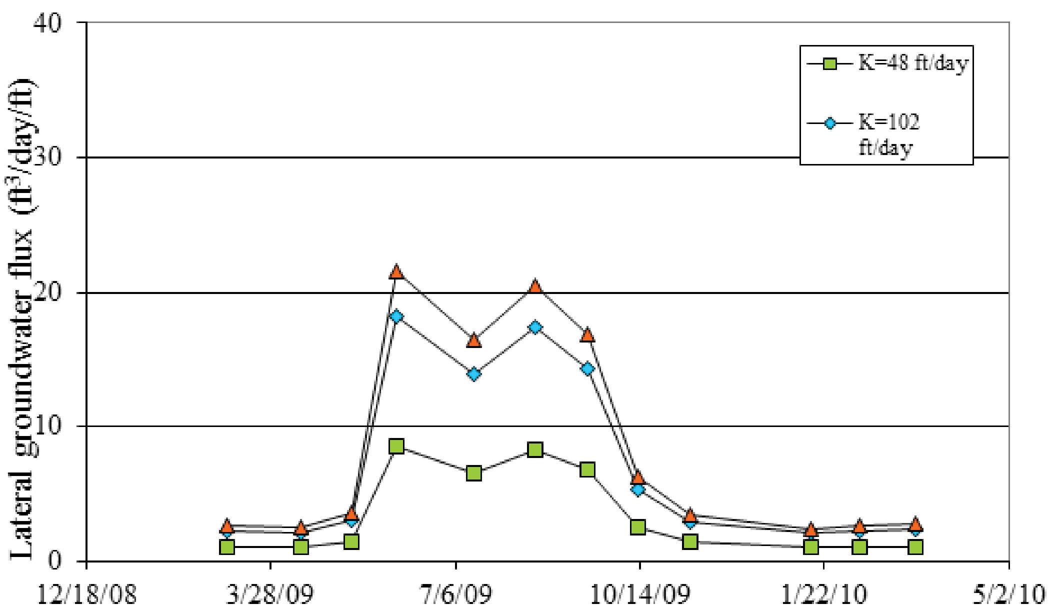


Figure 30. Estimated lateral groundwater flux in ft^3/day/ft (width) through the alluvial aquifer with varying hydraulic conductivities at different times of the year.

Alluvial Water Budget

All of the water diverted from the river to the irrigation ditches is either applied as flood irrigation or leaks through the sides and bottom of the ditches. The applied and leaked water evaporates, undergoes plant transpiration, returns to the river by surface flow, or recharges the alluvial aquifer. Water that recharges the aquifer is temporarily stored before discharging to the river. The volume of water temporarily stored in the alluvial aquifer can be estimated using equation 6:

$$Vw = S \; x \; A \; x \; \Delta h, \qquad (6)$$

where Vw is volume of water temporarily stored (length^3), S is storativity (dimensionless), A is areal extent of aquifer (length^2), and Δh is average decline in head (length; Fetter, 2001).

This can be accomplished by multiplying the effective porosity values of 0.15 (S), calculated from equation 6, by the irrigated land surface area, 3,200 acres (139,000,000 ft^2) (A), and the average water-level rise of 5 ft (Δh). The total volume of water stored in the alluvial aquifer was about 3,100 acre-ft. The water-level rise ranged from 0.93 to 17.77 ft, which results in a range in storage of 580 to 11,000 acre-ft. The gain at Johnson Bridge in table 1 can be used as a simple water budget for the study area. The chloride mass balance data estimated that about 50 percent of applied irrigation water recharges the aquifer and about 50 percent was lost to evapotranspiration. A total of 75 cfs was measured in the supply ditches in the study area in August 2009. If half of the measured ditch flow (38 cfs) was added to equation 1, then the gain at Johnson Bridge would be 56 cfs. Several non-measurable sources may be responsible for this gain, such as bedrock aquifer contribution, tributary stream underflow, and overland irrigation return flow.

Bedrock Aquifer System

Bedrock aquifers are present in the Tertiary, Cretaceous, and Jurassic units. The most extensive aquifers exist within in the Tongue River, Tullock, and Hell Creek formations. These bedrock units generally have ledge-forming fine-grained sandstones interbedded with mudstone, siltstone, claystone, and/or shale (Lopez, 2000). The hydraulic conductivity in the aquifers varies considerably, but they generally produce water of good, drinking-water quality.

According to well logs available in GWIC, the average drilling depth throughout the valley is about 120 ft. However, many wells are drilled up to 380 ft. Landowners typically do not drill past the first good-producing aquifer they encounter, which is generally the surficial geologic unit. Figure 31 is a map of the total depth of wells drilled into the bedrock aquifers. The primary controlling factor in drilling depth is the starting elevation.

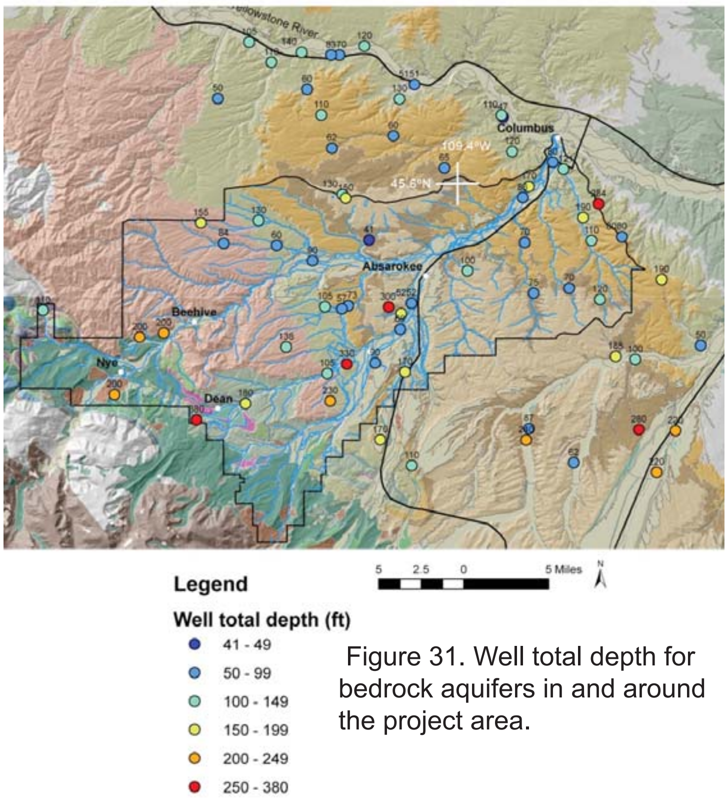


Figure 31. Well total depth for bedrock aquifers in and around the project area.

The bedrock aquifers discharge water into the alluvium through the valley and bedrock contacts and by upward groundwater gradients. The contact between the incised bedrock units and the alluvial valley has created a pathway for groundwater to flow into the alluvial system. This is evident by the water-level elevations in the bedrock wells, which are similar to nearby alluvial wells. It is also evident by increased specific conductance near bedrock outcrops, and by isotopic evidence from an alluvial well near the bedrock/alluvial contact. This particular well (192434) is located near the bedrock/alluvial contact and is downgradient from Mendenhall ditch (fig. 27). The well water was sampled and analyzed for stable isotopes of oxygen and hydrogen ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) during the irrigation season in August 2009 and again at baseflow conditions in February 2010. In the irrigation season, the isotope values resembled those of the Stillwater River, while the baseflow sample values resembled those of the bedrock aquifer. The SC was also measured during these times and the salinity values increased by 50 percent (355 to 531 µS/cm) during baseflow in February. These two groundwater tracers show evidence that the bedrock aquifer does discharge water into the alluvial aquifer.

Level-elevation surveys were performed at site 1 on well 99930 completed in the Hell Creek aquifer and 249723 completed in the overlying alluvial aquifer to evaluate vertical gradients. The vertical water-level gradient in March 14, 2009 was 0.09 ft/ft (fig. 32), indicating that a steep upward gradient exists in the bedrock aquifer. A similar elevation survey was performed at site 2 on well 252300, completed in the Tullock aquifer, and 252301, completed in the overlying alluvial aquifer. The vertical water-level gradient in March 12, 2008 was 0.06 ft/ft (fig. 32), also indicating that a fairly steep upward groundwater gradient exists in the bedrock aquifer. A third elevation survey was performed on well 150131, completed in the Hell Creek aquifer, and 252299, completed in the alluvial aquifer. The vertical water-level gradient in January 12, 2010 was 0.09 ft/ft

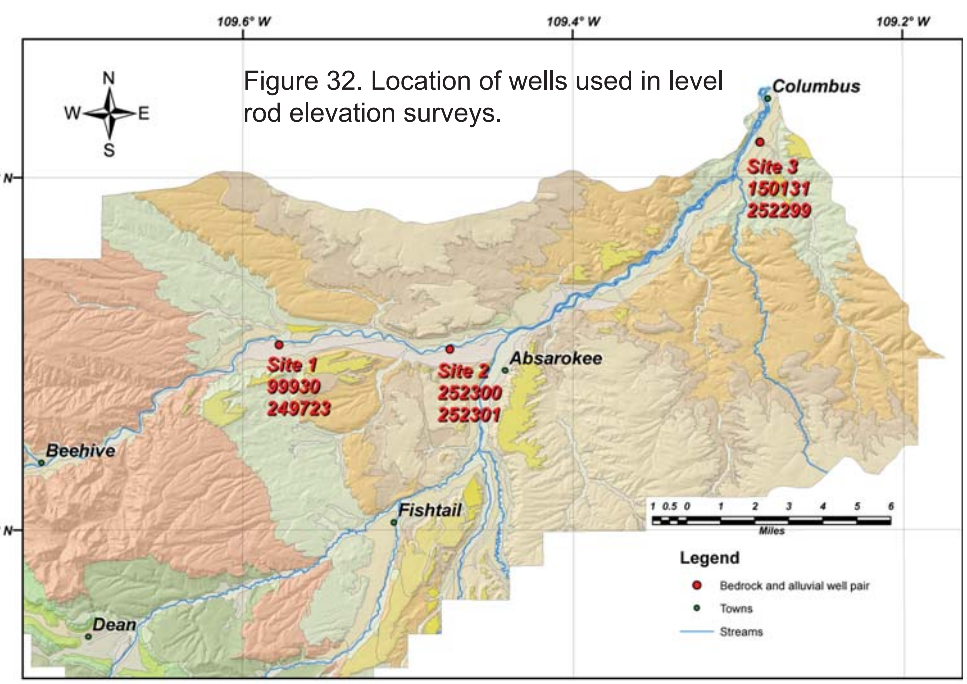


Figure 32. Location of wells used in level rod elevation surveys.

(fig. 32), confirming that a steep upward gradient exists in the bedrock aquifer. This implies that groundwater has the potential to migrate upward from the bedrock units into the gravel aquifer if an impermeable shale layer does not exist to separate them.

A potentiometric-surface map was contoured for the Hell Creek aquifer to represent the groundwater surface elevation and flow direction of the aquifer (fig. 33). The surface map indicates the aquifer has regional flow towards the Yellowstone River with a local component towards smaller valleys following topography. The Tullock aquifer has a similar flow path because both units are laterally continuous across the Yellowstone River Valley. The Yellowstone River Valley is

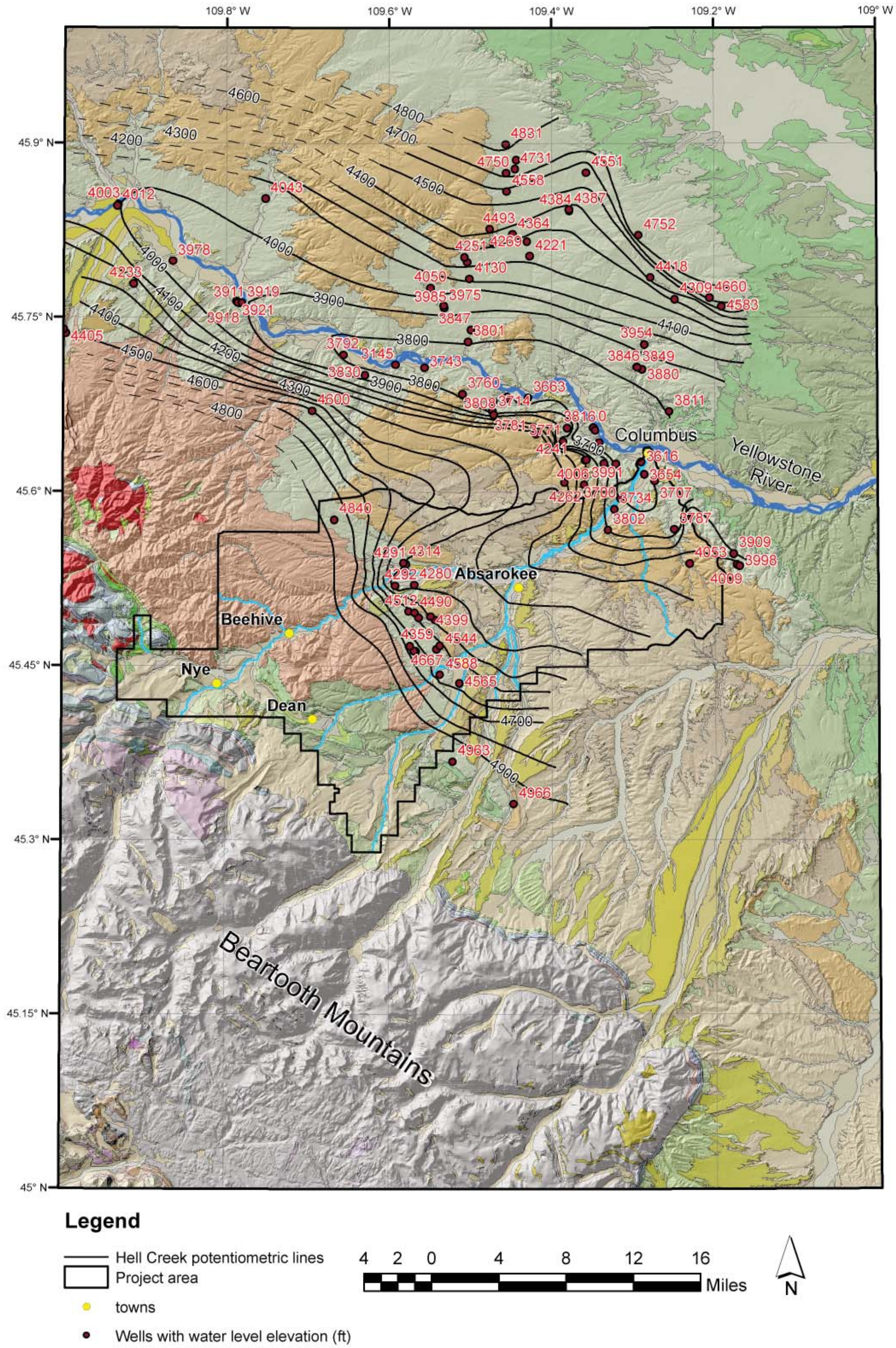


Figure 33. Hell Creek bedrock potentiometric map.

the dominant controlling factor for these aquifers. The Tongue River member and Livingston Group have different flow paths because they are not laterally continuous across the Yellowstone River Valley and will have flow directions controlled by local topography.

Bedrock Aquifer Tests

Monitoring wells were installed in the Tullock and Hell Creek bedrock units near to determine hydrologic properties of the sand aquifers (fig. 34). At T. 4 S., R. 18 E., sec. 17, one pair of monitoring wells (252295, 252296) was installed into the confined Tullock aquifer (fig. 35). The wells were completed 29 ft apart. The water-bearing unit consisted of well-sorted, very fine-grained gray sandstone with a saturated thickness of 13 ft. This aquifer is confined above and below by gray shale. An 18.5-hour aquifer test was conducted at this site. The pumping rate of the production well varied between 6 and 14 gpm throughout the test, so a weighted average of 9 gpm was used when evaluating the hydraulic properties. AQTESOLV software was used to estimate the hydraulic properties of the aquifer. The Cooper–Jacob straight line method was used to estimate a transmissivity of 190 ft^2/day and storativity of 0.02 (fig. 36). A hydraulic conductivity of about 15 ft/day was calculated using the above transmissivity value and the 13 ft of saturated thickness. The recovery data were also plotted in Microsoft Excel for comparison (fig. 37). The recovery data produced a similar calculated transmissivity value of 172 ft^2/day and an estimated hydraulic conductivity of about 13 ft/day.

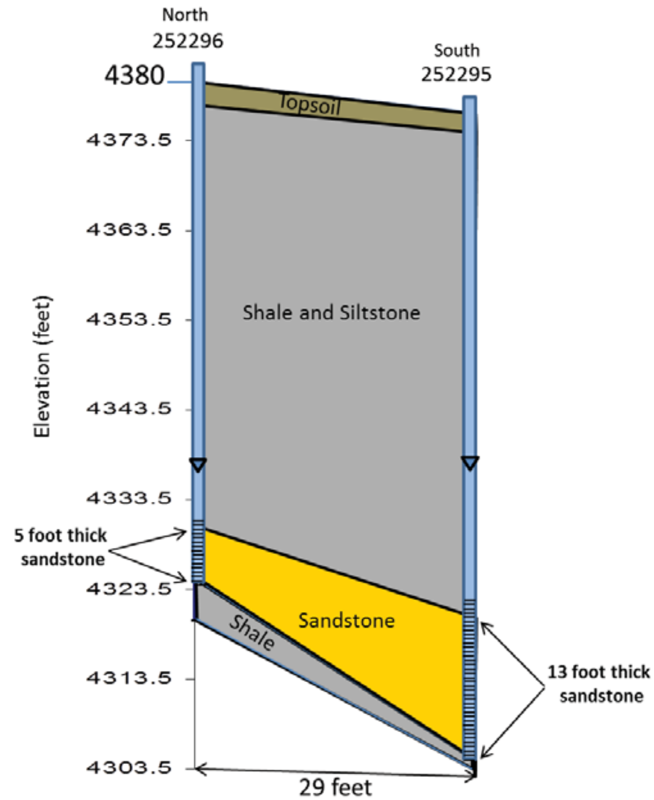


Figure 35. Well completion diagram for wells (252296, 252295) drilled into the Tullock aquifer.

At T. 3 S., R. 17 E., sec. 21, two monitoring wells were drilled into the Hell Creek Formation (fig. 34). The first well (252297) encountered a water-bearing zone about 54 ft below the surface. It was an 11-ft thick layer of well-sorted, very-fine, gray sandstone. The total depth of the well was 70 ft and the saturated thickness was 11 ft. At the time of drilling, the well produced 15 gpm as measured by bucket and stopwatch. The overburden and interbedded layers at this site consisted of a gray shale varying in hardness. The second well was drilled about 40 ft to the east. It was drilled to a total depth of 120 ft and only encountered dry shale (fig. 38). The well was then backfilled and abandoned, leaving only one well on site. A fluvial depositional environment explains the rapid geologic change from sandstone to shale.

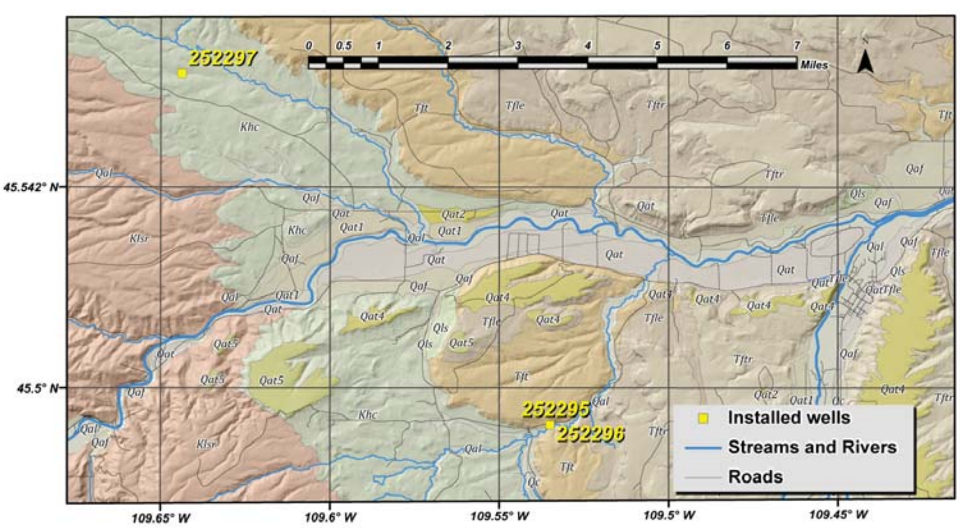


Figure 34. Location map for monitoring wells installed in the Tullock and Hell Creek units. Refer to figure 2 for the geologic legend.

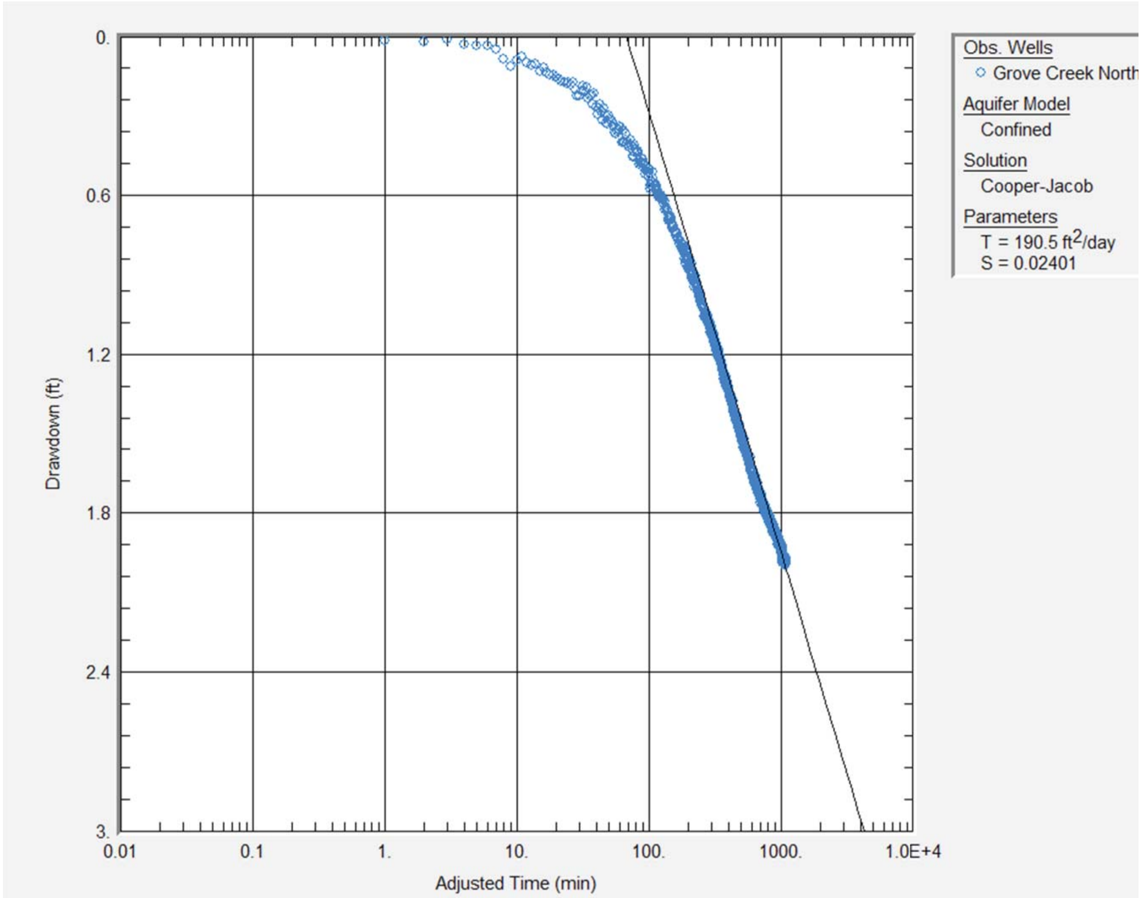


Figure 36. Cooper–Jacob plot of the observation well (252296) in the Tullock aquifer.

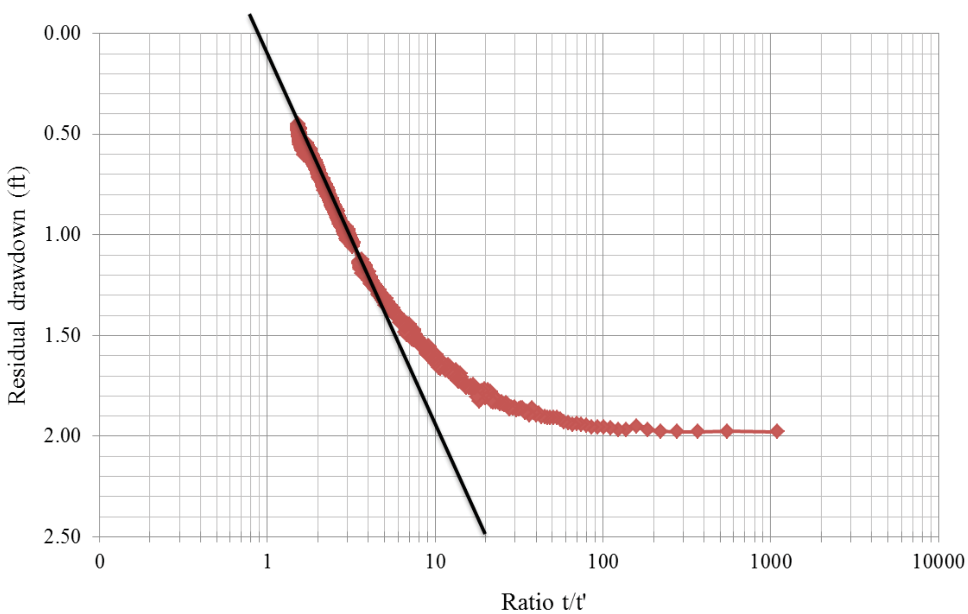


Figure 37. Water-level recovery plot for the observation well (252296) in the Tullock aquifer.

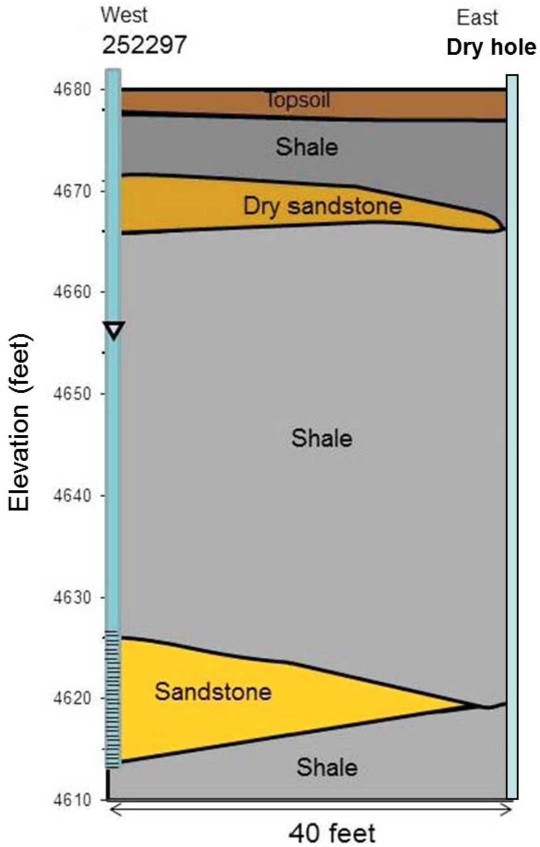


Figure 38. Well completion diagram for a well (252297) drilled into the Hell Creek aquifer.

The MBMG performed a 7.5-hour single-well aquifer pumping test at this site. The pumping rate varied from 5 to 11 gpm throughout the test, so a weighted average of 8 gpm was used for the analysis. The Theis recovery (1935) method was used to calculate a transmissivity of approximately 62 ft^2/day and thus yielded a hydraulic conductivity of about 6 ft/day (fig. 39). The recovery data suggest a positive boundary was encountered. This boundary condition may reflect an increase in aquifer thickness with more stored water. Table 5 shows the aquifer pumping test results for the bedrock wells. Well logs for the monitoring wells installed for this study are listed in appendix B.

Seasonal Changes in Groundwater Levels

Figure 40 is a hydrograph of a well completed in the Hell Creek aquifer. The red and green bar graph attached to the hydrograph represents precipitation departure from the yearly average from a nearby climate station. From 1998 to 2005 the area received below average precipitation, and therefore water levels show a declining trend. Drought sensitivity can be inferred from the water-level drop. One reason for drought sensitivity is the extent of outcrop surface area exposed for recharge to the aquifer. If the extent is relatively small, then not much outcrop is available for precipitation to

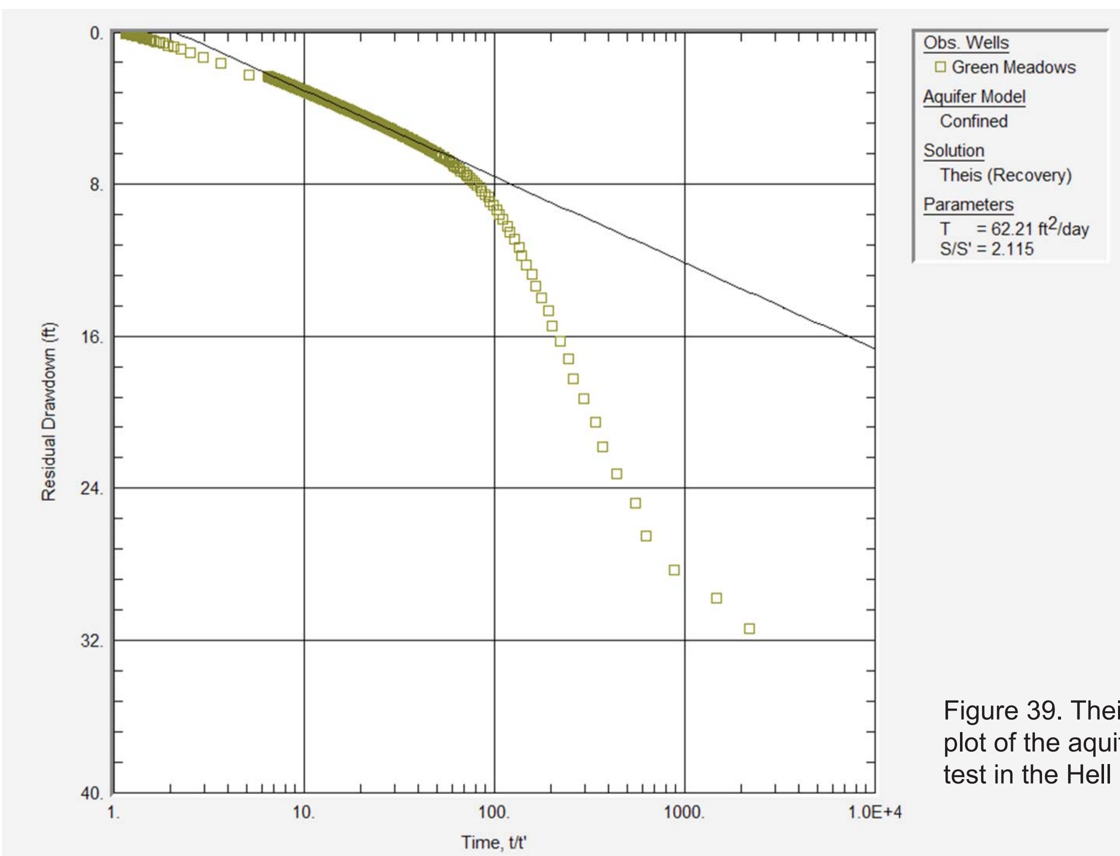


Figure 39. Theis recovery plot of the aquifer pumping test in the Hell Creek aquifer.

Table 5. Bedrock aquifer test results at the Grove Creek and Green Meadows site.

Site Name	Aquifer	Method	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)
Grove Creek	Tullock	Cooper–Jacob	190	15
		Recovery (residual drawdown vs. t/t')	172	13
Green Meadows	Hell Creek	Recovery (residual drawdown vs. t/t')	62	6

infiltrate and recharge the aquifer. The hydrograph also has a seasonal pattern of water levels rising in the spring and falling in the fall. Equation 4 and 5 (modified for confined aquifers $T = \mathrm{Sc} \times 2{,}000$) were used to calculate the specific capacity and transmissivity for well 124876 in the Hell Creek aquifer. A specific capacity of 1.1 gal/min*ft and transmissivity value of 300 ft^2/day were calculated from data collected during the well inventory.

Other bedrock wells in this area show long-term climatic changes but do not show dramatic seasonal fluctuations. The hydrograph in figure 41 is also a well completed in the Hell Creek aquifer. One explanation for the non-fluctuating seasonal patterns is the hydrologic storage of the aquifer. If more storage is available between pore spaces, dramatic fluctuations from recharge will be dampened. Both of the Hell Creek wells are located west of Columbus and south of the Yellowstone River.

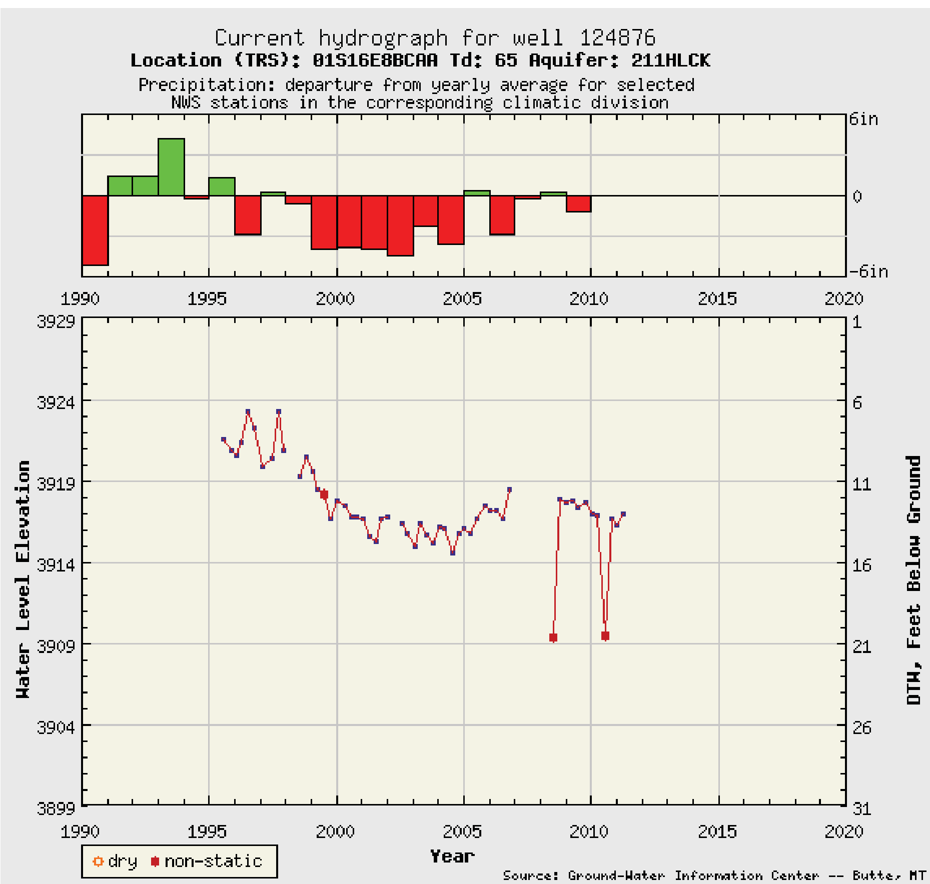


Figure 40. Hell Creek well sensitive to climactic changes and seasonal precipitation patterns.

WATER CHEMISTRY

Specific Conductance

Specific conductance (SC) expressed in units of micro-Siemens per centimeter (µS/cm) is a measure of water's ability to conduct an electric current and can be used to estimate the total dissolved solids in a water sample. The higher the SC value, the more dissolved salts are present in the water. Typically, groundwater has higher SC values than surface water, especially if surface water originates from snowmelt. Thus, SC increasing in a stream, such as the Stillwater River, could be interpreted as a sign of influent groundwater. Tributary streams in the study area originating from bedrock springs have SC values measured between 181 and 805 µS/cm at baseflow conditions. Specific conductance values for all rivers and streams collected are listed in appendix A2.

Specific conductance was measured in groundwater and surface water throughout the study area. On

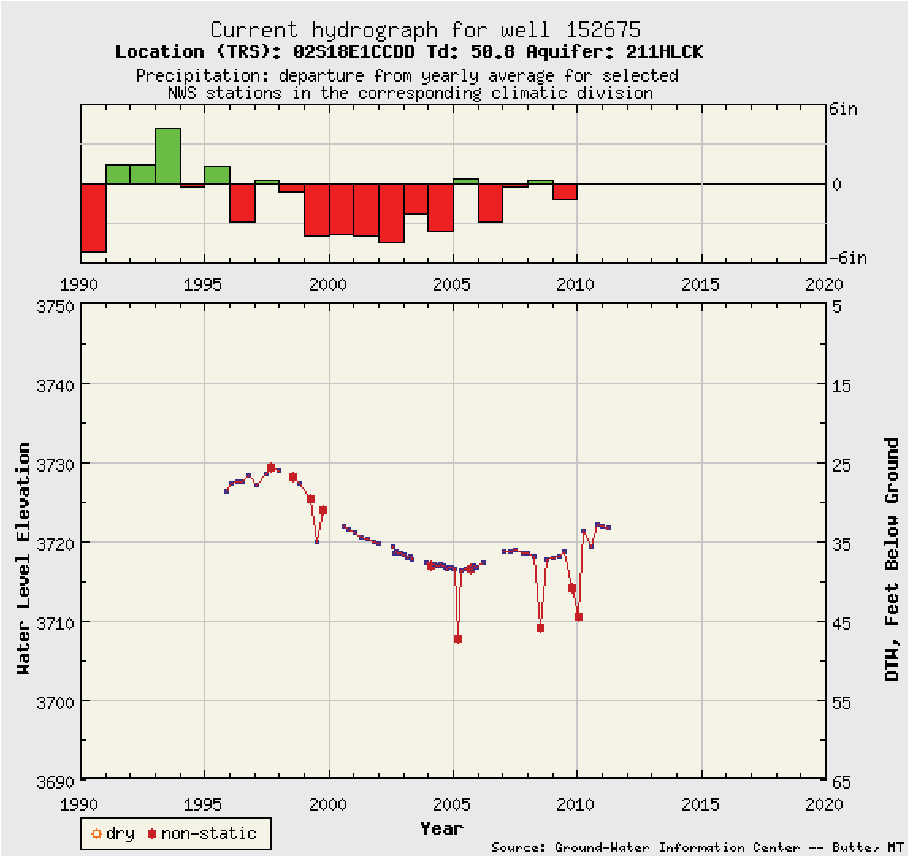


Figure 41. Hell Creek well (152675) sensitive to climactic changes.

September 6, 2008, SC measurements were collected along a transect down the Stillwater River. The values ranged from 140 µS/cm at the upgradient end to 190 µS/cm on the downgradient end of the river (figs. 42 and 43). SC measurements were also collected along a bank-to-bank transect across the Stillwater River at various locations (fig. 44). The values of SC are low in the Stillwater River because most of the water is from high-elevation snowmelt originating in the Beartooth Mountains. The increase in SC in the downstream direction reflects shallow groundwater discharging into the river. The shallow groundwater may include bedrock discharge. The SC values in the bedrock wells ranged from 236 to 1,672 µS/cm depending on the time of year. Some tributary streams also contribute high SC to the river such as Grove Creek and Jack Stone Creek. The SC of these streams range from 278 to796 µS/cm.

Relatively little irrigation exists upstream from the transect area, allowing the SC value to remain relatively low from the headwaters to the transect area. However, as the irrigation intensity increases downstream, the SC values also increase within the river (fig. 43). SC values can be increased in groundwater due to the ET processes of plants, which is a major factor below irrigated land. The salinity also increases as the surface-applied irrigation water infiltrates through the topsoil and dissolves native salts and any applied soil amendments. The SC values were higher near each bank, due to groundwater discharge, and decreased toward the center of the river where the water was well mixed (fig. 44).

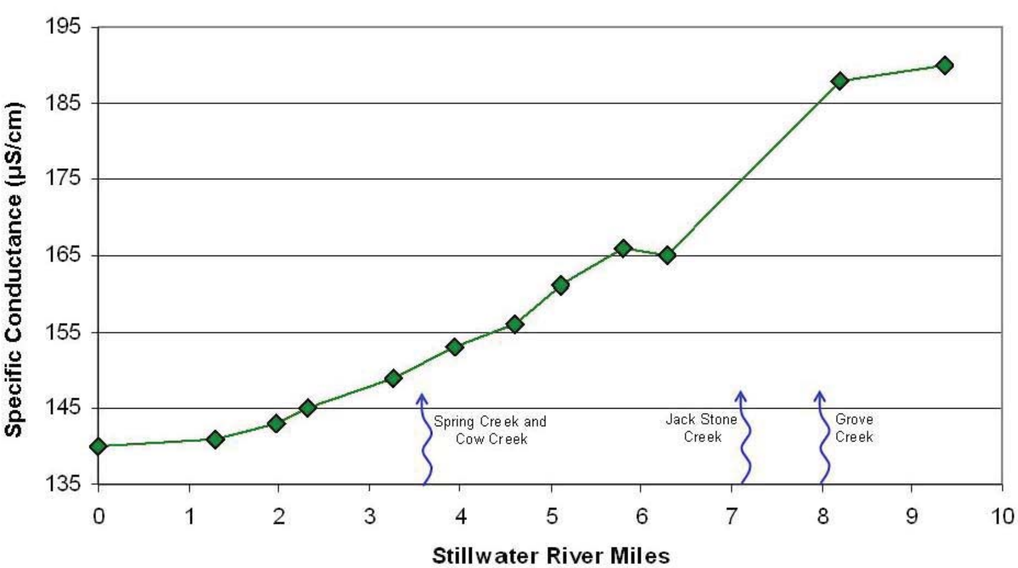


Figure 42. Longitudinal changes in specific conductance of the Stillwater River through the transect area collected in September 6, 2008.

Similar specific conductivity trends of increasing salinity with distance from the headwaters were measured on East and West Rosebud Creeks and Fishtail Creek (fig. 45). As with the Stillwater River, this increasing value of SC down river is mostly due to shallow groundwater discharging into the creeks.

The specific conductance of groundwater was measured when domestic wells were inventoried. During this and other groundwater projects (Carstarphen and Smith, 2007), numerous wells have been inventoried

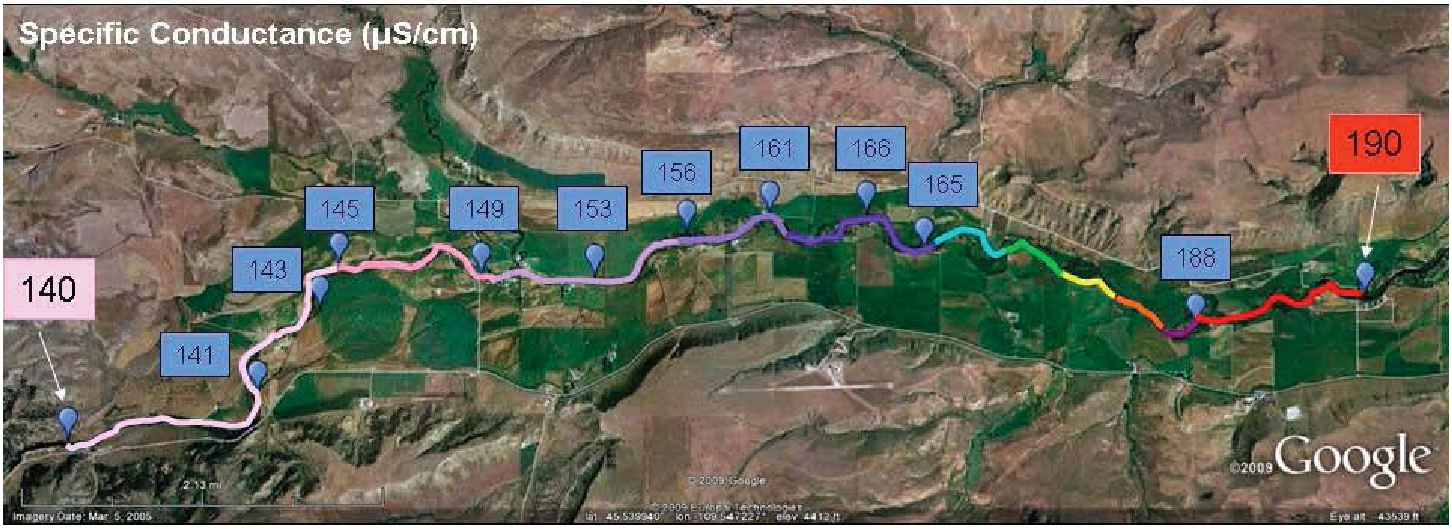


Figure 43. Specific conductance in µS/cm data shown in figure 42 in the Stillwater River overlain on an aerial photograph.

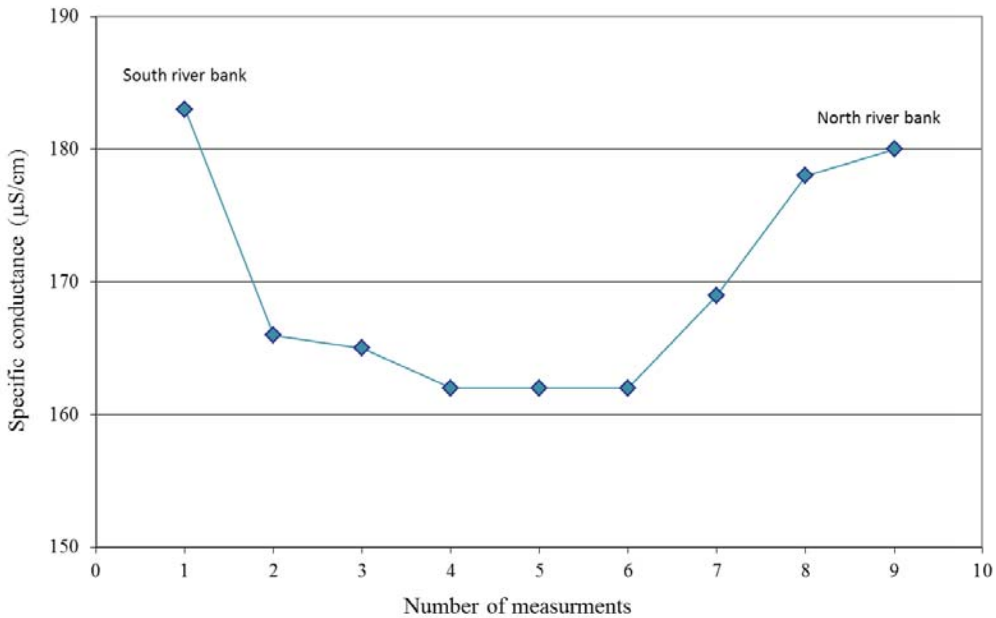


Figure 44. Lateral changes in specific conductance across the Stillwater River from bank to bank collected on September 6, 2008. The distance across the river from bank to bank was 80 ft.

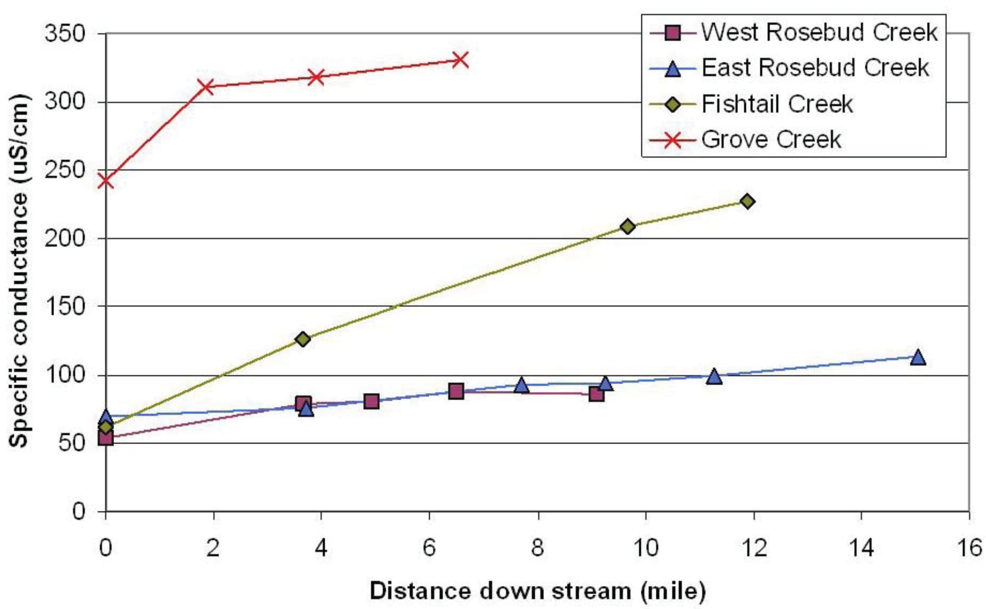


Figure 45. Longitudinal changes in specific conductance of creeks throughout the project area collected in April 2009.

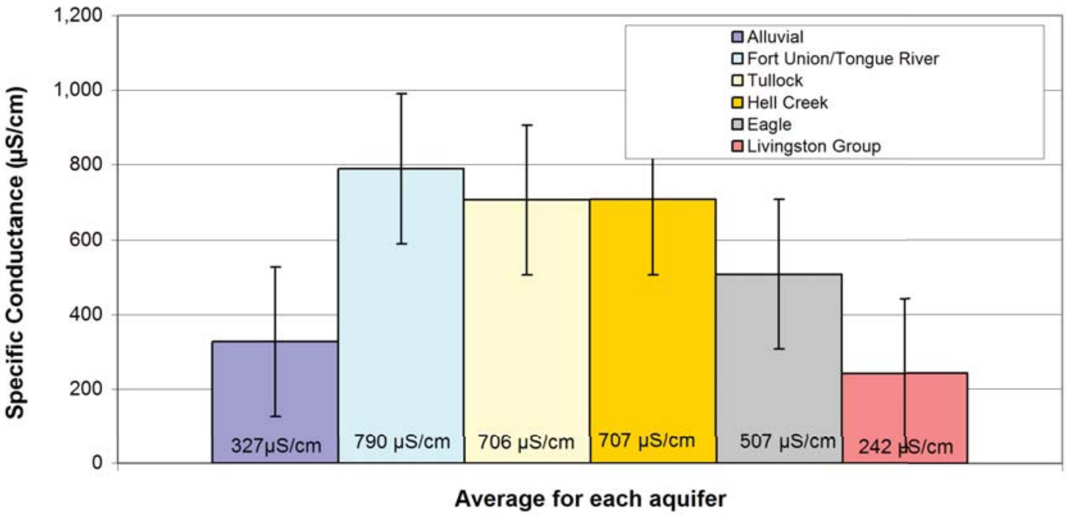


Figure 46. Average specific conductance values for groundwater in parts of Stillwater and Carbon counties. The one standard deviation bar shows the extent of variability within each aquifer.

and sampled in Stillwater County. Figure 46 shows the average SC values for major aquifers in and around the project area in parts of Carbon and Stillwater Counties. Error bars representing one standard deviation illustrate the variability within each aquifer. All bedrock aquifers, except the Livingston Group, have higher average SC values than the alluvial aquifer, with the aquifers within the Fort Union Formation being the highest (average of 790 µS/cm). The low SC values in the Livingston Group aquifer are due to the low availability of soluble salts within the volcanic unit. Groundwater in this unit travels through primary and secondary porosity, faults, and fractures.

A map of SC measurements from bedrock aquifers (fig. 47) indicates that the salinity within each aquifer varies with location. There does not appear to be a general trend. Typically, higher salinity is usually associated with older water further along a flow path; however, there is not a clear flow path in the Stillwater and Rosebud watersheds. Wells with the highest SC values were west of Columbus and near Rock Creek drainage to the east of the project area. The cause for the high salinity near Columbus is unknown but may be due to localized controls, as the surrounding wells do not show similarly high salinities. The high salinities near and south of Cooney Dam are consistent thoughout the watershed for the available data, and salinities may be high because they are completed in the Lebo shale aquifer. Shale aquifers traditionally have low yield and contribute high levels of soluble and exchangeable salts. Groundwater from most wells have low SC values that meet the drinking water standard of less than 1,000 µS/cm. All SC values are listed in appendix C.

The total dissolved solids (TDS) concentration of groundwater is one measure of groundwater quality. The TDS, or salinity, is measured in the field by the water's ability to conduct an electric cur-

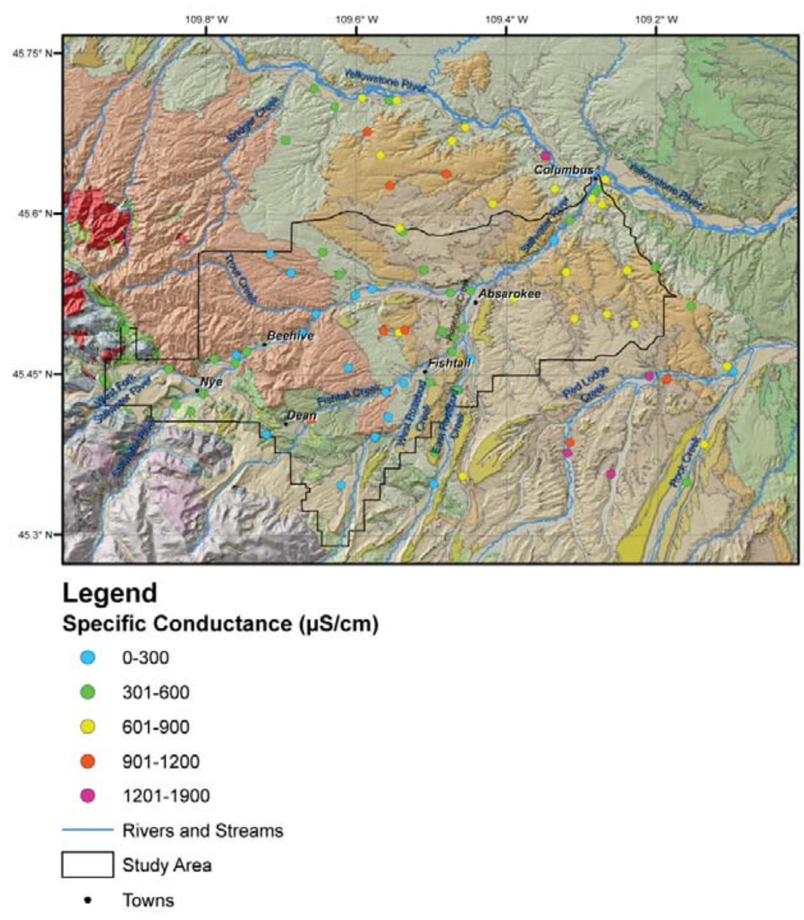


Figure 47. Groundwater salinity in bedrock aquifers in and near the study area (black outline) tends to be lower in the crystalline rock (volcanic Livingston Group) and higher in the sedimentary bedrocks (Tongue River, Tullock, Hell Creek).

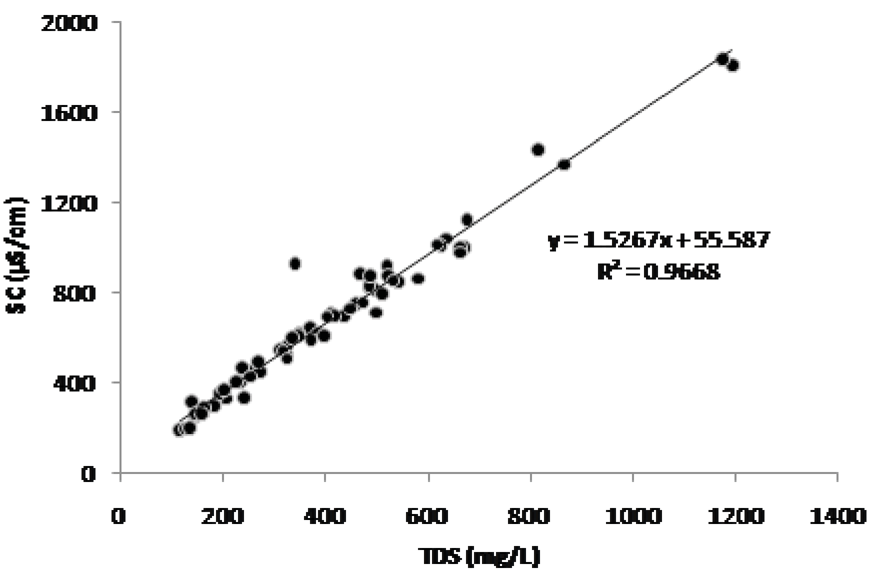


Figure 48. Specific conductivity as a function of the total dissolved solids.

rent (the SC) or in the lab by quantitatively measuring the concentration of the majority of ions present in the water. The TDS and SC are closely related (fig. 48). Salinity is one measure of whether groundwater is potable or non-potable. Fresh groundwater has lower TDS and SC values than more saline water. Measuring SC is a quick and inexpensive measurement and, by using the conversion listed in figure 48, it can easily be converted into an estimate of TDS for the Stillwater area. Figure 48 shows the linear relationship between TDS and SC of groundwater from the Tullock, Livingston, Eagle, Hell Creek, Tongue River, and Lebo aquifers in the Stillwater and Rosebud watersheds. All specific conductance values and total dissolved solids data are listed with the water-quality data in appendix D.

Oxygen and Hydrogen Isotopes

Stable isotopes of oxygen and hydrogen were used to determine groundwater recharge sources in the study area (all isotope data are included in appendix E). When using stable isotopes as tracers, the ratios of the two most abundant isotopes are measured. Oxygen and hydrogen isotopes are measured as ratios of heavy isotope to light: $^{18}O/^{16}O$ and $^{2}H/^{1}H$. These ratios are then compared to a standard, the Vienna Standard Mean Ocean Water, with the resulting δ-value indicating relative deviation away from the standard. The delta (δ) notation is used, as defined in equation 7 (using O-isotopes as an example):

$$\delta^{18}O \text{ (in ‰)} = \left[\frac{\left(\frac{180}{160}\right) sample}{\left(\frac{180}{160}\right) standard} - 1\right] \text{x } 1000 \qquad (7)$$

The δ-values are expressed as parts per thousand, or "per mil" (‰) because the fractionation process variations are small.

The Global Meteoric Water Line (GMWL; Rozanski and others, 1993) is derived from a compilation of precipitation from all over the world and is plotted on figures 49 and 50 as a reference line. Values of $\delta^{18}O$ and $\delta^{2}H$ in precipitation are influenced by meteorological processes and particularly by the temperature, elevation, and latitude of the rain or snowfall event (Clark and Fritz, 1997). Precipitation in the form of colder, higher latitude, and high-altitude snow has lower isotope ratios compared to warmer, lower latitude, and lower altitude rain. The warmer precipitation will have a more positive δ-value (more enriched in ^{18}O and ^{2}H) than the colder precipitation. In the study area, the Stillwater River (which is the irrigation supply water) is primarily composed of high-altitude snowmelt from the Beartooth Mountains. As expected, the Stillwater River water samples plot close to the GMWL, and have depleted $\delta^{18}O$ and $\delta^{2}H$ values typical of high-altitude recharge (fig. 49; yellow triangles). Within and surrounding the study area, 52 samples of precipitation, surface and alluvial groundwater, and ditch isotope samples were collected for isotope analysis (figs. 49 and 50). Some of the locations were sampled several times throughout the year, while others were sampled only once. Analyses of the Stillwater River (fig. 49; yellow triangles) collected from various locations along the river throughout 2008 and 2009 indicate a $\delta^{18}O$ range of -17.9 to -19.2 ‰ and a $\delta^{2}H$ range of -135 to -145 ‰ (fig. 49). In August 2009, when irrigation from the Stillwater River was at its peak, alluvial wells (fig. 49; green squares) and the nearest upgradient ditches (fig. 49; green triangles) to those wells were sampled. Analyses of these samples indicate a $\delta^{18}O$ range of -17.3 to -18.5 ‰ and a $\delta^{2}H$ range of -131 to -138 ‰ (fig. 49). These values for the alluvial groundwater are within range or slightly more positive than the Stillwater River and irrigation ditches, suggesting that the majority of the alluvial groundwater originated from irrigation water. The Rosebud Rivers and Fishtail Creek are also supplied by high-altitude snowmelt and plot near the range of the Stillwater River. Rivers and irrigation ditch water have isotope ratios that are dissimilar to bedrock isotope ratios (figs. 49 and 50).

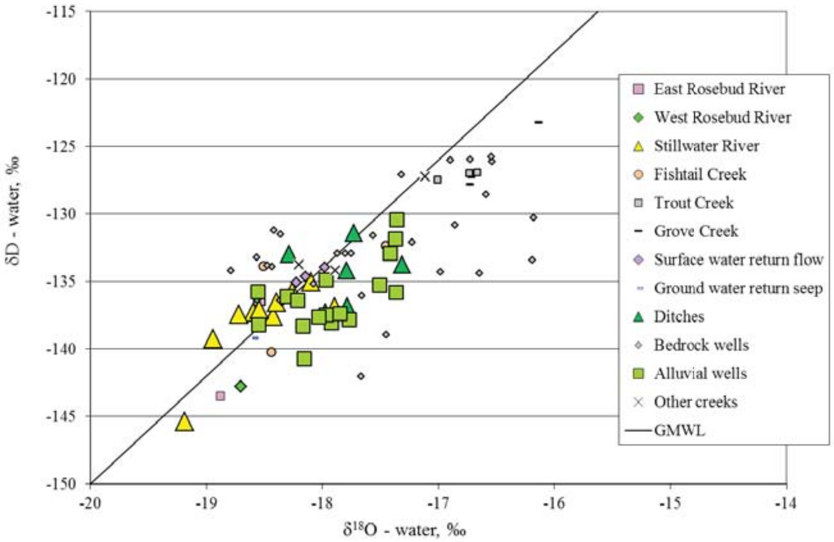


Figure 49. Stable isotope composition of surface water and alluvial groundwater in the study area, including several nearby rivers.

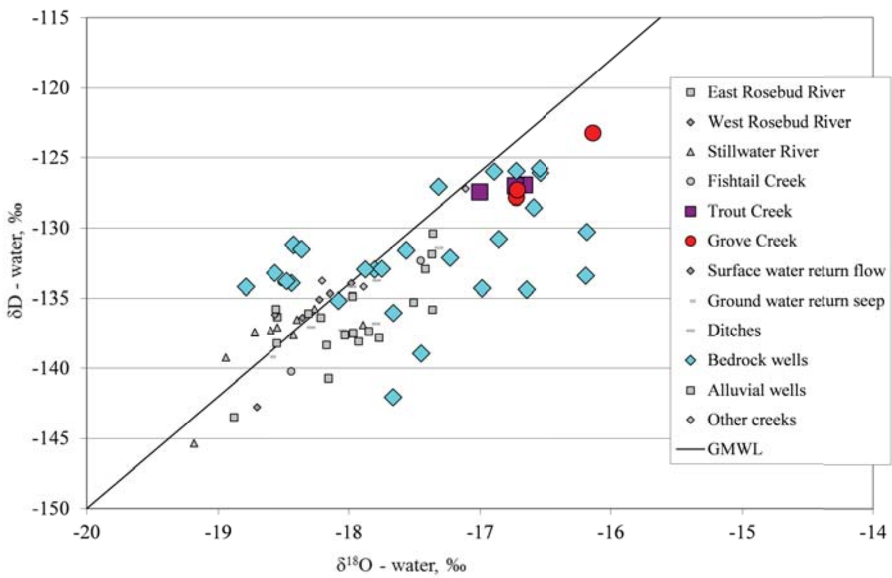


Figure 50. Stable isotope composition of bedrock aquifers and bedrock-fed creeks highlighted.

Within and surrounding the study area, 36 bedrock aquifers and bedrock-fed creeks were sampled (fig. 50). Analyses of the bedrock aquifers (fig. 50; blue diamond) indicate a $\delta^{18}O$ range of -15.1 to -18.1 ‰ and a $\delta^{2}H$ range of -125 to -135 ‰. Analyses of the bedrock-fed creeks (figs. 49 and 50; purple square and red circle) indicate a $\delta^{18}O$ range of -16.1 to -16.7 ‰ and a $\delta^{2}H$ range of -123.2 to -128 ‰. Both the bedrock wells and bedrock creeks plot more positive than the alluvial wells and high mountain rivers. This suggests that the bedrock aquifer was recharged at lower elevation. Most of the bedrock samples plot below the GMWL, indicating possible fractionation of the isotopes by evaporation. This indicates that recharge to the bedrock undergoes evaporation prior to infiltrating to the aquifer. This occurs when there is sufficient soil thickness overlying the recharge areas of the bedrock aquifers.

Chloride and Evapotranspiration

In the United States, chloride (Cl-) is more concentrated in rainwater near the coasts and less concentrated further inland (Drever, 1997). Values near the Pacific Coast average 0.6 mg/l, whereas values in Montana range from 0.08 to 0.17 mg/l (Drever, 1997). Chloride can be used as a natural water tracer because it is conservative during evaporation and transpiration, and does not precipitate except at extremely high salinities (Clark and Fritz, 1997). The concentration of chloride in groundwater will increase with increased evapotranspiration.

Chloride concentrations were analyzed in 19 samples to determine if evapotranspiration (ET) was a significant influence on the alluvial groundwater. The samples had chloride concentrations ranging from 0.7 to 5.1 mg/l in the alluvial wells, and non-detectable levels (<0.5 mg/l) in the ditch samples. Fifty-three USGS samples collected at various dates in the 1980s, from several locations along the Stillwater River, had an average chloride concentration of 0.66 mg/l. Assuming the main source of recharge to the alluvial aquifers is irrigation water, the percentage of ET loss can be calculated with equation 8, provided by Clark and Fritz (1997):

$$ET = (1-[Cl_{r} / Cl_{gw}]) \times 100, \qquad (8)$$

where ET is percent ET loss, Clr is recharge chloride concentration [0.66 mg/l], and Clgw is groundwater chloride concentration [0.7 to 5.1 mg/l].

Table 6. Chloride concentration and estimated ET loss in the alluvial and bedrock aquifer.

Group	Average Chloride Concentration (mg/l)	Estimated ET Loss
Alluvial aquifers average	1.8 (*n*=19)	53%
Fine-grained cover thickness less than 5 ft	1.5 (*n*=15)	48%
Fine-grained cover thickness between 5 and 20 ft	3.1 (*n*=4)	73%
Average Stillwater River	0.66 (*n*=53)	
Bedrock aquifers average	15.4 (*n*=41)	91%
Fort Union (undifferentiated) / Tongue River	5.5 (*n*=6)	82%
Tullock	11.4 (*n*=9)	94%
Hell Creek	33.8 (*n*=26)	98%
Rain precipitation (Drever, 1997)	0.17	

Note. *n* refers to sample size. ET loss is the percentage of water removed from the original recharge source by evapotranspiration.

The chloride mass balance results suggest that, overall, approximately half (53 percent) of the irrigation water applied to the fields was lost to ET (table 6). Olson and Reiten (2002) found in West Billings that as the soil cover became increasingly thicker, the estimated ET loss was greater. Well logs were examined in the Stillwater River study area to see if the losses were influenced by the fine-grained soil thickness as well. In places where the soil cover is thin (less than 5 ft), the estimated ET loss was 48 percent; where the soil cover was thick (greater than 5 ft), the estimated ET loss was 73 percent (table 6). The thin soil cover allows the irrigation water to quickly infiltrate. The thicker soil cover is less permeable, which causes the water to stay within the root zone longer, increasing the amount of water lost to ET, thereby increasing chloride concentration. The calculations presented in table 6 for ET loss estimate the maximum evaporation loss. Additional sources of chloride would cause this calculation to overestimate the true ET rate. Chloride can enter the flow path through dissolution of native salts in the soil during interaction with the aquifer matrix or from minor chloride contributions; sources include septic tanks, manure, and fertilizers.

Chloride was also analyzed in 41 bedrock groundwater samples to determine if ET influenced the bedrock aquifers. The samples were collected throughout Stillwater County. Drever's (1997) value of 0.17 mg/l was used for the chloride samples of rainwater in the calculation as the variable Cl_r in equation 8. The groundwater samples (Cl_{gw} in equation 8) have chloride concentrations ranging from 0.87 mg/l to 37.6 mg/l in the bedrock aquifers. Average chloride concentrations from 41 samples suggest that, on average, 91 percent of the recharge source was lost due to ET, if precipitation is the primary source of chloride (table 6). Typically the bedrock units have sandy to clayey material overlying the aquifers. The material can have very low hydraulic conductivity that will not allow recharge to infiltrate very quickly, thus giving plant roots and solar radiation ample time for ET to occur. However, calculation of losses due to ET for bedrock aquifers is subject to error due to the greater likelihood of dissolution of chloride salts from the Tertiary and Cretaceous bedrock units than the alluvial aquifers. Additional sources of chloride in the bedrock groundwater include dissolution of chloride salts in the soil and interaction with the aquifer material. Therefore, the calculations presented here for ET loss are maximums. All chloride data are listed in appendix F1,F2.

A distinction between the effects of transpiration and evaporation can be determined by comparing stable isotope ratios of oxygen to chloride concentrations (Clark and Fritz, 1997). Transpiration by plants will cause chloride in the soil water to increase but will not change the isotopic composition of the water. Evaporation will also cause the chloride in the soil water to increase but in doing so will cause the isotopic ratio of ^{18}O to ^{16}O to increase. Figure 51 shows that the chloride concentrations of the alluvial and bedrock groundwaters increased, while the oxygen isotope ratio stayed the same. This indicates that evaporation has little direct influence on groundwater. Therefore, transpiration may be the dominant source of water loss during irrigation. Samples analyzed for chloride concentrations and oxygen isotope ratios were also collected from the nearest upgradient ditches to the sampled wells. Ditch samples also show little influence from evaporation as compared to their source, the Stillwater River. The higher chloride concentrations in the bedrock wells as compared to alluvial groundwater (fig. 51) indicate recharge water may stay in the root zone for longer periods of time, allowing transpiration to occur, or there may be an additional source of chloride in the rock or through dissolution of soil salts.

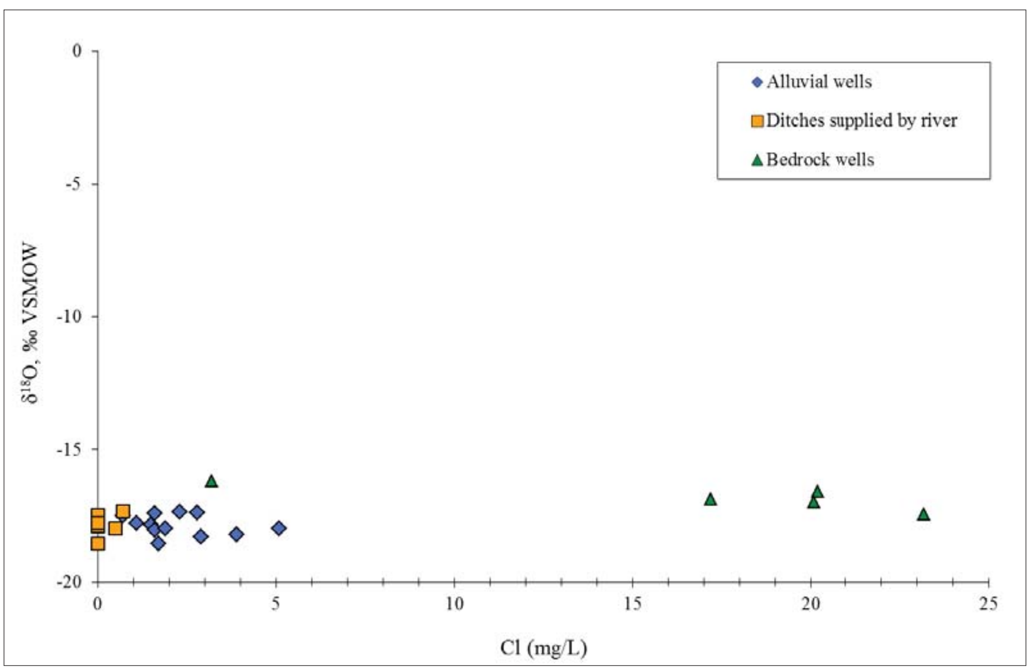


Figure 51. The relationship between δ^{18}O of water and chloride concentration for alluvial wells, bedrock wells, and irrigation ditches, indicating that transpiration, more than evaporation, plays a major role in groundwater evolution.

Tritium Analysis

Tritium concentrations in groundwater can be used to differentiate relative ages of groundwater and identify potential recharge sources. The age of groundwater is defined as the time elapsed since the water was last in contact with the atmosphere and entered the aquifer. Tritium (^3H) is a radioactive isotope of hydrogen with a half-life of 12.43 years, containing one proton and two neutrons. It decays into helium-3 (^3He) by emitting a beta particle. In the 1950s and 60s, a substantial amount of tritium was created in the atmosphere as a result of nuclear weapons testing. This overwhelmed the natural atmospheric production rate of ^3H, and these higher concentrations infiltrated into groundwater. Tritium and ^3He isotopes are often used to measure groundwater transport because they are not chemically reactive and because they migrate at the approximate speed of the groundwater. The ratio of parent (^3H) to daughter atoms (^3He) is used to measure the age of groundwater. It is also possible to just use the concentration of ^3H to provide a relative age of groundwater. Recently recharged water is modern and should contain a concentration of tritium (measured in tritium units, TU) similar to current atmospheric levels. Older water further along the groundwater flow path will have a lower concentration due to the decay of tritium. In practice, water with less than 0.5 TU has a pre-1952 age; water with tritium concentrations between 5 and 10 TU is modern; intermediate tritium concentrations of 0.8 to 4 TU is most likely a mixture of modern and older water; and tritium concentrations in excess of 15 show the influence of bomb testing in the 1950s (Clark and Fritz, 1997; Drever, 1997).

In the Stillwater project area, tritium concentrations were measured in nine groundwater samples; values ranged from -2 to 13 TU (table 7). Negative values of tritium are not valid, so the one reported

Table 7. Tritium results.

GWIC ID	Tritium (TU)	Error +/-	Approximate Age
150225	-2	2	pre-1952
188982	2	2	mixture
150131	2	2	mixture
101301	6	2	mixture
217303	6	3	mixture
252297	6	3	mixture
252300	8	2	mixture
252295	12	3	post-1952
192434	13	2	post-1952

value of -2 is representative of error associated with the value of zero. The spatial distribution of tritium values does not indicate an obvious pathway of groundwater flow (fig. 52). In general, younger waters are found in the southwest of the project area near the Beartooth Mountain range and progressively older waters are found to the northeast toward Columbus, Montana. The exception to this overall trend is the spurious value of -2. The source of this old groundwater may be from upward movement of water from underlying aquifers. Young recharge water may originate from the snowmelt of the Beartooth Mountain Range (see Oxygen and Hydrogen Isotopes discussion). Ultimately, we do not have sufficient data to characterize tritium distribution for the area, and therefore groundwater flow paths.

Common Ion Geochemistry

The hydrogeologic processes of groundwater recharge and discharge control fluctuations in the water potentiometric surface and contribute to its chemical composition. Systematic changes in ion composition can provide additional information about groundwater flowpaths. Groundwater recharge occurs when water at the surface infiltrates into groundwater systems. Groundwater near recharge sources in semi-arid climates is usually dominated by calcium, magnesium, and sulfate from the dissolution of gypsum, calcite, and epsomite found in soils. Areas of groundwater discharge are generally higher in relative concentrations of sodium and bicarbonate due to sulfate reduction and ion exchange (Brinck and others, 2008).

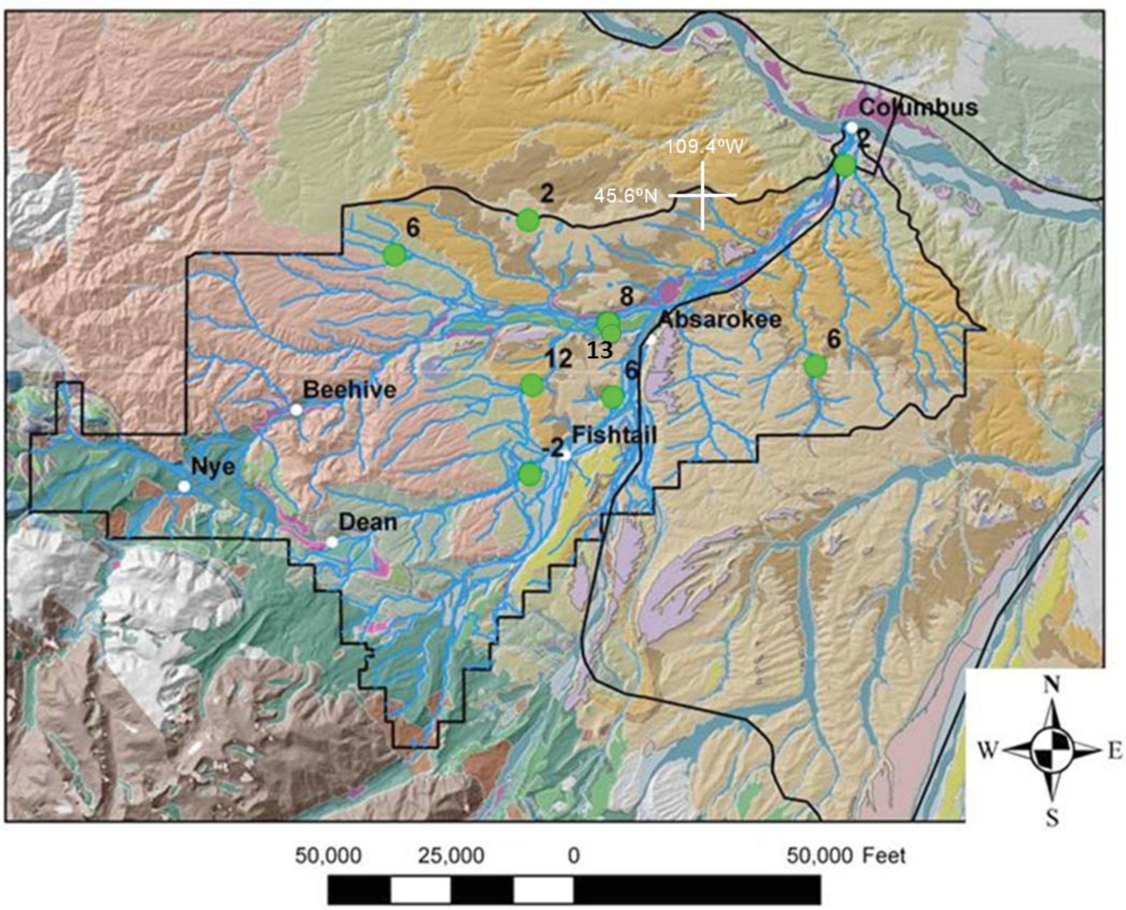


Figure 52. Measurement of tritium concentrations in the major aquifers (green circles show sample locations) indicates that most groundwater in the study area is modern or composed of a mixture of recent recharge and older water.

Trilinear, or Piper, diagrams are commonly used to show the relative percent concentrations in milliequivalents of major cations (magnesium, calcium, potassium, and sodium) and anions (sulfate, bicarbonate, carbonate, and chloride). Using Piper diagrams, we are able to graphically display the relative proportions of ions from multiple water samples. Piper diagrams can graphically illustrate:

1. when two or more separate water flow systems exist and mix between the systems, and

2. groundwater evolution along flow paths.

Groundwater that undergoes a progression from high relative calcium and magnesium to high sodium and bicarbonate suggests a flow path from recharge areas having "young water" to discharge areas where the water is more mature. Major and minor ion concentrations were measured by the MBMG Analytical Laboratory in Butte, Montana for 45 water samples from the Tullock and Hell Creek aquifers. Piper diagrams were created for these two aquifers (figs. 53 and 54).

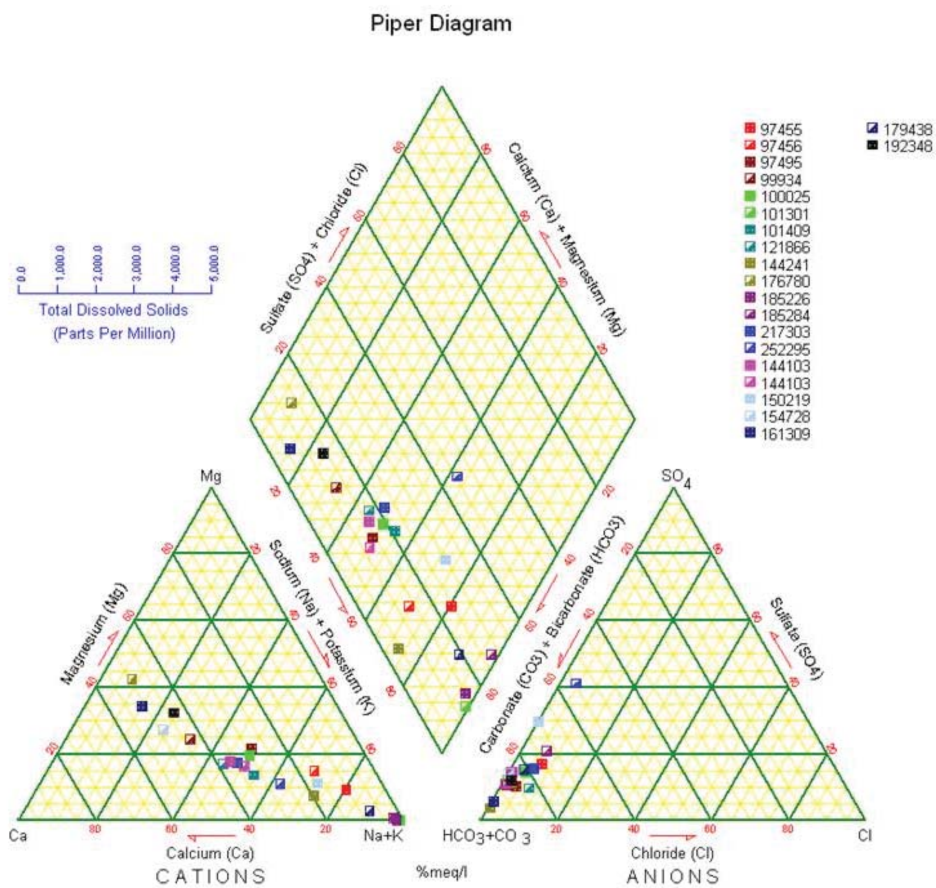


Figure 53. Piper diagram of Tullock aquifer water samples.

The Tullock aquifer (fig. 53) shows a succession in the groundwater from high calcium and magnesium to high sodium and potassium compositions. Given this progression, it would seem likely that the Tullock aquifer water-quality data would outline a flow path from recharge to discharge. From the chemistry data, distribution maps were generated using ESRI's ArcGIS to investigate spatial distribution of the geochemical data. However, a graphical depiction of the percent sodium composition in the study area does not provide a clear picture of the possible flow paths in the Tullock aquifer (fig. 55).

The Hell Creek Piper diagram (fig. 54) displays two distinct populations of water chemistry. In one group, cations are dominated by sodium and potassium, which together make up greater than 60 percent of total cations. The second group is characterized by sodium + potassium constituting less than 40 percent of the cations. Graphical depiction of the sodium content of the Hell Creek aquifer (fig. 56) indicates waters containing high sodium contents occur in all parts of the project area, not just those eastern areas near Columbus and the Yellowstone River, as would be expected if the overall groundwater flowpath was southwest to northeast. All water-quality values are listed in appendix D.

While the Piper diagrams and ArcGIS maps provide an insight to the project and surrounding area's groundwater composition and flow paths, ultimately data and spatial distribution are not sufficient to draw major conclusions about flow paths. Both the Tullock and Hell Creek are interbedded layers of sand and shale that could contain multiple aquifers. The shales within these formations likely provide an ample source of sodium. Many of the wells were completed at multiple depths, which suggests that water was being drawn from two sources within the same formation. The geology and depth where the water is produced could have an

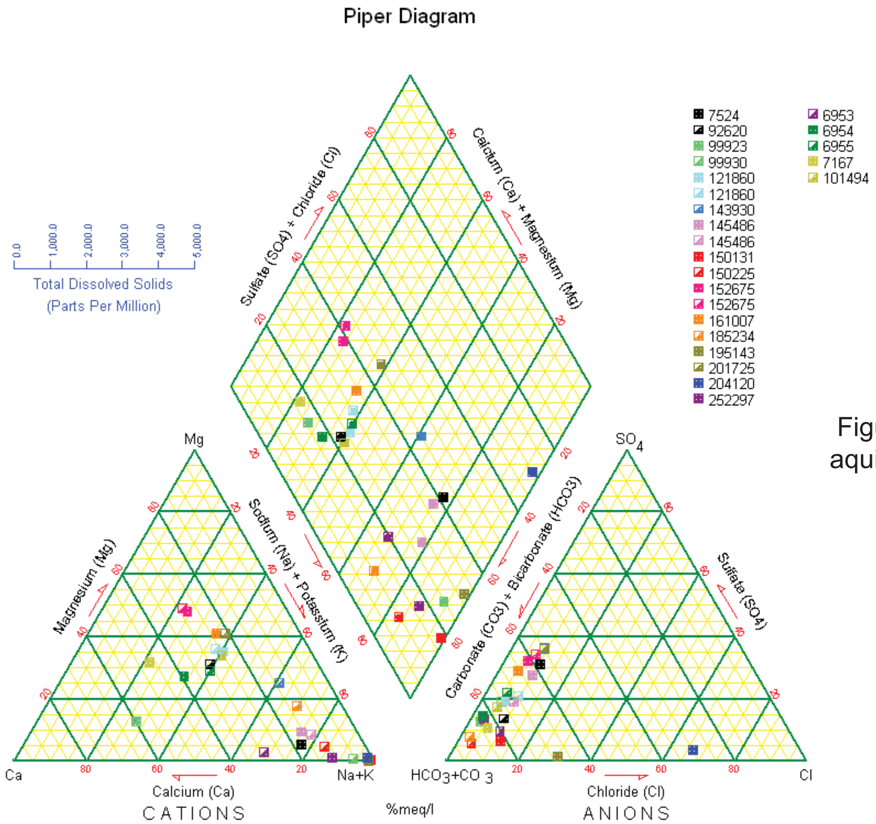


Figure 54. Piper diagram of Hell Creek aquifer water samples.

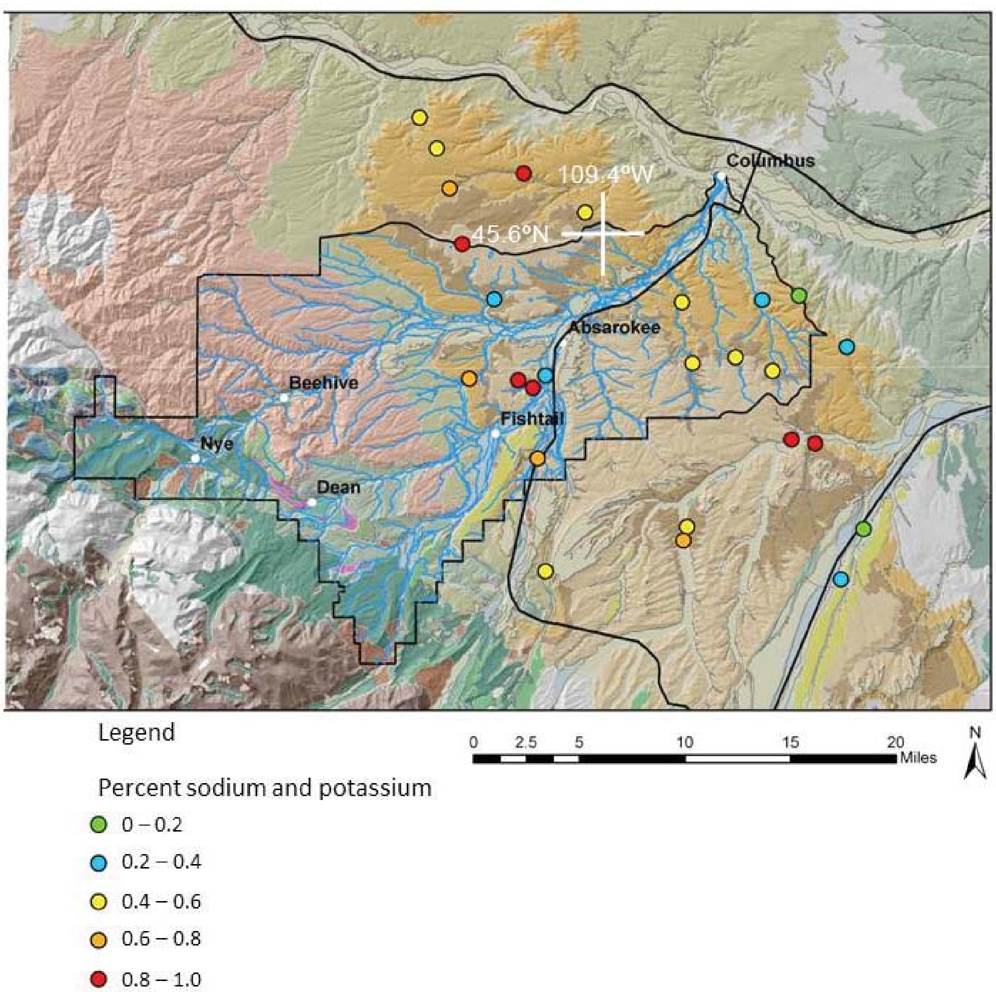


Figure 55. Percent sodium in the Tullock aquifer. Trends that would provide a clear picture of groundwater flowpaths are not apparent.

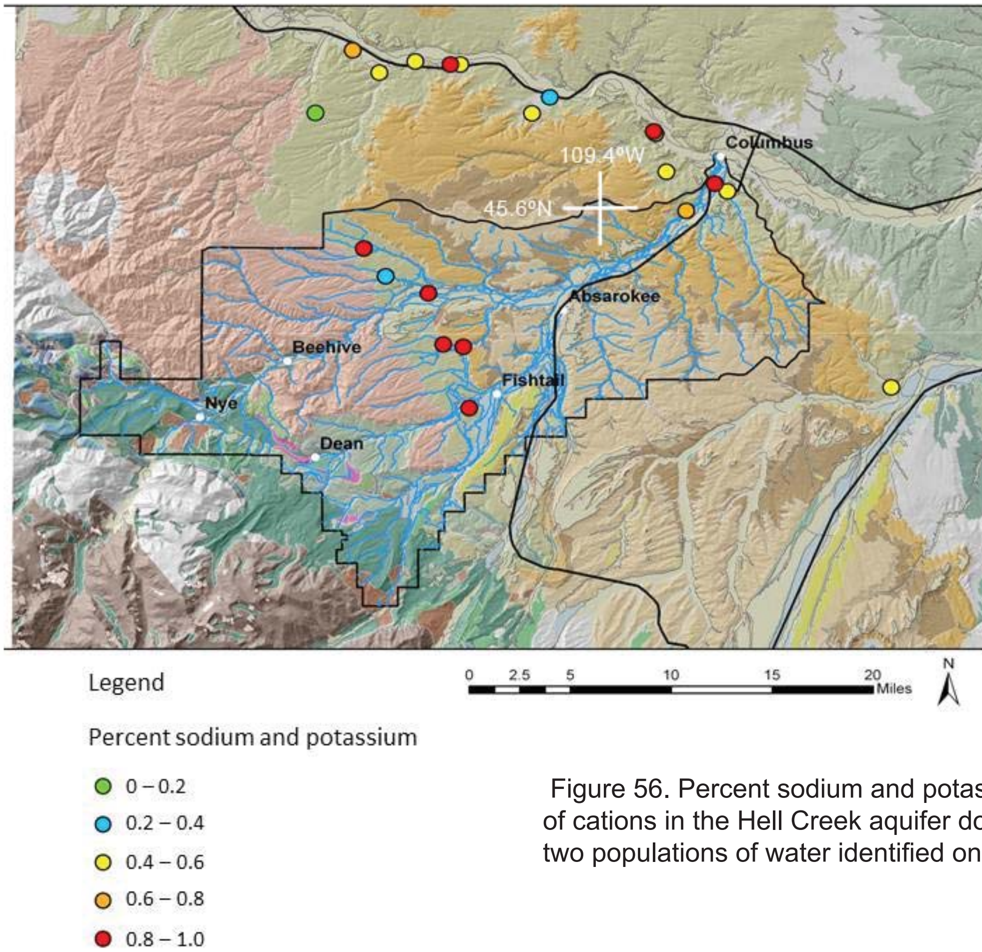


Figure 56. Percent sodium and potassium concentration of cations in the Hell Creek aquifer does not reflect the two populations of water identified on the Piper diagrams.

effect on its composition. Other factors that may affect the local composition of the groundwater are: land cultivation, irrigation, and the use of agricultural chemicals.

Nothing conclusive regarding flow paths could be ascertained from percent sodium data, so in order to define a possible flow path, available alternative data were analyzed. Total depth, bottom hole elevation, percent calcium and magnesium, well age, specific conductivity, and total dissolved solids were all examined for each well in those two aquifers. The examination of each of these variables did not produce consistent results that improved confidence in flow path interpretation. As mentioned previously, a general pattern was discovered demonstrating a succession of lower SC values in the southwest corner of the project area to higher SC values moving northeast. The water in the northeast, near Columbus and the Yellowstone River, is more saline than the water near Fishtail and Beehive. However, figures 55 and 56 show a scattering of high sodium and potassium points, so there is a combination of constituents causing this salinity increase. Throughout the study area, it appears that recharge occurs on upgradient and downgradient outcrops and that each aquifer has distinct lenses with varying salinity and chemical composition.

STEADY-STATE GROUNDWATER MODEL

Model Selection

Many different mathematical models have been created to depict and predict groundwater flow. These mathematical models can be solved analytically or numerically. Anderson and Woessner (2002) state that a numerical model should be used if assumptions used to derive an analytical solution are too simplistic or if the analytical problem involves complex superposition of solutions. The Stillwater River valley is filled with heterogeneous river deposits and is bounded by alternating bedrock units of shale and sandstone at various dip angles. Several streams and ditches snake through the valley bottom. The ditches supply irrigation water to agricultural lands and have subsequently created artificial recharge to the alluvial aquifer. The artificial recharge has complicated the natural groundwater flow patterns. A numerical model was needed to adequately represent this complex setting.

Several numerical methods are used in groundwater flow modeling, but finite-element and difference are the most commonly used to solve flow problems (Anderson and Woessner, 2002). For this study area, the finite-difference method using the modeling software MODFLOW (McDonald and Harbaugh, 1988) was chosen. The U.S. Geological Survey developed MODFLOW in the late 1980s to simulate the flow of groundwater through aquifers. Several graphical user interface software programs exist for MODFLOW. Groundwater Modeling System (GMS), created by Aquaveo, was chosen to create this model. The Layer-Property Flow (LPF) package was used with the conceptual model approach. The LPF package allows the user to simulate true geologic layers and allows different horizontal and vertical hydraulic properties to be assigned to each layer. The conceptual model allows the user to bring in a registered coordinate system on a base map from which one can create GIS-like features that can be imported into a MODFLOW program.

MODFLOW Input Requirements

The physical framework for the model includes the grid and model layers. The horizontal grid with dimensions in the x and y direction was oriented in the principal direction of groundwater flow. Three geologic layers and thicknesses were established to represent the aquifer being modeled. The user must also assign what type of aquifer is being modeled: confined or unconfined. The LPF package offers a convertible option, which allows the layer to be either confined or unconfined depending on the computed groundwater elevation. This model was set to represent an unconfined aquifer setting.

Starting head elevations must be assigned to all active cells in all layers. For this model, the starting head elevations were assigned by subtracting 5 ft from the digitized topographic surface of layer 1.

All cells in the model needed to have properties such as hydraulic conductivity and elevation assigned to them. The model uses the assigned hydraulic conductivity value to describe the flow of groundwater in the model and can then calculate transmissivity by multiplying the hydraulic conductivity by the saturated thickness of the modeled layer (equation 2).

It is very important to select the appropriate boundary conditions for the model based on the conceptual model. Head-dependent flow boundaries were used to simulate flow across boundaries calculated by the boundary head value as described by Anderson and Woessner (2002).

Conceptual Model

A conceptual model was developed to represent the actual observed conditions. Anderson and Woessner (2002) invoke three steps in building a conceptual model: defining the hydrostratigraphic units, preparing a water budget, and defining the flow system.

Hydrostratigraphy

The hydrostratigraphic units were defined using well logs, geologic maps, and cross sections. Layer 1 represents the topsoil layer that varies in thickness up to a maximum of several feet. Where the topsoil is thin and/or coarse-grained, recharge is rapid. In other areas where topsoil is relatively thick, this material acts as a semi-confining layer and vertical recharge in these areas may be limited. To account for these differences, the hydraulic conductivity in layer 1 was set to 5 ft/day, a relatively low value. This value was assigned using published tables for ranges in hydraulic conductivity for silty sand (Fetter, 2001).

Layer 2 represents the alluvial gravels of the water-table aquifer. The thickness of the alluvium as recorded by well logs ranges from 13 to 58 ft. The average saturated thickness at baseflow was 21 ft and average saturated thickness during the irrigation season was approximately 25 ft. Based on a 24-hour aquifer test, an estimated hydraulic conductivity range of 90 to 120 ft/day was calculated from the Cooper–Jacob and Neuman methods.

Layer 3 represents a gray shale (Tertiary or Cretaceous bedrock) acting as a confining unit. Well logs report a gray shale layer ranging in thickness from about 16 to 19 ft thick. The confining shale layer was assigned to have a very low hydraulic conductivity value of 0.05

ft/day based on published tables (Weight, 2008).

Water Budget

A water budget based on data collected in March 2009 was prepared for the steady-state model. During the month of March, essentially no precipitation or irrigation water recharges the aquifer, and excess stored irrigation recharge has already discharged to the river. However, field measurements indicate that bedrock aquifer contributions recharge the alluvial aquifer before discharging to the river. To account for contribution from the bedrock aquifer, synoptic flow measurements along the Stillwater River were collected in March 2009 from Cox Bridge to Johnson Bridge. The river flow data indicated a 10 cfs gain in the river by the time it reached Johnson Bridge. The observed water-budget values were used to compare with the model-computed values during the model calibration phase.

Flow System

The flow system was then defined using measured water levels, field water quality, and isotope data. A potentiometric map was hand drawn using water-level data collected March 4, 2009 at baseflow conditions. The interpretation shows an eastward direction of groundwater flow in the study area (fig. 14). Field water-quality and isotope data were used to determine that the bedrock aquifer is hydraulically connected to the alluvial aquifer.

Stillwater River Alluvial Numeric Model Design

Grid and Layers

The study area consists of a long narrow rectangular grid with uniform grid spacing and three layers. The grid was set to have 71 rows and 361 columns representing an area of 6.5 square miles. The cell sizes were 100 ft by 100 ft for the entire modeled area. The active grid area was refined using the alluvium and bedrock contact along the valley sides as the model boundary. This contact was identified using a Geographic Information System shapefile of the geologic map of Big Timber 30' by 60' quadrangle (Lopez, 2000).

The model consists of three layers: topsoil (layer 1), unconfined alluvial gravel (layer 2), and a confining shale bedrock (layer 3). The topsoil and alluvial layer thicknesses were assigned using geologic well logs within the area. The well-log information was entered to define the borehole stratigraphy. “Dummy wells” were interpolated from the well logs and added to the model to fill in where there were data gaps. Figure 57 shows the borehole and dummy well locations. Layer 3, a confining layer, was set to have a constant thickness of 20 ft of shale below layer 2.

Aquifer tests and published tables (Weight, 2008) provided hydraulic conductivity values for the alluvial and bedrock aquifers. These values were used as initial model input values for the bedrock and alluvial aquifer where applicable. An initial hydraulic conductivity value of 5.0 ft/day was assigned to layer 1, 370 ft/day to layer 2, and 0.05 ft/day for layer 3.

A topographic surface was digitized in GMS from the 1:24,000 foot scale Absarokee and Sandborn Creek topographic maps. A scatter point set of elevation points was used to define the top of layer 1. All other layer thicknesses were defined using well logs. Topographic elevations were used as a reference to guide the vertical locations of borehole tops and bottoms. Solid depictions of each layer were created in GMS from interpolations of borehole stratigraphy and show the different topographic features within the valley (fig. 58).

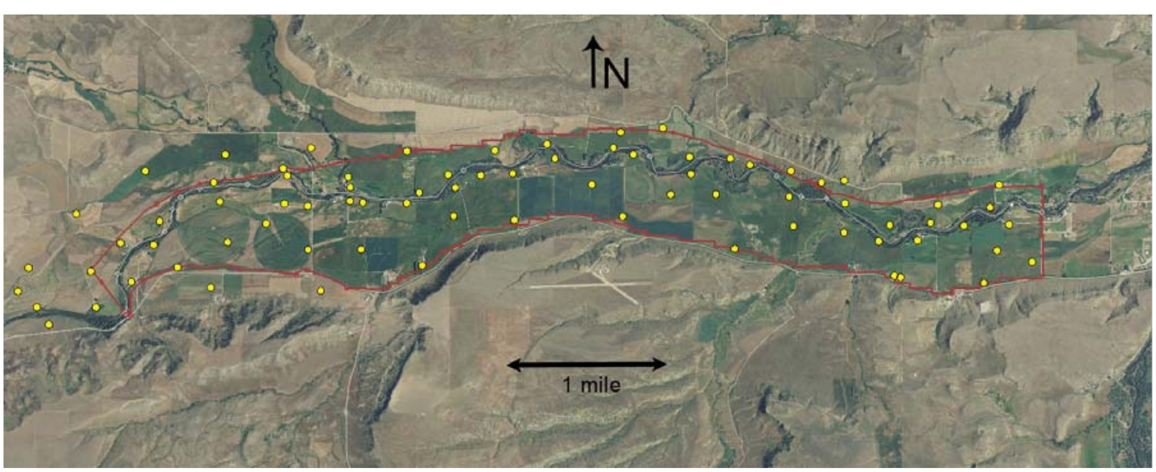


Figure 57. Yellow dots represent the locations for borehole and dummy well. Map scale and orientation in all subsequent models are the same as in this figure.

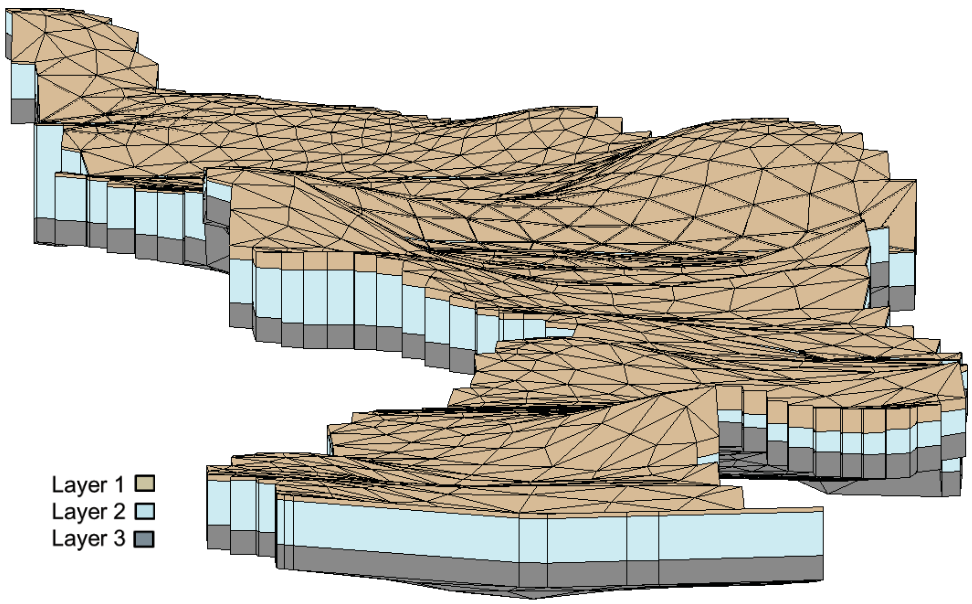


Figure 58. An oblique view looking up-river displaying the model solids with a digitized topographic surface.

Boundary Conditions

Finite-difference equations require the definition of boundary conditions, starting heads, and aquifer stresses (such as pumping or precipitation recharge) to converge on a solution. If the various parameters are well posed, the MODFLOW program will use a solver package to generate a head distribution.

Head-Dependent Flow Boundaries

Head-dependent flow boundaries are used to provide water into or out of a model at the boundary. Flow rates are calculated based on head differences between the boundary cells and adjacent aquifer cells. General head and river boundaries are also calculated in this way.

The entire model perimeter was modeled using general head boundary (GHB) cells because flux is occurring from all sides. The GHB on the north and south sides use head elevation and conductance values to specify the amount of bedrock groundwater that recharges the alluvial aquifer. The GHB on the west end of the model allows groundwater to enter the model and the GHB on the east end of the model allows water to exit the model as Neuman flux boundaries.

The north and south boundaries coincide with the Cretaceous and Tertiary sedimentary rocks and alluvial contact (fig. 2). These boundaries were assigned an initial conductance value of 7 ft/day based on aquifer test results. The head elevations were assigned to be higher than the river to establish gradients toward the river. On the west and east sides of the model, the boundary was initially assigned a conductance of 100 ft/day. This rate was chosen to represent the conductance established by the aquifer tests. In this model, the ground surface, water table, and river all have the same gradient; therefore, initial starting heads were assigned by subtracting 5 ft from the digitized ground surface.

River Package and Recharge

The river cells simulate the interaction of flow between the river water body and the aquifer. The river allows recharge to the aquifer if the stage elevation is higher than the groundwater elevation or allows aquifer water to discharge to the river if the stage is lower than the alluvial aquifer. Several synoptic flow measurements indicate the river gains water throughout the model area, so the river elevations were set to be lower than the alluvial aquifer, allowing the aquifer to discharge water to the river.

The river stage elevation, river bed elevation, and streambed conductance must be defined. The streambed conductance value is hard to determine in the field because it accounts for the length and width of the river channel, the thickness of the river bed sediments, and the vertical hydraulic conductivity (Anderson and Woessner, 2002). GMS defines streambed conductance as conductance per unit length in equation 9:

$$C_{riv} = KrW/M, \qquad (9)$$

where C_{riv} is stream bed conductance (length^2/day/ft), Kr is vertical hydraulic conductivity of streambed sediments (length), W is width of river channel (length), and M is thickness of riverbed sediments (length; Anderson and Woessner, 2002).

Initially, a conductance value of 100 ft/day was used for the river segment based on a stream cell width of 100 ft, a stream bed sediment thickness of 10 ft, and vertical hydraulic conductivity of 10 ft/day. The initial stage elevation was assigned from topographic maps and 10 ft was subtracted from the stage elevation to define the river bottom elevation, where the river bottom includes the depth of the river plus the riverbed sediments.

Sources of water that recharge the alluvial aquifer include precipitation, bedrock aquifer discharge, and irrigation infiltration. For the initial model, a precipitation recharge rate of 0.01 in/day (0.001 ft/day) was assigned for the entire area. This small rate was chosen to represent March conditions when surface recharge is minimal.

Model Revisions

Examination of the geologic map in figure 2 shows that the upgradient or western boundary of the alluvium pinches into a narrow valley (approximately the width of the Stillwater River) surrounded by steep bedrock units. This extremely narrow boundary created head convergence issues in the model. Many adjustments were made in an attempt to fix the problem with no success. The model boundary was then moved down-valley to allow the upgradient boundary to incorporate a wider section of the valley.

Convergence problems persisted on the northwest boundary of the model. This area was field checked, and it was determined that a geologically older alluvial bench unit (Qat1) was present that was hydraulically disconnected from the modeled alluvial aquifer. Observations in the field indicate that springs were surfacing along the bottom margin of the alluvial bench, and this indicated an impermeable layer existed. This older alluvial bench was therefore excluded from the model and the problem was alleviated.

A “dry cell” problem existed on the southwest side of the model where the model predicted the aquifer would be dry. The geologic map in figure 2 shows the surficial geology is an alluvial fan deposit (Qaf) and a well log located in the vicinity indicated only 5 ft of gravel. It is possible the thinning of this aquifer proved problematic for the model because the area was not hydrologically connected to the alluvial aquifer. The model boundary was adjusted to exclude this area.

Calibration Process

According to Anderson and Woessner (2002), calibration targets need to be evaluated qualitatively and quantitatively, and to date, there are no standard protocols for evaluating a calibration process. The calibration process is deemed complete when the set of entered parameters simulates the boundary conditions and measured heads, and flux rates are within a reasonable range of error. Calibration of this steady-state model demonstrates the capability of reproducing field measured heads and flows collected during March 2009. Some model parameters were calibrated by a trial and error process while others were calibrated by using an automated parameter estimation technique (PEST) (Doherty and others, 1994). PEST seeks a set of model parameters that minimizes the difference between the observed and simulated heads and flows (via a series of calculated error terms). PEST is constrained within user-defined ranges, ideally connected with field data. It is similar to a Monte Carlo simulation exercise where errors are minimized.

The calibration standards set for this model were to produce a modeled potentiometric pattern similar to the hand-contoured version, have the simulated head elevations similar to the measured head elevations, and have the modeled water balance be approximately what was field measured while maintaining appropriate field-based model parameters.

The GHB consists of 40 nodes placed around the perimeter of the study area. Each node was assigned an elevation and conductance value. The first calibration attempt used the initial conductance values from the bedrock and alluvial aquifer tests. The general head conductance values were then refined using PEST. Water levels from domestic wells and flow data collected in March 2009 were used as the field observation data required for PEST. PEST determined that the conductance for the north and south sides (representing the bedrock aquifer) of the model had an average value of 3 ft/day while the west and east sides (representing the alluvial aquifer) had an average value of 50 ft/day. The values that PEST computed are similar to the actual aquifer test data.

The river was divided into 15 arc lengths, each having individual elevations and conductance values. Once the general head boundaries were calibrated, PEST was used to calibrate the river conductance. A gain in the river of 10 cfs and observation-well data measured in March 2009 were used as the calibration targets for PEST. The river calibrated exceptionally well, with a MODFLOW output value for river gain of about 10 cfs. PEST determined that the river conductance values ranged between 11 and 59 ft/day.

Finally, the hydraulic conductivity for the alluvial aquifer was calibrated using PEST. The initial model had a single horizontal hydraulic conductivity value of 370 ft/day assigned to layer 2. In a fluvial depositional setting, one value is unrealistic because it does not accurately reflect the presence of sand and gravel bars and overbank deposits. The vertical hydraulic conductivity value was set to 10 ft/day.

A 2D scatter point set of pilot points was created for PEST calibration (fig. 59). The points were assigned a range of starting hydraulic conductivity values to mimic a fluvial system. High values were assigned near the river at 100 ft/day and lower values assigned near the model boundary edges at 10 ft/day. PEST ran iterations until a satisfactory data set was achieved based on measured water-level observation heads and measured river gains at Johnson Bridge. PEST determined a range of hydraulic conductivity values between 0.05 and 168 ft/day. These values are reasonable based upon the aquifer test. Figure 60 shows the distribution of hydraulic conductivity using PEST. An unnatural bullseye pattern appears due to the nature of calibrating around individual points. However, the general pattern of the contour map shows a higher hydraulic conductivity exists near the river decreasing towards the valley sides.

Calibration Results

As discussed in the previous section, the first target was to produce contours from modeled heads to have a pattern similar to the contours from the observation heads. Figure 61 shows the simulated potentiometric lines in the Stillwater River Valley alluvial aquifer (fig. 61B). The upper map (fig. 61A) shows the hand-contoured water table lines (fig. 14). When comparing the two figures, the contour lines produce a similar groundwater flow pattern and head elevation.

The second target was to have the simulated head elevations be similar to the measured head elevations. An observation coverage using water levels in wells was used to determine how accurately the computed head elevations matched. Water levels were collected from 19 wells in the study area in March 2009. These water levels were used as the observation points. The points

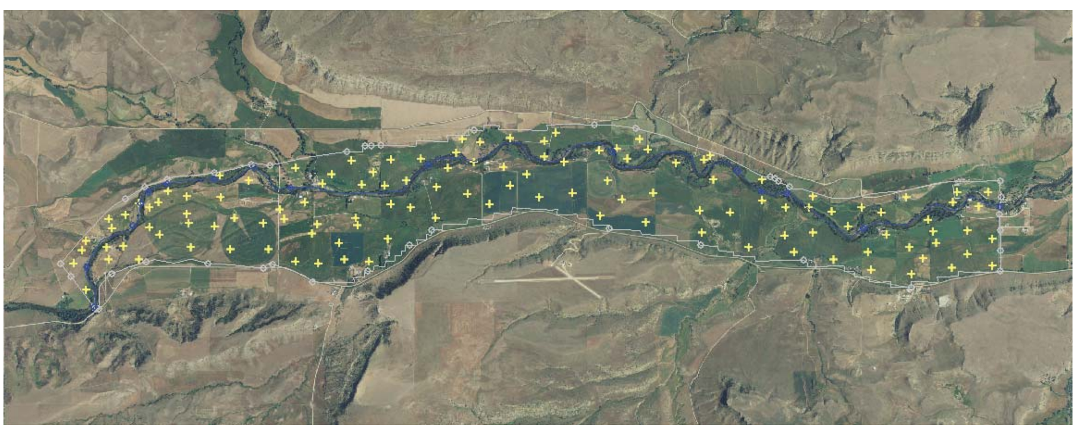


Figure 59. Map of the pilot point locations (yellow cross) used by PEST to calibrate the hydraulic conductivity.

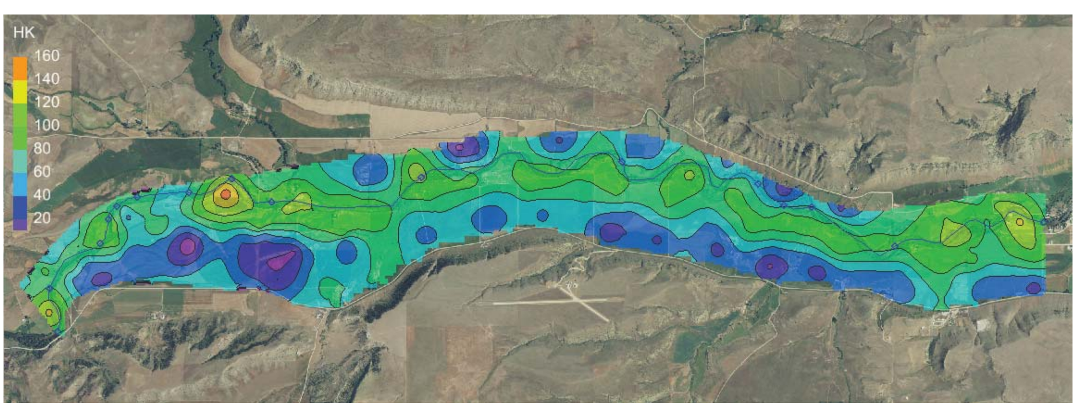


Figure 60. The Kriging method was used to interpolate the hydraulic conductivity values calibrated using PEST.

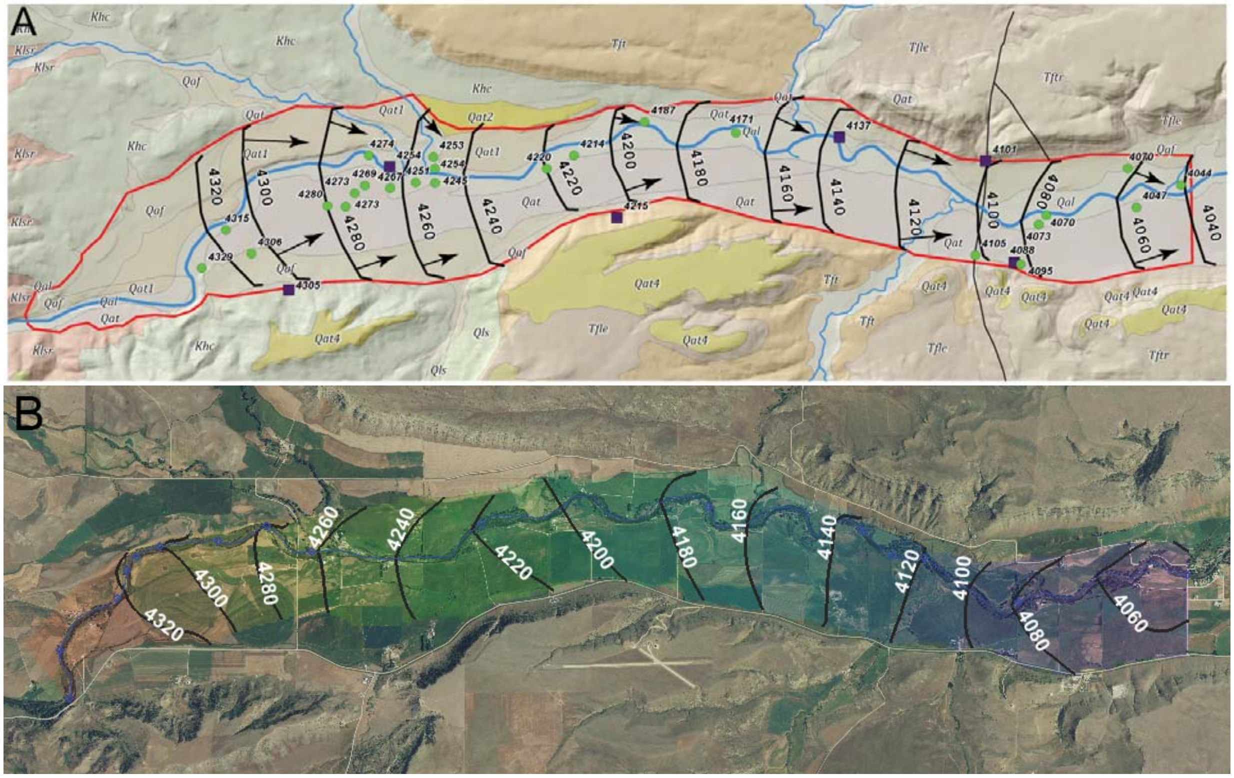


Figure 61. Modeled potentiometric pattern of the alluvial aquifer. The top map (A) is the hand-contoured water table map. March 2009 water levels were used to create and calibrate the maps.

are displayed as green, yellow, and red calibration targets in GMS. Green targets mean the simulated head target lies within 100 percent of the observed value. Red targets mean the simulated head errors were over 200 percent of the observed values. According to the observation targets, a little over 50 percent of the computed heads are within 5.5 ft and 95 percent are within 10 ft of the actual measured water levels (fig. 62). When assessing these errors, it should be restated that the well elevations were assigned with a topographic map that has an uncertainty of 10 ft. The computed and observed head values were compared with a linear plot to show how well they correlate (fig. 63).

The third target was to have the modeled water balance approximate the field measured values. The amount of water gained or lost in the Stillwater River was calculated with the model and compared to measured flows taken along the Stillwater River. In March 2009, a synoptic flow set was collected through the study area. It was determined that the river within the model area was a gaining reach with an increase in flow of about 10 cfs. However, 10 cfs is probably mostly from bedrock contribution, as some alluvial groundwater was still discharging to the river. According to the flow budget in table 8, 11.8 cfs was the total water out of the aquifer into the river. The GHB along the sides of the valley contributed nearly all the baseflow to the river.

Sensitivity Analysis

A sensitivity analysis quantifies the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions. To perform a sensitivity analysis, the hydraulic conductivity, storage parameters (if using a transient model), recharge, and boundary conditions are systematically changed. The magnitude of change in heads from the calibrated solution is a measure of the sensitivity of the solution to that particular parameter (Anderson and Woessner, 2002).

For this model, a sensitivity analysis was generated during PEST calibration and by manually adjusting the parameters. PEST generates a composite parameter sensitivity record that compares, in this case, the head values to the river and the head values to general head boundaries. The composite sensitivities help find

Figure 62. Observation point calibration for simulated head water levels.

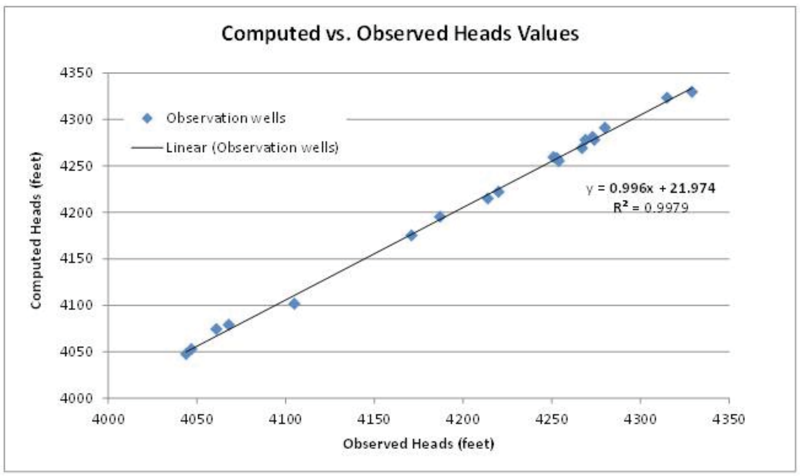


Figure 63. Computed versus observed head values correlate very well for the steady-state model.

the parameters that produce performance problems with the PEST process. The composite record produces relative sensitivity values for PEST parameters. The relative sensitivity is obtained by multiplying the composite sensitivity by the magnitude of the value of the parameter (PEST User Manual, 5th ed.). The PEST sensitivity record helps flag areas that may need to be conceptually investigated. The PEST flagged the northwest corner of the model, prompting a field visit to the area.

The relative sensitivity was plotted for the river and the GHB segments. According to the PEST sensitivity record, the river segment riv_403 appears to be the most sensitive to parameter changes (fig. 64). Also, the GHB segments located near the northwest corner of the model were the most sensitive (fig. 65). This area was field-visited and was determined to be hydrologically disconnected from the alluvial aquifer. The alluvial aquifer may also be thinning to the northwest as the bedrock appears to be near-surface. The thinning of the alluvium caused dry cell problems in the model. Thus the model may assist in identifying areas where more field information is required.

The GHB conductance was manually adjusted by systematically changing PEST values. The results of the change in head difference between the calibrated head and heads produced by changing the conductivity values were compared to the measured annual range of water levels. The general head conductivities were decreased by 50 percent and then increased by 200 percent. The percent change in head was monitored in three wells located in the center and on the west and east ends of the model (fig. 66). All three wells were sensitive to GHB conductance changes; the degree of sensitivity depended upon location. Adjusting the conductivities

Table 8. Flow budget for March 2009 calibration.

	Flow (ft^3/day)	Flow (cfs)
IN		
River leakage	17,909	0.21
General head boundary	873,509	10.11
Recharge	128,250	1.48
Total in	1,019,668	11.80
OUT		
River leakage	973,853	11.27
General head boundary	45,809	0.53
Recharge		
Total out	1,019,663	11.80
Percent discrepancy	0.0	

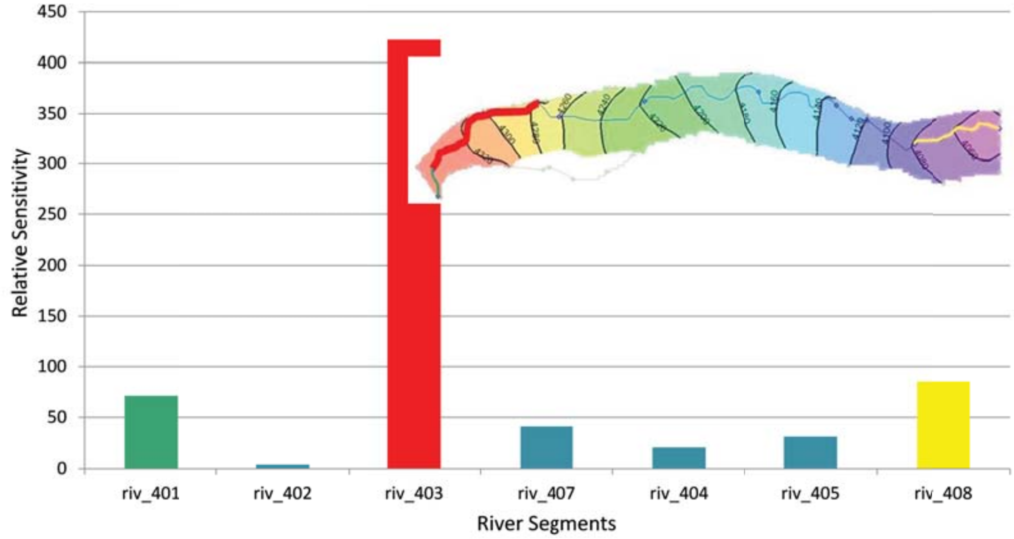


Figure 64. PEST output of relative sensitivity for each river segment; the problems (red) mostly occurred in the northwest corner of the model. Inset map shows the location of the problematic river segment.

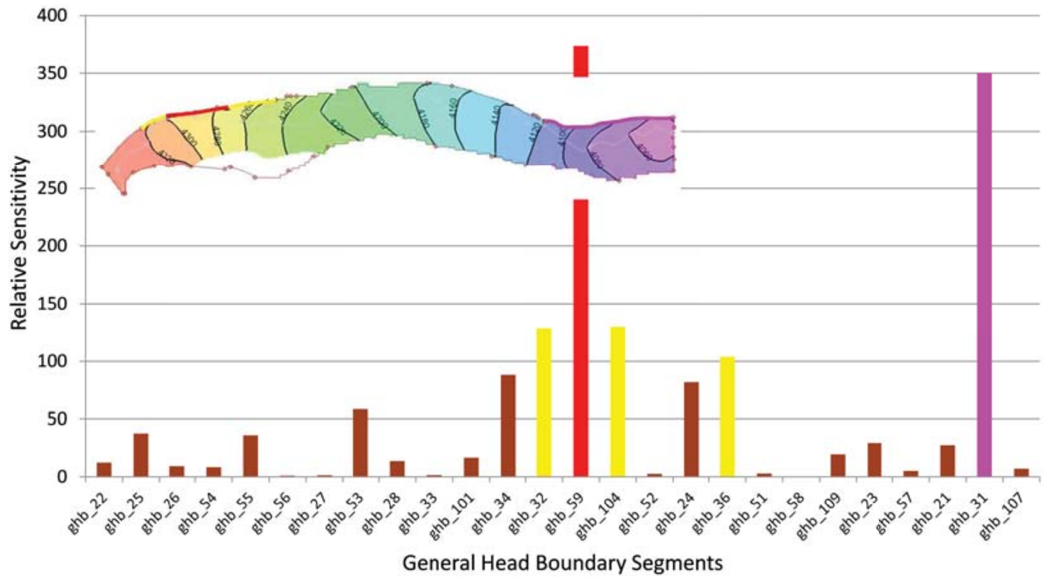


Figure 65. PEST output for the general head boundaries shows problem areas in the model (red and pink). Inset map shows the locations of the boundary problem areas.

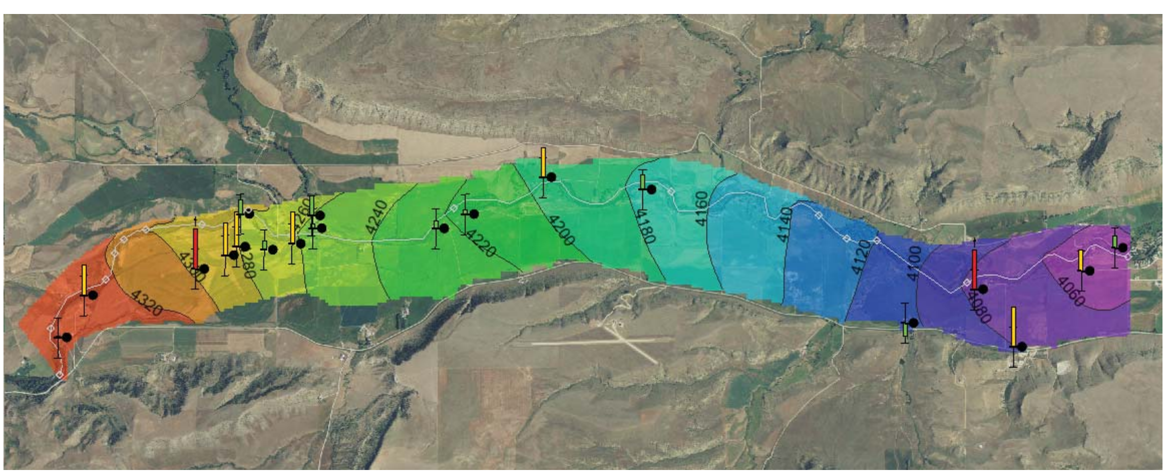


Figure 66. Location map for the three wells used for the sensitivity analysis.

caused well 156919 to have the greatest percent head change (16 to 18 percent), while well 161141 had a head change of 4 to 18 percent and 99929 had the least head change of 4 to 5 percent. Changing the conductance value increased or decreased the flow out of the river by about 18 percent.

The river conductance was manually adjusted by decreasing the conductance by 50 percent and then increasing by 200 percent. The results of the change in head difference between the calibrated head and heads produced by changing the conductivity values were compared to the measured annual range of water levels. The change in head elevation was monitored in the same three wells (fig. 66). Decreasing and increasing the conductance of the river changed the head elevations by 4 to 100 percent, indicating this parameter was very sensitive. In most cases the percent change was highest when the conductivity was decreased. The three wells used for the sensitivity check are located near the river cells, and this probably contributes to the extreme sensitivity. Decreasing and then increasing the conductivity increased the flow out of the river by 8 percent and 5 percent, respectively.

The original recharge rate of 0.01 in/day (0.001 ft/day) was increased to 0.10 in/day (0.01 ft/day) to compare the percent change in head elevation. The results of the change in head difference between the calibrated head and heads produced by changing the recharge value was compared to the measured annual range of water levels. The change was monitored in the same three wells (fig. 66). Increasing the recharge rate changed the head elevation in well 156919 by 84 percent, whereas the other wells changed by 5 percent (161141) and 11 percent (99929). The new rate created a 400 percent increase in recharge into the modeled alluvial aquifer (very sensitive).

TRANSIENT MODEL

Transient simulations are needed to analyze time-dependent problems. They are more complicated and require additional hydrologic information. According to Anderson and Woessner (2002), transient models must have storage parameters specified and initial conditions for head and boundaries, and time and space dimensions must be discrete.

Storage Parameters

In a transient model the amount of water allowed to be absorbed or drained from the aquifer depends on the storativities of the aquifer materials. The heads will change with time from the transfer of water and when the transfer stops, the system reaches equilibrium (Anderson and Woessner, 2002).

An aquifer test and a calculation of the volume of water drained were used to estimate the storage parameter for the unconfined aquifer in layer 2. These methods produced an estimate of specific yield of 0.16 and 0.15 respectively, which are typical values reported for sand and gravel (Weight, 2008). Therefore, a specific yield value of 0.16 was assigned to layer 2 within the model. The specific yield assigned to layer 1 was 0.01 and layer 2 was 0.001.

Initial Model Conditions

The initial conditions refer to the head distribution everywhere in the system at the beginning of the simulation and are considered boundary conditions with time (Anderson and Woessner, 2002). For this transient simulation the final calibrated head values from the steady-state model were imported as the starting heads. These head values represent a dynamic steady-state model condition. The term "dynamic" is used because the heads change monthly and incorporate stresses on the aquifer (Anderson and Woessner, 2002).

Discrete Time and Transient Conditions

Stress periods are used in transient models to allow stress conditions to change with time. They can be used to reset all boundary conditions and sources and sinks at any time during a model run. This model had 24 stress periods representing month-long periods over 2 years beginning in January 1, 2008 and ending on December 31, 2009.

Field data were collected periodically from groundwater wells from September 2008 to January 2011 to provide a framework for model calibration. Surface-water flows on the Stillwater River were collected 5 times from September 2008 to August 2009 (fig. 67). The differences in flow measurements between Cox and Johnson Bridge were used to determine flow gains at Johnson Bridge. Missing values

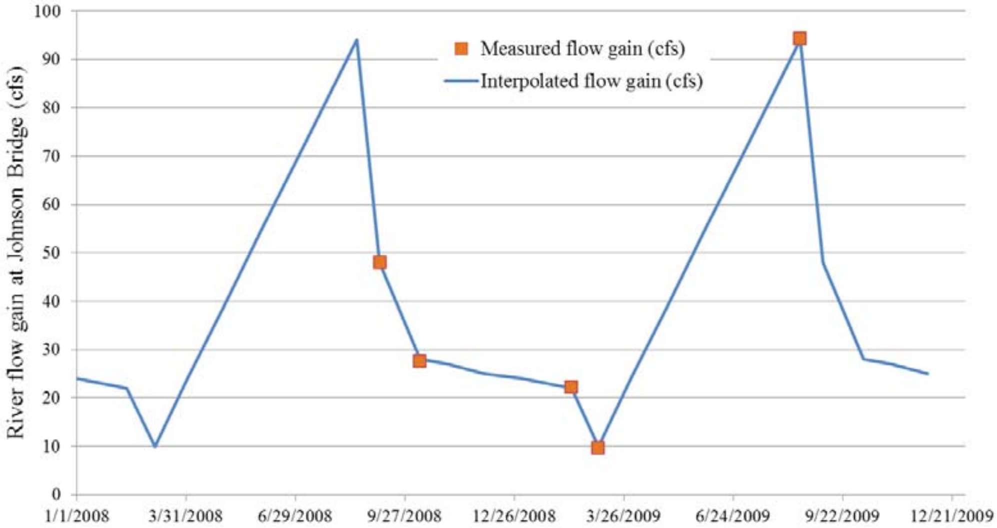


Figure 67. Measured and interpolated flow gains in cfs in the Stillwater River at Johnson Bridge from Jan 1, 2008 and Dec 31, 2009.

were interpolated to fulfill the 24 stress periods by extrapolating monthly river gain from a curve fit to the field data (fig. 67). It was assumed that the flow gain was identical for the two years.

Irrigation is an important recharge source to the Stillwater River alluvial aquifer. Flood irrigation and unlined ditch seepage have created an artificially elevated water table. Within a model it is difficult to simulate variable application periods and rates, and the large variation in ditch leakage, soil type, infiltration rate, and evaporation (Uthman and Beck, 1998). Simulation of the four different types of recharge sources (precipitation, ditch leakage, flood irrigation, and center pivot) were established through irrigation polygons. Factors were assumed constant for each irrigation polygon during the transient simulation model. Irrigation and non-irrigation polygons were created by tracing land features from the 1:24,000 ft scale topographic map in GMS. The amount of recharge from precipitation applied to the modeled aquifer was set to 5 percent of the actual measured monthly precipitation observed at the Fishtail RAWS Montana precipitation station for all of 2008 and 2009. The ditch leakage, flood, and center pivot recharge were only applied during the months of June, July, August, and September for both 2008 and 2009.

The chloride mass balance results determined that just over 50 percent of irrigation was lost to ET. Infiltration rates in polygons from flood irrigation were assumed to be 50 percent of the applied water. In August 2009, flows totaling 75 cfs were measured in the main supply ditches within the model area. Recharge rates of 9 in/month were assigned to flood irrigation polygons in the model. Ditch losses were measured on 2 ditches in the model area and they indicated leakage rates of 5 to 7 in/month. The rate of 5 in/month was applied to polygons representing the ditches. There are three center pivots located in the model area, and the pivots have intake systems supplied from nearby ditches. The pivot polygons were allowed to recharge the model aquifer at a rate of 0.25 in/month. Figure 68A shows the recharge rates assigned to each polygon

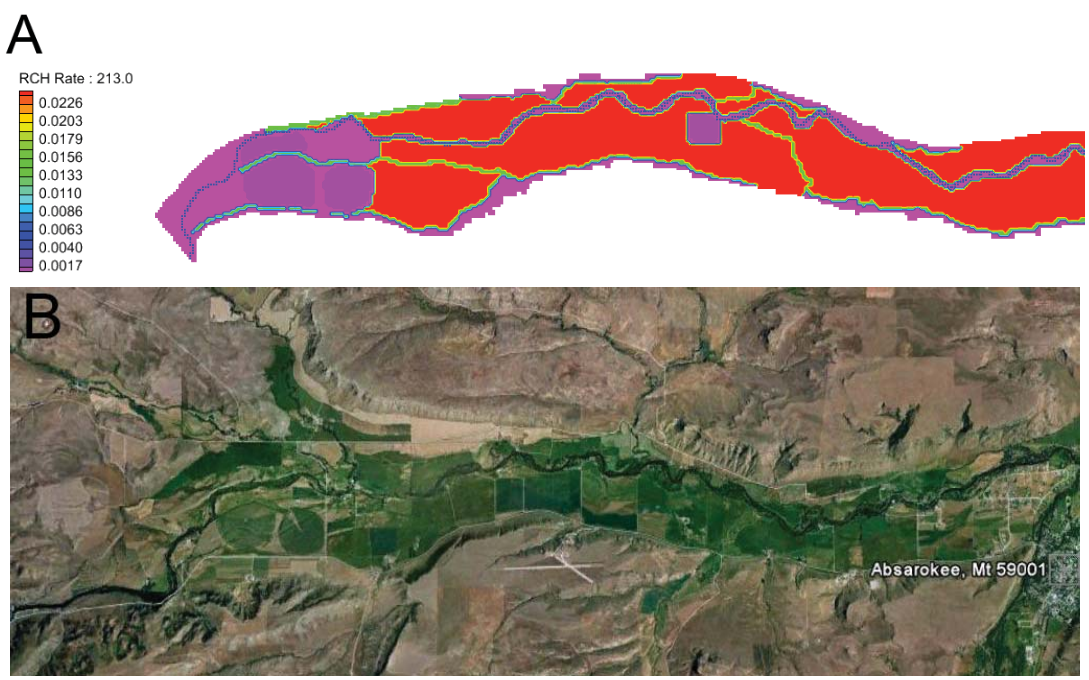


Figure 68. (A) Recharge polygons assigned to the model. (B) Google Earth image shows irrigated vegetation within the model area.

in the model. The red polygons indicate recharge from flood irrigation, purple from center pivots, pink from precipitation only, and green/yellow from the irrigation ditches. The photograph shows the irrigated vegetation within the model area (fig. 68B).

Calibration

The transient model was calibrated by matching modeled hydrographs to field-measured well hydrographs using a trial and error method. The storage and recharge values were manually adjusted to fit model hydrographs to observed hydrographs both in magnitude of head change and timing. The storativity was adjusted by decreasing and increasing the specific yield value assigned to the entire model. The specific yield value estimated from the aquifer test (0.16) was found to be the most appropriate storativity to represent the magnitude and timing of the heads.

Recharge was also assigned by decreasing and increasing the amount of application from flood irrigation and ditch leakage. Using 50 percent of the measured ditch flow in August 2009 combined with measured ditch loss fit the transient model well.

Calibration Results

Calibration targets for the transient model were achieved by comparing measured and computed time series heads and river gain values. Water levels from selected wells and gains in the Stillwater River at Johnson Bridge were compared to computed heads and river flow values in August 2009.

The observation targets allow the modeler to see the head change during different time steps of the model. According to the observation targets in August 2009, 75 percent of the computed heads (green and yellow targets) fall within 10 ft of the actual measured water levels (fig. 69). A hand-contoured map was also examined for August 2009, and the potentiometric lines became steeper near the well head but not enough to significantly change the 20-ft contour intervals. Very little data exist near the perimeter of the model, so hand contours do not show the mounding of groundwater from irrigation practices as are shown by the model. The computed and observed head values were also compared with a linear plot and the R^2 value was 0.99, indicating a very strong correlation (fig. 70).

Computed versus observed heads can also be checked by plotting hydrographs of water-level elevations. Figure 71 shows three hydrographs of wells located on the west, middle and east end of the model. These particular wells were chosen to represent the entire model because of their relative location and abundance of measured water level data.

A specific yield of 0.16 was used for the alluvial aquifer in producing the computed heads. Well 99929 had the largest magnitude of measured change in water level with a difference of 4.2 ft, while the other observation points had less than 2 ft of difference (fig. 72 A, B, C). For all three wells, the elevations of the water levels from the observed and computed heads were usually only a couple of feet different and only for part of the season. The timing of the water-level changes between the observed and computed matched well for each season.

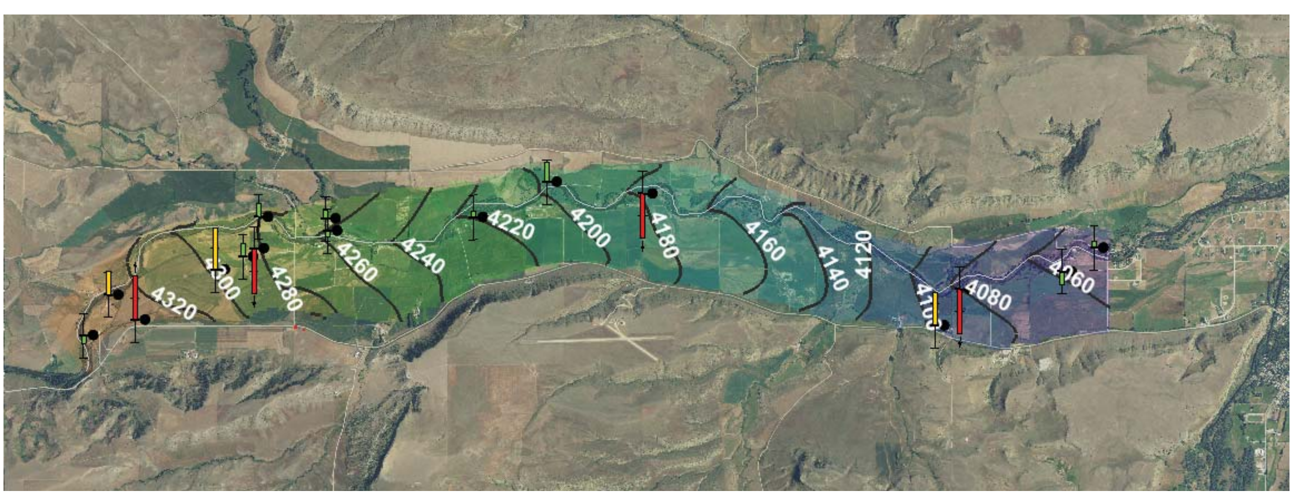


Figure 69. Observation wells used for the calibrated transient model. The observation coverage and potentiometric surface represents August 2009 levels.

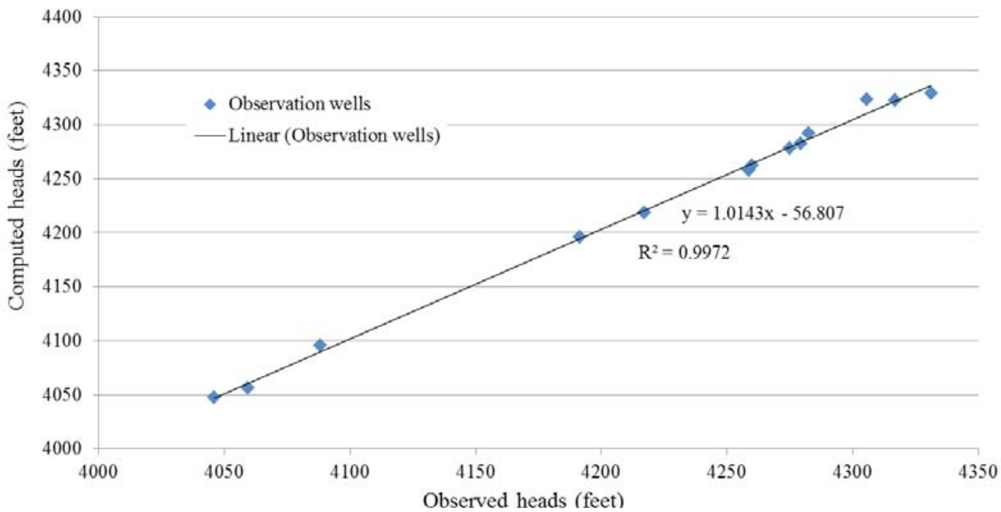


Figure 70. Computed versus observed head values for the transient model.

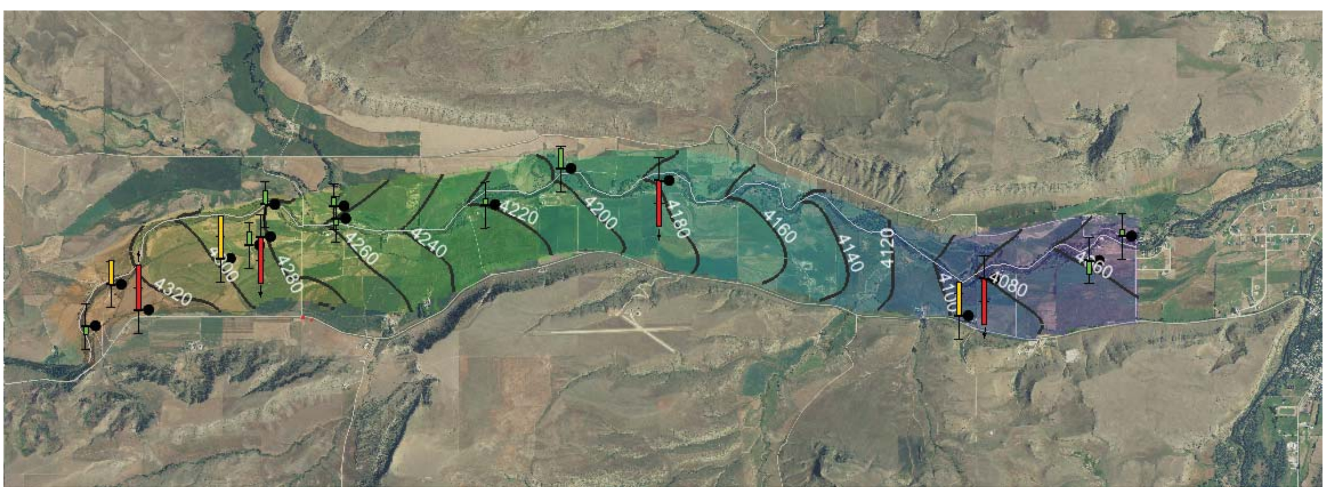
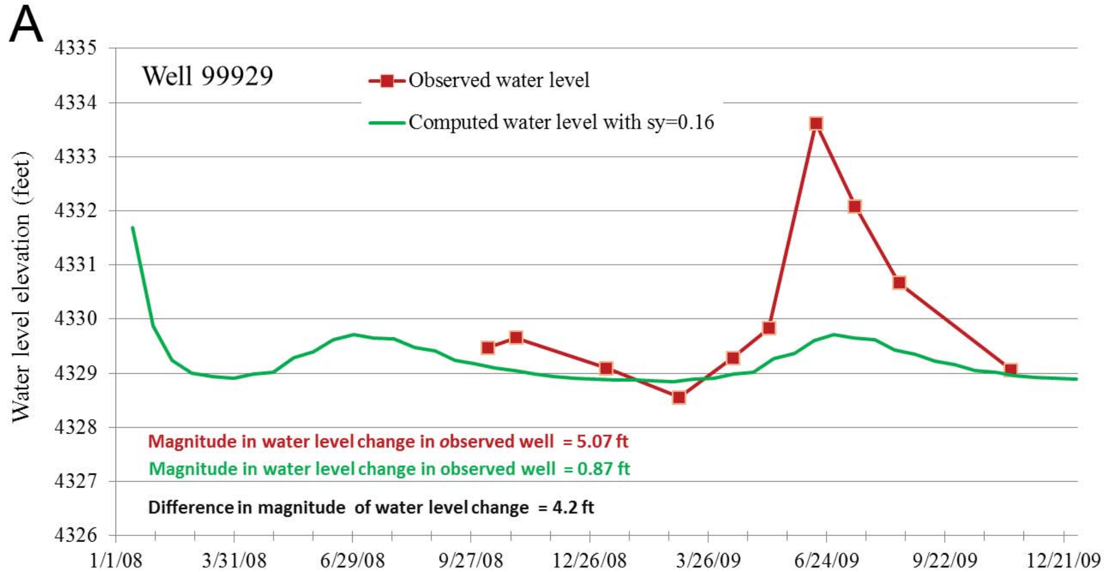
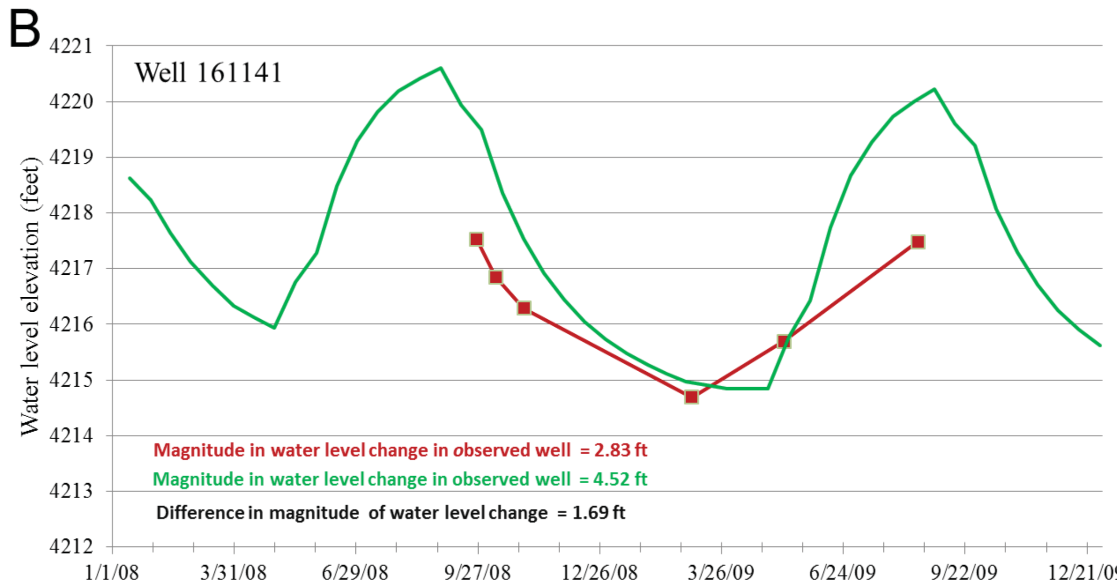


Figure 71. Location map of well hydrographs used for calibration and sensitivity analysis.





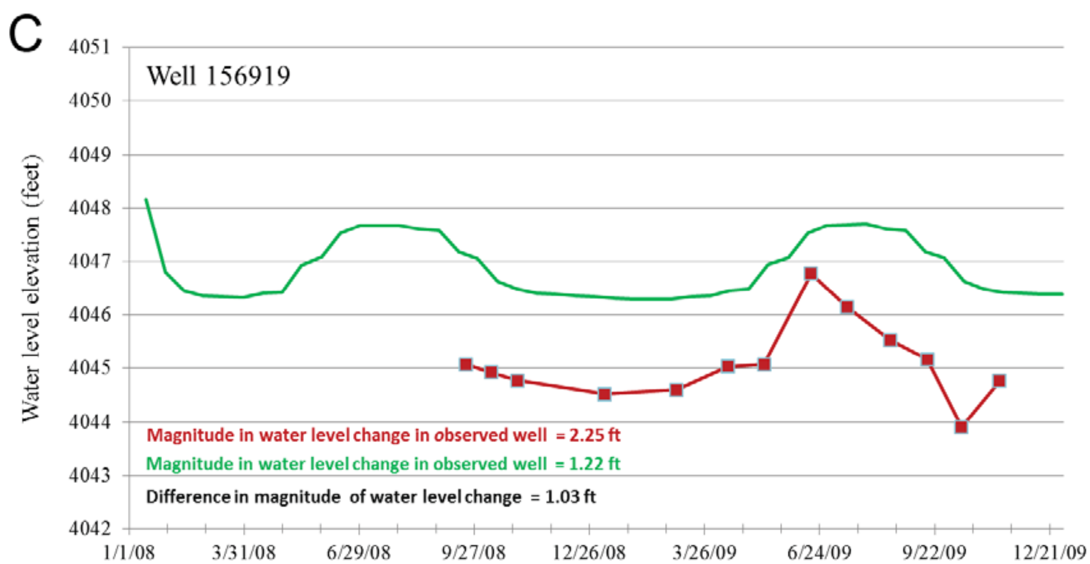


Figure 72. A, B, C . Hydrographs of observed and computed water levels.

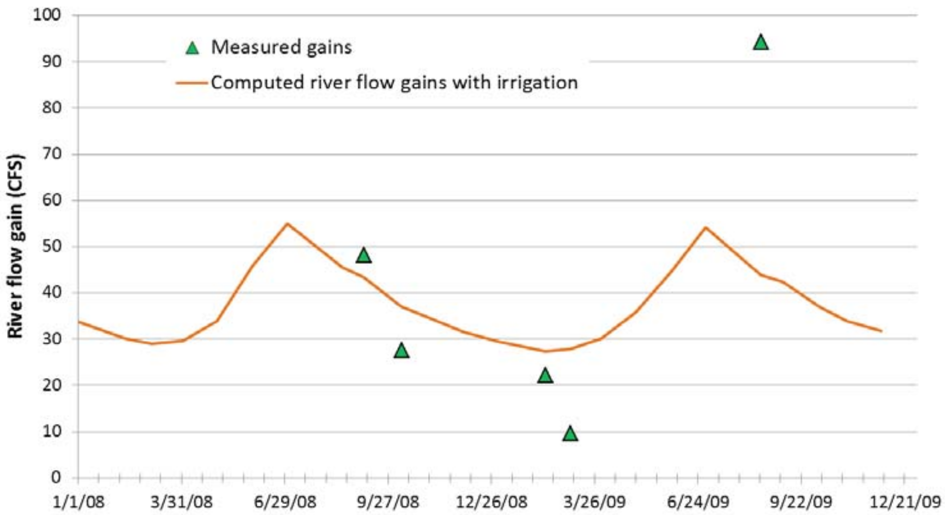


Figure 73. The calculated river flow gains (green triangles) are plotted with computed river flow gains from irrigation recharge.

Overall, the three wells demonstrate the computed head values are within the observed values.

Water-balance calibration can be examined by comparing the observed gain in the Stillwater River at Johnson Bridge to the computed gain during the 2-year period. Figure 73 is a graph comparing the magnitude and timing of river flow for the 2-year period. The seasonal irrigation patterns are clearly evident. The difference in magnitude between computed and observed river flows suggests other water sources, such as field runoff or underflow from smaller streams, might be contributing additional water to the observed river system, while the model river only receives flow from the alluvial and bedrock aquifer. The average observed gain in river flow was 39 cfs and the average computed gain in river flow was about 44 cfs for the 2-year period (tables 9 and 10). Monthly flow gains at Johnson Bridge that were extrapolated from figure 67 do not include groundwater passing through the flux boundary at Johnson Bridge (table 9). The output file created by MODFLOW does include groundwater passing through the flux boundary at Johnson Bridge (table 10).

Anderson and Woessner (2002) suggest that an ideal water balance of flow in minus flow out should have a percent discrepancy less than 0.1 percent. This model had a 0.0 percent discrepancy (table 10), indicating a good balance in the model.

Table 9. The average flow for Stillwater River from calculated and extrapolated rates.

Date	River Gain at Johnson Bridge (cfs)
1/1/2008	24
2/11/2008	22
3/5/2008	10
4/1/2008	24
5/1/2008	39
6/1/2008	55
7/1/2008	70
8/18/2008	94
9/6/2008	48
10/9/2008	28
11/1/2008	27
12/1/2008	25
1/1/2009	24
2/11/2009	22
3/5/2009	10
4/1/2009	24
5/1/2009	39
6/1/2009	55
7/1/2009	70
8/18/2009	94
9/6/2009	48
10/9/2009	28
11/1/2009	27
12/1/2009	25

Note. Average for 2 years was 39 cfs.

Table 10. Total model output file for the Stillwater River.

	Flow (cfs)
IN	
Storage	4.46
River leakage	22.03
General head boundary	8.84
Recharge	8.41
Total in	43.75
OUT	
Storage	2.58
River leakage	39.88
General head boundary	1.29
Recharge	0.00
Total out	43.75
Percent discrepancy	0.00

Sensitivity

A sensitivity analysis was performed on the transient model to determine uncertainty and sensitivity of the aquifer parameters. Aquifer storage (specific yield) was the only parameter analyzed for sensitivity in the transient model. All other parameters were previously analyzed in the steady-state model.

Specific yield values of 0.3, 0.16, and 0.02 were used to represent the aquifer materials. A value of 0.16 was estimated from the aquifer test, while 0.3 represents a well-sorted, fine sand and 0.02 represents silty clay (Anderson and Woessner, 2002). Figure 71 once again shows the locations of three wells used for the sensitivity check. Hydrographs representing the computed head elevations for the different specific yield values tested are shown in figures 72 A, B, and C. To check parameter sensitivity, the percent change in head elevation range was compared between the calibrated specific yield of (0.16) to a higher (0.3) and lower (0.02) value.

Changing the specific yield values in well 99929 (fig. 74A) created a 10 percent change in the head elevation. This well is located near the model boundary edge and river nodes. The well may be insensitive to storage changes because the other boundaries influence the head elevations. Well 161141 (fig. 74B), located near the center of the model area, was sensitive to both higher and lower specific yield values by 26 and 28 percent, respectively. Well 156919 (fig.74C) had only a 4 percent change in head elevation. This well is also located near the river and general head boundaries, which possibly dampen the effect of storage changes. Overall, the model was sensitive to storage changes and the degree of sensitivity depends on location in the model.

Model Simulations

The residents in the model area depend entirely upon groundwater for potable water and they obtain their water from individual domestic wells. Nearly all of these wells are concentrated in the center of the valley in thin alluvium. The main land use in the area is flood-irrigated agricultural land, which has been heavily irrigated for decades, creating an artificially recharged aquifer. The primary threat to the alluvial aquifer would be any land-use changes that would reduce flood-irrigated land, such as conversion from agriculture to residential housing.

Two predictive simulations were performed using this model to estimate how changes in irrigation affect the alluvial aquifer. The first simulation was to force land-use changes from irrigated farm land to non-irrigated land. In the second simulation, water was passed through the irrigation ditches, but no water was applied to the fields. Both simulations received recharge from precipitation. Differences in head elevation and total flow out of the model were compared between irrigated and non-irrigated model runs.

Figure 75 is a snapshot of the difference in heads between the irrigation and non-irrigation simulations for July 2008. The model computed up to 18 ft of head decrease in the areas where flood irrigation application is heavy and only 1 ft where precipitation and center pivots are the dominant recharge source.

The model computed a gain in river flow of 37 cfs with irrigation as compared to 34 cfs without recharge from irrigation. The lack of irrigation would reduce the amount of groundwater discharging to the Stillwater River by approximately 8 percent. This reduction in baseflow water may create problems when river stage is low, including negative impact on the aquatic ecology.

The computed flow shown by the hydrograph predicts a greater volume of water discharges to the river during the irrigation model run, and this supplies fresh cool groundwater to the river during its lowest summer stages when temperatures are also high (fig. 76). The flow difference calculated between the two model runs is shown in figure 77. Nearly 8 cfs was stored during the height of flood irrigation, decreasing to less than 1 cfs before the next irrigation season begins. Mendenhall ditch was also plotted on the hydrograph to evaluate the timing of recharge.

The second scenario was to allow irrigation ditch leakage and natural precipitation to recharge the alluvial aquifer. The ditch network was allowed to recharge the aquifer at a rate of 5 in/month during the irrigation season for the 2-year period. Figure 78 shows the seven ditch polygons used to supply recharge to the model.

The model computed the average gain in the river flow for the 2-year period as 34 cfs. This result was very similar to the model run with recharge from precipitation only. The results indicate that ditch leakage supplies a minimal amount of groundwater recharge to the system. Even though the ditches leak significantly,

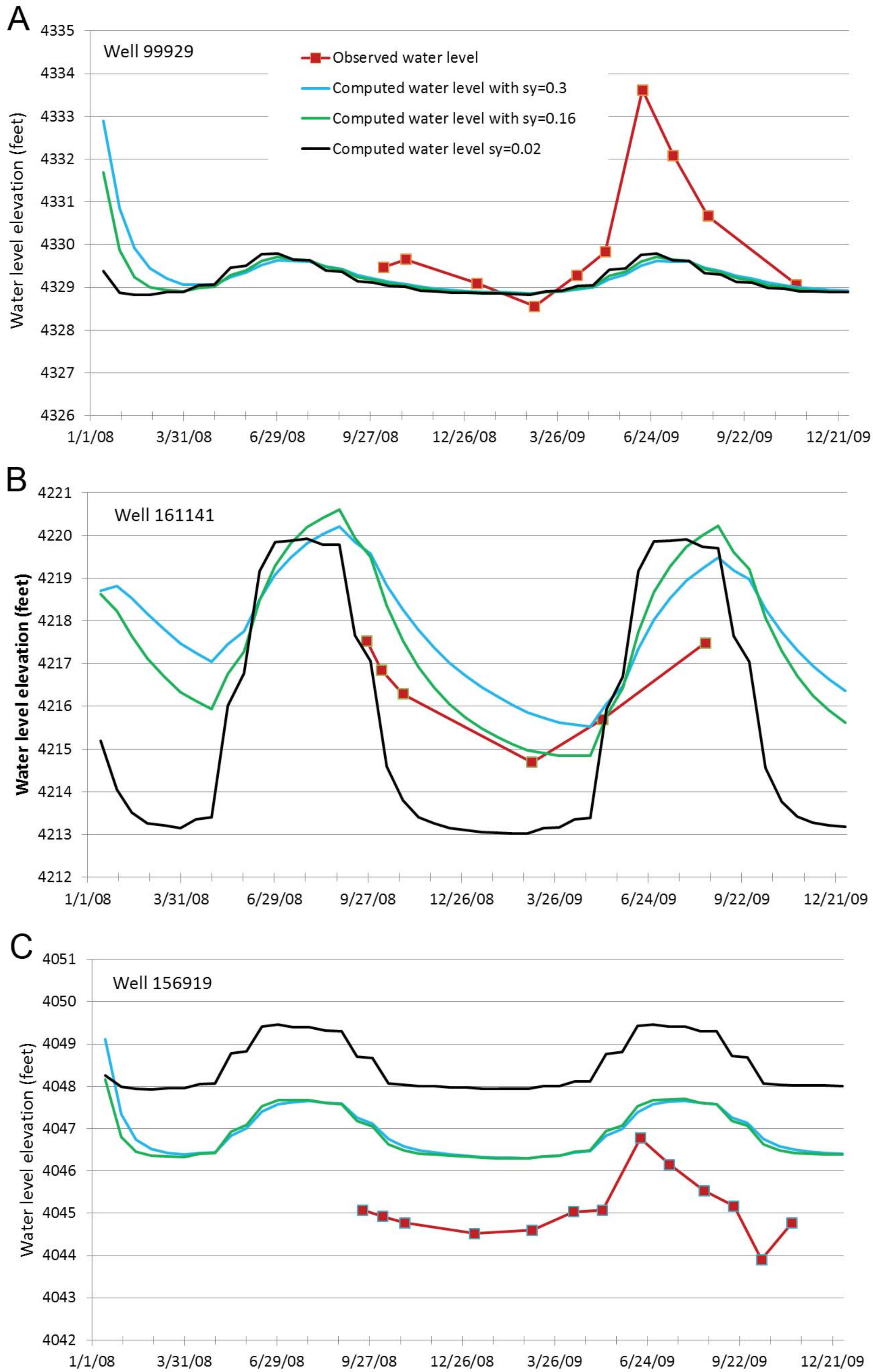


Figure 74A, B, C. Hydrographs of specific yield sensitivities for three different wells in the model area.

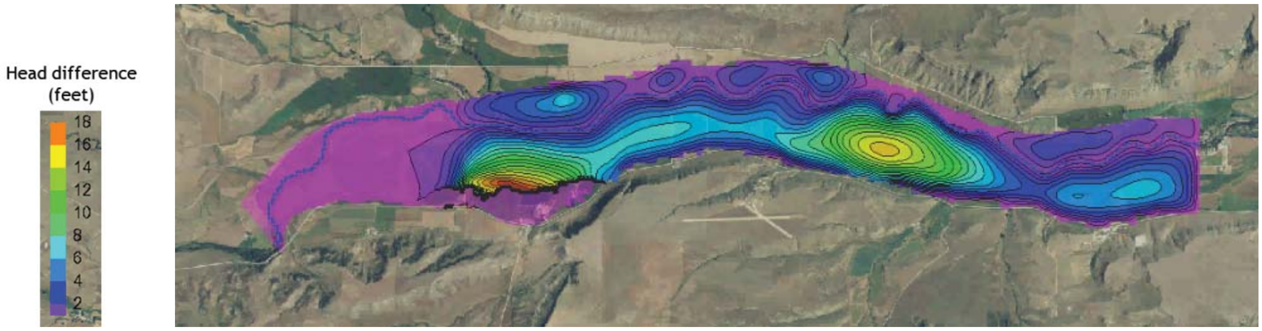


Figure 75. Computed head difference between irrigation and pre-irrigation shows an increase of up to 18 ft of head change in the heavily irrigated areas.

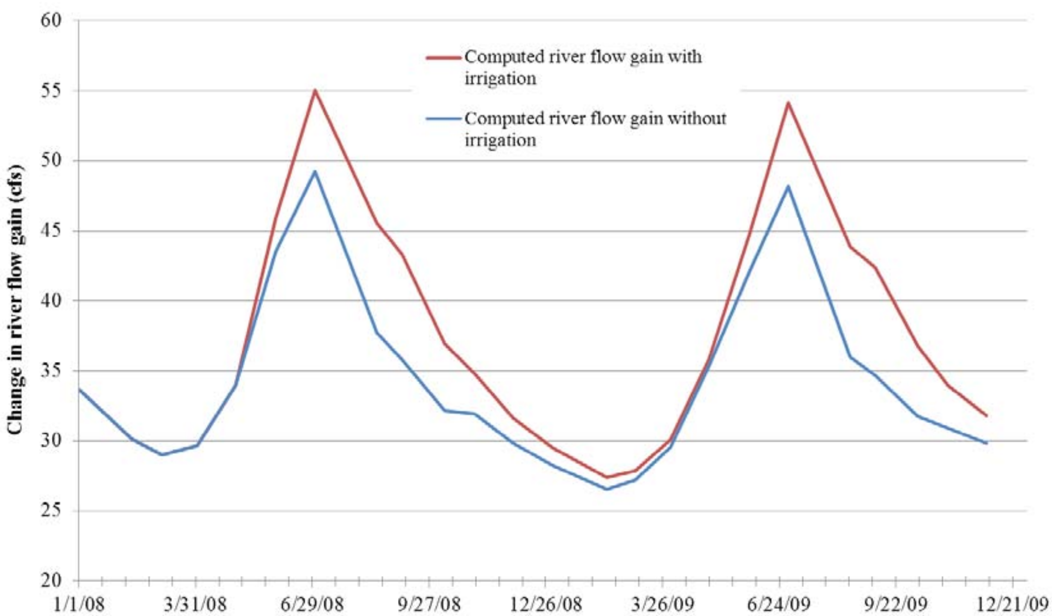


Figure 76. Comparison of computed gains in river flow with and without irrigation.

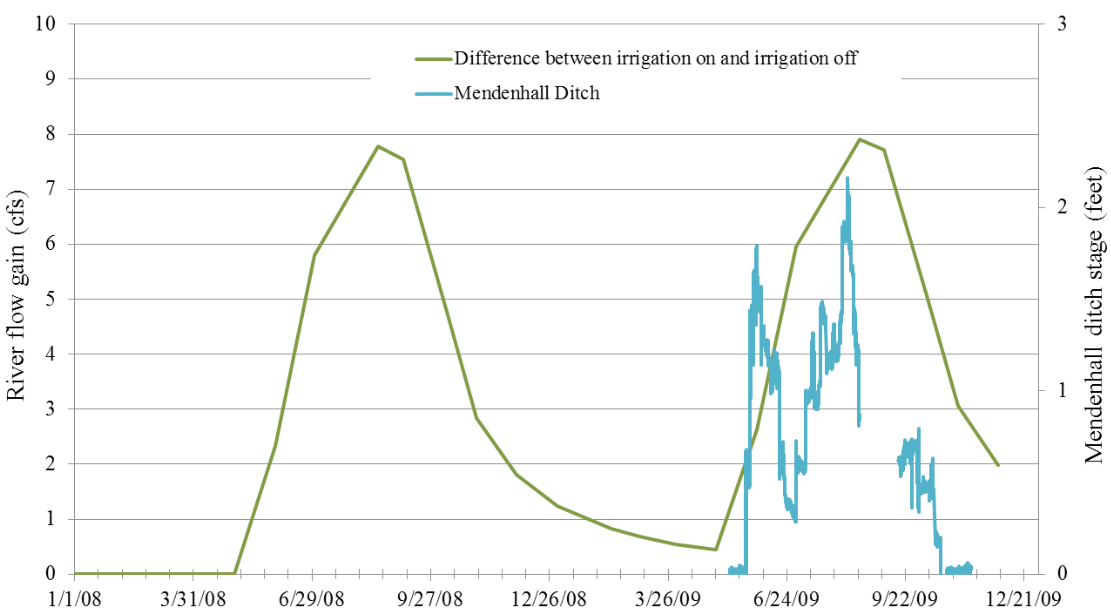


Figure 77. Computed river flow difference between the irrigation and pre-irrigation model runs. Mendenhall ditch shows timing and duration of irrigation applications.

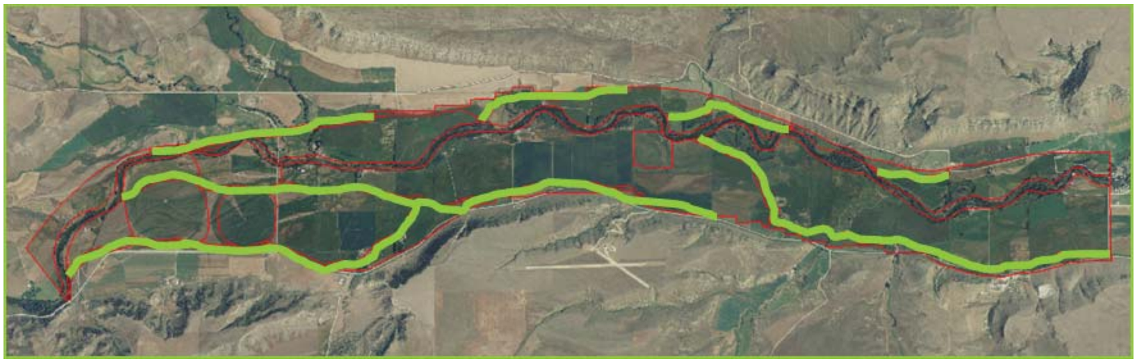


Figure 78. Green lines are the locations of ditch polygons used to supply recharge to the transient model.

they do not cover a large enough area to supply the alluvial aquifer with adequate recharge. The model area would experience conditions similar to the pre-irrigation model simulation in this case. A shift from flood irrigation to pivot irrigation would also result in decreased recharge to the aquifer. The low water levels in the aquifer may result in dry wells.

Model Limitations

When creating models, limitations usually exist with data availability and data accuracy. Some hydrological properties can easily be measured in the field, while others are usually estimated. Data accuracy can also produce problems for modeling. Field instrument error and human error are inherent with data collection. Below is a summary of the known limitations of this numerical model.

Measurable field data include streamflows and water levels from wells. In many cases, models have been developed using data collected from past projects. In this case, data gaps or lack of data tend to exist and modelers have to compensate for these problems. In this model area, data were collected for the purpose of a groundwater model and yet data problems still exist. Measured flow data were only collected at the top (Cox Bridge) and bottom (Johnson Bridge) of the model area. More flow collection points along the Stillwater River would help determine the flow contribution from stream underflow and bedrock aquifers.

Domestic and stock water wells were used as the observation wells in the model area. Many of the wells are in use during the monthly visits and accurate, undisturbed water levels could not be collected. Dedicated monitoring wells would provide more accurate water levels. The well coverage also had limited aerial extent, and nearly all the wells were located close to the Stillwater River. Calibration and sensitivity analysis would most likely produce more accurate results if more of the wells were located throughout the entire valley and along the bedrock alluvium contact.

Accurate ground, surface, and well measuring-point elevations are critical when modeling aquifers. The ground-surface topography was digitized from a topographic map that had an elevation accuracy of plus or minus 10 ft. Ten feet becomes a very large source of potential error when the aquifer's average saturated thickness is less than 25 ft.

SUMMARY AND RECOMMENDATIONS

Summary

The Stillwater and Rosebud watersheds consist of mixed sandstone—shale bedrock aquifers of Cretaceous and Jurassic ages and thin alluvial-valley aquifers (average thickness 40 ft) usually bounded on the bottom by shale and semi-confined on top, in most places, by clay-rich topsoil. The valleys are flanked on the sides by the bedrock units that extend up to 300 ft higher than the modern alluvial channel. The land use is mainly agricultural, consisting of irrigated and non-irrigated grassland, pasture/hay, and small grains. The local population depends entirely upon groundwater for potable water, and most obtain their water from individual domestic wells.

The hydrology of the alluvial aquifers is dominated by flood irrigation, which uses unlined ditches to convey water across the valley floor. Irrigation has consequently become the main source of recharge to the alluvial aquifer and has created an artificially high water table. The elevated water table acts as a temporary storage reservoir that slowly discharges groundwater back into the river system throughout most of the year.

Groundwater flow direction in the alluvial aquifers is primarily parallel to the rivers, with a smaller component of the flow moving into the rivers. The hydraulic conductivity of the Stillwater alluvium ranges between 48 and 120 ft/day. This was determined through aquifer pumping tests and specific capacity data. Hydrographs show the water levels in the alluvial aquifers respond rapidly to excess recharge and changes in ditch flow, indicating a close connection between surface water and groundwater. The highly conductive nature of the aquifer material and relatively thin soil overburden imply that the aquifers are highly vulnerable to surface contamination and changes in irrigation practices.

The bedrock aquifers discharge groundwater into the alluvium through bedrock contacts where upward groundwater gradients are present. Bedrock aquifer pumping tests yielded hydraulic conductivity values between 6 and 15 ft/day. Hydrographs for wells completed in the Hell Creek aquifer show varied long-term behavior to seasonal and climate changes. Some wells have dramatic seasonal fluctuations and sensitivity to drought conditions. One reason for drought sensitivity is the extent of outcrop surface area exposed for recharge to the aquifer. Others show long-term changes but do not show seasonal fluctuations. The lack of seasonal fluctuations in some wells suggests the recharge area may be at a far distance.

Specific conductance was used to determine the source of groundwater recharge and as a groundwater–surface water interaction tracer. Dissolved solids concentrations in the alluvial groundwater are relatively low due to the fact that the aquifer is recharged by the Stillwater River water though irrigation. Bedrock groundwater and bedrock-spring-fed creeks have higher levels of dissolved salts than alluvial groundwater but still meet drinking water standards. The SC values in rivers are low near the headwaters and progressively increase downstream, reflecting the influence of bedrock groundwater discharge to the surface water. Specific conductance measurements made during bank-to-bank transects across the Stillwater River showed higher SC along the banks and lower SC in the mixing zone of the river, and support the interpretation that groundwater discharge affects water quality of the river.

Stable isotopes of water indicate the bedrock aquifer is recharged from low-altitude rain or snow that has been partially evaporated. In contrast, the alluvial groundwater and the river water do not show evaporation signatures, and the isotopic compositions suggest these waters are sourced from precipitation at higher elevations along the Beartooth Plateau.

Chloride concentrations were used to determine if evapotranspiration was a significant influence on the alluvial groundwater. Chloride mass balance calculations suggest roughly half (53 percent) of the applied irrigation water is lost to evapotranspiration during the summer months. Comparison of stable isotope ratios of oxygen to chloride concentrations indicates little direct influence of evaporation on groundwater and that transpiration is the dominant source of irrigation water loss in the alluvium.

Steady-state and transient finite difference numerical models using MODFLOW were built to represent the hydrogeology of a representative section of alluvium in the study area. The Groundwater Modeling System developed by Aquaveo was chosen to create this model. The model consisted of three layers: a topsoil (layer 1), an unconfined alluvial gravel (layer 2), and a confining shale bedrock (layer 3).

The steady-state model was calibrated using water levels from domestic wells and flow data collected in March 2009. Calibration of the steady state model was optimized using an automated parameter estimation technique (PEST). Three calibration standards were set and all three calibration standards were met with this model. A sensitivity analysis showed that the heads were sensitive to conductance changes in all boundary types and that the degree of sensitivity depended on location within the study area.

The transient model was developed to analyze time-dependent groundwater flow. The transient model calibration was achieved by comparing model output heads and flows to measured well water levels and river flows collected in August 2009. A sensitivity analysis performed on specific yield showed the heads elevations were sensitive and the degree of sensitivity again depended upon location within the study area.

Predictive model simulations were used to determine if adequate groundwater would be available if the valley was no longer irrigated. In the study area, the primary threat to the availability of groundwater in the alluvial aquifer would be land-use changes that reduce flood-irrigated agricultural land. The first predictive simulation examined changes in groundwater properties with and without flood irrigation. Results indicate some areas within the Stillwater Valley would have up to 18 ft of water-level drop during August, possibly resulting in dry wells. The river baseflow would also be impacted by a reduced groundwater discharge of about 6 cfs. Less fresh, cool groundwater returning to the river, especially during low flow stages, could have negative effects on aquatic habitat. In the second predictive simulation, flood irrigation was stopped but the ditches were allowed to flow at their usual capacity, thus allowing irrigation ditch leakage to supply recharge to the alluvial aquifer. Results indicate that ditch leakage supplies an insignificant portion of groundwater to the system, and therefore the study area would experience conditions similar to those of the non-irrigated model simulation.

Recommendations

In the alluvial valleys, a close hydraulic connection exists among irrigation water, shallow groundwater, and river water. Because recharge occurs mainly from flood irrigation, land-use changes such as converting irrigated land to home site development or conversion to center-pivot systems could lower the groundwater level, and therefore the productivity, of the aquifer. The loss of significant recharge to the alluvial aquifer would mean loss of stored groundwater. This would cause decreased flows to the Stillwater River, which could have negative effects on the aquatic habitat, especially during low flow stages. Also, the highly transmissive alluvial aquifer is vulnerable to surface contamination, including septic tank effluent, which becomes more of a possibility as the area becomes more densely populated.

Bedrock aquifers in the area can be subject to limited recharge during periods of below-average precipitation. Recharge to these aquifers is most likely fairly localized because the surface exposures, where the majority of recharge takes place, are not laterally continuous over large areas. The bedrock aquifers that have larger, more continuous outcrops for recharge are buffered by their exposure to a large variety of climatic conditions. Developments in the areas outside of the alluvial valley depend on bedrock wells that will be more susceptible to failure from dropping water levels during drought than wells in the alluvial valley.

REFERENCES CITED

Anderson, M.P., and Woessner, W.W., 2002, Applied groundwater modeling: San Diego, California, Academic Press, 381 p.

Blaney, H.F., and Criddle, W.D., 1950, Determining water requirements in irrigated areas from climatological and irrigation data: U.S. Department of Agriculture Soil Conservation Service, SCS-Technical Paper 96, 44 p.

Brinck, E.L., Drever, J.I., and Frost, C.D., 2008, The geochemical evolution of water coproduced with coalbed natural gas in the Powder River Basin, Wyoming: Environmental Geosciences, v. 15, p. 153–171.

Cannon, M.R., and Johnson, D.R., 2004, Estimated water use in Montana in 2000: United States Geologic Survey Scientific Investigations Report 2004-5223, 61 p.

Carstarphen, C.A., and Smith, L.N., 2007, Data for sites visited during the Carbon-Stillwater groundwater characterization study: Montana Bureau of Mines and Geology GWAA 6B-01, 1 sheet.

Clark, I., and Fritz, P., 1997, Environmental isotopes in hydrogeology: New York, Lewis Publishers, 328 p.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Transactions of the American Geophysical Union, v. 27, p. 526–534.

Doherty, J., Brebber, L., and Whyte, P., 1994, PEST: Model-independent parameter estimation: Watermark Computing.

Drever, J.I., 1997, The geochemistry of natural waters: Surface and groundwater environments: Upper Saddle River, N.J., Prentice Hall, 436 p.

Du Bray, E.A., and Harlan, S.S., 1993, Geology and preliminary 40Ar/39Ar geochronology of the sliderock mountain volcano, south-central Montana.: Geological Society of America Abstracts with Programs 25, no. 5, p. 32.

Feltis, R.D., and Litke, D.W., 1987, Appraisal of water resources of the Boulder and Stillwater River basins, including the Stillwater Complex, south-central Montana: Montana Bureau of Mines and Geology Memoir 60, 121 p., 3 sheets.

Fetter, C W., 2001, Applied hydrogeology: New York, Macmillan College Publishing, 598 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice Hall, 604 p.

HydroSolve, Inc., 1998, Aquifer test analysis software: http://www.aqtesolv.com (accessed December 29, 2011).

Jacob, C.E., 1950, Flow of ground-water, *in* Engineering Hydraulics, H. Rouse, ed.: New York, John Wiley, p. 321–386.

Lopez, D.A., 2000, Geologic map of the Big Timber 30' x 60' quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open-File Report 405, 1 sheet, 1:100,000.

Lopez, D.A., 2001, Preliminary geologic map of the Red Lodge 30' x 60' quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open-File Report 423, 17 p., 1 sheet, 1:100,000.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference groundwater flow model: Techniques of Water-Resources Investigations, book 6, chapter A1.

Meredith, E.L., Wheaton. J.R., and Kuzara, S.L., 2009, Hydrogeology of the northern Bighorn River Valley: Montana Bureau of Mines and Geology Open-File Report 588, 45 p., 3 sheets.

Montana Bureau of Mines and Geology (MBMG), 2009, Ground water information center (GWIC): http://mbmggwic.mtech.edu/ (accessed 2009).

Montana Department of Commerce, 2000, Census and economic information center: http://www.ceic.mt.gov (accessed December 29, 2011).

Montana Department of Commerce, 1990, Stillwater County 1990 census of population and housing: http://ceic.mt.gov/Demog/1990dec/STF/StfData/c048_A1.htm (accessed 2010).

Montana Department of Natural Resources and Conservation (DNRC), 2009, Water resources division, Horse Creek controlled ground water area: http://dnrc.mt.gov/wrd/water_rts/cgwa/horsecreek/horsecreek_report.pdf (accessed December 29, 2011).

Montana Department of Naural Resources Information System (NRIS), 1992, GIS data list: http://nris.mt.gov/gis/gisdatalib/gisDataList.aspx (accessed 2009).

Natural Resources Conservation Service (NRCS), 2010, Water resources irrigaiton resources: http://www.wsi.nrcs.usda.gov/products/W2Q/water_mgt/Irrigation/nrcs_irrigation_page (accessed 2010).

Neuman, S.P., 1974, Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response: Water Resources Research, v. 10, no. 2, p. 303–312.

Olson, J.L., and Reiten, J.C., 2002, Hydrogeology of the west Billings area: Impacts of land-use changes on water resources: Montana Bureua of Mines and Geology Report of Investigation 10, 32 p., 2 sheets.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: v. 1, Measurement of stage and discharge: United States Geological Survey Water Supply Paper 2175.

Rozanski, K., Araguas-Araguas, L. and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation, *in* Continental Isotope Indicators of Climate: American Geophysical Union Monograph.

Theis, C.V., 1935, The lowering of the piezometer surface and the rate and discharge of a well using ground-water storage: Transactions of the American Geophysical Union, v. 16, p. 519–524.

U.S. Census Bureau, 2000, Montana by county, geographic comparison table: http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US30&-_box_head_nbr=GCT-PH1&-ds_name=DEC_2000_SF1_U&-format=ST-2 (accessed 2010).

Uthman, W., and Beck, J., 1998, Hydrogeology of the Upper Beaverhead Basin near Dillon, Montana: Montana Bureau of Mines and Geology Open-File Report 384, 549 p.

Weight, W.D., 2008, Hydrogeology field manual: New York, The McGraw-Hill Companies, Inc., 751 p.

Western Regional Climate Center, 2009, 2010 Period of record monthly climate summary, Fishtail Montana: Desert Research Institute, Nevada System of Higher Education. http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt2996 (accessed 2009).

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water: A single resource: United States Geological Survey Circular 1139, 79 p.

Woessner, W.W., 1998, Changing views of steam–groundwater interaction, *in* Van Brahana, J., Eckstein, Y., Ongley, L.W., Schneider R., and Moore, J.E. (eds.): Proceedings of the Joint Meeting of the XXVIII Congress of the International Association of Hydrogeologists and the Annual Meeting of the American Institute of Hydrology, American Institute of Hydrology, St. Paul, MN, p. 1-6.

APPENDIX A

Surface-Water Sampling and Monitoring Locations and Surface-Water Flow Rates and Water Quality

Appendix A1. Surface water sampling and monitoring locations

Site Name	GWIC ID (if assigned)	Location	Latitude	Longitude
East Rosebud above lake	M:244976	E. Rosebud above lake		
Upper East Rosebud		at wooden bridge	45.308201	-109.525371
East Rosebud at Roscoe		Old cement bridge in town	45.349003	-109.496132
East Rosebed at Tuttle Rd. 2		First Wooden private bridge	45.412012	-109.473075
West Rosebud near power 1			45.34326	-109.60016
West Rosebud at Sleepy Hollow 2				
Smith Bridge		Smith bridge	45.48644	-109.45522
Fishtail at Keller 1	M:244977	Fishtail Ck at Keller	45.388876	-109.678749
Fishtail at Yates 2		Fishtail Ck at Yates	45.446156	-109.5428
Fishtail at Bass 3		Fishtail Ck on Bass	45.457155	-109.517428
Butcher Creek				
Stillwater at Woodbine	M: 244974	below Woodbine bridge		
Stillwater at Beehive		Stillwater at Beehive	45.484221	-109.711524
Stillwater at Red bridge		45.503855	109.652636	old bridge
Stillwater at Cox		Stillwater at Cox	45.509095	-109.699216
Stillwater at Spring Creek Bridge				
Stillwater at Devilibus		Stillwater at Devilibus		
Stillwater at Johnson Bridge		bridge	45.528662	109.469451
Stillwater at North Stillwater Rd		Nstill Rd near USGS Gage	45.53741	-109.42123
Stillwater at Firemans Point	220496	Stillwater at Firemans Pt	45.61998	-109.289111
Stillwater at Whitebird		Stillwater at Whitebird	45.57657	-109.33704
Trout Creek				
Grove Creek				
Bad Canyon Creek				
Joe Hill Creek				
Gargison Ditch				
Whitebird Ditch		ditch at McNight	45.56982	-109.33093
Mendenhall Ditch		Ditch at Helbert bridge		
Aadland Pond		evaporation pan on pond		
Cow Creek		at N SW Rd		
Spring Creek		at Spring Creek Rd		
Engasol Creek				
Fiddler Creek		Fiddler Creek		
Jackstone Creek				
Shane Creek		near Pezoldt house		
Whitebird Creek 1		ditch at McNight	45.56982	-109.33093
Whitebird Creek 2		at Fishing Access		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
East Rosebud above lake	7/17/2008			9.6	7.69	28.4		Collected Isotope sample on 7/17/08 above lake in stream
Upper East Rosebud	6/18/2008	11.49		12.6	7.68	40.7	4.85	calm
	6/19/2008	11.3	804.47				5.1	windy
	7/15/2008	11.7		14.8		63.2	4.5	calm
	7/29/2008	12	430.51	16.7		40		
	8/13/2008	12.63		16.9		78.7	3.65	calm
	8/28/2008	13.05	145.72	13.3		39.1	3.3	
	9/18/2008	13.3		14.7		54	out of water	
	10/23/2008	13.55		6.9		59.2		
	1/8/2008							frozen
	3/3/2009	14		9.1	6.8	75	out of water	really windy
	4/5/2009	13.8	38.3	2.7	7.32	70.1	out of water	calm
	5/12/2009	13.29		8.8	6.95	43.1		calm
	6/16/2009	11.27		11.1	7.07	40.4	4.99	calm
	7/16/2009	11.9		17	7.12	42	4.4	est windy
	9/2/2009	12.9		18.9	8.04	45.6		calm
	10/14/2009	13.4		5.2		70.2		windy
	11/17/2009	13.7		3.1		36.7		windy, SC not corrected
East Rosebud at Roscoe	6/18/08	8.6		12.4	7.71	42.4		
	6/19/08	8.4						
	8/29/08	10.25	48.49	13.6		61.6		
	9/18/08	10.1		15.6		67		
	10/23/08	9.85						
	3/3/09	10.13		6.4	7.14	83.5		
	4/5/2009	10.15	46.41	2.3	7.45	76.3		
	5/12/2009	9.64		9.5	7.9	58.4		
	6/16/2009	8.42		10.8	7.46	41.3		
	7/16/2009	8.85		17.6	7.09	64.2		
	9/2/2009	9.79		18.2	7.95	55.1		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	10/17/2009	9.87		3.7		77.9		
	11/17/2009	9.95		2.8		40.3		
East Rosebed at Tuttle Rd. 2	6/19/2008	6.6	1252.67	13.6	6.83	45.8		
	7/15/2008	6.97		15.1		46.2		
	7/29/2008	7.3	310.55	15.4		54		
	8/13/2008	7.95		18.1		69		
	8/29/2008	8.5	21.5	16.4		123.5		
	9/18/2008	8.23		16.1		108.3		
	10/23/2008	8		7.6		91		
	1/8/2009	7.9		0.5	6.79	84.4		analyzed at home
	3/3/2009	8.2		5.8	7.02	100.3		
	4/5/2009	8.34	42.05					
	5/12/2009	7.85		10.2	8.05	65.6		
	6/16/2009	6.4		11.8	7.5	47.3		
	7/16/2009	7.01		18.6	7.22	49.1		
	9/2/2009	8.01		19.6	8.11	75.7		
	10/17/2009	7.98		4.3		90		
	11/17/2009	8.04		1.5		46.2		SC not temp corrected
West Rosebud near power 1	6/24/2008	12	659.73	13.7	6.86	35.9		12.26 was original dtw
	7/15/2008	11.75		16.7		44.7		
	7/17/2008	11.67		14.6	7.51	34.2		Isotope
	7/30/2008	12.1	441.09	14.9		35.7		
	8/28/2008	12.3	178.34	16.2		44		
	9/18/2008	12.53		14.7		42		
	1/8/2009							froze
	3/3/2009	12.72		5.7	6.56	52.2		
	4/2/2009	13	58.43	2.2	7.6	54		Isotope
	5/12/2009	12.85		9.7	7.56	42.5		calm
	6/16/2009	12.35		11.8	7.32	41.5		
	7/16/2009 0:00	12.05		16.2	7.18			

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	9/3/2009	12.36		12.6	7.81	42.9		
	10/17/2009	6.61						error in SC, too cold
	11/17/2009	12.4		3.4		44		
West Rosebud at Sleepy Hollow 2	6/5/2008	8.5						
	6/18/2008	8.85						
	6/24/2008	8.7	366.47	13.6		46.8		
	7/15/2008	8.2						
	7/29/2008	8.65	502.1	18.2		40.6		
	8/13/2008	9.2		17		50		
	8/28/2008	9.25	187.2	16.7		75.7		
	9/18/2008	9.4		14.6		54		
	10/23/2008	9.52		7.2		62		
	1/8/2009	9.2						
	3/3/2009	9.56		5.1	6.58	63.5		
	4/2/2009	9.84	73.19					
	5/12/2009	9.54		9.5	8.12	69.3		
	6/16/2009	8.62		12.3	7.5	53.7		
	7/16/2009	8.45		17.5	7.16	43		
	9/3/2009	9.1		12.7	8.19	48.4		
	10/17/2009	9.65		4.1		59.2		
	11/17/2009	9.95		3.4		31.2		SC uncorrected
Smith Bridge	4/25/2008	14.9	111.56	6.5	7.6	121		
	6/5/2008	12.65						
	6/13/2008	13.6		14.2	8.36	122		
	6/18/2008	12.43						
	6/20/2008	12.6	1156.87					
	6/24/2008	12.25						
	7/15/2008	12.85				66.7		
	7/17/2008	12.75		14.1		70.7		
	7/30/2008	13.2	732.23					

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	8/1/2008	13.33		15.70		66.00		
	8/13/2008	13.9		16.2		115		
	8/28/2008	14.35	214.76	13.3		141.5		
	9/19/2008	14.3		15.5		147.6		
	10/23/2008	14.3		4.2		119		logger laying out on ground
	1/8/2009	13.85		0.7	7.15	100.3		analyzed in office
	2/15/2009	14.5	168.97		8.19	104.4		analyzed in office; SC not remp corrected
	3/3/2009	14.45		5.5	6.84	117.6		
	3/5/2009	14.64	147.77	1.3	8.22			
	4/13/2009	13.86						runoff
	5/12/2009	14		10.6	7.86	107.3		rain shower
	6/16/2009	12.57		12.7	7.72	74.8		
	7/15/2009	12.64		17.8	7.97	61.2		
	9/2/2009	13.85		18.8	8.3	94.2		
	10/14/2009	14.24		2.5		127.5		
	11/11/2009	14		2.1		38		SC not temp compensated
	3/12/2010	14.75		2.7	8.32	uncorrected temp 2.4		uncorrected
Fishtail at Keller 1	6/5/2008	5.25						
	6/13/2008	5.99		11	8	69		
	6/18/2008	5.35						
	6/24/2008	4.8						
	7/15/2008	6		11.8		39		collected Isotope sample
	7/30/2008	6	62.16	15.1		39		
	8/13/2008	6.27		13.3		59		
	8/14/2008	6.52						
	8/29/2008	6.85	8.6	15.1		68.3		
	9/18/2008	6.75		11.4		71		
	10/23/2008	6.55		5.4		81.3		downloaded
	1/8/2009	6.8		0.5	6.52	77		analyzed at home

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	3/3/2009	6.7		2.8	7.04	93.9		
	4/6/2009	6.85	6.3					collected Isotope sample
	4/13/2009	6.6						downloaded logger
	5/12/2009	6.45		8.1	7.47	69.5		did not download
	6/16/2009	5.4		10	7.42	46.1		downloaded
	7/16/2009 0:00	6		13.6	7.67	49.6		
	9/3/2009	6.4		11	8.26	70.5		
	11/17/2009	6.69		2.00		92.40		
Fishtail at Yates 2	6/13/2008	5.15		11	7.4	138		
	6/20/2008	4.75	96.87					
	7/15/2008	5.2		15.7		86.8		
	7/30/2008	5.33	35.27	17.4		97.4		
	8/13/2008	5.45		14.5		145		
	8/29/2008	5.65	10.24	16.6		167.3		
	9/18/2008	5.55		14.5		155		
	10/23/2008	5.3		5		158		
	1/8/2009	5.5		2.9	6.7	179.5		
	3/3/2009	5.6		4.9	7.33	173.6		
	5/12/2009	5.03		8.6	8.1	134.1		
	6/17/2009	4.65		11.7	7.55	85.3		
	7/16/2009	5.06		15.7	7.83	96.8		
	9/2/2009	5.53		17.3	8.2	137		
	10/14/2009	5.2		2.2		152.2		
	11/17/2009	5.6		1.1		95.3		
Fishtail at Bass 3	6/20/2008	11.35	114.85	14.3	7.71	86.5		
	7/15/2008	11.45		18.1		118		
	7/30/2008	11.7	47.43	18.5		137		
	8/13/2008	11.83		17.8		186.9		
	8/29/2008	11.9	25.63	17.4		205.7		
	9/18/2008	11.8		16		205		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	10/23/2008	11.72		7		193		
	1/8/2009	11.95		3.6	7.63	208.6		
	3/3/2009	11.81		5.2	7.42	260		
	5/12/2009	11.6		9.5	7.82	145.2		
	6/17/2009	11.08		13.1	7.75	111.8		
	7/16/2009	11.35		17.4	8.08	136		
	9/2/2009	11.75		19.8	8.44	187		
	10/14/2009	11.75		3.2		185		
	11/17/2009	11.8		2.7		111.5		
Butcher Creek	6/17/2009			4.7	5.75	306.5		
	7/16/2009			22.8	8.86	288		
	10/17/2009			5.4		377		
Stillwater at Woodbine	7/17/2008			10.6	7.73	34.8		Collected Isotope sample on 7/17/08 below Woodbine bridge
	4/6/2009			3.3	7.04	55.4		Collected Isotope sample on 4-6-09 just above Woodbine bridge
Stillwater at Beehive							14.15	from mp to river bottom
	6/18/2008	9.8					4.35	
	6/24/2008	8.65					5.5	
	7/15/2008	10.6					3.55	
	8/14/2008	12.15		13.1		80	2	
	8/29/2008	12.53					1.62	
	10/23/2008	12.65		8.4		157	1.5	
	2/13/2009	12.93	140.26		8.19	176.4	1.22	pH-office param not temp corrected
	3/3/2009	12.95		7.6	7.02	163.5	1.2	
	5/12/2009	12.05		8.9	8	77.2		
	6/16/2009	9.65		10.3	7.75	53.5		
	9/3/2009	12.42		14.5	8.42	123		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
Stillwater at Red bridge	8/29/2008	10.25						
	9/6/2008	10.09	234.75					
	9/18/2008	10.31						
	10/4/2008	10.1						
	10/4/2008	12.36						
	10/9/2008	12.6	175.1					
	10/23/2008	12.65			7.1			
	10/31/2008	12.75						
Stillwater at Cox	9/18/2008	11.43		15.1		145		
	10/9/2008	11.2	175.1					
	10/31/2008	11.42	s from red bridge					
	1/13/2009	11.6						
	2/11/2009	11.85	57.7					calm
	2/13/2009	11.73						
	3/4/2009	11.66						
	3/5/2009	11.65	104.94	1.7	8.2	82.2	2.27 (s)	gus held tape stream bottom from mp is 13.92
	4/13/2009	11.35						windy
	4/14/2009	11.18						raining; installed logger
	5/8/2009	10.98						
	5/11/2009	10.94		12	8.96	118.3		
	5/27/2009	9.11						
	6/17/2009	9.05		8.7	7.47	55		downloaded
	7/15/2009	10.06		14.6	8.08	72.6		
	8/17/2009	11.1	330.08					
	9/3/2009	11.23						downloaded
	10/13/2009	11.43		3.7		163.6		
	9/18/2008	13.73						
Stillwater at Spring Creek Bridge	9/25/2008	13.74						
	10/23/2008	13.65		8.4		172		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	1/7/2009							Frozen
	2/11/2009	14.33						
	2/13/2009	14.17						
	3/4/2009	14.06						
	3/5/2009	14.11	100.22	3.5	8.25	173.8		gus held tape good reading
	5/11/2009	13.2						windy
	6/17/2009	10.82		10.1	7.3	59.6		
	7/15/2009	12.21		14.6	7.94	87.8		
	3/12/2010			7.8	8.71	206		
Stillwater at Devilibus	2/11/2009		96.77			185		this flow missed probably 1/4 flow into ditch path then back to river
	3/5/2009		113.8	4.05	8.24	172.7		
Stillwater at Johnson Bridge	9/4/2008	15.16						
	9/6/2008	15.1	199.25					used rod to measue distance across
	9/18/2008	15.1						
	9/21/2008	15.12						insstalled logger
	9/25/2008	15.1						
	10/9/2008	15.22	188.34					
	10/23/2008	15.02						downloaded
	10/31/2008	15.2						
	1/7/2009	16						windy estimated
	1/13/2009	15.7						downloaded
	2/11/2009	15.74	84.71					downloaded
	2/13/2009	15.6						
	3/5/2009	15.59	120.64				1.4 (s)	mp to river bottom is 16.99
	4/14/2009	14.47						downloaded
	5/8/2009	14.32						downloaded
	5/11/2009	14.4		9.8	8.79	154.2		calm
	5/27/2009	12.31						

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	6/17/2009	11.83		9.2	8.15	60.6		downloaded
	7/15/2009	13.38		13.3	7.86	90.3		calm
	8/17/2009	14.85	322.67					
	8/18/2009	14.84		14.4	7.71	175		downloaded
	10/13/2009	15.13		2.5		207.2		
	11/11/2009	15.16		6.8	6.74	233		calm
	2/13/2009	16.75	248.79		8.02	145.3		
Stillwater at North Stillwater Rd	3/3/2009	16.55						water is dirty from runoff
Stillwater at Firemans Point	2/13/2009	16.74	277.1	in office	7.28	151.8		not temp corrected
	3/3/2009	16.63						
	5/12/2009	15.54		10	8.43	113.9		
	7/15/2009	14.21		12.5	8.05	88		
	3/12/2010			4.1	8.34	117.1 temp 3		
Stillwater at Whitebird	2/13/2009		262.89		7.88	150.8		not temp corrected
Trout Creek	9/6/2008	7.45	2.93	12		232		collected isotope SK-1
	9/18/2008	7.45		15.6		218		
	10/9/2008	7.45		10.6		201.5		Isotope Trout
	10/31/2008	7.18						
	1/13/2009	7.45						
	2/11/2009	7.5	2.17	5.3	6.52	200		Isotope Trout
	3/4/2009	7.46						
	3/5/2009	7.47		3.7	8.11	206.6		
	4/13/2009	6.74						calm
	5/11/2009	7.3		12	7.73	181.9		
	5/27/2009	7.68						
	6/17/2009	7.66		9.2	6.78	200.5		
	7/15/2009	7.95		18.3	8.16	212		
	10/13/2009	8		8.8		199		
	11/11/2009	7.91		7.9		207.4		
	3/12/2010	14.75		2.7	8.32	77.6		temp 2.4 uncorected

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
Grove Creek	9/12/2008		3.78					clay
	9/20/2008	12.4						
	10/4/2008	11.98						
	10/9/2008	12.3						
	10/23/2008	12.28						
	1/7/2009							frozen
	2/11/2009	11	1.15					frozen at culvert had to est top of water; collected Isotope Grove; check param in office
	3/4/2009	12.42	1.77	4.6	8.67	334.2		
	4/7/2009	12.3	3.09	14.1	8.73	330.9		
	5/11/2009	11.82		13.3	9.1	278		
	6/174/09	12		17.1	8.54	310.7		
	7/15/2009	11.92		20.4	8.57	308		
	3/12/2010	frozen		5.6	8.7	400		
Bad Canyon Creek	6/16/2009		~2-3	17	8.55	203.7		flow estimated
	7/16/2009							almost dry
	9/3/2009							dry
Joe Hill Creek	4/13/2009		<1 est					less than 1 cfs & dry in winter
	7/15/2009			13.6	8.03	216.9		est flowing 1-2 cfs
Gargison Ditch	6/17/2009 10:01						1.38	
	7/15/2009						1.12	
Whitebird Ditch								
							3.25 (swl)	
	5/1/2009	dry					3.25 (swl)	MP from cement top to dirt
	6/16/2009						2.92 (swl)	
	7/15/2009						1.85 (swl)	downloaded
	8/10/2009			20.8	9.39	137		
	9/4/2009						2.28 (swl)	
	10/13/2009						3.04 (swl)	
	11/11/2009	3.08						
Mendenhall Ditch	10/22/2008	dry		14.4		115		3.5 from bridge when dry

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	4/22/2009	dry						Well is 46.9 feet from Menenhall ditch
	6/4/2009						3.48 (swl)	installed logger; MP top of plank E side of bridge
	7/16/2009						3.66 (swl)	swl in pvc
	9/16/2009						4 (swl)	swl in pvc
	10/13/2009	2.95					4.27 (swl)	swl in pvc
Aadland Pond	4/22/2009			16.9	8.5	486.81	2.23 (s)	installed logger & cleaned pan; adjusted pan, put pvc around hose
	5/1/2009							downloaded logger; did not need to add water to holding tank
Cow Creek	3/4/2009							bit of water present 15-20 gpm est
	5/11/2009		1	13.2	8.68	346.7		cfs estimated
	6/17/2009		>3					cfs estimated, flowing a lot
	7/15/2009			15.9	8.17	329		1 cfs est
	11/10/2009							less than 1 cfs
	3/12/2010			10	8.76	520		no runnoff
Spring Creek	3/4/2009							dry
	5/11/2009		1	15.1	8.11	257.1		cfs estimated
	6/17/2009		>3					cfs estimated
	7/15/2009			17.7	7.43	201.5		
	11/10/2009							less than 1 cfs
	3/12/2010			9.3	8.8	805		in gpm no runnoff good param
Engasol Creek	6/16/2009		~2-3	16.3	8.43	295.3		flow estimated
Fiddler Creek	5/12/2009			8.6	8.31	114.1		
	6/16/2009			12.4	8.2	129.4		
	7/16/2009			16.8	8.15	138		
Jackstone Creek	3/5/2009			3.7	8.53	764		

Appendix A2. Surface water flow rates and water-quality

Site Name	Date/time	Depth to Water (ft)	Measured Flow Rate (cfs)	Water Temperature (Celcius)	pH	Specific Conductance (µS/cm)	Staff / Stage (s) / Static Water Level (swl) (feet)	Notes
	5/12/2009	3.84		14.1	8.41	607		
	6/17/2009		~1	10.9	6.9	680		flow estimated
	7/1/2009					713		
	7/15/2009			17.1	8.47	712		less than 1 cfs est
	11/10/2009							less than 1 cfs est
				9.6	8.89	796		
Shane Creek	4/13/2009			6.8	8.52	667		Est flow 10 gpm; water was frozen over in winter
	6/16/2009			13.4	8.15	604		flowing at a good rate
	7/15/2009			13.2	8.08	598		
	11/10/2009			0.9	8.29	383		SC not temp corrected
	11/10/2009							less than 1 cfs
	3/12/2010							frozen
Whitebird Creek 1								3.25 when dry
Whitebird Creek 2	5/1/2009	dry						MP from cement top to dirt
	6/16/2009			12	8.02	188.2		flowing big
	7/15/2009			14.3	8.18	263.7		flowing less than 1cfs est
	11/11/2009							dry at Dahlstroms
	3/12/2010	dry						

APPENDIX B

Well Logs

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View water quality for this site
View scanned well log (9/30/2009 3:01:52 PM)

Site Name: JOHNSON FAMILY FOUNDATION GROVE S
GWIC Id: 252295

Section 1: Well Owner

Owner Name
JOHNSON FAMILY FOUNDATION
Mailing Address
P O BOX 173610

City	State	Zip Code
BOZEMAN	MT	59717

Well Address
GROVE CREEK BEDROCK SOUTH

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
04S	18E	17	NE¼ NW¼ NW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.49252	109.53495	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4376.5			

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Monday, August 10, 2009

Section 6: Well Construction Details
Borehole dimensions

From	To	Diameter
0	18	10.75
18	73	7.625

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	18	8.625	0.25		WELDED	STEEL
1.5	73	4.5			SOLVENT WELD	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
45	73	4.5		.025	SCREEN-CONTINUOUS-PVC

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	42	BENTONITE	

Section 7: Well Test Data

Total Depth: 73
Static Water Level: 45
Water Temperature:

Air Test *

10 gpm with drill stem set at 73 feet for 1 hours.
Time of recovery 0.17 hours.
Recovery water level 45 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log
Geologic Source
125TLCK - TULLOCK MEMBER (OF FT UNION FM.)

From	To	Description
0	2	TOPSOIL DARK SOFT
2	30	SANDY CLAY TAN SOFT
30	31.5	SANDSTONE TAN MEDIUM
31.5	59	SHALE DARK MEDIUM
59	72	SANDY SHALE DARK MEDIUM
72	73	SHALE DARK GREY MEDIUM

Driller Certification
All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: PAUL STEINMETZ
Company: AAQUA DRILLING INC
License No: WWC-542
Date Completed: 8/10/2009

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned well log (9/30/2009 3:02:01 PM)

Site Name: JOHNSON FAMILY FOUNDATION GROVE N
GWIC Id: 252296

Section 1: Well Owner

Owner Name
JOHNSON FAMILY FOUNDATION
Mailing Address
P O BOX 173610

City	State	Zip Code
BOZEMAN	MT	59717

Well Address
GROVE CREEK BEDROCK NORTH

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
04S	18E	17	NE¼ NW¼ NW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.49252	109.53495	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4380			

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Friday, August 07, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	18	10.75
18	60	7.625

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	18	8.625	0.25		WELDED	STEEL
1.5	60	4.5			SOLVENT WELD	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
46	55	4.5		.025	SCREEN-CONTINUOUS-PVC

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
-1.5	44	BENTONITE	

Section 7: Well Test Data

Total Depth: 60
Static Water Level: 45
Water Temperature:

Air Test *

30 gpm with drill stem set at 60 feet for 1 hours.
Time of recovery 0.17 hours.
Recovery water level 45 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
125TLCK - TULLOCK MEMBER (OF FT UNION FM.)

From	To	Description
0	2	TOPSOIL TAN SOFT
2	19	SANDYCLAY TAN SOFT
19	22	CLAY TAN SOFT
22	24	SANDSTONE TAN MEDIUM
24	27	SHALE TAN SOFT
27	29	SANDSTONE GREY HARD
29	48	SHALE DARK MEDIUM
48	50	FRACTURED SHALE GREY HARD WATER
50	55	SANDSTONE GREY HARD WATER
55	60	SHALE DARK SOFT

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	PAUL STEINMETZ
Company:	AAQUA DRILLING INC
License No:	WWC-542
Date Completed:	8/7/2009

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View water quality for this site
View scanned well log (9/30/2009 3:00:49 PM)

Site Name: ARNOLD GREEN MEADOW RANCH
GWIC Id: 252297

Section 1: Well Owner

Owner Name
ARNOLD GREEN MEADOW RANCH
Mailing Address
RR1 64 SPRING CREEK ROAD

City	State	Zip Code
ABSAROKEE	MT	59001

Section 2: Location

Township	Range	Section	Quarter Sections
03S	17E	21	NW¼ NW¼ NW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.56538	109.64387	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4680			

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Tuesday, August 04, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	18.5	10.75
18.5	70	7.825
70	130	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	18.5	8.625	0.25		WELDED	STEEL
-1.5	70	4.5			SOLVENT WELD	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
56	70	4.5		.025	SCREEN-CONTINUOUS-PVC

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	56	BENTONITE	
54	70	GRAVEL 3/8 ROUND	

Section 7: Well Test Data

Total Depth: 130
Static Water Level: 25
Water Temperature:

Air Test *

15 gpm with drill stem set at 70 feet for 1 hours.
Time of recovery 0.17 hours.
Recovery water level 25 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

HOLE BACK FILLED TO 70'

Section 9: Well Log

Geologic Source
211HLCK - HELL CREEK FORMATION

From	To	Description
0	2	TOPSOIL DARK SOFT
2	9	SANDY CLAY TAN SOFT
9	14	SANDSTONE TAN SOFT
14	26	SHALE DARK MEDIUM
26	54	SHALE DARK SOFT
54	65	SANDSTONE DARK HARD
65	130	SHALE DARK HARD

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: PAUL STEINMETZ
Company: AAQUA DRILLING INC
License No: WWC-542
Date Completed: 8/4/2009

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned well log (9/30/2009 3:02:19 PM)

Site Name: PEZOLDT L. J. SOUTH
GWIC Id: 252298

Section 1: Well Owner

Owner Name
PEZOLDT, L. J.
Mailing Address
50 WAGON TRAIL

City	State	Zip Code
COLUMBUS	MT	59019

Well Address
QA1 - SOUTH

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
02S	20E	32	NE¼ NE¼ SW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.61515	109.28625	SUR-GPS	WGS84

Altitude	Method	Datum	Date
3660			

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Thursday, July 30, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	10	8.75
10	23	7
23	24	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	23	6.625	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
23	24	6			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 24
Static Water Level: 9.2
Water Temperature:

Air Test *

75 gpm with drill stem set at 23 feet for 1 hours.
Time of recovery 0.08 hours.
Recovery water level 9.2 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
112SNGR - SAND AND GRAVEL (PLEISTOCENE)

From	To	Description
0	2	TOPSOIL TAN SOFT
2	4.5	SANDY LOAM TAN SOFT
4.5	23	GRAVEL DIRTY TAN MEDIUM
23	24	CLAY BROWN SOFT

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: PAUL STEINMETZ
Company: AAQUA DRILLING INC
License No: WWC-542
Date Completed: 7/30/2009

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned well log (9/30/2009 3:03:27 PM)

Site Name: PEZOLDT L. J. NORTH
GWIC Id: 252299

Section 1: Well Owner

Owner Name
PEZOLDT, L. J.
Mailing Address
50 WAGON TRAIL

City	State	Zip Code
COLUMBUS	MT	59019

Well Address
QU1 - NORTH

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
02S	20E	32	NE¼ NE¼ SW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.61515	109.28625	SUR-GPS	WGS84

Altitude	Method	Datum	Date
3660			

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Thursday, July 30, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	10	8.75
10	23	7
23	24	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	23	6.625	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
23.5	24	6			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 23.5
Static Water Level: 9.2
Water Temperature:

Air Test *

75 gpm with drill stem set at 23 feet for 1 hours.
Time of recovery 0.08 hours.
Recovery water level 9.2 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
112SNGR - SAND AND GRAVEL (PLEISTOCENE)

From	To	Description
0	2	TOPSOIL
2	5	SANDY LOAM TAN SOFT
5	23	GRAVEL DIRTY TAN MEDIUM
23	23.5	CLAY BROWN SOFT

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: PAUL STEINMETZ
Company: AAQUA DRILLING INC
License No: WWC-542
Date Completed: 7/30/2009

MONTANA WELL LOG REPORT	Other Options
This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.	Plot this site on a topographic map View hydrograph for this site View water quality for this site View scanned well log (9/30/2009 3:03:37 PM)

Site Name: JOHNSON FAMILY FOUNDATION BED ROCK
GWIC Id: 252300

Section 1: Well Owner

Owner Name
JOHNSON FAMILY FOUNDATION
Mailing Address
P O BOX 173610

City	State	Zip Code
BOZEMAN	MT	59717

Well Address
BED ROCK WELL

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
03S	18E	35	SE¼ NW¼ SW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.52725	109.47432	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4060			

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Thursday, July 30, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	13	10.75
13	47	8.625
41	71	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	41	8.625	0.25		WELDED	STEEL
-1.5	71	4.5			SOLVENT WELD	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
56	69	4.5		.025	SCREEN-CONTINUOUS-PVC

Section 7: Well Test Data

Total Depth: 71
Static Water Level: 8.75
Water Temperature:

Air Test *

30 gpm with drill stem set at 71 feet for 1 hours.
Time of recovery 0.17 hours.
Recovery water level 8.75 feet.
Pumping water level _ feet.

* *During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
125TLCK - TULLOCK MEMBER (OF FT UNION FM.)

From	To	Description
0	1	TOPSOIL DARK SOFT
1	41	GRAVEL TAN MEDIUM
41	42	SANDSTONE TAN HARD
42	58	SHALE GREY MEDIUM
58	67	SANDSTONE TAN MEDIUM
67	71	SHALE DARK MEDIUM

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	PAUL STEINMETZ
Company:	AAQUA DRILLING INC
License No:	WWC-542
Date Completed:	7/30/2009

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	54	BENTONITE	
54	71	GRAVEL 3/8 ROUND	

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View water quality for this site
View scanned well log (9/30/2009 3:03:42 PM)

Site Name: JOHNSON FAMILY FOUNDATION QAL W
GWIC Id: 252301

Section 1: Well Owner

Owner Name
JOHNSON FAMILY FOUNDATION
Mailing Address
P O BOX 173610

City	State	Zip Code
BOZEMAN	MT	59717

Well Address
QA1 - WEST

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
03S	18E	35	SE¼ NW¼ SW¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.52725	109.47432	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4060			

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Thursday, July 30, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	10	8.75
10	38.5	7

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	38.5	6.625	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
38.5	38.5	6.625			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 38.5
Static Water Level: 10.67
Water Temperature:

Air Test *

100 gpm with drill stem set at 38 feet for 1 hours.
Time of recovery 0.08 hours.
Recovery water level 10.67 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log
Geologic Source
110ALVM - ALLUVIUM (QUATERNARY)

From	To	Description
0	2	TOPSOIL DARK SOFT
2	33	GRAVEL GREY MEDIUM
33	38.5	SAND AND GRAVEL TAN MEDIUM

Driller Certification
All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	PAUL STEINMETZ
Company:	AAQUA DRILLING INC
License No:	WWC-542
Date Completed:	7/30/2009

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned well log (9/30/2009 2:30:39 PM)

Site Name: AADLAND DANIEL AND EMILY WEST
GWIC Id: 252302

Section 1: Well Owner

Owner Name
AALAND, DANIEL AND EMILY
Mailing Address
P O BOX 578

City	State	Zip Code
ABSAROKEE	MT	59001

Well Address
QA1 - WEST

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
04S	18E	24	NW¼ NW¼ SE¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.46533	109.44737	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4295			

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Wednesday, July 29, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	10	8.75
10	36	7
36	37	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	36	6.625	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
37	37	6.625			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 37
Static Water Level: 13
Water Temperature:

Air Test *

60 gpm with drill stem set at 36 feet for 1 hours.
Time of recovery 0.08 hours.
Recovery water level 13 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
110ALVM - ALLUVIUM (QUATERNARY)

From	To	Description
0	2	TOPSOIL DARK SOFT
2	36	GRAVEL GREY MEDIUM
36	37	CLAY BROWN SOFT

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name: PAUL STEINMETZ
Company: AAQUA DRILLING INC
License No: WWC-542
Date Completed: 7/29/2009

MONTANA WELL LOG REPORT	Other Options
This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is complied electronically from the contents of the Ground-Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.	Plot this site on a topographic map View hydrograph for this site View water quality for this site View scanned well log (9/30/2009 2:30:34 PM)

Site Name: AADLAND DANIEL AND EMILY EAST
GWIC Id: 252303

Section 1: Well Owner

Owner Name
AADLAND, DANIEL AND EMILY
Mailing Address
P O BOX 578

City	State	Zip Code
ABSAROKEE	MT	59001

Well Address
QA1 - EAST

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
04S	18E	24	NW¼ NW¼ SE¼

County	Geocode
STILLWATER	

Latitude	Longitude	Geomethod	Datum
45.4653	109.4473	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4295			

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Wednesday, July 29, 2009

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	10	8.75
10	36	7
36	37	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1.5	36	6.625	0.25		WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
36	36	6.625			OPEN BOTTOM

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	0	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 37
Static Water Level: 12.42
Water Temperature:

Air Test *

60 gpm with drill stem set at 36 feet for 1 hours.
Time of recovery 0.08 hours.
Recovery water level 12.42 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
110ALVM - ALLUVIUM (QUATERNARY)

From	To	Description
0	2	TOPSOIL DARK SOFT
2	36	GRAVEL GREY MEDIUM
36	37	CLAY BROWN SOFT

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	PAUL STEINMETZ
Company:	AAQUA DRILLING INC
License No:	WWC-542
Date Completed:	7/29/2009

APPENDIX C

Groundwater Sample Locations and Water Quality

Appendix C. Groundwater sample locations and water quality

Gwic ID	Sample ID	Latitude	Longitude	Aquifer	Sample Date	Water Temp (C)	Lab pH	Lab SC (µS/cm)
161141		45.53225	-109.55238	110ALVM	9/26/2008 11:35	10.1	6.52	231.6
220784		45.53352	-109.51513	110ALVM	9/25/2008 12:14	11.9	7.22	682
198691		45.52551	-109.48774	110ALVM	9/4/2008 14:30	10	7.64	357
198691		45.52551	-109.48774	110ALVM	8/18/2009	12.9	7.68	386
161144		45.5727	-109.331766	110ALVM	8/1/2008	12.2	7.52	414.1
101131	1982Q1072	45.4611	-109.7593	111SNGR	9/22/1982 14:10	10.5	7.77	259.1
148586	2003Q0630	45.3921	-109.5742	111SNGR	10/17/2002 10:50	9.8	6.61	186
102736	2003Q0633	45.3927	-109.5744	111SNGR	10/17/2002 9:36	8.8	7.2	206
101131	2003Q0733	45.4611	-109.7593	111SNGR	11/19/2002 14:10	10	7.77	369
100008	2003Q1153	45.5763	-109.3367	111SNGR	5/27/2003 13:03	6.7	7.32	166
132590	2004Q0116	45.5075	-109.653	111SNGR	8/18/2003 13:22	10.5	7.53	125
144216	2004Q0118	45.4557	-109.8477	111SNGR	8/26/2003 11:06	11.9	7.36	456
172250	2005Q0025	45.4923	-109.9056	111SNGR	7/19/2004 17:04	6.7	7.86	442
174838	2005Q0026	45.525	-109.6009	111SNGR	7/19/2004 16:52	9.8	7.88	246
188988	2005Q0029	45.5288	-109.4478	111SNGR	7/27/2004 10:17	10.9	8.13	397
172537	2005Q0070	45.4365	-109.4647	111SNGR	8/4/2004 9:24	12.3	7.72	282
102696	2005Q0518	45.4323	-109.8021	111SNGR	5/17/2005 16:07	8.7	7.83	394
101131	2010Q0068	45.4611	-109.7593	111SNGR	7/17/2009 13:00	9.9	7.77	288
100008	2010Q0122	45.5763	-109.3367	111SNGR	8/14/2009 14:00		7.35	180
252301	2010Q0267	45.52725	-109.47432	111SNGR	9/2/2009 18:30	11.8	7.76	372
97524		45.52254	-109.4966	111SNGR	9/26/2008 10:57	10.6	7.33	512
252299		45.61515	-109.28625	111SNGR	7/31/2009	12.9	8.12	505
252298		45.61515	-109.28625	111SNGR	8/5/2009	13.1	8.21	487
174838		45.525	-109.6009	111SNGR	8/18/2009	9.4	7.8	219
234274		45.52736	-109.58346	111SNGR	9/20/2008 17:15	10.3	7.68	260
234274		45.52736	-109.58346	111SNGR	8/18/2009	10	7.83	257.2
220782		45.52857	-109.58217	111SNGR	9/20/2008 16:50	9.9	7.15	211
249723		45.52907	-109.57779	111SNGR	9/20/2008 15:05	10.9	8.77	250
181692		45.53104	-109.55539	111SNGR	9/20/2008 13:30	9.6	7.19	249.8
156919		45.52949	-109.46725	111SNGR	9/20/2008 11:45	11.7	7.06	255
156919		45.52949	-109.46725	111SNGR	8/18/2009	10.1	7.11	245.6
252301		45.52725	-109.47432	111SNGR	9/2/2009 18:30	11.8	7.82	355
192434		45.52036	-109.482408	111SNGR	8/18/2009	10.1	7.57	355
181694		45.46704	-109.445766	111SNGR	4/13/2009	5.2	7.13	346
102792		45.4095	-109.4753	111SNGR	9/2/2009	8.7	7.43	268
143942	2003Q0306	45.6205	-109.2824	112SNGR	8/21/2002 16:27	11.2	7.7	535
198578	2004Q0073	45.4881	-109.6691	112SNGR	8/13/2003 15:34	9.6	7.51	275
144221	2004Q0074	45.4717	-109.7447	112SNGR	8/12/2003 16:32	11	7.78	301
196118	2005Q0516	45.394	-109.7176	112SNGR	5/17/2005 13:39	7.1	7.64	127
209848	2005Q0529	45.3479	-109.6192	112SNGR	5/25/2005 12:42	7.7	7.33	266
143942	2010Q0120	45.6205	-109.2824	112SNGR	8/11/2009 13:05	12.9	7.65	576
150349	2001Q1472	45.4947	-109.4581	125FRUN	5/3/2001		7.32	351
144084	2004Q0527	45.4436	-109.5023	125FRUN	4/22/2004 13:31	10.4	7.89	453
150349	2010Q0066	45.4947	-109.4581	125FRUN	7/17/2009 10:15	12.2	7.55	328
7527	1982Q1066	45.4724	-109.4718	125TGRV	9/24/1982 10:30	9	8.43	356.1
182107	2005Q0129	45.5223	-109.3902	125TGRV	8/11/2004 10:45	10	8.09	817
187173		45.53099	-109.57184	125TGRV	9/26/2008 13:03	11.8	7.01	339
217422		45.53403	-109.51553	125TGRV	9/25/2008 11:24	14.3	7.87	484.7
101288		45.49194	-109.458162	125TGRV	8/1/2008 12:15	16.6	9.13	466.3
101362		45.44573	-109.543045	125TGRV	6/13/2008 13:17	8.4	8.61	250

Appendix C. Groundwater sample locations and water quality

Gwic ID	Sample ID	Latitude	Longitude	Aquifer	Sample Date	Water Temp (C)	Lab pH	Lab SC (µS/cm)
102741		45.38936	-109.677119	125TGRV	6/18/2008 15:40	7.5	7.43	490.2
102741		45.38936	-109.677119	125TGRV	9/3/2009	12.5	7.5	400
99934	2005Q0031	45.5488	-109.5097	125TLCK	7/28/2004 8:42	10.1	7.8	525
121866	2005Q0032	45.4976	-109.2296	125TLCK	7/28/2004 14:00	11.5	7.86	709
144241	2005Q0069	45.4358	-109.4661	125TLCK	8/4/2004 8:16	10.9	8.01	313
101301	2005Q0497	45.48586	-109.470724	125TLCK	5/12/2005 11:25	16.1	8.64	447
185284	2005Q0498	45.4914	-109.4857	125TLCK	5/12/2005 10:22	11.1	8.76	591
100025	2005Q0517	45.5465	-109.3207	125TLCK	5/19/2005 9:50		7.63	757
101409	2006Q0052	45.5073	-109.2668	125TLCK	7/18/2005 14:20	9.7	8.02	622
217303	2010Q0027	45.50324	-109.31002	125TLCK	7/1/2009 20:18	9.9	7.57	728
252300		45.52725	-109.47432	125TLCK	7/31/2009		8.25	370.4
245384		45.52175	-109.49117	125TLCK	6/13/2008 11:00	10.9	6.78	489
245384		45.52175	-109.49117	125TLCK	9/5/2008 12:45	11.1	7.39	468
245384		45.52175	-109.49117	125TLCK	4/7/2009	10.9	7.39	519
245384		45.52175	-109.49117	125TLCK	8/18/2009	10	7.46	419
252296		45.49252	-109.53495	125TLCK	8/7/2009	13.6	8.22	871
252295		45.49252	-109.53495	125TLCK	8/10/2009	17.3	8.36	995
171725	2003Q0596	45.4087	-109.6593	211EGLE	10/2/2002 17:20	9.1	7.66	1124
101159	2004Q0075	45.4653	-109.7877	211EGLE	8/7/2003 10:05	12.2	8.21	506
148582	2004Q0076	45.4689	-109.7585	211EGLE	8/6/2003 12:30	11	7.35	191.5
171104	2004Q0117	45.4161	-109.818	211EGLE	8/19/2003 13:29	8.4	7.96	466
102714	2004Q0119	45.3948	-109.7186	211EGLE	8/26/2003 16:36	8.7	8.47	248
7524	1982Q1077	45.4898	-109.5427	211HLCK	9/24/1982 9:20	10	8.22	851.9
10200	1985Q0020	45.8141	-109.4713	211HLCK	10/23/1984 11:00	10.5	7.86	1280
10200	2001Q1473	45.8141	-109.4713	211HLCK	5/3/2001 17:10	10.5	7.36	1672
152675	2002Q1537	45.6819	-109.4543	211HLCK	6/20/2002 13:10	11.7	7.83	884
195143	2003Q0267	45.7071	-109.5559	211HLCK	8/13/2002 18:55	11	8.81	492
121860	2003Q0305	45.6092	-109.2735	211HLCK	8/20/2002 8:46	13.1	7.81	816
152675	2003Q0307	45.6819	-109.4543	211HLCK	8/15/2002 15:35	12	7.93	831
121803	2003Q0308	45.727	-109.2855	211HLCK	8/21/2002 11:12	12.5	8.11	1061
150131	2003Q0424	45.6152	-109.2863	211HLCK	8/29/2002 9:25	11.2	8.4	824
161007	2003Q0427	45.6245	-109.3357	211HLCK	9/4/2002 10:29	11.4	7.72	879
145486	2003Q0631	45.4917	-109.5631	211HLCK	10/15/2002 11:43	10.5	7.7	1015
99930	2005Q0024	45.531	-109.5782	211HLCK	7/19/2004 15:35	8.7	9.39	284
99923	2005Q0030	45.5441	-109.6218	211HLCK	7/27/2004 15:01	10.7	7.69	335
201725	2005Q0469	45.6696	-109.4727	211HLCK	4/28/2005 11:41	10.8	7.89	853
204120	2005Q0470	45.6556	-109.3486	211HLCK	5/3/2005 13:50	11.8	8.68	1440
143930	2005Q0471	45.6539	-109.3467	211HLCK	5/3/2005 16:32	9.6	7.76	1012
180042	2005Q0512	45.8158	-109.4301	211HLCK	5/19/2005 13:41	9.7	7.96	1321
150225	2005Q0515	45.4426	-109.5366	211HLCK	5/18/2005 10:43	11.7	9.11	297
185234	2005Q0528	45.5944	-109.3155	211HLCK	5/26/2005 9:29	9.6	8.27	426
92572	2006Q0028	45.7586	-109.5319	211HLCK	6/27/2005 14:00	10.9	7.91	1102
220681	2006Q0031	45.7602	-109.5326	211HLCK	6/27/2005 15:24	13.1	8.01	1092
177158	2006Q0051	45.8918	-109.4391	211HLCK	7/18/2005 14:20	10.9	7.73	825
176223	2006Q0104	45.7057	-109.2888	211HLCK	7/29/2005 15:45	12.3	8.02	960
145486	2010Q0065	45.4917	-109.5631	211HLCK	7/17/2009 11:45	10.8	7.86	864
121860	2010Q0121	45.6092	-109.2735	211HLCK	8/11/2009 15:00	13.1	8.01	796
121803	2010Q0125	45.727	-109.2855	211HLCK	8/11/2009 11:00	14	7.83	911
150131		45.6152	-109.2863	211HLCK	7/31/2009	11.5	9.13	740
252297		45.56538	-109.64387	211HLCK	8/27/2009	11	8.87	359

Appendix C. Groundwater sample locations and water quality

Gwic ID	Sample ID	Latitude	Longitude	Aquifer	Sample Date	Water Temp (C)	Lab pH	Lab SC (µS/cm)
99930		45.531	-109.5782	211HLCK	8/14/2008 12:00	9.6	9.16	290
185234		45.5944	-109.3155	211HLCK	8/28/2008	12.9	8.38	546
150225		45.4426	-109.5366	211HLCK	3/20/2009	12	9.7	236.4
7319	1979Q3163	45.5632	-109.7138	211LVIS	8/1/1979 2:30	7.5	7.08	195.5
169866	2005Q0027	45.4111	-109.5567	211LVIS	7/28/2004 12:34	10.3	8.18	287
213653	2005Q0127	45.4572	-109.6101	211LVIS	8/11/2004 13:52	10.7	7.45	201
183029	2005Q0128	45.5458	-109.6861	211LVIS	8/17/2004 10:58	10.6	7.61	261
102780	2005Q0514	45.4345	-109.5603	211LVIS	5/17/2005 11:56	8.3	7.12	264

APPENDIX D

Groundwater Quality Samples

Appendix D. Groundwater quality samples

Gwic Id	Sample	Site Name	Latitude
97455	2005Q0496	BRUMFIELD TERRY	45.638
97456	2003Q0425	PLYMALE MIKE	45.6274
97495	2005Q0311	ATKINS RICHARD	45.6104
99934	2005Q0031	STUDINER MIKE	45.5488
100025	2005Q0517	WOLLSCHLAGER DEWAYNE	45.5465
101301	2005Q0497	CHANDLER KEVIN AND KATRIN	45.485861
101409	2006Q0052	PIERSON FRANK E.	45.5073
121866	2005Q0032	ROUANE ROBERT & TONI	45.4976
144241	2005Q0069	STAIGMILLER BOB	45.4358
176780	2005Q0319	BOTT ARCHIE	45.5511
185226	2003Q0426	PLYMALE MIKE	45.5879
185284	2005Q0498	ALLEY STEVE	45.4914
217303	2010Q0027	BEARTOOTH INT (FINKLE RANCH)	45.50324
252295	2010Q0248	JOHNSON FAMILY FOUNDATION GROVE S	45.49252
144103	2003Q0422	PLYMALE MIKE	45.3557
144103	2010Q0059	PLYMALE MIKE	45.3557
150219	2005Q0265	INDRELAND TRENT- DADS HOUSE-JOHN INDRELAND	45.3775
154728	2003Q0451	BELL HUNTER	45.3495
161309	2003Q0420	ROBERTS REST AREA	45.3851
179438	2006Q0053	ANDERSON BILL	45.4461
192348	2005Q0033	LOHRENZ HAROLD J	45.5144
6953	1981Q0101	DUVAL DON * 2 MI SE KENT SCHOOL	45.718028
6954	1981Q0102	GREEN LEAMON	45.700833
6955	1981Q0104	RAYBORN BILL	45.709415
7167	1981Q0182	BUE * 4 MI SOUTH OF KENT SCHOOL *	45.6697
7524	1982Q1077	TYLER ROBERT	45.4898
92620	2002Q1447	REED POINT ELEMENTARY SCHOOL	45.7071
99923	2005Q0030	FLANAGAN TOM	45.5441
99930	2005Q0024	FRAZER CATHERINE	45.531
101494	2005Q0250	KROOK RONALD	45.4579
121860	2003Q0305	NICHOLSON JACK	45.6092
121860	2010Q0121	NICHOLSON JACK	45.6092
143930	2005Q0471	COUNTRYMAN CREEK HOMEOWNERS ASSOC	45.6539
145486	2003Q0631	BAXTER MARTHA AND TEEGARDIN CLINTON B	45.4917
145486	2010Q0065	BAXTER MARTHA AND TEEGARDIN CLINTON B	45.4917
150131	2003Q0424	PEZOLDT L J	45.6152
150225	2005Q0515	ESP ERIC	45.4426
152675	2003Q0307	HOLDEN SCOTT	45.6819
152675	2002Q1537	HOLDEN SCOTT	45.6819
161007	2003Q0427	JENSEN ANDY	45.6245
185234	2005Q0528	SUTHERLAND OPAL	45.5944
195143	2003Q0267	STILLWATER COUNTY SOLID WASTE	45.7071
201725	2005Q0469	BRUMFIELD TERRY	45.6696
204120	2005Q0470	NITZEL KEN	45.6556
252297	2010Q0249	ARNOLD GREEN MEADOW RANCH	45.56538

Appendix D.

Gwic Id	Longitude	Geomethod	Datum	Basin	Twn	Rng	Sec	Q Sec	County
97455	-109.48	NAV-GPS	NAD83	HD	02S	18E	27	AAAA	STILLWATER
97456	-109.5548	NAV-GPS	NAD83	HD	02S	18E	30	CADC	STILLWATER
97495	-109.4181	NAV-GPS	NAD83	HD	02S	19E	32	CCBC	STILLWATER
99934	-109.5097	NAV-GPS	NAD83	HE	03S	18E	28	ABBC	STILLWATER
100025	-109.3207	NAV-GPS	NAD83	HE	03S	19E	25	ACAA	STILLWATER
101301	-109.470724	SUR-GPS	NAD83	HE	04S	18E	14	CAAA	STILLWATER
101409	-109.2668	MAP	NAD83	HE	04S	20E	9	BABA	STILLWATER
121866	-109.2296	MAP	NAD83	HE	04S	20E	11	CBDC	STILLWATER
144241	-109.4661	NAV-GPS	NAD83	HE	04S	18E	35	DCDC	STILLWATER
176780	-109.2026	NAV-GPS	NAD83	HE	03S	20E	25	BAAA	STILLWATER
185226	-109.542	NAV-GPS	NAD83	HD	03S	18E	7	ADDD	STILLWATER
185284	-109.4857	NAV-GPS	NAD83	HE	04S	18E	15	ABAD	STILLWATER
217303	-109.31002	NAV-GPS	NAD27	HD	04S	20E	7	BCAD	STILLWATER
252295	-109.53495	SUR-GPS	WGS84	HE	04S	18E	17	BBA	STILLWATER
144103	-109.4581	NAV-GPS	NAD83	HE	05S	18E	36	BCCC	CARBON
144103	-109.4581	NAV-GPS	NAD83	HE	05S	18E	36	BCCC	CARBON
150219	-109.3195	MAP	NAD83	HF	05S	19E	24	DDCC	CARBON
154728	-109.1617	NAV-GPS	NAD83	HF	05S	21E	32	CDCD	CARBON
161309	-109.1387	NAV-GPS	NAD83	HF	05S	21E	21	CAAB	CARBON
179438	-109.1871	MAP	NAD83	HF	04S	21E	31	BCBA	CARBON
192348	-109.1548	MAP	NAD83	HD	04S	21E	5	DBAC	CARBON
6953	-109.655669	TRS-SEC	NAD83	HD	01S	17E	29	BDDD	SWEET GRASS
6954	-109.628594	TRS-SEC	NAD83	HD	01S	17E	33	DACB	SWEET GRASS
6955	-109.591826	TRS-SEC	NAD83	HD	01S	17E	35	ABB	SWEET GRASS
7167	-109.6936	MAP	NAD27	HD	02S	16E	12	DCBA	SWEET GRASS
7524	-109.5427	NAV-GPS	NAD83	HE	04S	18E	18	ADAA	STILLWATER
92620	-109.5458	MAP	NAD27	HD	01S	18E	31	AADC	STILLWATER
99923	-109.6218	NAV-GPS	NAD83	HE	03S	17E	27	BCCD	STILLWATER
99930	-109.5782	NAV-GPS	NAD83	HE	03S	17E	36	BCDA	STILLWATER
101494	-109.1076	NAV-GPS	NAD83	HF	04S	21E	27	ADDD	CARBON
121860	-109.2735	NAV-GPS	NAD83	HE	03S	20E	4	BBBB	STILLWATER
121860	-109.2735	NAV-GPS	NAD83	HE	03S	20E	4	BBBB	STILLWATER
143930	-109.3467	NAV-GPS	NAD83	HD	02S	19E	14	CDDA	STILLWATER
145486	-109.5631	NAV-GPS	NAD83	HE	04S	17E	13	AAAD	STILLWATER
145486	-109.5631	NAV-GPS	NAD83	HE	04S	17E	13	AAAD	STILLWATER
150131	-109.2863	NAV-GPS	NAD83	HE	02S	20E	32	CAAC	STILLWATER
150225	-109.5366	NAV-GPS	NAD83	HE	04S	18E	32	CBAA	STILLWATER
152675	-109.4543	NAV-GPS	NAD83	HD	02S	18E	1	CCDD	STILLWATER
152675	-109.4543	NAV-GPS	NAD83	HD	02S	18E	1	CCDD	STILLWATER
161007	-109.3357	NAV-GPS	NAD83	HB	02S	19E	25	CCCB	STILLWATER
185234	-109.3155	NAV-GPS	NAD83	HE	03S	19E	12	AAAA	STILLWATER
195143	-109.5559	NAV-GPS	NAD83	HD	01S	18E	31	BDBB	STILLWATER
201725	-109.4727	NAV-GPS	NAD83	HD	02S	18E	11	CDBA	STILLWATER
204120	-109.3486	NAV-GPS	NAD83	HD	02S	19E	14	CDAB	STILLWATER
252297	-109.64387	SUR-GPS	WGS84	HE	03S	17E	21	BBB	STILLWATER

Appendix D.

Gwic Id	Aquifer	Depth (ft)	Comp Date	Agency	Sample Date	Water Temp	Lab pH	Lab SC
97455	125TLCK	60	1/1/1950	MBMG	4/28/2005 9:41	9.7	7.76	1040
97456	125TLCK	62	1/1/1961	MBMG	8/28/2002 17:41	8.2	7.67	921
97495	125TLCK	65	1/1/1984	MBMG	10/22/2004 11:09	10.8	7.86	646
99934	125TLCK	41	8/16/1971	MBMG	7/28/2004 8:42	10.1	7.8	525
100025	125TLCK	70	4/4/1979	MBMG	5/19/2005 9:50		7.63	757
101301	125TLCK	170	11/13/1979	MBMG	5/12/2005 11:25	16.1	8.64	447
101409	125TLCK	70	4/13/1988	MBMG	7/18/2005 14:20	9.7	8.02	622
121866	125TLCK	120	7/30/1990	MBMG	7/28/2004 14:00	11.5	7.86	709
144241	125TLCK	170	4/19/1990	MBMG	8/4/2004 8:16	10.9	8.01	313
176780	125TLCK	80	9/28/1999	MBMG	11/18/2004 14:00	12.2	7.81	545
185226	125TLCK	130	9/12/2000	MBMG	8/28/2002 11:11	9.7	8.51	608
185284	125TLCK	300	11/16/2000	MBMG	5/12/2005 10:22	11.1	8.76	591
217303	125TLCK	75		MBMG	7/1/2009 20:18	9.9	7.57	728
252295	125TLCK	73	8/10/2009	MBMG	8/27/2009 8:53		7.96	978
144103	125TLCK	110	8/13/1992	MBMG	8/28/2002 14:33	11.3	7.39	700
144103	125TLCK	110	8/13/1992	MBMG	7/16/2009 17:00	9.9	7.62	607
150219	125TLCK	240	6/5/1995	MBMG	10/22/2004 16:00	9.1	7.71	1370
154728	125TLCK	220	1/26/1994	MBMG	9/8/2002 18:40	11	7.36	566
161309	125TLCK	220	10/29/1996	MBMG	8/28/2002 12:15	11.2	7.59	618
179438	125TLCK	100	9/11/1999	MBMG	7/18/2005 10:33	9.4	8.19	1001
192348	125TLCK	190	8/27/2001	MBMG	7/27/2004 11:05	9.5	7.93	542
6953	211HLCK	105	11/9/1973	USGS	3/10/1981 9:45	10.5	8.01	406
6954	211HLCK	110	3/7/1977	USGS	3/10/1981 13:45	9	7.59	598.7
6955	211HLCK	140	4/6/1976	USGS	3/11/1981 14:10	8.5	7.98	692.5
7167	211HLCK	50		USGS	4/1/1981 12:30	10	7.97	370.7
7524	211HLCK	57		USGS	9/24/1982 9:20	10	8.22	851.9
92620	211HLCK	70	6/20/1979	MBMG	6/6/2002 12:30	14.6	7.47	711
99923	211HLCK	60	3/15/1961	MBMG	7/27/2004 15:01	10.7	7.69	335
99930	211HLCK	90	4/7/1989	MBMG	7/19/2004 15:35	8.7	9.39	284
101494	211HLCK	50	11/11/1974	MBMG	10/7/2004 17:25		7.8	879
121860	211HLCK	121	12/11/1990	MBMG	8/20/2002 8:46	13.1	7.81	816
121860	211HLCK	121	12/11/1990	MBMG	8/11/2009 15:00	13.1	8.01	796
143930	211HLCK	47	5/17/1985	MBMG	5/3/2005 16:32	9.6	7.76	1012
145486	211HLCK	105	11/19/1993	MBMG	10/15/2002 11:43	10.5	7.7	1015
145486	211HLCK	105	11/19/1993	MBMG	7/17/2009 11:45	10.8	7.86	864
150131	211HLCK	80	12/9/1993	MBMG	8/29/2002 9:25	11.2	8.4	824
150225	211HLCK	330	11/10/1994	MBMG	5/18/2005 10:43	11.7	9.11	297
152675	211HLCK	50.8		MBMG	8/15/2002 15:35	12	7.93	831
152675	211HLCK	50.8		MBMG	6/20/2002 13:10	11.7	7.83	884
161007	211HLCK	120	12/18/1999	MBMG	9/4/2002 10:29	11.4	7.72	879
185234	211HLCK	170	11/14/2000	MBMG	5/26/2005 9:29	9.6	8.27	426
195143	211HLCK	83	3/13/2002	MBMG	8/13/2002 18:55	11	8.81	492
201725	211HLCK	130	1/14/2003	MBMG	4/28/2005 11:41	10.8	7.89	853
204120	211HLCK	110	6/18/2003	MBMG	5/3/2005 13:50	11.8	8.68	1440
252297	211HLCK	130	8/4/2009	MBMG	8/28/2009 18:00	11	8.52	406

Appendix D.

Gwic Id	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Fe (mg/l)	Mn (mg/l)	SiO2 (mg/l)	HCO3 (mg/l)
97455	23.4	12.7	207.3	2.21	0.052	0.012	8.15	523
97456	28.6	16.4	143	2.28	0.103	0.005	7.19	523.1
97495	42	19	81.3	2.32	0.009	<0.001	6.68	353.5
99934	51.6	17.8	43.7	1.37	0.011	<0.001	8.64	329.7
100025	52.3	20.4	98.1	2.56	0.06	0.003	8.01	436
101301	0.817	0.1	115	0.514	0.109	0.004	7.78	215
101409	45.7	11.8	88.1	1.44	0.012	<0.001	8.36	332.8
121866	59.3	15.9	77.8	1.85	0.012	0.003	8.12	383.7
144241	9.15	2.13	39.1	0.34	0.01	<0.001	8.32	149.1
176780	63.3	32.9	11.2	1.64	0.013	<0.001	11.2	311.1
185226	2.56	0.608	136	0.472	<0.025	<0.005	7.22	289.9
185284	2.19	0.13	141	0.188	<0.005	<0.001	7.95	253
217303	56.6	17.4	88.8	2.62	0.017	0.004	7.76	393.5
252295	58	14.7	156	0.896	<0.002	0.005	7.95	374.5
144103	54.2	16.1	78.5	1.75	0.008	<0.001	7.79	402.1
144103	47.8	14.3	82	1.82	<0.002	<0.001	18.5	385.5
150219	51.8	20.8	252	1.15	4.7	0.154	8.13	637
154728	57.2	19.4	31	1.94	0.008	<0.001	10.9	326
161309	67.5	27.5	21.4	2.58	0.021	0.105	8.57	402.1
179438	18.1	4.53	252	2.68	0.213	0.051	7.59	559.98
192348	51.6	23.2	30.5	3.66	0.019	<0.001	9.04	318.4
6953	22	0.8	67	0.3	0.051	0.024	10.8	214.4
6954	51.2	13	57.4	0.7	0.047	0.003	9.4	327
6955	47.9	16.3	79.6	1.6	0.089	0.096	9.5	346
7167	37.9	9.5	23.2	0.6	0.026	0.026	10.3	197.6
7524	29.8	3.3	170	0.6	0.053	0.055	10.1	371
92620	55.7	21.1	93	2.76	0.013	<.001	17	475.8
99923	44.3	3.5	26.6	<.5	0.025	<0.001	46	201.3
99930	2.91	0.124	62.9	0.161	<0.005	0.002	8.27	88.1
101494	55.7	27.2	116	2.09	0.025	0.009	7.59	476.7
121860	47.6	25.4	104	2.23	0.011	<0.001	7.56	449.9
121860	54.6	27.7	104	2.38	0.002	0.001	8.02	436.2
143930	31.7	20.9	182	2.05	0.006	<0.001	9.76	396.2
145486	30.7	6.84	195	0.409	<0.005	0.016	6.82	459.5
145486	25.7	6.15	199	0.405	0.002	0.008	15.9	475.8
150131	1.32	0.178	195	0.484	<0.025	<0.005	7.86	461.6
150225	6.67	0.952	62.6	0.173	0.013	<0.001	10.7	180.3
152675	59.3	37.4	66.3	2.84	0.015	<0.001	15.9	354.9
152675	56.6	35.5	56.5	2.87	0.013	<.001	16.4	330.6
161007	46.8	30	92.6	1.98	0.011	<0.001	6.75	384.7
185234	11.2	5.73	79.9	1.27	0.046	0.012	8.1	261
195143	1.37	0.058	109	0.133	<0.005	<0.001	8.41	172.8
201725	43.8	31.6	105	2.61	0.027	0.001	8.38	353.5
204120	3.39	1.03	320	0.699	0.009	0.005	8.22	311.3
252297	7.79	0.262	80.3	0.217	<0.002	<0.001	7.51	191.8

Appendix D.

Gwic Id	CO3 (mg/l)	SO4 (mg/l)	Cl (mg/l)	NO3 (mg/l)	F (mg/l)	OPO4 (mg/l)	Ag (ug/l)	Al (ug/l)
97455	0	92.5	30	<0.05 P	0.406	0.062	<1	<10
97456	0	54	6.8	<0.5 P	1.68	<0.05		<30
97495	0	33.7	9.38	3.03 P	0.259	<0.05	<1	<10
99934	0	31.8	3.27	0.709 P	0.222	<0.05	<1	<10
100025	0	61.4	13.8	<0.5 P	0.211	<0.05	<1	<10
101301	10.1	25.8	1.59	<0.05 P	2.79	<0.05	<1	<10
101409	0	52.1	12.6	0.967 P	0.338	0.163	<1	<10
121866	0	35.8	20.5	<0.05 P	0.216	<0.05	<1	<10
144241	0	4.65	0.5	0.083 P	0.108	<0.05	<1	<10
176780	0	31.7	4.77	0.363 P	0.401	<0.05	<1	<10
185226	12	42	1.6	<0.5 P	1.29	<0.05		<30
185284	15.6	64.4	15.6	2.33 P	0.225	<0.05	<1	<10
217303	0	61.7	17.9	1.30 P	<0.5	<0.5	<0.11	<0.41
252295	0	222.4	17.2	1.13 P	0.622	<0.5	<0.04	<7.60
144103	0	55	2.5	<0.5 P	0.47	<0.05		<30
144103	0	37.55	2.62	1.44 P	0.561	<0.05	<0.04	<7.68
150219	0	212	1.25	<0.50 P	0.255	<0.25	<5	<30
154728	0	42.2	0.5	<0.5 P	0.26	<0.05		<30
161309	0	18.9	1.6	<0.5 P	0.22	<0.05		<30
179438	0	83.7	15.1	<0.10 P	0.673	<0.05	<1	<10
192348	0	35.1	4.07	<0.05 P	0.216	<0.05	<1	<10
6953	0	15.6	9.1	0.09	1.82			
6954	0	36	3.7	0.09	0.69			
6955	0	65.8	9.4	0.01	0.61			
7167	0	15.9	4.9	0.17	0.4		<2.	<30.
7524	0	122	22.1	<.01	0.8		<2.	<30.
92620	0	52.1	18.7	2.08	<.5	<.5	<1	<30
99923	0	19.1	2.38	0.106 P	0.319	<0.05	<1	<10
99930	16.8	24.7	4.1	<0.05 P	<0.05	<0.05	<1	<30
101494	0	65.8	11.2	0.472 P	0.144	<0.05	<1	<10
121860	0	72.6	13.8	.601 P	0.474	<.05		<30
121860	0	80.4	20.14	1.24 P	<0.5	<0.5	<0.04	<7.60
143930	0	161	22.4	<0.5	<0.5	<0.5	<1	<30
145486	0	125	25	0.9 P	0.8	<0.5		<30
145486	0	78.9	20.2	4.95 P	0.653	<0.5	<0.04	<7.68
150131	3.84	23	23.2	<0.5 P	1.88	<0.05		<30
150225	0	7.06	2.73	0.585 P	1.28	<0.05	<1	18.5
152675	0	115	13	2.18 P	0.44	<0.05		<30
152675	0	121	14.5	2.73 P	0.381	<.05	<1	<30
161007	0	105	10.9	0.8 P	0.66	<0.05		<30
185234	0	14.1	2.64	<0.5 P	0.449	<0.05	<1	<10
195143	19.2	3.35	37.6	<.5 P	5.43	0.188		<30
201725	0	146	19.9	2.51 P	<0.5	<0.5	<1	<30
204120	14.9	26.8	283	<0.5 P	3.96	<2.5	<5	<30
252297	5.76	22.01	3.2	1.10 P	1.94	<0.05	<0.04	<7.60

Appendix D.

Gwic Id	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)
97455	<1	389	33.7	<2	50	<1	<2	<2	3.09
97456	<10	450	81.9	<2	<50	<1	<2	<10	<5
97495	3.26	65.1	48.4	<2	<50	<1	<2	<2	<2
99934	<1	59.4	66.5	<2	<50	<1	<2	2.8	2.17
100025	<1	60.4	81.5	<2	<50	<1	<2	2.82	<2
101301	1.88	92.7	15.2	<2	<50	<1	<2	<2	<2
101409	<1	58.3	123	<2	<50	<1	<2	2.11	<2
121866	<1	45.7	177	<2	56	<1	<2	3.49	<2
144241	<1	<30	17.8	<2	<50	<1	<2	<2	<2
176780	<1	<30	99.5	<2	<50	<1	<2	4.37	<2
185226	<10	256	36.8	<2	<50	<1	<2	<10	<5
185284	1.09	34.4	9.23	<2	<50	<1	<2	<2	3.68
217303	0.211	67.3	85.9	<0.33	<500	<0.11	<0.11	<0.17	0.767
252295	0.197	62.8	30.4	<0.20	<500	<0.05	<0.10	0.112	<0.40
144103	<10	<30	57.9	<2	<50	<1	<2	<10	<5
144103	0.136	21.4	46.6	<0.20	<50	<0.05	<0.10	0.101	1.46
150219	<5	210	26.4	<2	<250	<1	<2	<10	<5
154728	<10	<30	132	<2	<50	<1	<2	<10	40.7
161309	<10	50.3	442	<2	<50	<1	<2	<10	<5
179438	<1	54	125	<2	78	<1	<2	2.61	<2
192348	<1	62.4	89.4	<2	<50	<1	<2	<2	<2
6953									
6954									
6955									
7167		<111.				<2.		<2.	6
7524		130				<2.		<2.	2
92620	2.93	333	77.8	<2	<500	<2	<2	2.02	35.8
99923	<1	73.9	97.8	<2	<50	<1	<2	<2	3.09
99930	6.58	5.06	15.5	<2	<50	<1	<2	<2	<2
101494	<1	186	56.7	<2	<50	<1	<2	<2	3.03
121860		121	104	<2	<50	<1	<2	<10	10.2
121860	0.265	108	101	<0.20	<500	<0.05	<0.10	0.19	1.07
143930	1.62	339	21.3	<2	<500	<1	<2	<2	3.91
145486	<10	121	59.3	<2	<500	<1	<2	<10	<5
145486	0.762	106	44.8	<0.20	<500	<0.05	<0.10	0.049	2.11
150131	<10	741	65.4	<2	110	<1	<2	<10	<5
150225	1.33	143	8.42	<2	<50	<1	<2	<2	2.12
152675		155	51.3	<2	<50	<1	<2	<10	<5
152675	<1	159	50.9	<2	146	<2	<2	2.34	2.33
161007	<10	184	60.5	<2	<50	<1	<2	<10	<5
185234	<1	122	246	<2	<50	<1	<2	<2	<2
195143		1380	24.3	<2	262	<1	<2	<10	<5
201725	1.07	239	26.7	<2	<500	<1	<2	<2	<2
204120	<5	1106	110	<2	<2500	<1	<2	<10	<10
252297	2.12	428	48.1	<0.20	<50	<0.05	<0.10	<0.04	<0.04

Appendix D.

Gwic Id	Tl (ug/l)	U (ug/l)	V (ug/l)	Zn (ug/l)	Zr (ug/l)	TDS (mg/L)	SAR
97455	<5	<0.5	<5	31.2	<2	636	8.6
97456	<20		<10	7.61	<2	519	5.3
97495	<5	20.9	5.21	51.6	<2	371	2.6
99934	<5	1.8	<5	26.1	<2	322	1.3
100025	<5	0.851	<5	8.64	<2	473	2.9
101301	<5	<0.5	<5	28	<2	270	32.0
101409	<5	1.22	<5	7.01	<2	386	3.0
121866	<5	1.68	<5	21.5	<2	410	2.3
144241	<5	0.745	<5	3.22	<2	138	3.0
176780	<5	4.09	<5	13.5	<2	311	0.3
185226	<20		<10	2.57	<2	347	19.8
185284	<5	1.52	<5	<2	<2	372	25.0
217303	<0.19	2.6	0.183	7.97	<0.10	448	2.6
252295	<0.03	2.35	0.12	9.87	<0.05	663	4.7
144103	<20		<10	28.4	<2	415	2.4
144103	<0.03	2.77	<0.10	4.44	<0.05	396	2.7
150219	<20	4.4	<10	<2	<2	866	7.5
154728	<20		<10	11.7	<2	324	0.9
161309	<20		<10	17.4	<2	348	0.6
179438	<5	1.22	<5	7.19	<2	661	13.7
192348	<5	2.71	<5	<2	<2	317	0.9
6953						233	3.8
6954						333	1.9
6955						401	2.5
7167			<1.	272	<4.	203	0.9
7524			<1.	6	<3.	542	7.9
92620	<5	6.52	<5	132	<2	498	2.7
99923	<5	0.69	<5	<2	<2	242	1.0
99930	<5	<1	<5	<2	<2	163	9.8
101494	<5	3.72	<5	67.6	<2	522	3.2
121860	<20		<10	3.16	<2	497	3.0
121860	<0.03	5.19	0.107	<0.90	<0.05	514	2.9
143930	<5	2.18	<5	11	<2	626	6.2
145486	<20		<10	7.97	<2	617	8.3
145486	<0.03	7.93	0.735	<0.91	<0.05	581	9.2
150131	<20		<10	<2	<2	485	42.3
150225	<5	1.49	<5	<2	<2	181	6.0
152675	<20		<10	12.5	<2	487	1.7
152675	<5	4.45	<5	11.4	<2	468	1.5
161007	<20		<10	<2	<2	486	2.6
185234	<5	<0.5	<5	<2	<2	252	4.8
195143	<20		<10	2.12	<2	271	24.8
201725	<5	3.43	<5	4.75	<2	533	3.0
204120	<25	<2.5	<10	4.43	<2	816	39.1
252297	<0.03	0.255	0.523	<0.90	<0.05	224	7.7

APPENDIX E

Oxygen and Hydrogen Stable Isotopes

Appendix E. Oxygen and hydrogen stable isotopes

Site Name	Site Type	Collection Date	D	^{18}O
East Rosebud Creek above ER lake	River	7/17/2008	-143.5	-18.88
East Rosebud Creek at Top	River	4/5/2009	-136.4	-18.5
West Rosebud Creek Near Power Station	River	7/17/2008	-142.8	-18.70
West Rosebud Creek at top	River	4/2/2009	-136.2	-18.6
Fishtail Creek at Keller	River	7/15/2008	-140.2	-18.44
Fishtail Creek at Keller	River	4/6/2009	-133.9	-18.5
Fishtail Creek at Keller	River	9/3/2009	-132.3	-17.45
Fiddler Creek	River	4/5/2009	-133.8	-18.2
Bad Canyon Creek	River	4/6/2009	-127.2	-17.1
Butcher Creek	River	4/7/2009	-134.2	-17.9
Stillwater River at Woodbine	River	7/17/2008	-145.4	-19.18
Stillwater River at Woodbine	River	4/6/2009	-139.2	-18.9
Stillwater River at Red Bridge	River	10/9/2008	-135.8	-18.3
Stillwater River at Johnson Bridge	River	10/9/2008	-135.0	-18.1
Stillwater River near Cliff Swallow	River	9/6/2008	-137.6	-18.4
Stillwater River at Johnson Bridge	River	9/6/2008	-136.5	-18.4
Stillwater River at Johnson Bridge	River	2/11/2009	-137.3	-18.6
Stillwater River at Red Bridge	River	2/11/2009	-137.4	-18.7
Stillwater River at Cox Bridge	River	8/17/2009	-137.1	-18.54
Stillwater River at Johnson Bridge	River	8/17/2009	-136.9	-17.89
Trout Creek	River	10/9/2008	-127.0	-16.7
Trout Creek	River	9/6/2008	-127.0	-16.7
Trout Creek	River	2/11/2009	-127.5	-17.0
Grove Creek	River	9/6/2008	-134.5	-18.1
Grove Creek	River	10/9/2008	-123.2	-16.1
Grove Creek at Top	River	4/7/2009	-127.8	-16.7
Grove Creek	River	2/11/2009	-127.3	-16.7
SK-4 Retrun Flow at Pond	Suface water return flow	9/6/2008	-134.7	-18.1
SK-5 Ditch Return	Suface water return flow	9/6/2008	-133.9	-18.0
Up Return	Suface water return flow	10/9/2008	-136.4	-18.4
Down Return	Suface water return flow	10/9/2008	-135.1	-18.2
SK-3 Side Seep Sand	Spring	9/6/2008	-139.2	-18.6
Mendenhall Ditch	Ditch	9/5/2008	-137.3	-18.0
Whitebird Ditch	Ditch	10/4/2008	-134.2	-18.0
Mendenhall Ditch	Ditch	8/18/2009	-136.8	-17.79
Demptster Ditch	Ditch	9/2/2009	-133.8	-17.79
Aadland Ditch	Ditch	8/25/2009	-131.4	-17.31
Tuttle Ditch	Ditch	9/2/2009	-133.0	-17.73
Schaff spring/Ditch	Ditch	9/2/2009	-131.4	-17.14
9-16-09 Shane Ditch	Ditch	9/16/2009	-137.1	-18.3
3-12-10 Gravel pit	Bedrock well	3/12/2010	-142.0	-17.7
3-12-10 Johnson 3	Bedrock well	3/12/2010	-132.1	-17.2
3-12-10 Rex 1	Bedrock well	3/12/2010	-126.0	-16.7
3-12-10 Chandler house well	Bedrock well	3/13/2010	-131.6	-17.6
3-13-10 Zook spring	Bedrock well	3/13/2010	-133.0	-17.8
3-12-10 Rex 4	Bedrock well	3/12/2010	-125.8	-16.5
3-13-10 Lannen Spring	Bedrock well	3/13/2010	-132.9	-17.7
3-13-10 State Spring	Bedrock well	3/13/2010	-132.9	-17.9
3-13-10 State Well	Bedrock well	3/13/2010	-126.0	-16.9
3-12-10 Bass old well	Bedrock well	3/12/2010	-133.9	-18.4
3-13-10 CP-1	Bedrock well	3/13/2010	-134.2	-18.8

Appendix E. Oxygen and hydrogen stable isotopes

Site Name	Site Type	Collection Date	D	^{18}O
3-13-10 Rex 6	Bedrock well	3/13/2010	-131.2	-18.4
3-13-10 Rex Monitor well	Bedrock well	3/13/2010	-131.5	-18.4
3-13-10 CP2	Bedrock well	3/13/2010	-73.5	3.9
3-13-10 Rex 2	Bedrock well	3/13/2010	-127.1	-17.3
3-13-10 Grove P1	Bedrock well	3/13/2010	-133.2	-18.6
3-13-10 Johnson 1	Bedrock well	3/13/2010	-133.8	-18.5
3-12-10 Rex P1	Bedrock well	3/12/2010	-157.6	-21.8
Helbert Bedrock Well	Bedrock well	9/5/2008	-125.4	-15.1
Helbert Bedrock Well	Bedrock well	4/7/2009	-126.1	-16.5
M:145486 Baxter	Bedrock well	4/13/2009	-128.6	-16.6
Schlachter Well	Bedrock well	4/13/2009	-135.2	-18.1
Grove Creek Well N 8-7-09	Bedrock well	8/7/2009	-134.4	-16.64
school sec spring 6-25-09	Bedrock well	6/25/2009	-133.4	-16.19
MSU-BR 7-31-09	Bedrock well	7/31/2009	-136.1	-17.66
pezoldt BR 9-4-09	Bedrock well	9/4/2009	-138.9	-17.45
Nicholson M# 121860 8-11-09	Bedrock well	8/11/2009	-134.3	-16.98
LA-W 8-6-09	Bedrock well	8/6/2009	-130.3	-16.18
Grove CP tullck-S 8-10-09	Bedrock well	8/10/2009	-130.8	-16.86
Dahlstrom Well	Alluvial well	10/4/2008	-134.9	-18.0
Heimer	Alluvial well	9/2/2009	-135.3	-17.51
M: 101131 Moraine FA	Alluvial well	7/17/2009	-138.1	-17.92
R. Green	Alluvial well	8/11/2009	-137.5	-17.97
MSU-Qal-E	Alluvial well	7/30/2009	-137.8	-17.77
Mattingly	Alluvial well	8/18/2009	-136.1	-18.31
Ames	Alluvial well	8/18/2009	-135.8	-18.55
M:100008 Whitebird Fa	Alluvial well	8/11/2009	-138.2	-18.55
Schaff Stock Well	Alluvial well	9/2/2009	-138.3	-18.17
Hart Stock Well	Alluvial well	8/18/2009	-137.6	-18.03
DA-E	Alluvial well	7/29/2009	-132.9	-17.42
Keller Well	Alluvial well	9/3/2009	-131.8	-17.37
Cummins rental	Alluvial well	8/18/2009	-135.8	-17.36
Deuilibus	Alluvial well	8/19/2009	-137.4	-17.85
Rp-Qal-N	Alluvial well	7/31/2009	-136.4	-18.21
9-16-09 Butler well	Alluvial well	9/16/2009	-140.7	-18.2
2-10-10 Ames	Alluvial well	2/10/2010	-130.4	-17.4
8-19-09 Still water Rain	Precipitation	8/19/2009	-70.9	-5.1
10-7-09 Snow chandler	Precipitation	10/7/2009	-143.0	-20.0
2-13-10 snow	Precipitation	2/13/2010	-141.3	-18.3
Absarokee snow 3-30-10 1	Precipitation	3/30/2010	-156.7	-23.1
rain	Precipitation	6/1/2010	-114.2	-14.2
rain	Precipitation	7/5/2010	-97.6	-11.8
Absarokee snow 4-13-10 2	Precipitation	4/13/2010	-69.0	-13.9

APPENDIX F

Groundwater and Surface-Water Chloride Samples

Appendix F1. Groundwater chloride samples

Gwic Id	Sample ID	Latitude	Longitude	Aquifer	Sample Date	Cl (mg/l)	Estimated % ET loss	Fine-grained cover thickness (ft)
144084	2004Q0527	45.4436	-109.5023	125FRUN	4/22/2004 13:31	7.11	98	
150349	2001Q1472	45.4947	-109.4581	125FRUN	5/3/2001	0.873	81	
150349	2010Q0066	45.4947	-109.4581	125FRUN	7/17/2009 10:15	1.64	90	
7527	1982Q1066	45.4724	-109.4718	125TGRV	9/24/1982 10:30	4.1	96	
182107	2005Q0129	45.5223	-109.3902	125TGRV	8/11/2004 10:45	19.2	99	
188982	2010Q0470	45.584615	-109.537992	125TGRV	11/10/2009 16:00	0.25	32	
99934	2005Q0031	45.5488	-109.5097	125TLCK	7/28/2004 8:42	3.27	95	
100025	2005Q0517	45.5465	-109.3207	125TLCK	5/19/2005 9:50	13.8	99	
101301	2005Q0497	45.485861	-109.470724	125TLCK	5/12/2005 11:25	1.59	89	
101409	2006Q0052	45.5073	-109.2668	125TLCK	7/18/2005 14:20	12.6	99	
121866	2005Q0032	45.4976	-109.2296	125TLCK	7/28/2004 14:00	20.5	99	
144241	2005Q0069	45.4358	-109.4661	125TLCK	8/4/2004 8:16	0.5	66	
185284	2005Q0498	45.4914	-109.4857	125TLCK	5/12/2005 10:22	15.6	99	
217303	2010Q0027	45.50324	-109.31002	125TLCK	7/1/2009 20:18	17.9	99	
252295	2010Q0248	45.49252	-109.53495	125TLCK	8/27/2009 8:53	17.2	99	
101159	2004Q0075	45.4653	-109.7877	211EGLE	8/7/2003 10:05	1.61	89	
102714	2004Q0119	45.3948	-109.7186	211EGLE	8/26/2003 16:36	0.505	66	
148582	2004Q0076	45.4689	-109.7585	211EGLE	8/6/2003 12:30	0.976	83	
171104	2004Q0117	45.4161	-109.818	211EGLE	8/19/2003 13:29	0.566	70	
171725	2003Q0596	45.4087	-109.6593	211EGLE	10/2/2002 17:20	0.25	32	
7524	1982Q1077	45.4898	-109.5427	211HLCK	9/24/1982 9:20	22.1	99	
10200	1985Q0020	45.8141	-109.4713	211HLCK	10/23/1984 11:00	22.7	99	
92572	2006Q0028	45.7586	-109.5319	211HLCK	6/27/2005 14:00	32	99	
99923	2005Q0030	45.5441	-109.6218	211HLCK	7/27/2004 15:01	2.38	93	
99930	2005Q0024	45.531	-109.5782	211HLCK	7/19/2004 15:35	4.1	96	
101494	2005Q0250	45.4579	-109.1076	211HLCK	10/7/2004 17:25	11.2	98	
121803	2003Q0308	45.727	-109.2855	211HLCK	8/21/2002 11:12	21	99	
121803	2010Q0125	45.727	-109.2855	211HLCK	8/11/2009 11:00	29.42	99	
121860	2003Q0305	45.6092	-109.2735	211HLCK	8/20/2002 8:46	13.8	99	
121860	2010Q0121	45.6092	-109.2735	211HLCK	8/11/2009 15:00	20.14	99	
143930	2005Q0471	45.6539	-109.3467	211HLCK	5/3/2005 16:32	22.4	99	
145486	2010Q0065	45.4917	-109.5631	211HLCK	7/17/2009 11:45	20.2	99	
145486	2003Q0631	45.4917	-109.5631	211HLCK	10/15/2002 11:43	25	99	
150131	2003Q0424	45.6152	-109.2863	211HLCK	8/29/2002 9:25	23.2	99	
150225	2005Q0515	45.4426	-109.5366	211HLCK	5/18/2005 10:43	2.73	94	
152675	2003Q0307	45.6819	-109.4543	211HLCK	8/15/2002 15:35	13	99	
152675	2002Q1537	45.6819	-109.4543	211HLCK	6/20/2002 13:10	14.5	99	
161007	2003Q0427	45.6245	-109.3357	211HLCK	9/4/2002 10:29	10.9	98	
176223	2006Q0104	45.7057	-109.2888	211HLCK	7/29/2005 15:45	24.7	99	
177158	2006Q0051	45.8918	-109.4391	211HLCK	7/18/2005 14:20	23.4	99	
180042	2005Q0512	45.8158	-109.4301	211HLCK	5/19/2005 13:41	35.7	100	
185234	2005Q0528	45.5944	-109.3155	211HLCK	5/26/2005 9:29	2.64	94	
195143	2003Q0267	45.7071	-109.5559	211HLCK	8/13/2002 18:55	37.6	100	
201725	2005Q0469	45.6696	-109.4727	211HLCK	4/28/2005 11:41	19.9	99	
220681	2006Q0031	45.7602	-109.5326	211HLCK	6/27/2005 15:24	35.5	100	
252297	2010Q0249	45.56538	-109.64387	211HLCK	8/28/2009 18:00	3.2	95	
7319	1979Q3163	45.5632	-109.7138	211LVIS	8/1/1979 2:30	1.7	90	
102780	2005Q0514	45.4345	-109.5603	211LVIS	5/17/2005 11:56	2.32	93	
169866	2005Q0027	45.4111	-109.5567	211LVIS	7/28/2004 12:34	4.82	96	
183029	2005Q0128	45.5458	-109.6861	211LVIS	8/17/2004 10:58	1.5	89	

Appendix F1. Groundwater chloride samples

Gwic Id	Sample ID	Latitude	Longitude	Aquifer	Sample Date	Cl (mg/l)	Estimated % ET loss	Fine-grained cover thickness (ft)
213653	2005Q0127	45.4572	-109.6101	211LVIS	8/11/2004 13:52	1.84	91	
101131				Alluvial	9/18/2009	1.13		1
102696				Alluvial	5/17/2005	1.49		1
102741				Alluvial	9/3/2009	2.8		2
102792				Alluvial	9/2/2009	0.7		2
143942				Alluvial	8/11/2009	1.9		2
143942				Alluvial	8/11/2009	1.95		2
144216				Alluvial	8/26/2003	0.701		2
144221				Alluvial	8/12/2003	1.46		1
148586				Alluvial	10/17/2002	1		1
156919				Alluvial	8/18/2009	1.5		1
161144				Alluvial	9/4/2009	5.1		12
174838				Alluvial	8/18/2009	2.3		2
188988				Alluvial	7/27/2004	0.921		3
192434				Alluvial	8/18/2009	1.7		3
198578				Alluvial	8/13/2003	1.77		16
198691				Alluvial	8/18/2009	1.6		17
252299				Alluvial	7/31/2009	3.9		5
252301				Alluvial	7/30/2009	1.1		2
252303				Alluvial	7/29/2009	1.6		2

Appendix F2. Surface water chloride samples

Gwic Id	Sample Name	Latitude	Longitude	Sample Date	Cl (mg/l)
7177	Stillwater River near Columbus	45.6236	-109.288	8/28/1981 11:45	1.5
				10/22/1981 15:00	1.5
				12/3/1981 11:45	0.7
				1/15/1982 9:00	0.5
				3/11/1982 9:45	0.7
				5/4/1982 15:30	0.8
				6/25/1982 11:45	0.4
				9/10/1982 12:15	0.6
				11/19/1982 10:00	0.8
				1/14/1983 15:15	0.7
				3/4/1983 8:00	0.9
				5/12/1983 14:20	1.3
				6/17/1983 9:00	0.5
				8/19/1983 8:00	0.3
220496	Stillwater River at Firemans Point	45.6231	-109.2886	6/2/2005	2
				7/27/2005 13:00	0.616
7322	Stillwater River Abv Rosebud Creek Nr Absarokee	45.5286	-109.4688	6/22/1982 8:30	0.7
7321	Stillwater River Nr Absarokee *	45.5286	-109.4688	8/4/1981 14:00	1.6
7491	West Fork Stillwater River Bl Castle Creek Nr Nye	45.4547	-109.8444	10/22/1981 16:00	1.5
				12/2/1981 13:00	0.3
				1/13/1982 12:30	1.3
				3/9/1982 11:45	1.4
				5/3/1982 19:00	0.6
				7/1/1982 15:30	0.3
				9/8/1982 15:15	0.4
				11/15/1982 16:30	0.5
				1/14/1983 10:45	0.3
				3/16/1983 13:40	1.1
				5/12/1983 11:40	0.2
				6/15/1983 15:00	0.3
				8/18/1983 12:30	0.3
7503	West Fork Stillwater River Nr Nye *	45.4547	-109.8444	8/27/1981 14:15	1.3
7513	Stillwater River at Beehive	45.4777	-109.7266	1/1/1900	0.4
				3/10/1982 10:45	0.8
				5/4/1982 12:30	0.6
				6/24/1982 16:15	0.2
				9/9/1982 15:00	0.4
				11/16/1982 10:15	0.6
				1/14/1983 12:30	0.4
				3/3/1983 9:30	0.6
				5/11/1983 14:30	0.3
				6/16/1983 18:00	0.3
				8/18/1983 15:15	0.1
7681	Stillwater River Abv Nye Crk Nr Nye	45.3961	-109.8705	10/22/1981 10:30	1.5
				1/13/1983 15:30	0.3
				3/3/1983 16:00	0.5
				5/11/1983 12:00	0.2
				8/24/1981 14:30	0.2
7690	Stillwater River at Woodbine Bridge * STL-01	45.3536	-109.8947	9/24/1980 12:25	0.8
				6/14/1981	0.2
				9/17/1981 9:00	0.3