HYDROGEOLOGY OF THE NORTHERN BIGHORN RIVER VALLEY

OPEN FILE REPORT ***588***

A JOINT PROJECT BETWEEN:

BIG HORN CONSERVATION DISTRICT
AND
MONTANA BUREAU OF MINES AND GEOLOGY

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ABSTRACT

Residents of the northern Bighorn River valley are primarily – in many cases entirely – dependent upon the alluvial aquifer system as their source of potable water. Over 70 percent of the residents of Big Horn County live outside the city limits of Hardin. In these rural areas, groundwater is typically the only source of drinking water. The thin, locally recharged terrace and alluvial aquifers are susceptible to contamination, drought and changes in land use and irrigation practices. The terrace and alluvial aquifers encompassed by this study extend north from Hardin, Montana to the Big Horn County line.

This project was initiated to evaluate the potential impacts of land-use change to the Bighorn River alluvial aquifer system in the valley north of Hardin. Field work for this project was conducted between March, 2006 and July, 2008. Research methods consisted of compiling previously existing data, measuring groundwater elevations and field parameters, collecting surface- and groundwater samples for water quality and environmental isotope analysis, and performing aquifer tests at two locations.

Seventy-seven wells, six stream sites, and three springs within the project area were inventoried and the data entered into the Montana Bureau of Mines and Geology's Groundwater Information Center (GWIC). Inventory data includes location, altitude, total depth, static water level, temperature, specific conductivity, and, on some wells, pH, redox potential, and nitrate. Within this set of wells, eight private wells were visited periodically to monitor temporal changes in static water level. The water quality, including major ions and trace elements, was determined for eleven well and five stream samples. The stable oxygen and hydrogen isotope ratios were determined for 25 samples including 17 well and 8 surface-water samples. Tritium analyses were performed on 8 well samples and one surface-water sample. Chloride concentrations were measured on 27 samples including 22 well and 5 surface water samples. The majority of water samples had nitrate concentrations less than the national drinking water standard.

Seven monitoring wells were installed for aquifer tests. Water levels were monitored by continuous recorders (both digital and analog) and manually during monthly visits. Hydraulic conductivities estimated from aquifer tests ranged from 65 to 208 feet/day. These highly conductive gravels allow groundwater levels to respond almost immediately to the introduction of water from irrigation ditches; one well rose eight feet in four months. Groundwater moves through the alluvium from the edge of the valley toward the river at an approximate rate of 0.1 to 0.2 miles per year. Isotope and chloride analysis indicates the majority of recharge to the groundwater is through leakage from irrigation ditches.

In the 1950s and 1960s, the United States Geological Survey (USGS) inventoried 150 wells throughout the valley and within this set analyzed 33 groundwater samples for water chemistry. Twenty-two of these wells were within the study area of this project and were used for historical analysis of groundwater change over 50 years. While the salinity levels of groundwater in most of the valley are above the recommended drinking water standard, the overall salinity in alluvial groundwater has improved since the 1960s.

INTRODUCTION

Residents of the northern Bighorn River valley are primarily – in many cases entirely – dependent upon the alluvial aquifer system as their source of potable water. Over 70 percent of the residents of Big Horn County live outside the city limits of Hardin. In these rural areas, groundwater is typically the only source of drinking water. The thin, locally recharged terrace and alluvial aquifers are susceptible to contamination, drought and changes in land use and irrigation practices. The terrace and alluvial aquifers encompassed by this study extend north from Hardin, Montana to the Big Horn County line (Figure 1).

This study provides detailed information on the groundwater availability, water level fluctuations, water quality, and groundwater/surface water interactions for the Bighorn River valley aquifer north of Hardin (Figure 1). The compilation of data in this report is intended to provide the information necessary to allow land-use and water resource decisions that will protect the primary source of groundwater for the area.

The northern Bighorn River valley is used almost entirely for agricultural purposes, including both ranching and farming. Cultivated crops in this area include spring and winter wheat, corn, oats, barley, sugar beets, alfalfa, and hay. In 2007 in Big Horn County, 91,700 acres of winter wheat were harvested, 900 acres of corn, 500 acres of oats, 17,400 acres of barley, and 9,670 acres of sugar beets, producing 257,000 tons of beets (National Agricultural Statistics Service, 2008). The majority of these crops are irrigated through a series of ditches that serve as the source of flood irrigation. The ditches divert water from the Bighorn River to the middle or western edge of the valley, returning to the Bighorn River down stream.

Construction of the Yellowtail Dam in southern Big Horn County near Fort Smith was completed during 1966. The dam was constructed with the purpose of, among other reasons, stabilizing flows in the Bighorn River and providing a reliable supply of irrigation water. Prior to completion of the dam, the United States Geological Survey (USGS) collected groundwater data and published a report describing the gravel aquifers of the Bighorn River valley (Hamilton and Paulson, 1968). This study included the Bighorn River Valley from the mouth of the canyon at Fort Smith (T6S R31E) to the

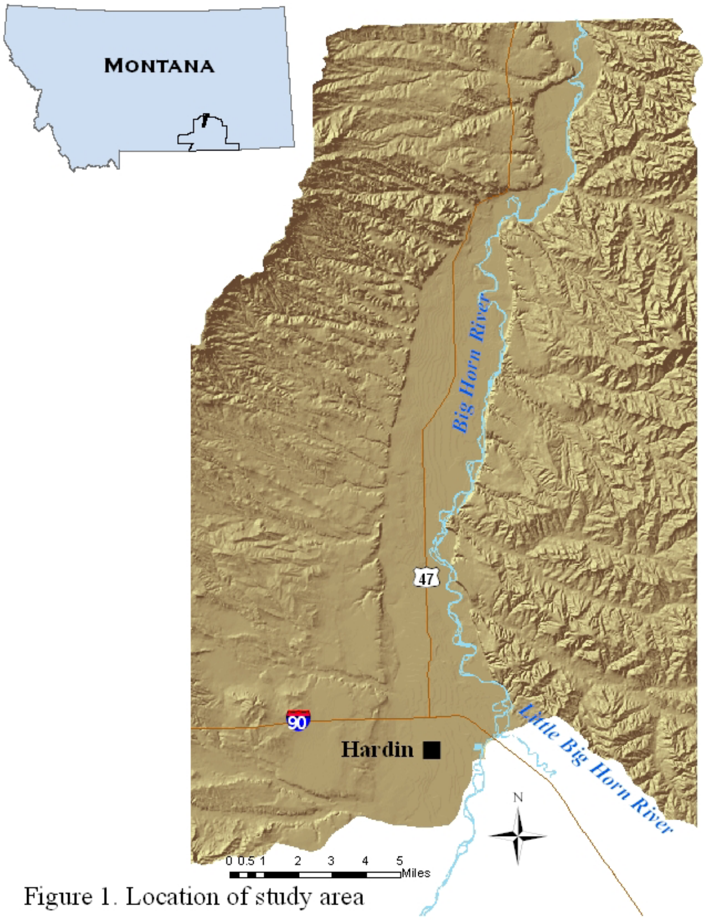

Figure 1. Location of study area

confluence with the Yellowstone River (T5N R34E), providing water levels for eight wells over approximately ten years (1957-1966, some missing data) including wells on both irrigated and non-irrigated lands. Samples were collected for 33 water-chemistry analyses and 121 measurements of specific conductance.

The current study provides a unique opportunity to observe and compare water quality and quantity changes, 40 years after the USGS study. This study includes an evaluation of the changes brought about by the dam construction and increased agricultural activity, providing a better understanding of the long-term effects of flood irrigation. This information will be used for more accurate predictions of the effects that switching to sprinkler irrigation or changing land use may have upon groundwater quantity and quality.

PURPOSE AND SCOPE OF RESEARCH

This project was conducted to evaluate the potential impacts of land-use change to the Bighorn River alluvial aquifer system in the valley north of Hardin. Field work for this project was conducted between March, 2006 and July, 2008. Research methods consisted of compiling previously existing data, measuring groundwater elevations and field parameters, collecting surface- and groundwater samples for water quality and environmental isotope analysis, and performing aquifer tests at two locations.

FUNDING SOURCE

Funding for this project was provided by a Renewable Resources Grant to the Big Horn Conservation District administered by the Montana Department of Natural Resources and Conservation. Technical assistance was provided by the Montana Bureau of Mines and Geology (MBMG), a department of Montana Tech of The University of Montana. The Montana Legislature established these grants to fund “the conservation, management, development and preservation of Montana’s renewable resources” (Montana Department of Natural Resources and Conservation, 2008).

RESEARCH METHODS

Data collection for this project included database compilation, surface- and groundwater measurements, and sampling for water-quality, stable isotopes of hydrogen and oxygen, and tritium analyses. Data collected for this project are available on the MBMG on-line Ground Water Information Center database (GWIC; http://mbmggwic.mtech.edu/). Private wells and dedicated monitoring wells are identified in this report by their GWIC identification number.

INVENTORY AND SAMPLING

Seventy-seven wells, 6 stream sites, and 3 springs identified within the project area were inventoried and the data entered into GWIC under the project group Regional Water Resource Investigations and the project code BHORN. Inventory data include location, altitude, total depth, static water level, temperature, specific conductivity, and, on some wells, pH, redox potential, and nitrate concentration. Locations of inventoried wells are shown on Figure 2 and data are listed in Appendix A. Within this set of wells, 8 private wells were visited periodically to monitor temporal changes in static water level (Figure 3). Twenty-two wells were inventoried by the USGS during the 1950's and 1960's. Data from these inventories are included in Appendix B and have been added to GWIC in order to consolidate data for future uses.

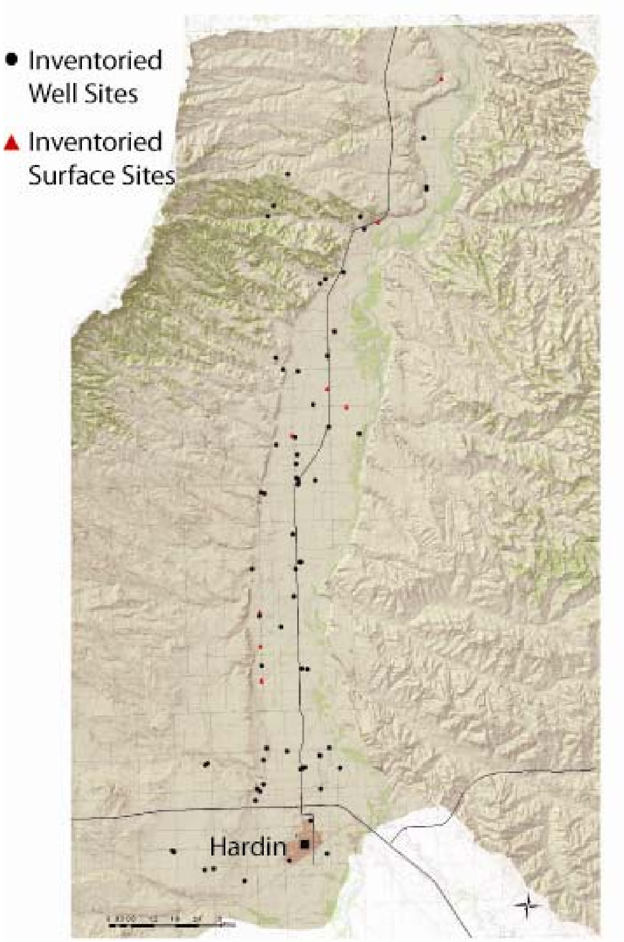

Figure 2. Inventoried sites in the northern Bighorn River Valley.

The water quality, including major ions and trace elements, was determined for 11 well and 5 stream samples (Appendix C; also available online in the GWIC database). The stable oxygen and hydrogen isotope ratios were determined for 25 samples including 17 well and 8 surface water samples. Tritium analyses were performed on 8 well samples and 1 surface water sample. Chloride concentrations were measured on 27 samples including 22 well and 5 surface water samples.

Water sampling for nitrate and nitrite, chloride, major and trace elements, and isotope analysis included pumping three casing volumes of water from a well to ensure that collected water represented the aquifer. River water samples were collected at fishing access points using a rowboat to ferry across the river 4 times to create a composite depth and width integrated sample. Samples were collected with a peristaltic pump and clean tubing attached to a probe. Samples from smaller ditches were collected using a grab-sampling method. Field parameters of temperature, pH and redox potential were taken using calibrated electronic probes and field instruments. Samples for laboratory analysis include raw, filtered (0.45 micron), filtered and preserved with HNO_3 and filtered and preserved with H_2SO_4.

Major ion and trace element analyses were performed by the MBMG analytical laboratory. Nitrate + nitrite and chloride analyses were performed by Energy Labs in Billings, Montana. Oxygen and hydrogen isotopes were analyzed by the Light Stable Isotope Laboratory at the University of Wyoming and the University of Waterloo, Ontario. Tritium analyses were performed by the University of Waterloo, Ontario.

Figure 3. Location of monitored wells

WELL INSTALLATION

The majority of wells utilized for this project were existing domestic and stock wells. However, two pumping wells and five observation wells were installed for this project (Plate 1). These wells were used to perform aquifer tests and for regular water-level monitoring beginning in October, 2007 including some hourly datalogger and F-chart monitoring. The locations for the well sites were chosen to represent flood irrigated land and non-irrigated land. Locations were chosen based on land-use and land-owner cooperation. The non-irrigated aquifer test was performed on well WAT-1 (GWIC ID# 239729) with the observation wells WAT-2 and WAT-3 (239727 and 239728). Wells near the flood irrigated field include the aquifer test well WEB-1 (239730) and observation wells WEB-2, WEB-3 and WEB-4 (239731, 239733 and 239734).

AQUIFER TESTING

Aquifer tests were performed to determine hydraulic parameters of the aquifer. Aquifer tests can provide information on the aquifer's hydraulic conductivity (and transmissivity), specific storage, specific yield and the presence of aquifer boundaries such as a recharge and no-flow boundaries (Fetter, 2001). During the aquifer tests, water was pumped from the test wells at constant rates and water levels monitored in the pumping wells and nearby observation wells. At each of the two aquifer tests sites, 24-hour tests were performed with data loggers monitoring the water levels in the wells in addition to periodic hand measurements made with sounders. Water-level recovery data were collected until the water levels in the pumped well had recovered to 90 percent of baseline.

HYDROGEOLOGIC SETTING

CLIMATE

The Governor's Drought Advisory Committee has listed Big Horn County under dry conditions from February 2006 through June 2008, excepting summer of 2007, including three months of severely dry conditions (Montana National Resource Information System, 2008). Average total annual precipitation from July 1948 to June 2007 in Hardin is 11.85 inches (including 21.2 inches of snow). Overall, precipitation in Hardin over the last five years has been below average (Figure 4). Average temperatures range from 7.7^{o}F to 33.5^{o}F in January and 55.4^{o}F to 90.6^{o}F in July (Western Regional Climate Center, 2008).

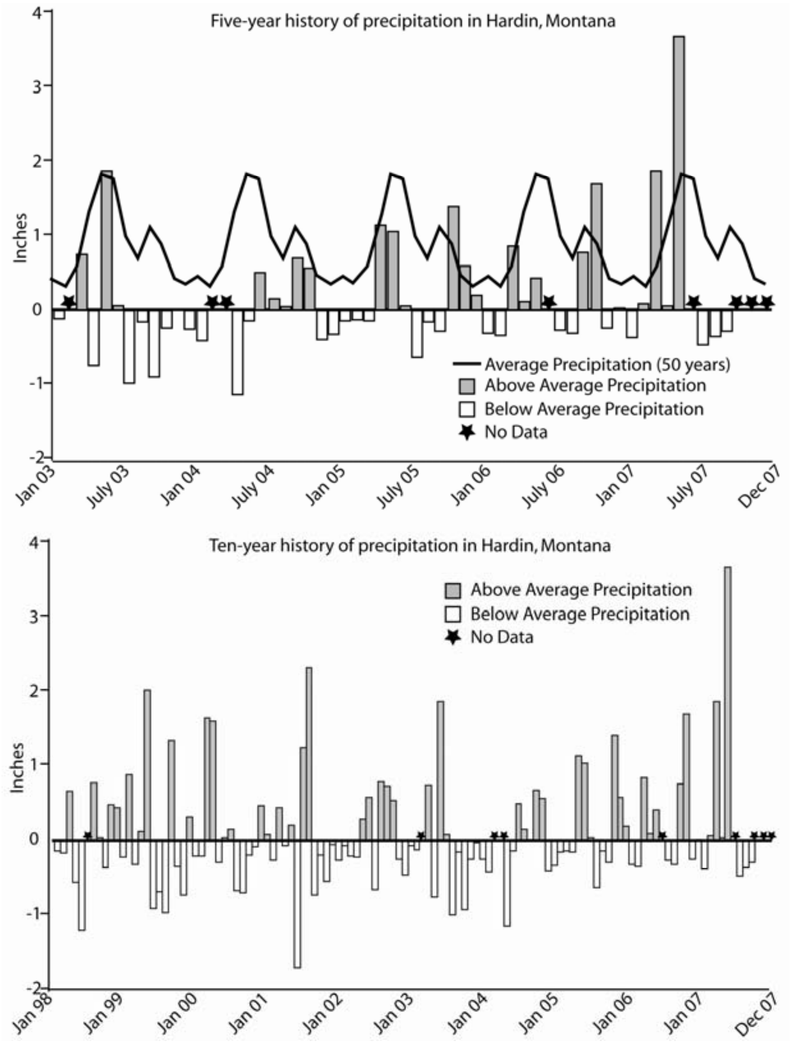

Figure 4. Deviation from monthly average precipitation in Hardin, Montana (Western Regional Climate Center, 2008).

AQUIFER SYSTEM

STRATIGRAPHIC COMPONENTS

Bedrock units present beneath the northern Bighorn River valley area include Precambrian basement through Upper Cretaceous formations. In the valley floor and on some benches above the valley the Cretaceous bedrock formations are overlain by unconsolidated Pleistocene and Holocene deposits (Plate 1). The potential aquifers in the area include: Madison Group; Tensleep Sandstone; Pryor Conglomerate; and the terraces and alluvium.

BEDROCK AQUIFERS

Bedrock aquifers are not a focus of this study but are briefly mentioned to describe the relationships with the shallow alluvial aquifer system. Aquifer characteristics for the bedrock units can be found in Hamilton and Paulson (1968). Bedrock aquifers exist throughout the area but are found at depths that make drilling expensive. The Pryor Conglomerate at the base of the Cretaceous Kootenai Formation and the Mississippian Madison Group limestone are regional aquifers in eastern Montana. The Madison limestone is recharged along the periphery of the Pryor and Bighorn Mountains and regional groundwater flows to the north in the project area. Wells targeting the Madison Group would likely be about 3,400 feet deep in the south and over 4,000 feet deep in the north of the study area. The hydrostatic pressure in the Madison would cause wells completed in it to flow at ground surface throughout the project area (Feltis, R.D., 1980a). The quality of the water in the Madison deteriorates with increasing distance from recharge areas, however, beneath the project area, water quality is likely useable for some purposes (Feltis, R.D., 1980b).

The Pryor Conglomerate Member of the Kootenai Formation is a dependable aquifer to the southwest of this study area (Wheaton and Lopez, 1999) and, while it is not currently used, it likely could be utilized in the project area. Within the study area, drilling depths to reach the Pryor Conglomerate would be in the range of 1,500 feet in the south to 2,300 feet in the north.

Overlying the Kootenai Formation is a series of Cretaceous shales that separate the shallow, unconsolidated alluvial aquifers from deeper bedrock aquifers. During the Cretaceous Period, approximately 2,000 feet of shale was deposited in the area where the Bighorn River valley is located (Hamilton and Paulson, 1968). The shale forms the majority of the bedrock units directly underlying and surrounding the valley fill (Plate 1). These shale sequences are typically dry or extremely low-yielding aquifers with unsuitable water quality.

The Judith River sandstone is a potential aquifer in some areas of eastern Montana, but its occurrence in the Bighorn River valley is limited to low yielding shale and siltstone layers exposed in a thin strip north of Hardin. The Bearpaw, Claggett, Gammon and Niobrara shales and siltstones underlie most of the northern Bighorn River valley. In the areas underlain by these formations, groundwater resource development is limited to the alluvial and terrace aquifers. North of the Sorrel House Road turnoff (near the border between townships 2 and 3 north), the valley fill is underlain by the Upper Cretaceous Lance Formation which is composed mostly of sandstone. Where it is saturated, the Lance is typically an adequate aquifer and is used as an aquifer by the residents of the northern Bighorn River valley.

HIGH TERRACE AQUIFERS

Alluvial deposits have been cut into and deposited over bedrock in the 3-to-4-mile-wide river valley (Vuke and others, 2000; 2003). Six Pleistocene alluvial terraces are evident in the southern part of the valley, while in the northern part of the valley encompassed by this study, three to four terrace levels are present (Plate 1). Pleistocene alluvial terraces lie higher than approximately 6 feet above the current river level. The geologic cross sections on Plate 1 show the relationship between the alluvium and the alluvial terraces, with as many as 4 terraces shown on the individual cross sections.

For the most part, the higher terraces are not irrigated and are underlain by shale aquitards. Therefore, the only source of recharge to the terrace gravels is snow melt and short duration, intense rainfall that exceeds evapotranspiration demand. Groundwater discharges intermittently at springs along the side of the valley or is lost to transpiration. The gravel deposits of the terraces are discontinuous with each terrace separated from the next by escarpments (Plate 1). It is unlikely that any movement of groundwater can occur from higher terraces to the lower terraces.

LOW TERRACE AND ALLUVIAL AQUIFERS

The primary aquifer in the north valley is the combined Holocene alluvium and the lowest Pleistocene alluvial terrace (Plate 1). These combined units are referred to in the remainder of this report as the alluvial aquifer and are shown on Plate 1 as the combined tan Qat and pink Qal formations. These units are, in essence, a single aquifer with continuous groundwater flow from the terrace edge to the Bighorn River. As described by Vuke and others (2000; 2003), the alluvium in this area is up to 35-feet thick and includes the unit that lies no more than 6 feet above the level of the river. The alluvium is in direct hydrologic connection with the Bighorn River, as is the lowest terrace through its connection to the alluvium. Underlying the unconsolidated alluvial material in most of the valley are the Cretaceous shale formations, through which very little water flows. These units do not provide recharge to the alluvial groundwater system, nor are they recharged by the overlying, unconsolidated system.

Within the project area the total depth of the alluvial deposits beneath the valley floor ranges from less than 10 feet to about 70 feet (Plate 2A). The area having generally the least alluvial thickness is where the river is currently flowing along the east side of the valley. Alluvial thickness increases to the west, where land surface is higher. Along cross-section B on Plate 1, where the thickest alluvium is found, the land surface altitude near the river is 2820 feet, whereas near the west edge of the valley it is about 2890 feet, a difference of 70 feet. Saturated sandy gravel layers that are a few feet thick (up to a maximum of 30 feet) are the target aquifers in the alluvial system.

Near the southern edge of township 3 north, where the river crosses the contact between the Bearpaw Shale and the sandstones of the Lance Formation, the valley narrows noticeably. The total thickness of alluvium is less to the north of this contact than to the south. The cross-sectional area of total alluvial sediment decreases from over 500,000 square feet (ft^2) along line B-B' on Plate 1, to about 100,000 ft^2 along line A-A'. The transmission of water through the alluvial aquifer must similarly decrease and, though not quantified by river-flow measurements, it is assumed that much of the groundwater discharges to the river along this area.

ALLUVIAL AQUIFER PROPERTIES

Hydraulic conductivity is a measure of the ease with which water can move through an aquifer along a flow path or to a discharge point such as a well. Gravel aquifers typically have hydraulic conductivity values in the range of 30 to 3,000 feet per day (ft/d) (Fetter, 1980). The alluvial aquifer in the project area is moderately sorted, containing significant sand among the gravel, and is therefore expected to be in the lower end of the theoretical range of hydraulic conductivity values. As part of a previous study, an aquifer-pumping test of 1.5 hours provided a value of 495 ft/d for a well in T2N, R33E, Section 35 (Hamilton and Paulson, 1968). This well is completed in the alluvium and located near the river.

Two aquifer tests were conducted by MBMG as part of this project. The Watson test site included a pumping well with observation wells completed near the river in the alluvium (labeled "Wat Site" on Plate 1, T1S, R33E, Section 1). The Watson site is near an irrigation ditch, but not immediately near irrigated fields. At the second site, the Webber test site, the pumping and observation wells were completed in the low terrace gravels near the western edge of the valley floor (labeled "Web Site" on Plate 1, T1N, R33E, Section 4). This site is completely surrounded by flood irrigated fields.

During the test at the Watson site, the production well was pumped at 48 gallons per minute (gpm) for about 24 hours. The calculated hydraulic conductivity was 208 ft/d. At the pumping well the maximum drawdown was 6.5 feet, indicating a specific well capacity of about 7 gallons per minute per foot of drawdown. The aquifer is unconfined at this site with a saturated gravel thickness of 10 feet.

The pumping rate at the Webber site during the 24 hour test was 75 gpm and the hydraulic conductivity was calculated to be 62 ft/d. Maximum drawdown while pumping the production well was 25.2 feet, indicating a specific well capacity of about 3 gallons per minute per foot of drawdown. The saturated thickness of the tested gravel aquifer at the Webber site is 17 feet. The alluvial aquifer in this part of the valley is semi-confined. The initial head, prior to the start of the aquifer test, was 65 feet above the base of the aquifer. The tested gravel aquifer is 14 feet thick (bottom of the aquifer is 72 feet below ground surface) and is separated from the overlying saturated gravel by 15 feet of clayey silt and sand. Water levels were measured at a nested set of observations wells located 22 feet from the pumped well. The maximum drawdown measured in the observation wells for the tested gravel layer was 21.8 feet. The water level in the upper gravel also responded to the aquifer test, but with a maximum drawdown of 0.5 feet.

Another important physical parameter for unconfined aquifers is specific yield, which is the quantity of water that can be drained from a unit volume of material (unitless). For clean, well sorted gravel, specific yield can be as high as 0.25 (Fetter, 1980). Considering the poor sorting of the gravel in the tested aquifer – significant sand was noted during drilling – the specific yield for gravels in the north valley project area is likely much less than 0.25. For the purpose of this report, a value in the lower range of expected values, 0.15, is assumed for specific yield.

ALLUVIAL GROUNDWATER FLOW

Groundwater flows from aquifer recharge areas to discharge areas. In alluvial aquifers, recharge can occur by seepage from the river or irrigation ditches, infiltration of precipitation or applied irrigation water, or from upward gradients from underlying bedrock aquifers. Recharge is heavily influenced by land use, which is largely agricultural in the project area – predominantly irrigated fields. Primary irrigation ditches, sources of seep recharge, are shown on Plate 1. Land use for the project area, including agricultural land, is shown on Plate 2B (Natural Resource Information System, 2006). In the northern Bighorn River valley, an insignificant quantity of groundwater moves from bedrock aquifers to the alluvial aquifer system due to the shale content of the bedrock (cross sections on Plate 1).

Seepage from the river to the alluvial aquifer can only occur when the level of the river is higher than the adjacent water table. Plate 2C shows the water table elevation of the valley during late summer and fall, when groundwater levels are at their highest. At this time, groundwater flows from the edges of the valley toward the river. During spring, groundwater levels are at the lowest level of the year, however the gradient does not appear to shift such that the river feeds the alluvial system.

The seasonal high and low water levels for groundwater and surface water at the Watson site are shown on Figure 5. A side channel of the Bighorn River, shown on the cross-section, parallels the main channel of the river for three miles. The groundwater gradient is toward the river during the entire one-year monitoring period; the river, therefore, serves as a discharge area and never a recharge area.

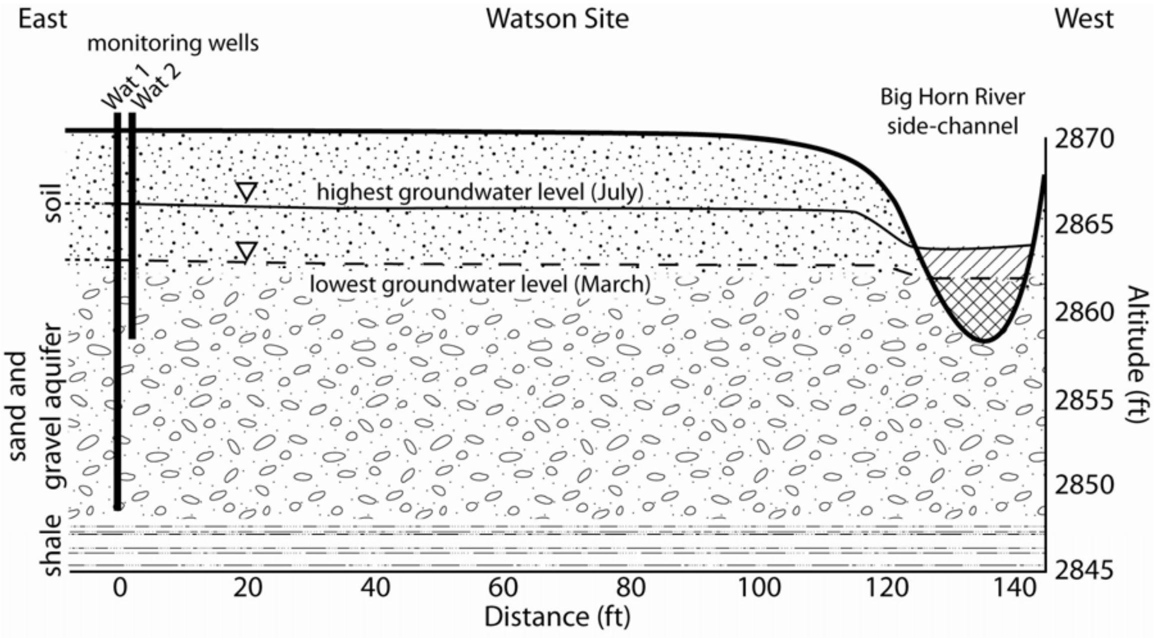

Figure 5. Cross-section view of the Watson Site, including 2 of 3 monitoring wells and a side-channel of the Big Horn River. Groundwater levels are 1.5 feet higher than the river in July and 0.3 feet higher than the river in March indicating a gradient towards, and discharge to, surface water. (Note: vertical scale is not equal to horizonal scale)

Within gravel aquifers, vertical and horizontal hydraulic conductivity values are likely similar. Water levels at both WAT-1 and WAT- 2 monitoring wells respond to recharge that occurs some distance away from the site at irrigation ditches and irrigated fields. The Watson site is approximately 1,800 feet downgradient from the nearest irrigated field and the water level response in the monitoring wells is due to groundwater recharge from these fields migrating toward the river. Water elevations are identical in the nested monitoring wells including the well completed near the top of the gravel (WAT-2) and those completed at the base of the gravel (WAT-1, -3), indicating horizontal flow toward the river (Figures 5 and 6). The irrigation season in this area began in 2008 around April 9, when water was diverted into the Two Leggins Canal from the Bighorn River. The water levels began to rise at the Watson site May 21 (figure 6), lagging 42 days behind the Two Leggins Canal; however, the timing of irrigation applications and ditch usage in the immediate area is not known.

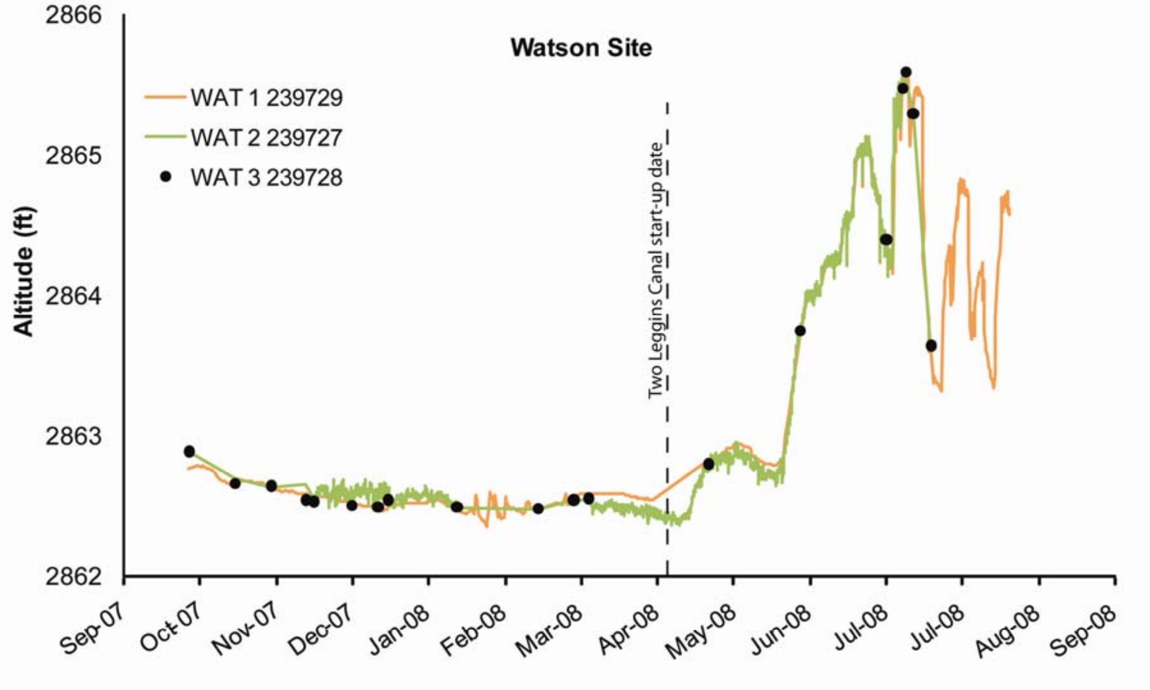

Figure 6. Watson site hydrograph showing no vertical gradient between deeper wells (Wat-1 and Wat-3) and the shallow well (Wat-2).

The set of nested terrace-aquifer-monitoring wells at the Webber Site is within 50 feet of irrigated fields and 200 feet of the Two Leggins canal. Wells WEB-2 and WEB-4 are completed in an overlying gravel unit that is separated from the zone monitored by wells WEB-1 and WEB-3 by a semi-confining layer. Within one day, water levels in both gravel layers rise in response to water entering the Two Leggins Canal (Figure 7). The upper gravel, under water table conditions, responds to the arrival of infiltrating water. The lower gravel, under semi-confined conditions, may respond to infiltrating water or to the pressure transmitted through the intermediate material.

Groundwater elevations measured between late August and early October in 2006 and 2007 and the altitude of the Bighorn River were used to contour the potentiometric surface of the terrace and alluvial aquifer for the fall season (Plate 2C). In the study area, the hydraulic gradient is generally east – northeast. Groundwater in the alluvium generally flows toward, and then parallel to, the river. The valley narrows where the Bighorn River crosses the Lance Sandstone – Bearpaw Shale contact causing the hydraulic gradient, and therefore the groundwater flow rate, to decrease above the narrows. Through the narrows the groundwater gradient increases. Throughout the study area, the Bighorn River is a gaining stream: groundwater flows into the river, increasing its discharge.

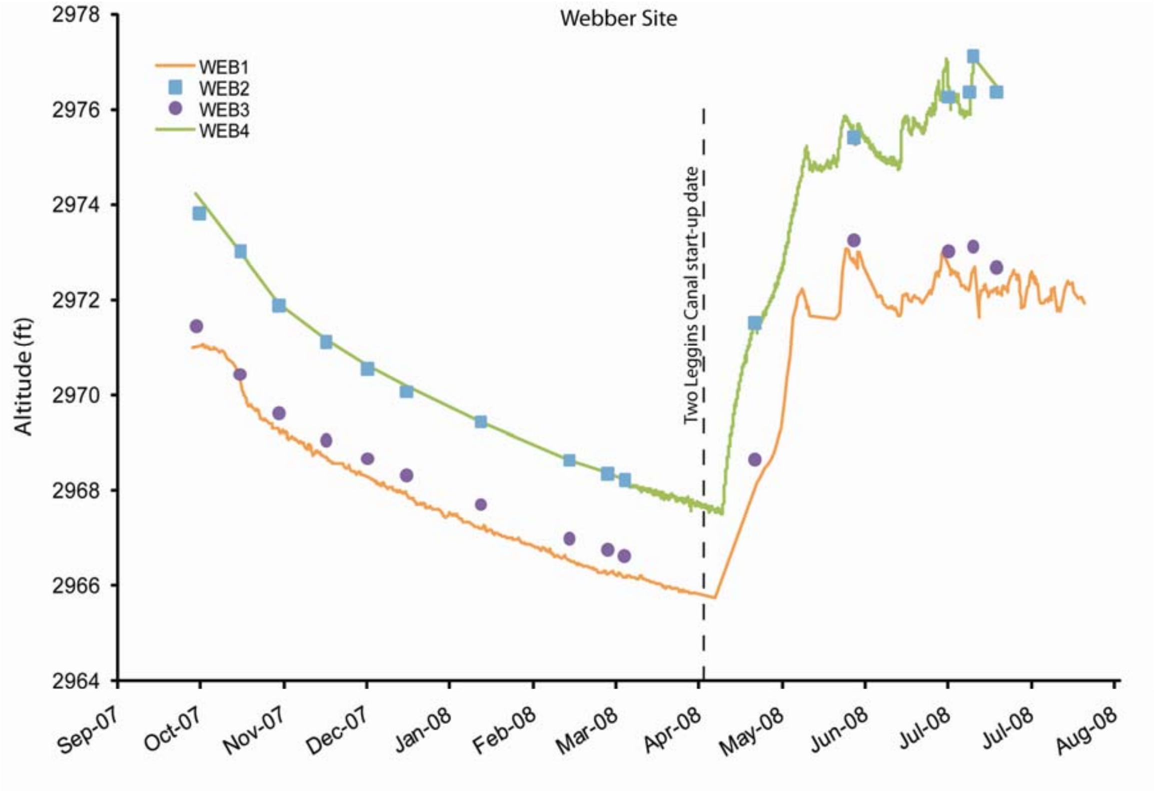

Figure 7. Hydrograph for the Webber Site showing a semi-confined lower aquifer (WEB-1 and -3) and an unconfined overlying aquifer (WEB-2 and -4).

Hamilton and Paulson (1968) estimated the rate of groundwater movement in the Bighorn River valley as less than 350 feet per year (ft/yr). They describe the typical range of rates for most aquifers as generally less than 1 ft/yr for shale to greater than 20,000 ft/yr for clean gravel. Based on the hydraulic conductivity values discussed above in the aquifer test section, values for the Webber and Watson sites were calculated using the standard formula:

$$v = \frac{365 * i * K}{S_y}$$

Where:

v = average linear velocity (ft/yr)
K = hydraulic conductivity (ft/d)
i = gradient (ft/ft)
S_y = Specific yield (dimensionless)

At the Webber site, the gradient is about 0.01 (Plate 2C) and the average velocity is estimated at 4 ft/d or about 1,500 ft/yr. At the Watson site, the gradient is less, about 0.005 and the average velocity is estimated at 7 ft/d or about 2,600 ft/yr. When irrigation water is rapidly infiltrating at the start of the growing season, the gradient will steepen and the velocity will increase. In late winter and early spring, when the water level is lowest, the gradient will be less and the velocity will decrease.

Groundwater travel times were calculated for each flow line on Plate 2C. The calculated time required for groundwater to flow from the extreme western edge of the alluvium to the river was based on an assumed average hydraulic conductivity value of 255 ft/d and specific yield value of 0.15. Estimated times of travel range from 1.1 years in the north to 16.8 years in the center of the valley. The average calculated travel time is 8.6 years. Actual rates of groundwater movement throughout the valley will vary widely depending upon hydraulic conductivity and gradient.

GROUNDWATER QUALITY

NITRATE AND NITRITE CONCENTRATIONS

Nitrate and nitrite are health concerns for infants (younger than 6 months) who may experience shortness of breath and blue-baby syndrome from drinking contaminated water (United States Environmental Protection Agency, 2008). Potential anthropogenic sources of nitrate in groundwater include septic systems, sewage, agricultural fertilizers, animal manure and land use changes. Nitrate impacts from septic systems will depend upon soil characteristics, system design and efficiency, and housing density. The impacts of nitrate from other sources are largely controlled by plant uptake, agricultural practices and soil characteristics. The United States Environmental Protection Agency (2008) sets a maximum contaminant level for nitrate to 10 mg/L and nitrite to 1 mg/L (both measured as nitrogen).

Nitrate and nitrite concentrations in groundwater in the northern Bighorn River valley range from below detection to 17 mg/L with an average of 2.8 mg/L (Table 1; Plate 3A). Of the 55 groundwater samples, 4 (7.3%) exceeded the recommended human health limit of 10 mg/L and 6 (10.9%) approached that limit by exceeding 5 mg/L. Higher concentrations of nitrate in samples 226395 (10.4 mg/L) and 94475 (16.2 mg/L) correspond to a mixture of older and younger water and older water samples respectively (see tritium discussion), however there are not enough tritium data to support a general conclusion that older water samples will have higher nitrate concentrations. The few groundwater samples that exceed the drinking water standard are generally isolated cases, which implies high nitrate concentrations are controlled by local sources (septic systems, nearby feed lots), rather than an extensive pollution source.

Surface-water samples collected from irrigation ditches and drains throughout the study area predominantly had nitrate and nitrite concentrations less than 1 mg/L and therefore pose little nitrogen-based risk to human health (Table 2). Of the 29 surface-water samples, nitrate and nitrite concentrations range from 0.01 to 2.38 mg/L with an average of 0.7 mg/L. Samples were collected in the spring and fall along several large drains and irrigation ditches. For those samples collected in both spring and fall, the latter samples show slightly higher nitrate and nitrite concentrations.

Table 1. Nitrate and nitrite in groundwater

GWIC ID	Sample Date	Nitrate and Nitrite (mg/l)	GWIC ID	Sample Date	Nitrate and Nitrite (mg/l)
6997	5/4/2006	8.86	234891	3/15/2007	3.16
11817	9/18/2006	0.69	234905	3/16/2007	0.59
11825	11/21/2006	2.77	234927	5/5/2006	6.38
11838	3/16/2007	0.01	234943	3/31/2006	0.06
11839	3/16/2007	0.01	234948	3/31/2006	<0.01
11843	4/25/2007	0.35	234954	4/20/2006	0.01
14074	4/12/2006	1.08	234958	4/20/2006	6.68
14078	3/16/2007	0.66	234959	4/20/2006	<0.01
14094	9/18/2006	0.72	234983	11/21/2006	0.23
14095	4/10/2007	0.10	234984	11/21/2006	0.24
94349	9/18/2006	1.95	234993	5/4/2006	7.51
94355	4/26/2006	5.39	235032	11/21/2006	0.11
94355	6/1/2006	3.87	235034	11/21/2006	1.09
94391	5/4/2006	17.10	235037	4/27/2006	0.01
94392	5/4/2006	2.14	235069	4/5/2006	0.13
94440	5/2/2007	2.84	235095	6/1/2006	0.05
94475	5/4/2006	16.20	235099	9/18/2006	2.60
124168	5/2/2007	0.13	235100	9/18/2006	4.28
127752	4/25/2007	0.02	235102	11/21/2006	3.45
156833	9/18/2006	0.83	235476	5/2/2007	0.37
208709	4/26/2006	1.07	236871	4/27/2006	1.85
212402	11/21/2006	1.48	236872	5/16/2007	3.39
212723	3/16/2007	0.15	238665	5/2/2007	0.05
226392	4/26/2006	2.05	238689	5/2/2007	12.60
226395	4/14/2006	10.40	238692	5/2/2007	7.78
226396	5/5/2006	0.64	238702	5/2/2007	0.05
234889	3/15/2007	1.98	244831	5/16/2007	2.09

Table 2. Nitrate and nitrite in surface water

Site Name	Sample Date	Nitrate and Nitrite (mg/l)	Site Name	Sample Date	Nitrate and Nitrite (mg/l)
Com School at Highway	4/14/2006	1.37	Vanzandt	4/14/2006	0.02
Com School (ditch)	11/22/2006	1.64	Vanzandt	11/22/2006	0.14
Com School West	11/22/2006	2.38	Whitman at Dorn	11/22/2006	1.29
Com School at Community	4/18/2007	0.39	Whitman at Arapooish Fishing Access	4/14/2006	0.13
Com School Branch	4/18/2007	1.37	Webber Drain	11/22/2006	1.81
General Custer Drain	4/13/2006	0.38	Webber Drain	4/18/2007	0.70
Kingley East	11/22/2006	1.45	Grant Marsh Drain	4/13/2006	0.96
Lone Tree at Highway	4/13/2006	0.45	Grant Marsh Drain	11/22/2006	2.00
Lone Tree at Highway	4/18/2007	0.27	Two Leggins at Railroad	5/19/2006	0.19
Lone Tree at Upper Road	4/13/2006	0.01	Two Leggins at Tunnel Exit	5/25/2006	0.14
South Lone Tree	4/18/2007	0.03	Two Leggins at T1N R33E S32-33 along Upper Road	4/13/2006	0.03
South Lone Tree at Center Road	11/22/2006	0.46			
Lowline at General Custer Fishing Access	5/25/2006	0.24	Two Leggins at T1N R33E S29-28 along Upper Road	4/13/2006	0.02
Low Line at Lind	5/25/2006	0.24	Two Leggins at General Custer Fishing Access	5/25/2006	0.13
Drain at T2N R33E S22-23 along Highway	4/14/2006	1.78	Drain at Lower Road / Highway 47 Y	4/13/2006	0.47

For example Grant Marsh drain increased from spring to fall (0.96 to 2.00 mg/L) as did Vanzandt (0.02 to 0.14 mg/L). South Lone Tree and Webber drain had higher nitrate and nitrite concentrations in the fall of 2006 (0.46 and 1.81 mg/L respectively) than in spring of 2007 (0.03 and 0.70 mg/L respectively). This is most likely due to the increasing use of fertilizers during the growing season, which, with time, migrate to the ditches. It should be noted that all samples collected from the irrigation ditches and drains were below the health standard of 10 mg/L. Of the 30 samples measured for water-quality parameters in the 1960 USGS study (Hamilton and Paulson, 1968), nitrate values were generally very low and the authors identified only one sample as exceeding drinking water standards.

SALINITY

A general indication of water quality can be assessed by its salinity as measured by the total dissolved solids (TDS), which can be approximated by measuring specific conductance (SC). The TDS is the sum of all the dissolved constituents in the water, whereas SC is a measure of the electrical conductivity of the water – generally directly related to the TDS of the water. Drinking water has a secondary standard for TDS of 500 mg/L (an approximate SC of 800 micro Siemens/cm). Secondary standards are non-enforceable regulations based on aesthetic or cosmetic effects (United States Environmental Protection Agency, 2008). Limits on the TDS of irrigation water vary by crop and constituent composition. In general, dissolved solids should be less than 2,000 mg/L, which, in this area, is approximately equivalent to 2,400 micro Siemens/cm. Using 15 water quality samples and their field SC measurements, a conversion chart was generated to assist in converting SC measured in the Northern Bighorn Valley to TDS (Figure 8).

Salinity of groundwater accessed by domestic and stock wells varies by aquifer and location within the valley (Plate 3B). In general, groundwater is freshest near the irrigation ditches and the river. This is most likely due to low-salinity river water and irrigation water – which is diverted river water – infiltrating through the river bed and ditches into the near-surface alluvial aquifers. As the water moves down-gradient away from the ditches it picks up salts and agricultural additives, increasing its salinity. There are three locations in the northern valley where the groundwater salinity is higher than the surrounding area. The reason for these high salinity areas is not clear; however, data collected for the 1960 study (Hamilton and Paulson, 1968) exhibit the same pattern and to a greater extent (Plate 3C). Maximum SC

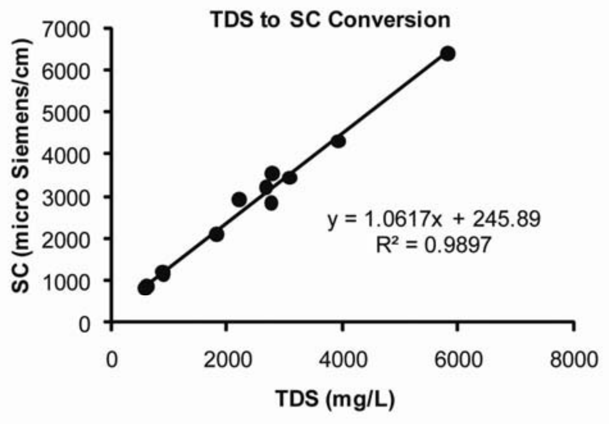

Figure 8. Conversion between TDS and SC using measured field SC values and laboratory TDS values for water samples collected in the northern Big Horn valley (data from MBMG GWIC, 2008).

values in the 1960 study exceeded 8000 micro Siemens/cm (8000 micro Siemens/cm was the maximum detection limit of their sensors) in the same three locations that reached between 5000 and 6000 micro Siemens/cm in this investigation.

There are several causes that may have precipitated the improved water quality seen in this study as compared to the 1960 USGS study (Hamilton and Paulson, 1968):

- Construction of the Yellowtail Dam (near Fort Smith) between 1961 and 1966 may have improved the consistency and volume of irrigation water, allowing for more effective flushing of salts added though agricultural practices and salts that naturally accumulate in soil.

- The main irrigation ditch, the Two Leggins Canal, was expanded and improved in the mid 1990s, which would increase the amount of irrigation water that could be added to the fields.

- Much of the land under cultivation and irrigation has been shifted away from grain crops, such as barley, to sugar beets in recent years. Sugar beets require more irrigation during their growing season than do cereals, which would allow better flushing of salt from the soil.

- Introduction of improved agricultural practices, such as yearly soil analyses, reduces the amount of fertilizers applied to the soil. Applied fertilizers are specific to plant and soil needs, which reduces the amount of fertilizer that reaches the water table.

- The USGS study outlined the problem of water logging below irrigated lands, especially on the higher terraces. They recommended improving drainage ditches. Water logging can cause increases in salinity by bringing the water table to the surface, which, when transpired or evaporated, leaves salt near the surface. The salt can then be mobilized by the introduction of irrigation water. Improving drainage and return flow ditches can improve the water quality by reducing water logging on cultivated land.

The primary source of groundwater salinity is salt that has been dissolved and mobilized along its flow path. Higher water levels lead to thicker saturation zones and potentially more dissolution of salt. Water moving along a flow path should flush the available salts and the salinity should eventually decrease. Salt mobilization and flushing has been studied in coal mine spoils in eastern Montana for several decades (Van Voast and Reiten, 1988). Speculation on the required number of pore volumes before a decrease occurs varies from a few (Van Voast and Reiten, 1988) to several thousand (Davis, 1984). Using the time of travel calculations presented in the Alluvial Groundwater Flow section, between 2 and 35 pore volumes of water have moved through and improved the aquifer since the Yellowtail Dam was completed and the USGS study was released about 40 years ago.

Laboratory data for major and minor inorganic constituents for water samples collected in the study area are listed in Appendix C. The TDS for alluvial samples collected from 2006 through 2008 range from 729 to 5,842 mg/L, with an average of 2,320 mg/L. Sodium adsorption ratio (SAR) is a measure of the ratio of sodium to calcium and magnesium concentrations and is useful for evaluating water for irrigation uses. For the same samples, the SAR values range from 1.5 to 21.1. Samples collected from the Bighorn River during December baseflow showed much lower values, with TDS average of 602 mg/L and SAR value of 2. Even this limited comparison of river water and groundwater indicates the dissolution of salts, particularly sodium salts, as the irrigation water is applied to fields and moves along groundwater flow paths.

The major ion concentrations (calcium, magnesium, sodium, bicarbonate, sulfate, chloride) for groundwater samples (figure 9) are compared in the Piper diagram presented in Figure 10. The samples are broken into three families: 1) western or upgradient side of the aquifer (in orange); 2) middle area (in green); and 3) downgradient or discharge side near the river (in blue). One sample collected from an upper terrace (94475) is in red. Cation concentrations are mixed, with sodium domination increasing along the flow paths. This is not surprising, considering the Cretaceous shales that cover much of the upland areas and have contributed sediment to the valley material. These shales no doubt provide an ample source of sodium.

Figure 9. Water-qualiy sample locations.

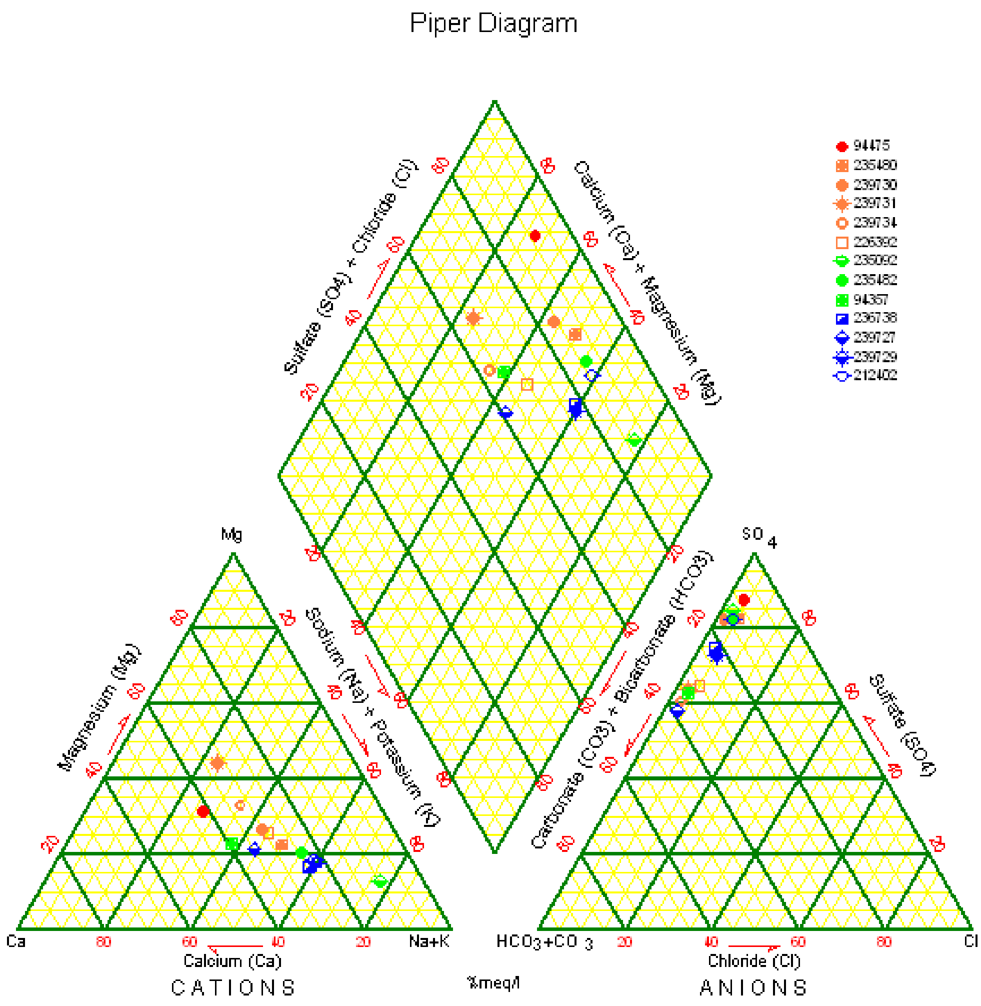

Figure 10. Chemistry of alluvial groundwater. Color of point indicates relative position along the flow path. Orange is along the western (recharge) edge, green is mid-path, and blue is near the down-gradient (discharge) edge. The red sample was taken from an upper terrace.

RECHARGE EVALUATION

Groundwater recharge to the alluvial aquifer was evaluated by assessing groundwater level fluctuations, oxygen and hydrogen isotopes, chloride concentrations, and tritium isotope analysis.

Water levels change over an annual cycle that reflects recharge (primarily irrigation water during the spring and summer) and discharge throughout the year to the river and to evaporation and transpiration. Water levels measured regularly at eight wells illustrate that the timing of recharge is very fast (Figure 11). As shown by the hydrographs in Figures 6, 7, and 11, water levels, in some instances, responded to irrigation water within a day or two. Figure 11 presents annual hydrographs with water levels compared to the lowest water altitude reached in the spring. All wells reached their lowest point immediately before ditches were turned on. This may indicate that water levels would have continued to fall if water had not been introduced to the irrigation ditches and fields. Figure 11 illustrates the rate of change of the water levels, which, in monitored wells, rose between 1.8 and 8.1 feet during the year.

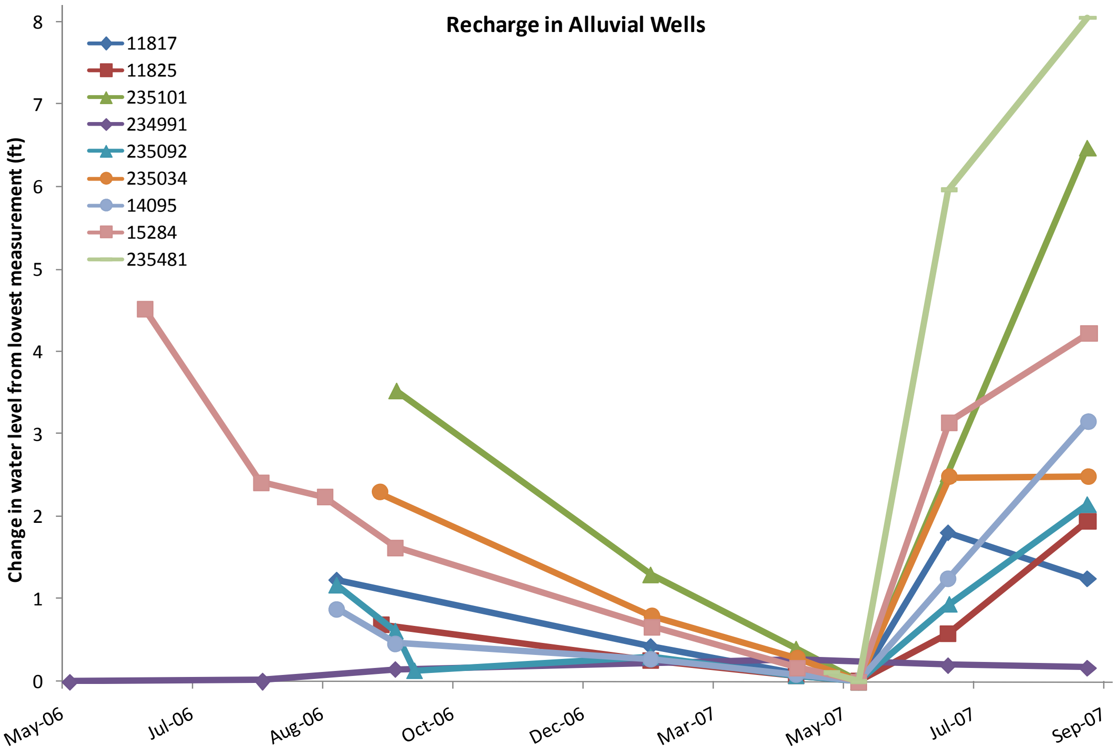

Figure 11. Example hydrographs for nine wells showing the influence of irrigation water on water levels.

At the end of the irrigation season, alluvial groundwater levels decrease throughout the winter and early spring. When the irrigation ditches are turned on in the spring, the water levels quickly rise to the levels attained during the previous irrigation season or higher. The quick response of the groundwater level to the introduction of irrigation water indicates a responsive aquifer with a predominantly local recharge source: the irrigation ditches and the irrigated fields.

The single exception to these trends is well 234991, which does not show seasonal water level changes. This well is on the second terrace above the main terrace of the valley, which is not actively irrigated. Well 234991 is close (less than half a mile) to well 94475, which was analyzed for tritium isotope concentrations. Well 94475 – we conclude well 234991 is similar – contains older water (see tritium section) that is not isotopically similar to irrigation water (see water isotope analysis section). The groundwater of this second terrace is not from irrigation water and the hydrograph indicates a lack of irrigation-driven recharge.

The water level responses to infiltration of irrigation water, as illustrated in Figures 6, 7, and 11, can be used to estimate the quantity of recharge using the formula:

$$R = 12\frac{in}{ft} S_y \frac{dh}{dt}$$

Where:
R = recharge (in/yr)
dh/dt = change in water level over time (ft/yr)
S_y = specific yield, assumed 0.15

Within the alluvial aquifer, calculated recharge rates range from 3.3 to 17.3 inches per year (in/yr). The average of the 10 wells on the alluvial aquifer (not including well 234991 on the second terrace) is 7.8 in/yr (Table 3). Outside of irrigated areas, such as on the second terrace, recharge occurs through infiltration of precipitation from storms that exceed the evapotranspiration demand. Recharge in well 234991 was 0.5 inches, which is about 4% of the annual precipitation. In eastern Montana, recharge has been estimated as averaging 0.1% to 3% of annual precipitation (Rose, 1996; Miller, 1978; 1981). However, these studies were performed on bedrock aquifers, not terrace aquifers, and would therefore have different associated soils and different recharge rates. Recharge from precipitation in eastern Montana typically only occurs during wetter-than-normal years (Van Voast and Reiten, 1988). The marked difference in recharge rates and groundwater availability in areas with irrigation (7.8 in/yr) as opposed to precipitation dependent recharge (0.5 in/yr) is illustrated by well 234991.

Table 3. Recharge rates estimated from change in water levels

Well	Sy	SWL high	SWL low	SWL change (ft)	R (in/yr)	Comment *	Year
11817	0.15	2833.50	2831.69	1.81	3.3	NI, margin area	2007
11825	0.15	2849.83	2847.88	1.95	3.5	NON, margin area	2007
235101	0.15	2891.12	2884.64	6.48	11.7	NI	2007
235092	0.15	2812.88	2810.73	2.15	3.9	ND, margin area	2007
235034	0.15	2835.33	2832.84	2.49	4.5	NI ND	2007
14095	0.15	2827.73	2824.57	3.16	5.7	NI	2007
15284	0.15	2768.48	2763.95	4.53	8.2	NI	2007
235481	0.15	2880.55	2872.60	7.95	14.3	ND	2007
239734	0.15	2977.12	2967.50	9.62	17.3	WEB-4 NI ND	2008
239727	0.15	2865.55	2862.35	3.20	5.8	WAT-2 NI ND	2008
234991	0.15	2,998.17	2,997.90	0.27	0.5	Upper terrace, NON	2007

* NI - near irrigated fields, ND - near irrigation ditches, NON - not near irrigation

WATER ISOTOPE ANALYSIS

Oxygen and hydrogen isotopes can be useful tracers of a water's origin. Oxygen and hydrogen isotopes are measured as ratios of the heavy isotope to the light: $^{18}O/^{16}O$ and $^{2}H/^{1}H$. These ratios are then compared to standard mean ocean water to produce a number which represents the variation away from this standard. This variation is the del value (represented as $\delta^{18}O$ and δD), with more negative numbers representing higher ratios (more heavy isotopes) as compared to ocean water and positive numbers representing lower isotope ratios (more light isotopes) compared to ocean water. By measuring the isotope ratios of groundwater in the northern Bighorn River valley and of potential recharge sources, it is possible to discern the source of the groundwater.

In a given location, precipitation that falls as snow has more negative $\delta^{18}O$ and δD values than precipitation that falls as rain. Additionally, precipitation that falls at higher altitudes and latitudes have generally more negative $\delta^{18}O$ and δD values than precipitation that falls at lower elevations and latitudes. Precipitation, in the form of rain or snow, generally has a predictable ratio of $\delta^{18}O$ to δD and will fall along a straight line on a graph of $\delta^{18}O$ versus δD (figure 12). The world-wide average of the oxygen and hydrogen isotopes in precipitation is known as the Global Meteoric Water Line. However, many groups have produced meteoric water lines for more localized areas including a water line for Butte, Montana (Gammons and others, 2006) and a water line for southeastern Idaho, western Wyoming, and south-central Montana (Benjamin and others, 2004). Currently, there is no defined water line specific to the Bighorn River valley; therefore the data collected for this study were compared to the Global Meteoric Water Line, and the local meteoric water lines for Butte, Montana and south-central Montana (Figure 12).

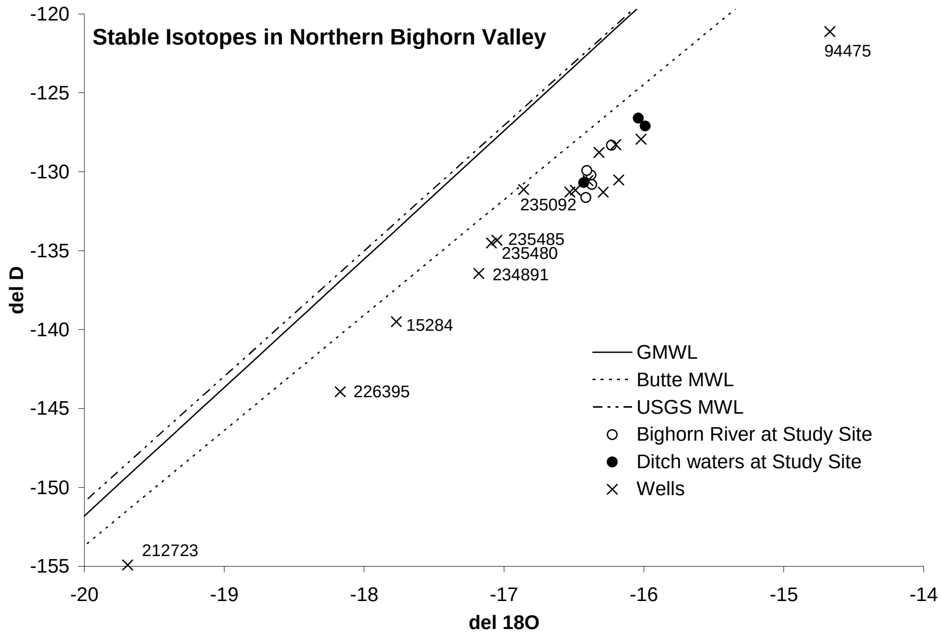

Figure 12. Oxygen and hydrogen stable isotope ratios for surface water and groundwater collected in the northern Bighorn Valley.

Samples were collected from several wells throughout the valley and from three irrigation ditches and five locations along the Bighorn River (Figure 12; Table 4). The Bighorn River and irrigation ditches have very similar isotope ratios because very little modification (evaporation, additional water input) happens along the length of the ditches. The surface-water samples fall slightly off the meteoric water lines because of the influence of evaporation. Most of the groundwater samples have oxygen and hydrogen ratios very similar to the Bighorn River and irrigation ditches. This implies that the original source of the majority of the groundwater in the alluvial aquifer is leakage from irrigation ditches or application of irrigation water. Ditch leakage in Agency Canal near Crow Agency south of Hardin was computed to vary between 100 and 400 gallons per day per linear foot of canal. Leakage from the Two Leggins Canal is predicted to be less due to a higher sediment load in the water causing the canal to seal more effectively (Hamilton and Paulson, 1968).

Table 4. Light stable isotope composition of groundwater and surface water

GWIC ID #	Date Collected	^{18}O	D	
WELLS				
11838	3/16/2007	-16.32	-128.78	
11843	4/26/2007	-16.40	-130.56	
15284	6/8/2006	-17.77	-139.50	
94475	6/8/2006	-14.67	-121.13	
212401	10/26/2006	-16.49	-131.17	
212723	3/16/2007	-19.69	-154.91	
226392	6/9/2006	-16.20	-128.28	
226395	6/8/2006	-18.17	-143.94	
226396	6/8/2006	-16.29	-131.30	
234891	3/15/2007	-17.18	-136.44	
234905	3/16/2007	-16.18	-130.52	
235092	9/6/2006	-16.86	-131.12	
235101	10/4/2006	-16.02	-127.94	
235480	4/26/2007	-17.05	-134.34	
235482	5/2/2007	-16.43	-130.69	
235485	4/26/2007	-17.09	-134.51	
238692	5/2/2007	-16.53	-131.30	
SURFACE WATER				Site Name
	5/2/2007	-16.43	-130.69	Low Line at Lind
	10/26/2006	-15.99	-127.10	Two Leggins at Railroad
	10/26/2006	-16.04	-126.60	Two Leggins at Tunnel
240468	12/13/2007	-16.23	-128.3	BHR at Two Leggins FA
240466	12/13/2007	-16.37	-130.8	BHR at Arapooish FA
240469	12/14/2007	-16.38	-130.2	BHR at Grant Marsh FA
240471	12/14/2007	-16.41	-131.6	BHR at General Custer FA
240472	12/14/2007	-16.41	-129.9	BHR at Manuel Lisa FA

Those samples that do not fall near the isotope ratios of the irrigation water tend to have more negative oxygen and hydrogen isotope values. The samples from wells 212723 and 226395, which are on the western-most edge of the valley in the northern-most extent of the study area, represent groundwater which is primarily recharged from snow melt. Additionally, sample 212723 shows very little evaporation or transpiration indicating little time spent as surface water (see chloride section). The age of sample 226395 is a mixture of older and modern water (see tritium section) and may therefore be a mixture of old snow-melt and a small contribution of modern irrigation water. Samples taken from wells 15284, 234891, 235480 and 235485, have stable isotope ratios only slightly lower than the irrigation water and are therefore most likely mixtures of snow melt and irrigation water. However, because there is no defined local meteoric water line for this area it is not possible at this time to calculate the relative contribution of each source. The sample collected from well 94475, in contrast to the other groundwater samples, has more positive stable isotope values than the irrigation water. Additionally, this sample is the oldest of the samples analyzed for tritium (see tritium section) at approximately 30 to 40 years old and shows no influence of irrigation water input (see groundwater level fluctuation section). This well, unlike the other sampled wells, is on the second terrace above the river valley. The stable isotope values in the groundwater on this terrace indicate a highly evaporated recharge source and/or a source that was not originally from snow melt. These higher terraces, therefore, will be less susceptible to changes in irrigation practices and drought conditions because the source of recharge is neither from recent snow melt nor recent application of irrigation water.

CHLORIDE TRACER EVALUATION

Chloride in rain water varies inversely with distance from the oceans from 0.6 mg/l near the Pacific Coast to 0.08-0.17 mg/l in Montana (Drever, 1997). Chloride in water is conserved during evaporation because it does not precipitate except at high salinities (Drever, 1997) nor is it taken up in plants. Chloride was analyzed in 24 samples to identify the influence of evaporation on the groundwater (Table 5). The source of high chloride concentrations in groundwater in most locations is due to evaporative concentration of chloride in irrigation water and dissolution of chloride salts in the soil. The source of groundwater that shows little evaporation (14078) is most likely primary recharge from precipitation (Clark and Fritz, 1997).

Table 5. Chloride concentrations in groundwater and surface water

GWIC ID / Site Name	Sample Date	Chloride (mg/l)	GWIC ID / Site Name	Sample Date	Chloride (mg/l)
WELLS					
11838	3/16/2007	267	235032	11/21/2006	22
11839	3/16/2007	193	235034	11/21/2006	20
14078	3/16/2007	5	235099	9/18/2006	26
14094	9/18/2006	26	235100	9/18/2006	17
14095	4/10/2007	34	235476	5/2/2007	25
94440	5/2/2007	123	236872	5/16/2007	13
156833	9/18/2006	16	238665	5/2/2007	31
212723	3/16/2007	20	238692	5/2/2007	244
234889	3/15/2007	142	238702	5/2/2007	17
234891	3/15/2007	170	244831	5/16/2007	146
234905	3/16/2007	13			
SURFACE WATER					
Two Leggins	9/18/2006	13	South Lone Tree	4/18/2007	64
Com Ditch	4/10/2007	57	Webber drain	4/18/2007	36
Com Branch	4/18/2007	25			

Separating the affect of transpiration and evaporation can be done by comparing the concentration of chloride to the stable isotope ratios. Transpiration will cause the chloride concentrations to increase without changing the hydrogen and oxygen isotope ratios. In contrast, evaporation will also increase the concentration of chloride, but will also cause the stable isotope ratios to increase. Figure 13 shows that, in the northern Bighorn valley, the increasing groundwater chloride concentrations are not associated with a corresponding increase in stable isotope ratios. This lack of correlation suggests that transpiration, not evaporation, plays the dominant role in groundwater consumption. Lack of evaporation evidence in groundwater implies that very little water infiltrates from the surface of the fields, where evaporation would be significant. Most of the groundwater is recharged by the irrigation ditches and is subsequently transpired by crops.

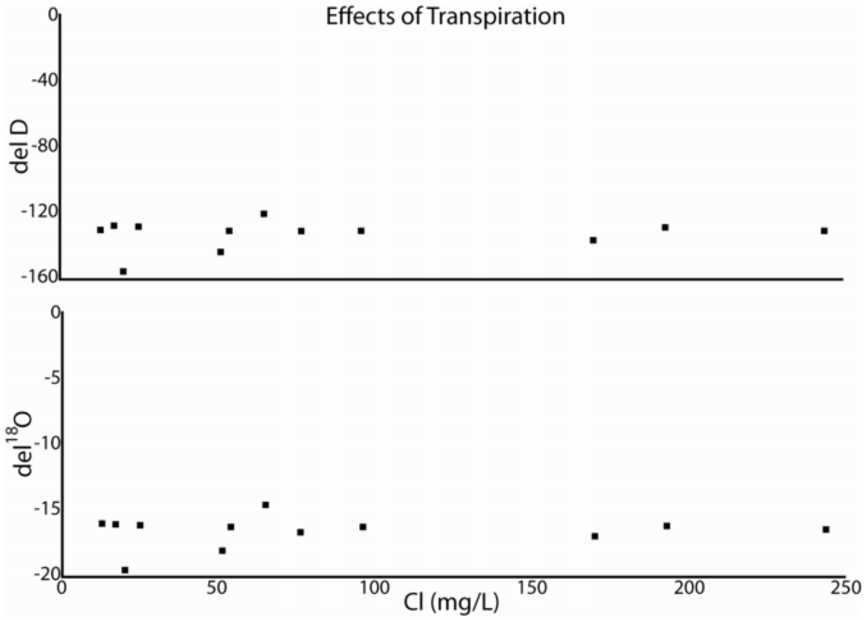

Figure 13. Chloride in groundwater versus stable isotope ratios. No correlation between isotope ratios and chloride concentrations implies the greatest influence on groundwater is transpiration, not evaporation.

TRITIUM ANALYSES

The age of groundwater, considered to be the time since the water fell as rain or was last in contact with the atmosphere, can be a useful measurement to determine characteristics of an aquifer. Estimation of the age of water in an aquifer can be done in a number of ways; one common way is through measurement of the tritium concentration of the aquifer water. Tritium is a radioactive isotope of hydrogen that is produced in low levels naturally in the atmosphere and also during nuclear power generation. Tritium was also produced in great quantities during nuclear bomb testing prior to The Partial Test Ban

Treaty of 1963. The radioactive decay of tritium to helium-3 occurs relatively rapidly with a half life of 12.5 years. Due to this short decay time, tritium is not present in measureable quantities in water that is over 60 years old. The spike in tritium levels produced during nuclear testing in the 1950s allows the identification of water that originated as meteoric water during that time frame. Tritium is measured in Tritium Units (or TU).

As a general rule:

- Water with no measureable tritium recharged the aquifer prior to 1952.
- Water with intermediate tritium concentrations of 0.8 to 4 TU is most likely a mixture of modern water and older, tritium dead, water.
- Water with measured 5 to 15 TU is young, less than 10 years old.
- Water that has TU values of 15 to 30 shows some influence of "bomb" era tritium indicating at least some of the water originated after bomb testing.
- Water with over 30 TU shows a considerable amount of tritium from the 1960s and 1970s.
- Water with over 50 TU most likely recharged the aquifer during the peak of nuclear testing (Clark and Fritz, 1997).

The results of the tritium sampling and analyses for the northern Bighorn valley indicate the majority of the groundwater recharged the aquifer recently; these results support the interpretation of the stable isotope and chloride analyses that the majority of groundwater in the valley originated with infiltrating irrigation water (Table 6). However, some of the wells which are over a mile down-gradient from the western edge of the terrace, such as 212401 and 235092, are measurably older than wells in close proximity to the irrigation ditches along the western edge of the terrace aquifer. This may give an indication of the rate of groundwater movement at approximately 1/10th of a mile or less per year (14.5 ft/d). This is less than was estimated by the Webber aquifer test of 62 ft/d.

The tritium analyses have supported conclusions drawn from the light stable isotope analyses. Well 94475 is on the second terrace above the main valley terrace and is the oldest sample at approximately 30 to 40 years old. Water levels in this well do not vary seasonally and have light stable isotope ratios dissimilar to irrigation water. Well 2269395 is a mixture of old and modern water, an observation supported by the stable isotope analysis which indicates groundwater at this site is a mixture of snow melt and infiltrating irrigation water.

Table 6. Tritium in groundwater and surface water

GWIC ID / Site Name	^{3}H (TU)	error	era	approximate age (years)
WELL				
15284	8.2	0.7	modern	less than 10
94355	9.7	0.9	modern	less than 10
94475	26.6	1.9	50s-70s	approximately 30
212401	19.1	1.4	70s-90s	10 to 30 years
226395	3.5	0.5	mixture	
226396	12.5	1.0	modern	less than 10
235092	14.8	1.1	70s-90s	10 to 30 years
235101	9.8	0.9	modern	less than 10
SURFACE WATER				
Two Leggins at Railroad	8.0	0.7	modern	less than 10

CONCLUSIONS

GROUNDWATER AVAILABILITY

The majority of groundwater in the alluvial aquifers in the northern Bighorn River valley originates from the irrigation water in the ditches. The relationship between ditch leakage and aquifer recharge must be taken into account before changes to the ditches are made. Lining ditches or reducing the amount of water they carry could potentially reduce the available groundwater used domestically and for stock water. Reducing the area of irrigated land, on the other-hand, may not impact the groundwater levels significantly so long as the irrigation ditches are maintained. Additional private wells, if installed in moderation and consuming a modest amount of water for domestic use, should not impact the groundwater availability significantly; however, further monitoring of water levels would be necessary to ensure protection of this resource.

GROUNDWATER QUALITY

Water quality in the valley has improved over the last 50 years and should not degrade so long as alluvial groundwater levels are kept at their current levels. Allowing the water levels to fluctuate greatly, or increase over the current levels, will mobilize more soil salts thereby increasing salinity in the groundwater. Further improvements in salinity may be possible by closely monitoring agricultural amendments to ensure they do not exceed plant uptake and to allow the ditches to maintain a constant water level throughout most of the year, irrespective of irrigation usage.

Nitrate concentrations, a health concern especially in children and infants, are low throughout most of the valley. High nitrate levels in individual wells are likely due to localized sources such as high animal concentrations or septic systems in close proximity to the well.

RECOMMENDATIONS

Continuing the monitoring program established for this project would help further establish the alluvial aquifer characteristics including discerning the respective influences of ditch leakage versus irrigation water application on the quantity of water recharging the aquifer. Taking the data collected for this project, continuing the monitoring and running more long-term aquifer tests would allow the development of a predictive groundwater model. A model such as this would be useful in predicting drawdown in theoretical situations such as increased development, reduced irrigation and possible effects of contaminant spills.

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Appendix A. Site Inventories

Gwic Id	Latitude	Longitude	T R S Qsect	Site Type	Altitude (ft)	Well Depth (ft)	Inventory Date	Aquifer	Inventoried Water Level (ft)	Temp (C)	Field SC	Field pH	Redox
6997	45.7302	-107.6843	01S 33E 19 DAAD	WELL	3035	24	5/4/2006	112TRRC	20.48	11.3	2984	7.33	
11817	45.8695	-107.6100	01N 33E 3 BBBB	WELL	2841	38	9/6/2006	112TRRC	8.33	13.6	2214	7.37	
11825	45.8503	-107.6138	01N 33E 9 ADAB	WELL	2862	50	9/27/2006	112TRRC	14.93	10.7	1550	7.4	
11838	45.7987	-107.6072	01N 33E 27 CCDA	WELL	2854	20	3/16/2007	112TRRC	7.75	9.8	6040	6.87	-7.7
11839	45.7990	-107.6105	01N 33E 27 CCCB	WELL	2855	28	3/16/2007	112TRRC	7.95	6.4	3740	8.24	-72.3
11843	45.8004	-107.6329	01N 33E 29 DDAA	WELL	2875	30	4/26/2007		8.75	10.3	4237	7.37	6.7
14074	45.9274	-107.5873	02N 33E 14 BBAB	WELL	2800	28	4/12/2006	112TRRC	10.11	11.7	1731	7.39	
14076	45.9177	-107.6209	02N 33E 16 DBC	WELL		32	6/28/2007		10.43	10.9	7590	7.51	
14078	45.9131	-107.6170	02N 33E 21 ABAA	WELL	2880	40	3/16/2007	112TRRC	17.7	9.2	1156	7.74	-47.5
14080	45.8997	-107.6005	02N 33E 22 CDDA	WELL	2890	65	9/6/2006	112TRRC	8.53				
14095	45.8706	-107.6002	02N 33E 34 DCCC	WELL	2831	28	9/6/2006	112TRRC	6.65				
15284	46.0003	-107.5346	03N 34E 18 DCDD	WELL	2775	16	6/8/2006	112TRRC	7.22	10.6	1743	7.6	
94349	45.7676	-107.6195	01S 33E 3 DDDD	WELL	2893	30	9/21/2006	112TRRC	8.42	12.7	3714	7.2	
94355	45.7533	-107.6370	01S 33E 10	WELL	2948	48	4/26/2006	112TRRC		12.3	2755	7.46	
94357	45.7604	-107.6121	01S 33E 11	WELL	2900	31	10/4/2006	110TRRC	9.84	14	1163	7.37	
94392	45.7307	-107.6853	01S 33E 19 DAAB	WELL	3034	45	5/4/2006	112TRRC	23.42	11.9	2986	7.55	
94440	45.7258	-107.6198	01S 33E 23 CC	WELL	2910	26	5/2/2007	110TRRC	7.47	13.5	5013	7.96	-26
124168	45.7605	-107.5901	01S 33E 12	WELL		25	5/2/2007		12.2	10.68	1583	7.57	5
156833	45.9500	-107.5814	02N 33E 2 BDDD	WELL	2827	55	9/18/2006	112TRRC	12.73	14.3	1200	7.54	
208709	45.8873	-107.6111	02N 33E 27 CCBC	WELL	3835	37	4/26/2006	112TRRC	9.93	11.9	1836	7.52	
212401	45.7655	-107.6010	01S 33E 11 AADA	WELL	2887	35	10/4/2006		13.13	12	1145	7.09	
212402	45.7656	-107.6013	01S 33E 11 AAAC	WELL	2885	35	10/4/2006	112TRRC	14.1	12.6	4320	7.02	
212723	45.9710	-107.5714	03N 33E 35 AAAD	WELL	2878	240	3/16/2007	211LNCE	113.09	12.5	2040	8.72	-100.4
226392	45.7552	-107.6333	01S 33E 10 CDAC	WELL	2920	85	6/9/2006	112TRRC	7.07	12.6	1223	7.49	
226395	45.8374	-107.6368	01N 33E 17 AACC	WELL	2905	100	4/12/2006	211BRPW	18.02	10.6	2421	7.64	
226396	45.7636	-107.6645	01S 33E 8 ADBA	WELL	3010	60	6/8/2006	211BRPW		15	2115	7.05	
234889	46.6941	-107.6389	02S 33E 3 BBAA	WELL	2929	30	3/15/2007	112TRRC	11.07	10.9	3938	6.98	-12.1
234891	45.6936	-107.6380	02S 33E 3 BBAA	WELL	2929	44	3/15/2007	112TRRC	11.5	11.2	4596	6.62	-3.7
234905	45.9661	-107.5690	03N 33E 36 BCBB	WELL	2815	75	3/16/2007	211LNCE	30	12.9	1000	7.66	-43.9
234927	45.7630	-107.6658	01S 33E 8 ADBC	SPRING	3020		5/5/2006	112TRRC		12.3	2600	7.17	
234943	45.8396	-107.6101	01N 33E 15 BBBC	WELL	2845	26	3/31/2006	112TRRC	3.42	12.3	3999	8.97	
234948	45.8395	-107.6093	01N 33E 15 BBBC	WELL	2845		3/31/2006	112TRRC		11.3	2856	9.47	
234954	45.9458	-107.5947	02N 33E 3 DACC	WELL	2855	100	4/20/2006	211BRPW		8.87	2417	7.3	

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Gwic Id	Latitude	Longitude	T R S Qsect	Site Type	Altitude (ft)	Well Depth (ft)	Inventory Date	Aquifer	Inventoried Water Level (ft)	Temp (C)	Field SC	Field pH	Redox
234958	45.9759	-107.6202	03N 33E 28 DBCA	SPRING	3010		4/20/2006	211LNCE		10.06	2796	6.81	
234983	45.9815	-107.5337	03N 34E 30 AACC	WELL	2790	20.5	9/26/2006	112TRRC	14.53	10.6	1109	8.1	
234984	45.9181	-107.5917	02N 33E 15 DADA	WELL	2815		9/27/2006	112TRRC		10.8	2127	8.29	
234991	45.7233	-107.6625	01S 33E 29 AAAD	WELL	3010	25	5/4/2006	112TRRC	16.5	10.2	3720	7.31	
234993	45.7184	-107.6450	01N 33E 28 ADCA	WELL	2935		5/4/2006	112TRRC	18.15	11.3	5930	7.16	
235030	45.8719	-107.6109	02N 33E 34 CCBC	WELL	2841	38	9/26/2006	112TRRC	8.33	12.9	1375	7.49	
235032	45.8714	-107.6102	02N 33E 34 CCBC	WELL	2841		9/26/2006	112TRRC					
235034	45.8772	-107.6109	02N 33E 34 BCCD	WELL	2837	20	9/26/2006	112TRRC	3.57	11.4	2397	7.69	
235037	45.8266	-107.6138	01N 33E 16 DDDC	WELL	2852	36	4/27/2006	112TRRC	12.15	11.9	2181	7.31	
235067	45.7688	-107.6311	01S 33E 3 CDDD	WELL	2915	7	4/5/2006	112TRRC	3.85	10	1183	7.51	
235069	45.7690	-107.6309	01S 33E 3 CDDD	WELL	2915	11	4/5/2006	112TRRC	7.55				
235092	45.8910	-107.5919	02N 33E 27 DAAC	WELL	2817	25	9/6/2006	112TRRC	7	16.5	6930	7.5	
235095	45.9806	-107.5335	03N 34E 30 AACC	WELL	2788	35	6/1/2006	112TRRC	13.5	12.5	783	7.28	
235099	45.9124	-107.6085	02N 33E 15 CCCD	WELL	2851		9/21/2006	112TRRC		14	1900	7.63	
235100	45.9877	-107.6117	02N 33E 27 BBCB	WELL	2839	24	9/18/2006	112TRRC	8.85	13.5	1234	7.33	
235101	45.7609	-107.6111	01S 33E 11 BCCA	WELL	2898	30	10/4/2006	112TRRC	9.84		1163		
235102	45.7611	-107.6098	01S 33E 11 BCCB	WELL	2898		10/4/2006	112TRRC	12.91	11.9	3365	6.72	
235476	45.7644	-107.6332	01S 33E 10 BACA	WELL	2916		4/26/2007		7.1	10.9	978	9.11	10
235480	45.8195	-107.6335	01N 33E 20 ADDB	WELL	2874		4/26/2007		2.9	10.43	2936	7.5	78
235482	45.8370	-107.6126	01N 33E 16 ADAA	WELL	2847	29.6	4/26/2007		8.33	11.84	3492	7.62	-71
235485	45.8150	-107.6217	01N 33E 21 DBCD	WELL	2857		4/26/2007		4.43	10.63	4510	7.81	-127
236738	45.8880	-107.5748	02N 33E 26 DBDD	WELL			6/28/2007	111ALVM	8.85	11.5	3458	7.14	
236871	47.7680	-107.6080	01S 33E 2 DCDC	WELL	2890	35	4/27/2006			11.5	4780	7.09	
236872	45.7525	-107.6354	01S 33E 15	WELL	2920	24	5/16/2007		6.05		1013		
238664	45.8807	-107.6101	02N 33E 34 BBCD	WELL	2835	42.5	8/24/2007	112TRRC	0.41	11.4	4313		
238665	45.7409	-107.6073	01S 33E 14 DCAC	WELL	2900	26.5	5/2/2007	112TRRC	9.44	13	1972	9.54	
238689	45.7489	-107.6380	01S 33E 15 BC	WELL	2930	16	5/2/2007	112TRRC	11.99	8.75	7118	7.16	
238692	45.7491	-107.6379	01S 33E 15 BCBA	WELL	2930	58	5/2/2007		11.02	9.29	6297	7.25	-21
238694	45.7143	-107.6430	01S 33E 28 DADB	WELL	2935		5/4/2006		12.46				
238702	45.7529	-107.6012	01S 33E 13 BBBB	WELL	2878		5/2/2007			13.01	1482	7.84	31.2
239727	45.7684	-107.5959	01S 33E 1	WELL	2870	12.4	7/1/2008		7.29	11.7	2606		
239728	45.7684	-107.5958	01S 33E 1	WELL	2870	21.6	7/1/2008		6.95	10.2	2421		
239729	45.7685	-107.5959	01S 33E 1	WELL	2870	23.4	7/1/2008		7.26	10.5	3572		

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Gwic Id	Latitude	Longitude	T R S Qsect	Site Type	Altitude (ft)	Well Depth (ft)	Inventory Date	Aquifer	Inventoried Water Level (ft)	Temp (C)	Field SC	Field pH	Redox
239730	45.8661	-107.6290	01N 33E 4	WELL	2980	74	7/1/2008		8.65	10.4	3211		
239731	45.8660	-107.6291	01N 33E 4	WELL	2980	32	7/1/2008		5.06	10.4	1450		
239733	45.8660	-107.6290	01N 33E 4	WELL	2980	68.6	7/1/2008		8.29	10.7	3360		
239734	45.8660	-106.6290	01N 33E 4	WELL	2980	22.6	7/1/2008		5.12	10.3	1163		
240466	45.7562	-107.5645	01S 34E 7 D	STREAM			12/13/2007			3.3	863	8.37	
240468	45.6443	-107.6562	02S 33E 21 BDC	STREAM			12/13/2007			4.5	837	8.3	
240469	45.8441	-107.5823	01N 33E 11 C	STREAM			12/14/2007			3.3	831	8.49	
240471	45.9273	-107.5740	02N 33E 14 A	STREAM			12/14/2007			3.4	832	8.74	
240472	46.1447	-107.4635	05N 34E 34 BCB	STREAM	2690		12/14/2007			2	871	8.51	
240474	45.7685	-107.5959	01S 33E 1	STREAM	2859		5/28/2008			6.5	1063		
244831	45.7281	-107.5986	01S 33E 24 CCBA	WELL			5/16/2007		6.26		2360		
244839	45.8847	-107.6218	02N 33E 28 CDDD	WELL			7/8/2008		7.41	15.7	2273	7.32	-266

Appendix B. USGS WSP 1876 Site Inventories

Gwic Id	Latitude	Longitude	T R S Qsect				Site Type	Well Depth (ft)	Inventory Date	Aquifer	Agency	Field SC
244993	45.8463	-107.6095	01N	33E	10	CB	WELL	17.6	1/1/1967	110TRRC	USGS	5900
244994	45.8536	-107.5888	01N	33E	11	BB	WELL	11	1/1/1967	110TRRC	USGS	3600
244995	45.8281	-107.6301	01N	33E	16	CC	WELL	65	1/1/1967	110TRRC	USGS	2550
244996	45.8281	-107.6145	01N	33E	16	DD	WELL	65	1/1/1967		USGS	6000
244997	45.8208	-107.6350	01N	33E	20	AD	WELL	75	1/1/1967	211BRPW	USGS	6000
244998	45.8209	-107.6144	01N	33E	21	AD	WELL		1/1/1967		USGS	5100
244999	45.8246	-107.6247	01N	33E	21	BA	WELL	44	1/1/1967	211BRPW	USGS	500
245000	45.7993	-107.6093	01N	33E	27	CC	WELL	20	1/1/1967	111ALVM	USGS	8000
245001	45.7992	-107.6247	01N	33E	28	CD	WELL	18	1/1/1967	110TRRC	USGS	5470
245002	45.7848	-107.6666	01N	33E	31	CD	WELL	27	1/1/1967	110TRRC	USGS	700
245003	45.7849	-107.6350	01N	33E	32	DD	WELL	60	1/1/1967	211BRPW	USGS	1380
245004	45.7921	-107.6248	01N	33E	33	BD	WELL	21	1/1/1967	110TRRC	USGS	8000
245005	45.7849	-107.6248	01N	33E	33	CD	WELL		1/1/1967		USGS	2900
245006	45.7849	-107.6145	01N	33E	33	DD	WELL	30	1/1/1967	110TRRC	USGS	8000
245007	45.9513	-107.5835	02N	33E	2	BD	WELL	55	1/1/1967	110TRRC	USGS	1400
245008	45.9440	-107.5887	02N	33E	2	CC	WELL	42	1/1/1967		USGS	2350
245009	45.9439	-107.5937	02N	33E	3	DD	WELL	120	1/1/1967	211BRPW	USGS	6100
245010	45.9368	-107.5782	02N	33E	11	AC	WELL	20	1/1/1967	111ALVM	USGS	3400
245011	45.9405	-107.5885	02N	33E	11	BB	WELL	45	1/1/1967	110TRRC	USGS	1490
245012	45.9224	-107.5833	02N	33E	14	BD	WELL	40	1/1/1967	110TRRC	USGS	4000
245013	45.9261	-107.5937	02N	33E	15	AA	WELL	47	1/1/1967	110TRRC	USGS	2100
245014	45.9151	-107.6093	02N	33E	15	CC	WELL	54	1/1/1967	110TRRC	USGS	2100
245015	45.9005	-107.6145	02N	33E	21	DD	WELL	65	1/1/1967	110TRRC	USGS	1500
245016	45.9116	-107.5937	02N	33E	22	AA	WELL	40	1/1/1967	110TRRC	USGS	3400
245017	45.9006	-107.5989	02N	33E	22	DC	WELL	55	1/1/1967	110TRRC	USGS	2400
245018	45.8971	-107.6093	02N	33E	27	BB	WELL	45	1/1/1967	110TRRC	USGS	2500
245019	45.8862	-107.6041	02N	33E	27	CD	WELL	15	1/1/1967	110TRRC	USGS	3000
245020	45.8860	-107.6145	02N	33E	28	DD	WELL	15	1/1/1967	110TRRC	USGS	1800
245021	45.8716	-107.6302	02N	33E	33	CC	WELL	80	1/1/1967	211BRPW	USGS	1950
245022	45.8826	-107.5989	02N	33E	34	AB	WELL	28	1/1/1967	110TRRC	USGS	8000
245023	45.8753	-107.5938	02N	33E	34	DA	WELL	25	1/1/1967	110TRRC	USGS	8000
245024	45.8788	-107.5681	02N	33E	36	BC	WELL	120	1/1/1967	211HLCK	USGS	1150
245025	46.0128	-107.5314	03N	34E	18	AA	WELL	30	1/1/1967	111ALVM	USGS	2500
245026	46.0057	-107.5366	03N	34E	18	DB	WELL	48	1/1/1967		USGS	940
245027	45.9873	-107.5316	03N	34E	19	DD	WELL	100	1/1/1967	211HLCK	USGS	3900
245028	45.9694	-107.5420	03N	34E	31	BA	WELL	38	1/1/1967	211HLCK	USGS	1600
245029	46.0925	-107.5105	04N	34E	17	DA	WELL	10	1/1/1967	111ALVM	USGS	1400
245030	45.7735	-107.6141	01S	33E	2	CA	WELL	30	1/1/1967	110TRRC	USGS	5500
245031	45.7696	-107.6141	01S	33E	2	CD	WELL	27	1/1/1967	110TRRC	USGS	4400
245032	45.7773	-107.6231	01S	33E	3	AD	WELL	21	1/1/1967		USGS	5000
245033	45.7694	-107.6231	01S	33E	3	DD	WELL	33	1/1/1967	110TRRC	USGS	3900
245034	45.7659	-107.6342	01S	33E	10	BA	WELL	12	1/1/1967	110TRRC	USGS	1250
245035	45.7585	-107.6342	01S	33E	10	CA	WELL		1/1/1967		USGS	1650
245037	45.7548	-107.6342	01S	33E	10	CD	WELL	55	1/1/1967		USGS	1100
245036	45.7585	-107.6295	01S	33E	10	DB	WELL	32	1/1/1967	110TRRC	USGS	3900
245038	45.7442	-107.6094	01S	33E	14	DB	WELL	28	1/1/1967	110TRRC	USGS	3000
245039	45.7258	-107.6039	01S	33E	23	DD	WELL		1/1/1967		USGS	8000
245040	45.7183	-107.5983	01S	33E	25	BC	WELL	7	1/1/1967	111ALVM	USGS	3200
245041	45.7222	-107.6038	01S	33E	26	AA	WELL	20	1/1/1967		USGS	8000

Appendix B. USGS WSP 1876 Site Inventories

Gwic Id	Latitude	Longitude	T	R	S	Qsect	Site Type	Well Depth (ft)	Inventory Date	Aquifer	Agency	Field SC
245042	45.7185	-107.6242	01S	33E	27	AD	WELL	32	1/1/1967	110TRRC	USGS	3000
245043	45.6964	-107.6542	01S	33E	33	CD	WELL	26	1/1/1967	110TRRC	USGS	2000
245044	45.7002	-107.6390	01S	33E	34	CB	WELL	24	1/1/1967	110TRRC	USGS	1300
245045	45.7003	-107.6192	01S	33E	35	CB	WELL	16	1/1/1967		USGS	3200
245046	45.6966	-107.6088	01S	33E	35	DC	WELL	9	1/1/1967	110TRRC	USGS	1900
245047	45.6962	-107.5983	01S	33E	36	CC	WELL	16	1/1/1967	111ALVM	USGS	2900
245048	45.7515	-107.5783	01S	34E	18	BB	WELL	20	1/1/1967	111ALVM	USGS	3500
245049	45.7367	-107.5783	01S	34E	19	BB	WELL	10	1/1/1967	111ALVM	USGS	1300
245050	45.6652	-107.7053	02S	32E	12	DD	WELL	55	1/1/1967	110TRRC	USGS	1600
245051	45.6932	-107.6129	02S	33E	2	BA	WELL	24	1/1/1967	110TRRC	USGS	1850
245052	45.6932	-107.6187	02S	33E	2	BB	WELL	18	1/1/1967	110TRRC	USGS	3200
245053	45.6820	-107.6129	02S	33E	2	CD	WELL	11	1/1/1967	110TRRC	USGS	2400
245054	45.6929	-107.6396	02S	33E	3	BB	WELL	50	1/1/1967	110TRRC	USGS	2000
245055	45.6819	-107.6396	02S	33E	3	CC	WELL	16	1/1/1967	110TRRC	USGS	3400
245056	45.6927	-107.6808	02S	33E	5	BB	WELL	30	1/1/1967	110TRRC	USGS	1900
245057	45.6674	-107.6446	02S	33E	9	DD	WELL	20	1/1/1967	110TRRC	USGS	1100
245058	45.6749	-107.6396	02S	33E	10	BC	WELL	21	1/1/1967	110TRRC	USGS	3600
245059	45.6676	-107.6343	02S	33E	10	CD	WELL		1/1/1967		USGS	2500
245060	45.6676	-107.6291	02S	33E	10	DC	WELL	9	1/1/1967	110TRRC	USGS	3300
245061	45.6676	-107.6239	02S	33E	10	DD	WELL	50	1/1/1967	111ALVM	USGS	4300
245062	45.6786	-107.6127	02S	33E	11	BA	WELL	22	1/1/1967	111ALVM	USGS	2500
245063	45.6641	-107.6332	02S	33E	15	BA	WELL	17	1/1/1967	110TRRC	USGS	2100
245064	45.6566	-107.6547	02S	33E	16	CA	WELL	9	1/1/1967	110TRRC	USGS	1250
245065	45.6637	-107.7009	02S	33E	18	BB	WELL	55	1/1/1967	110TRRC	USGS	1400
245066	45.6382	-107.6698	02S	33E	20	DC	WELL	26.2	1/1/1967	111ALVM	USGS	2000
245067	45.6235	-107.6694	02S	33E	29	DC	WELL	11	1/1/1967	111ALVM	USGS	1950
245068	45.6125	-107.6690	02S	33E	32	DB	WELL	13	1/1/1967	111ALVM	USGS	2600
245069	45.5211	-107.7039	03S	32E	36	DD	WELL	70	1/1/1967		USGS	8000
245070	45.5938	-107.6741	03S	33E	5	CD	WELL	20	1/1/1967	111ALVM	USGS	6200
245071	45.5832	-107.6635	03S	33E	8	DA	WELL		1/1/1967		USGS	6500
245072	45.5904	-107.6533	03S	33E	9	BA	WELL	70	1/1/1967	110TRRC	USGS	6500
245073	45.5613	-107.6683	03S	33E	20	AB	WELL		1/1/1967		USGS	600
245074	45.5467	-107.6682	03S	33E	29	AB	WELL	80	1/1/1967	110TRRC	USGS	2200
245075	45.5467	-107.6785	03S	33E	29	BB	WELL	49	1/1/1967	110TRRC	USGS	8000
245076	45.5466	-107.6835	03S	33E	30	AA	WELL	49	1/1/1967	110TRRC	USGS	8000
245077	45.5138	-107.7039	04S	32E	1	AD	WELL	40	1/1/1967	110TRRC	USGS	6200
245078	45.4921	-107.7038	04S	32E	12	DD	WELL	56	1/1/1967	110TRRC	USGS	8000
245079	45.4777	-107.7194	04S	32E	13	CC	WELL		1/1/1967		USGS	4800
245080	45.4704	-107.7241	04S	32E	23	AD	WELL	26	1/1/1967	110TRRC	USGS	3000
245081	45.4741	-107.7035	04S	32E	24	AA	WELL	29	1/1/1967		USGS	4000
245082	45.4633	-107.7190	04S	32E	24	CC	WELL	55	1/1/1967	110TRRC	USGS	2900
245083	45.4633	-107.7087	04S	32E	24	DC	WELL	7	1/1/1967	110TRRC	USGS	4600
245084	45.4597	-107.7189	04S	32E	25	BB	WELL	55	1/1/1967	110TRRC	USGS	2500
245085	45.4559	-107.7239	04S	32E	26	AD	WELL	60	1/1/1967	110TRRC	USGS	2600
245086	45.4523	-107.7239	04S	32E	26	DA	WELL	45	1/1/1967	110TRRC	USGS	2800
245087	45.4451	-107.7237	04S	32E	35	AA	WELL	38	1/1/1967	110TRRC	USGS	2600
245088	45.4451	-107.7289	04S	32E	35	AB	WELL	34	1/1/1967	110TRRC	USGS	2000
245089	45.4379	-107.7083	04S	32E	36	DB	WELL	66	1/1/1967	110TRRC	USGS	2500
245090	45.5174	-107.6835	04S	33E	6	AA	WELL	60	1/1/1967		USGS	2600

Appendix B. USGS WSP 1876 Site Inventories

Gwic Id	Latitude	Longitude	T R S Qsect				Site Type	Well Depth (ft)	Inventory Date	Aquifer	Agency	Field SC
245091	45.5065	-107.6987	04S	33E	6	CC	WELL	50	1/1/1967	110TRRC	USGS	5900
245092	45.5029	-107.6886	04S	33E	7	AB	WELL	70	1/1/1967	110TRRC	USGS	1900
245093	45.5029	-107.6987	04S	33E	7	BB	WELL	66	1/1/1967	110TRRC	USGS	3800
245094	45.4814	-107.6935	04S	33E	18	CA	WELL	80	1/1/1967	110TRRC	USGS	4700
245095	45.3534	-107.8565	05S	31E	35	BD	WELL	50	1/1/1967		USGS	2400
245096	45.3535	-107.8254	05S	31E	36	AD	WELL	50	1/1/1967		USGS	1450
245097	45.4305	-107.7235	05S	32E	2	AA	WELL	38	1/1/1967	110TRRC	USGS	3100
245098	45.4269	-107.7235	05S	32E	2	AD	WELL	43	1/1/1967	110TRRC	USGS	5900
245099	45.4157	-107.7745	05S	32E	9	BA	WELL	25	1/1/1967	110TRRC	USGS	2200
245100	45.4122	-107.7592	05S	32E	10	BC	WELL	100	1/1/1967	110TRRC	USGS	2300
245101	45.4122	-107.7540	05S	32E	10	BD	WELL	45	1/1/1967	110TRRC	USGS	2300
245102	45.3901	-107.7643	05S	32E	16	DD	WELL	80	1/1/1967	110TRRC	USGS	1800
245103	45.3901	-107.8002	05S	32E	17	CC	WELL	33	1/1/1967	111ALVM	USGS	1750
245104	45.3791	-107.8052	05S	32E	19	DA	WELL	32	1/1/1967	111ALVM	USGS	2300
245105	45.3721	-107.7845	05S	32E	29	AA	WELL	65	1/1/1967	110TRRC	USGS	1400
245106	45.3719	-107.8051	05S	32E	30	AA	WELL	45	1/1/1967	110TRRC	USGS	2400
245107	45.3719	-107.8051	05S	32E	30	AA	WELL	25	1/1/1967	110TRRC	USGS	2000
245108	45.3719	-107.8204	05S	32E	30	BB	WELL	8	1/1/1967	111ALVM	USGS	2300
245109	45.3609	-107.8051	05S	32E	30	DD	WELL	60	1/1/1967	110TRRC	USGS	2400
245110	45.3574	-107.8049	05S	32E	31	AA	WELL	37	1/1/1967	110TRRC	USGS	3200
245111	45.3206	-107.8752	06S	31E	11	DC	WELL	30	1/1/1967	110TRRC	USGS	1000
245112	45.3062	-107.9215	06S	31E	16	CD	WELL	395	1/1/1967	110TRRC	USGS	840

Appendix C1. Alluvial and Terrace Groundwater Quality

	Gwic Id	Location				Site Type	Aquifer	Depth (ft)	Agency	Sample Date
		Latitude	Longitude	T R S Qsect	County					
Alluvial and Terrace Ground Water	114	45.8113	-107.6105	01N 33E 27 BBBB	Big Horn	WELL	110ALVM	12	USGS	9/18/1916
	115	45.8113	-107.6105	01N 33E 27 BBBB	Big Horn	WELL	110ALVM	10	USGS	4/14/1960
	116	45.7988	-107.6238	01N 33E 28 CD	Big Horn	WELL	110TRRC	17	USGS	4/14/1960
	117	45.7919	-107.6344	01N 33E 32 ADD	Big Horn	WELL	110TRRC	24	USGS	4/14/1960
	1012	45.9294	-107.5930	02N 33E 10 DD	Big Horn	WELL	110TRRC	43	USGS	8/25/1960
	1015	45.8716	-107.5827	02N 33E 35 CD	Big Horn	WELL	110ALVM	11	USGS	8/25/1960
	1211	46.0016	-107.5361	03N 34E 18 DC	Big Horn	WELL	110TRRC	18	USGS	9/18/1916
	6994	45.7527	-107.6005	01S 33E 14 ABBB	Big Horn	WELL	110TRRC	20	USGS	4/14/1960
	6994	45.7527	-107.6005	01S 33E 14 ABBB	Big Horn	WELL	110TRRC	20	USGS	8/25/1960
	6995	45.7394	-107.6230	01S 33E 15 DDD	Big Horn	WELL	110TRRC	28	USGS	4/14/1960
	6997	45.7302	-107.6843	01S 33E 19 DAAD	Big Horn	WELL	112TRRC	24	USGS	1/11/1935
	6997	45.7302	-107.6843	01S 33E 19 DAAD	Big Horn	WELL	112TRRC	24	USGS	5/31/1945
	6997	45.7302	-107.6843	01S 33E 19 DAAD	Big Horn	WELL	112TRRC	24	USGS	1/11/1935
	6997	45.7302	-107.6843	01S 33E 19 DAAD	Big Horn	WELL	112TRRC	24	USGS	5/31/1945
	6999	45.7333	-107.5986	01S 33E 24 BCB	Big Horn	WELL	110TRRC	28	USGS	8/25/1960
	7000	45.7147	-107.6186	01S 33E 26 CB	Big Horn	WELL	110TRRC	16	USGS	8/25/1960
	7001	45.7130	-107.6250	01S 33E 27 D	Big Horn	WELL	110TRRC	37	USGS	10/20/1921
	7002	45.7202	-107.6872	01S 33E 30 A	Big Horn	WELL	110TRRC	18	USGS	10/10/1921
	7217	45.6325	-107.7263	02S 32E 26 AB	Big Horn	WELL	110TRRC	21	USGS	10/11/1921
	7350	45.5858	-107.6722	03S 33E 8 BDD	Big Horn	WELL	110TRRC	28	USGS	8/25/1960
	7552	45.5183	-107.7225	04S 32E 2 AAA	Big Horn	WELL	110TRRC	52	USGS	8/24/1960
	7553	45.4630	-107.7288	04S 32E 23 DC	Big Horn	WELL	110TRRC	30	USGS	8/24/1960
	7554	45.4633	-107.7294	04S 32E 23 DCAD	Big Horn	WELL	110TRRC	45	USGS	10/18/1921
	7555	45.4550	-107.7322	04S 32E 26 BDD	Big Horn	WELL	110TRRC	35	USGS	4/15/1960
	7556	45.4413	-107.7127	04S 32E 36 BD	Big Horn	WELL	110TRRC	38	USGS	4/15/1960
	7556	45.4413	-107.7127	04S 32E 36 BD	Big Horn	WELL	110TRRC	38	USGS	8/24/1960
	7725	45.3505	-107.8327	05S 31E 36 DBB	Big Horn	WELL	110TRRC	44	USGS	4/15/1960
	7726	45.4161	-107.7394	05S 32E 11 BBB	Big Horn	WELL	110TRRC	35	USGS	4/15/1960
	7727	45.3869	-107.7930	05S 32E 20 BAA	Big Horn	WELL	110TRRC	47	USGS	4/15/1960
	15284	46.0003	-107.5346	03N 34E 18 DCDD	Big Horn	WELL	112TRRC	16	MBMG	6/8/2006
	94357	45.7604	-107.6121	01S 33E 11	Big Horn	WELL	110TRRC	31	MBMG	10/4/2006
	94475	45.7231	-107.6674	01S 33E 29 ABAD	Big Horn	WELL	112TRRC	28	MBMG	6/8/2006
	212402	45.7656	-107.6013	01S 33E 11 AAAC	Big Horn	WELL	112TRRC	35	MBMG	10/4/2006
	226392	45.7552	-107.6333	01S 33E 10 CDAC	Big Horn	WELL	112TRRC	85	MBMG	6/9/2006
	235092	45.8910	-107.5919	02N 33E 27 DAAC	Big Horn	WELL	112TRRC	25	MBMG	9/6/2006
	235480	45.8195	-107.6335	01N 33E 20 ADDB	Big Horn	WELL			MBMG	4/26/2007
	235482	45.8370	-107.6126	01N 33E 16 ADAA	Big Horn	WELL		29.6	MBMG	4/26/2007
	236738	45.8880	-107.5748	02N 33E 26 DBDD	Big Horn	WELL	111ALVM		MBMG	6/28/2007
	239727	45.7684	-107.5959	01S 33E 1	Big Horn	WELL		12.4	MBMG	7/18/2008
	239729	45.7685	-107.5959	01S 33E 1	Big Horn	WELL		23.4	MBMG	7/9/2008
	239730	45.8661	-107.6290	01N 33E 4	Big Horn	WELL		74	MBMG	7/10/2008
	239731	45.8660	-107.6291	01N 33E 4	Big Horn	WELL		32	MBMG	7/8/2008
	239734	45.8660	-106.6290	01N 33E 4	Big Horn	WELL		22.6	MBMG	7/18/2008

Appendix C1. Alluvial and Terrace Groundwater Quality

					Cations (mg/L)							Anions (mg/L)						
	Gwic Id	Water Temp	Lab pH	Lab SC	Ca	Mg	Na	K	Fe	Mn	SiO_2	HCO_3	CO_3	SO_4	Cl	NO_3	F
Alluvial and Terrace Ground Water	114				183	23					22	317	0	392	28	0.013	
	115	3.8	7.4	3320	202	143	410	5.7	0.21		17	583	0	1390	86	0.113	0.3
	116	8.9	7.5	5470	190	101	1060	18	0.17		25	338	0	2700	135	1.11	0.5
	117	8.3	7.3	2010	188	81	193	4.1	0.12		21	347	0	900	21	0.75	0.5
	1012	11.1	7.4	2160	73	50	372	5.6	0.07		25	521	0	725	20	2.49	0.6
	1015	18.8	7.2	2320	175	59	304	6.1	0.42		24	432	0	933	31	0.07	0.7
	1211				123	89					24	1160	0	1340	48	4.06	
	6994	8.3	7.1	6590	470	235	1020	13	0.11		26	603	0	3580	143	2.1	0.3
	6994	10	7	5830	439	198	908	13	0.03		27	602	0	3250	116	1.69	0.4
	6995	6.7	7.3	3380	249	124	410	8.8	0.13		27	290	0	1730	33	0.023	0.4
	6997				138	58			<.01		20	316	0	365	80	<.023	
	6997				112	28			1.2		37	406	0	249	43	<.023	
	6997				138	58			<.01		20	316	0	365	80	<.023	
	6997				112	28			1.2		37	406	0	249	43	<.023	
	6999	11.1	7.2	7010	315	137	1380	20	0.82		28	415	0	3580	280	0.14	0.8
	7000	11.1	7.2	2190	142	50	300	7.8	2		26	347	0	885	30	0.07	0.7
	7001				103	39	329 K		0.12		28	325	0	771	43	<.023	
	7002				74	35	70 K		1.3		30	270	0	202	20	0.68	
	7217				91	54	215 K		0.12		35	285	0	630	22	0.29	
	7350	11.1	7.1	7520	428	273	1290	19	0.08		28	493	0	4400	111	2.94	0.5
	7552	12.8	7	6670	524	249	1000	10	0.09		27	455	0	3930	155	1.99	0.5
	7553		7	2720	419	84	200	6.8	1.3		22	446	0	1360	24	0.14	0.6
	7554				286	114	275 K		1.6		21	425	0	1376	22	<.023	
	7555	10	7.3	3780	213	189	490	9.2	0.14		26	471	0	1930	38	2.1	0.7
	7556	10.6	7.1	2130	259	82	168	5.9	0.34		20	457	0	938	16	0.75	0.5
	7556	11.7	6.9	2690	377	121	197	6.8	0.17		24	516	0	1330	19	1.63	0.6
	7725	8.9	7.5	1180	55	41	148	3.3	0.08		25	304	0	365	11	1.08	0.7
	7726	10	7.1	6030	458	282	775	14	0.16		30	430	0	3450	65	27.56	0.6
	7727	8.9	7.2	1640	168	71	118	4.5	0.18		27	458	0	550	17	4.97	0.4
	15284	10.6														7.00 P	
	94357	14	7.26	1282	112	39.7	123	3.79	0.404	0.008	16.8	307.4	0	448	16.9	<0.5 P	<0.5
	94475		7.25	3460	393	180	291	10.4	0.028	<0.005	27.6	252.5	0	2007	64.7	15.5 P	<2.5
	212402	12.6	6.98	4520	272	137	815	10.5	0.113	0.399	23.9	511.2	0	2352	78.7	<2.5 P	<2.5
	226392	12.6	7.3	1254	84.8	45	147	3.57	0.011	<0.001	15	264.3	0	444	24.9	0.886 P	<0.5
	235092		7.68	6410	172	131	1511	10.1	0.449	0.686	18	688.1	0	3579	76.7	<2.50 P	<2.50
	235480	10.43	7.98	2540	188	91.7	380	4.56	0.021	0.03	24.4	261.9	0	1351	58.3	<2.5 P	<1.0
	235482		7.76	3240	200	101	521	7.32	0.647	0.463	17.9	340.4	0	1616	53.7	<2.5 P	<1.0
	236738		7.16	3560	210	85.4	575	7.29	1.28	0.761	15	579.5	0	1560	55.7	<1.0 P	<2.5
	239727	18.8	7.44	1044	80.7	29.9	109	13.4	0.184	0.017	12	282.2	0	330	13.2	1.078 P	0.544
	239729	11.2	7.42	2840	151	73.1	463	10.8	1.93	0.752	21	435.5	0	1111	52.1	<0.5 P	0.613
	239730	11.5	7.64	3390	278	147	444	14.1	0.99	0.19	22.4	475.8	0	1935	34.2	9.838 P	0.331
	239731	12.1	7.58	1234	101	85.9	85	5.68	0.178	0.294	9.78	316.2	0	472	14.6	0.682 P	<0.5
	239734	13.7	7.54	1110	87.3	54.2	104	6.85	0.251	1.24	11.1	327.9	0	424.4	12.9	<0.5 P	<0.5

Appendix C1. Alluvial and Terrace Groundwater Quality

	Gwic Id	Trace Elements (ug/L)																
		As	B	Ba	Br	Cu	Li	Mo	Ni	Pb	Se	Sn	Sr	Ti	Tl	U	V	Zn
Alluvial and Terrace Ground Water	114																	
	115		290															
	116		920															
	117		490															
	1012		420															
	1015		270															
	1211																	
	6994		1600															
	6994		1600															
	6995		650															
	6997																	
	6997																	
	6997																	
	6997																	
	6999		1000															
	7000		520															
	7001																	
	7002																	
	7217																	
	7350		1500															
	7552		810															
	7553		450															
	7554																	
	7555		1100															
	7556		530															
	7556		830															
	7725		230															
	7726		1300															
	7727		240															
	15284																	
	94357	1.06	224	10.8	<500	14.2	66.8	<10	<2	<2	3.99		1187	3.05	<5	9.56	<5	24.1
	94475	6.24	677	29	<2500	<10	140	<50	<10	<10	105		4093	<5	<25	57.8	<25	24
	212402	<10	1128	<20	<2500	<20	229	<100	<20	<20	<10		3901	<10	<50	47.9	<50	95.4
	226392	<1	217	11.8	<500	3.09	52.2	<10	<2	<2	10.5		1026	<1	<5	12.8	<5	3.77
	235092	<10	1021	<20	<2500	<20	155	<100	<20	<20	<10		3693	<10	<50	22.1	<50	20.5
	235480	1.82	7.04	7.25	<1000	3.18	136	6.74	1.52	<1.0	4.84		2406	2.76	<0.5	15.4	0.81	52.1
	235482	2.25	418	27.1	<1000	<1.0	131	5.09	0.883	<1.0	<2.5		2708	<5	<0.5	21.5	<0.5	3.79
	236738	1.05	546	11.9	<2500	<1.0	110	<5.0	0.887	2.03	<2.5		3688	17.1	<0.5	4.63	<0.5	9.55
	239727	<1.0	195	12.3	<500	<0.5	54.4	3.9	<0.5	<0.5	3.82	<0.5	787	4.61	<0.5	5.77	<0.5	0.945
	239729	4.6	683	12.7	285	<1.0	154	6.96	<1.0	<1.0	<5.0	<1.0	1806	21	<1.0	10.6	<1.0	12.8
	239730	2.03	624	11.4	237	1.06	167	6.94	<1.0	2.84	<5.0	1.32	4957	31.2	<1.0	26.4	<1.0	3.86
	239731	<1.0	263	15.5	<500	0.625	82.9	14	1.1	<0.5	<2.5	<1.0	1222	7.24	<1.0	14.3	<1.0	39.7
	239734	<1.00	270	37	<500	<0.5	42.9	14.6	1.76	<0.5	<2.5	<0.5	913	6.15	<0.5	6.62	<0.5	25.5

Appendix C2. Bedrock Groundwater and Surface-Water Quality

		Location											
	Gwic Id	**Latitude**	**Longitude**	**T R S Qsect**	**County**	**Site Type**	**Aquifer**	**Depth (ft)**	**Agency**	**Sample Date**	**Water Temp**	**Lab pH**	**Lab SC**
Bedrock Groundwater	113	45.8350	-107.6138	01N 33E 16 AD	Big Horn	WELL	211BRPW	190	USGS	9/9/1916			
	1014	45.9258	-107.6086	02N 33E 15 BB	Big Horn	WELL	211HLCK	81	USGS	12/2/1914			
	1210	46.0016	-107.5361	03N 34E 18 DC	Big Horn	WELL	211HLCK	62	USGS	10/17/1921			
	6990	45.7305	-107.7311	01S 32E 23 BD	Big Horn	WELL	330MDSN	4000	USGS	11/17/1960	39.4	7.6	3040
	7356	45.5658	-107.4391	03S 35E 18 DC	Big Horn	WELL	211PRKM	120	USGS	12/19/1945			
	7724	45.3447	-107.8627	05S 31E 35 CCC	Big Horn	WELL	217PRYR	1033	USGS	8/24/1960	20	8	825
	226395	45.8374	-107.6368	01N 33E 17 AACC	Big Horn	WELL	211BRPW	100	MBMG	6/8/2006	13	7.24	3020
	226396	45.7636	-107.6645	01S 33E 8 ADBA	Big Horn	WELL	211BRPW	60	MBMG	6/8/2006	15	7.06	2260

		Cations (mg/L)						Anions (mg/L)						
	Gwic	**Ca**	**Mg**	**Na**	**K**	**Fe**	**Mn**	**SiO_2**	**HCO_3**	**CO_3**	**SO_4**	**Cl**	**NO_3**	**F**
Bedrock Groundwater	113	62	18					18	396	0	105	2480		
	1014	33	22					48	654	0	527	12		
	1210	27	18			0.07		33	431	28	338	15	<.023	
	6990	665	136	14	24	1.5		18	180	0	1980	4	<.023	4
	7356	12	9			1		11	393	35	954	32		
	7724	0.3	0.4	186	0.9	0.23		10	319	0	125	7.9	0.02	1.4
	226395	439	143	230	8.52	<0.005	0.006	12.8	445.3	0	1669	51.4	19.3 P	<2.5
	226396	247	86.5	194	6.41	0.05	0.036	16.3	316.4	0	1029	96.2	<2.5 P	<1.0

		Trace Elements (ug/L)																	
	Gwic	**As**	**B**	**Ba**	**Br**	**Co**	**Cu**	**Li**	**Mo**	**Ni**	**Pb**	**Se**	**Sr**	**Ti**	**Tl**	**U**	**V**	**Zn**	**Zr**
Bedrock Groundwater	113																		
	1014																		
	1210																		
	6990		140																
	7356																		
	7724		80																
	226395	<10	835	13.8	<2500	<20	<20	266	<10	2.14	<10	90.8	4045	1.07	28.7	<50	<10	50.1	<2
	226396	<5	350	30.6	<1000	<2	<5	100	<10	<2	<10	8.9	2367	1.26	<20	5.07	<10	5.61	<2

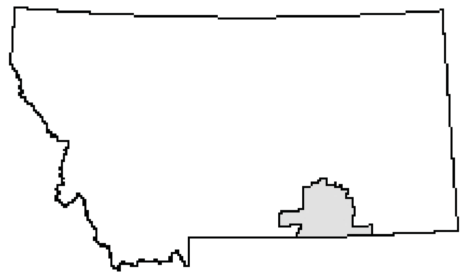
Appendix C2. Bedrock Ground-Water and Surface-Water Quality

	Location										
	Gwic Id	Latitude	Longitude	T R S Qsect	County	Site Type	Agency	Sample Date	Water Temp	Lab pH	Lab SC
Surface Water	240466	45.7562	-107.5645	01 S 34E 7 D	Big Horn	Stream	MBMG	12/13/2007		8.09	879
	240468	45.6443	-107.6562	02S 33E 21 BDC	Big Horn	Stream	MBMG	12/13/2007	4.5	8.03	873
	240469	45.8441	-107.5823	01N 33E 11 C	Big Horn	Stream	MBMG	12/14/2007	3.3	8.11	868
	240471	45.9273	-107.5740	02N 33E 14 A	Big Horn	Stream	MBMG	12/14/2007	3.4	8.21	857
	240472	46.1447	-107.4635	05N 34E 34 BCB	Yellowstone	Stream	MBMG	12/14/2007	2	8.14	899

		Cations (mg/L)						Anions (mg/L)						
	Gwic	Ca	Mg	Na	K	Fe	Mn	SiO_2	HCO_3	CO_3	SO_4	Cl	NO_3	F
Surface Water	240466	82.4	29.1	81.3	4.3	<0.005	0.009	7.37	231.8	0	283	11.1	0.571 P	0.438
	240468	79.9	27.9	78.8	4.49	<0.005	0.011	7.36	219	0	277	10.4	0.49 P	0.457
	240469	79.1	28.3	75.9	4.13	<0.005	0.008	6.96	226	0	270	10.2	0.427 P	0.416
	240471	79.2	28.3	76.5	4.09	<0.005	0.007	6.8	221.1	0	273	10.2	0.426 P	0.398
	240472	81.8	29.8	78.8	4.17	<0.005	0.006	6.98	223.3	0	287	11	0.509 P	0.429

		Trace Elements (ug/L)																		
	Gwic	As	B	Ba	Br	Co	Cu	Li	Mo	Ni	Pb	Se	Sn	Sr	Ti	Tl	U	V	Zn	Zr
Surface Water	240466	1.59	102	60.3	<100	0.229	0.636	41.6	2.18	1.3	0.232	2.29	<0.1	1023	3.62	<0.1	5.56	1.62	1.15	0.434
	240468	1.59	97.7	60.3	<100	0.219	0.56	41.6	2.18	1.28	<0.2	2.26	<0.1	995	3.62	<0.1	5.55	1.63	0.573	0.118
	240469	1.93	97.9	59.8	<100	0.238	0.645	37.9	2.13	1.49	<0.2	3.19	<0.1	971	3.91	<0.1	5.23	1.62	0.649	0.406
	240471	2.03	97.8	59.4	<100	0.232	0.686	37.4	2.16	1.35	1.25	3.48	<0.1	967	3.68	<0.1	5.26	1.54	1.2	0.172
	240472	1.49	100	59.1	<100	0.239	0.573	39.3	2.15	1.39	<0.2	2.26	<0.1	1016	3.98	<0.1	5.5	1.42	1.08	0.182

Plate 1



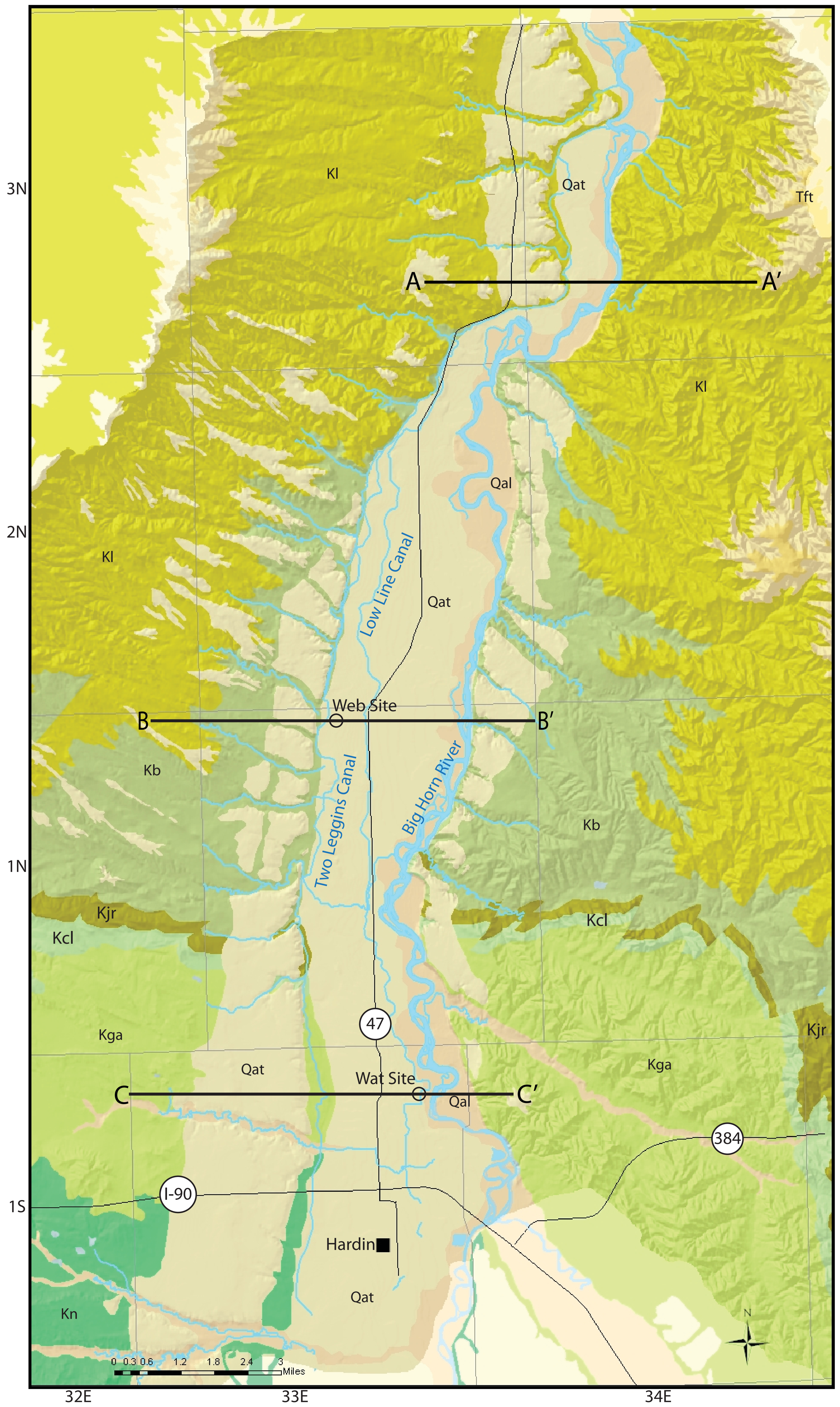
Legend

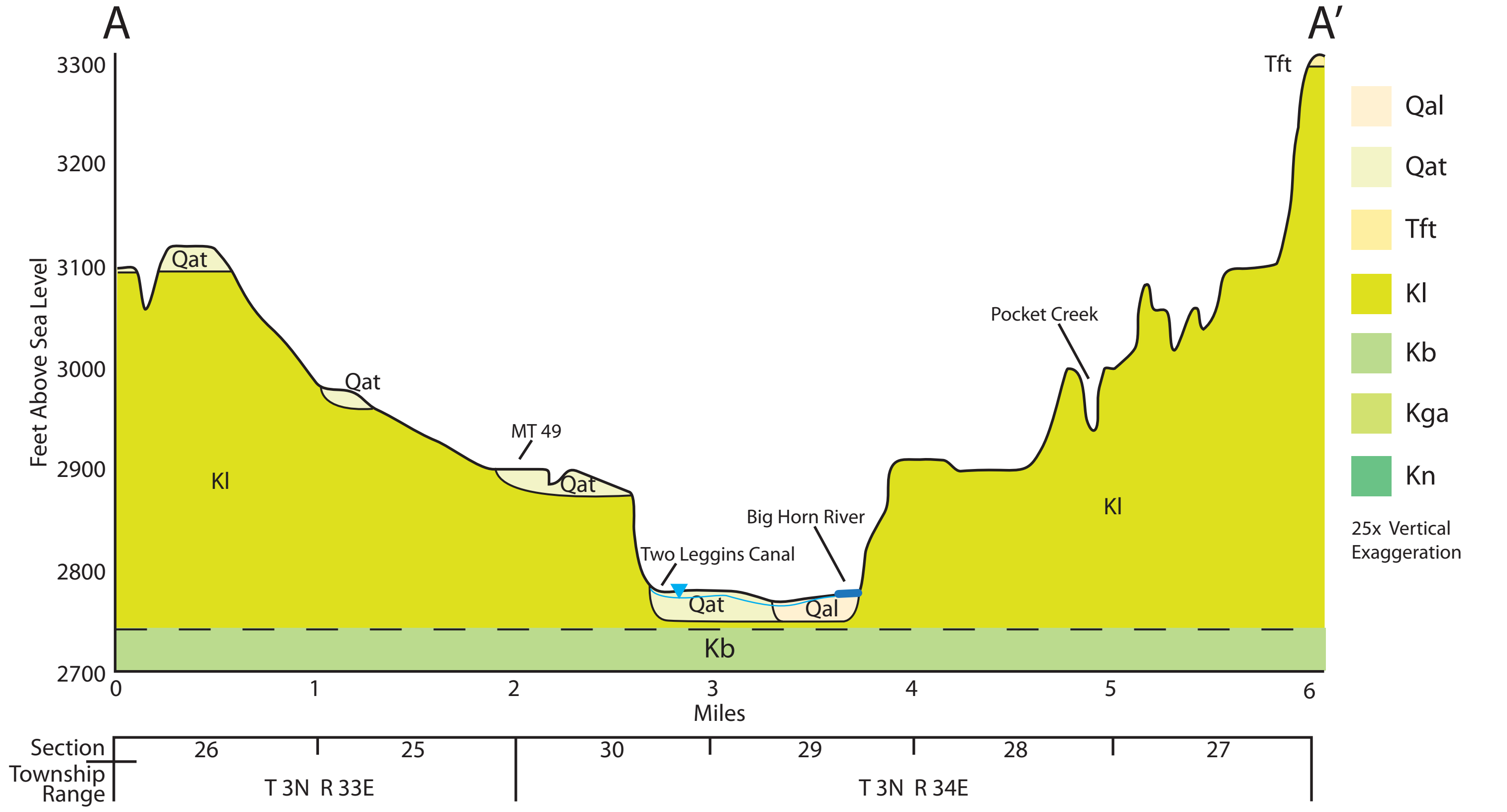
*	Qal	Alluvium	Gravel, sand, silt and clay. Thickness as much as 35 feet.
*	Qat	Terrace	Gravel, sand, silt and clay. Thickness 15 to 50 feet.
	Tft	Tullock Member of the Fort Union Formation	Yellowish-gray, massive sandstone. Thickness 195 to 230 feet.
**	Kl	Lance Formation	Brownish-grey sandstone. Thickness 400 to 500 feet.
	Kb	Bearpaw Shale	Dark grey shale. Thickness up to 860 feet.
**	Kjr	Judith River Formation	Yellow-grey, brown-grey sandstone. Thickness up to 260 feet.
	Kcl	Clagett Shale	Brown-grey shale. Thickness 150 to 200 ft.
	Kga	Gammon Formation	Yellow-brown siltstone. Thickness 0 to 860 feet.
	Kn	Niobrara Shale	Dark brown-grey shale. Thickness 390 to 410 feet.

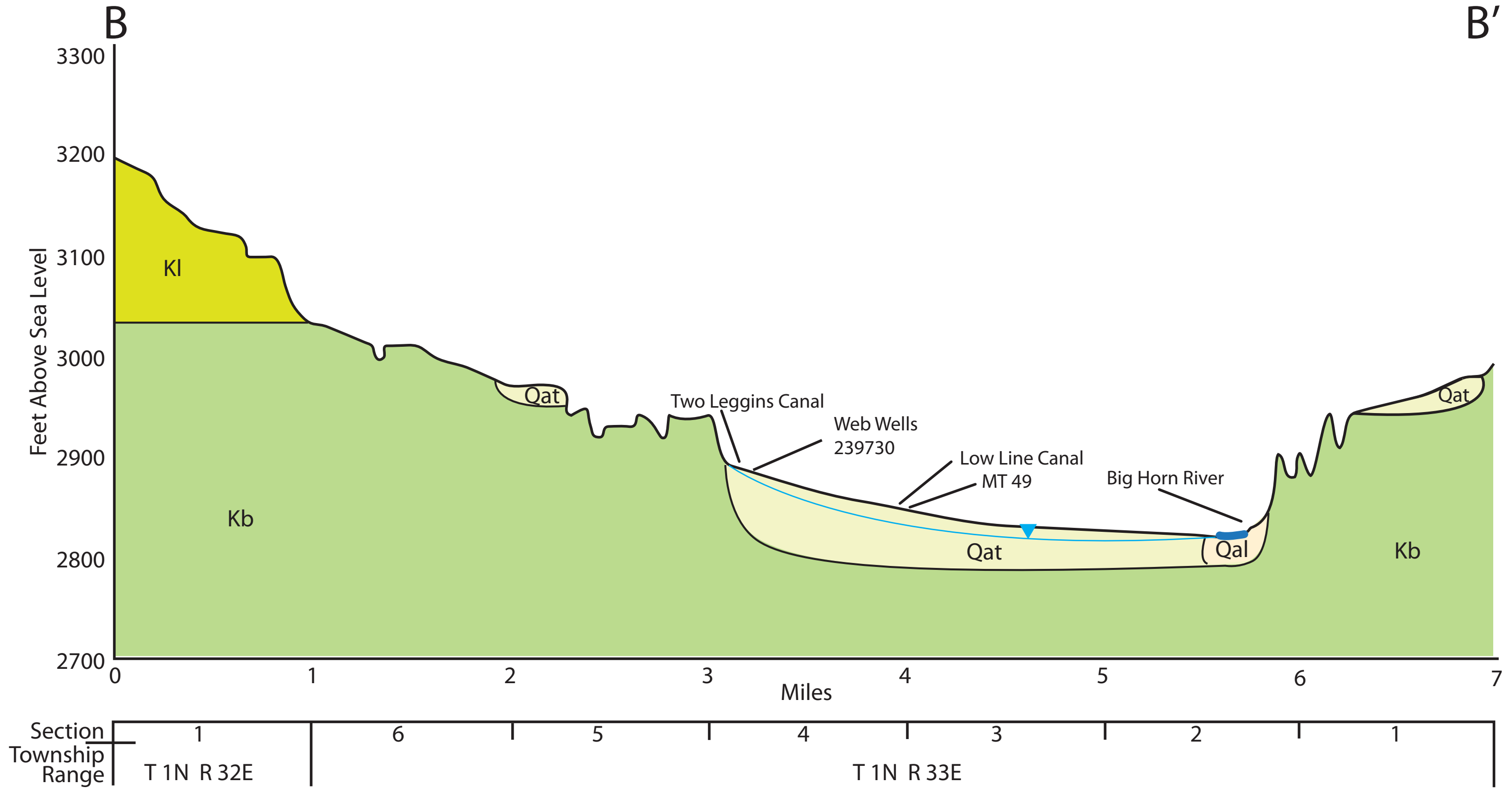
* Regional aquifer

** Possible aquifer

▼	Approximate water table, top of saturated material (cross-section only)
—	Roads
∿	Rivers, streams and ditches







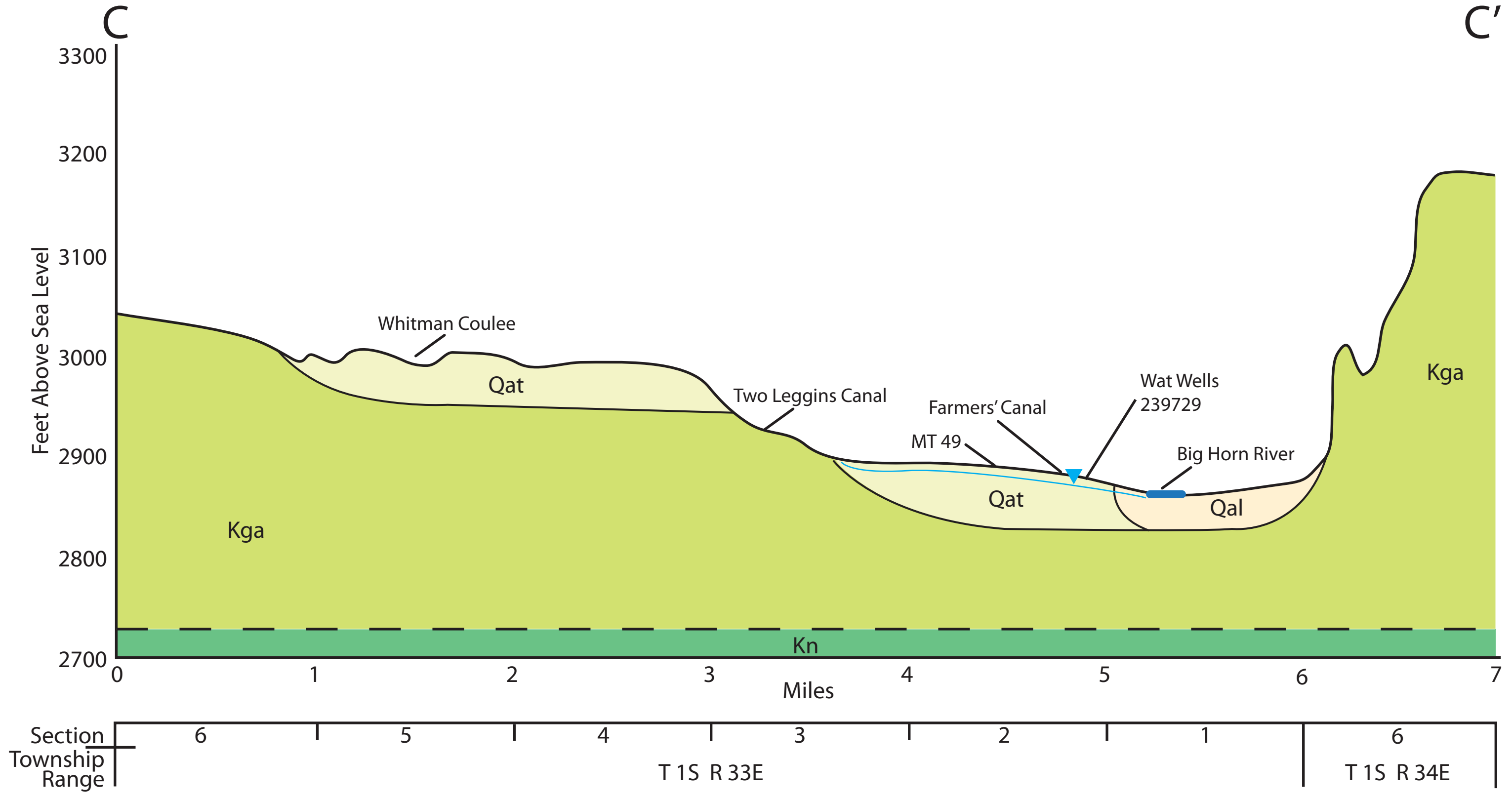


Plate 2

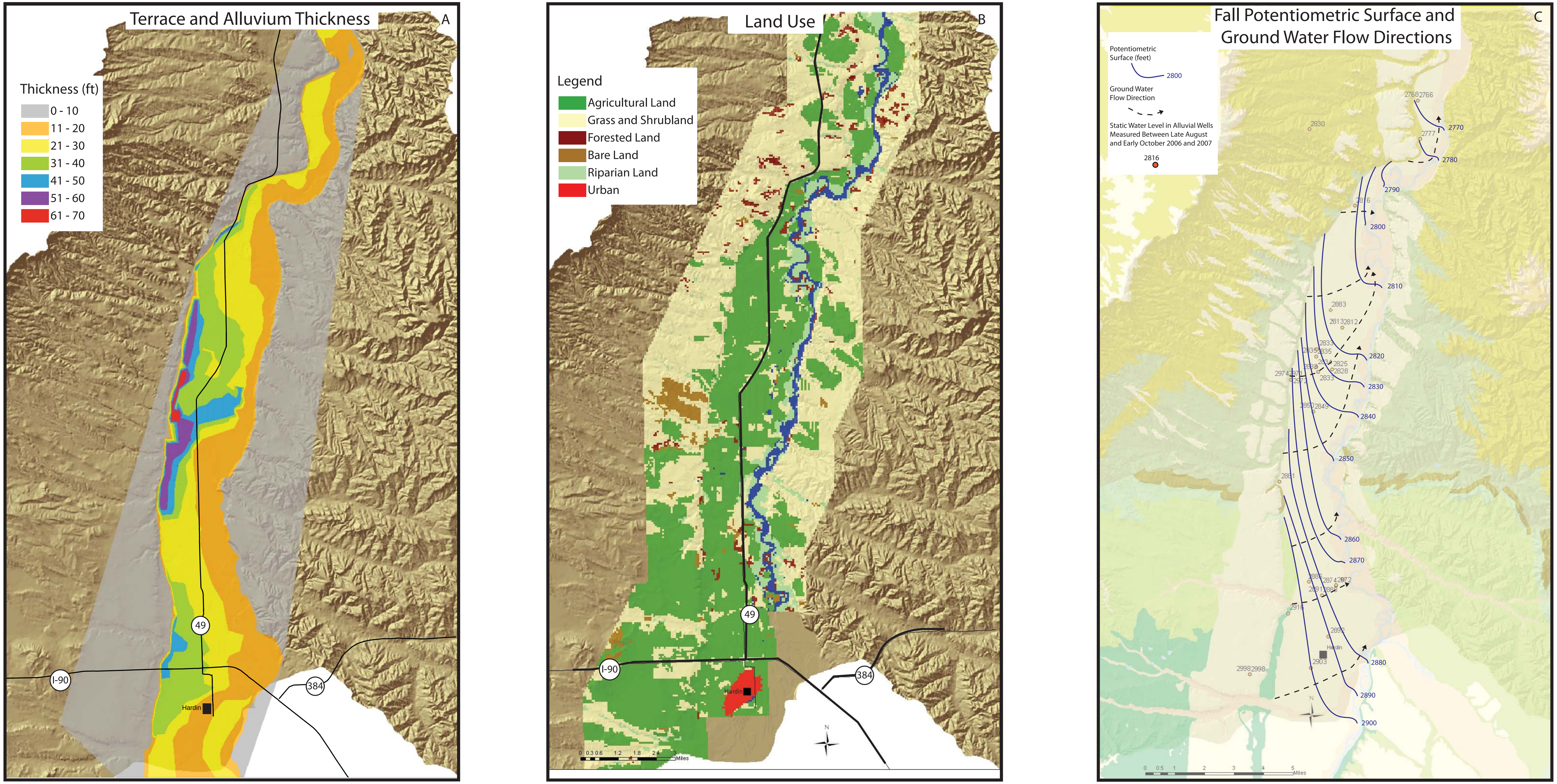
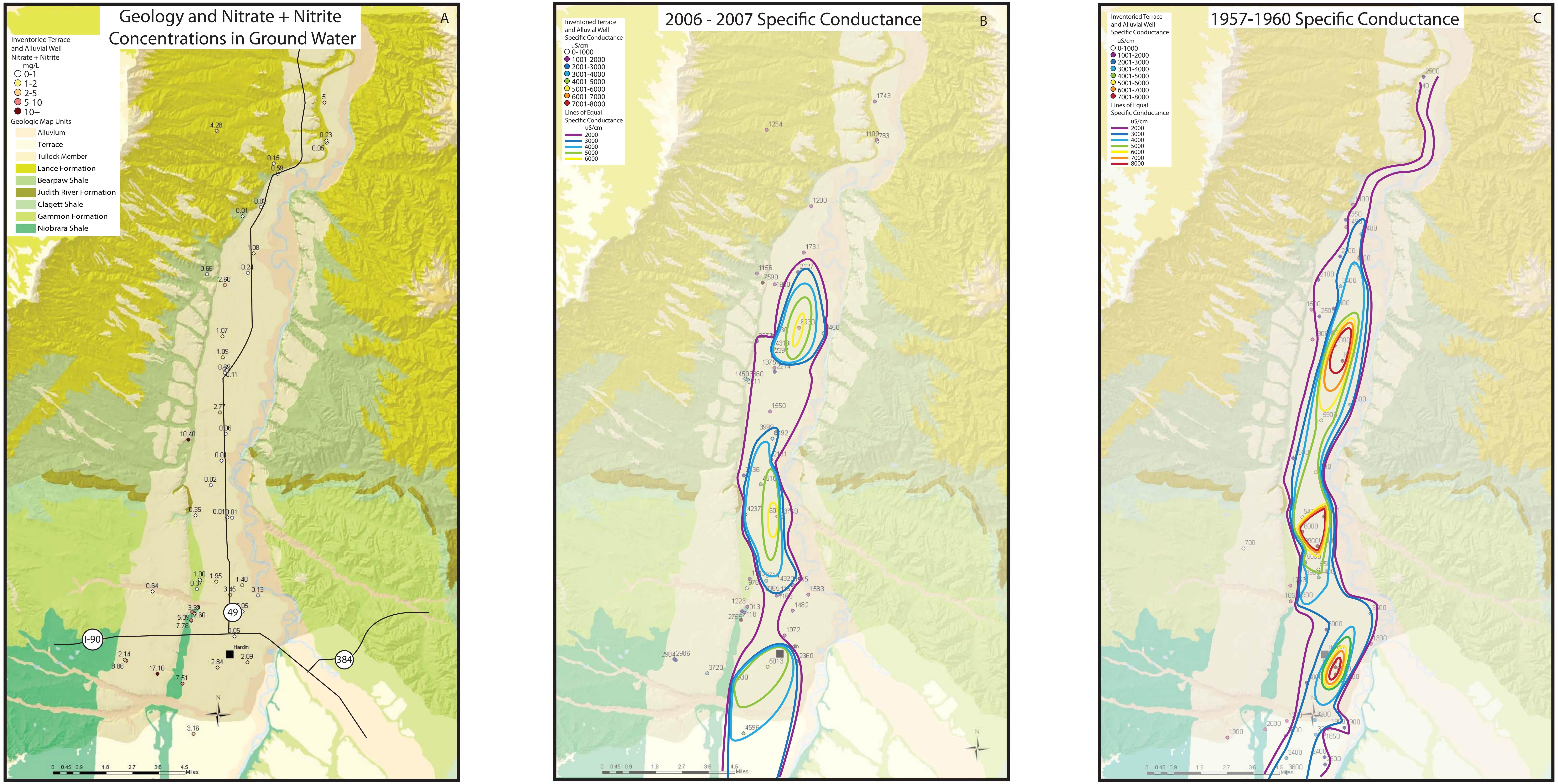

Terrace and Alluvium Thickness
A
Thickness (ft)
0 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
49
I-90
384
Hardin
Land Use
B
Legend
Agricultural Land
Grass and Shrubland
Forested Land
Bare Land
Riparian Land
Urban
49
I-90
384
Hardin
N
0 0.3 0.6 1.2 1.8 2.4 3 Miles
Fall Potentiometric Surface and Ground Water Flow Directions
C
Potentiometric Surface (feet)
2800
Ground Water Flow Direction
Static Water Level in Alluvial Wells Measured Between Late August and Early October 2006 and 2007
2816
27682766
2830
2777
2770
2780
2790
2816
2800
2810
2820
2830
2840
2850
2860
2870
2880
2890
2900
2998 2998
Hardin
N
0 0.5 1 2 3 4 5 Miles

Plate 3


Geology and Nitrate + Nitrite Concentrations in Ground Water
A
Inventoried Terrace and Alluvial Well Nitrate + Nitrite mg/L
○ 0-1
● 1-2
● 2-5
● 5-10
● 10+
Geologic Map Units
Alluvium
Terrace
Tullock Member
Lance Formation
Bearpaw Shale
Judith River Formation
Clagett Shale
Gammon Formation
Niobrara Shale
5
4.28
0.23
0.05
0.15
0.59
0.83
0.01
1.08
0.66
0.24
2.60
1.07
1.09
0.69
0.11
2.77
0.06
10.40
0.01
0.02
0.35
0.01
0.01
1.00
0.37
1.95
1.48
0.64
3.45
0.13
3.39
2.60
5.39
7.78
0.05
0.05
49
I-90
Hardin
2.14
8.86
17.10
7.51
2.84
2.09
384
3.16
N
0 0.45 0.9 1.8 2.7 3.6 4.5 Miles
2006 - 2007 Specific Conductance
B
Inventoried Terrace and Alluvial Well Specific Conductance uS/cm
○ 0-1000
● 1001-2000
● 2001-3000
● 3001-4000
● 4001-5000
● 5001-6000
● 6001-7000
● 7001-8000
Lines of Equal Specific Conductance uS/cm
2000
3000
4000
5000
6000
1743
1234
1109
783
1200
1731
1156
7590
2127
1990
6330
458
4313
1375
2214
1450
1550
3990
4510
4237
1583
1223
1482
1972
2984
2986
5013
2360
3720
4596
N
0 0.45 0.9 1.8 2.7 3.6 4.5 Miles
1957-1960 Specific Conductance
C
Inventoried Terrace and Alluvial Well Specific Conductance uS/cm
○ 0-1000
● 1001-2000
● 2001-3000
● 3001-4000
● 4001-5000
● 5001-6000
● 6001-7000
● 7001-8000
Lines of Equal Specific Conductance uS/cm
2000
3000
4000
5000
6000
7000
8000
2500
1400
2100
3400
2500
5900
700
8000
1900
2000
3400
3600
1850
0 0.45 0.9 1.8 2.7 3.6 4.5 Miles