

GROUND-WATER DISCHARGE AND AQUIFER RECHARGE ZONES NEAR  
FOUR CORNERS, GALLATIN COUNTY, MONTANA

by

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## ABSTRACT

The West Gallatin River is closed to new surface water appropriations. Montana law recognizes the potential for new ground-water developments to compromise existing surface-water rights. Determining the effects of new ground-water development upon existing surface-water users requires a detailed understanding of the hydrologic system and the surface and ground water exchanges, which is not available in the Four Corners area of Gallatin County Montana.

Hydrologic data was collected during the 2006 water year. Data was collected on stream discharge, streambed hydraulic gradients, temperature, ground-water levels, and specific electrical conductance to characterize zones of upwelling ground water and downwelling surface water. The river and aquifer share a complex hydrologic connection. Some reaches of river gained streamflow from the aquifer and contained zones of downwelling surface water. Other reaches of river which lost water to the aquifer, contained zones of upwelling ground water. Water moved back and forth between the river and aquifer through a variety of hydrologic pathways including; seepage below irrigation canals and irrigated land, drainage ditches from irrigated lands, spring channels, and the porous alluvial riverbed. Ground-water discharge to the stream contributed 8% of the streamflow when no irrigation was occurring in November 2005. In August 2006 during the irrigation season, the volume and relative contribution of ground-water discharge increased to 28% of the streamflow.

The data collected from this study was compared to historic water-level data collected during the 1950's and later in the 1990's. This study's analysis benefited from the comparison of surface-water levels to ground-water levels, streambed hydraulic gradients, continuous records of ground-water levels and temperatures from near stream wells. Data from this study indicates that a consistent zone of downwelling surface water was present north of Four Corners which had not been identified in past surveys. However, the baseline data was found to be insufficient for a comparison to this analysis due to a lack of surface water data collected in the previous studies. As a result, it remains unclear whether the zone of downwelling has always been present or represents a change to the hydrologic system at Four Corners.

## INTRODUCTION

The interaction between the West Gallatin River, ground water, and irrigation has been recognized as significant in Gallatin County (Fig. 1-1) since the first hydrologic surveys were conducted in the 1950's (Hackett et al., 1960). At that time hydrologists and irrigators were addressing the problem of too much water, which inhibited the development of agriculture in the valley (Hackett et al., 1960). To remedy the situation, spring creeks were straightened and drainage channels were constructed to convey excess ground water away from the irrigated fields. Half a century later, the Gallatin Valley's landscape has changed and the land once used for agriculture is now being converted into residential areas, irrigation ditches are being abandoned, and existing agriculture is being converted from flood to sprinkler irrigation.

Changes to the hydrologic system have been predicted, as a result of increasing irrigation efficiency and irrigated land being converted into residential developments along the West Gallatin River (Hackett et al., 1960; Kendy and Bredehoeft, 2006). Increased ground-water development which exceeds aquifer recharge has been predicted to result in decreased streamflows (Hackett et al., 1960). The loss of irrigation has been projected to reduce aquifer recharge and the development of residential areas which rely on wells for water may increase ground-water consumption. The combined effect of these changes has been hypothesized to reduce historic streamflows in late summer, fall, and winter (Kendy and Bredehoeft, 2006).

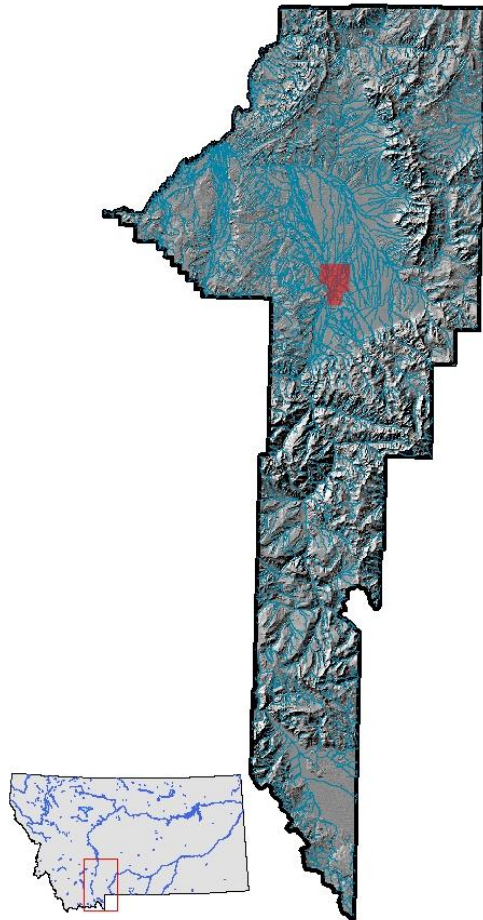


Figure 1-1. Location maps of study area in Four Corners within Gallatin County with inset map of Montana and county location. Study area is red polygon located in county map. Blue lines are streams from the National Hydrography data set.

In the Four Corners Area of Montana (Fig. 1-1) water law, public interest, property rights, and capitalist ventures are intersecting and as a result hydrologic information is needed to inform the discussion on land use changes and hydrology in the area. The West Gallatin River is closed to new appropriations of surface-water. Montana law also recognized the hydrologic connection between surface and ground water and the potential for junior ground-water developments to compromise senior surface-water rights in the Montana Supreme Court case, Trout Unlimited vs. The Montana Department of Natural Resources.

As a result of the Trout Unlimited Case, new ground and surface-water users along the West Gallatin River are required to mitigate for their impact on existing water rights holders. Additionally, residents of the Four Corners area expressed interest in the creation of a Controlled Ground-Water Area in 2002 to further protect surface and ground-water resources from development pressures. The Four Corners Controlled Groundwater Area was denied in 2005 partially due to a lack of evidence that ground-water development was causing water levels to decline. In response to the current Montana law which recognizes the connection between surface and ground water, an aquifer storage and recovery facility is currently being operated near Four Corners to mitigate the effects of new ground-water development on surface water flows which allows for more ground-water development in the area. Other aquifer storage and recovery operations are also being considered along this section of river to mitigate the effects of continued ground-water development on surface-water flows. As a result of the predicted hydrologic changes, local public opinion, and legality concerning the connection of surface and ground water, time and money have been committed in the local area by the public to address potential effects of the land use changes and continued water development. Assessing the potential for aquifer storage and recovery projects and determining the effects of new water developments upon existing water users requires a detailed understanding of the hydrologic system which can be costly and is not readily available in the Four Corners area.

This study was initiated to begin assessing the surface and ground-water interactions near Four Corners and the effects of ground-water development and land use changes on streamflows in the West Gallatin River. The goal of this study was to identify where zones of ground-water discharge and recharge occur along a 6 mile reach of the West Gallatin River

near Four Corners in Gallatin County, Montana (Fig. 1-1). To identify ground-water discharge and recharge zones, stream discharge measurements were conducted to assess ground-water exchange between the river and aquifer. Discharge measurements were used in conjunction with data from streambed piezometers and water levels from monitoring wells for the assessment of ground-water discharge and recharge zones. This information was gathered to help develop a conceptual model of the surface and ground-water exchange, which will assist the calibration of numerical models, and begin the collection of baseline information which can help address whether land use changes have altered the hydrology of the river near Four Corners.

#### Literature Review of Surface and Ground-Water Exchange on Alluvial Rivers

A general understanding of the complexity of surface and ground-water exchange processes was necessary to guide collection of this data and to develop a conceptual model for the West Gallatin River and aquifer. The following section is a review of some of the processes of surface and ground-water exchange observed on other alluvial systems. The principles of surface and ground-water exchange which were found to occur on these alluvial systems are assumed to be representative of the processes occurring on the West Gallatin River which is a; complex fifth-order, anabranching stream channel, alluvial aquifer system, with a complex series of irrigation canals (Fig. 1-2). The information gathered from other complex alluvial river systems was used as a conceptual model for the interpretation of data from the Gallatin River near Four Corners.

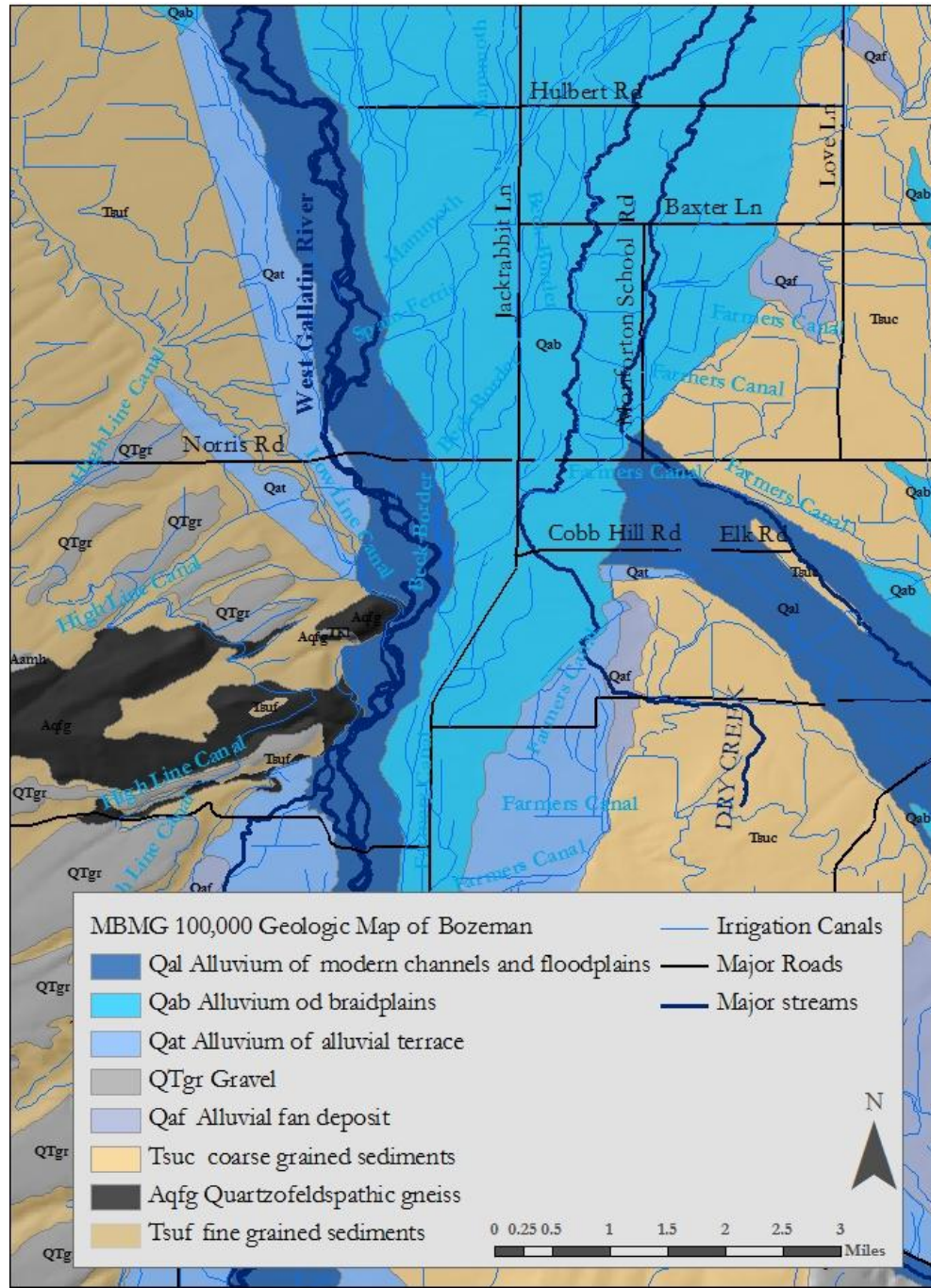


Figure 1-2. Geologic map and surface water resources of the Four Corners area at the intersection of Norris Rd. and Jackrabbit Lane. The West Gallatin River, Dry Creek, and Hyalite Creek are displayed in dark blue. Irrigation canals are light blue. Modified from the Montana Bureau of Mines and Geology 100,000 scale geologic map of Bozeman (Vuke, et. al, 2002) and the national Hydrography data set, and the DNRC's 1952 Water Resources Survey.

### Factors Influencing Spatial Variation

A river channel's geomorphology influences much of the spatial variation of the surface and ground-water exchange process (Poole et al., 2006; Storey et al., 2003; Kasahara, 2003; Malard et al., 2002; Woessner, 2000; Morrice, 1997; Hill, 1998; Wondzell and Swanson, 1999; Wroblicky et al., 1998; Wondzell and Swanson, 1996; Valett, 1996; Vervier et al., 1993; D'Angelo, 1993). Other factors which influence the spatial distribution of exchange include upwelling ground water (Poole et al., 2006; Storey et al., 2003; Malcolm, 2003; Morrice, 1997), the inundation of a river's floodplain, presence of secondary channels (Poole, 2006; Morrice, 1997; D'Angelo, 1993), and the shape of the alluvial aquifer (Poole, 2006; Storey et al., 2003; Malcolm, 2003; Morrice, 1997).

The topography of a river channel influences the spatial variability of exchange by rapidly changing the elevation potential along the river channel as it descends riffles, glides across pools, meanders through side channels, and cascades over obstructions (Poole et al., 2006; Kasahara, 2003; Malard et al., 2002; Storey et al., 2003; Woessner, 2000; Hill, 1998; Morrice, 1997). The influence of streambed topography on surface and ground-water exchange has also been shown to vary with stream order. In small 2nd order streams, pool-riffle sequences control the pattern of exchange (Kasahara, 2003). In larger 5th order streams, such as the West Gallatin near Four Corners (Fig. 1-2), the spatial pattern of exchange is controlled by the interaction of multiple morphologic features (Kasahara, 2003).

In complex 5th order anabranch channels, pool-riffle sequences, meander bends, and secondary channels interact which results in a hierarchy of surface and ground-water flow paths (Poole, 2006; Kashara, 2003; Harvey and Bencala, 2003; Storey et al., 2003). Within this hierarchy the flow paths created by meander bends overwhelm the flow paths created by

pool-riffle sequences (Malard, 2002). In addition to the interaction between pool-riffle sequences and meander bends, the presence of secondary channels can have a major influence upon exchange patterns in a channel (Kasahara, 2003; Wondzell and Swanson, 1999; Wondzell and Swanson, 1996). The elevated position of secondary channels above the main channel creates the strongest hydraulic gradients in the ground-water system near the stream between the secondary and main channels. This ground-water flow path can mute flow paths with weaker hydraulic gradients created by pool-riffle sequences and meander bends (Poole, 2006; Storey et al., 2003; Malard, 2002). Along stream reaches with hillslope aquifers connected to the stream channel, ground-water inflow from the hillslope has been observed to dominate flow paths created from other influences, such as channel topography (Malcolm, 2003).

In locations where upwelling ground-water occurs in the stream channel, the extent and magnitude of channel-scale exchange can be attenuated or completely overwhelmed by the upwelling ground water (Poole, 2006; Storey et al., 2003; Malcolm, 2003; Morrice, 1997). In locations where the stream channel is ubiquitously losing water, the ground-water flow paths between pools and riffles, meander bends, and secondary channels are less frequent. The exchange in losing reaches is dominated by stream water downwelling into the aquifer (Storey et al., 2003; Malcolm, 2003). Because the upwelling and downwelling of water in an aquifer is controlled by its' physical characteristics, such as hydraulic conductivity and aquifer thickness (transmissivity), the physical characteristics of an aquifer contribute to the pattern of surface and ground-water exchange.

Hydraulic conductivity and gradient control exchange rates and the extent of ground-water flow paths near the stream. Fluvial aquifer material is well sorted by size, but

highly variable throughout the aquifer. As a result, zones of higher hydraulic conductivity are present where larger cobbles have been deposited. These zones are capable of conducting more water through the aquifer either into or out of the river channel, resulting in concentrated high flow zones in the system (Poole et al., 2006; Kasahara, 2003). As the complexity of the sorted material increases so does complexity of exchange as a function of the increased variation in hydraulic conductivity (Woessner, 2000).

On the Middle Fork of the Flathead River, changes in aquifer thickness and width (aquifer transmissivity) accounted for the presence of upwelling ground water and downwelling surface water which influenced the exchange process near the surface of the streambed (Poole et al., 2006; Kasahara, 2003). In locations where aquifer width or depth increased the primary exchange process in the streambed consisted of downwelling stream water. Conversely, in locations where width or depth decreased, upwelling ground water dominated the exchange and overwhelmed the flow paths created by the channel's topography (Poole et al., 2006; Kasahara, 2003). In addition to an aquifer's shape and size the rate at which water passes through an aquifer influences the pattern of exchange.

#### Factors Influencing Temporal Variation

The direction of flow between a stream and aquifer is determined by the difference in total head. This differential may change in response to changes in either surface-water elevations or water-table elevations. Changes through time in river-surface elevation, the water-table elevation, streambed morphology, and the inundation of secondary channels affect the volume and location of surface and ground-water exchange in streams by changing the total head in either the stream or the aquifer (Malard et al., 2002). During flood events,

the complexity of surface and ground-water exchange increases significantly with the additional influences of inundated side channels, fluctuating ground-water levels in response to aquifer recharge, and rapidly changing surface water elevations altering the ground-water movement in the aquifer near the stream (Poole, 2006; Malard et al., 2002).

Precipitation events which increase streamflow and raise surface-water elevations can have varied effects on surface and ground-water exchange patterns depending on the location of the precipitation. Precipitation which falls directly on the stream and the aquifer will raise both the stream and ground-water levels. As a result of the concurrent rise in surface-water and ground-water elevations, the difference between the total heads in the stream and aquifer is not drastically altered and the pattern of surface and ground-water exchange remains relatively stable. Alternatively, increased discharge and surface water elevations which resulted from distant mountain snow melt or rain events will increase surface water elevations without initially raising ground-water elevations. The increased surface water elevations will change the difference in total head of the stream without initially changing the total head of the aquifer. In locations where the surface-water elevation was above the ground-water elevation before the event, aquifer recharge will increase. In locations where the surface-water elevation was below the ground-water elevation before the event, ground-water discharge to the stream will decrease. If the surface-water elevation rises above the ground-water elevation then aquifer recharge will occur in the same location where ground-water discharge occurred prior to the event.

Increased stream discharge and surface-water elevation from local precipitation is often associated with a rise in the water table which affects the aerial extent of the surface and ground-water mixing zone in the aquifer (Malard, 2002). The rise in water-table and river

surface elevations results in an increase in the total head of both the stream the aquifer which decreases the hydraulic gradient between them and causes a reduction of the surface and ground-water mixing zone area. Modeling experiments and observations have shown a reduction of the surface and ground-water-exchange zone area by 30% to 50% during high flow events caused by local precipitation (Valett, 1996; Morrice, 1997; Wondzell, 1996). The reduction of the surface and ground-water-exchange zone is caused by a greater increase in the water-table elevation than the river-surface elevation, which reduces the hydraulic gradient from the stream to the aquifer and decreased the distance from the stream that surface water can travel into the aquifer.

Increases in stream discharge which occur from snow melt or mountain rain fall are initially associated with a greater increase in the total head at the stream with no increase in the total head at the water table. As a result the aerial extent of surface and ground-water-exchange zone will initially expand further from the stream into the aquifer (Malard, 2002). However this expansion is not infinite and eventually may increase ground-water elevations as aquifer recharge occurs from the stream. As a result of the aquifer recharge, the water-table elevations will rise, increase the total head in the aquifer, and decrease the hydraulic gradient between the stream and the aquifer. The decreased hydraulic gradient will reduce the area of the surface and ground-water-exchange zone in the aquifer (Storey et al., 2003). During these distant precipitation events the aerial extent of ground-water exchange zone will initially extend further from the stream as surface water elevations and the hydraulic gradient between the stream and aquifer increase. Then after aquifer recharge has raised ground-water elevations and surface water elevation decline, the surface and ground-water-

exchange zone will decrease as the hydraulic gradient between the stream and aquifer is reduced.

When increases in river elevation occur which are large enough to cause the inundation of secondary channels and the floodplain, the amount of aquifer recharge which can occur increases substantially (Poole et al., 2006; Wondzell and Swanson, 1996). In locations where water inundates previously dry channels, aquifer recharge takes place and the aerial extent of near-stream recharge increases. The increase is due to the secondary channel's elevated position above the water table elevation.

The inundation of the secondary channels during flooding is critical to maintaining aquifer recharge during high-flow events. During extended high-flow events, such as spring runoff, water-table elevations will eventually rise as a result of the aquifer recharge related to the flooding. The elevated water table can eventually reduce or stop aquifer recharge if they rise above surface water elevations. When this occurs, surface water no longer recharges the aquifer. However if side channels are available which can transport flood water above the water table, then aquifer recharge can continue during high flow events (Poole et al., 2006; Morrice, 1997; Valet, 1996; Wondzell, 1996).

Strong zones of upwelling ground water and downwelling surface water create temporal stability in near-stream-ground-water-flow paths (Poole, 2006). The presence of these ground-water upwelling zones attenuates the effects of changes in surface-water elevations on near-stream-ground-water-flow paths (Harvey and Bencala, 1993; Storey et al., 2003). In areas where ground water is upwelling into the streambed, total head in the aquifer will decrease the hydraulic gradient at the streambed and decrease the extent of shallow-near-stream-ground-water flow paths created by the streambed's topography. However in

locations where the surface water is downwelling, hydraulic gradients between the stream and aquifer are more negative. In these zones the vertical hydraulic gradients will also fluctuate more over time as result of changes in river surface elevations. The greater variation occurs because total head in the streambed does not change over time with changes in the water-table elevation. So in a precipitation event which raises both the water-table and the river-surface elevation, the vertical hydraulic gradient will become more negative than in upwelling zones where increases in total head of the aquifer will offset increases in total head from the river by increasing the positive total head at the streambed.

Channel change can also alter the pattern of near stream flow paths. The migration of pool-riffle sequences, meander bends, and secondary channels can change the location of flow paths associated with channel forms (Malard et al., 2002; Wondzell and Swanson, 1999). Additionally, scouring or aggradation in a channel can effect local ground-water elevations, changing the location of zones of upwelling ground water into downwelling stream water, and areas of downwelling stream water into upwelling ground water. A channel which erodes into the aquifer could increase aquifer discharge without increasing recharge, resulting in a loss of ground water and a subsequent decline in ground-water elevations. Conversely, channel aggradation may result in a local increase in aquifer recharge and a subsequent rise in water table elevations (Wondzell and Swanson, 1999).

Changes to the surface and ground-water exchange mosaic can be expected over time. Increases in stream discharge may affect the pattern of exchange during precipitation or snow melt events. However, the effects upon these flow paths are varied depending on the source of elevated stream stage and the presence or absence of upwelling ground water from the aquifer. Flood events are also capable of rearranging channel topography which

dictates the location of flow paths between surface and ground water and maintains ground-water elevations. Scouring and aggradation in a stream channel is capable of altering the balance of recharge and discharge to an aquifer, resulting in an adjustment of ground-water elevations next to a channel. Understanding how the surface and ground-water exchange mosaic changes through time, requires an understanding of the location and timing of recharge to a stream and aquifer as well as the channel's morphologic condition through time.

#### Measuring the Spatial and Temporal Variation of Surface and Ground-Water Interactions

Measuring the temporal and spatial variability of surface and ground-water exchange requires measurements from the stream, aquifer, and the riverbed. The phenomenon of surface and ground-water exchange varies quickly through space and time, complicating data collection efforts. Spatially, the flux of water between a river and aquifer can vary on a scale of feet driven by variations in topography and hydraulic conductivity. Furthermore, large volumes of ground-water discharge can be concentrated into small area in the streambed (Poole et al., 2006; Conant, 2003; Wondzell and Swanson, 1999).

Multiple studies have found that zones of strong upwelling ground water and downwelling surface water occur in concentrated areas in the streambed and these areas constitute a small percentage of the streambed's area. In Ontario on the Pine River, 5-7% of the streambed's area discharged 20 -24% of the total upwelling ground water (Conant, 2003). Less than 12 % of the area contributed to aquifer recharge. On the Nyack Floodplain upwelling ground water and downwelling stream water were also found to be concentrated in a small portion the river's channel (Poole et al., 2006; Wondzell and Swanson, 1999).

Measuring zones of upwelling ground water and downwelling surface water is complicated by the heterogeneity of ground water exchange within the streambed. As a consequence there is a high probability of misrepresenting the surface and ground-water exchange regime in a streambed by collecting an inadequate number of samples to accurately represent the variability of exchange. Temporal variation further complicates the exchange mosaic making data collection schemes even more demanding.

Selected Example Studies. Most of the studies which have successfully described the spatial and temporal variation of surface and ground-water exchange have been conducted in short reaches of river or single channel features in a riverbed such as a pool-riffle sequence or meander bends. Because of the small extent of these study areas, fine scale measurements are feasible, and measurements can be collected from grid networks of piezometers installed on the scale of feet. These methods are highly effective at documenting variation in small areas or single features but present problems when studying the variation along an entire river corridor. A few studies have applied the techniques used in the studies of small areas to larger area with mixed success.

Along a 75 meter reach of stream in Scotland, researchers installed piezometers along both sides of a stream channel to address the effects of upwelling water upon spawning salmonid (Malcolm et al., 2003). Each measurement station was comprised of three piezometers penetrating to increasing depths on both sides of the channel. Using this technique, areas which received ground-water discharge from hillslope aquifers were differentiated from areas in the stream which did not receive the ground-water discharge. While the scale of observation in the Malcolm study was appropriate for assessing salmonid

survival under varied upwelling ground-water regimes, it is impractical for documentation of surface and ground-water exchange processes along a six mile reach.

In Oregon researchers attempted to document surface and ground-water exchange along a 52 km reach of the Middle Fork of the Jon Day River with little success (Wright et al., 2005). The researchers used topographic, photographic, and thermal map images to initially predict large scale zones of upwelling and downwelling along the river corridor. To test their hypothesis the researchers instrumented 10 sites along the 52 km reach and collected data during base flow conditions. Each site was 50 m long, comprised of 3 piezometers per site, located mid channel, and 25 meters apart. The researchers speculated, their monitoring network was too coarse and as a result determined their findings were inconclusive and did not support their hypothesis that zones of upwelling and downwelling occurred along the river corridor as documented on other rivers. Consequently, the researchers could not confidently determine whether the Middle Fork of the Jon Day River had a unique exchange pattern compared to other rivers or if their sampling network was insufficient. The possibility still remained that an insufficient sampling network did not capture floodplain scale exchange phenomenon, because of the localized behavior of upwelling of ground water and downwelling surface water at the measuring points.

In-stream piezometers have been successfully applied to document zones of surface and ground-water exchange in other studies. Pepin and Hauer (2002) successfully documented reach scale upwelling and downwelling zones in the braided channels of McDonald Creek, MT. The researchers installed multiple in-stream piezometers only in the main channel to sample bed form areas where they suspected ground-water upwelling and surface-water downwelling.

On the Rio Grande River, the United States Geologic Survey validated conceptual models of aquifer recharge using in-stream piezometers and monitoring wells in the fluvial plain (Bartolino, 2000). The piezometers and wells were situated in a single transect perpendicular to the stream. By measuring ground-water temperatures in the river, wells, and piezometers, the researchers were able to validate a conceptual model of aquifer recharge at the transect location. While this method confirmed the researcher's conceptual model at a single location, it did not address the entire river corridor which should be understood for the development of conjunctive surface and ground-water management plans.

Water-chemistry data were used successfully to study the surface and ground-water interactions through space and time in the Swiss Alps. Along a 2.6 km braided stream channel, water chemistry was sampled in multiple channels along transects running perpendicular to the river. Fourteen transects were evenly spaced along the 2.6 km reach, or approximately one transect every 200 meters. The data were used to describe annual variation of water sources in glacial floodplain (Malard et al., 2002). The technique relied upon distinct chemical signals from each water source and as a result was able to collect samples from the within the stream's channel and determine the relative proportion of each water source in an individual side channel. While this technique is ideal in situations where each water source has a distinct chemical signal, it would not be effective in situations where the surface and ground water had similar chemical signals.

## METHODS

To identify zones of upwelling ground water and downwelling surface water in the West Gallatin River, measurements were made of water levels, specific electrical conductance and discharge. These measurements were used to calculate ground-water seepage and hydraulic gradients. These measurements were taken from the river's main channel, spring channels, near-stream wells, and shallow piezometers in the Gallatin River's streambed.

### Ground Water

#### Well Installation and Construction

The wells used for this analysis were a combination of preexisting wells installed specifically for a project funded by the State of Montana (Custer and Schaffer, 2009) to study surface and ground-water interactions. Some of these wells were installed in pairs to calculate vertical hydraulic gradients in the aquifer. These wells were grouped in pairs adjacent to one another at varied depths. All monitoring wells for this project were installed using a Geoprobe™ in October and November 2005. This method of installation is described by Schwartz and Zhang (2003, p. 156-158).

After installation of the Geoprobe wells, the cavity between the well casing and the aquifer was filled with sand to within approximately a foot below ground surface then capped with bentonite. Screen lengths for the Geoprobe wells ranged from one to fifteen feet long. The Geoprobe wells have a one inch inside diameter; some preexisting wells in the network have a six inch inside diameter. Specific well information regarding construction is

also located at the Montana Bureau of Mines and Geology's web site GWIC (Ground-Water Information Center) and the Montana State University Earth Science Department (Custer and Schaffer, 2009). Information on the preexisting wells used in this study can also be found at GWIC.

### Well Locations

Well casing-tops' vertical and horizontal positions were determined from a combination of surveys conducted by, the Montana Department of Natural Resources and Conservation (DNRC), and HKM Engineering of Bozeman. Both parties used survey grade GPS equipment. The DNCR conducted two surveys, the first on August 7<sup>th</sup> 2006 and the following winter on February 25<sup>th</sup> 2007. The second survey was conducted to resurvey portions with unacceptable error which was attributed to the thick cottonwood canopy obstructing satellite reception. In situations where multiple measurements were available for a single point, the best measurement was chosen by Dr. Stephan Custer of MSU based on the least amount of reported error. The final position data is located in the Four Corners Database, within the table "Ground-Water Measurement Points" which was provide to the Montana Department of Natural Resources and Conservation (Custer and Schaffer, 2009).

### Instrumentation of Wells

Water level and temperature data from monitoring wells was recorded with Solinst<sup>TM</sup> data loggers. The data loggers measured absolute pressure and therefore required a barometric compensation to separate the height of water from atmospheric pressure. Small holes were drilled in the well casings to equalize the pressure between the inside of the well and the atmosphere. Software provided by the logger's manufacturer (Solinst, Levellogger

2.0) was used for the compensation. Barometric pressure was measured within the study area using a Solinst Barologger™ suspended above the water level in Well 224087.

To convert the height of water above the logger to an absolute elevation, the depth to water from the surveyed well top was measured manually using a Solinst™ electrical sounding tape. The loggers' suspended elevations were determined by adding the height of water above the logger to the manually measured depth to water and subtracting this distance from the surveyed well top's elevation. After each logger's suspended elevation was calculated, the height of water above the logger was converted to an elevation by adding the height of water above the data logger to its elevation. Hydrographs including temperature data were created by MSU were provided to the DNRC and are available from the MSU Earth Science Department.

#### Ground-Water Measurements from Wells

Water Levels and Temperature. Water levels and temperature were collected at hourly intervals in wells instrumented with data loggers. Water levels in non-instrumented wells were periodically measured by hand using an electrical tape to calibrate distance to water from the surveyed casing top. Water levels are reported as water surface elevations.

Specific Electrical Conductance. Specific conductance and temperature were also measured manually. Conductance measurements were made using a hand held YSI-30 Specific Conductance probe at the end of a 10 foot cable which was lowered into the well. The potential effect of taking specific conductance measurements in the wells was

considered because the close proximity of well casing to the probe had the potential to affect specific conductance readings.

A small variation in SC value was observed after testing conductance measured in the wells to SC values measured after pumping seven gallons of water from the wells before making a measurement in a bucket. The variation between pumped bucket water and measurements inside the well was less than  $10 \mu\text{S per cm @ } 25^\circ \text{C}$ , roughly less than 5% of the value. This variation was deemed acceptable given the large number of measurement locations and the required time to pump water from the wells.

## Streambed

### Streambed Piezometer Installation

Sixty-five streambed piezometers (SBPs) were hand driven into the streambed along the 6.2 mile study reach. The piezometers penetrated to depths of 20-42 inches below the bed surface. The piezometers were installed by hand, using a 5.7' long steel shaft with a drive head (Fig. 2-1a and b). This unit resembled a giant nail. The drive shaft was inserted through a one inch diameter schedule 40 PVC pipe which was 66 inches long (Fig. 2-1d). The shaft and PVC pipe were driven into the bed with a fence post pounder modified with extra weight welded to the top (Fig. 2 -1c). Other methods of installation using a jack hammer were tested, however the use of jack hammer did not allow for the piezometers to be inserted any deeper into the river bed than the method described above.

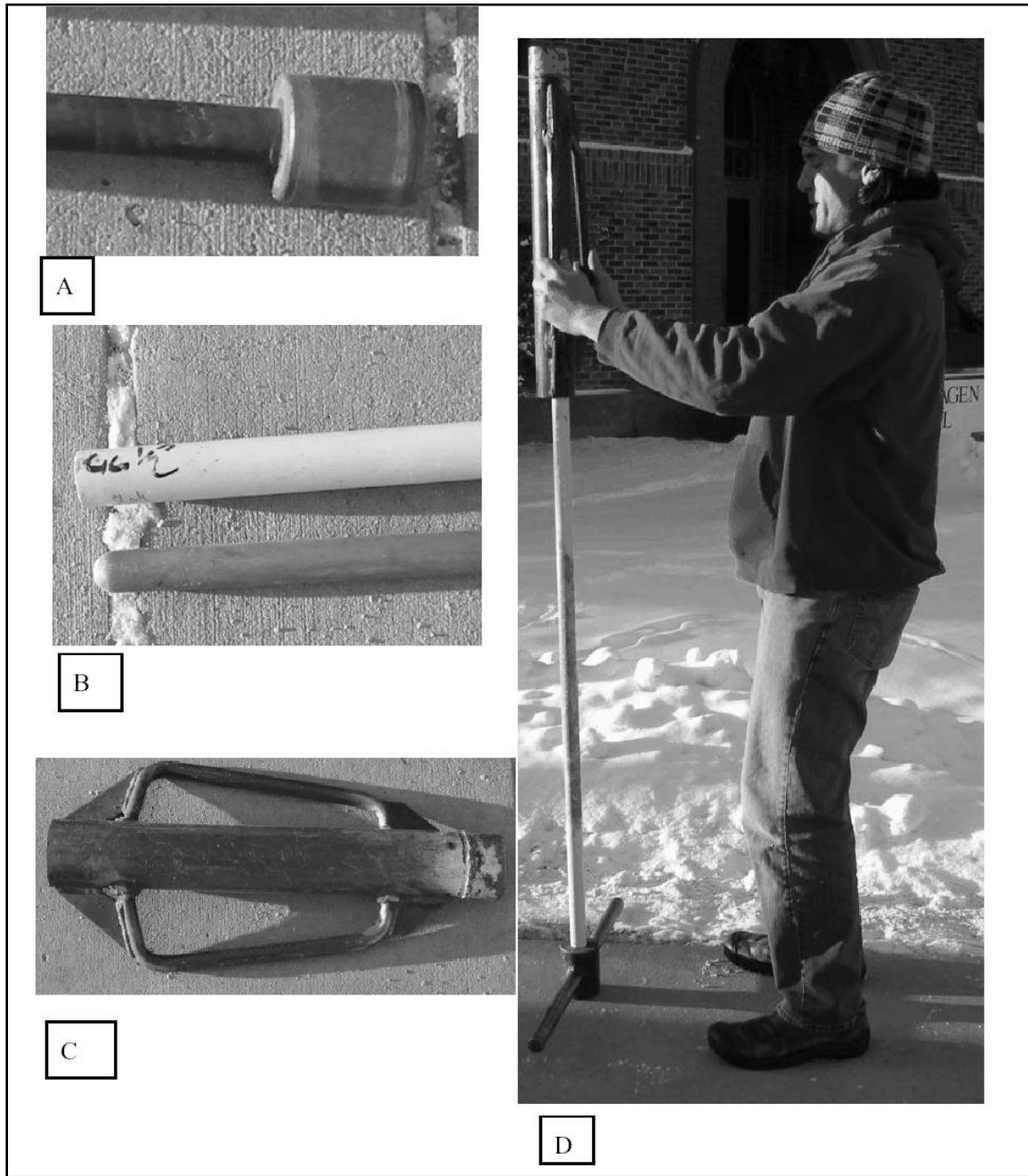


Figure 2-1. Stream bed piezometer installation equipment used to install the PVC piezometers to a depth of two feet into the alluvial streambed. A.) Drive head for the installation spike. B.) Drive point for the installation spike and 1 inch diameter PVC piezometer. C.) Reinforced fence post pounder with additional five pound weight welded to the top. D.) Installation set up including the removal handle located at the base of the piezometer.

### Streambed Piezometer Locations

The location of most streambed piezometers was measured using a recreational grade GPS unit. However some piezometer locations were measured using survey grade equipment in conjunction with the survey of monitoring wells. Piezometer top elevations were recorded when measured with the survey grade equipment. This information is stored in the Four Corners Data Base provided to the DNRC (Custer and Schaffer, 2009) and is also available at the MSU Earth Science Department.

The 65 individual SBPs were grouped into 22 sets of 2 to 5 individual piezometers within a pool. Each group was spaced roughly 0.3 miles apart in pools. Piezometer installation was only possible in pools. Piezometer installation in riffles was not possible due to the coarse nature of the bed material which caused refusal and swift current which made wading dangerous.

The individual piezometers within a pool were considered to be a set and each piezometer in the set was positioned to sample either the pool head, pool tail, or intermediate position between the head and tail of the pool (Fig. 2-2). These sample positions were chosen because other studies indicate that the flux of water through the streambed varies with position in pools (Woessner 2000, Wright and others, 2006).

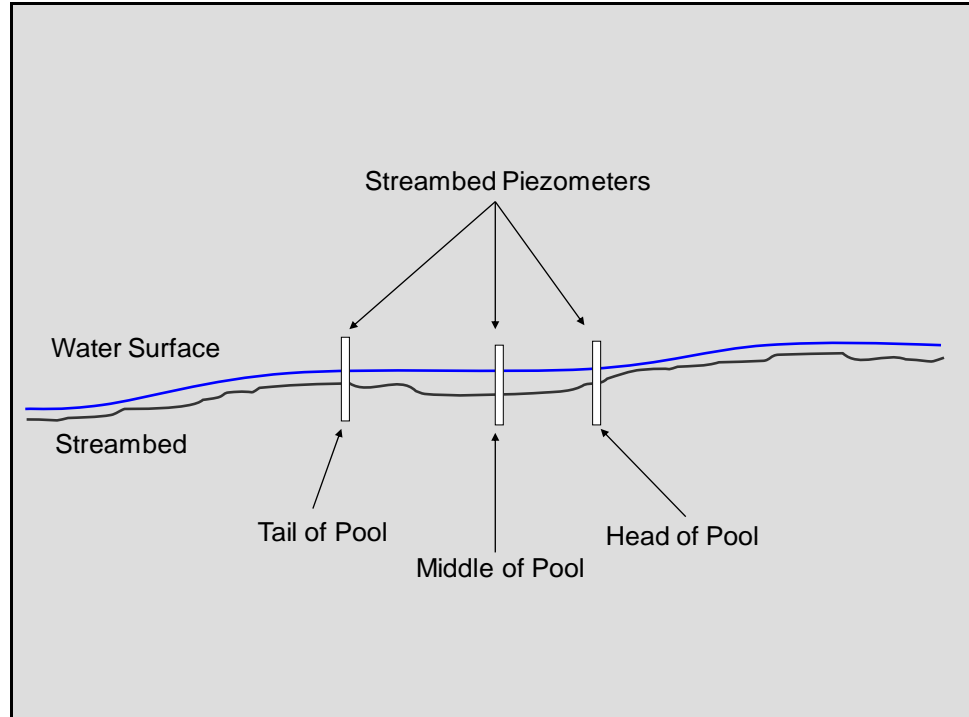


Figure 2-2. Idealized diagram of three individual streambed piezometer arranged in a set to sample the pool head, middle, and tail.

### Measurements from Streambed Piezometers

Water levels, temperature, and specific electrical conductance were measured in the piezometers and in the surface water adjacent to the piezometer. Piezometers were sampled four times during the 2006 water year. Two complete sampling events on July 17<sup>th</sup> and 18<sup>th</sup> and the second event occurred on August 23<sup>rd</sup> and 24<sup>th</sup>. Two incomplete sampling events were also conducted on August 18<sup>th</sup> and 19<sup>th</sup> and November 18<sup>th</sup> and 20<sup>th</sup>. The November event did not include all the piezometers because wells were removed by people on the river and because of difficulties associated with accessing the sites caused by river ice and drifting snow. All measurements from the streambed piezometers are available in data base associated with the report to the DNRC (Custer and Schaffer, 2009) which is also available at the MSU Earth Science Department in Bozeman.

Water Levels. Water levels were measured inside the piezometer and at the stream's surface adjacent to the piezometers. Measurements were made using an electrical tape to measure the distance from the top of the piezometer to water surface inside and outside of the piezometer. A piece of one inch diameter schedule 40 PVC was used as a stilling well to dampen the effects of turbulence at the surface of the stream (Fig. 2-3). These measurements were used to calculate vertical hydraulic gradients between the surface water and the streambed.

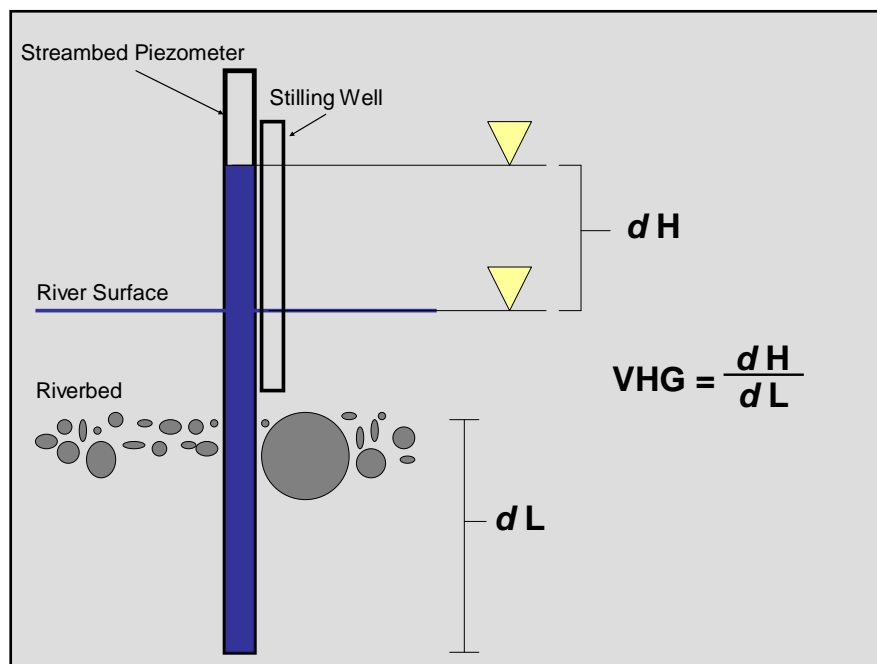


Figure 2-3. Schematic of values used to calculate the vertical hydraulic gradient in the streambed at a streambed piezometer. In the above figure;  $dH$  is difference in hydraulic head between the waters,  $dL$  is length between the bottom of the piezometer and the streambed, and  $VHG$  is result as vertical hydraulic gradient.

Calculation of Vertical Hydraulic Gradients. Vertical and horizontal hydraulic gradients were calculated from the water levels and elevations measured at piezometers. Values measured inside the piezometer were compared to surface water elevations adjacent

to the piezometer (Fig. 2-3). The water surface elevation was assumed to be equal to the hydraulic head of the stream at the piezometer location. Surface water elevations were measured inside a stilling well. Values for dH were calculated by subtracting the piezometer water elevation from the stream surface elevation and dividing by the absolute value of the distance between the streambed and piezometer opening. As a result, positive gradients indicate water movement into the stream and negative gradients indicate water movement from the stream into the bed. All measurements are available in data base associated with the report to the DNRC (Custer and Schaffer, 2009) which is also available at the MSU Earth Science Department in Bozeman.

### Surface Water

#### Location of Surface-Water Measurements

Specific conductance and water level measurements were collected from the Gallatin River's main channel, springs in the river's floodplain, and tributaries to the river. The location of these sites were documented in the field using a recreational grade GPS, and geographic information system software (ArcMap 8.0) to visually identify the locations using aerial photography taken in September 2005. The GIS software and aerial photograph were used to visually/manually correct for the error inherent in a recreational grade GPS unit. Surface water diversions were assigned to appropriate reaches based on locations identified by the former water commissioner for the West Gallatin, Dave Pruitt, using a USGS 1:24,000 topographic map. Based on his notes the coordinates for those locations were found using the GIS software and a digital version of the same 1:24,000 map to visually identify the locations and read the corresponding coordinates.

### Surface-Water Instrumentation

Irrigation ditches, spring features, tributaries to the West Gallatin, and two main channel sites were instrumented with data loggers which recorded water levels and temperature data at hourly intervals. The data loggers were suspended within stilling wells which were driven into the streambed and perforated. TruTrack™ capacitance rods measured water levels and temperatures in; Fish Creek, Dry Creek, and in irrigation ditches (Spain Ferris, Valley, Mammoth, Owenhouse, and Beck Border). Solinst Level Loggers were used to measure water levels at two sites on the Gallatin River at the upstream and downstream ends of the study area (Fig. 2-4). In the Gallatin River ground-water monitoring equipment was preferred over the TruTrack capacitance rods because peak flows had the potential to submerge the gauges, and ground-water equipment is designed to be fully submerged. The capacitance rods do not have a water proof seal over the data logger and are not designed for submersion. All hydrographs are available in data base associated with the Custer and Schaffer report to the DNRC (2009) which is also available at the MSU Earth Science Department in Bozeman.

### Surface-Water Measurements

Specific Electrical Conductance. A YSI 30 Hand Held Salinity, Conductivity, and Temperature Probe was used to measure specific electrical conductance. The probe was one inch in diameter and was inserted into the piezometer to measure conductivity. Conductivity was also measured in the stream at 50 percent of the water column depth at the piezometer location for comparison and the calculation of the percent ground water in the piezometer. All measurements are available in a data base associated with the report to the DNRC

(Custer and Schaffer, 2009) which is also available at the MSU Earth Science Department in Bozeman.

Discharge Measurements. Stream discharge was calculated by measuring stream velocity across the channel at sixty percent of the stream's total depth below the surface. Measurements were made with a Marsh-McBirney Flow Mate Model 2000<sup>TM</sup> velocity meter attached to a top-setting wading rod used to measure stream depth and measurement height. Discharge was taken in locations where the channel was single thread, straight, and uniform as possible, often in the center of pools. Measurements were made and calculated as recommended by the U.S. Forest Service (Harrelson et. al. 1994). In locations where the river had multiple channels, all channels were measured and included in the discharge calculation. Two measurement locations had multiple channels, the West Gallatin at Norris Road and the West Gallatin at the study area's downstream boundary (Fig. 2-4, locations III and V). At these locations the measurements from the side channels and main channel were added together to calculate total discharge. Tributaries were also measured using the same method described above. Surface water diversions (for irrigation) were reported from the water commissioner (George Alberda), who either measured the outflow from established flumes or measured discharge manually. Even though discharge measurements were conducted twice at some locations to assess the measurements accuracy, an uncertainty of plus and minus 5% of all measured discharge values was assumed when comparing seepage based on estimates from the USGS (Rantz, 1982).

### Calculation of Ground-Water Seepage

Ground water seepage between the stream and aquifer was assumed to be the change in stream discharge between two points which is attributed to the exchange with ground water (ground-water seepage). Ground-water seepage was assessed by measuring discharge at five locations along the study reach (Fig. 2-4). The difference in discharge at these locations was considered a measure of the net flux of water between the aquifer and river between the two locations, because surface water gains and losses from irrigation diversions and tributaries were accounted for between the river measurement points (Eq. 2-1). Discharge was measured at five locations which yielded net flux values for four individual reaches. Net flux was measured three times during water year 2006 to examine temporal variability; November 2005, July 2006, and August 2006.

Equation. 2-1

$$(Q_{\text{Downstream}} + Q_{\text{Surface diversions}}) - (Q_{\text{upstream}} + Q_{\text{tributary inflow}}) = Q_{\text{Net Flux between Aquifer and River}}$$

To assess potential measurement error, discharge was measured more than once at each site. The mean value from the multiple measurements was used in the ground-water seepage calculation (Eq. 2-1). Measuring stream discharge at five locations allowed the ground-water seepage to be assessed in a maximum of four sub reaches (Fig. 2-3). Two days were required to make all discharge measurements along the 6 mile study reach. Changes in river discharge during those two days were monitored using staff gauges located within the study reach. When changes in river stage occurred overnight, discharge was measured again in appropriate locations to calculate seepage on the day of sampling. The only significant

change in discharge over night occurred during the July measurements and was associated with the diurnal fluctuation of snowmelt affecting streamflow.

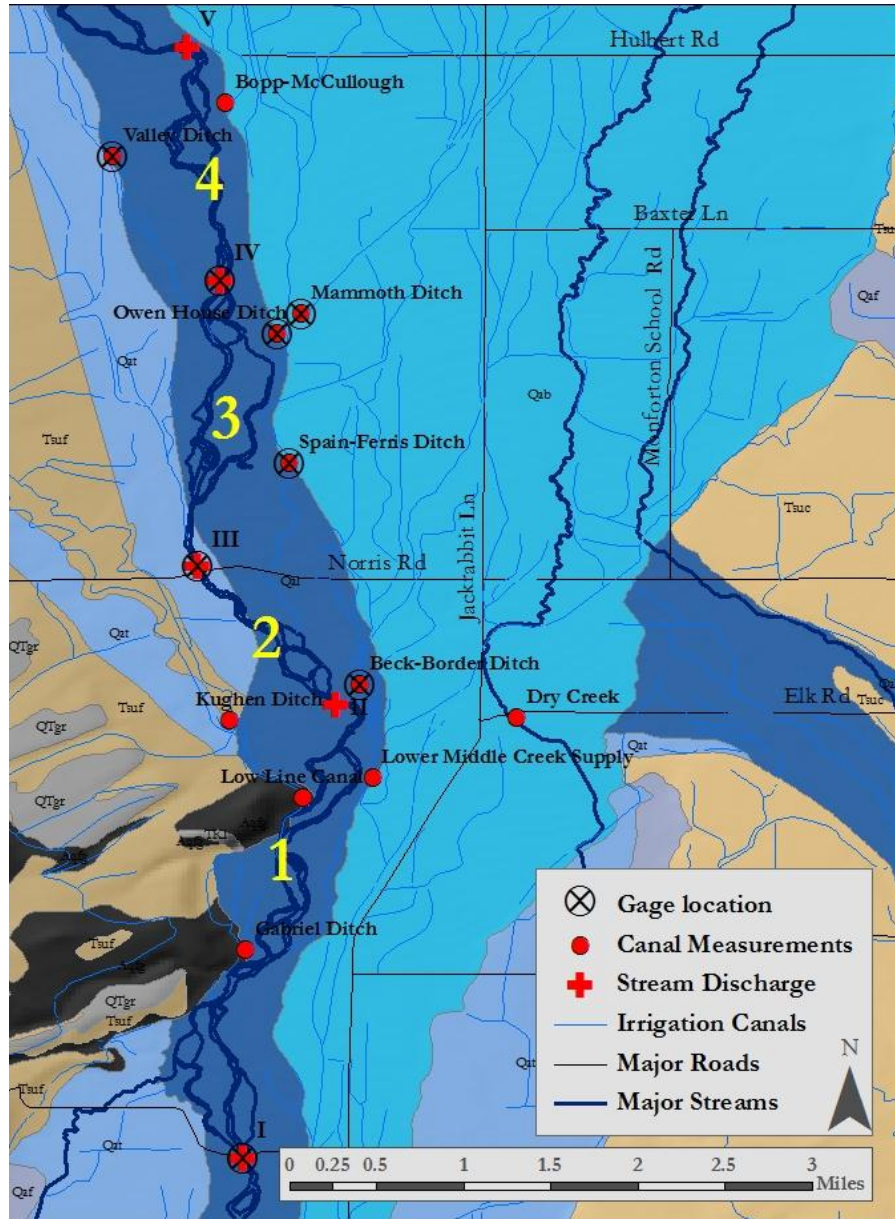


Figure 2-4. Discharge measurement and gauge locations used to calculate ground-water seepage. Main channel discharge locations are marked as crosses and labeled with roman numerals. The five main channel measurement locations allowed net gains or losses to be assessed in four sub-reaches of the study area. The location of measurements from surface water diversions are marked as circles. Gauge locations are shown with an overlying black circle and cross. The base layer for this map is the Bozeman 1:100,000 MBMG geologic map of Bozeman (Vuke, et. al. 2002). Key for geologic units located in Figure 1-2.

## RESULTS

Ground Water

Thirty-seven Geoprobe wells were installed for this study with funding provided by a Renewable Resource Grant from the 60<sup>th</sup> Montana State Legislature (RRG 06-1242). Nine additional preexisting wells were also measured regularly. Well depths varied from 4.3 to 63.3 feet deep. The preexisting wells in the study area range from 7.9-63.3 feet in depth and Geoprobe wells range from 4.3 to 32.8 feet deep. One hundred and fifty measurements of specific conductance were made in the 40 wells. One hundred-eight-eight vertical hydraulic gradients were calculated at 10 locations. Data loggers collected hourly water level and temperature data at 25 wells beginning October 2005. All measurements are available in data base associated with the report to the DNRC (Custer and Schaffer, 2009) which is also available at the MSU Earth Science Department in Bozeman.

Monitoring Well Locations

The locations of monitoring wells used for this analysis are documented in the associated database on file at the Earth Science Department at Montana State University in Bozeman. Latitude, longitude, datum, survey method, elevations, and well construction details are described in the Four Corners data base provided the DNRC (Custer and Schaffer, 2009) and available at the MSU Earth Science Department. This information is contained with that data base under the table, "Ground-Water Measurement Points." Monitoring wells installed for this study were dispersed throughout the study area centered on Four Corners. Land use at well locations varied from residential, active agricultural land,

retired agricultural land and, riparian areas. The associated database also includes the interpreted land-use classification for each. All the monitoring wells, except one (224121) were completed within the extent of the Gallatin River Alluvium, as mapped by the Montana Bureau of Mines and Geology on the 1:100,000 scale Geologic Map of Bozeman (Fig. 3-1). However during the Geoprobe installation process, layers of hard and resistant material were encountered at depths which were hypothesized to be areas of unmapped Tertiary material by Dr. Stephan Custer. Due to the nature of the Geoprobe installation however, no material was available to sample which is typical during the installation of typical rotary drilled wells.

#### Ground-Water Hydrographs

Twenty five ground-water hydrographs were created from the hourly data collected by the data loggers. These hydrographs also include hourly temperature data. Ground-water elevations fluctuated over time throughout the study area. The hydrograph data are available at the Montana Bureau of Mines and Geology Ground-Water Information Center (GWIC).

#### Ground-Water Specific Conductance

Ground-water specific conductance was measured 150 times from 40 wells between March 27<sup>th</sup> and August 11<sup>th</sup> 2006. Specific conductance values fluctuated more in some wells than in others (Table 3-1, Appendix A). Average specific electrical conductance was 376  $\mu\text{S}$  per cm @ 25° C for all wells. The minimum observed value, 169  $\mu\text{S}$ , occurred on June 16<sup>th</sup> at well 224113. The maximum value, 760  $\mu\text{S}$ , was observed on July 6<sup>th</sup> at well 224116.

Individual specific conductance values measured in wells are located in the Four Corners Streambed Database in the table, Ground-Water Measurement Values (Custer and Schaffer,

2009), and is also available at the Montana State University Earth Science Department in Bozeman.

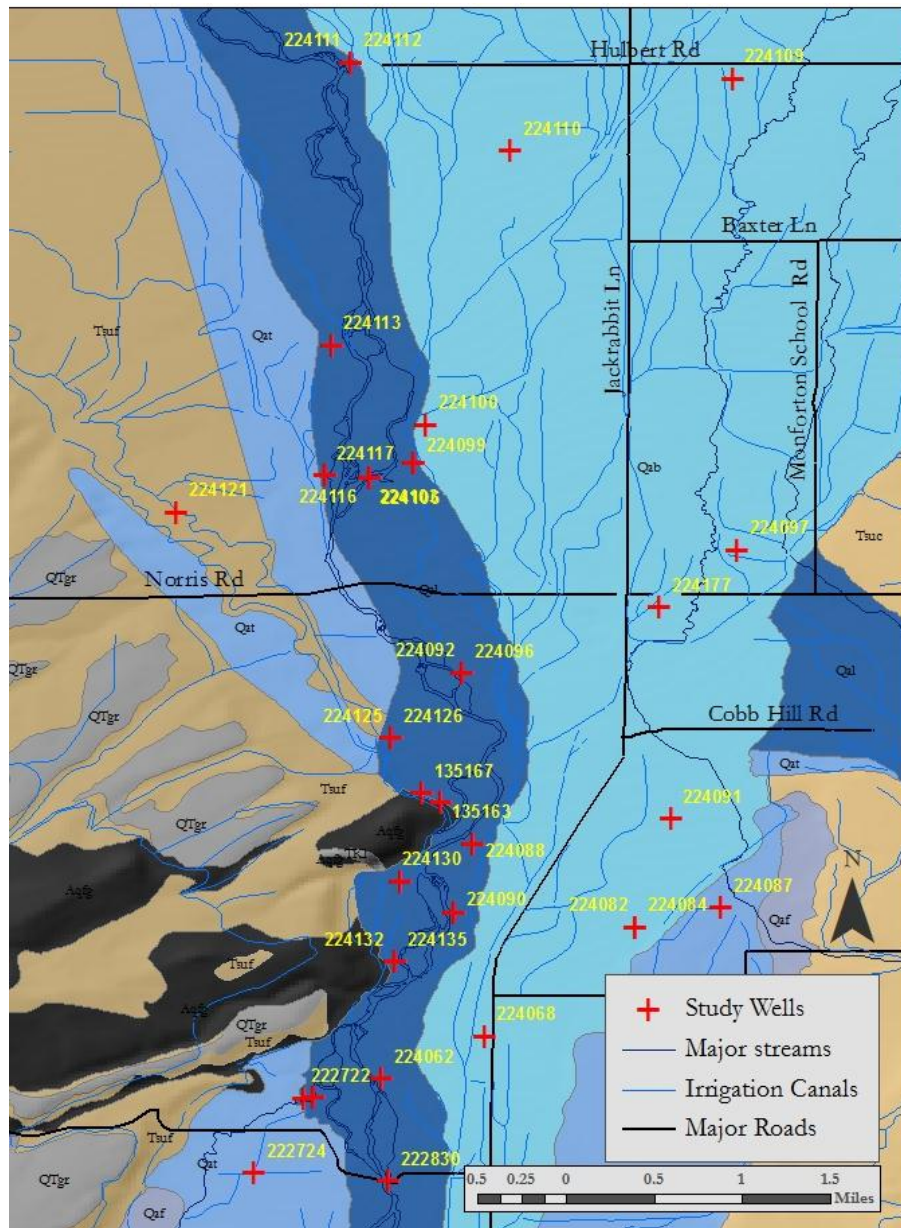


Figure 3-1. Monitoring well locations with continuous data loggers. Modified from the Montana Bureau of Mines and Geology 1:24,000 Geologic Map of Bozeman (Vuke et. al., 2002). Key for geologic units is located in Figure 1-2.

### Surface Water

Specific conductance, discharge, water levels, and temperature were measured at 21 locations, from November 2005 through August 2006. The measurements were taken from irrigation head gates, the river's main channel, tributaries, and spring features in the floodplain. Discharge along the main channel was measured at five locations during three separate events for the purpose of identifying gaining and losing reaches of the stream (Fig. 2-4). Tributaries and irrigation head gates were also measured during these events (Fig. 2-4). Specific conductance was measured routinely at Axtell Bridge in the river's main channel, spring features, and at the streambed piezometer locations. Temperature and water level data were recorded at hourly intervals in the river's main channel, spring features, and at irrigation head gates (Fig. 2-4).

#### Surface Water Measurement Locations

Two staff gauges, instrumented with data loggers collected hourly temperature and water-level data at the beginning and end of the study reach (Fig. 2-4). Discharge was measured in the main river channel at five locations; at the two gauged sites on the main channel and three additional sites between them. Discharge was also measured in Fish Creek, a tributary to the Gallatin River (Fig. 2-4). Head gates at the diversion ditches were instrumented with TruTrack data loggers at five locations (Fig. 2-4). Discharge at 12 diversions along the study reach, including the five instrumented sites, were measured by the water commissioner using a combination of flumes and direct discharge measurements. Specific conductance was measured regularly in the river at Axtell Bridge, Fish Creek at River Road, 3 sites on the Elk Grove Slough, and two additional spring features to the west

of the river, near Axtell Bridge and River Road (Fig. 3-2). River specific conductance was also measured in the river at piezometer locations (Fig. 3-3) during piezometer sampling events. Data loggers also collected stage and temperature at two sites on the Elk Grove Slough, near Gooch Hill Rd. and an emerging spring channel south of the Elk Grove Development (Fig. 2-4).

### Discharge

Discharge measurements at all six sites along the study reach were made during three specific events for the purpose of identifying gaining and losing reaches of the stream (Tables 3-2, 3-3, and 3-4; Fig. 2-4). Surface water inflows and outflows from the main channel were also measured to help estimate the volume of water exchanged with the aquifer (Tables 3-2, 3-3, 3-4, and 3-5). Spreadsheets which contain the discharge calculations and associated information are contained in the report to the DNRC (Custer and Schaffer, 2009) and also available at the Montana State University Earth Science Department.

Table 3-2. Discharge measurements from 11/21/05 and 11/23/05.

Reach	Upstream discharge (cfs)			Downstream discharge (cfs)			Change in mean discharge (cfs)	Tributary inflow (cfs)			Diversions (cfs)	Seepage (cfs)
	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>		1	Q <sub>2</sub>	Q <sub>x̄</sub>		
1	358	343	351	373	380	377	26	14	18	16	0	10
2	373	380	377	388	386	388	11	0			0	11
3	390	Na	390	414	384	399	9	0			0	9
4	414	384	399	399	402	400	1	0			0	1

Table 3-3. Discharge measurements from 7/12 and 7/13 2006.

Reach	Upstream discharge (cfs)			Downstream discharge (cfs)			Change in mean discharge (cfs)	Tributary inflow (cfs)			Diversions (cfs)	Seepage (cfs)
	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>		Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>		
1	606	629	617	505	503	504	-114	15	17	16	178	49
2	505	503	504	520	Na	520	16	0			18	34
3	558	576	567	424	410	417	-151	0			115	-36
4	424	410	417	394	424	409	-8	0			15	7

Table 3-4. Discharge measurements from 8/18/ and 8/19 2006. \* Discharge estimated based on stage. Stage on Fish Creek 12:00 8/18/06 = 0.31. Stage at Fish Creek on 7/12/06 was 0.38', measured discharge equals 15.8 CFS. This is a likely a low and conservative estimate.

Reach	Upstream discharge (cfs)			Downstream discharge (cfs)			Change in mean discharge (cfs)	Tributary inflow (cfs)			Diversions (cfs)	Seepage (cfs)
	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>	Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>		Q <sub>1</sub>	Q <sub>2</sub>	Q <sub>x̄</sub>		
1	353	352	352	309	314	311	-41	16*	Na	16	99	42
2	309	314	311	277	277	277	-34	0			10	-24
3	277*	na	277	202	206	204	-73	0			77	4
4	202	206	204	249	254	252	48	0			0	48

Table 3-5. Irrigation withdrawals as reported by the water commissioner, George Alberda, for the time periods corresponding to main channel discharge measurements. The conversion used for miner's inches to cubic feet per second is, 0.025 cfs = 1 miner's inch

DITCH NAME	INSTRUM.	REACH	Nov. 21 2005		July 12 2006		Aug. 18 2006	
			miner's inches	cfs	miner's inches	cfs	miner's inches	cfs
Gabreil Ditch	No	1	0	0	0	0	0	0
Lower Middle Creek Supply Ditch	Yes	1	0	0	1384	34.6	1950	48.6
Low Line Canal	No	1	0	0	3400	85.0	0	0
Kughen Ditch	No	1	0	0	2351	58.8	2024	50.6
<b>TOTAL REACH 1</b>	-	<b>1</b>	<b>0</b>	<b>0</b>	<b>7135</b>	<b>178.4</b>	<b>3974</b>	<b>99.4</b>
Beck and Border Ditch	Yes	2	0	0	705	17.6	279	7.0
Hathaway Pump Site	No	2	0	0	0	0.0	0	0
<b>TOTAL REACH 2</b>	-	<b>2</b>	<b>0</b>	<b>0</b>	<b>705</b>	<b>17.6</b>	<b>279</b>	<b>7.0</b>
Spain Ferris Ditch	Yes	3	0	0	826	20.7	108	2.7
Mammoth Ditch	Yes	3	0	0	1942	48.6	1808	45.2
Owenhouse Ditch	Yes	3	0	0	504	12.6	738	18.45
Valley Ditch	Yes	4	0	0	1343	33.6	548	13.7
<b>TOTAL REACH 3</b>	-	<b>3</b>	<b>0</b>	<b>0</b>	<b>4615</b>	<b>115.4</b>	<b>3202</b>	<b>80.1</b>
Knadler Ditch	No	4	0	0	0	0.0	0	0
Bopp-McMullough	No	4	0	0	594	14.9	0	0
<b>TOTAL REACH 4</b>	-	<b>4</b>	<b>0</b>	<b>0</b>	<b>594</b>	<b>14.9</b>	<b>0</b>	<b>0</b>

#### Surface Water Specific Conductance

Fifty five measurements of specific conductance were made from 8 locations between the 3/31/06 and 7/27/06. These measurements were collected from the Gallatin River, spring features, and tributaries to the river (Fig. 3-2). The range of observed values at individual locations varied between sites. Some locations remained relatively stable over time while other locations fluctuated. The greatest observed fluctuation occurred in Dry Creek Spring @ Blackwood Rd and was 18 times larger than the most stable fluctuation at the Stone House Spring (Table 3-6).

Table 3-6. Descriptive statistics of specific conductance ( $\mu\text{S}$ ) values measured in surface water features. The table below is sorted by the range of observed values from highest to lowest.

ID	Description	Mean	Range	Min	Max	Start	End	#
SW4	Dry Creek Spring @ Blackwood Rd.	452	277	178	455	3/31/06	7/27/06	7
SW1	Gallatin River at Axtell Bridge Fishing Access	213	190	131	321	3/16/06	7/27/06	11
SW7	Wildcat Creek at River Rd.	249	181	178	359	3/31/06	6/1/06	4
SW6	Dry Creek @ Cobb Hill Rd.	346	59	316	375	7/17/06	7/27/06	2
SW5	Fish Creek at Axtell Ancency Rd.	343	57	317	374	3/16/06	7/27/06	11
SW11	Axtell Bridge Slough	381	23	370	393	3/16/06	7/27/06	11
SW9	Elk Grove Slough @ Violet Rd	459	18	450	468	7/17/06	7/27/06	2
SW10	Stone House Spring	429	16	422	438	3/16/06	7/17/06	7

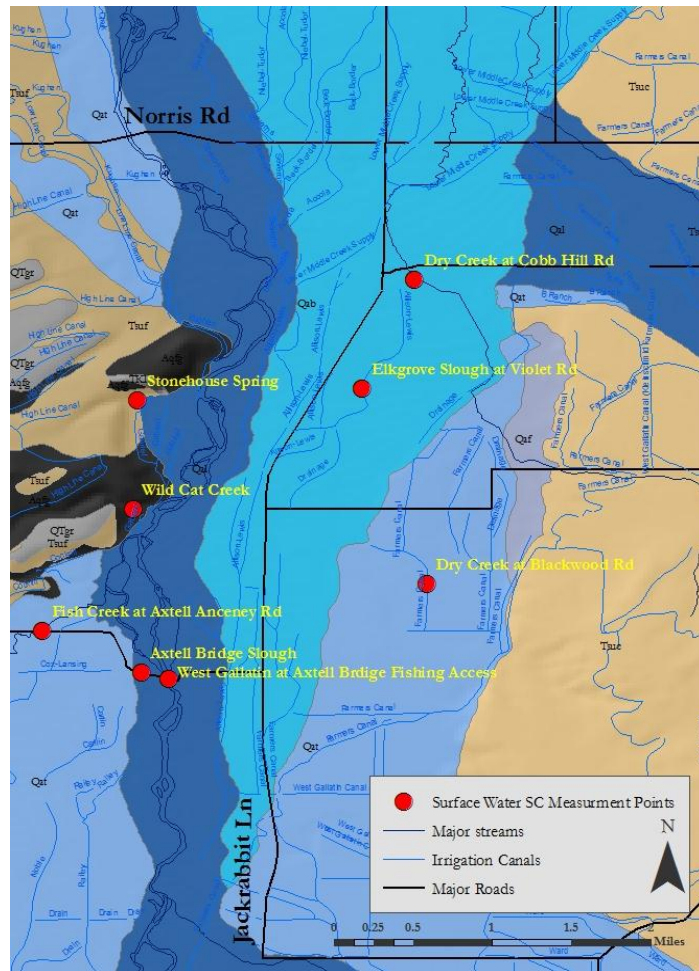


Figure 3-2. Surface water specific conductance measurement points near Four Corners, Montana. The base layer for this map is the Bozeman 1:100,000 MBMG geologic map of Bozeman (Vuke, et. al. 2002). Key for geologic units located in Figure 1-2.

### Streambed Piezometers

Sixty-one streambed piezometers were installed in the Gallatin River (Fig. 3-3). These piezometers had openings at 1.31 to 3.97 feet below the surface of the streambed. Vertical hydraulic gradients were measured at the piezometers from 7/17/06 to 11/10/06. The data used in this analysis and extensive specific conductance and temperature data not used in the analysis is available in the report to the DNRC (Custer and Schaffer, 2009), under the Four Corner's Streambed Database and is also available at the Montana State Earth Science Department.

#### Streambed piezometer locations

The 61 piezometers were assembled into 21 sets located in pools (Fig. 3-3). A complete set had piezometers located at the head, middle, and tail of each pool. However, because of poor placement or missing piezometers not all 21 sets were complete for all measurement periods (Table 3-7, Appendix A). Of all the installed piezometers, 18 were at the head of the pools, 22 at the middle of the pools, and 21 at the tail of the pools. Fifteen of the 21 sets were complete through the August 2006. Six sets remained complete through November. Four sets had two measurements taken in August.

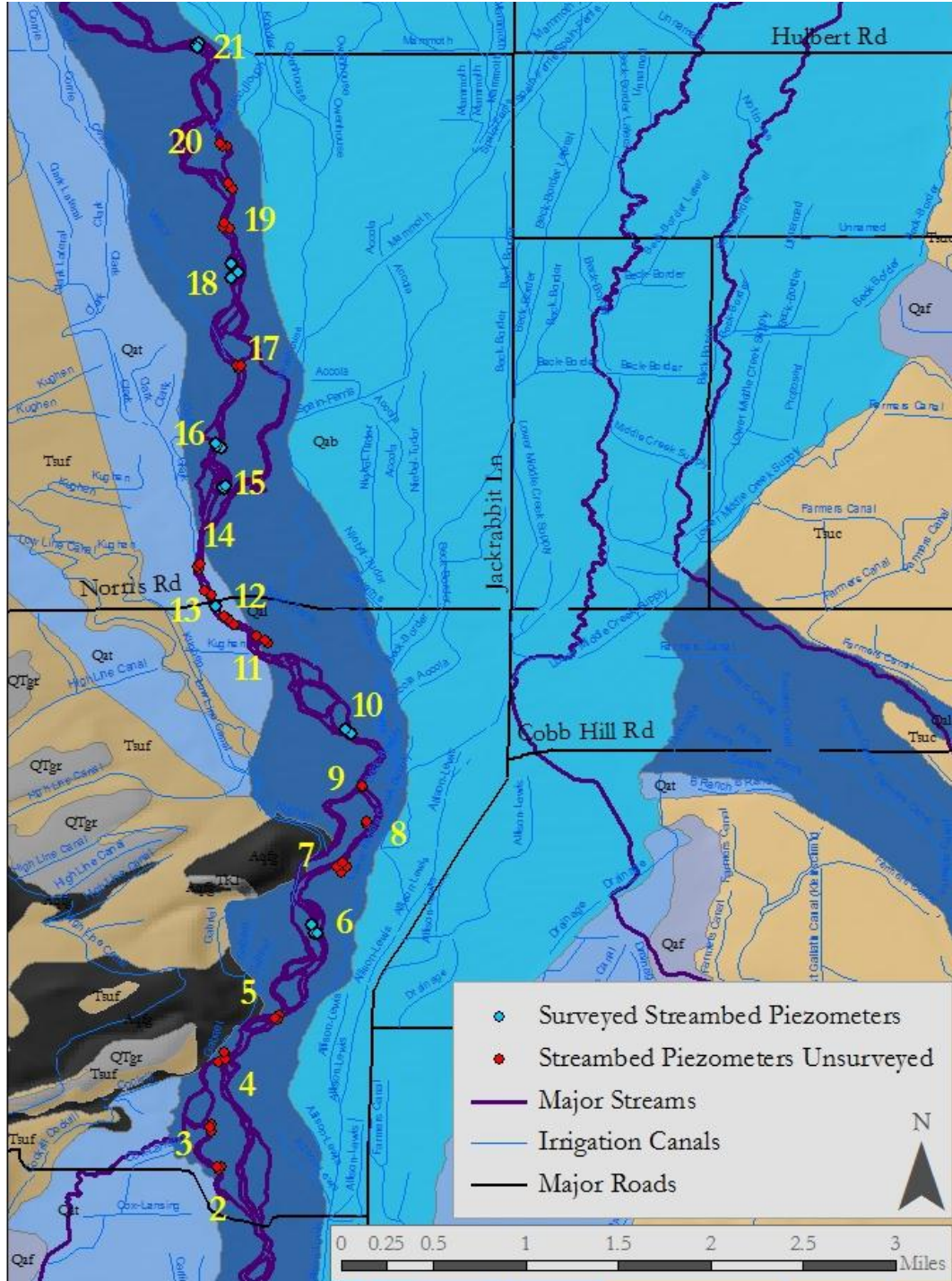


Figure 3-3. Streambed piezometer sets along the West Gallatin River. Sixty five individual piezometers were arranged into 21 sets (numbers 2-22) along the 6.2 mile reach of river. Blue piezometers were surveyed using a precision grade GPS, red piezometers locations were located using a recreational grade GPS unit. The base layer for this map is the Bozeman 1:100,000 MBMG geologic map of Bozeman (Vuke, et. al. 2002). Key to geologic features in Figure 1-2.

### Vertical Hydraulic Gradients

Vertical hydraulic gradients measured at piezometers fluctuated over time. Some gradients oscillated between positive and negative. The range of fluctuation varied from piezometer to piezometer (Table 3-8, Appendix A).

### Specific Conductance

Specific conductance measured in the streambed piezometers varied between piezometers. Values also varied over time at individual piezometers. The range of variation over time at the individual piezometers differed between piezometers (3-9, Appendix A). All measurements are available in data base associated with the report to the DNRC (Custer and Schaffer et. al., 2009) which is also available at the MSU Earth Science Department in Bozeman.

## DISCUSSION

Measurement Uncertainty and the Assessment of Ground-  
Water Discharge and Aquifer Recharge Zones

Assessing ground-water upwelling and surface-water downwelling zones was difficult using only discharge measurements. Seepage estimates from discharge measurements could be ambiguous because of the uncertainty associated with each discharge measurements' accuracy and the compounded uncertainty which occurred when multiple discharge measurements were used for comparison. Many discharge measurements were required to account for the volume of surface water diverted for irrigation. Twelve canals (Table 3-6) diverted over 50% of the incoming surface water (Table 4-1) and needed to be accounted for in seepage calculations (Eq. 2-1).

Table 4-1. Ground-water seepage and discharge values along the entire six miles study reach of the West Gallatin River near Four Corners.

Date	Ground-water Seepage (% downstream)	Upstream Discharge	Downstream Discharge	Surface Water Diversions (% upstream)	Surface Water Contributions (% downstream)
Nov. 21&23 2005	+34 cfs (8%)	351 cfs	400 cfs	0 cfs (0%)	16 cfs (4%)
July 12&13 2006	+55 cfs (15%)	617 cfs	409 cfs	326 cfs (53%)	16 cfs (4%)
Aug. 18&19 2006	+71 cfs (28%)	352 cfs	252 cfs	187 cfs (53%)	16 cfs (6%)

The uncertainty for individual discharge measurements, including the canals, was assumed to be plus or minus 5% of the discharge value. This uncertainty value is based upon accuracy estimates of discharge established by the USGS (Rantz, 1982). The total uncertainty for a seepage value was the result of summing 5% of each individual discharge measurement

used in the seepage calculation including the canals. As a result the cumulative uncertainty from all the discharge values required for a calculation was often greater than the seepage value and determining if a stream was gaining or losing water to the ground water system was ambiguous (Table 4-2). Seepage values for the study reaches only exceeded the cumulative uncertainty of discharge measurements in August (Table 4-2) when the river discharge was small, few irrigation diversions were occurring, and seepage values were greatest (Tables 4-1).

Table 4-2. Comparative table of calculated seepage values (cfs) and the cumulative uncertainty of 5% for each discharge measurement used in the seepage calculation (cfs). Measurements with seepage values greater than the cumulative uncertainty are listed in blue. Measurements with seepage values less than the cumulative uncertainty are listed in red. Positive values represent seepage from the aquifer to the river. Negative values represent seepage from the river to the aquifer. The total reach represents seepage calculated by summing values from all sub reaches (Fig. 2-4, Table 3-3, 3-4, and 3-5).

	November 21 & 23 2005		July 12 & 13 2006		Aug 18 & 19 2006	
	Seepage	Uncertainty	Seepage	Uncertainty	Seepage	Uncertainty
Total Reach	31	38	54	68	70	40
Sub Reach 1	10	37	49	66	42	39
Sub Reach 2	11	38	34	52	-24	30
Sub Reach 3	9	39	-36	55	4	28
Sub Reach 4	1	40	7	42	48	23

To account for surface water diversions in a seepage calculation, discharge measurements were made at the same time canals were measured by the water commissioner. Relying on the periodic measurements of diversions introduced several potential sources of error into the seepage calculation. Diversions to the canals could have changed at the headgates between the time of the commissioner's measurement and the

stream discharge measurement. Flumes used to estimate diversion volumes may not have been calibrated and therefore the values reported from the commissioner may have been inaccurate. Many canals along the study reach were capable of diverting volumes of water greater than the seepage values (Tables 4-1 and 3-6). Failing to account for a single diversion could have resulted in reaches which gained ground water from the aquifer to be assessed as a reach which lost water to the aquifer or, a losing reach could have been assessed as a gaining reach.

Data from other sources helped in the assessment of gaining and losing reaches when the uncertainty which resulted from discharge measurements was greater than the seepage value. Vertical hydraulic gradients from streambed piezometers and ground-water hydrographs provided other lines of evidence that ground-water discharge or aquifer recharge was occurring. The comparison of streambed piezometer data to the seepage run data mixed two scales of measurement. The vertical hydraulic gradient data from the streambed piezometers measured the hydraulic gradients of the shallow streambed and the variation of shallow-flow paths in the streambed. However, the variation of measurements from the shallow streambed over the six mile study reach were useful for identifying larger zones of upwelling ground water from the aquifer and zones of downwelling surface water which recharged the aquifer. Ground-water hydrographs were also useful for identifying periods of aquifer recharge.

Ground-Water Discharge and Aquifer Recharge  
Determined by Streamflow Measurements

During all three seepage runs, the West Gallatin River was found to gain streamflow from ground-water discharge along the entire six mile study reach (Table 4-1, Fig. 4-1). In November 2005, ground-water discharge accounted for 8% (34 cfs) of the streamflow in the study reach (Table 4-1). However it should be noted this value was slightly less than the estimated cumulative uncertainty of all the discharge measurements used for the seepage calculation (Table 4-2). The volume of ground-water discharge to the stream increased from November 2005 to July 2006 by 33% (Table 4-1, Fig. 4-1). During July, ground-water discharge contributed 15% of the streamflow at the bottom of the study reach (Table 4-1). Later during the summer, in August, ground-water discharge continued to increase and contributed 28% of the streamflow, 70 cfs (Table 4-1, Fig. 4-1). Total ground-water discharge in August was greater than the estimated uncertainty (Table 4-2).

Ground-water discharge increased throughout the summer as irrigation diversion decreased (Fig. 4-1). This trend suggests summer streamflows may have been increased by seasonal aquifer recharge from irrigation which was temporarily stored in the aquifer. Ground-water discharge along the entire study reach increased by 69% from November to August. Irrigation diversions decreased by 43% from July to August while ground-water discharge to the stream increased by 30% (Table 4-1). This trend indicates that the effects of seasonal aquifer recharge from irrigation on streamflow are not instantaneous but that some storage of recharge water from irrigation occurs in the aquifer and that ground water is released later to the river which bolsters late season streamflows. The greatest volume of

ground-water discharge, 70 cfs, occurred in August after the peak of irrigation diversions in July (Table 4-2 Fig. 4-1). As the summer progressed from July to August, irrigation

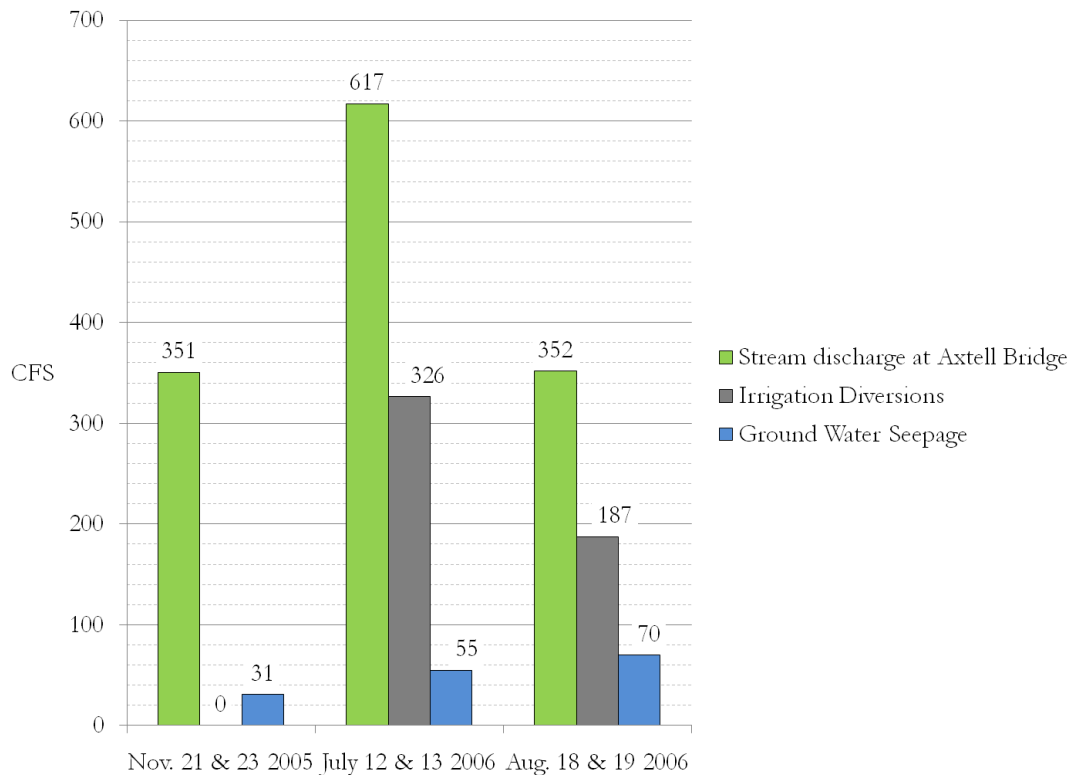


Figure 4-1. West Gallatin River discharge at Axtell Bridge Fishing Access, Irrigation diversions along the 6 mile study reach, and ground-water seepage for three seepage measurements from the entire study reach (Table 4-2).

withdrawals decreased and ground-water discharge increased (Fig. 4-1). The increase in ground-water discharge to the stream during the summer indicates that some ground-water storage occurs in the aquifer locally along the West Gallatin River which bolstered late summer streamflow.

### Ground-Water Discharge and Aquifer Recharge in Sub-Reaches

Ground-water discharge did not occur ubiquitously along the six mile study reach (Fig. 4-2). Discharge measurements made within the reach resulted in four sub-reaches for the comparison of ground-water discharge and aquifer recharge from the stream (Fig. 2-4). Seepage values from the sub-reaches revealed a pattern of gains and losses which changed along the stream reach and over time (Fig. 4-2). The pattern of ground-water discharge in sub-reaches was simplest in November 2005 and became more complex during the summer of 2006 in July and August. During the summer 2006, stream reaches which lost water to the ground-water system occurred intermittently in Reaches Two and Three (Fig. 4-2). Reaches One and Four gained ground water during all seepage runs. Ground-water discharge in Reach Two initially increased but in August, this reach lost water to the ground-water system (Fig. 4-2). Reach Three switched from gaining ground water to recharging the aquifer from November to July and returned to gaining ground water in August (Fig. 4-2).

The effects of seasonal aquifer recharge on streamflow occurred locally within the study reach and resulted in locally varied ground-water discharge to the stream. In November 2005, ground-water discharge to the stream was relatively uniform compared to ground-water discharge during the summer of 2006 (Fig. 4-2). The key difference between these two time periods is that, aquifer recharge was actively occurring in July and August however in November the hydrologic system was relatively static with no irrigation occurring (Table 4-1) which could recharge the aquifer (Fig. 4-2). In November no irrigation was actively occurring (Table 4-1) and ground-water levels were steadily declining after the

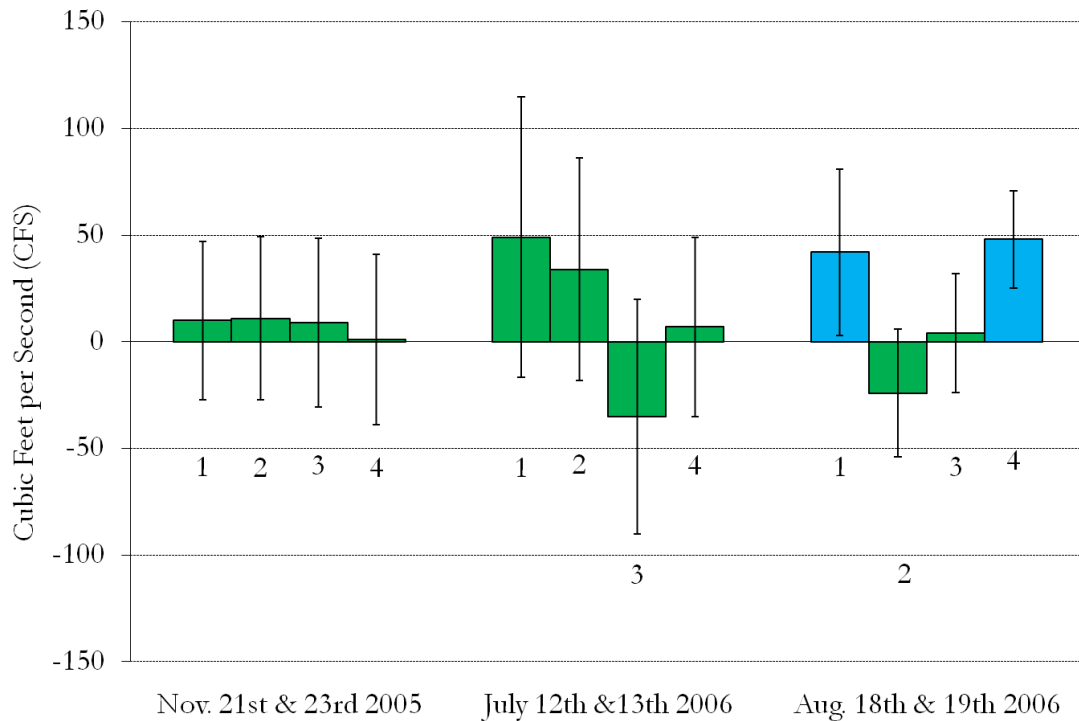


Figure 4-2. Ground-water seepage associated with aquifer discharge and recharge. Seepage values are calculated from discharge measurements along four sub-reaches within the six mile study reach. The error bars represents a estimated cumulative error of plus and minus 5% for each discharge value. Blue bars represent seepage values which are positive and the range of uncertainty also indicates positive seepage. Green bars represent seepage values with uncertainty ranges which encompass both positive and negative seepage values (Fig. 2-3 shows reach locations).

seasonal recharge from the previous irrigation season (Custer and Schaffer, 2009). In July and August, seasonal ground-water recharge was actively occurring from effluent streams and irrigation activities and ground-water levels were fluctuating (Custer and Schaffer, 2009). During the summer months irrigation withdrawals diverted over 50% of the incoming surface water along the study reach. However these diversions did not occur uniformly along the reach. For instance in August, irrigation diversions were concentrated in Reaches One and Three, while little to no irrigation withdrawals occurred in Reaches Two and Four (Fig.

3-5). As a result of the variable aquifer recharge occurring and elevated water levels in the aquifer, ground-water discharge to the stream increased and became more variable during July and August (Fig. 4-2).

During the irrigation season ground-water discharge varied from July to August. Ground-water discharge increased in Reaches Three and Four, and remained constant in Reach One (Fig. 4-2). The pattern of localized ground-water discharge in sub-reaches indicates that aquifer recharge from local irrigation activities likely contributed to streamflow. However the effects of aquifer recharge were not uniform. Specifically, increased ground-water discharge occurred later in Reach Four compared to Reach One (Fig. 4-2). During August, 69% of the seepage which contributed to streamflow at the study reaches' downstream end came from Reach 4 (Tables 4-1, 4-2, and Fig. 4-2). However in July only 2% of the streamflow was from ground-water discharge in Reach Four.

Ground-water discharge to the stream did not occur ubiquitously within the study area (Fig. 4-2). Intermittently, some sub-reaches were found to lose water to the ground-water system and provide aquifer recharge. Stream reaches Two and Three switched between gaining and losing streamflow in July and August, however their transition was not uniform (Fig. 4-2). The occurrence of these temporarily losing stream reaches indicates that aquifer recharge from the West Gallatin was intermittent during the summer months, changed locations, and possibly was the result of different factors. Many factors could have resulted in the occurrence of these intermittent losing reaches. The occurrence of these losing reaches is discussed later in the section on "Aquifer Recharge in Reach Three".

Ground-Water Discharge and Aquifer Recharge  
Assessed with Streambed Piezometer Data

Pool-riffle bedforms created shallow ground-water flow paths in the streambed. The pattern of shallow ground-water flow paths created by the channel forms was useful for identifying zones of upwelling ground water and downwelling surface water. The vertical hydraulic gradient data characterized the shallow flow system in the streambed. The shallow flow system in the streambed varied along the longitudinal profile of the study reach as a result of its' interaction with floodplain scale ground-water upwelling zones and aquifer recharge zones. This interaction between the two scales of flow paths was reflected in the variation of the vertical hydraulic gradients measured in piezometer sets.

Vertical hydraulic gradient values in the streambed piezometers varied with their position in a pool. At the head of pools the median vertical hydraulic gradient was positive and indicated upwelling in the shallow streambed, in the middle of pools the median vertical hydraulic gradient was neutral indicating horizontal flow in the shallow streambed, and at the tail of pools the median gradient was negative indicating downwelling in the shallow streambed (Fig. 4-3). Therefore a "typical" set with piezometers located at the head, middle, and tail of a pool, would have positive, neutral, and negative vertical hydraulic gradients which characterized the flow paths in the shallow streambed. However not all piezometer sets contained positive, negative, and neutral values which reflected the typical arrangement of flow paths in the shallow streambed. Some sets of piezometers contained entirely negative or positive values at all piezometer locations in a pool. This longitudinal variation of the vertical hydraulic gradients measured in pools was attributed to the interaction between the shallow flow system in the streambed and the floodplain scale upwelling and downwelling

zones. At piezometer sets where the pattern of shallow ground-water flow paths deviated from the “typical” variation described above, the shallow ground-water flow paths were interpreted to be interacting with the presence of ground-water upwelling from the aquifer or downwelling surface water which recharged the aquifer.

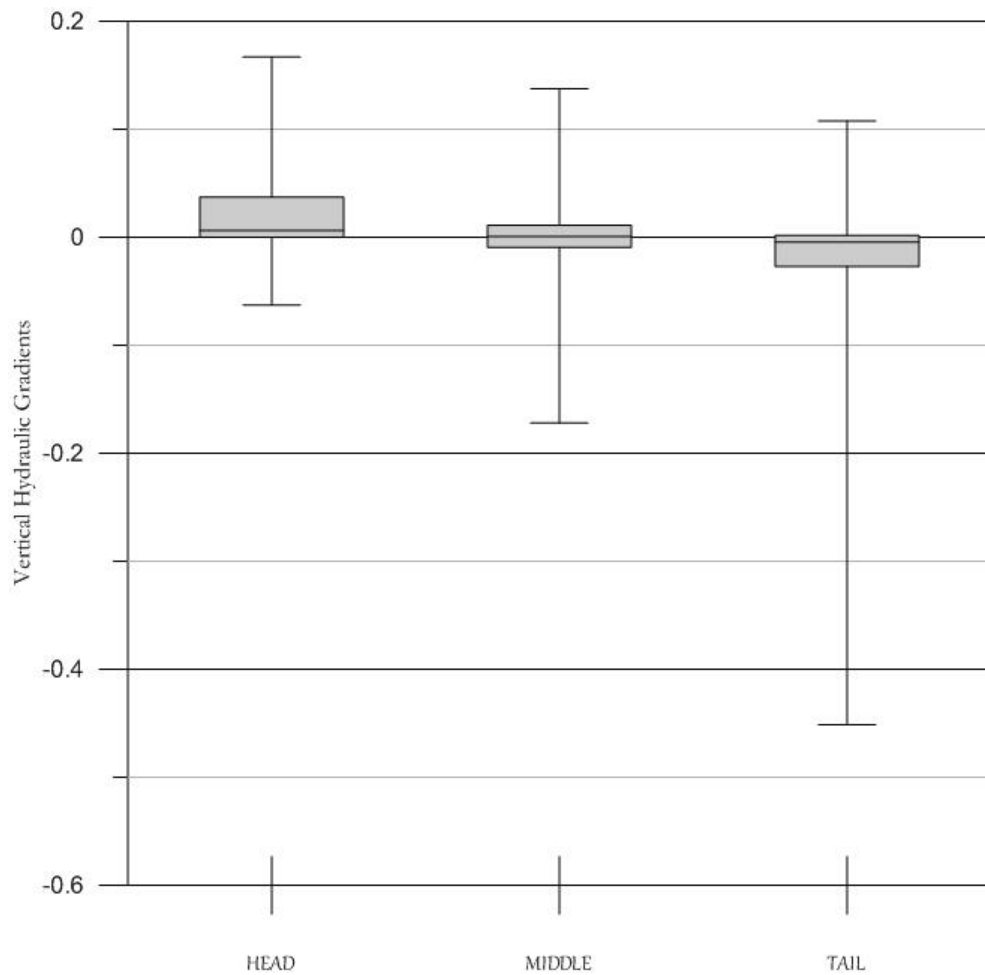


Figure 4-3. Comparative box plots displaying the inner quartile range of vertical hydraulic gradients at the head, middle, and tail of pools for all measurement periods. The center bar in the box plots displays the median value. The box sections represent the second and third quartiles. The whiskers represent the first and fourth quartiles. Outliers are not represented.

Three patterns of shallow-ground-water flow paths at pools were observed along the study reach (Fig. 4-4). The patterns were considered to be indicative of the interaction of the shallow flow paths with deeper and stronger ground-water upwelling zones in the aquifer. These interpretations were based upon other research of the interaction between shallow ground-water flow paths in a streambed and stronger flow paths from an aquifer (Storey et al., 2003; Malcom, 2003; Malard, 2002). The vertical hydraulic gradient values from piezometer sets were interpreted based on the following criteria;

1. Ground-water upwelling zone: The median vertical hydraulic gradient value was positive and the range of gradient values was small compared to other sets. At these locations upwelling ground water from the aquifer compressed the range of vertical hydraulic gradients in the shallow flow paths created by streambed topography and resulted in mostly positive gradients with less variation than other sets.
2. Surface water downwelling zone: The median vertical hydraulic gradient was negative and the range of gradients was the largest compared to other sets. In locations where vertical hydraulic gradients were mostly negative, the direction of flow was from the river into the aquifer with little to no pressure from upwelling ground water to resist the shallow flow paths created by the streambed topography. Mostly negative vertical hydraulic gradients were observed at these locations with greater variation than other sets.

3. Neutral surface and ground-water exchange zone: The median vertical hydraulic gradients were both positive and negative. Indicating the typical pattern of upwelling at the head of a pool and downwelling at the tail end of the pool.

The interpreted vertical hydraulic gradient data from the shallow streambed reveal a general pattern of ground-water flow to the stream. However, some locations within the study reach have concentrated sections of stronger ground-water upwelling zones and zones of downwelling surface water (Fig. 4-4). These concentrated zones of upwelling remained consistent during all the observation periods in July, August, and November 2006. A zone of downwelling surface water occurred in Reach Three, north of Norris Road, during all three observation periods (Fig. 4-5). The pattern of ground-water upwelling and surface-water downwelling depicted by interpreted piezometer sets corroborates the results of the seepage runs which indicate that the study reach gains flow from ground water in most locations with one exception. Within the study reach, a larger zone of downwelling surface water was present. A zone of downwelling that occurs within a gaining reach or upwelling which occurs in a losing reach has been documented elsewhere and has been described in other research as “hydrologic spiraling” (Poole 2008).

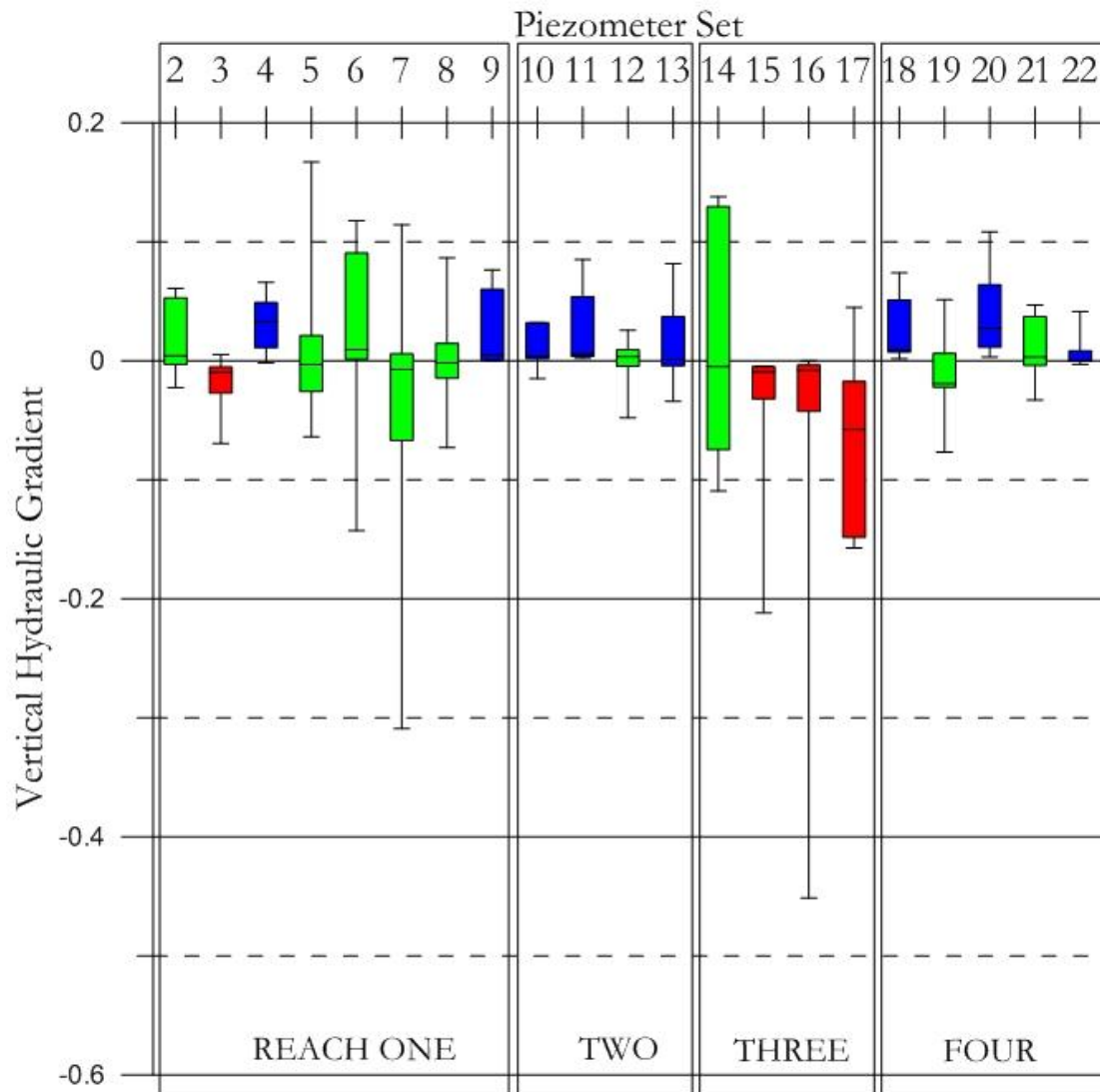


Figure 4-4. Interpretation of vertical hydraulic gradients, grouped by piezometer set, from observation in July, August and Nov 2006. Piezometer sets are arranged in downstream order from left to right. Numbers located along the top of the graph identify piezometer sets. Seepage reaches are defined by large clear rectangles. Colors represent the interpreted surface and ground-water exchanges described previously; green box plots represent neutral surface and ground-water exchange zones, blue piezometers represent upwelling ground-water exchange zones, and red box plots represent downwelling surface water zones. The center bar in the box plots displays the median value. The box sections represent the second and third quartiles. The whiskers represent the first and fourth quartiles. Outliers are not represented.

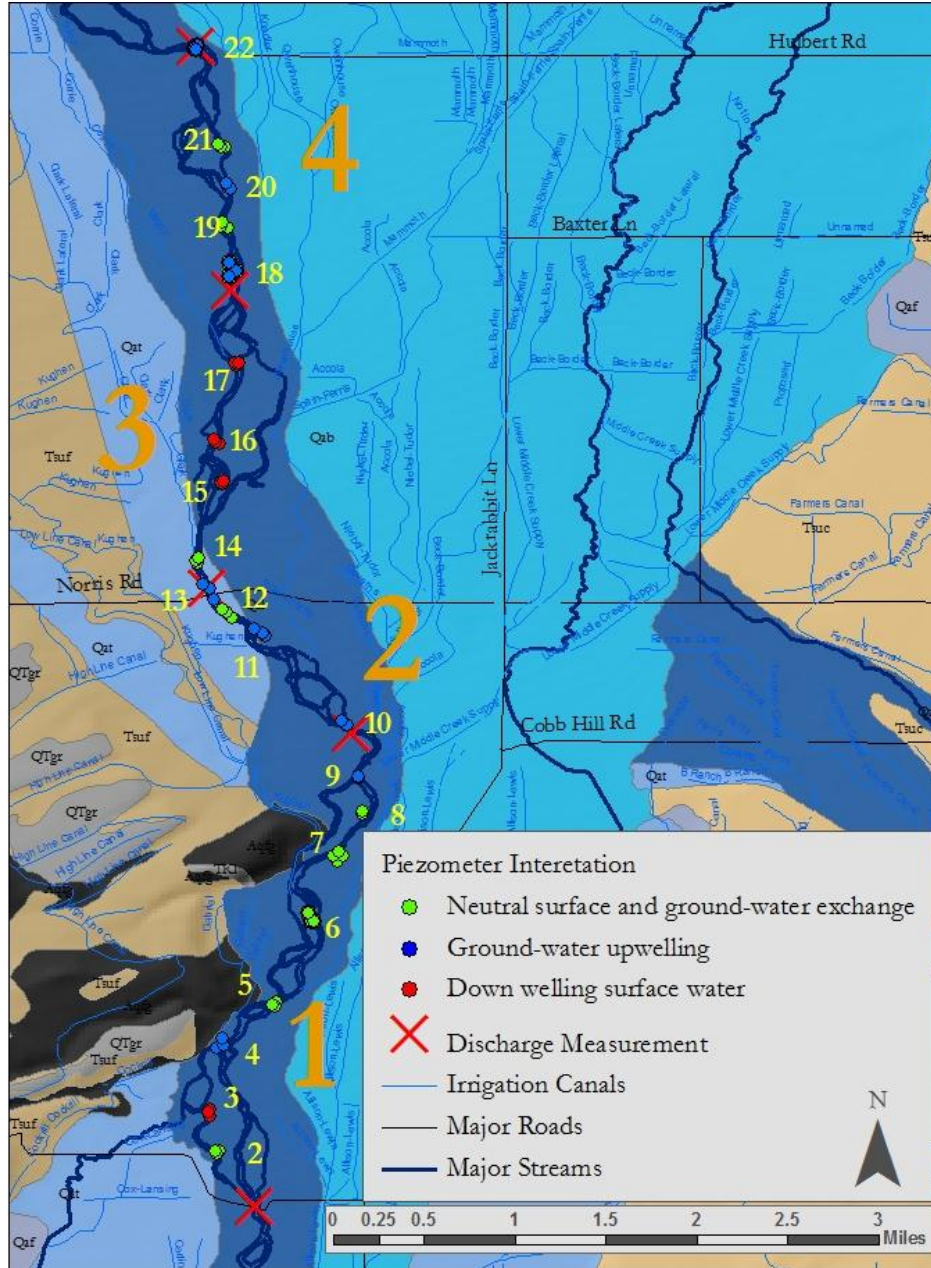


Figure 4-5. Map of the West Gallatin Alluvial Aquifer and the interpreted surface and ground-water interaction. Green points represent piezometer sets interpreted as neutral surface and ground-water exchange zones. Red points represent piezometer sets interpreted as downwelling surface water zones. Blue points represent piezometer sets interpreted as ground-water upwelling zones. Sun-reaches from for seepage measurements are between discharge measurement locations and identified labeled with large orange numbers. Piezometer set numbers are bright yellow. The base layer for this map is the Bozeman 1:100,000 MBMG geologic map of Bozeman (Vuke, et. al. 2002). Key for geologic units is located in Figure 1-2.

### Ground-Water Discharge Zones in Reaches One and Four

#### Reach One and Spring Discharge from the Floodplain

Spring channels discharged ground water to the main channel of the West Gallatin River. Water temperatures were recorded continuously for 3 days during September 2005 at the river's main channel and a spring which emerged in the floodplain (Fig.4-6). Surface water temperature in the spring channel showed very little diurnal temperature fluctuation compared to the main channel temperatures (Fig. 4-7). Spring temperatures varied between 11° and 12° Celsius, which approximated the average annual temperature for the area and is similar to average ground-water temperatures (Custer and Schaffer, 2009). The lack of diurnal fluctuation in the spring channel compared to the main channel is likely a function of abundant ground water discharge emerging in the spring channel which buffered the spring's temperature from the effects of daily heating by the sun.

In the spring channel, a slight peak in diurnal temperature occurred routinely in the early morning, 12-16 hours after the peak in the main channel (Fig. 4-7). The delayed peak suggests some surface water was mixing with the ground-water in the aquifer. However the minimal diurnal temperature fluctuation in the spring channel compared to the main channel indicates that, the spring channel discharged ground water from the aquifer in the floodplain to the main channel.

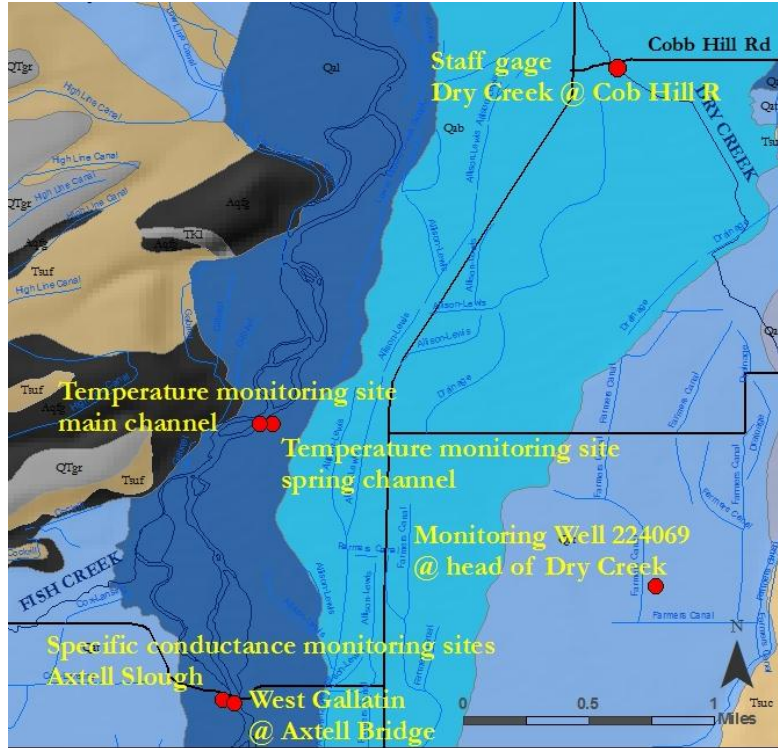


Figure 4-6. Location map of measurement points for spring features in Reach One. The base layer for this map is the Bozeman 1:100,000 MBMG geologic map of Bozeman (Vuke, et. al. 2002). Key for geologic units located in Figure 1-2.

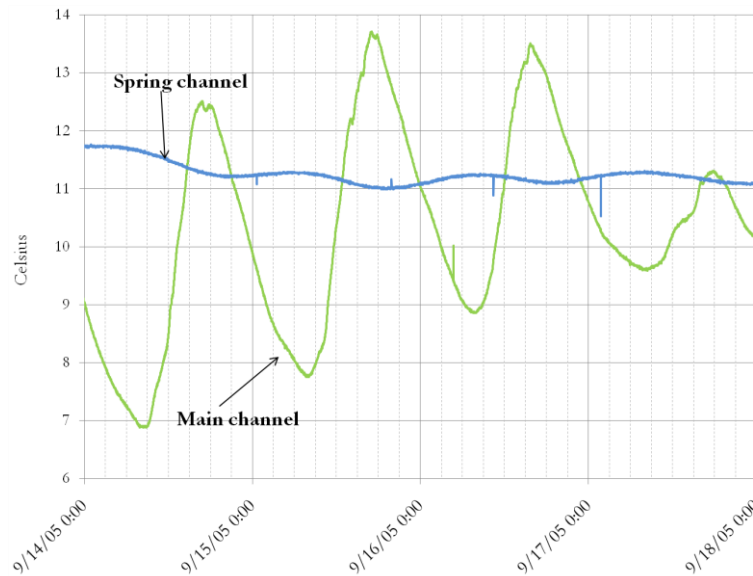


Figure 4-7. Surface-water temperature fluctuations from the main channel and a spring channel which emerged from the floodplain.

Specific electrical conductance was measured regularly at another spring channel in Reach One which contributed to streamflow (Fig. 4-6). This spring channel confluences with the main channel near the Axtell Bridge at Axtell Anceny Road. Conductance values remained relatively stable in the spring channel compared to the river's main channel (Fig. 4-8), despite the spring's close proximity to the river's main channel (Fig. 4-6). The consistent specific conductance values observed in the spring channel were similar to the average value for ground water, 381  $\mu\text{S per cm @ } 25^\circ \text{ C}$  (Fig. 4-25, Table 3-2 Appendix A). Throughout the season, specific conductance values only fluctuated by 20  $\mu\text{S per cm @ } 25^\circ \text{ C}$  in the spring channel and fluctuated by 190  $\mu\text{S per cm @ } 25^\circ \text{ C}$  in the main channel. The stability of specific electrical conductance values in the spring channel indicates that the source of water in the spring channel was mostly ground water and little surface water mixing occurred from the main channel with the spring through the ground-water system. This data suggest that spring features which emerged in the floodplain provided a mechanism to convey ground water from the aquifer directly into the main channel of the river.

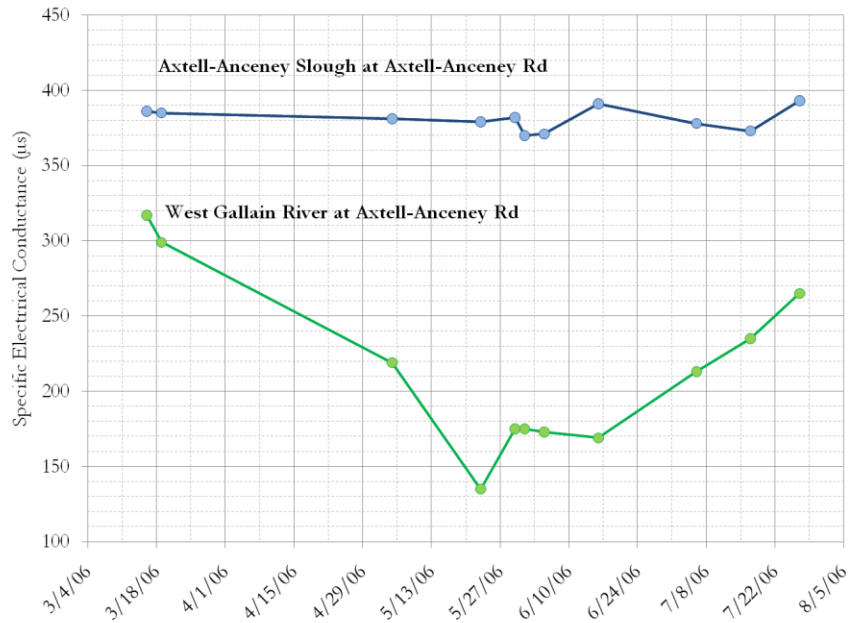


Figure 4-8. Specific electrical conductance values measured at Axtell-Ancney Road in the West Gallatin River and slough.

#### Enhanced Spring Features and Irrigation Drainage Ditches in Reach One

Dry Creek south of Blackwood Road has been altered to facilitate drainage so that soils which were previously too wet to farm could be used for crop production. This channel has been straightened, dredged, and perforated pipes have been installed which extend into the adjacent irrigated field to increase ground-water discharge into Dry Creek. This irrigation drainage ditch contributed streamflow to Dry Creek and eventually the Gallatin River by enhancing ground-water discharge from below the adjacent irrigated field. Well 224069, is in the irrigated field at the head of Dry Creek (Fig. 4-6). Water level data from this well shows ground-water recharge associated with irrigation and a corresponding rise in streamflow at the Dry Creek gauge near Cobb Hill Road (Fig. 4-9, 4-6). Ground-water levels began to rise in May, reached a maximum in July, and remained constant throughout the irrigation season until late September. However, surface water discharge in Dry Creek continued to increase

in July as ground-water elevations remained constant adjacent to the spring creek (Fig. 4-9).

The constant ground-water level and increased stream stage are the products of the manipulated channel which effectively discharged excess irrigation water and in turn increased surface water flows during the summer.

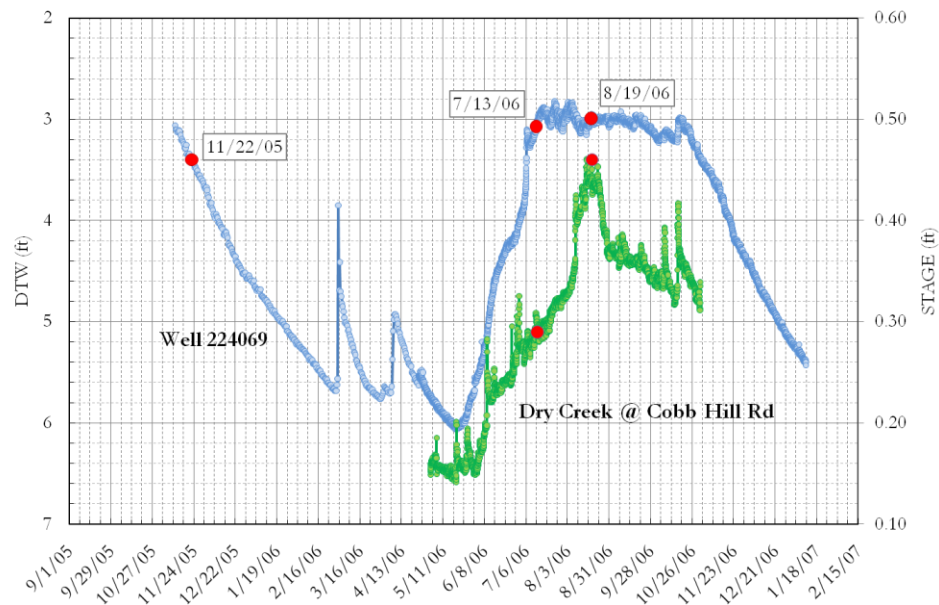


Figure 4-9. Depth to water hydrograph from Well 224069 and stage on Dry Creek at Cobb Hill Rd. Well 224069 is located in an irrigated field adjacent to the head of Dry Creek. Red dot denote dates of seepage runs conducted on the main channel of the West Gallatin River.

The Dry Creek system drains into the Middle Creek Supply Canal and not directly into the West Gallatin. However the relationship between stage in Dry Creek and the ground-water levels illustrates the general relationship between enhanced spring features designed to drain the aquifer and surface water discharge. Aquifer recharge from irrigation exceeds the storage capacity of the aquifer early in the irrigation season, irrigation activities continue to provide recharge water to the aquifer, which is quickly discharged through the enhanced spring features and provided a source of streamflow to surface water bodies. An

example of an enhanced spring feature which does drain directly to the main channel in the West Gallatin is Fish Creek (Fig. 2-4). Although no data is available for Fish Creek, it could be assumed that Fish Creek functioned similarly to Dry Creek and discharged excess irrigation water quickly from the ground-water system. Partly as a result of the enhanced spring features, ground-water discharge to the stream increased early during the irrigation season. Seepage measurements from Reach One indicate that ground-water discharge increased early and substantially in July (Fig. 4-2). Seepage increased quickly in Reach One and remained constant during the irrigation season compared to the eventual increase in ground-water discharge which occurred in Reach Four later in August (Fig. 4-2). It should also be noted that differences in aquifer widths may have also contributed to the differences in the timing of ground-water discharge in Reaches One and Four.

#### Reach Four and Delayed Irrigation Return Flow to the River

Ground-water discharge increased later in Reach Four compared to Reach One (Fig. 4-2). From July to August ground-water seepage increased 500%, from 8 to 48 cfs in Reach Four. The ground-water discharge from Reach Four accounted for 19 % of the streamflow in the West Gallatin at the lower end of the study reach. Its' contribution was 69% of all the ground-water discharge measured in the six mile study reach during the August seepage measurements and was a significant contribution to streamflow. In conjunction with the dramatic increase in ground-water discharge measured at Reach Four in August, near stream ground-water levels in Well 224111 indicate that ground-water levels rose between the two seepage measurement periods (Fig. 4-10).

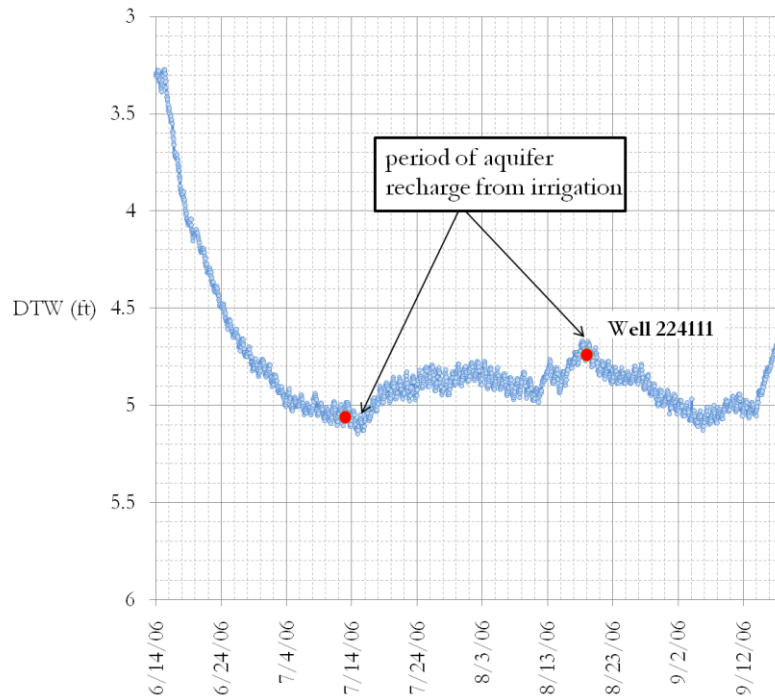


Figure 4-10. Ground-water hydrograph from Well 224111 located adjacent to the West Gallatin River (Fig. 2-4 and 3-1). Red dots on hydrographs indicate the time of seepage runs conducted on the main channel of the West Gallatin (Tables, 3-3, 3-4, and 3-5).

Well 224111 is in a non-irrigated field adjacent to the river, therefore the source of aquifer recharge at this location was not the infiltration of excess irrigation water locally (Fig. 3-1). However, irrigation activities did occur within 2 miles of the well which recharged the aquifer (Custer and Schaffer, 2009). Ground water levels increased below the irrigated fields as much as 10 feet during the irrigation season (Custer and Schaffer, 2009). The irrigation recharge which occurred in the vicinity could have resulted in the elevated ground-water levels observed in the nonirrigated area at Well 224111. Ultimately, the pulse of ground water from the distant irrigated areas contributed to streamflow later in the summer than in other reaches. Ground-water discharge related to irrigation return flow increased significantly from July to August (Fig. 4-2), likely as result of irrigation activities located two miles away from the river channel. As a result of the distant irrigation activities, ground-

water discharge from Reach Four provided a significant source of streamflow in the late summer (Fig. 4-2).

#### Aquifer Recharge Zone in Reach Three

A zone of downwelling surface water occurred in Reach Three within the river's main channel between piezometer sets 15 and 17 which recharged the aquifer (Fig. 4-4 and 4-5). The zone of downwelling surface water was significant in July 2006 when seepage estimates indicated a loss of 36 cfs within Reach Three (Fig. 4-2, Table 4-1). The volume of seepage lost from streamflow accounts for approximately 6% of the streamflow entering Reach Three in July (Fig. 4-2, Table 3-4). Aquifer recharge was also documented in streamside monitoring wells along Reach Three (Fig. 4-11). The aquifer recharge in these wells was associated with fluctuations in river stage (Fig. 4-12). Other evidence of aquifer recharge from the stream was also observed at piezometer sets 15 through 17 in Reach Three (Fig. 4-4, 4-5). The interpretation of data from streambed piezometers (Fig. 4-4), hydrographs (Fig. 4-12), and temperatures (Fig. 4-13) all indicate a zone of surface-water downwelling occurred north of Norris Road which recharged the aquifer. Additionally a comparison of surface-water elevations to ground-water elevations also indicated that a zone of downwelling occurred in Reach Three (Table 4-3). The comparison of water levels is discussed in more detail in the following section, "Comparison of Water-level Data in Downwelling Zone to Previous Studies".

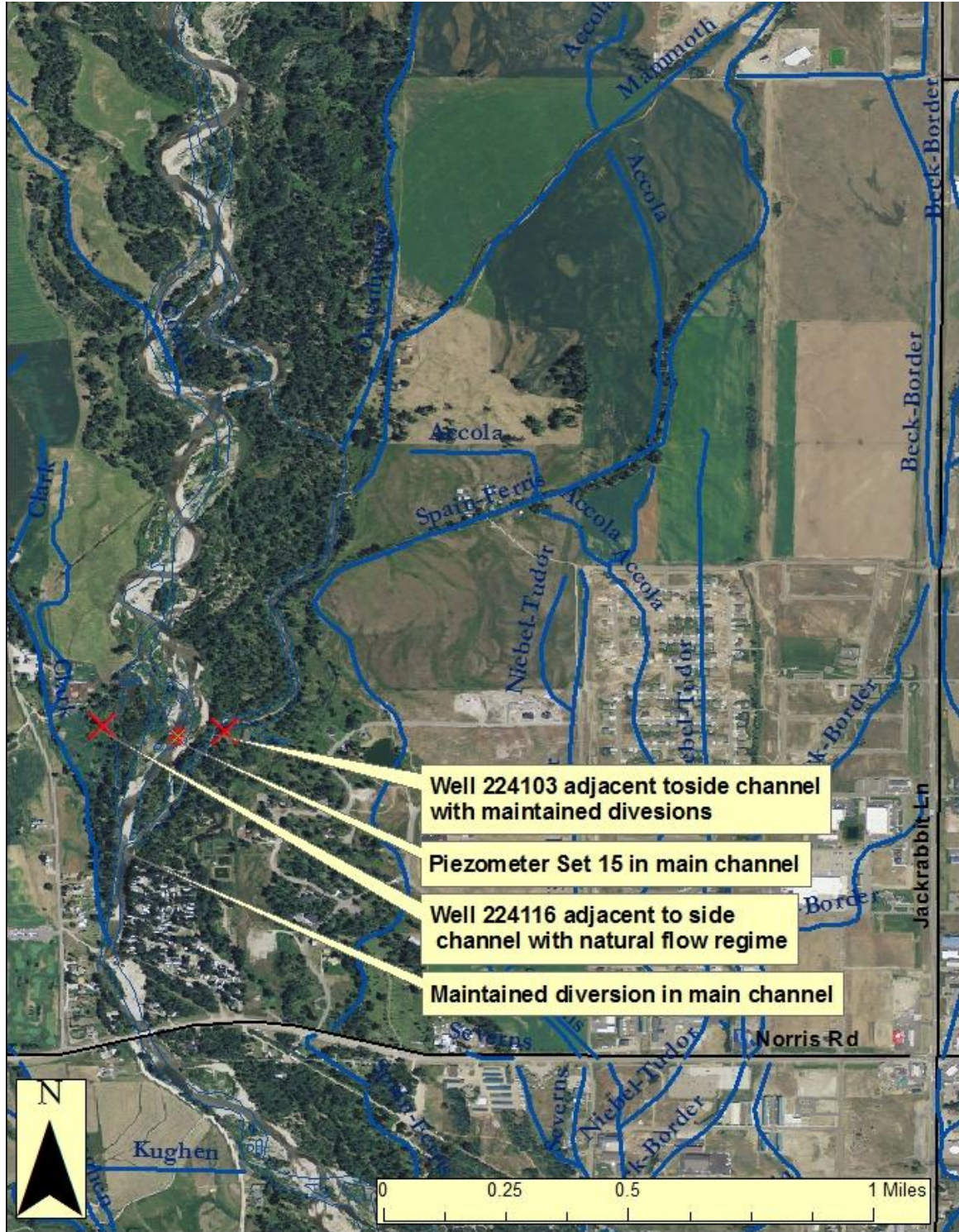


Figure 4-11. Location of wells and streambed piezometers used for relative water level comparisons downstream of Shed's Bridge and northwest of Four Corners. For reference the main channel and irrigation canals are presented with blue lines.

Ground-water recharge from the stream did not occur uniformly in streamside monitoring wells on the east and west side of the river (Fig. 4-11, 4-12). Water levels responded to changes in surface water stage independently during different time periods (Fig. 4-12). Ground-water levels in well 224103 (east bank) were affected by concrete blocks which served as a diversion in the river's main channel. This diversion continuously directed water into the eastern side channel for use in the Owenhouse and Mammoth Ditches (Fig. 4-11).

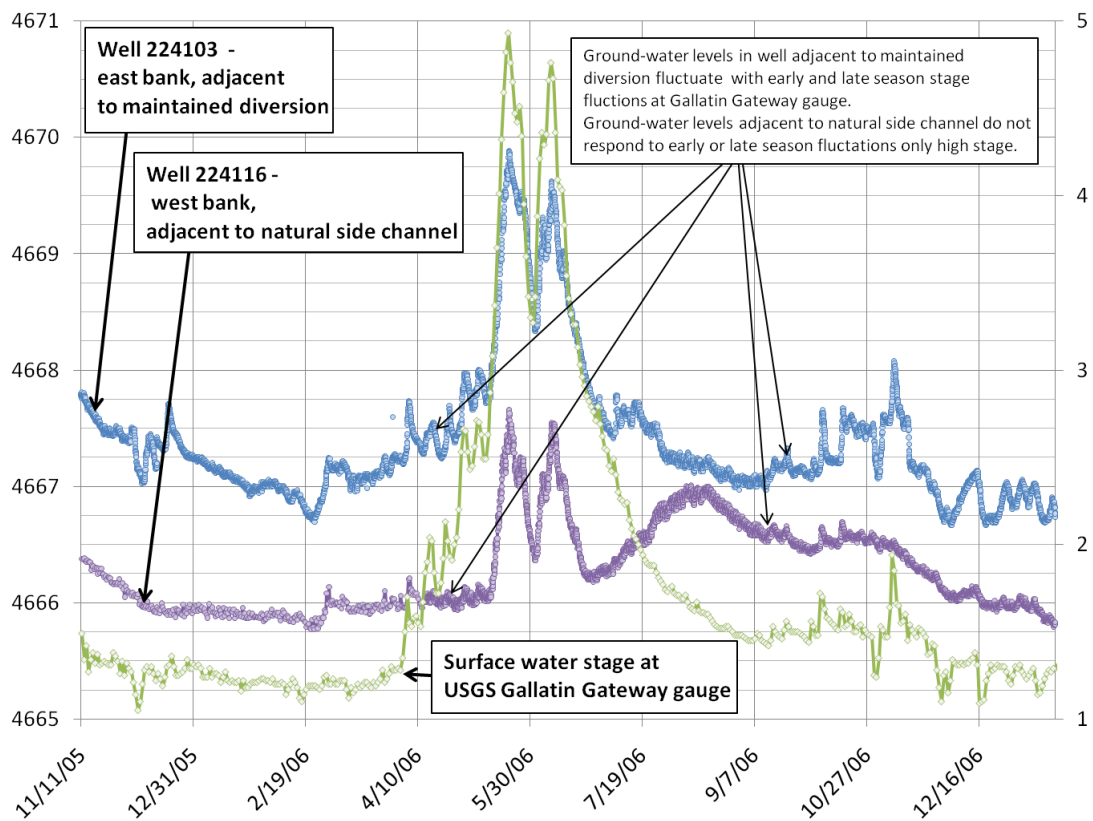


Figure 4-12. Ground-water elevations from Well 224103 located on the river's east bank and Well 224116 located on the rivers west bank (Fig. 3-1), stream stage recorded at the USGS Gallatin Gateway Gauge, and dates for water level comparisons to streambed piezometers. Ground-water elevations are located on the left axis and river stage on the right. The dates for relative water level comparisons are marked with red circles.

As a result of the continuously maintained diversion, surface-water downwelling continuously occurred in the eastern side channel because surface water was continually routed from the main channel, into the side channel, above the water table, which then seeped through the channel bottom, and recharged the aquifer (Fig. 4-12). Well 224103, located adjacent to the channel with the maintained diversion, began responding to fluctuations in stream stage during April (Fig. 4-12). On the opposite side of the river in Well 224116, adjacent to the unmaintained side channel (Fig. 4-11), ground-water levels did not respond to the initial fluctuations in stage (Fig. 4-12). However once stream stage increased beyond 2.5 ft at the USGS gauge, ground-water levels in this well responded to surface-water levels closely indicating that the western side channel had become inundated with flood water and was recharging the aquifer on the west bank (Fig. 4-12). Later in the season during September, ground-water levels in the well adjacent to the maintained side channel (well 224103) responded immediately to late season stage fluctuations (Fig. 4-12). However in the unmaintained side channel with a “natural” flow regime, well 224116 showed minimal responses to the late season fluctuations in stage, indicating that the side channel was no longer inundated with surface water (Fig. 4-12).

Ground-water levels adjacent to the western unmaintained channel with a “natural” flow regime, showed little response to early or the late season stage fluctuations. The muted response at well 224116 to stream stage indicates that the aquifer on the west bank did not receive direct recharge from the early and late season streamflow rises when the stage was below 2.5 feet at the USGS gauge in Gallatin Gateway. Although the wells on both sides of the river received recharge from the stream at some point during the season, they received recharge for different periods of time as a result of the maintained surface water diversion.

The diversion continued to direct water at lower stream stages into the eastern side channel when the western side channel was dry. As a result, the concrete blocks continuously directed water into the eastern side channel and above the aquifer's water table and increased aquifer recharge compared to the western channel which was not continually inundated with surface water.

#### Temperature Indications of Aquifer Recharge in Maintained Side Channel

Ground-water temperatures from Well 224103, on the Stream's east bank adjacent to the side channel with the maintained diversion (Fig. 4-11), also indicated that aquifer recharge occurred from the river during the study period. When aquifer recharge began in May at Well 224103 (Fig. 4-12), the surface water temperature was slightly warmer than the ground-water temperature (Fig. 4-13). In response to the infiltration of relatively warm surface water, ground-water temperatures began to rise during this time (Fig. 4-13). The increase in ground-water temperature also coincides with an increase in ground-water levels and stage which both increased sharply on May 10 (Fig. 4-12). The rise in water levels indicates that the river was actively recharging the aquifer during this period. During the period of warmer surface water temperatures, ground-water temperatures continued to increase from the infiltration of warmer surface water which transported heat into the aquifer. This trend continued until August 25<sup>th</sup>. Once the surface water cooled below the ground water temperature in late August, ground-water temperatures began to decline in response to the continued infiltration of cooler surface water (Fig 4-13). The relationship between ground and surface-water temperatures suggest that aquifer recharge occurred

consistently at Well 224103 in the side channel with the maintained diversions, even after surface water elevations had decreased.

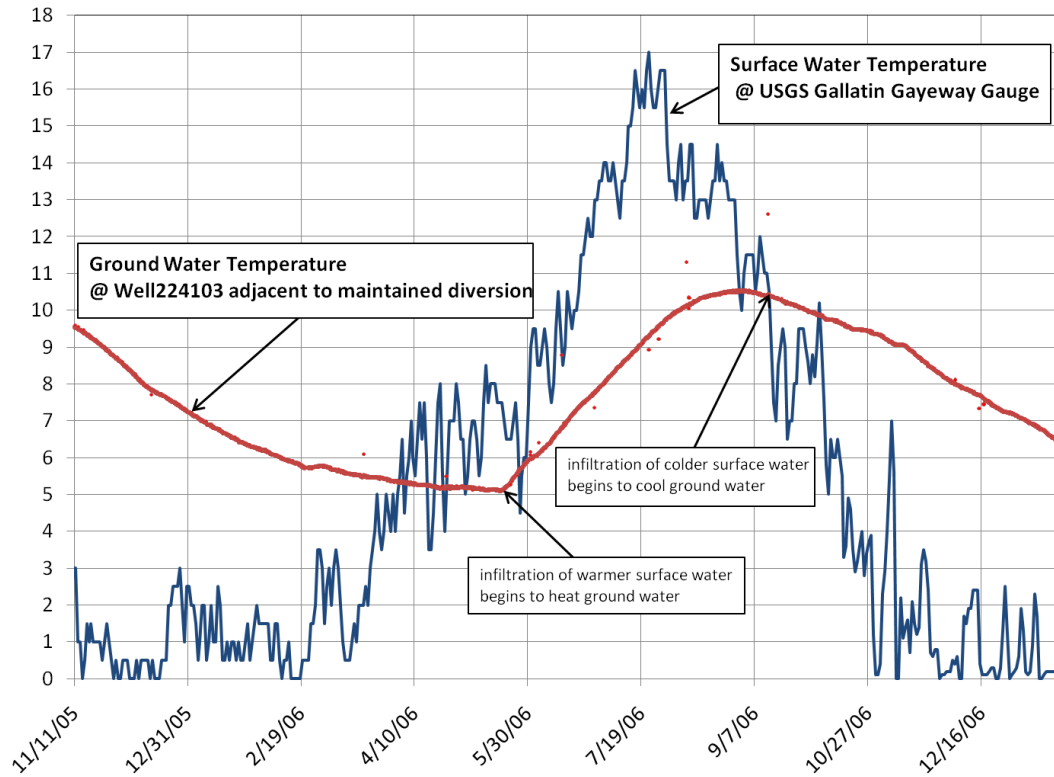


Figure 4-13. Ground-water elevation and temperature (Celsius, right axis) from Well 224103 compared to surface water temperature measured at the USGS gauge in Gallatin Gateway.

#### Comparison of Water-Level Data in Aquifer Recharge Zone to Previous Studies

Water level elevations were compared between surface water levels in the main channel, streambed piezometers, and wells north of Norris Road in Reach Three (Fig. 4-11). The wells used for this comparison were on the east and west edge of the anabranching channel system along side channels to the river. Well 224103, on the river's west bank, was adjacent to an ephemeral side channel (Fig 4-11). Well 224116, on the river's east bank, was

adjacent to a channel with a maintained diversion from the river which is used to direct water to the Mammoth and Owenhouse Ditches (Fig. 4-11). The comparison of water levels indicates that surface water downwelling occurred north of Norris Road (Table 4-12).

Ground-water elevations were as much as 1.58 feet below surface water elevations. Other evidence of aquifer recharge from the stream was also observed in Reach Three which was previously discussed (Fig. 4-4, 4-5). The interpretation of data from streambed piezometers (Fig. 4-4), hydrographs (Fig. 4-12), and temperatures (Fig. 4-13) all indicate a zone of surface water downwelling occurred north of Norris Road which recharged the aquifer.

Table 4-3. Water surface elevations measured from streambed piezometer Set 15 (Fig. 3-3) and wells located on the east and west banks. Values indicating ground-water flow to the stream are listed in blue and values indicating surface water flow to the aquifer are listed in red.

Date	Difference stream surface (ft)		Difference streambed (ft)		West Gallatin River Elevation		Ground-Water Elevation	
	East	West	East	West	Streambed	Water surface	East Bank (224103)	West Bank (224116)
July 18th 2006	1.11	0.07	1.25	0.21	4666.36	4666.50	4667.61	4666.57
August 24th 2006	-0.33	-0.61	-0.04	-0.32	4667.13	4667.42	4667.09	4666.81
November 16th 2006	-0.89	-1.58	-0.54	-1.23	4667.75	4668.10	4667.21	4666.52

Water level differences between the stream and aquifer were small (Table 4-3). The relative position of surface and ground-water levels fluctuated between surface water downwelling and ground-water upwelling from July to August. Consequently, potentiometric maps in the vicinity of the West Gallatin River near Four Corners require very small contour intervals to accurately depict the relationship between the stream and aquifer. Because the water levels fluctuate over time (Fig. 4-12), and the fluctuations of surface and ground-water

levels are greater than the difference between them (Fig. 4-12, Table 4-3), comparative water levels should always be measured simultaneously to accurately assess the surface and ground-water exchange in this area.

Because of the variable nature and small difference between surface and ground-water levels, the amount of data necessary to create precise potentiometric maps of influent and effluent reaches is a problem when addressing questions regarding the changes in the hydrologic system over time. The potentiometric maps produced by the 1950's USGS survey (Hackett et al., 1960) had little ground-water elevation data near the stream and no surface water elevation data to control the potentiometric lines near the river (Fig. 4-14). The influent and effluent reaches for the Hackett et al. study (1960) were determined from a coarse monitoring network using 40 foot ground-water contour intervals, limited ground-water data, and no surface water elevations. This scale of analysis could not accurately depict the complex surface and ground-water interactions given the small difference between water levels in the stream and aquifer or the variable relationship between them.

Ground-water elevations at wells 224116 and 224103 were between 4665 and 4670 feet above sea level during the water level comparisons for this study, which indicated surface water downwelling. These elevations are similar to or possibly even higher than the ground-water elevations from the 1950s potentiometric maps of the same area (Fig. 4-14, Table 4-3). However, the comparison of water surface elevations in this study (Table 4-3) indicate aquifer recharge, not ground-water discharge indicated by the 1950's map (Fig. 4-15). However, the comparison of the higher resolution data collected for this study to the data collected in the 1950's does not necessarily indicate that conditions have changed over time. The data used for the Hackett et al. study (1960) survey were likely too coarse to

accurately depict the surface and ground-water interactions at the scale of interest for this study.

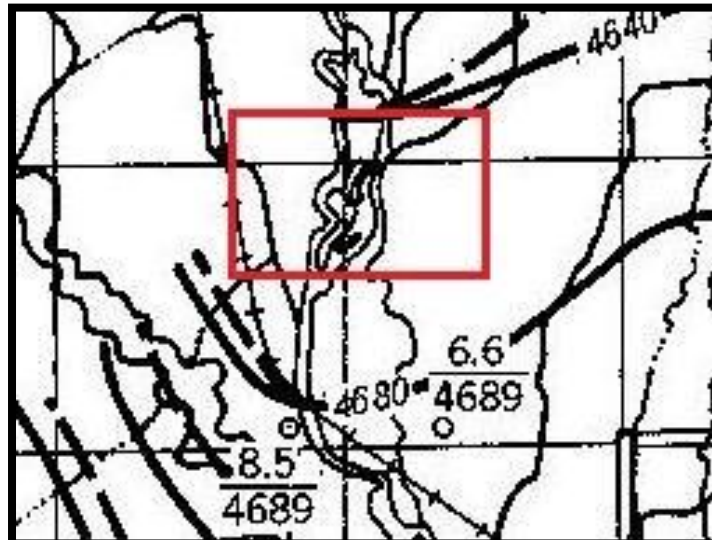


Figure 4-14. USGS potentiometric map of West Gallatin River downstream of the Norris Road Bridge for 1952 -1953. Depth to water at well locations (circles) is displayed as the top number and elevation in the lower position. Approximate location of piezometers and wells used for relative water level comparisons in this survey are contained within the red box (from Hackett et al. 1960).

Water levels were resurveyed during the 1990's by the USGS (Slagle, 1995) to assess the impacts of changing land use on hydrologic conditions between 1955 and 1990. The potentiometric maps constructed for Slagle's analysis were also coarse and used 50 foot ground-water contour intervals. Slagle's analysis relied on even less data than the 1950's survey in Four Corners area north of Norris Road (Fig. 4-14, 4-15). Slagle's survey also indicated ground-water discharge to the river (Fig. 4-15). Additionally, the single well used in Slagle's survey was located adjacent to the Beck Border Ditch and could have been under the influence of recharge from ditch seepage, further misleading his assessment of the relationship between the river and the aquifer at this location.

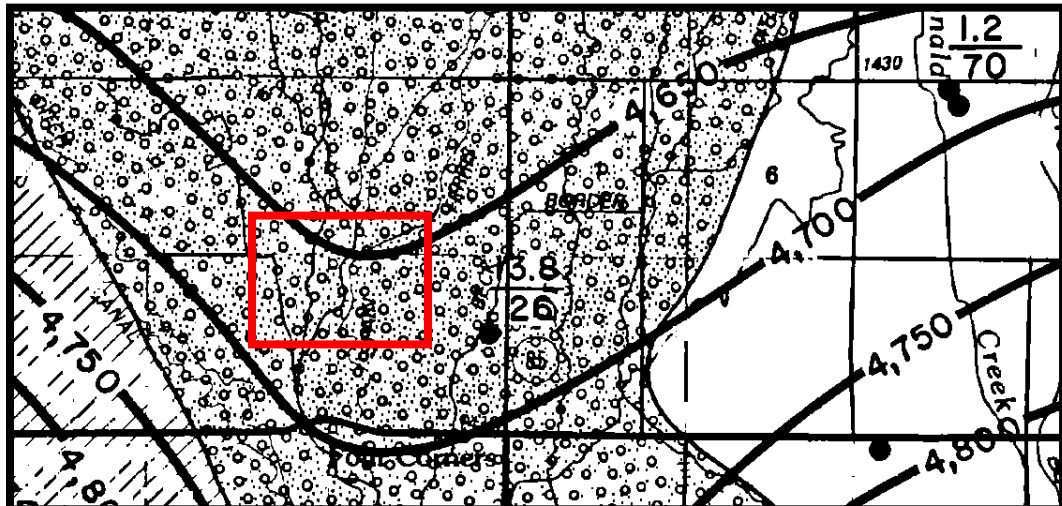


Figure 4-15. USGS potentiometric map of West Gallatin River downstream of Shed's Bridge produced with data collected from 1992-1993. Depth to water at well locations (dark circles) is displayed as the top number and well depth in the lower position. Approximate location of piezometers and wells used for relative water level comparisons are contained within the red box (from Slagle 1995).

The ground-water elevations from this 2006 study (Table 4-3) are also similar to, or greater than the ground-water elevations depicted by Slagle in the 1990's. Again, data from this study indicates aquifer recharge and Slagle (1990) interpreted ground-water discharge north of Norris Road (Fig. 4-15). Similar to Hackett et al. (1960), Slagle (1990) relied only upon ground-water elevations. Slagle concluded that ground-water levels had undergone no discernable change since the Hackett et al. (1960) survey. However it should be noted, the initial predicted results of increased ground-water consumption patterns which exceed aquifer recharge were reduced streamflow, not declines in ground-water levels (Hackett et al. 1960). If Hackett et al. (1960) was correct, and increases in ground-water consumption which exceeded aquifer recharge would be initially manifested as decreased streamflow before ground-water levels declined; then changes associated with increased ground-water

consumption would be initially manifested in depleted streamflow which was not assessed in the 1990's survey (Slagle, 1990).

As a result of the lack of surface water data used for comparison in historic surveys, and the lack of any surface water data used in Slagle's analysis (1990) it remains unclear as to whether or not ground-water consumption has exceeded ground-water recharge. Water elevations from this study (Table 4-3) are similar to those from the previous studies (Fig. 4-14, 4-15, Table 4-3). However data used in this study from monitoring wells (Fig. 4-12, 4-13) and streambed piezometers (Fig. 4-4, 4-5) indicated that surface water was downwelling in this area and recharged the aquifer. Historic and current surface water data was insufficient to detect whether a decline in streamflow had occurred as a result of ground-water consumption exceeding ground-water recharge.

The identified zone of downwelling surface water North of Norris Rd. does occur in a section of the aquifer where the aquifer's width increases (Fig. 4-5). Zones of downwelling have also been observed on other rivers where aquifer widths and transmissivity increases (Poole et al., 2006; Kasahara, 2003). Hence, the possibility does exist that a zone of surface-water downwelling has always been present at this location, but the lack of surface water data used in previous studies resulted in the zone of downwelling surface water to be overlooked. Incorporating surface water data into a future ground water is critical in the analysis of hydrologic changes over time in the Gallatin Valley, because the initial changes to the hydrologic system will be manifested in decreased surface water discharge before ground water levels decline (Hackett et. al., 1960).

## CONCLUSIONS

The goal of this study was to identify where ground-water discharge and recharge occurred along a six mile stretch of the West Gallatin River. Based on the interpretation of data from multiple sources it was found the West Gallatin gained streamflow from ground-water discharge along the six mile study reach near Four Corners (Table 4-1). Ground-water discharge entered the stream through the porous alluvial streambed and from spring channels which discharged ground water from the floodplain to the main channel. However within the study reach there were also zones of local downwelling. Small zones of downwelling were consistently observed at the down-stream end of pools along the entire study reach in the shallow ground-water-flow system. A larger zone of downwelling was consistently observed north of Norris Rd which recharged the alluvial aquifer (Fig. 4-5). Generally the patterns of upwelling ground water and downwelling surface-water were highly variable along the entire study reach and became more variable during the irrigation season (Fig. 4-2).

Ground-water discharge to the stream contributed 8% of the streamflow when no irrigation was occurring in November 2005. During the irrigation season ground-water discharge to the river increased in volume and its' relative contribution to streamflow. In July ground-water discharge accounted for 15% of the streamflow. In August, discharge measurements indicate that ground-water discharge contributed 70 cfs, 28% of the streamflow. Within the irrigation season, the volume of ground-water discharge increased as the irrigation diversion decreased (Fig. 4-1, Table 4-2). The relationship between irrigation and ground-water discharge suggest that irrigation return flow contributed significantly to

streamflow during the irrigation season due to the storage of excess irrigation water which recharged the aquifer and later contributed to streamflow.

Not all ground water discharge to the stream occurred through the river's porous streambed. Springs and sloughs which joined the main channel were observed in the river's floodplain throughout the study area. Limited data from these features indicates that ground-water discharge from them was consistent and concentrated in Reach One. These features may serve as significant mechanisms for ground water discharge into the stream; however they are unmapped and difficult to identify from aerial photographs. Because these features may discharge a large volume of ground water into the stream, it may be important to identify them for the calibrations of numerical models. Therefore these features would be an excellent topic for future research on surface and ground-water interaction along the West Gallatin River.

The pattern of ground-water discharge was not uniform along the six mile study reach (Fig. 4-5). Seepage increased in complexity during the irrigation season and zones of downwelling surface water occurred north of Four Corners (Fig. 4-2). Furthermore, the complex pattern of seepage also changed during the irrigation season (Fig. 4-2). Although the river gained flow from ground-water contributions throughout the study reach, zones of aquifer recharge were observed within the study area. Reaches Two and Three near Norris Road alternated between gaining flow and losing flow from July to August 2006. However the calculated seepage values were less than the uncertainty for a seepage calculation and other data was necessary to identify the zones of surface water downwelling.

Multiple lines of evidence did indicate that aquifer recharge consistently occurred south of Four Corners. These lines of evidence included; consistently negative vertical hydraulic

gradients in the streambed, surface-water elevations above ground-water elevations, and aquifer recharge from the river in near stream wells. Previous investigations have identified this reach as gaining flow from ground water based on observations of ground-water levels. However insufficient water-level elevation data was collected during those surveys in the Four Corners area to assess changes to the hydrologic system over time. Therefore it is unclear whether this zone of aquifer recharge has always been present and is a result of the aquifer and river channel properties' or if the hydrologic system has changed over time. This finding illustrates the importance of incorporating surface-water data into a ground-water analysis which assess changes over time. Hydrogeologic assessments of the Gallatin Valley need to incorporate surface water data into the analysis because the initial changes to the hydrologic system from increased ground-water development will be manifested in surface water discharge before ground-water levels decline (Hackett et. al., 1960).

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APPENDICES

APPENDIX A

MEASUREMENT SUMMARY TABLES  
FROM THE RESULTS – CHAPTER 3

Measurement Summary Tables from the Results - Chapter 3

Table 3-1. Descriptive statistics (average, range, minimum, and maximum, including the period of observation) of specific conductance values ( $\mu\text{S}$ ) sampled from monitoring wells during water year 2006. The table below is sorted by range from highest to lowest. The fluctuation of specific conductance values observed at a well is estimated in the Range/Ave column, where the range was divided by the average value to approximate the percent fluctuation. Wells with less than 10% fluctuation were considered to be unaffected surface water recharge and representative of the average ground-water value. Mean values for ground water are calculated for all wells and wells with less than 10% fluctuation.

<b>ID</b>	<b>Mean</b>	<b>Range</b>	<b>Max</b>	<b>Min</b>	<b>Start</b>	<b>End</b>	<b>Obs</b>	<b>Range/Ave</b>
GW18	506	371	708	337	6/16/06	8/11/06	4	73%
GW10	336	193	386	193	3/27/06	8/11/06	4	57%
GW21	243	185	354	169	5/31/06	8/10/06	5	76%
GW23D	643	179	760	581	5/31/06	8/10/06	5	28%
GW4	329	163	409	246	3/27/06	8/11/06	5	50%
GW25S	346	125	425	300	6/2/09	8/11/06	4	36%
GW13S	223	103	292	189	5/31/06	8/11/06	5	46%
GW11S	270	99	333	234	6/1/06	8/11/06	3	37%
GW20D	345	98	413	315	5/31/06	8/11/06	4	28%
GW17D	272	95	318	223	5/31/06	8/10/06	5	35%
GW17E	395	94	465	371	5/31/06	8/10/06	5	24%
GW31	223	94	277	183	6/2/06	8/11/06	3	42%
GW20S	340	88	400	312	5/31/06	8/11/06	4	26%
GW11D	295	86	347	261	6/1/06	8/11/06	3	29%
GW17S	194	80	254	174	5/31/06	8/10/06	5	41%
GW27S	303	80	333	253	6/2/06	8/11/06	5	26%
GW13D	240	72	293	221	5/31/06	8/11/06	5	30%
GW32	217	48	245	197	6/2/06	8/11/06	3	22%
GW23S	599	47	622	575	5/31/06	8/10/06	5	8%
GW28	483	44	504	460	3/27/06	8/11/06	3	9%
GW26	327	43	353	310	6/2/06	8/11/06	4	13%
GW27D	307	40	330	290	6/2/06	8/11/06	5	13%
GW15S	414	35	437	402	5/31/06	8/10/06	5	8%

Table 3-1 continued.

ID	Mean	Range	Max	Min	Start	End	Obs	Range/Ave
GW19	486	34	502	468	5/31/06	8/11/06	3	7%
GW8D	472	34	487	453	3/27/06	8/11/06	5	7%
GW6	427	33	440	407	3/27/06	8/11/06	4	8%
GW16	483	25	501	476	5/31/06	8/10/06	4	5%
GW1	384	23	395	372	6/5/06	8/11/06	2	6%
GW15D	423	22	437	415	5/31/06	8/10/06	5	5%
GW25D	442	22	454	432	6/2/06	8/11/06	3	5%
GW2S	389	22	398	376	6/5/06	8/11/06	3	6%
GW9	492	22	502	480	3/27/06	8/11/06	3	4%
GW5	379	19	395	376	3/27/06	7/7/06	5	5%
GW7	460	15	465	450	3/27/06	8/11/06	5	3%
GW12	483	11	488	477	6/5/06	8/5/06	2	2%
GW2D	389	10	394	384	6/2/06	8/11/06	3	3%
GW3	390	8	395	387	5/29/06	8/11/06	3	2%
GW14	427	0	427	427	8/11/06	8/11/06	1	0%
GW8S	480	0	480	480	8/11/06	8/11/06	1	0%
<b>Total Mean</b>	<b>381</b>	<b>71</b>	<b>421</b>	<b>350</b>	-	-	<b>4</b>	<b>21%</b>
<b>Mean &lt;10% fluctuation</b>	<b>436</b>	<b>20</b>	<b>447</b>	<b>427</b>	-	-	<b>3</b>	<b>5%</b>

Table 3-7. Summary table of measurements made from piezometer sets.

Set ID	Number of Piezometers	Number of Observations	First	Last	Notes
7	4	16	7/28/2006	11/4/2006	Complete set through November. Two sets of measurement in August. Two middle position piezometers.
2	3	12	7/17/2006	11/4/2006	Complete set through November. Two sets of measurements in August
3	3	12	7/17/2006	11/4/2006	Complete set through November. Two sets of measurements in August
4	3	12	7/17/2006	11/4/2006	Complete set through November. Two sets of measurements in August
12	3	9	7/28/2006	11/10/2006	Complete set through November.
16	3	9	7/28/2006	11/10/2006	Complete set through November.
5	3	11	7/17/2006	11/4/2006	Complete set through August. Missing head measurement on 11/4/06.
18	3	6	7/28/2006	8/24/2006	Complete set through August.
19	3	6	7/28/2006	8/24/2006	Complete set through August.
20	3	6	7/28/2006	8/24/2006	Complete set through August.
21	3	6	7/28/2006	8/24/2006	Complete set through August.
22	3	6	7/28/2006	8/24/2006	Complete set through August.
13	3	8	7/28/2006	11/10/2006	Complete set through August. Missing head measurement on 11/10/06
14	3	8	7/28/2006	11/10/2006	Complete set through August. Missing middle measurement on 11/10/06.
11	3	7	7/28/2006	11/4/2006	Complete set through August. Missing middle and tail measurement on 11/4/06.
6	3	12	7/17/2006	11/4/2006	Incomplete set, two tail positions no head position. Two measurements in August.
8	2	6	7/28/2006	11/4/2006	Incomplete set, missing middle position piezometer.
9	2	6	7/28/2006	11/4/2006	Incomplete set, missing middle position piezometer.
15	3	9	7/28/2006	11/10/2006	Incomplete set, two middle positions, piezometers, no head position.
17	3	6	7/28/2006	8/24/2006	Incomplete set, two middle positions, no head position.
10	2	5	7/28/2006	11/4/2006	Incomplete set, missing middle position piezometer. One head measurement on 11/4/06 no middle measurements.

Table 3-8. Vertical hydraulic gradients measured in streambed piezometers sorted by range.  
This table is continued on the following page.

SBP ID	Set ID	Feature Type	Depth	Range	Average	Max	Min	Start	End	#
SB47	16	Tail	2.1	4.4E-01	-1.7E-01	-7.9E-03	-4.5E-01	7/28/06	11/10/06	3
SB21	7	Middle	1.75	3.0E-01	-1.3E-01	-8.7E-03	-3.1E-01	7/17/06	11/4/06	4
SB39	14	Head	1.31	2.4E-01	4.9E-03	1.3E-01	-1.1E-01	7/28/06	11/10/06	3
SB44	15	Tail	2.13	2.1E-01	-7.5E-02	-4.9E-03	-2.1E-01	7/28/06	11/10/06	3
SB49	17	Middle	2.6	2.0E-01	-5.6E-02	4.5E-02	-1.6E-01	7/28/06	8/24/06	2
SB50	17	Tail	2.49	2.0E-01	-5.6E-02	4.5E-02	-1.6E-01	7/28/06	8/24/06	2
SB22	7	Tail	2.99	1.9E-01	-6.7E-02	5.7E-03	-1.8E-01	7/17/06	11/4/06	4
SB20	7	Middle	2.36	1.5E-01	1.8E-02	1.1E-01	-3.8E-02	7/17/06	11/4/06	4
SB13	5	Head	2.64	1.5E-01	1.0E-01	1.7E-01	2.1E-02	7/17/06	8/23/06	3
SB18	6	Tail	1.82	1.4E-01	-9.1E-02	1.3E-03	-1.4E-01	7/17/06	8/23/06	3
SB48	17	Middle	2.56	1.3E-01	-8.3E-02	-1.7E-02	-1.5E-01	7/28/06	8/24/06	2
SB40	14	Middle	2.4	1.3E-01	7.5E-02	1.4E-01	1.2E-02	7/28/06	8/24/06	2
SB17	6	Tail	2.04	1.1E-01	5.9E-02	1.2E-01	3.2E-03	7/17/06	11/4/06	4
SB46	16	Middle	2	9.8E-02	-4.1E-02	-6.8E-03	-1.1E-01	7/28/06	11/10/06	3
SB57	20	Head	2.22	9.2E-02	6.2E-02	1.1E-01	1.6E-02	7/28/06	8/24/06	2
SB15	6	Middle	2.32	8.8E-02	4.6E-02	9.1E-02	2.6E-03	7/17/06	11/4/06	4
SB30	11	Head	2	8.3E-02	3.0E-02	8.5E-02	2.0E-03	7/17/06	11/4/06	3
SB37	13	Middle	1.96	8.3E-02	2.8E-02	8.2E-02	-1.1E-03	7/28/06	11/10/06	3
SB23	8	Head	3.23	8.2E-02	3.5E-02	8.7E-02	4.3E-03	7/17/06	11/4/06	3
SB26	9	Head	2.35	7.6E-02	2.8E-02	7.6E-02	8.5E-04	7/17/06	11/4/06	3
SB43	15	Middle	2.89	7.2E-02	-3.6E-02	-8.1E-03	-8.0E-02	7/28/06	11/10/06	3
SB41	14	Tail	2.54	7.0E-02	-3.0E-02	-4.5E-03	-7.5E-02	7/28/06	11/10/06	3
SB25	8	Tail	1.92	6.6E-02	-3.2E-02	-7.4E-03	-7.3E-02	7/17/06	11/4/06	3
SB52	18	Middle	2.44	6.5E-02	4.2E-02	7.4E-02	9.3E-03	7/28/06	8/24/06	2
SB6	3	Head	2.88	6.4E-02	-3.9E-02	-5.3E-03	-7.0E-02	7/17/06	11/4/06	4
SB9	4	Head	2.28	6.2E-02	3.4E-02	6.6E-02	3.8E-03	7/17/06	11/4/06	4
SB12	5	Tail	2.35	6.1E-02	-2.7E-02	-2.7E-03	-6.4E-02	7/17/06	11/4/06	4
SB27	9	Tail	2.83	6.0E-02	2.1E-02	6.0E-02	0.0E+00	7/17/06	11/4/06	3
SB3	2	Head	3.14	5.9E-02	3.2E-02	6.1E-02	1.3E-03	7/17/06	11/4/06	4
SB56	19	Tail	3.13	5.9E-02	-4.7E-02	-1.8E-02	-7.7E-02	7/28/06	8/24/06	2
SB58	20	Middle	3.29	5.2E-02	3.8E-02	6.4E-02	1.1E-02	7/28/06	8/24/06	2
SB4	2	Middle	3.97	5.1E-02	2.7E-02	5.3E-02	1.7E-03	7/17/06	11/4/06	4
SB11	4	Tail	1.84	5.1E-02	3.0E-02	4.9E-02	-1.7E-03	8/14/06	11/4/06	3
SB31	11	Middle	2.23	4.9E-02	2.9E-02	5.4E-02	4.6E-03	7/17/06	8/23/06	2
SB60	21	Head	2.35	4.7E-02	2.3E-02	4.7E-02	0.0E+00	7/28/06	8/24/06	2
SB55	19	Middle	2.15	4.5E-02	2.9E-02	5.1E-02	6.3E-03	7/28/06	8/24/06	2
SB51	18	Head	2.54	4.4E-02	2.9E-02	5.1E-02	7.3E-03	7/28/06	8/24/06	2
SB35	12	Tail	2.09	4.3E-02	-2.0E-02	-4.5E-03	-4.8E-02	7/28/06	11/10/06	3
SB28	10	Head	2.53	4.3E-02	4.9E-03	2.8E-02	-1.5E-02	7/17/06	11/4/06	3
SB59	20	Tail	2.53	3.6E-02	2.1E-02	3.9E-02	3.2E-03	7/28/06	8/24/06	2
SB19	7	Head	1.68	3.5E-02	1.3E-02	3.6E-02	8.5E-04	7/17/06	11/4/06	4
SB36	13	Head	2.42	3.5E-02	2.0E-02	3.7E-02	2.7E-03	7/28/06	8/24/06	2
SB63	22	Head	2.42	3.3E-02	2.5E-02	4.1E-02	8.3E-03	7/28/06	8/24/06	2

Table 3-8 continued.

SBP ID	Set ID	Feature Type	Depth	Range	Average	Max	Min	Start	End	#
SB8	3	Tail	3.74	3.2E-02	-8.7E-03	5.3E-03	-2.7E-02	7/17/06	11/4/06	3
SB61	21	Middle	2.69	3.1E-02	2.2E-02	3.7E-02	6.0E-03	7/28/06	8/24/06	2
SB62	21	Tail	2.73	2.9E-02	-1.8E-02	-3.8E-03	-3.3E-02	7/28/06	8/24/06	2
SB29	10	Middle	2.19	2.8E-02	1.8E-02	3.2E-02	3.7E-03	7/17/06	8/23/06	2
SB42	15	Middle	3.13	2.7E-02	-1.4E-02	-4.6E-03	-3.2E-02	7/28/06	11/10/06	3
SB14	5	Middle	2.33	2.6E-02	-9.7E-03	0.0E+00	-2.6E-02	7/17/06	11/4/06	4
SB5	2	Tail	3.09	2.3E-02	-9.6E-03	0.0E+00	-2.3E-02	7/17/06	11/4/06	4
SB33	12	Head	1.96	2.2E-02	1.2E-02	2.6E-02	3.6E-03	7/28/06	11/10/06	3
SB10	4	Middle	2.74	2.2E-02	2.2E-02	3.3E-02	1.1E-02	8/14/06	8/23/06	2
SB32	11	Tail	2.69	1.3E-02	1.2E-02	1.9E-02	5.8E-03	7/17/06	8/23/06	2
SB7	3	Middle	3.05	9.1E-03	-1.0E-02	-7.2E-03	-1.6E-02	7/17/06	11/4/06	4
SB34	12	Middle	2.17	9.0E-03	4.3E-03	9.2E-03	2.1E-04	7/28/06	11/10/06	3
SB53	18	Tail	3.14	7.7E-03	5.7E-03	9.6E-03	1.9E-03	7/28/06	8/24/06	2
SB45	16	Head	2.4	3.6E-03	-2.4E-03	0.0E+00	-3.6E-03	7/28/06	11/10/06	3
SB64	22	Middle	2.79	3.2E-03	-1.6E-03	0.0E+00	-3.2E-03	7/28/06	8/24/06	2
SB54	19	Head	2.6	2.6E-03	-2.1E-02	-2.0E-02	-2.2E-02	7/28/06	8/24/06	2
SB38	13	Tail	1.76	0.0E+00	-1.3E-02	-3.4E-02	-3.4E-02	7/28/06	11/10/06	3
SB65	22	Tail	2.25	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7/28/06	8/24/06	2

Table 3-9. Specific conductance values ( $\mu\text{S}$ ) measured in streambed piezometers sorted by the range of observations. This table is continued on the following page.

SBP ID	Set ID	Feature Type	Depth (ft)	Range	Average	Max	Min	Start	End	#OBS
SB45	16	Head	2.40	295	488	644	349	7/28/2006	11/10/2006	3
SB18	6	Tail	1.82	146	367	429	283	7/17/2006	8/23/2006	3
SB12	5	Tail	2.35	118	329	365	247	7/17/2006	11/4/2006	4
SB3	2	Head	3.14	110	345	404	294	7/17/2006	11/4/2006	4
SB30	11	Head	2.00	108	351	390	282	7/28/2006	11/4/2006	3
SB4	2	Middle	3.97	105	368	415	310	7/17/2006	11/4/2006	4
SB11	4	Tail	1.84	98	327	358	260	7/17/2006	11/4/2006	4
SB14	5	Middle	2.33	96	321	360	264	7/17/2006	11/4/2006	4
SB31	11	Middle	2.23	93	323	369	276	7/28/2006	8/23/2006	2
SB39	14	Head	1.31	92	338	396	304	7/28/2006	11/10/2006	3
SB9	4	Head	2.28	89	302	352	263	7/17/2006	11/4/2006	4
SB50	17	Tail	2.49	89	324	368	279	7/28/2006	8/24/2006	2
SB5	2	Tail	3.09	87	305	333	246	7/17/2006	11/4/2006	4
SB41	14	Tail	2.54	80	327	368	288	7/28/2006	11/10/2006	3
SB7	3	Middle	3.05	73	302	336	263	7/17/2006	11/4/2006	4
SB59	20	Tail	2.54	73	346	382	309	7/28/2006	8/24/2006	2
SB20	7	Middle, above log jam	2.36	72	324	347	275	7/28/2006	11/4/2006	4
SB22	7	Tail	2.99	71	298	323	252	7/28/2006	11/4/2006	4
SB 23	8	Head	3.23	71	342	386	315	7/28/2006	11/4/2006	3
SB33	12	Head	1.96	69	319	350	281	7/28/2006	11/10/2006	3
SB10	4	Middle	2.74	68	302	328	260	7/17/2006	11/4/2006	4
SB19	7	Head	1.68	67	310	338	271	7/28/2006	11/4/2006	4
SB21	7	Middle, below log jam	1.75	66	307	337	271	7/28/2006	11/4/2006	4
SB54	19	Head	2.69	65	326	358	293	7/28/2006	8/24/2006	2
SB58	20	Middle	3.29	64	356	388	324	7/28/2006	8/24/2006	2
SB17	6	Tail	2.04	62	306	335	273	7/17/2006	11/4/2006	4
SB32	11	Tail	2.69	60	293	323	263	7/28/2006	8/23/2006	2
SB8	3	Tail	3.74	58	286	310	252	7/17/2006	11/4/2006	4
SB25	8	Tail	1.92	57	303	323	266	7/28/2006	11/4/2006	3
SB57	20	Head	2.22	57	379	407	350	7/28/2006	8/24/2006	2
SB27	9	Tail	2.83	52	412	430	378	7/28/2006	11/4/2006	3
SB51	18	Head	2.54	52	326	352	300	7/28/2006	8/24/2006	2
SB38	13	Tail	1.76	51	322	345	294	7/28/2006	11/10/2006	3
SB34	12	Middle	2.17	47	307	335	288	7/28/2006	11/10/2006	3
SB15	6	Middle	2.32	46	312	335	289	7/17/2006	11/4/2006	4
SB43	15	Middle	2.89	45	317	342	297	7/28/2006	11/10/2006	3
SB49	17	Middle	2.60	44	313	335	291	7/28/2006	8/24/2006	2
SB28	10	Head	2.53	43	346	367	324	7/28/2006	11/4/2006	3
SB62	21	Tail	2.73	42	305	326	284	7/28/2006	8/24/2006	2
SB44	15	Tail	2.13	40	308	333	293	7/28/2006	11/10/2006	3
SB35	12	Tail	2.09	38	303	320	282	7/28/2006	11/10/2006	3
SB61	21	Middle	2.69	38	279	298	260	7/28/2006	8/24/2006	2
SB46	16	Middle	2.00	38	306	321	238	7/28/2006	11/10/2006	3

Table 3-9. continued.

SBP ID	Set ID	Feature Type	Depth (ft)	Range	Average	Max	Min	Start	End	#OBS
SB48	17	Middle	2.56	35	298	315	280	7/28/2006	8/24/2006	2
SB37	13	Middle	1.96	32	305	326	294	7/28/2006	11/10/2006	3
SB53	18	Tail	3.14	32	295	311	279	7/28/2006	8/24/2006	2
SB36	13	Head	2.42	30	379	394	364	7/28/2006	8/24/2006	2
SB6	3	Head	2.88	29	304	322	293	7/17/2006	11/4/2006	4
SB47	16	Tail	2.10	29	323	335	306	7/28/2006	11/10/2006	3
SB60	21	Head	2.35	29	357	371	342	7/28/2006	8/24/2006	2
SB42	15	Middle	3.13	27	304	320	293	7/28/2006	11/10/2006	3
SB55	19	Middle	2.15	25	346	358	333	7/28/2006	8/24/2006	2
SB26	9	Head	2.35	22	387	400	378	7/28/2006	11/4/2006	3
SB29	10	Middle	2.19	16	312	320	304	7/28/2006	8/23/2006	2
SB13	5	Head	2.64	10	384	388	378	7/17/2006	8/23/2006	3
SB52	18	Middle	2.44	2	329	330	328	7/28/2006	8/24/2006	2
SB40	14	Middle	2.40	0	395	395	395	7/28/2006	8/24/2006	2

APPENDIX B

STREAMBED DATABASE DESCRIPTION

### Streambed Database Description

The streambed database is composed of six tables which contain data used to assess the surface and groundwater interactions along the river's streambed. Please see Figure B-1 which is a schema for database. The six tables are grouped into 3 linked categories; ground water, surface water, and streambed. Each category consists of two tables; a location table and a values table. The location tables contain geographic data and the method by which it was collected. The values tables contain the measurements collected. The two tables in each category are linked by the field "Site ID".

The values contained in the ground water and surface water categories consist entirely of specific conductance. Water levels and temperature data from data logger are available through the Montana Bureau of Mines and Geology's Groundwater Information Center or the Montana State University Earth Science Department (Custer and Schaffer, 2009). The Streambed Values table has values other than specific conductance which may be useful for other analysis. These values include; vertical hydraulic gradients, temperatures, and water-surface elevations. The data from this table can be queried using the fields; Value Type, Site Id, Value, Date, or any other field of interest in the tables. Some fields are provided specifically for this purpose, such as seepage group, which identifies the location of each piezometer within a reach defined for the seepage run/net flux analysis. Other fields, such as morphologic feature, Hackett group, and set are also provided for this purpose. A short description of these fields is contained in the Access Database.

**Surface Water Measurement Point**

Name	Type
Site ID	Text
Feature Type	Text
Water Body	Text
Northing	Double
Easting	Double
Horizontal Datum	Text
Horizontal Survey Method	Text
Horizontal Survey Organization	Text
Elevation	Double
Elevation Survey Method	Text
Elevation Survey Organization	Text
Notes	Text

**Surface Water Measurement**

Name	Type
ID	Long Integer
Site ID	Text
Date and Time	Date/Time
Value Type	Text
Value	Double
Value Unit	Text
Collection Method	Text
Logger Serial Number	Double
Organization	Text
Notes	Text

**Streambed Measurement Point Table**

Name	Type
Site ID	Text
Seepage Group	Text
Hackett Group	Text
Feature Type	Text
Depth	Double
Stick up	Double
Temperature Depth	Double
Northing	Double
Easting	Double
Horizontal Datum	Text
Horizontal Survey Method	Text
Horizontal Survey Organization	Text
Elevation	Double
Elevation Datum	Text
Elevation Survey Method	Text
Elevation Survey Organization	Text
Notes	Text

**Streambed Measurement Table**

Name	Type
ID	Long Integer
Site ID	Text
Value Type	Text
Date and Time	Date/Time
Value	Double
Value Units	Text
Location	Text
Collection Method	Text
Logger Serial Number	Double
Organization	Text
Notes	Text

**Groundwater Measurement Points**

Field Name	Field Type
Site ID	Text
Northing	Double
Easting	Double
Horizontal Datum	Text
Horizontal Survey Method	Text
Horizontal Survey Organization	Text
Elevation	Double
Elevation Datum	Text
Elevation Survey Method	Text
Elevation Survey Organization	Text
Notes	Text
GWIC Number	Double
Stick Up	Double
Well Type	Text
Screen length	Double
Total Depth	Double
Colloquial ID	Text

**Groundwater Measurement Table**

Field	Type
ID	Long Integer
Site ID	Text
Value Type	Text
Value	Double
Value Units	Text
Date and Time	Date/Time
Collection Method	Text
Logger Serial Number	Double
Collecting Organization	Text
Notes	Text

Figure B-1. Database schema for the Access database used to store surface water, ground water, and streambed measurements.