2013

Montana Bureau of Mines and Geology Open-File Report 637

HYDROGEOLOGIC INVESTIGATION OF THE BEAVERHEAD RIVER STUDY AREA, BEAVERHEAD COUNTY, MONTANA

Ginette Abdo, Julie Butler, Todd Myse, John Wheaton, Dean Snyder, John Metesh, and Glenn Shaw[1]

Montana Bureau of Mines and Geology
Ground Water Investigations Program

[1]Montana Tech of the University of Montana

Cover photo by Ginette Abdo, MBMG, from the top of Beaverhead Rock.

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PREFACE

This report has been prepared by the Montana Bureau of Mines and Geology (MBMG) Ground Water Investigations Program (GWIP). The purpose of GWIP is to investigate specific areas, as prioritized by the Ground-Water Assessment Steering Committee (2-15-1523 MCA), where factors such as current and anticipated growth of industry, housing, and commercial activity or changing irrigation practices have created elevated concern about groundwater issues. Additional program information and project ranking details can be accessed at http://www.mbmg.mtech.edu/gwip/gwip.asp. GWIP uses various scientific tools to interpret hydrogeologic data, investigate how the groundwater resource has responded to past stresses, and project future responses.

The final products of the Lower Beaverhead study include:

An Interpretive Report that presents interpretations of the data and summarizes the project results within the context of the study area and the issues to be addressed. The Interpretive Report includes all results, and is intended for use by the general public, special interest groups, decision-makers, and hydrogeologists.

A Groundwater Modeling Report that documents in detail the procedures, assumptions, and results for the numeric groundwater flow models. This report is designed so that qualified individuals can evaluate and use the groundwater flow models to test specific scenarios of interest, or to provide a starting point for a site-specific analysis. The files needed to run the models are posted to the GWIP website (http://www.mbmg.mtech.edu/gwip/gwip.asp).

A comprehensive data set permanently stored on MBMG's Groundwater Information Center online database (http://mbmggwic.mtech.edu/).

ABSTRACT

The purpose of this investigation was to determine the magnitude and extent of groundwater drawdown and stream depletion occurring in the Beaverhead River study area due to high-capacity irrigation pumping from aquifers. Possible impacts to sloughs and the Beaverhead River from future groundwater development were also evaluated. A computer model was developed as part of these evaluations, and will be released in a companion publication. The study area extends from Dillon, Montana to Beaverhead Rock, a distance of about 14 miles. It includes the Beaverhead River floodplain and the benches to the east and west of the valley.

The main economy in the lower Beaverhead River Basin is irrigated agriculture based on groundwater and surface-water sources. The basin was closed to new surface-water appropriations in 1993. Subsequent legislation in 2007 revised water laws in closed basins by requiring a "hydrogeologic assessment" to determine if a new well would result in a net depletion of surface water and have an "adverse effect" on a prior appropriator. Applications for new well permits in the study area are typically challenged by senior water-rights holders. A primary objection is that groundwater withdrawals will reduce stream flow and lower groundwater levels.

Groundwater and surface water are connected and interchange seasonally. The Beaverhead River within the study area generally loses water to groundwater in the fall and winter months and gains water from groundwater during the irrigation season as a result of irrigation return flows. Closer to Beaverhead Rock, the river consistently gains water from the alluvial aquifer. Water primarily exits the study area through surface water where the valley constricts near Beaverhead Rock, forcing groundwater to the surface. The sloughs on the West Bench also gain water from irrigation return flow.

About 475,000 acre-ft of water enters and leaves the study area. Surface water is the major inflow and outflow component in the 2010 water budget. Precipitation and evapotranspiration are the second most dominant water budget components, accounting for 25 and 30% of the inflow and outflow, respectively. Within the study area during 2010, flow in the Beaverhead River realized an annual net gain from groundwater of about 38,000 acre-ft/year.

Irrigation systems provide significant groundwater recharge in the study area, both through canal leakage and water applied to fields. This recharge is the driving mechanism that controls groundwater levels on the East and West Benches. Canal seepage contributed about 23,000 acre-ft of water to groundwater in 2010. The rate of canal seepage and groundwater recharge varies along the length of the East Bench and West Side canals, depending on factors that include the type of sediment underlying the canal and the depth to water. In areas where the pre-irrigation season depth to groundwater is deep, recharge may be delayed, whereas less permeable sediments underlying the canal can result in less recharge to groundwater.

Water-level trends in long-term monitoring wells show strong correlation with either precipitation or canal flows/applied irrigation water. Long-term depletion of groundwater caused by high-capacity irrigation groundwater withdrawals is not obvious in these records. If irrigation withdrawals are causing long-term groundwater-level declines, the declines are overshadowed by other influences such as changes in irrigation recharge. However, numerical modeling indicates that increased groundwater withdrawals in the future could cause water levels to stabilize at a somewhat lowered level.

Data during a 3-day aquifer test in the volcanic rock aquifer did indicate a connection between the aquifer and a nearby slough, which recovered as the groundwater level recovered. If any stream depletion has occurred in the Beaverhead River as a result of irrigation wells, it is not apparent in the field measurement data. Numerical modeling indicates that future groundwater development may result in stream depletion in the Beaverhead River and its tributaries. Within the 20-year modeled period, the magnitude of maximum depletion decreased the further the wells were from the river and the timing of depletion was delayed with increasing distance. Modeling also showed that extending the period of canal flow can help offset stream depletion and groundwater drawdown by providing additional groundwater recharge.

INTRODUCTION

The principal economy in the lower Beaverhead River Basin is agriculture, which depends on groundwater and surface-water irrigation. The basin was closed to new surface-water appropriations by Legislative authority effective April 1, 1993 as part of the Jefferson–Madison River Basin closure (http://www.dnrc.mt.gov/wrd/water_rts/appro_info/basinclose-cgw_areas.pdf). In a closed basin, the Montana Department of Natural Resources (DNRC) may not grant new surface-water rights except in restricted circumstances. This closure, combined with increasing irrigation demands, resulted in an increased number of high-discharge irrigation wells. However, a Montana Supreme Court decision in 2006 recognized impacts to stream flow by pre-stream capture of tributary groundwater and effectively closed the basin to new groundwater development (Montana Supreme Court, 2006). In 2007, the Montana Legislature passed House Bill 831, which resulted in revising water laws in closed basins by requiring a "hydrogeologic assessment" to determine if a new well would result in a "net depletion" of surface water and have an "adverse effect" on a prior appropriator. If an adverse effect is shown, the applicant then needs to submit a plan for mitigation or aquifer recharge.

Applications for new well permits have led to conflicts between senior and junior groundwater and surface-water rights holders. A primary objection is that groundwater withdrawals will reduce stream flow and lower groundwater levels.

Purpose and Scope

This project was located in southwestern Montana between Dillon and Beaverhead Rock (fig. 1). Irrigators in this area rely primarily on surface-water sources; however, since 1993 the use of groundwater has increased. The purpose of the project was to determine the magnitude and extent of groundwater drawdown and stream depletion occurring due to high-capacity irrigation pumping from aquifers, and to evaluate possible impacts to sloughs and the Beaverhead River from future groundwater development. Groundwater/surface-water interactions and pumping effects on water resources were examined through a detailed hydrogeologic investigation of the study area, which included field studies, analysis of data and numerical modeling.

The major objectives of the Lower Beaverhead River investigation were to:

- Determine aquifer properties,
- Define groundwater movement,
- Develop a water budget,
- Quantify groundwater recharge from canals and irrigated fields,
- Evaluate groundwater trends,
- Assess groundwater/surface-water interaction, and
- Evaluate potential stream depletion and aquifer drawdown due to pumping from irrigation wells.

The results of this project will provide scientific information to help landowners, county, State, and Federal agencies make informed, data-driven management decisions. Other interest groups will also benefit from this report as baseline information for future projects such as improving watershed health and stream restoration activities.

Stream Depletion

The quantity of stream depletion, as used in this report, refers to the reduction in baseflow to the Beaverhead River and sloughs as a result of pumping from a well(s). This reduction in flow is expressed as the change in rate of flow, and it is also sometimes expressed as a percentage of the discharge from the pumped well(s) .

To meet demands for increased irrigation in the Beaverhead River Valley, ranchers have turned to groundwater to augment surface-water supplies. However, groundwater withdrawals can impact surface water. Stream depletion occurs when groundwater that otherwise would discharge to surface water is intercepted, or by inducing the surface water to infiltrate to the aquifer. These impacts may be immediate or may take years before they affect surface water, depending on the hydrogeologic setting and the location and magnitude of groundwater withdrawals. Water resource managers must be able to determine how groundwater develop-

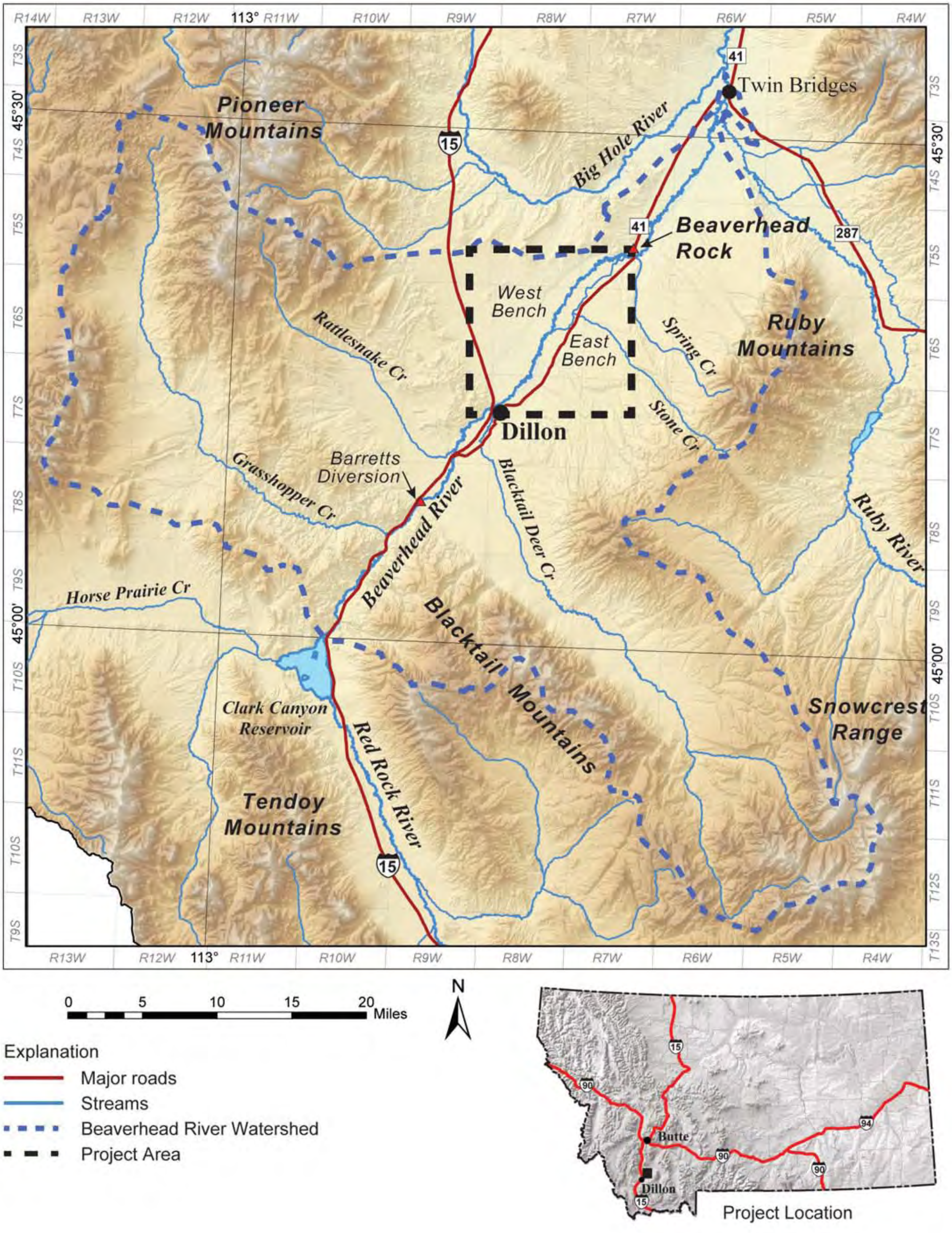


Figure 1. The Lower Beaverhead study area is located in southwestern Montana north of Dillon, in the Beaverhead River valley.

ment affects surface-water resources. A discussion on stream depletion is available in a case study report from the Montana Bureau of Mines and Geology (MBMG, 2008).

The distance between a pumping well and the stream strongly influences the timing and magnitude of depletion. Figure 2 illustrates a hypothetical case of the effect of stream depletion as a function of distance from the pumped well. If the well is located close to the stream, stream depletion will be in phase with the pumping schedule of the well, and the immediate effect on stream flow will be greater than for a more distant well. The farther the well is located from the stream, the longer it takes for groundwater drawdown to affect the stream, and the more stream depletion is out of phase with the pumping schedule. The greater proportion of annual depletion may actually occur when the well is not pumping (Kendy and Bredehoeft, 2006; Jenkins, 1968). As shown in figure 2, the effects compound with each additional yearly pumping cycle.

In an evaluation of a hypothetical ensemble of irrigation wells spread uniformly across an aquifer several miles wide, only one-third of the resultant stream depletion occurred during the pumping season (Bredehoeft, 2011). After a decade of pumping, a steady-state condition was reached in which the impact on the stream was the same every year. Depletion was nearly constant through the year with only a small amount of seasonal fluctuation. Conversely, in that hypthetical example, it took more than a decade for the stream to fully recover once the wells were shut down.

Physiography

The Beaverhead River drainage encompasses an area of about 2,895 square miles below the Clark Canyon Reservoir, which is located 23 miles southwest of Dillon, Montana (fig. 1). The reservoir receives water from Red Rock River and Horse Prairie Creek. The Beaverhead River flows northeast through the Beaverhead Canyon and into the Beaverhead River Valley for about 45 miles until its confluence with the Big Hole and Ruby Rivers near Twin Bridges to form the headwaters of the Jefferson River, a tributary to the Missouri River.

The basin is bounded by the Pioneer Mountains to the west, the Ruby Mountains to the east, and

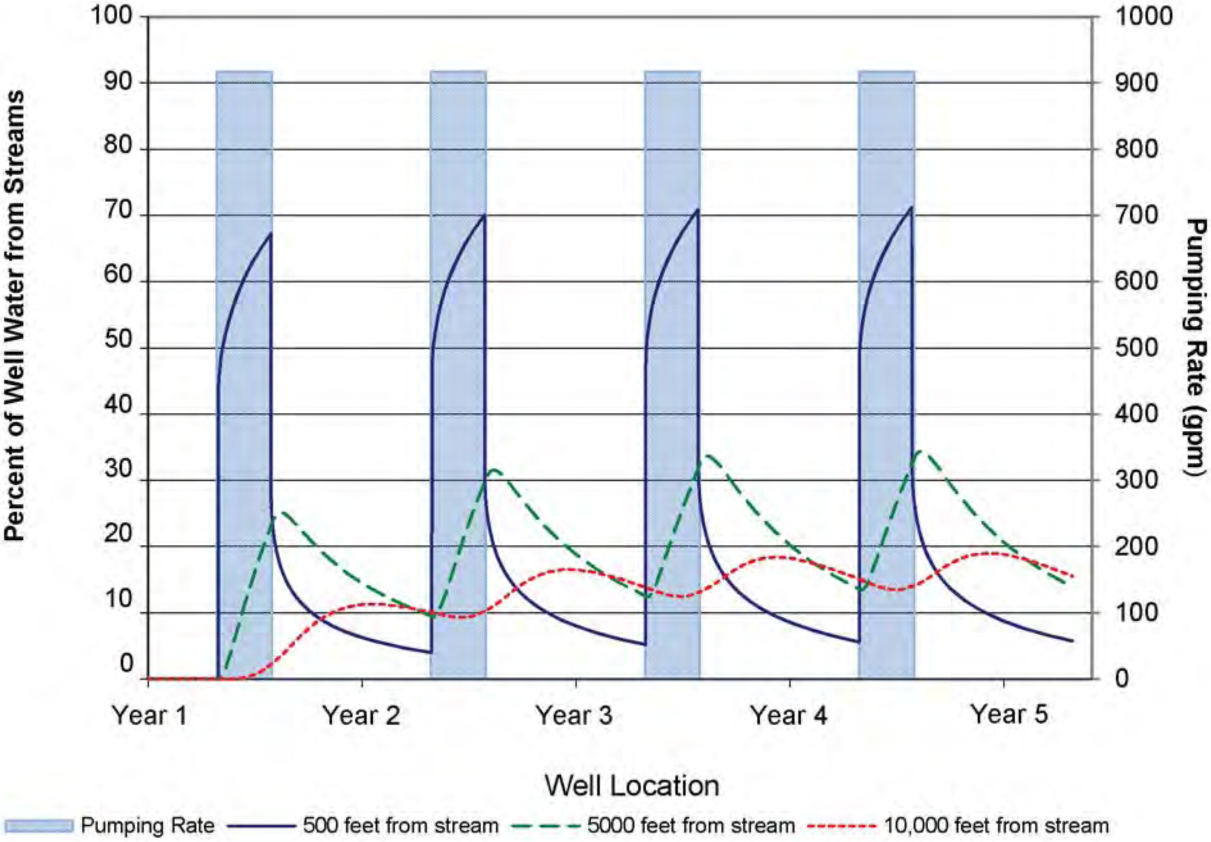


Figure 2. The stream-depleting effects of pumping a well are proportional to the distance between the well and the stream. The amount of depletion increases with each pumping cycle until a new dynamic equilibrium is reached.

the Tendoy, Snowcrest, and Blacktail Ranges to the south (fig. 1). A major tributary to the Beaverhead River is Grasshopper Creek, which flows towards the southeast, joining the Beaverhead River above Barretts Diversion. Blacktail Deer Creek flows to the northwest in a northwest–southeast-trending valley that is nearly at right angles to the Beaverhead River Valley, joining the Beaverhead River near Dillon. Rattlesnake Creek flows towards the southeast and also joins the Beaverhead River near Dillon.

North of Dillon to Beaverhead Rock, a distance of about 16 miles, Stone Creek and Spring Creek flow into the Beaverhead River from the Ruby Mountains to the southeast. From Beaverhead Rock to Twin Bridges, the Ruby River flows into the Beaverhead River from the Ruby Mountains.

In the Dillon area, the valley is about 2 miles wide, increasing to a maximum of about 3 miles to the north. The floodplain is bounded to the east and west by thick sequences of sediments that form benches. These benches are referred to in this report as the East and West Benches. The East Bench refers to land on the east side of the river with a relief of about 80 to 100 ft above the floodplain. The West Bench refers to land on the west side of the river with a relief of about 20 to 40 ft above the floodplain.

At Beaverhead Rock, the floodplain is less than a quarter-mile wide and is constricted by bedrock. The river valley ranges in elevation from 5,100 ft in Dillon to about 4,800 ft near Beaverhead Rock.

Geology

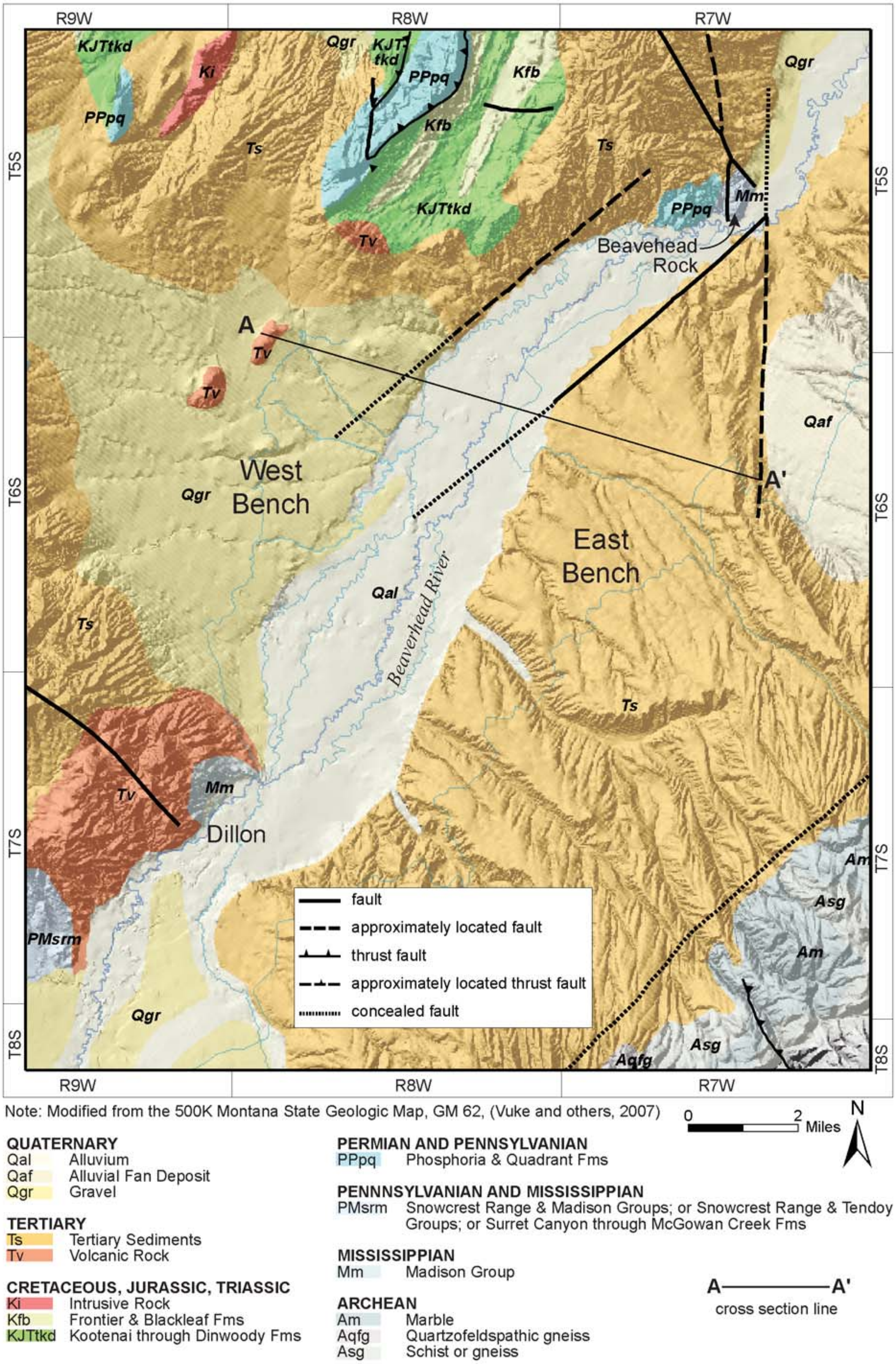
Most of the bedrock associated with the Pioneer, Ruby, Tendoy, Snowcrest, and Blacktail Ranges that border the Beaverhead River Basin is composed of crystalline metamorphic rock and folded and faulted Paleozoic and Mesozoic sedimentary rocks. The structural controls in the Beaverhead Valley are the northeast-trending Ruby Fault Zone along its southeast side (Ruppel, 1993), and in part the northeast-trending faults in the river valley (Ruppel and others, 1993). The Blacktail Deer Creek Valley is controlled by the northwest-trending Blacktail Fault Zone (Ruppel, 1993). The July 25, 2005 Dillon earthquake and other recent seismic activity in the area are indications that some of the faults in the basin are active (Mike Stickney, MBMG Seismologist, oral commun., 2011).

By Beaverhead Rock, a northwest-trending fault zone bisects the basin (fig. 3). In this area, faulting has brought the Madison Limestone (Mm) to the surface, constricting the floodplain. Permian and Pennsylvanian age rocks consisting of mudstone, siltstone, and limestone are also exposed in this area.

The valley fill between Dillon and Beaverhead Rock may be about 1,000 ft thick (R. Thomas, Professor of Geology, Western Montana College, Dillon, Montana, oral commun. 2011). The main geologic units within the study area are the Quaternary deposits that underlie the Beaverhead River, the valley bottom, and tributaries (Qal), and the Tertiary sediments (Ts) that form the upper benches and underlie the Quaternary deposits in the floodplain. The Quaternary deposits consist mainly of clay, silts, sands, and gravels deposited from the modern fluvial system.

The two main Tertiary units in southwestern Montana are the Renova and Six Mile Creek Formations. The following summary is from Fritz and others (2007). The Renova Formation consists of volcanic flows and volcaniclastic sediments of Middle Eocene to Early Miocene age. The Renova Formation was deposited in a basin surrounded by volcanic fields and includes sedimentary facies of sandstone, conglomerate, lignite, and limestone deposited in lakes and streams. The formation thins from west to east (about 10,000 ft in the Lemhi Valley, Idaho to about 1,300 ft in the Ruby Valley). Deposition occurred on a low-relief floodplain with a large fluvial alluvial system in the west grading into a lacustrine system in the east, resulting in fine-grained, low-permeability material.

During middle Miocene, the basin was segmented into several grabens by basin and range style faulting. Sequences of non-volcanic and volcanic sediments known as the Six-Mile Creek Formation filled the Beaverhead and other grabens in southwest Montana during the middle Miocene to late Pliocene. The Six-Mile Creek Formation is generally coarser-grained than the underlying Renova Formation and consists of mudstone, siltstone, conglomerate with local occurrences of limestone,



Note: Modified from the 500K Montana State Geologic Map, GM 62, (Vuke and others, 2007)

Figure 3. The study area includes mainly Quaternary and Tertiary sediments. Tertiary volcanic rock outcrops near Dillon and on the West Bench.

volcanic fallout ash, pyroclastic ash flow tuffs, fallout tuffs, and basalt flows. The Six Mile Creek Formation is generally thickest near the axis of the valleys and thins as it overlaps the uplands.

In the northern section of the West Bench and near Dillon, volcanic rock outcrops in the area and also has been identified in several well logs. The volcanic rock has been identified as rhyodacite (Dick Berg, MBMG geologist, oral commun., 2011) and is Tertiary age (Ruppel and others, 1993). The volcanics have intruded through older rocks and are overlain by Tertiary sediments. A few well logs in the area indicate the volcanics may also interfinger with the Tertiary sediments.

Hydrogeologic Setting

Groundwater within the study area occurs within three main aquifers, the shallow alluvium that underlies the Beaverhead River Valley, the Tertiary sediments, and the volcanic rock. The Tertiary sediments underlie the alluvium and also blanket the East and West Benches. The geologic map for the area (fig. 3) indicates Quaternary sands and gravels (Qgr) overlying the Tertiary sediments on the West Bench. The Quaternary/Tertiary contact is not well defined and the depositional setting during both periods of time were probably similar. For this reason, the Quaternary sediments that blanket the West Bench are considered part of the Tertiary sediment aquifer within the study area. The volcanic rock outcrops on the West Bench and is capable of producing large amounts of water with minimal drawdown.

Groundwater flow from the Tertiary sediment aquifer moves from the East and West Benches towards the valley bottom. Groundwater in the Tertiary sediments and the shallow alluvium then moves towards the northeast. Faulting near Beaverhead Rock has brought the Madison Limestone to the surface and constricts the valley, forcing groundwater to discharge to the Beaverhead River. The groundwater/surface-water budget, the role of evapotranspiration, irrigation field and canal recharge, and pumping from non-exempt and exempt wells on the hydrogeology were not well documented prior to this study. In addition, a predictive groundwater flow model was not publicly available.

Climate

Average annual precipitation in Dillon is 13.17 in, based on a 111-yr period of record, and the 30-yr annual average is 11.46 in (1981–2010) as recorded by the University of Montana-Western weather observation station (Western Regional Climate Center (WRCC), 2011). This station is located within the study area in Dillon. In general, precipitation was above average from 1900 to 1930 (fig. 4). Starting in the 1930s, during the Dust Bowl to 2007, most of the annual precipitation is below the long-term average. Only 17 years during that 77-year period had annual precipitation greater than the average. With the exception of the past 2 years, there have not been any years in the past decade with above average precipitation, and 7 of those years the deviation below normal was 3 inches or greater. Most of the rainfall, nearly half of

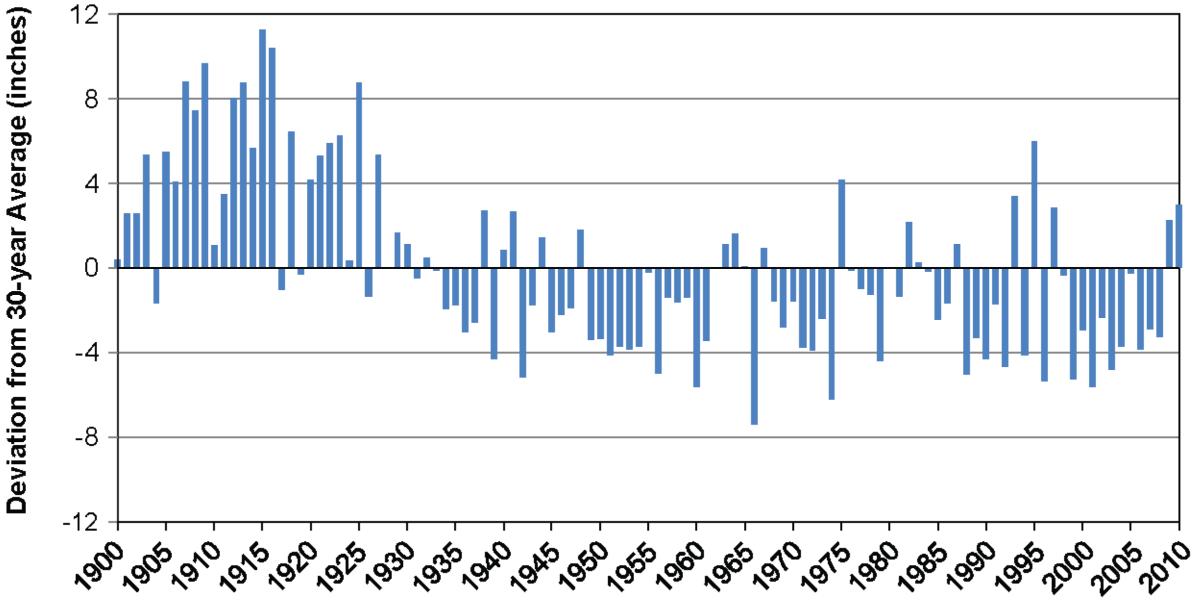


Figure 4. Annual precipitation has been below the long-term average for most of the last 80 years. Since 1930 there have only been three times when the annual total precipitation has been above the long-term average for two consecutive years.

the annual average, occurs from April through July. The average monthly maximum temperature over the period of record occurs in July (83.3°F), and the average monthly minimum temperature in January (12.6°F).

The average annual snowfall in Dillon is 37.3 inches based on the 111-yr period of record (WRCC, 2011). On average, almost 90% of this snowfall can be expected to occur from November through April.

Located about 20 miles northwest of Dillon, at an elevation of 8,300 ft, is the Mule Creek SNOTEL (Snopack Telemetry) station. These stations measure snowpack and other climatic information in order to aid water supply forecasts throughout the western states. Water-equivalent data (31-yr record) indicate that the annual average maximum water-equivalent is 17.36 in for this site (ranging between 10.1 and 26.7 in; SNOTEL, 2011). The average date for the maximum water-equivalent is May 11th (ranging between April 18th and May 31st), and an average date for the disappearance of the snowpack is June 15th (ranging between May 29th and July 4th), giving an average of 35 days for complete melting of the accumulated snowpack.

Irrigation Infrastructure

Two main irrigation canals divert water from the Beaverhead River to the East and West Benches. The East Bench Canal is operated by the East Bench Irrigation District and the West Side Canal is operated by the Clark Canyon Water Supply Company. The 53-mile East Bench Canal, completed in 1964, provides full irrigation service to 21,800 acres and supplemental service to 28,000 acres (U.S. Bureau of Reclamation, 2011) on the East Bench. The canal diverts water at Barretts Diversion Dam 11 miles downstream from the Clark Canyon Dam. The full capacity of the canal is 440 cubic feet per second (cfs) and it extends about 21 miles through the study area.

The West Side Canal supplies water to about 6,855 acres along the West Bench with a capacity of approximately 160 cfs. This canal diverts water from the Beaverhead River at Dillon and extends about 14 miles.

Previous Studies

Uthman and Beck (1998) performed a hydrogeological study in the upper Beaverhead Basin south of Dillon, encompassing the Blacktail and Rattlesnake Creek drainages, to study the effects of groundwater development on groundwater and surface-water availability. They defined three aquifers in their study area: a Pre-Cenozoic bedrock aquifer that provided recharge to the valley-fill aquifers, a lower Tertiary aquifer that produced low water yields, and a coarser Quaternary/upper Tertiary aquifer. Groundwater monitoring revealed that water levels were stable from 1991 to 1996, but responded to seasonal recharge. They noted that in irrigated areas, drawdown occurred in the summer in response to pumping but rapidly recovered after irrigation ended.

Uthman and Beck (1998) used a groundwater flow model to assess the interaction between surface water and groundwater. One modeled scenario simulated the elimination of all irrigation well withdrawals; the second scenario doubled the irrigation well withdrawals; a third scenario simulated a severe 3-year drought; and the fourth scenario increased the amount of irrigation recharge while eliminating irrigation well withdrawals. The predictive model results indicated that, in each of the hypothetical scenarios, baseflow to the Beaverhead River and its tributaries varied only slightly from the baseflow of the initial model. Thus, they concluded that withdrawing water from the aquifer system did not substantially affect baseflow accretions. A comparison of the third (drought) scenario and fourth (irrigation-recharge) scenario revealed that the 3-year drought had less effect on baseflow accretions than irrigation return flow.

Based on both the study's field and model results, Uthman and Beck (1998) concluded that large amounts of water could be withdrawn from the Quaternary/upper Tertiary aquifer without causing widespread drawdown of groundwater levels or depletion of the surface-water system.

Sessoms and Bauder (2005) used a water balance approach to predict and estimate stream flows in the Beaverhead River. Although there were multiple smaller diversions, tributaries, and sloughs that were not monitored and not accounted for in the predicted water balance, they estimated unaccounted sources and losses of water to the river. Within this Ground Water Investigations Program (GWIP) study area, they indicated that the river lost water between Dillon and about 7 miles downstream (where Anderson Lane crosses the river) and then gained water from there to Beaverhead Rock. The gain in flow between Anderson Lane and Beaverhead Rock was consistent throughout the monitoring period (May–October 2005), and cumulative gains in flow during this period were 28,930 acre-ft.

Warne and others (2006) monitored 15 irrigation diversions, most of which were along the Beaverhead River. They determined that there were discrepancies between diversion amounts reported by the Clark Canon Water Supply Company and cumulative calculations by Warne and others (2006). Company estimates were at least 800 acre-ft less than those measured by Warne and others (2006) (from May 5 to September 30, 2006). To assess the efficiency of the East Bench Canal, 10 monitoring sites were established above and below check stations. Although there were some difficulties with placement of monitoring equipment within the canal, they determined the greatest cumulative loss, 682 acre-ft per mile, occurred in a 13-mile reach within the present GWIP study area. This represents an average loss of 2.3 cfs/mile (June 1–September 10, 2006).

Weight and Snyder (2007) determined that groundwater levels in the Dillon area declined 2 to 5 ft from 1995 to 2005 as a result of a 7-year drought and the shutdown of the East Bench Canal from July 2003 to May 2005. Based on a potentiometric surface map (May 2006), Weight and Snyder concluded that the Beaverhead River loses water to the groundwater system until after its confluence with Stone Creek. North of Stone Creek to Beaverhead Rock, the valley constricts and groundwater is forced up to the surface, enhancing the wetlands near Beaverhead Rock.

The U.S. Bureau of Reclamation (2008) examined seepage losses along the East Bench Canal during May and August 2007. Variability in seepage rates between May and August were attributed to factors such as bank storage capacity, suspended sediments in canal water, ground-water levels and their relation to aquifer storage capacity, varying canal discharge amounts, and permeability of soils lining the canal. The average seepage loss in May was about 4 cfs/mile, with a maximum loss of 7.9 cfs/mile measured in a 2.4-mile reach. During August 2007, the average canal loss was about 2 cfs/mile, with a maximum loss of 4.7 cfs/mile in a 3.1-mile reach.

The MBMG investigated the Lower Beaverhead River Valley as one of three studies of closed basins in Montana to assess the range of potential impacts of groundwater development on surface flows (MBMG, 2008). The investigation focused in the northern part of this GWIP project area about 3 miles upstream from Beaverhead Rock, including the East Bench. The hydrogeologic investigation resulted in improved knowledge of the spatial extent of the hydrogeologic units in the study area, aquifer interaction, estimates of aquifer properties, and groundwater flow gradients.

The MBMG (2008) used field data as inputs to a groundwater model to simulate pumping scenarios in the floodplain and East Bench and to examine their effects on stream depletion. Pumping a near-stream shallow well showed an immediate and direct effect on the stream. In this case, the stream depletion rate reached the pump discharge rate quickly and continued to expand after pumping stopped. Depletion was also evaluated from four wells completed in the deeper aquifer at varying distances from the river and one well completed in the alluvium. A repeated cycle of pumping resulted in a trend of decreasing stream discharge because the stream never fully recovered from the previous pumping cycle. Pumping a well in the deeper aquifer at 1,800 ft from the river for 30 days at 850 gpm showed that stream depletion was about 18% of the total well discharge, while pumping at 20,000 ft from the river showed that stream depletion was less than 1% of the total well discharge. When the well completed in the alluvial aquifer 150 ft from the river was pumped at the same rate and period (850 gpm for 30 days), it showed that stream depletion was 94% of the total well discharge. This reflects the higher transmissivity of this aquifer and close proximity to the river.

METHODS

Data collection efforts were designed to better characterize the hydrogeology and provide data that are needed to develop a water budget for the study area. This information was also used to assess the impacts of groundwater pumping on surface water. A groundwater flow model was used to simulate long-term pumping on the West Bench and evaluate the timing and magnitude of stream depletion in several sloughs and the Beaverhead River.

Data Management

Data collected during this study are permanently archived in the MBMG Groundwater Information Center (GWIC), http://mbmggwic.mtech.edu/. Within GWIC, data are grouped into project areas. This allows those interested in a particular project to easily access information. The Beaverhead River Project is found on GWIC's Projects page under Groundwater Investigation Program (http://www.mbmg.mtech.edu/gwip/gwip.asp).

Groundwater and Surface-Water Monitoring

A total of 172 monitoring sites were used for this study, including 155 wells and piezometers, and 17 surface water and irrigation canal sites. Water levels, hydrographs, water chemistry, flow rates, and other pertinent data were collected at the sites. Sites referred to in this report are denoted by the site's GWIC identification number for wells (e.g., well 242417) and for surface water (e.g., site 242228). Details on the monitoring sites are included in appendix A. All sites were surveyed for accurate location and elevation. The wells monitored for this study were domestic, stock, irrigation, 32 monitoring wells installed specifically for this project, and wells installed from a previous MBMG study (MBMG, 2008; fig. 5). Depth to groundwater was manually measured at regular intervals throughout the study period. Twenty-five groundwater monitoring sites were equipped with pressure transducer data loggers (referred to as pressure transducers throughout the report) that measured groundwater levels hourly.

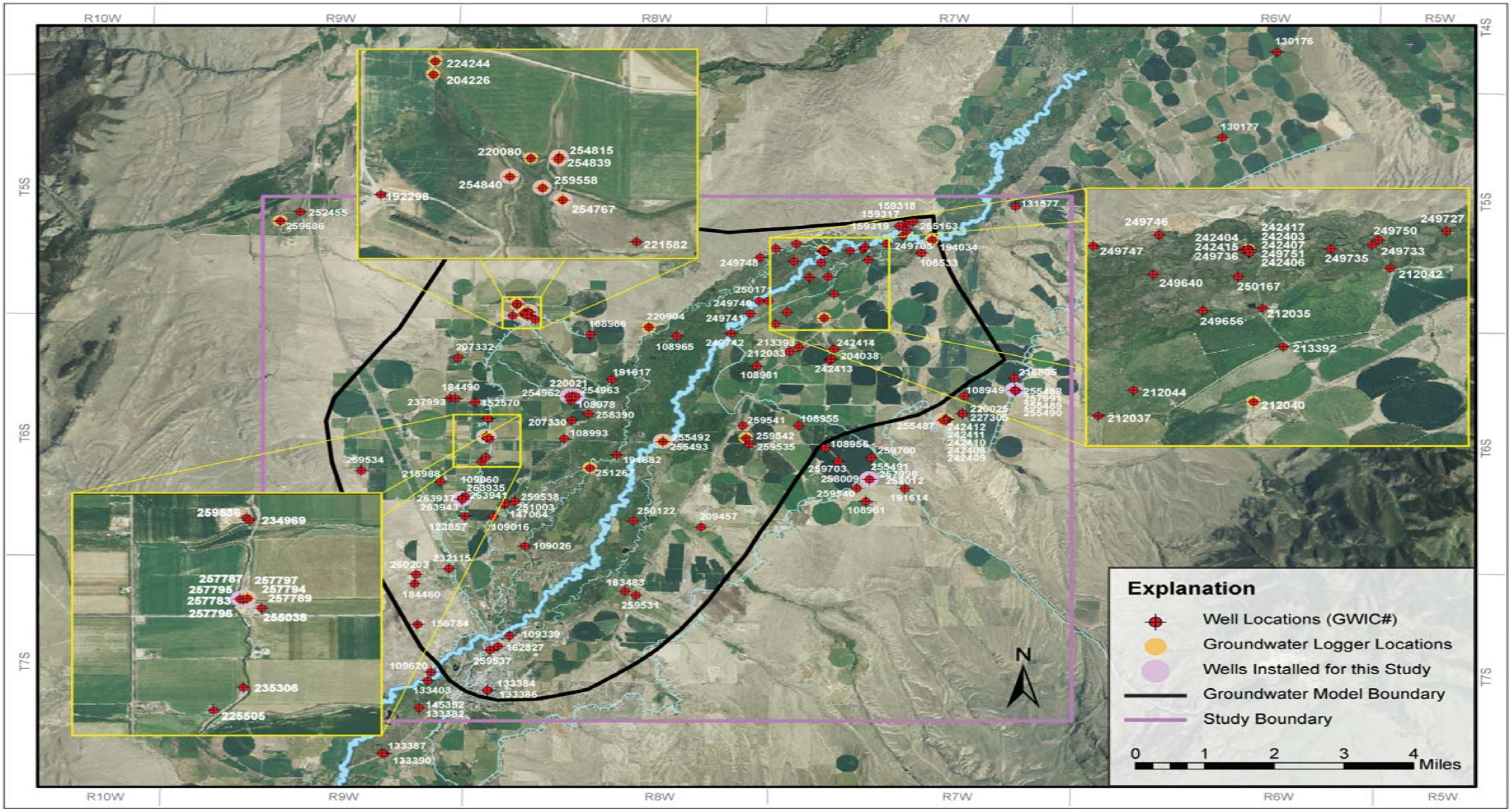
Seventeen surface-water sites were monitored for discharge and stage at major inflows to the Beaverhead River, several smaller sloughs on the West Bench (Black, Willard, and Albers), and a ditch near Beaverhead Rock (fig. 6). Data were also obtained from two United States Geologic Survey (USGS) gauging sites on the Beaverhead River (USGS 06017000, site 147977, and USGS 06018500, site 242525). Two additional sites were monitored by the MBMG along the Beaverhead River at Anderson Lane (site 247284) and at about 3 miles upstream from Beaverhead Rock (site 242228). These two sites were equipped with pressure transducers to measure and record stage hourly. Flows at the other surface-water sites were measured monthly, or every 2 weeks during the end of spring through summer 2010.

Aquifer Testing

Two constant-discharge aquifer tests were performed within the project area to estimate the hydraulic conductivity (K) of the Tertiary sediment and volcanic rock aquifers and to examine potential effects on surface water during pumping. During each test one well was pumped for 3 days and water levels were recorded in the pumping well and in the observation wells for the duration of pumping, and during recovery after the pump was turned off. Pressure transducers were installed prior to the start of the tests to measure background water levels and were left in place after the tests ceased, to measure recovery water levels. Transducer data were corrected for barometric fluctuations. All water-level data are available in the MBMG GWIC database. A digital flow meter was used to record flow rates and the total amount of water pumped for each test. Groundwater and surface-water monitoring locations for the Tertiary sediment and volcanic rock aquifer tests are shown in figures 7 and 8, respectively. Detailed aquifer test information is presented in appendix B.

Hydrogeologic Setting

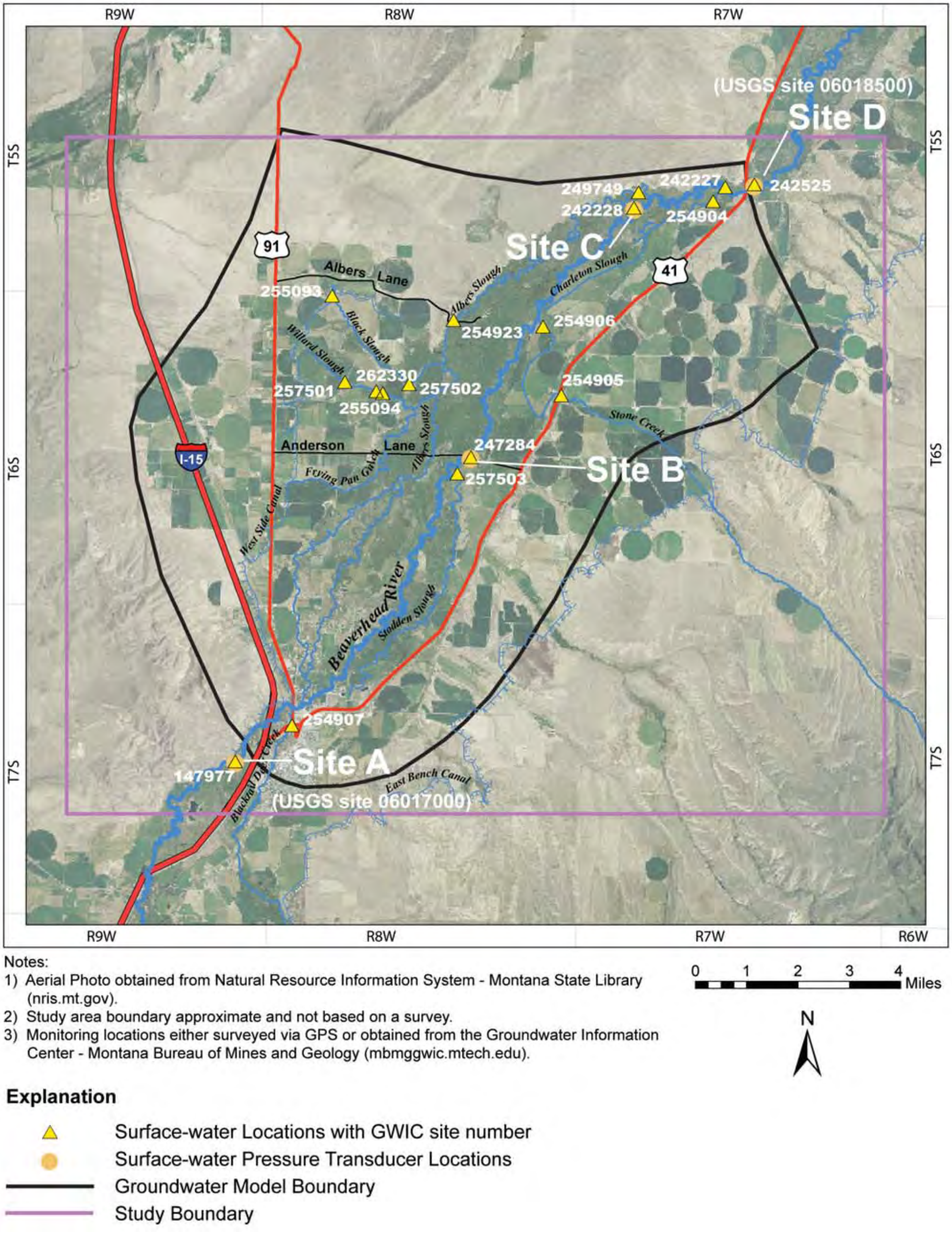
The aquifers were mapped using geologic maps and driller's logs. The elevation for each driller's log was obtained by using online elevation software with an accuracy of ±5 ft (GPS Visualizer, 2011). Driller's logs are somewhat limited because the geologic descriptions can be inconsistent or inaccurate, and well locations may be recorded poorly. Some interpretation is necessary when working with driller-provided information.



Notes: 1) To avoid additional label clutter, only one GWIC number was listed in nested wells. These additional wells were also used in the study: wells 238662 and 238663 are associated with 212042; wells 238652 and 238653 are associated with 212035; wells 238696 and 238698 are associated with 212044; and wells 238708 and 238709 are associated with 212037.

2) Groundwater data loggers were installed only during aquifer testing in wells 220021, 254962, 254840, 254767, 204226, and 259558.

Figure 5. The groundwater monitoring network includes private wells and dedicated monitoring wells.



Notes:
1) Aerial Photo obtained from Natural Resource Information System - Montana State Library (nris.mt.gov).
2) Study area boundary approximate and not based on a survey.
3) Monitoring locations either surveyed via GPS or obtained from the Groundwater Information Center - Montana Bureau of Mines and Geology (mbmggwic.mtech.edu).

Explanation

△	Surface-water Locations with GWIC site number
●	Surface-water Pressure Transducer Locations
—	Groundwater Model Boundary
—	Study Boundary

Figure 6. Sixteen surface-water sites were monitored that include the Beaverhead River, creeks, and sloughs.

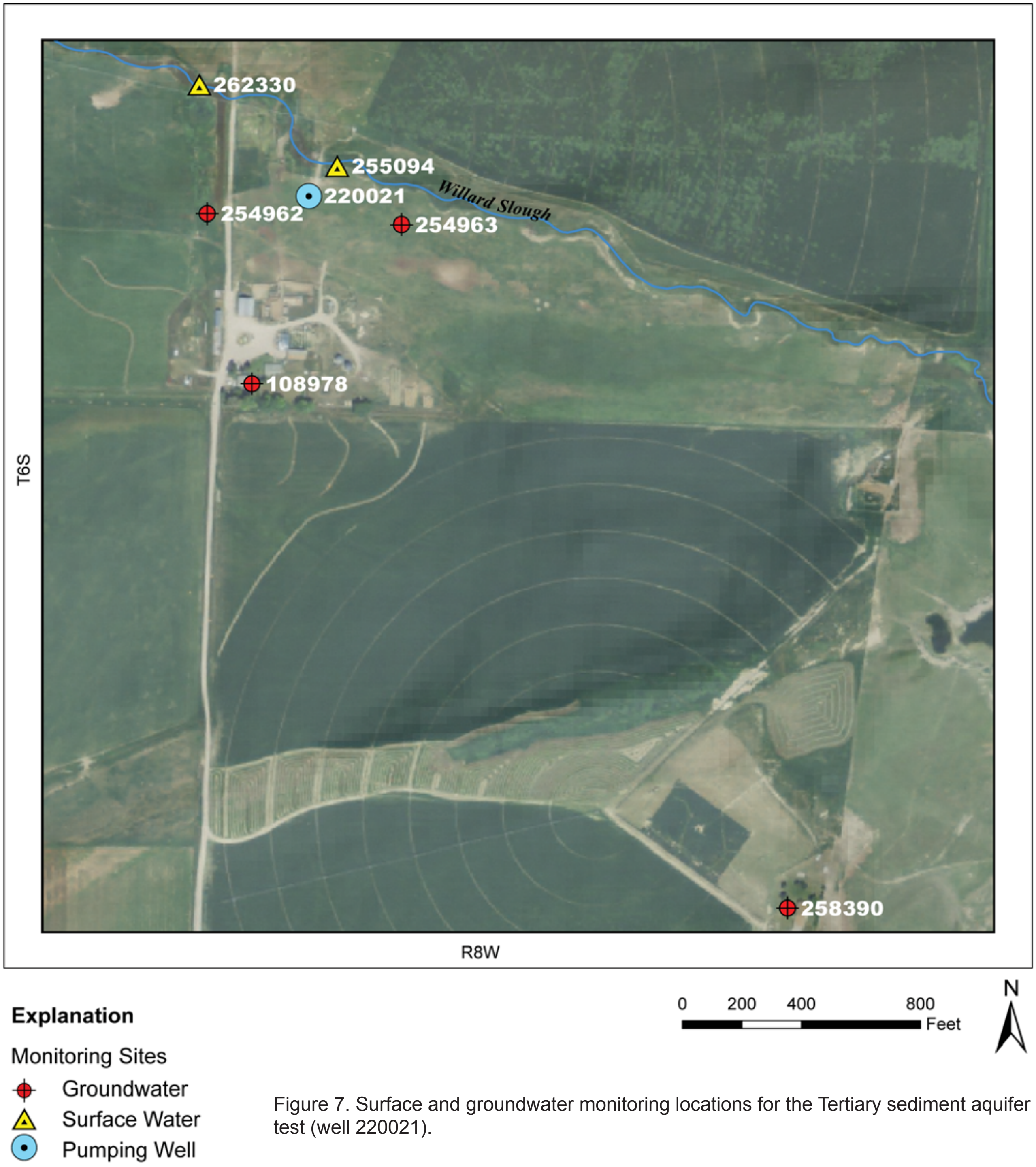


Figure 7. Surface and groundwater monitoring locations for the Tertiary sediment aquifer test (well 220021).

Canal Study

Irrigation canal leakage recharging groundwater and aquifer drainage to canals was investigated at the two main canals in the study area, the East Bench Canal and West Side Canal. Canal seepage values were used in the water budget created for the study area and for the groundwater flow model. The inflow–outflow method was used to determine canal seepage (Sonnichsen, 1993). Additionally, monitoring wells were drilled at two sites along both canals to examine the connection and arrival times of water seeping from the canals into the groundwater. Figure 9 shows the locations of where canal flows were measured using the inflow–outflow method and the four sites along both canals in which monitoring wells were installed (EBC-1, EBC-2, WSC-1, and WSC-2)

Canal Seepage Measurements

Seepage runs were performed on the East Bench Canal on August 2 and August 17, 2010. Six sites were chosen along the East Bench Canal

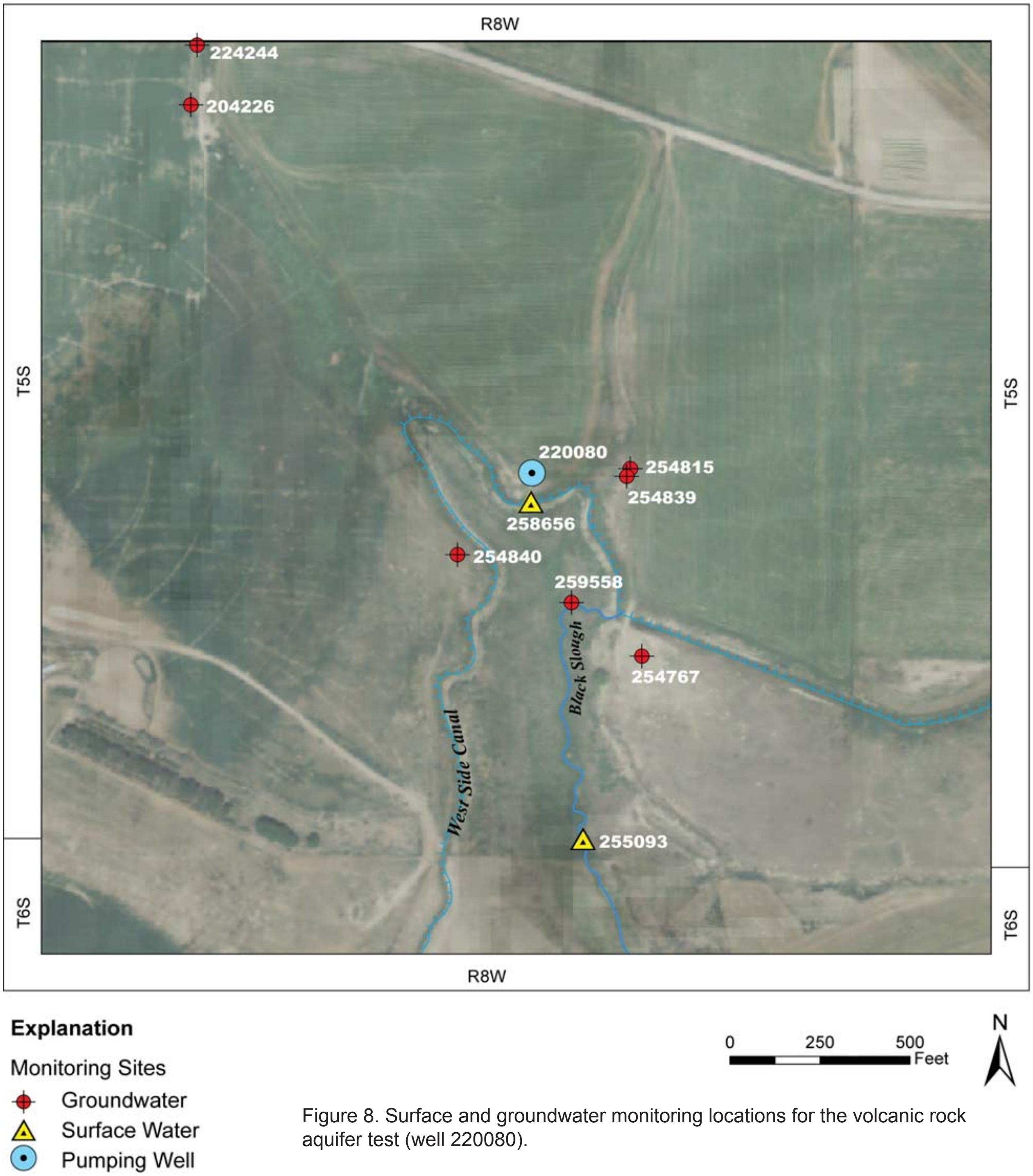


Figure 8. Surface and groundwater monitoring locations for the volcanic rock aquifer test (well 220080).

to measure flows (fig. 9). Two seepage runs were performed on the West Side Canal on July 19 and August 16, 2010. Flow in the West Side Canal was measured at five stations during each event (fig. 9). An acoustic Doppler current profiler was used to measure flows. The manufacturers reported measurement accuracy is ±4%. The amount of water diverted by irrigators between each station was obtained from East Bench Irrigation District records. Diversions are measured with weirs and flumes, and the accuracy of the data are assumed to be ±10%. The rate of loss and gain is expressed as the total loss and gain divided by the distance between two stations (cfs/mile).

Canal Stage—Groundwater Investigation

Monitoring wells were installed and instrumented with pressure transducers to document the effect of canal seepage on groundwater at two sites along the East Bench (EBC-1 and EBC-2) and two sites along the West Bench Canal (WSC-1 and WSC-2; figs. 9–13). A total of 19 wells were installed among the four sites (appendix A).

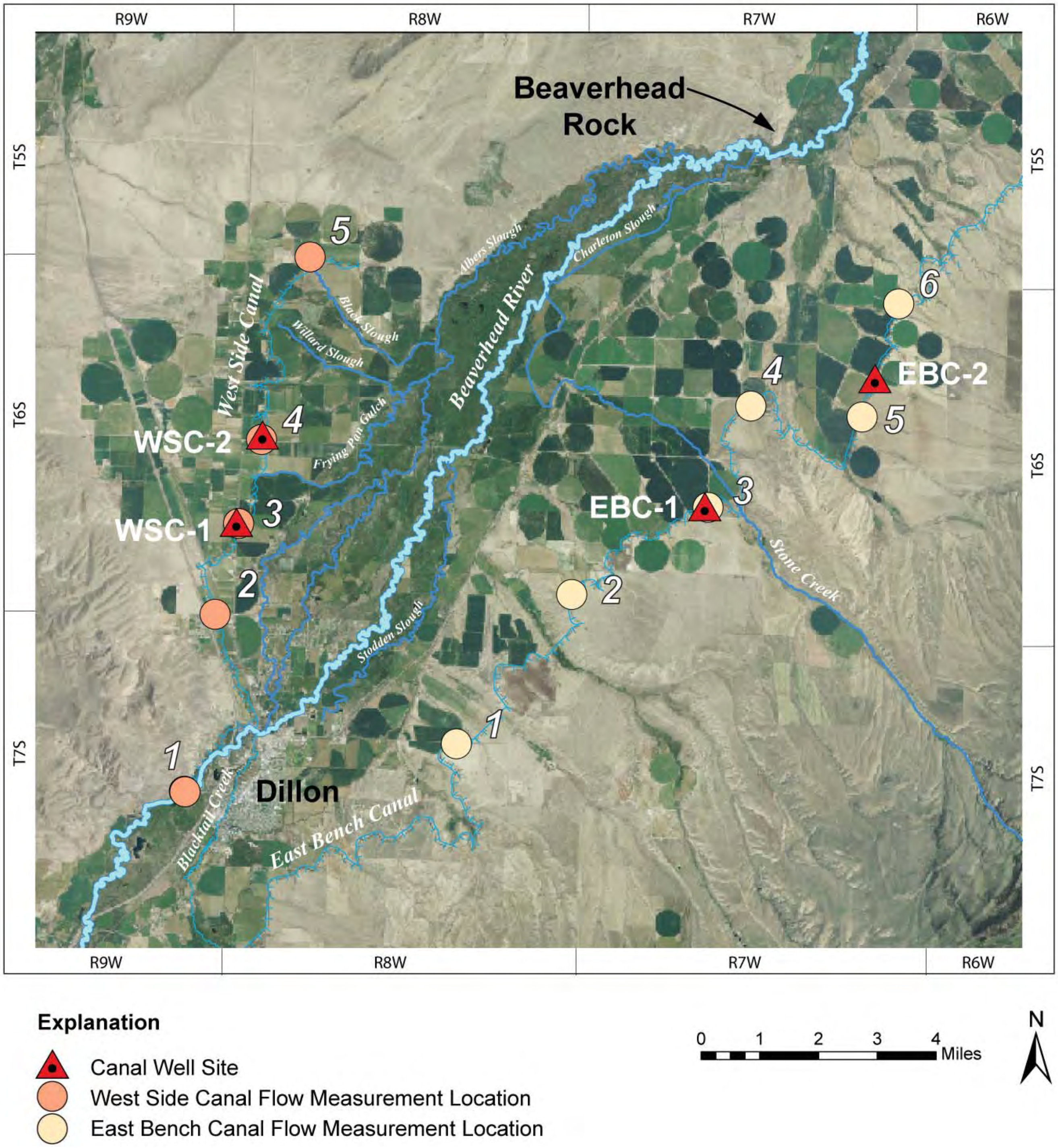


Figure 9. Canal seepage measurements were made at five sites on the West Side Canal and at six sites on the East Bench Canal.

Canal stage was measured by installing staff gauges and pressure transducers at each of the four sites. Surface-water and groundwater levels were measured manually once a week through August, every other week through October, and once during November, December, and April (2011).

Groundwater and Surface-Water Chemistry

Water-quality samples were collected to assess water quality and groundwater/surface-water interaction and to evaluate possible sources of groundwater recharge. Water samples were collected from 33 wells and 13 surface-water locations (appendix C). Water-quality data collected since 2000 as part of other projects are also included in this evaluation. For this study, groundwater samples were mostly collected in March through May 2010 from 17 domestic wells, 2 irrigation wells, 4 stock wells, and 10 monitoring wells. Samples for stable isotopes (^{18}O and D) were collected at each surface-water monitoring site between 8 and 15 times between March 2010 and December 2010.

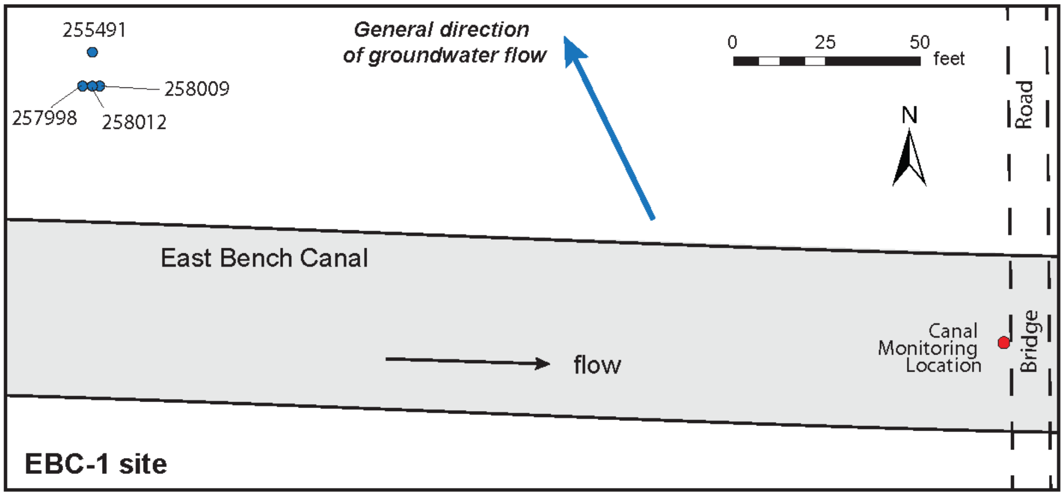


Figure 10. Four monitoring wells north of the East Bench Canal were used for lithologic and hydrogeologic data collection during canal seepage studies at site EBC-1. Refer to figure 9 for site location.

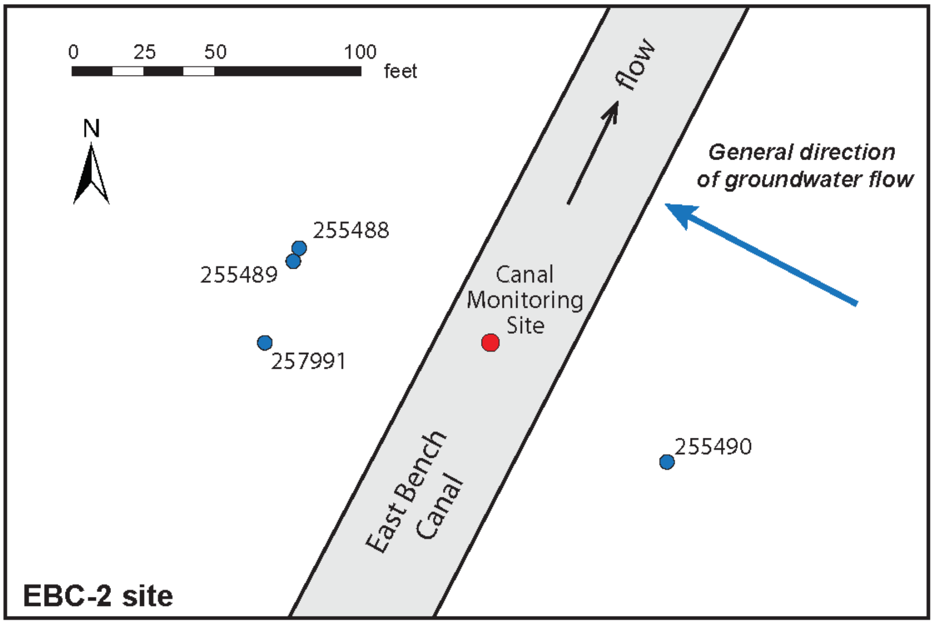


Figure 11. Monitoring wells east and west of the East Bench Canal were used for lithologic and hydrogeologic data collection during canal seepage studies at site EBC-2. Refer to figure 9 for site location.

All samples were collected and handled according to MBMG standard operating procedures. Specific conductance, pH, and temperature were measured in the field. Samples were analyzed for major ions, trace elements, and ^{18}O and D. A subset of samples were analyzed for tritium (^{3}H).

Stream Depletion and Aquifer Drawdown

Stream depletion and aquifer drawdown were investigated using analytical and numerical groundwater flow models and water-quality data.

Analytical Model

An analytical model developed by the Integrated Decision Support Group (IDS) at Colorado State University was used to predict stream depletion using input parameters from the volcanic rock aquifer test (well 220080). This method provides a spreadsheet adapted from the analytical stream depletion model developed by Schroeder (1987). The model computes stream depletion based on a well pumping from an aquifer hydraulically connected to a stream. The model input parameters include pumping rate, transmissivity, specific yield, and the distance from the well to the stream (Integrated Decision Support Alluvial Water Accounting System, 2003). Schroeder's work was based on the analytical solution by Glover and Balmer (1954) and assumes an isotropic, homogeneous aquifer of infinite extent and a fully penetrating well and stream.

Numerical Groundwater Flow Model—Site-Specific

A focused groundwater flow model was developed to incorporate multiple aquifers and to specifically simulate the conditions of the aquifer test performed on well 220080.

MODFLOW 2000 and Groundwater Vistas (version 5.51; Rumbaugh and Rumbaugh, 2007) was used to estimate stream depletion during a 3-day aquifer test based on the idealized hydrogeologic conditions. The model incorporated 100 ft of the Tertiary sediment aquifer (layer 1) with a hydraulic conductivity of 5 ft/day and the upper 200 ft of the volcanic aquifer with a hydraulic conductivity of 200 ft/day. Storativity (S), based on values reported for the aquifer test, were 0.0026 for the volcanic

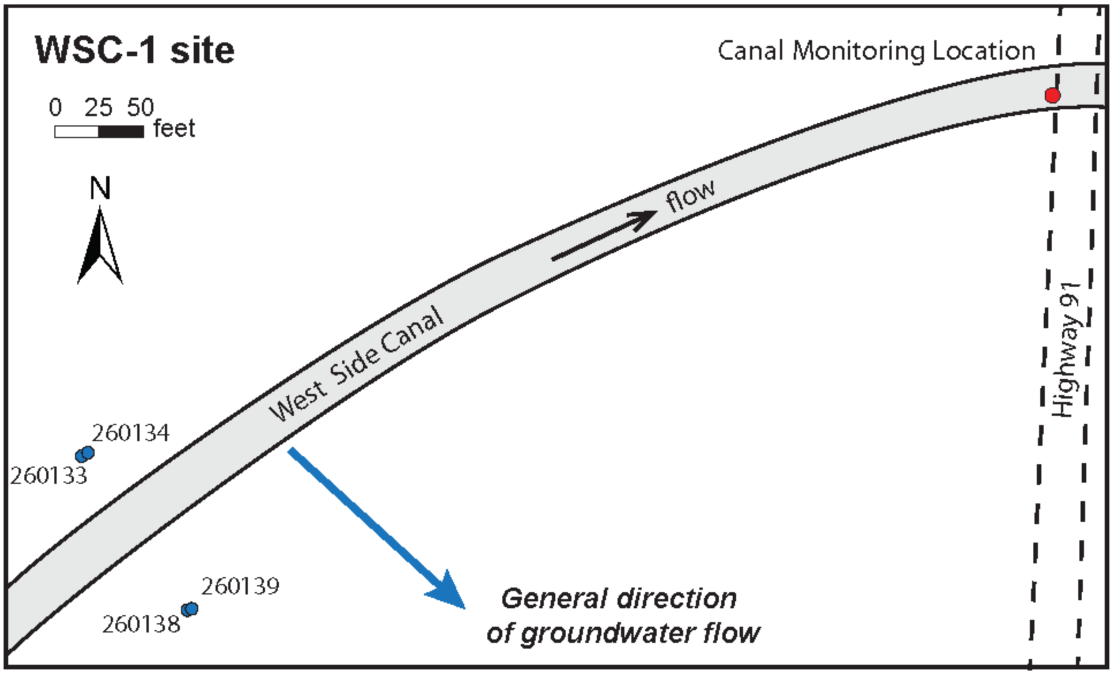


Figure 12. Monitoring wells north and south of the West Side Canal were used for lithologic and hydrogeologic data collection during canal seepage studies at site WSC-1. Refer to figure 9 for site location.

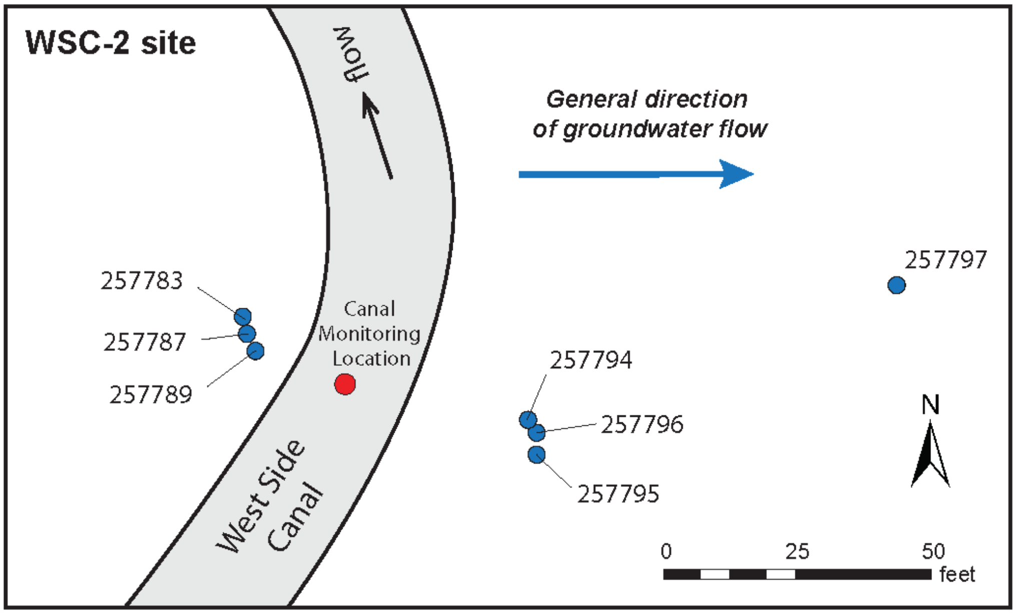


Figure 13. Monitoring wells east and west of the West Side Canal were used for lithologic and hydrogeologic data collection during canal seepage studies at site WSC-2. Refer to figure 9 for site location.

rock aquifer. A value of 0.10 was used for the unconfined Tertiary sediments.

Figure 14 presents details of the 100 by 100 grid model domain with 100 ft equal spacing for a domain of 10,000 ft by 10,000 ft. The general hydraulic gradient of the area, 0.007 ft/ft, was based on data from wells 204226 and 220080 and simulated by using 200 injection wells (well package) for groundwater flux into model and a river (river package, 153 cells) for groundwater flux to a river with a tributary. The model was set up initially as a steady-state model, with no pumping, to establish the hydraulic gradient across the site. The steady-state heads were used as starting heads for the transient simulation, which consisted of three stress periods: (1) 10 days, no pumping to extend steady-state conditions, (2) 3 days of pumping at a discharge rate of 1,422 gpm, and (3) 30 days, no pumping to simulate drawdown and recovery.

Calibration of the model consisted of attempting to match drawdown between the model and monitoring wells after 3 days of pumping; hydraulic conductivity and storage coefficient were narrowly constrained to those reported for the aquifer test. Vertical hydraulic conductivity (held at 10% of horizontal value), anisotropy (none), and streambed conductance (reflective of the shallow aquifer) were not evaluated. The change in flux to the tributary river caused by pumping was used to calculate stream depletion of the tributary.

Numerical Groundwater Flow Model–Study Area

A three-dimensional groundwater flow model of the entire study area was created to help predict impacts of pumping irrigation wells on groundwater and surface water. The model was also used to evaluate canal seepage scenarios to offset stream depletion and groundwater declines that result from groundwater withdrawals. Although the

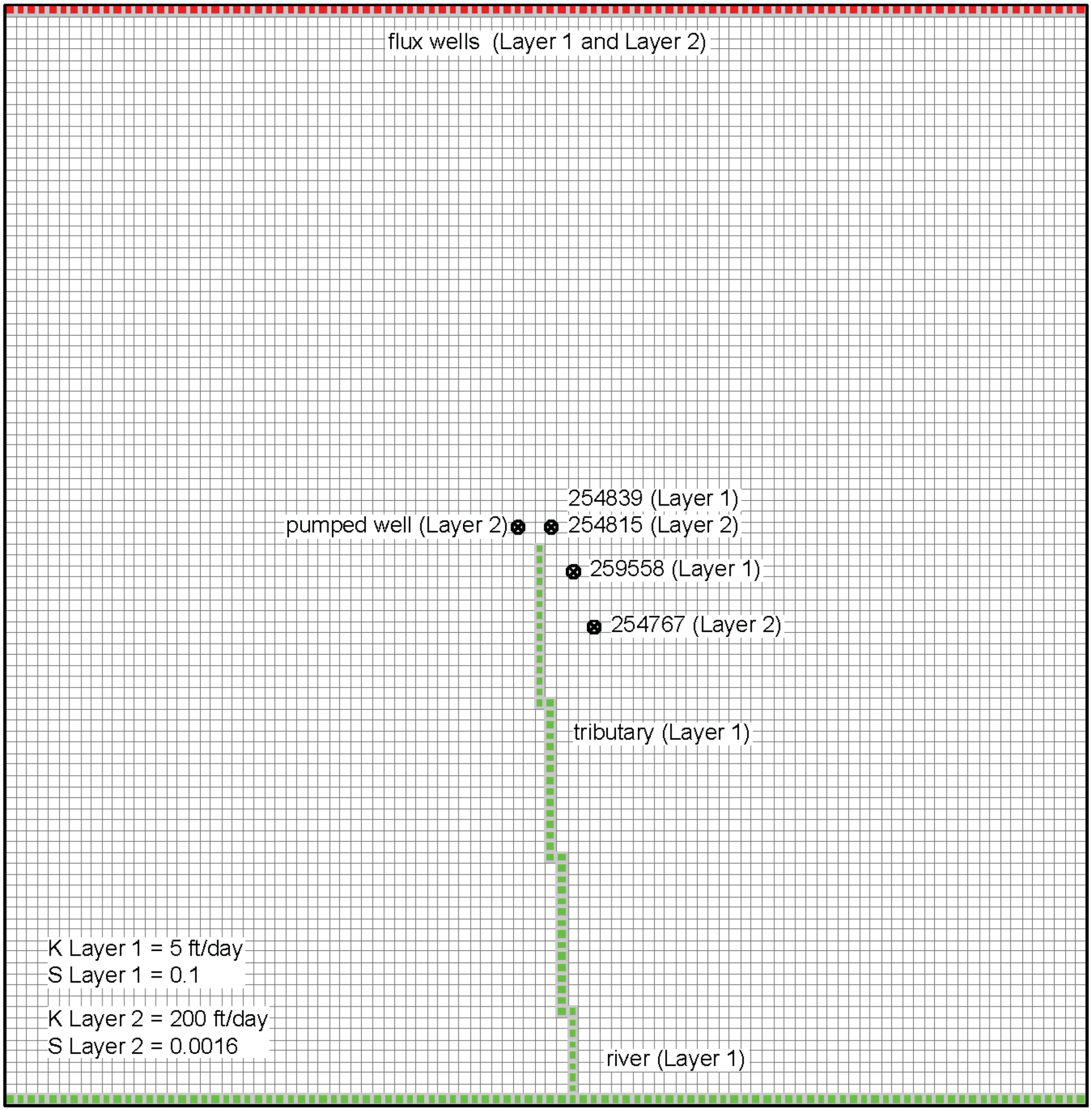


Figure 14. A numeric model of the 3-day pumping test near Black Slough.

model area encompasses the east and west sides of the river, modeling efforts were focused on the West Bench to simulate pumping scenarios in the volcanic rock aquifer and the Tertiary sediments. The effects of pumping were evaluated for Black Slough, Willard Slough, Albers Slough, and the Beaverhead River.

MODFLOW-2000 (Harbaugh and others, 2000) was selected as the modeling program, and GMS (Aquaveo, 2010) served as the user-interface program. The model represents the aquifer system using a three-dimensional grid. Hydraulic properties and stresses were assigned to the model grid to mathematically mimic the groundwater flow system. The Lower Beaverhead Modeling Report (Butler and others, 2013) provides a detailed account of the model. This discussion summarizes the model design and input parameters.

Model Design

The model domain encompasses the main portion of the study area from Dillon to Beaverhead Rock, and includes most of the irrigated area on the East and West Benches (fig. 15). The three-dimensional grid was assigned a uniform horizontal discretization of 200-ft cells in order to optimize grid resolution while reducing model run times. Vertically, the grid thickness was set at 500 ft to approximate the portion of the aquifer in which most irrigation wells are completed (based on reported total depths of irrigation wells). The model was discretized into two layers. The top of layer 1 represents the land surface and was defined by importing data directly from the U.S. Geological Survey 1/3-Arc Second National Elevation Dataset (USGS, 2009). The thickness of layer 1 (top layer) was about 30 ft where the model represents the alluvium in the floodplain, and about 250 ft thick in the East and West Benches where the model represents the Tertiary sediments and volcanic bedrock. This thickness ensured that the maximum depth to groundwater would remain above the bottom of layer 1 and prevent cells from drying. In the floodplain, layer 2 represented the Tertiary sediments underlying the alluvium; as with layer 1, layer 2 represented the Tertiary sediments on the East Bench and a combination of Tertiary sediments and volcanic bedrock on the West Bench. Because the model thickness was held constant (500 ft), the thickness of layer 2 was variable; it was relatively thick in the floodplain (approximately 470 ft) and thinner at the east and west edges of the benches (approximately 250 ft).

Model Boundary Conditions

Boundary conditions represent the sources of recharge and/or discharge to the groundwater flow system, and/or the head at the edges of the modeled domain. (Head refers to the water elevation in a well.) The boundary conditions for this model consisted of four general categories: the model borders, surface-water bodies, aerial recharge (precipitation and applied irrigation water), and well withdrawals (figs. 15, 16).

Specified-flux boundaries were used to represent inflow along the model borders, which include the East and West Benches, and from the upper Beaverhead River basin into Dillon from the south. A specified-flux boundary simulates water inflow or outflow to the aquifer system as a user-defined volumetric rate. Flux values were estimated using a flow net approach, with hydraulic conductivity (K) and gradient values based on aquifer property estimates; the East Bench influx also accounted for recharge due to seepage from the East Bench Canal. At Beaverhead Rock, the floodplain constricts and serves as the area of baseflow exiting the model domain; the Drain Package was assigned to this model border. The Drain Package allows groundwater flow to exit the modeled aquifer either as surface-water flow or as groundwater flow. A no-flow boundary was set along a groundwater flow line along the rest of the north and northeast model border based on the potentiometric map.

A specified-flux boundary was used to represent seepage from the West Side Canal; the flux rate was based on the average rate obtained from two 2010 canal seepage runs. Because the Beaverhead River both contributes (recharges) water and drains (discharges) water from the aquifer system, the MODFLOW River Package was used; this package allows groundwater flow to enter as well as exit the model. The larger sloughs within the study area most likely only drain water from the aquifer system, and were simulated as drains. It should be noted that the River Package and Drain Package of MODFLOW do not calculate stream discharge; the modules are used to calculate the gain or loss of groundwater to those features. Stream depletion from pumping is determined by the change in gain or loss to the surface water.

A groundwater recharge rate was calculated for the irrigated areas within the model as follows:

$$\text{Recharge Rate} = P_{IN} + R_{IRR},$$

where P_{IN} is total precipitation and R_{IRR} is the groundwater recharge from irrigation that was calculated by the NRCS IWR method (Butler and others, 2013). The IWR method considers the recharge rates for three irrigation types: flood, pivot, and sprinkler. In non-irrigated areas within the modeled area, groundwater recharge from precipitation was assumed to be negligible. Irrigation field recharge for much of the floodplain, especially the northern section of the model, was eliminated during the calibration process, as discussed further in the Numerical Modeling—Area-Wide section of the report (under Steady-State Calibration).

Only irrigation wells and public water supply wells were simulated in the model. Pumping rates for the irrigation and public water supply wells were estimated using information from water

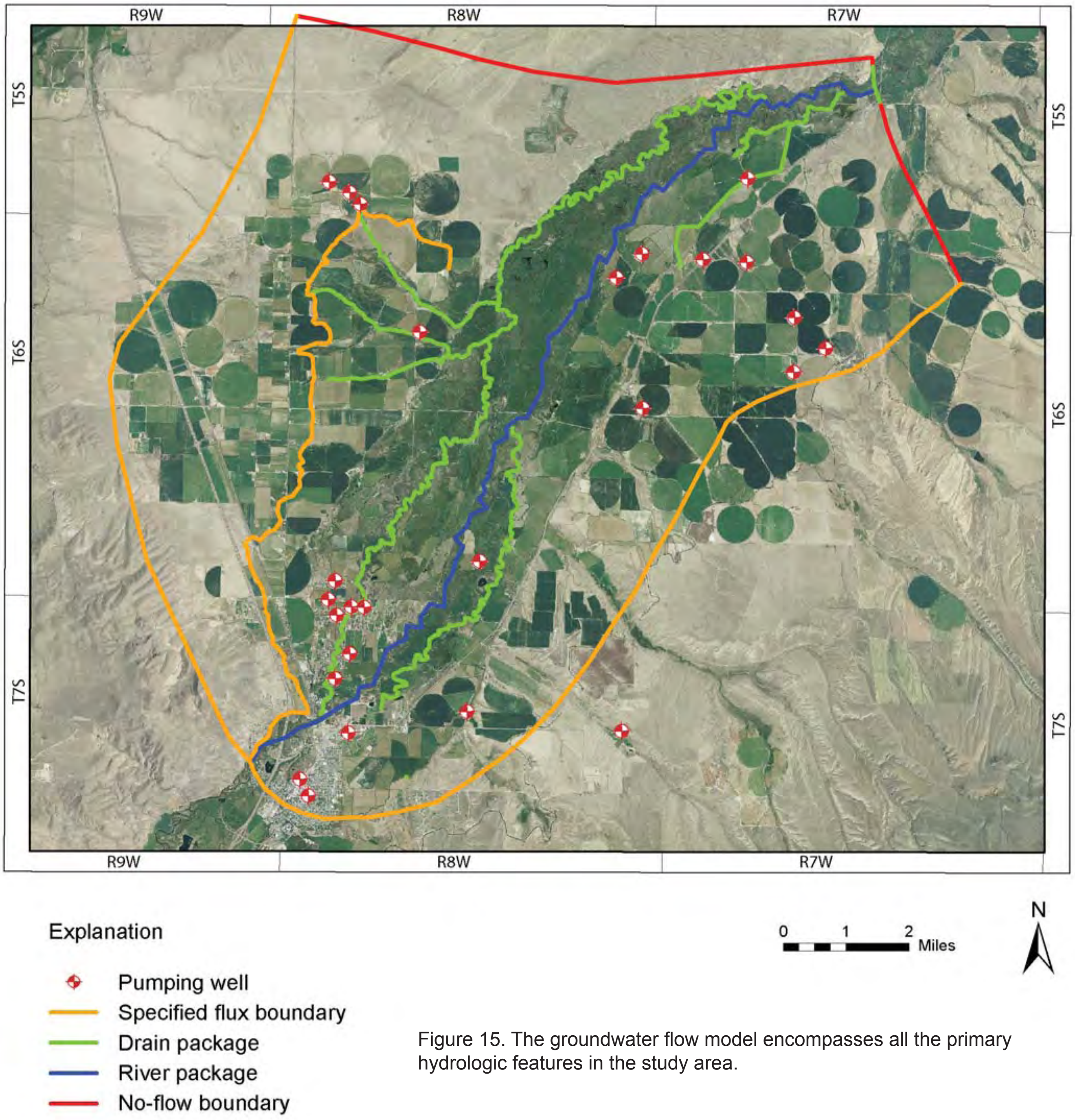


Figure 15. The groundwater flow model encompasses all the primary hydrologic features in the study area.

rights documentation, GWIC, and the Beaverhead County Public Works Division. The wells were simulated using a specified-flux boundary (Well Package).

Model Calibration

Two models were produced for the Lower Beaverhead study area. The steady-state model simulates average annual conditions for all components of recharge and discharge and evaluated the overall budget. Optimal K values were generated as part of the steady-state model calibration. K and S values were initially assigned to polygonal zones in the model based on the aquifer property estimates from aquifer tests performed during this investigation and previous investigations (See Results: Hydrogeologic Setting). Calibration was performed manually and then refined using automated parameter optimization (or PEST). Water-level elevations in 69 monitoring wells from July 2010 were used as calibration targets for the steady-state calibration. The calibration tolerance interval was set at 5% of the overall range in the target value (i.e., the observed water-level elevation) across the model domain, which was ±15 ft.

The transient model includes storativity and

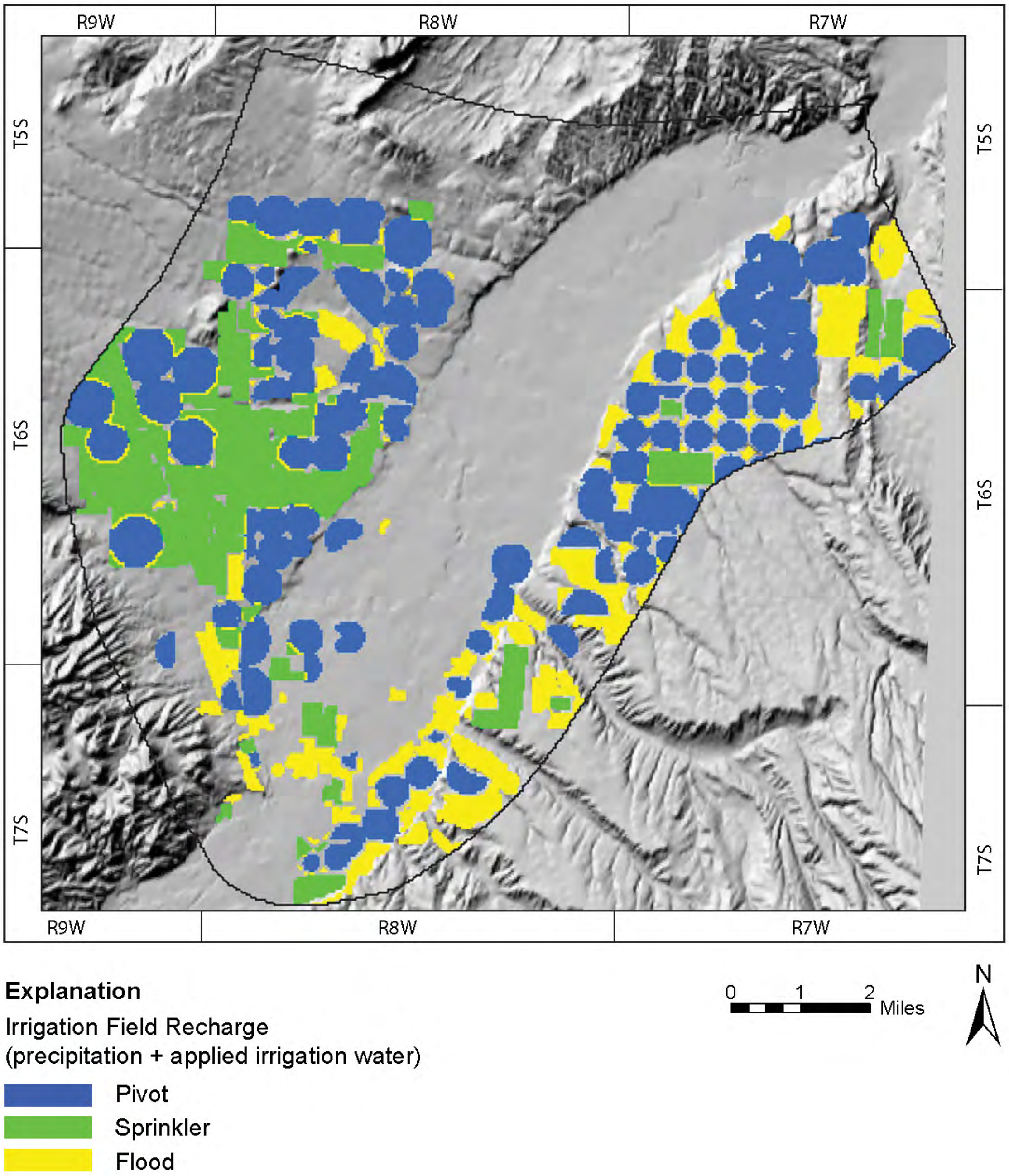


Figure 16. The amount of aerial recharge applied to the model was based on precipitation and applied irrigation water. During calibration, irrigation recharge within the northern part of the floodplain was removed to better fit modeled heads to observation data.

simulated time-dependent stresses such as seasonal irrigation and pumping activities. The calibrated simulation spanned monthly time steps from January through December, 2010, the time period in which the majority of groundwater and surface-water information was collected. The model was calibrated using the same monitoring wells as in the steady-state calibration; however, the number of available water levels varied slightly from month to month. The calibration tolerance interval was the same as that of the steady-state model (±15 ft).

Because modeling stream depletion was one objective, stream baseflow was also used as a calibration measure in the steady-state and transient models. Baseflow is the component of stream flow supplied by groundwater (Fetter, 2001). Calibration efforts were focused on the sloughs used in the pumping scenarios (Black, Willard, and Albers Sloughs). For each slough, flow measurements from an upstream and downstream location measured during the non-irrigation season were used to determine a gain in flow per mile. This baseflow amount was projected over the stream distance featured in the model and used as a calibration target for each slough. A difference of 15% or less between this value and the model results was considered reasonable.

Pumping and Canal Seepage Scenarios

Pumping scenarios were simulated with the transient model to help predict the effects of pumping high-capacity wells in the volcanic rock and Tertiary sediment aquifers on surface water and groundwater. Three canal seepage scenarios were also modeled to simulate the additional groundwater recharge by extending flow in the canal into the pre- and/or post irrigation season.

The first scenario was the baseline scenario and featured only the pumping wells from the transient model, pumping at their assigned 2010 rates throughout the 20-year simulation. The results of each subsequent scenario were compared to those of the baseline scenario in order to predict stream depletion and groundwater drawdown due to pumping. Canal seepage scenarios were compared to baseline and the pumping scenario results to examine how the additional groundwater recharge offset stream depletion. Stream depletion was examined in the Beaverhead River, Black Slough, Willard Slough, and Albers Slough. All scenarios were run for 20 years. Table 1 provides a description of the modeling scenarios.

RESULTS

Aquifer Tests

Two aquifer tests were performed to determine transmissivity, hydraulic conductivity, and storativity values for the Tertiary sediment and volcanic rock aquifers. Further details on the aquifer test design, data analysis, and results are presented in appendix B. Results from these aquifer tests compare well with, and augment, previous test results in the area.

Tertiary Sediment Aquifer

Irrigation well 220021 was pumped for 72 hours (May 18–21, 2010) at 300 gpm. Water levels were measured in monitoring wells 254962 and 254963, shallow domestic wells 108978 and 258390, and two locations on Willard Slough (fig. 7).

Maximum drawdown in the pumping well was about 230 ft; drawdowns in wells 254962 and 254963 were about 42 and 34 ft, respectively. There were no observed drawdowns in shallow wells 108978 and 258390, and no apparent influence to surface water at either of the Willard Slough monitoring locations.

Aquifer Properties

Transmissivity estimates obtained using the Cooper-Jacob (1946) Composite Plot and the Cooper-Jacob (1946) Straight-Line analysis are provided in table 2 and appendix B. The transmissivity derived from the composite plot and from the Cooper-Jacob straight line method agree (412 ft^2/day and 405–522 ft^2/day, respectively). A storativity of 0.00098 was calculated using the Cooper-Jacob composite plot. This storativity value is indicative of a confined aquifer.

Table 1. Parameters used to simulate long-term pumping and stream depletion mitigation scenarios.

Pumping Scenarios						
Scenario	Description	Number of New Wells	Well Names	Pumping Rate of Wells (gpm)	Pumping Duration (months/year)	Pumping Period
1	2010 conditions	0	N/A	N/A	N/A	N/A
2	New well in volcanic zone	1	Well A	1,500	2	June & Aug
3	2 new wells in volcanic zone	2	Well A, B	1,500/well	2	June & Aug
4	2 new wells in Tertiary zone	2	Well C, D	375/well	2	June & Aug
Mitigation Scenarios						
Scenario	Description	Canal Pre/Post Season Period	Well Names	Pumping Rate of Wells (gpm)	Pumping Duration (months/year)	Pumping Period
5	Pre-season canal flow	1 month early (March)	Well A, B	1,500/well	2	June & Aug
6	Post-season canal flow	1 month late (November)	Well A, B	1,500/well	2	June & Aug
7	Pre- and post-season canal flow	March & Nov	Well A, B	1,500/well	2	June & Aug

Table 2. Summary of transmissivity and storativity obtained during the Tertiary sediment aquifer test on well 220021.

GWIC ID	Transmissivity (T), ft^2/day		Storativity (S)	
	Cooper-Jacob Straight Line Method			
	Composite Plot	Using Recovery Data	Composite Plot	Using Recovery Data
220021		522		N/A
254962	412	405	9.83 x 10^{-4}	N/A
254963		435		N/A

Note. 220021 data are not used in the Composite Method because of headlosses due to pumping during the aquifer test. N/A, storativity is not calculated with this method.

Water Chemistry

Specific conductivity of the discharge water was 425 µsiemens/cm (µS/cm) at the start of the test and stabilized between 490 and 494 µS/cm about 32 hours after pumping started up to the end of the test. pH remained fairly stable, ranging from 7.6 to 7.9 throughout the test.

The discharge water was a calcium-bicarbonate water type. A tritium value of 0.66 TU in the groundwater sample from the discharge water indicates that the groundwater was likely recharged prior to 1952 (Clark and Fritz, 1997). There was no significant difference in the isotopic composition (^{18}O and D) in the sample of discharge water collected at the beginning and end of pumping.

Volcanic Rock Aquifer

An irrigation well (220080), completed in the volcanic rock aquifer, was pumped from October 15 to 18, 2010 to obtain aquifer hydraulic properties, examine how groundwater in the Tertiary sediments responded to pumping, and whether pumping induced a response in Black Slough (fig. 8). The well was pumped at an average rate of 1,420 gpm. Drawdowns due to pumping were observed in all monitoring wells, though the effects on water levels in the shallow well (259558) were not observed until after pumping ceased. The maximum amount of drawdown in the pumping well (220080) was 4 ft.

Aquifer Properties

The van der Kamp (1989) method was used to enhance the drawdown data since water levels in the pumped well did not reach steady-state. The drawdown and recovery data were analyzed using the Cooper-Jacob (1946) Composite Plot, the Copper-Jacob (1946) Straight-Line analysis, and the Cooper-Jacob (1946) Distance Drawdown method.

The transmissivity estimates ranged from 42,500 to 62,000 ft^2/day, and storativity values ranged from 0.0026 to 0.016 using the three aquifer test analysis methods (table 3 and appendix B). The storativity values indicate that the aquifer ranges from unconfined to semi-confined.

Hydrographs

Several monitoring well hydrographs are presented to examine how pumping the volcanic rock

Table 3. Summary of transmissivity and storativity obtained during the volcanic aquifer test on well 220080.

GWIC ID	Transmissivity (T), ft^2/day			Storativity (S)	
	Cooper-Jacob Straight Line Method			Cooper-Jacob	
	Composite Plot	(Using Recovery Data)	Distance Drawdown	Composite Plot	Distance Drawdown
204226 (Area 1)	49,800	50,600	42,500	0.016	0.018
224244 (Area 1)		49,500			
254767 (Area 2)	62,000	57,900		0.0026	
254815 (Area 2)		72,900			
254840 (Area 2)		66,900			
220080 (Area 4)	59,700	75,500		N/A	

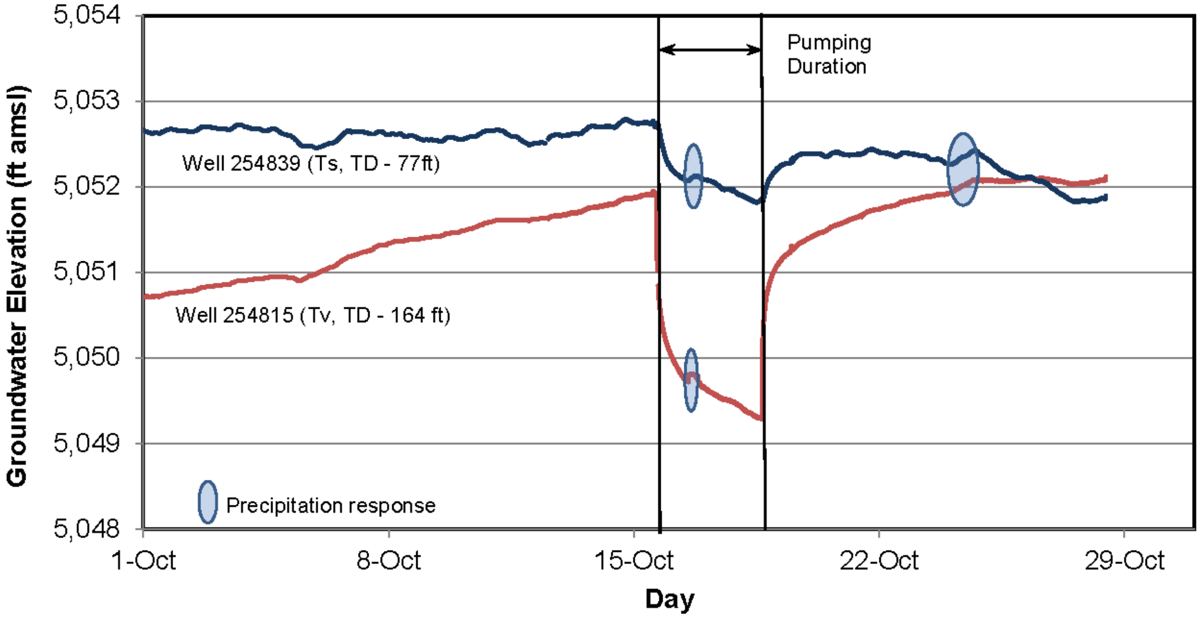


Figure 17. Hydrographs of wells 254839 and 254815 indicate that pumping in the volcanic rock aquifer induced a response in the overlying Tertiary sediments. Both aquifers showed a temporary increase in water levels in response to precipitation.

aquifer affected the overlying Tertiary sediments, the shallow Black Slough alluvium, and Black Slough. Wells 254839 (Tertiary sediments) and 254815 (volcanic rock) are about 320 ft from the pumping well (fig. 8) and illustrate that pumping the volcanic rock aquifer induced a drawdown response in the overlying Tertiary sediments (fig. 17). Precipitation occurred on October 16–17 (0.28 in) and October 24–25 (0.19 in) and caused water-level responses that are apparent on both hydrographs. Comparison of the recovery curves for the hydrographs show different trends. Water levels did not fully recover to pre-pumping levels in the Tertiary sediments and showed a post-aquifer test decreasing trend (fig. 17).

Water-level elevations in the Tertiary sediments (well 254839) and the shallow Black Slough alluvium (well 259558) were plotted to compare the responses during the test (fig. 18). The pre- and post-test groundwater elevations follow similar trends; most noticeable is the declining trend in both the shallow and deeper groundwater after the West Side Canal was shut down. The two precipi-

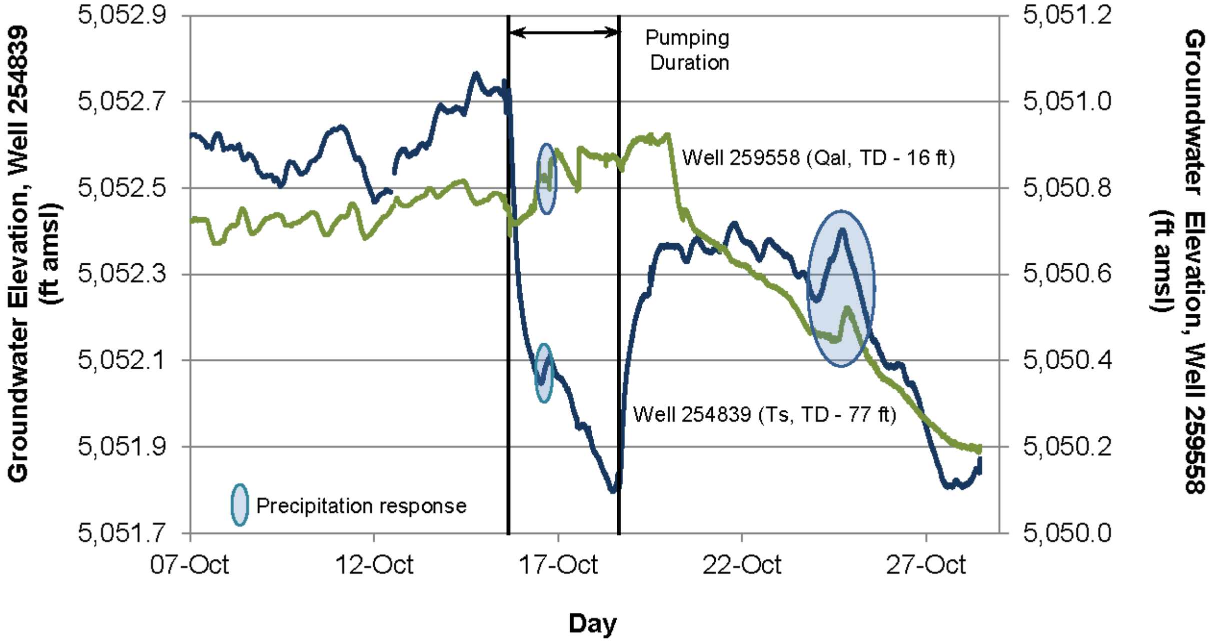


Figure 18. Hydrographs for wells 254839 and well 259558 show a similar groundwater response before and after the aquifer test and during the two precipitation events.

tation events noted above were apparent on both hydrographs. The groundwater drawdown due to pumping was evident in well 254839. It was not evident in well 259558, which responded more to the stage in Black Slough (discussed below). The increasing groundwater levels in the alluvium during pumping were the result of an influx of water into Black Slough and are described below.

The Black Slough stream monitoring location is about 945 ft downstream from well 259558 (fig. 8). In the early part of the aquifer test, water levels in both the shallow well and Black Slough mirrored one another (fig. 19). Then, about 48 hours into the test, a headgate was opened to divert water from the West Side Canal to Black Slough. As a result, water levels increased in both Black Slough and the shallow well. The water levels remained stable for the remainder of the test. Simultaneous with the end of pumping, water levels increased in the shallow piezometer and in Black Slough, indicating a hydrologic connection between Black Slough and the shallow alluvium. The canal was shut down on October 19 and a decrease in water levels in both Black Slough and the shallow well were observed.

Water Chemistry

Specific conductivity in the pumped well varied from 1318 to 1283 µS/cm throughout the duration of pumping. Although this is only a 3% difference, since the specific conductivity decreased

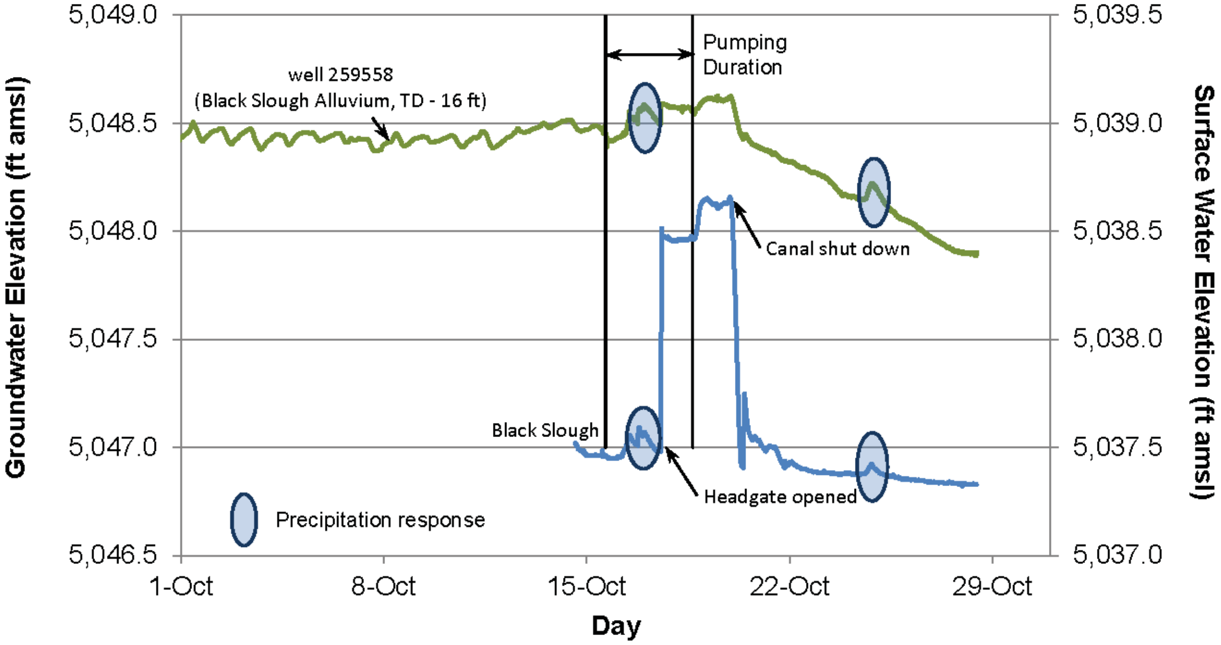


Figure 19. Fluctuations in groundwater levels in Black Slough alluvium are similar to those in Black Slough stage. The rise in water levels on October 18 was in response to an influx of water into Black Slough from the West Side Canal.

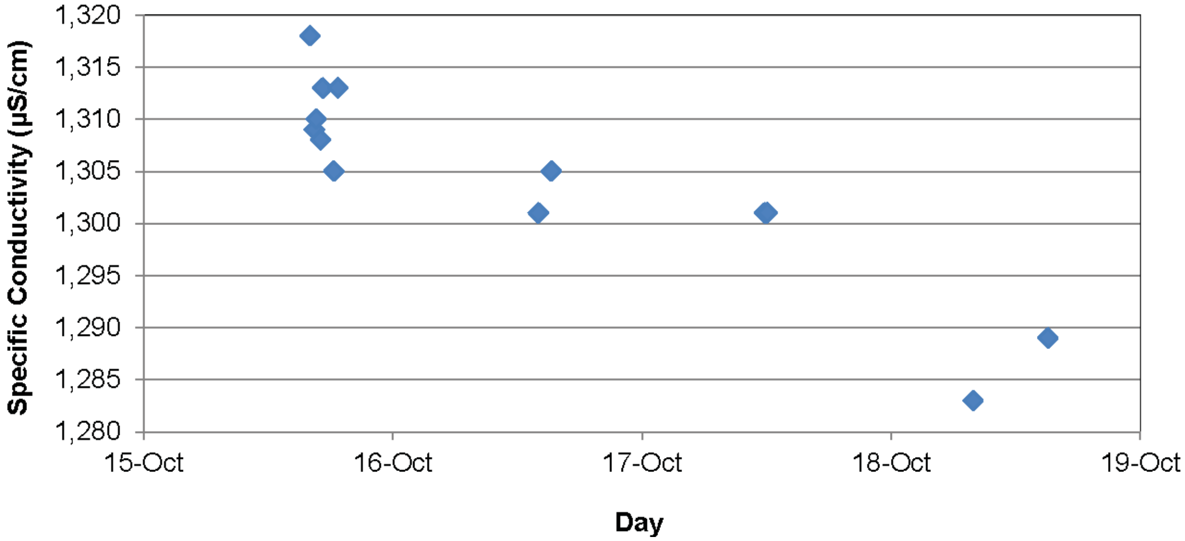


Figure 20. Specific conductivity of the discharge water from well 220080 decreased during pumping.

consistently throughout the test (fig. 20), the values are interpreted as change in TDS in the discharge water. Specific conductivity readings measured in Black Slough on October 15 and 17 were 1,001 and 1,116 µS/cm, respectively. Specific conductivity decreased to around 600 µS/cm after the headgate from the West Side Canal was opened, channeling water into Black Slough. Specific conductivity of the West Side Canal ranged from 564 to 577 µS/cm.

Except for nitrate, there were no significant differences between the concentration of inorganic constituents in the discharge water collected at the beginning and end of the test. Nitrate decreased from 15.3 mg/L to 12.46 mg/L (20% decrease), exceeding the drinking water standard of 10 mg/L in both samples. Nitrate in Black Slough was 0.44 mg/L.

There were no significant differences between tritium concentrations from samples collected at the start of the test and before the pump was turned off (6.6 TU and 6.0 TU, respectively). Water isotopes of ^{18}O and D also did not show any significant differences during the test.

Hydrogeologic Setting

This section provides detailed descriptions of the three main aquifers identified in the study area: (1) the alluvium; (2) the Tertiary sediments; and (3) the volcanic rock (fig. 21). Photographs of the alluvial, Tertiary sediment, and volcanic rock aquifers are shown in figure 22. The geologic map for the area (fig. 3) indicates Quaternary sands and gravels (Qgr) overlying the Tertiary sediments on the West Bench. The Quaternary sediments that blanket the West Bench are considered part of the Tertiary sediment aquifer within the study area.

Alluvial Aquifer

Depth to groundwater in the unconfined alluvial aquifer ranged from about 3 to 13 ft, with an average depth of 7 ft. Based on previous data, transmissivity of the alluvial aquifer ranged from about 18,000 to 37,000 ft^2/day and storativity ranged between 0.003 and 0.15 (table 4). Based on driller's logs and monitoring wells drilled by the MBMG, the alluvial aquifer is 25 to 30 ft thick and can extend as deep as 60 ft below ground surface. It consists of surficial deposits of sand, gravel, and cobble. Well 242403 is located about 150 ft from the Beaverhead River and about 3 miles south of Beaverhead Rock (fig. 5). At this location there was a 30-ft-thick gray silty clay layer underlying the shallow alluvial aquifer. Beneath the clay layer was gray indurated silt identified as Tertiary sediments.

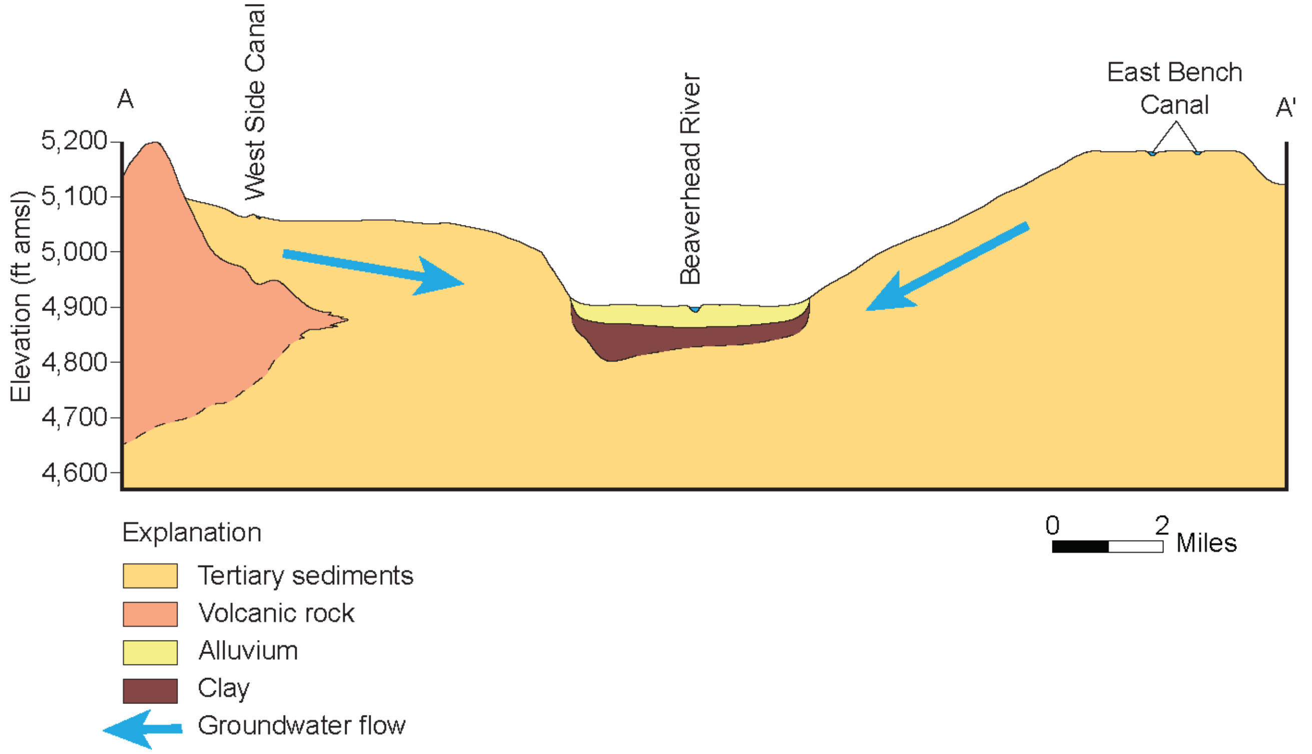


Figure 21. A schematic geologic cross section illustrates the relation of the alluvial aquifer, Tertiary sediments, and volcanic rock aquifers. The cross section line is shown in figure 3.


Alluvium that underlies the floodplain consists mainly of sands and gravels.

Tertiary sediments are typically fine-grained with discontinuous interbeds of sands and gravels.

Volcanic rock outcrops in the northern part of the West Bench. The rock is fractured and is the most productive aquifer in the study area.

Figure 22. These photographs show the three main aquifers in the study area. Note the fine-grained nature of the Tertiary sediments. Secondary porosity in the volcanic rock makes this the most prolific aquifer in the study area.

During drilling of well 255492, located near the Beaverhead River about 4 miles south of well 242403 (fig. 5), light brown clay and silty clay were noted at two intervals, 22 to 50 ft and 65 to 85 ft below ground surface. Indurated silt encountered at 85 ft below ground surface was considered to be the top of the Tertiary sediments. GWIC well logs in the area also indicated the presence of clay or less permeable units underlying the alluvium. The implications of an extensive clay layer include:

Table 4. Aquifer properties for the alluvium, Tertiary sediments and volcanic rock used in this study.

Aquifer Type	Transmissivity (ft^2/day)	Storativity	Typical Hydraulic Gradient	Saturated Thickness (ft)	Source
Alluvium	18,000–37,000	0.003–0.15	0.0035	30	3-day aquifer test[1]
Tertiary sediments (West Bench)	405–520	0.00098	0.009	333	3-day aquifer test[2]
Tertiary sediments (East Bench)	1,570–2,550	0.04	0.011	443	Water rights permits[3]
Tertiary sediments (floodplain)	2,860-5,890	NR	0.006	470	3-day aquifer test/water rights information[4]
Volcanic rock	42,500–75,500	0.0026–0.018	NA	300	3-day aquifer test[5]

[1] Pumping Well 242404 (MBMG, 2008)
[2] Pumping Well 220021 (MBMG, this report)
[3] Unpublished data, Montana Provisional Water Rights Permit 41B-3001905, 2002; written commun., 2008, Water Rights, Inc, Missoula, Montana
[4] Pumping Well 242406 (MBMG, 2012); unpublished data, written commun., 2013, Water Rights, Inc, Missoula, Montana
[5] Pumping Well 220080 (MBMG, this report)

(1) The confining nature and extent of the clay can affect the degree of connection among the Tertiary aquifer, alluvial aquifer, and surface water, and

(2) A confining clay will influence the design of the groundwater flow model.

Cross sections illustrate that the less permeable material underlying the valley is continuous in some areas and less so in others (fig. 23). In the more continuous areas these layers may effectively form confining beds separating the alluvial from the Tertiary sediment aquifer.

Tertiary Sediment Aquifer

The Tertiary sediment aquifer (Ts; figs. 3, 21) underlies the East and West Benches and the alluvium beneath the floodplain. This unit, dominated by fine-grained sediments, consists of silts and clays interbedded with sands and gravels (fig. 22). The thickness of the Tertiary sediments beneath the floodplain and East Bench are unknown. The deepest wells drilled in Tertiary sediments beneath the floodplain and on the East Bench penetrated to depths of 460 and 700 ft, respectively. Bedrock noted in some of the driller's logs on the West Bench indicates that the overlying Tertiary sediments may only be about 60 ft thick in some areas. The deepest wells on the West Bench completed in Tertiary sediments are about 400 to 500 ft deep.

In the floodplain, depth to groundwater in Tertiary sediments ranged from 3 to 35 ft in the monitoring network wells. On the benches, depth to groundwater varies more widely, ranging from 2 to 300 ft (average depth of about 54 ft) on the West Bench and 13 to 127 ft below the ground surface (average depth of about 68 ft) on the East Bench.

Aquifer test data indicate that transmissivity values for the Tertiary sediments range from about 400 to 5,990 ft^2/day (table 4). Beneath the floodplain, transmissivity ranged from 2,900 to 5,990 ft^2/day, and aquifer response to pumping indicated that in the vicinity of well 242403 the aquifer was confined. On the West Bench, transmissivity of the Tertiary sediments ranged from approximately 400 to 520 ft^2/day, and storativity (based on aquifer testing of well 220021, fig. 5) is 0.00098. This storativity value indicates that in the vicinity of well 220021 the aquifer is confined. Aquifer tests indicate that transmissivity of the Tertiary sediment aquifer on the East Bench ranged from approximately 1,600 to 2,600 ft^2/day, and storativity was about 0.04 (table 4). This storativity value indicates an unconfined aquifer; however, based on the presence of clay and less permeable units, locally the aquifer probably also exhibits confined conditions.

Volcanic Rock Aquifer

Tertiary volcanic rocks occur in several places in the north-central part of the West Bench (Tv, fig. 3). Figure 24 shows the volcanic rock outcrops

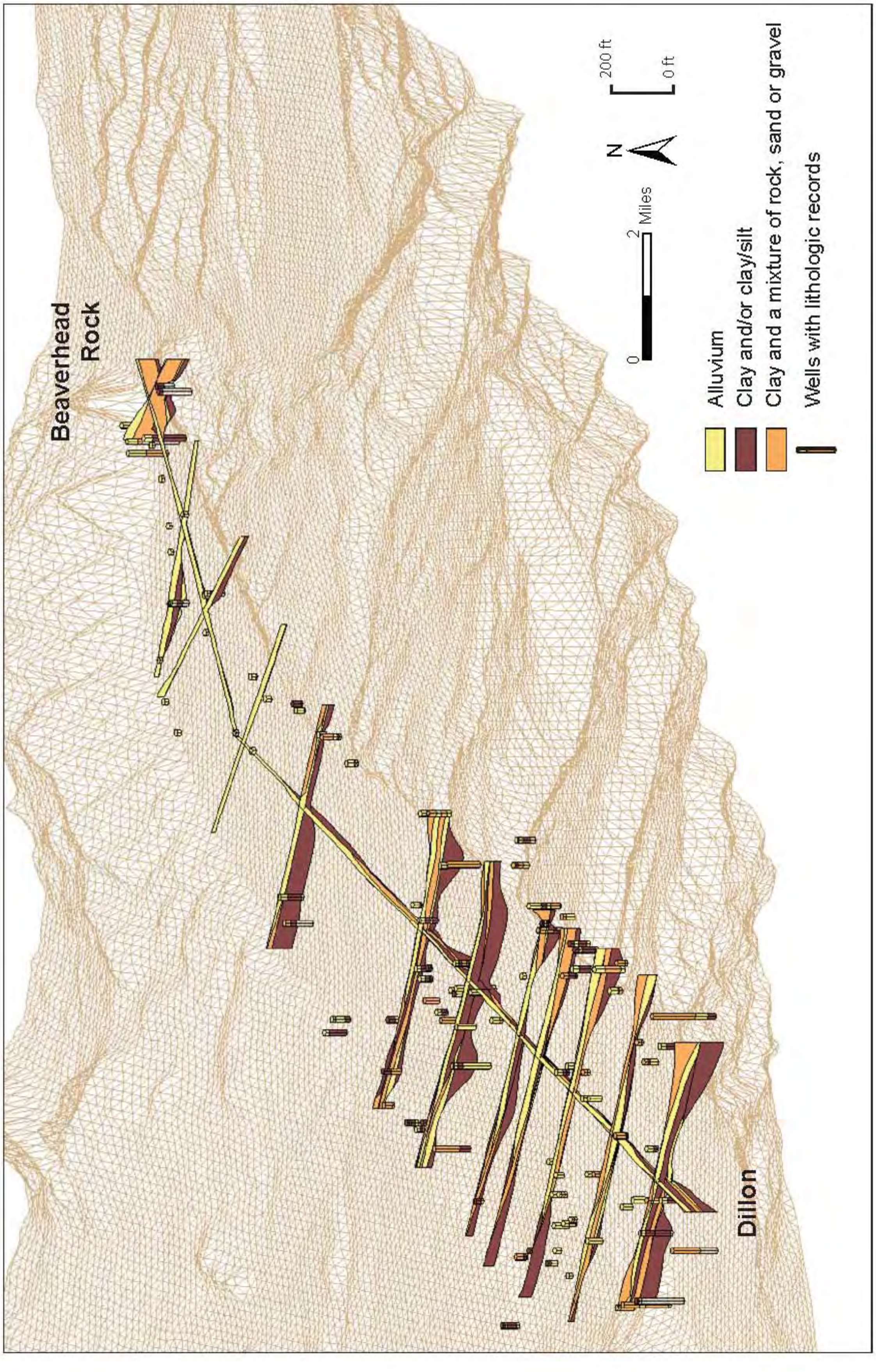


Figure 23. Geologic cross sections were generated from GWIC data to examine the extent of clay/silt that underlie the alluvium in the floodplain.

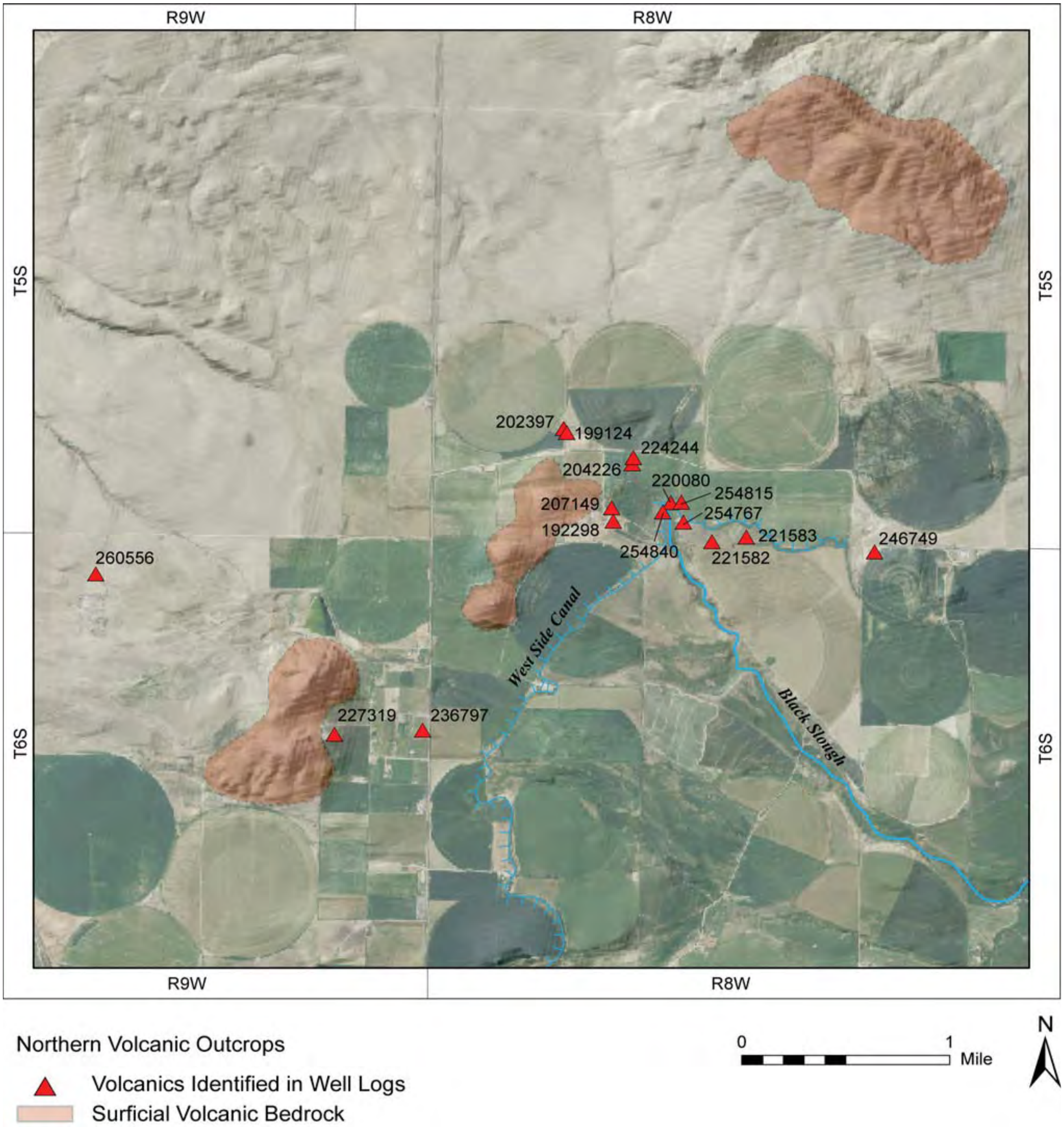
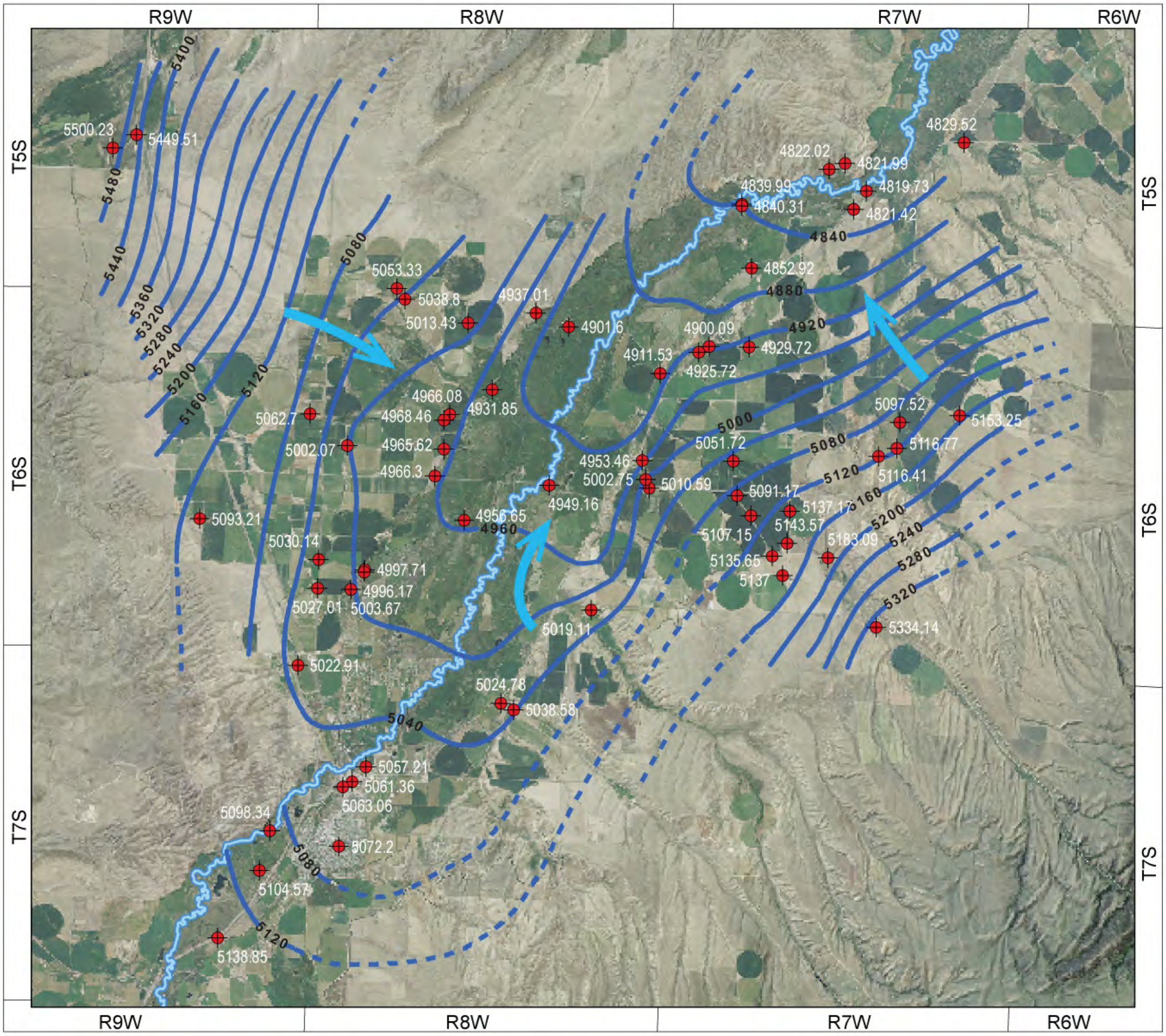


Figure 24. Location of volcanic rock outcrops in the north-central part of the West Bench and wells in which volcanic rock was noted in the driller's log.

based on the geological map and field observations. The aquifer consists mainly of rhyodacite, an extrusive volcanic rock. The rhyodacite is vesicular and exhibits secondary porosity as a result of dissolution of phenocrysts and fractures in the rock. The fractures allow for the rapid flow of groundwater. Although the extent of the volcanic rock aquifer is unknown, fig. 24 illustrates the distribution of wells completed in the aquifer.

The volcanic rock aquifer, in the vicinity of well 220080 (fig. 24), is overlain by approximately 100 ft of Tertiary sediments. The thickness of the volcanic rock aquifer is unknown; however, in this area it reportedly extends to a depth exceeding 300 ft in well 204226 (fig. 24). The reported depths to groundwater range from about 9 to 40 ft with an average of 13 ft. Transmissivity of the aquifer ranges from about 42,000 to 75,000 ft^2/day, which is two orders of magnitude greater than that of the Tertiary sediments (table 4), and storativity values range from 0.0026 to 0.018. These storativity



Notes:

1) Contour Interval 40 feet
2) Units are feet above mean sea level

Explanation

⊕ Tertiary Monitoring Wells

—5120— Tertiary sediment aquifer potentiometric contours

← Groundwater flow

Figure 25. Groundwater in the Tertiary sediment aquifer flows towards and along the Beaverhead River.

values and drawdown data from the aquifer test (Results: Aquifer Tests) indicate an unconfined to semi-confined aquifer. Wells completed in the volcanic rock are high-yielding, ranging up to 1,500 gpm.

Groundwater Movement

Potentiometric Surface Map

Data from 61 wells were used to compile a potentiometric surface map for the Tertiary sediment aquifer. In general, groundwater moves from the higher benches and converges in the floodplain (fig. 25). As groundwater moves north out of Dillon, it flows away from the Beaverhead River and flows parallel or towards the river further north. The groundwater gradient on the East and West Benches is about 0.01 and flattens to about 0.006 in the floodplain.

Figure 26. Groundwater in the alluvial aquifer flows to the northeast, subparallel to the river.

Groundwater in the alluvial aquifer is flowing northeast towards Beaverhead Rock (fig. 26). The river loses water as it flows north out of Dillon and then begins to gain water from the alluvial aquifer on the north end of the study area.

Vertical Gradients

Vertical gradients between the Beaverhead River, alluvial aquifer, and Tertiary sediments were evaluated at three sites during 2010: near Dillon at site A; the middle of the study area at site B; and near Beaverhead Rock at site C (fig. 6). At site A (well 133403) during the irrigation season (May through mid-October), water-level elevations indicate flow from groundwater to the river, while during the non-irrigation season river water moved to the alluvial aquifer (mid-October through mid-April; fig. 27). The differences in water-level elevations between the Beaverhead River and the groundwater at this site were generally less than 0.40 ft.

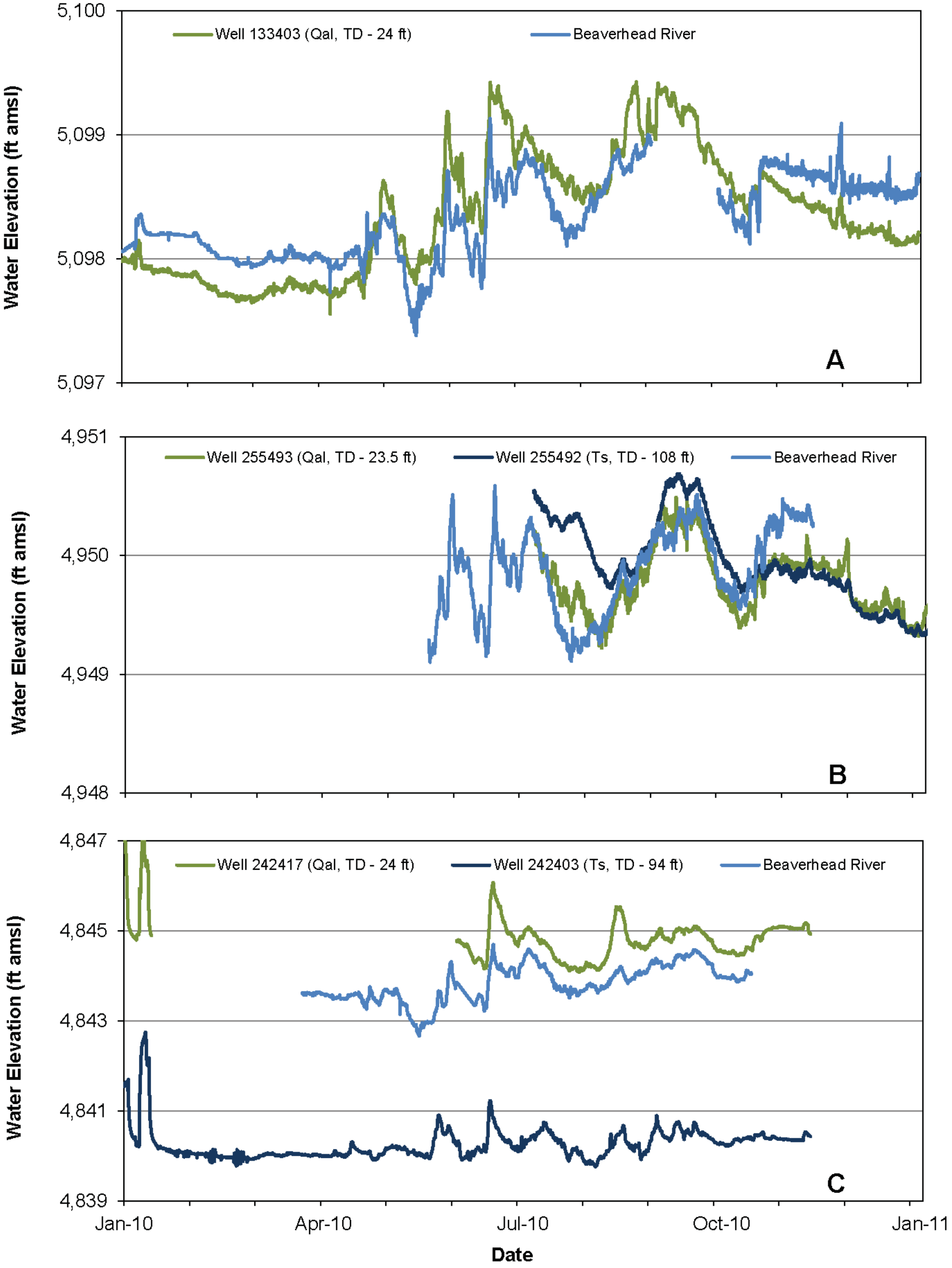


Figure 27. Water elevations in the Beaverhead River and in nearby monitoring wells at three sites, A, B, and C (see fig. 6 for locations). At sites A and B, water elevations indicate that groundwater discharges to or recharges from the river depending on the time of year. At site C, the alluvial aquifer discharged to the river throughout the year. Conversely, groundwater in the Tertiary sediments is not directly connected to the shallow flow system.

Site B (fig. 6) includes an alluvial monitoring well (255493), a Tertiary monitoring well (255492) and the Beaverhead River. During the 2010 irrigation season water elevations were higher in the Tertiary sediment aquifer than in the shallow well and the river (fig. 27). This may be due to groundwater recharge as a result of application of irrigation water on the benches. There was a temporary small upward gradient between the alluvium and the river during part of this time, indicating alluvial groundwater flow to the river. However, during most of the irrigation season, river and alluvial groundwater elevations were similar. At the end of the irrigation season, the gradient reversed and river elevations were higher than groundwater, implying that the river was recharging the alluvial aquifer. Both aquifers had near-equal water levels; however, the deeper Tertiary aquifer exhibits confined conditions, as the water level is about 90 ft above the top of the aquifer and showed responses to barometric pressure.

Site C (fig. 6) includes an alluvial monitoring well (242417), a Tertiary monitoring well (242403), and the Beaverhead River. The difference between the alluvial groundwater and river elevations indicate that the groundwater discharges to the river throughout the year (fig. 27). Water levels in the deeper aquifer show moderate seasonal responses and rise about 55 ft above the top of the aquifer, indicating confined conditions. The water-level elevations in the shallower aquifer were higher by about 4 ft than the deeper monitoring well, indicating a downward gradient between the aquifers.

Vertical groundwater gradients were examined on the West and East Benches. Three sets of well pairs on the West Bench (wells 259536 and 234969; wells 184490 and 237993; and wells 108978 and 254963) and one well pair on the East Bench (wells 242413 and 242414) all show a downward gradient. Note that these well pairs were located between 85 and 715 ft apart and that these distances are great enough to lend some uncertainty in geologic discontinuities that could affect the accuracy of the vertical gradients.

Two adjacent wells, located in the upper reach of Black Slough below the West Side Canal, are completed in the Tertiary sediments at 77 ft deep (well 254839) and in the volcanic rock at 158 ft deep (well 254815; fig. 8). Data from these wells (fig. 28) indicate that the gradient changes seasonally. During the 2010 non-irrigation season, water levels were higher in the volcanic rock aquifer, indicating an upward flow. During the late summer and fall portion of the irrigation season that gradient reverses when pumping lowers the water levels in the volcanic rock aquifer.

Groundwater-Level Trends

Long-term hydrographs were presented for

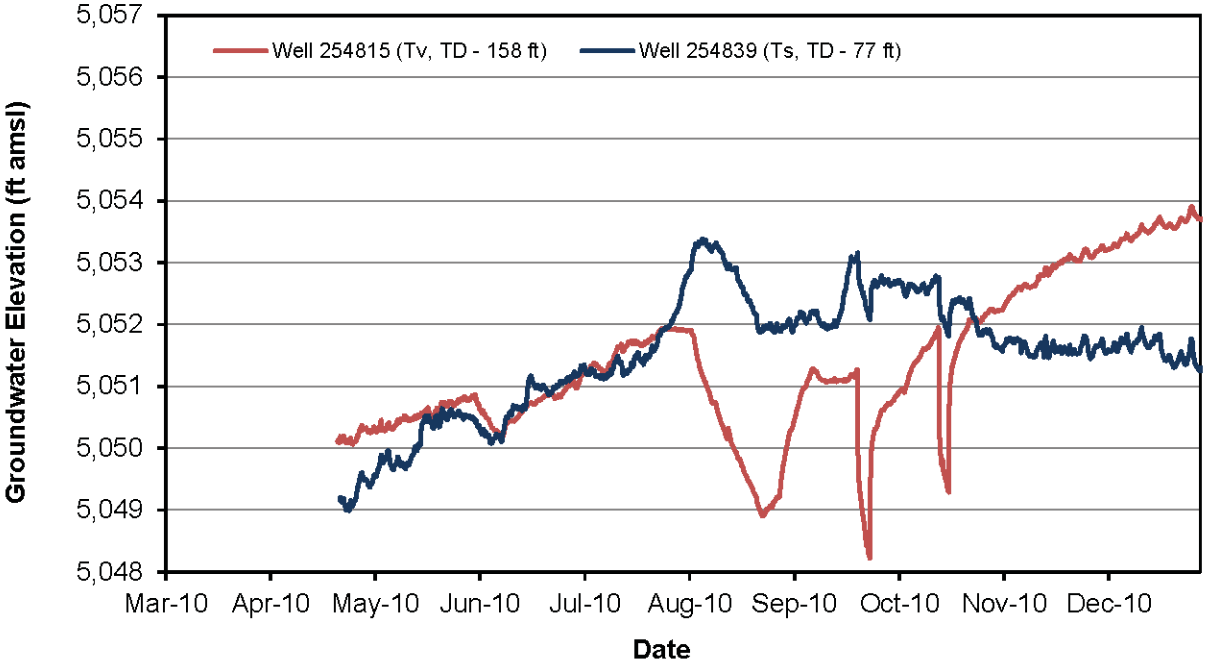


Figure 28. Hydrographs in nearby monitoring wells 254815 and 254839 indicate that during 2010 there was a downward gradient from the Tertiary sediments to the volcanic rock during the irrigation season and an upward gradient during the non-irrigation season.

nine wells, some with records from the mid-1960s through the present (locations shown in fig. 5). These wells are representative of the groundwater level trends in the alluvial and Tertiary sediment aquifers. These records were used to identify possible influences of climate and irrigation on groundwater levels. In addition to long-term data, groundwater response was examined in the monitoring network wells during the time frame of this project (2010) to examine the seasonal/annual response and to determine if groundwater storage increased during 2010. Precipitation during the 1960s was below the long-term average except for 5 years in which it was normal or slightly above average (fig. 4). Precipitation was mostly below normal for the 1992–2011 period of record (fig. 29). However, during 2009–2010 precipitation for most quarters was above average.

Floodplain

In the floodplain area, water levels in wells completed in both the Tertiary sediments and alluvium exhibited seasonal patterns, with the lowest groundwater levels during the winter months from January through March, and the highest during the irrigation season of April through September (fig. 30). The magnitude of annual fluctuation was generally less than 5 ft, with a median of 2.0 ft in the alluvial wells and a median of 3.4 ft in the Tertiary wells. Typically, there was a more muted water-level response in the shallow alluvial wells. Long-term water levels indicate very little upward or downward trend; however, the Tertiary sediments (well 133384) showed a groundwater decline of about 3 ft between 1999 and 2004, and then water levels remained fairly consistent.

Water-level fluctuations in shallow groundwater near the Beaverhead River follow patterns that are similar to the river stage, illustrating the groundwater/surface-water connection. Well 249640, completed in the alluvium and located approximately 1000 ft from the river, demonstrates this pattern (fig. 31). Water levels in monitoring wells throughout the floodplain showed an overall average increase of 0.26 ft from January 2009 to January 2010.

East Bench

Water levels in the Tertiary sediments on the East Bench have risen since the installation and subsequent operation of the East Bench Canal (fig. 32). These wells were located north of Beaverhead Rock and were completed in Tertiary sediments. Groundwater levels rose approximately 19 ft in well 131577 (63 ft deep) between 1965 and 1993, and approximately 55 ft in well 130177 (200 ft deep) between 1965 and 1973.

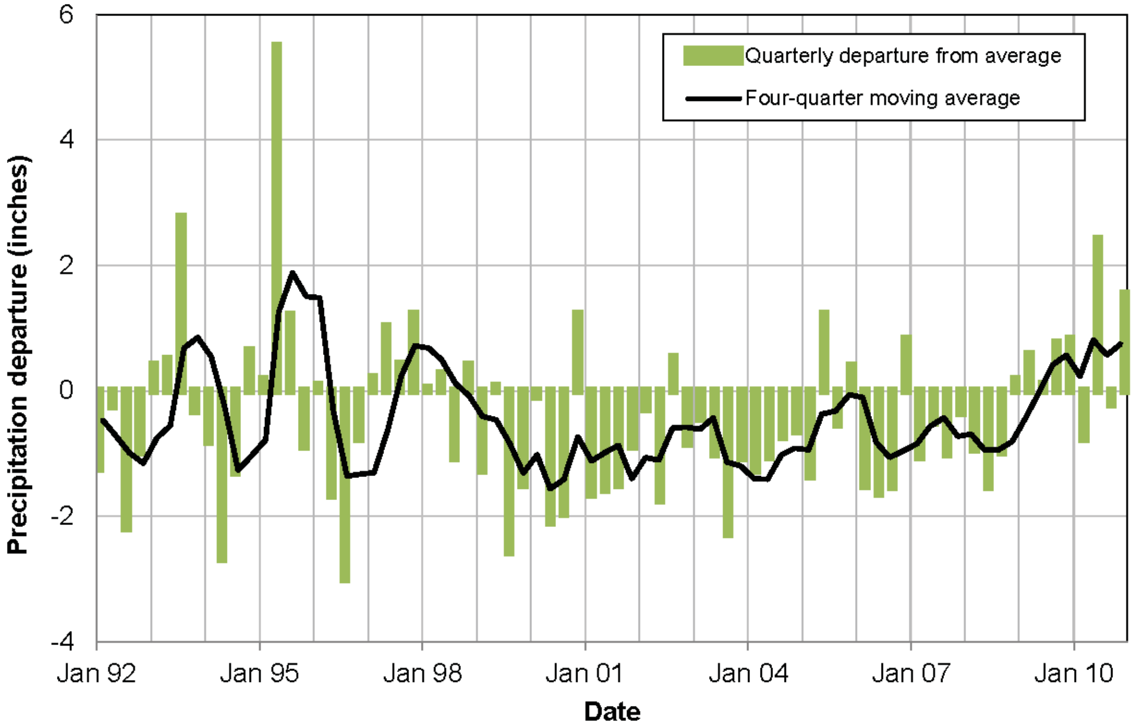
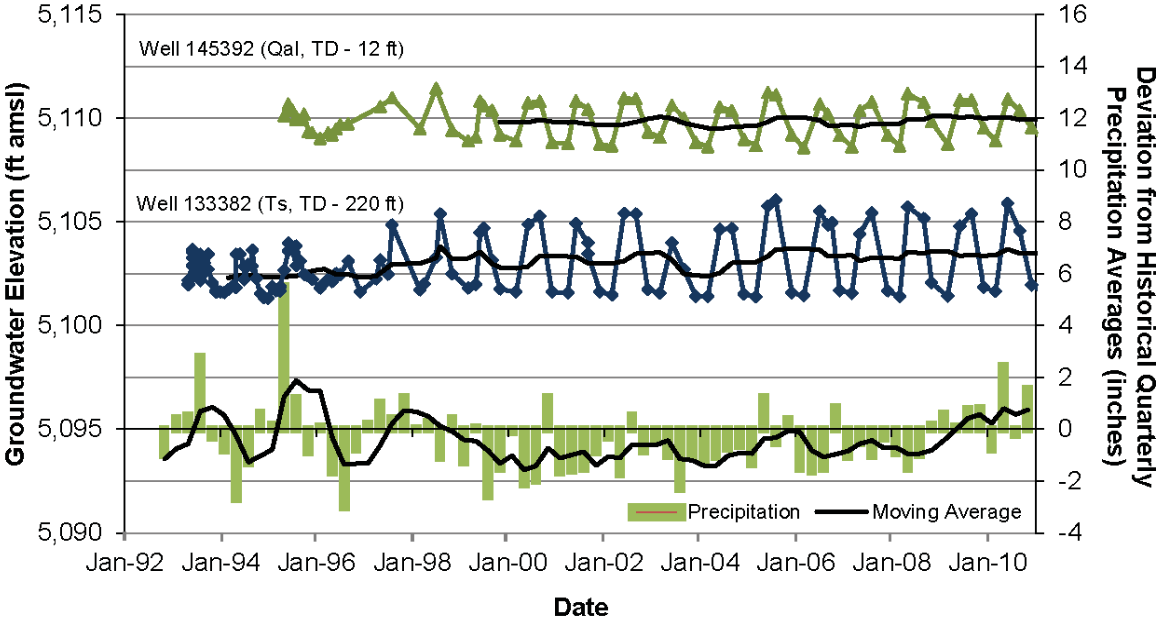


Figure 29. Precipitation was mostly below the historic quarterly average (1992–2010) for most years. Note that during 2009–2010 precipitation for most quarters was above average, which was preceded by 11 years of below-average precipitation.



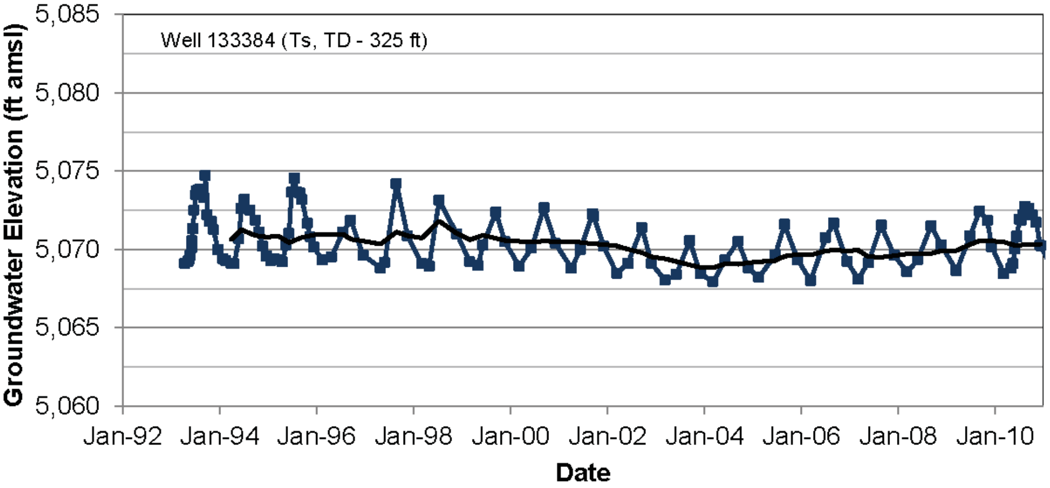


Figure 30. Hydrographs for wells 145392 and 133382 are representative of long-term water-level trends in the floodplain near Dillon that have been consistent through time. The hydrograph for well 133384 shows a decline between 1 and 3 ft from 1999 to 2004.

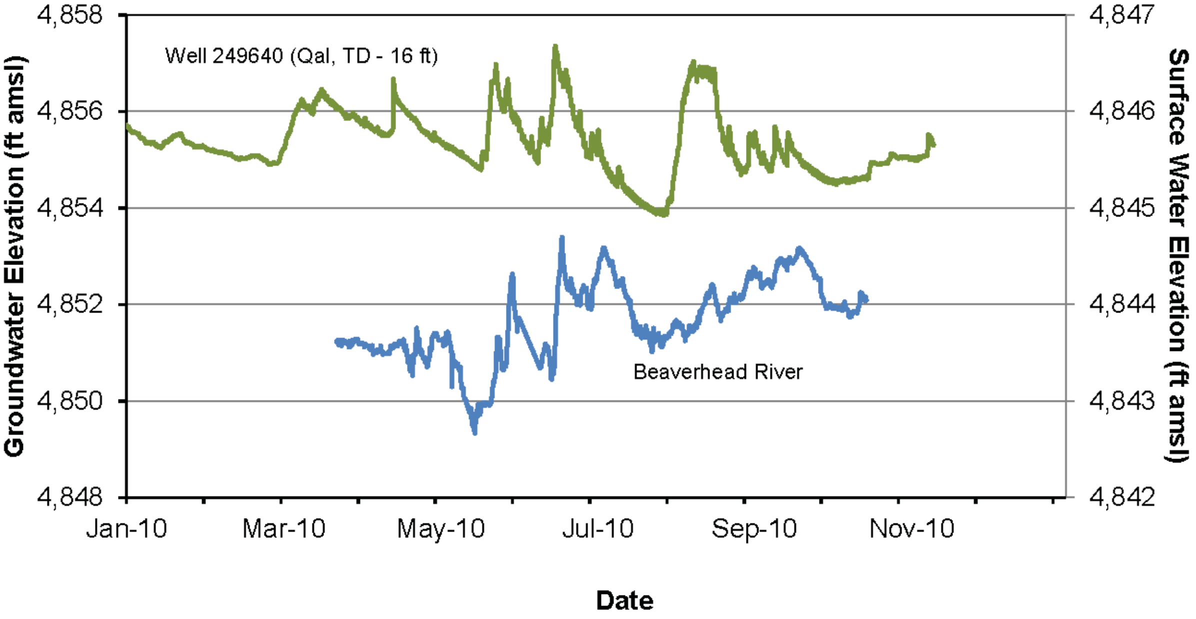


Figure 31. Groundwater levels in well 249640 fluctuated about 3 ft throughout the year and followed a pattern similar to river elevations.

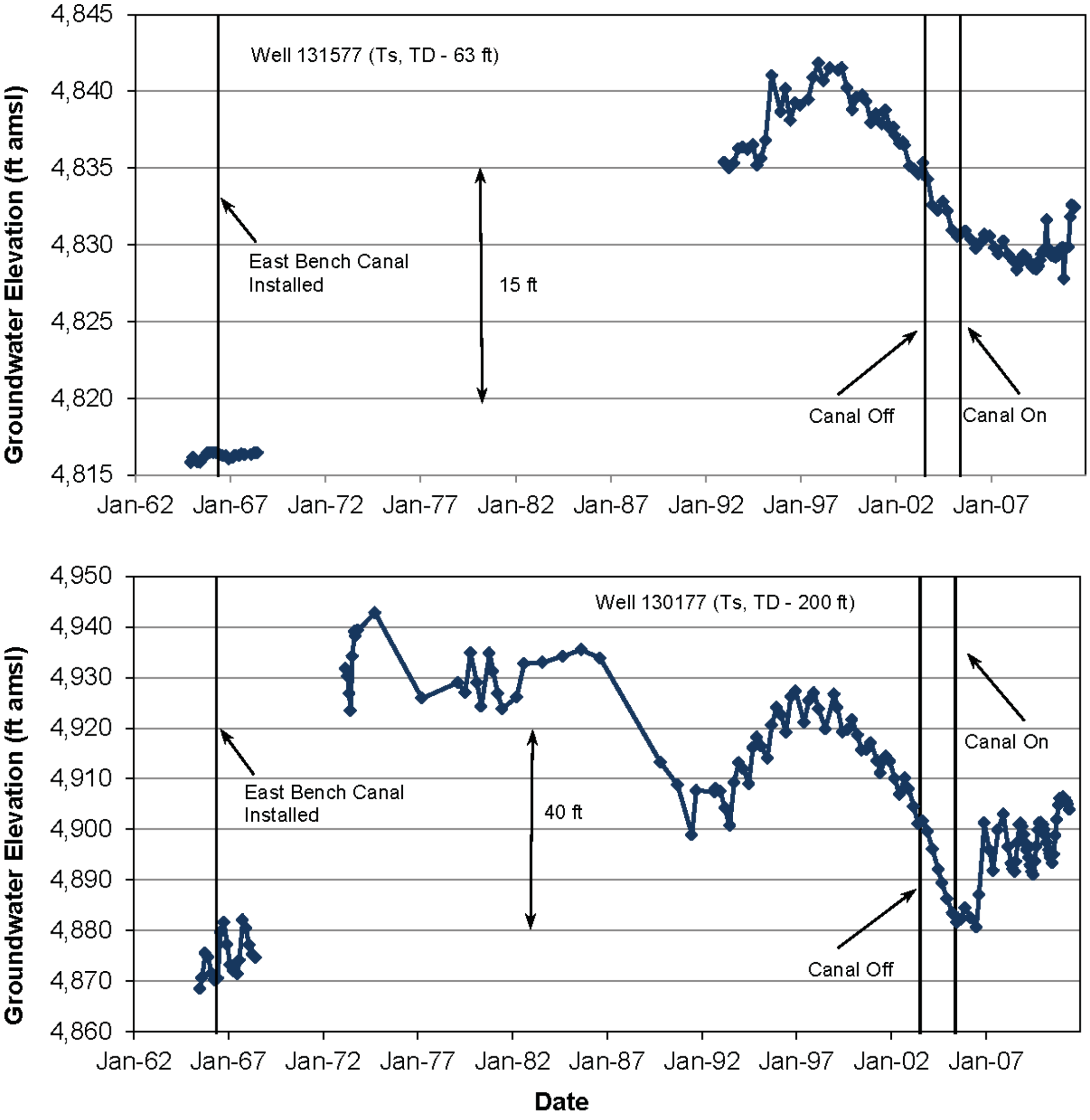


Figure 32. Groundwater levels rose in the Tertiary sediments to about 19 ft in well 131577 and 55 ft in well 130177 after construction of the East Bench canal.

Other controls on East Bench groundwater levels include: (a) climate, (b) irrigation, and/or (c) groundwater pumping.

From the early 1960s to the early 1990s, precipitation was mostly below normal (fig. 4). From 1993 through 1998, annual total precipitation was above average during 3 years. This period was followed by about 11 years of below-average annual precipitation, with 2009 and 2010 having above-average annual precipitation (figs. 4, 29).

Most of the irrigation water on the East Bench is supplied by the East Bench Canal. Groundwater is recharged from seepage losses from the canal (see Results: Canal Study) and from applied irrigation water that percolates into the subsurface once crop needs are met. In the long and the short term, climate plays a significant role in water available for irrigation. The amount of annual precipitation drives water storage volumes in the Clark Canyon Reservoir, which ultimately affects flows in the Beaverhead River, the flow diverted for the East Bench Canal and, therefore, water available for irrigation on the East Bench.

Twenty-three irrigation wells have been installed in the Beaverhead Valley since 1953, according to the DNRC database, water rights applications, and local knowledge of the study area. The majority of the wells were installed during 2003 (fig. 33).

The amount of water that flows in the East

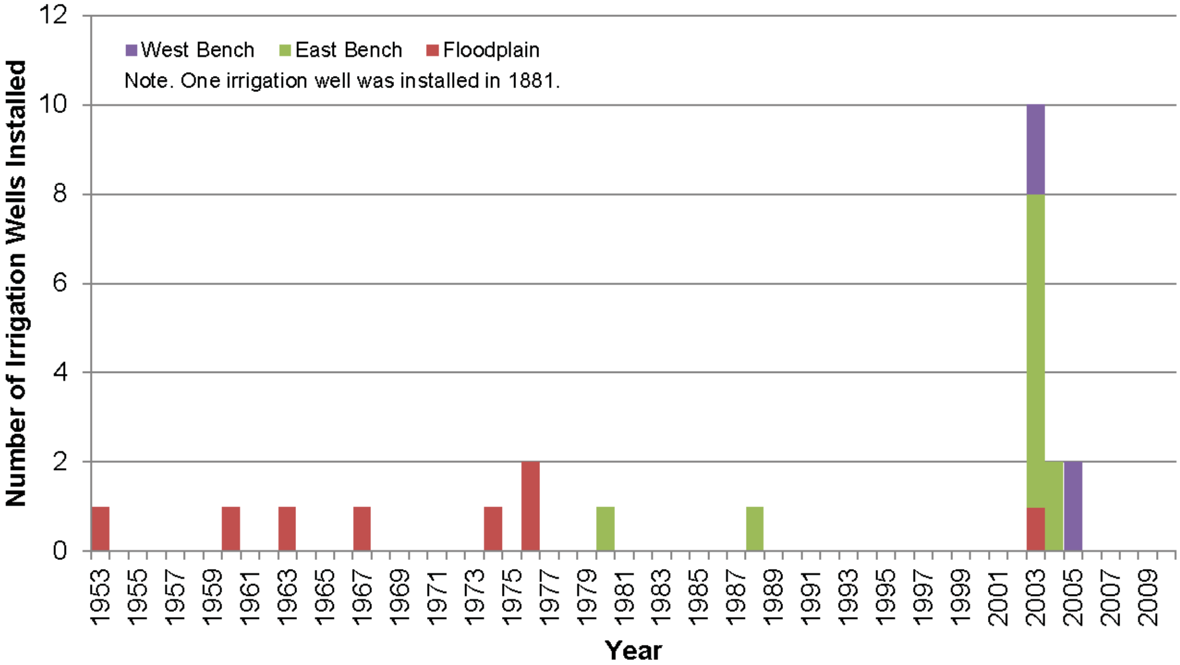


Figure 33. During 2003, 10 irrigation wells were drilled in the study area in response to prior low water years and drought conditions.

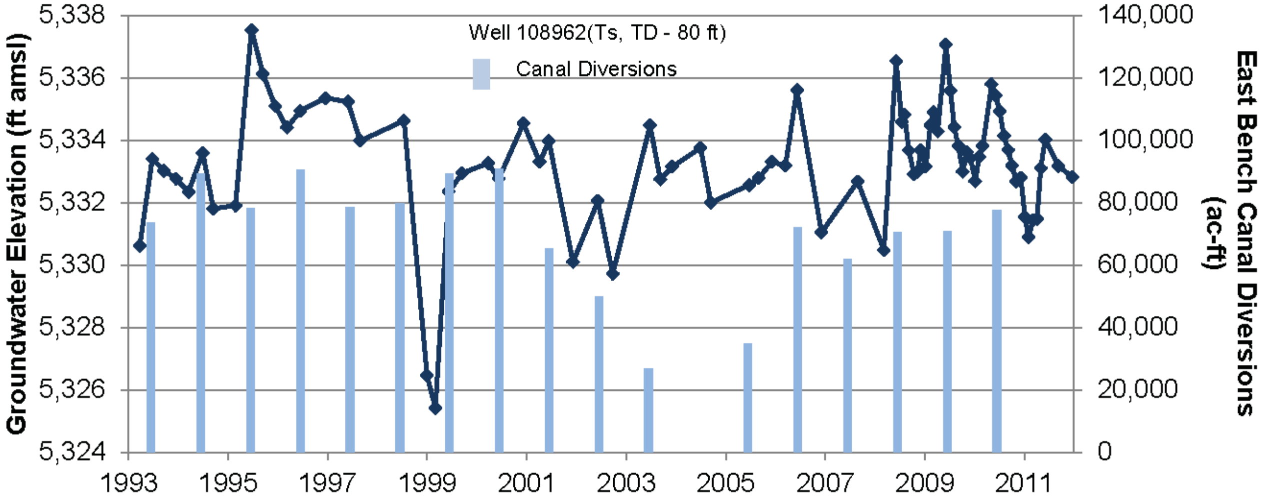
Bench Canal varies yearly, depending on water availability and requirements (bar graphs in fig. 34; Jeremy Giovando, U.S. Bureau of Reclamation, written commun., 2008; East Bench Irrigation District, written commun., 2011). Although the annual water allotments from the East Bench Canal were for the entire area served by the East Bench Irrigation District, it is assumed to be representative of the relative flow and diversion within the study area.

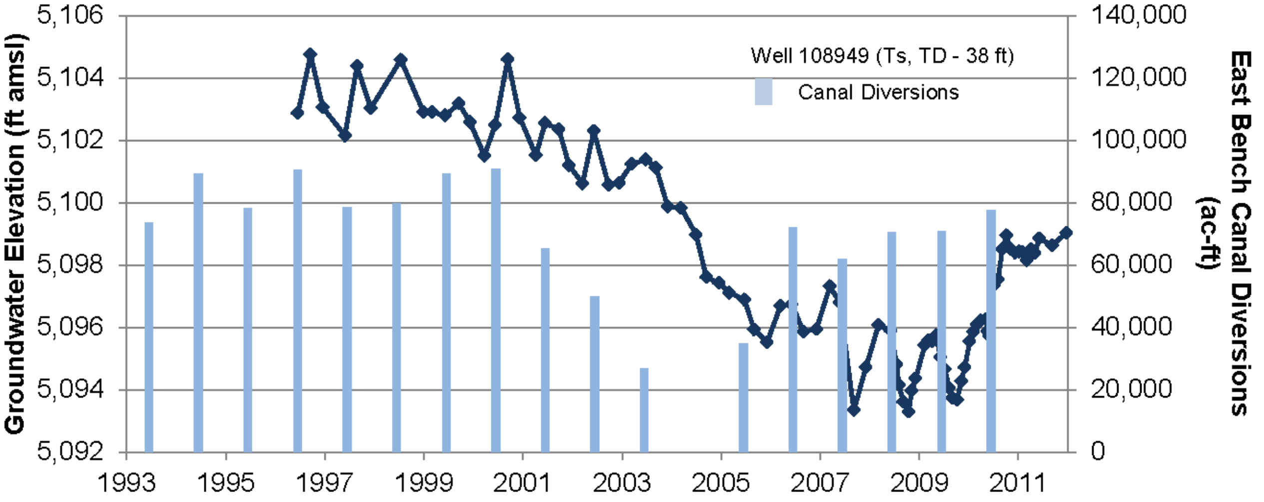
Well 108962 is located upgradient of the East Bench Canal (fig. 5) and is completed in Tertiary sediments. Water levels fluctuated over a range of about 12 ft throughout the period of record (fig. 35). There is no apparent long-term upward or downward trend in the data despite years of higher and lower precipitation (fig. 4). There is no correlation between the groundwater levels and flow in the East Bench Canal.

Water levels in wells 108949 and 130177, both located downgradient from the East Bench Canal and completed in Tertiary sediments, show a strong correlation with water diversions from the East Bench Canal (fig. 34). Groundwater levels in well 108949 (38 ft deep) show decreasing levels during drought years, which correspond to years of lower water allotments used from the East Bench Canal (2001 through 2004). With longer term data available for well 130177, the trends are even more discernible. Groundwater follows a pattern similar to climate and diversions amounts from the East Bench Canal. Groundwater levels rose in the early to mid-1990s and declined after 1998. A steeper decline in groundwater levels occurred in 2003 and continued until mid-2005. Interestingly, the East Bench was not operated from July 20, 2003 to May 24, 2005 due to drought conditions.

Of the 10 irrigation wells drilled within the study area during 2003, 7 of them were drilled on the East Bench (fig. 34). This period corresponds to the same time frame that the East Bench Canal was shut down (July 2003–May 2005) and in which there was a steeper decline in water levels. For example, groundwater levels in well 130177 (fig. 34) declined about 12 ft between December 6, 2001 and June 4, 2003 (538 days) but declined 18 ft between September 8, 2003 and March 29, 2005 (561 days). After 2005–2006, groundwater levels increased about 20 ft and remained relatively constant until 2010–2011, when they began to rise again.

Wells 242408 and 242411 are located in the Spring Creek drainage downgradient from the East Bench Canal (fig. 5). Well 242408, completed in Tertiary sediments at a depth of approximately 515 ft, shows an overall rise in water levels of about 4 ft during 2010 (fig. 35). Groundwater levels decreased during the irrigation season (April–August) by about 10 ft. Well 242411 was also completed in





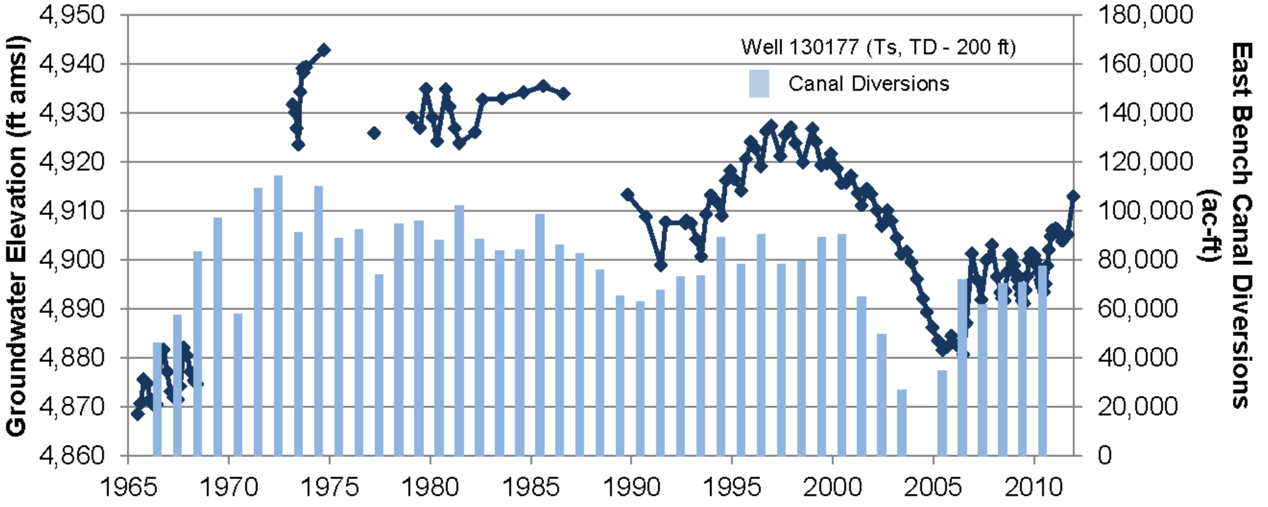


Figure 34. Long-term hydrographs for East Bench wells show that upgradient of the canal (well 108962), groundwater levels remained fairly consistent, reflecting local pumping. Groundwater levels in wells downgradient of the canal (wells 108949 and 130177) correlate primarily to climate and water diverted from the East Bench Canal.

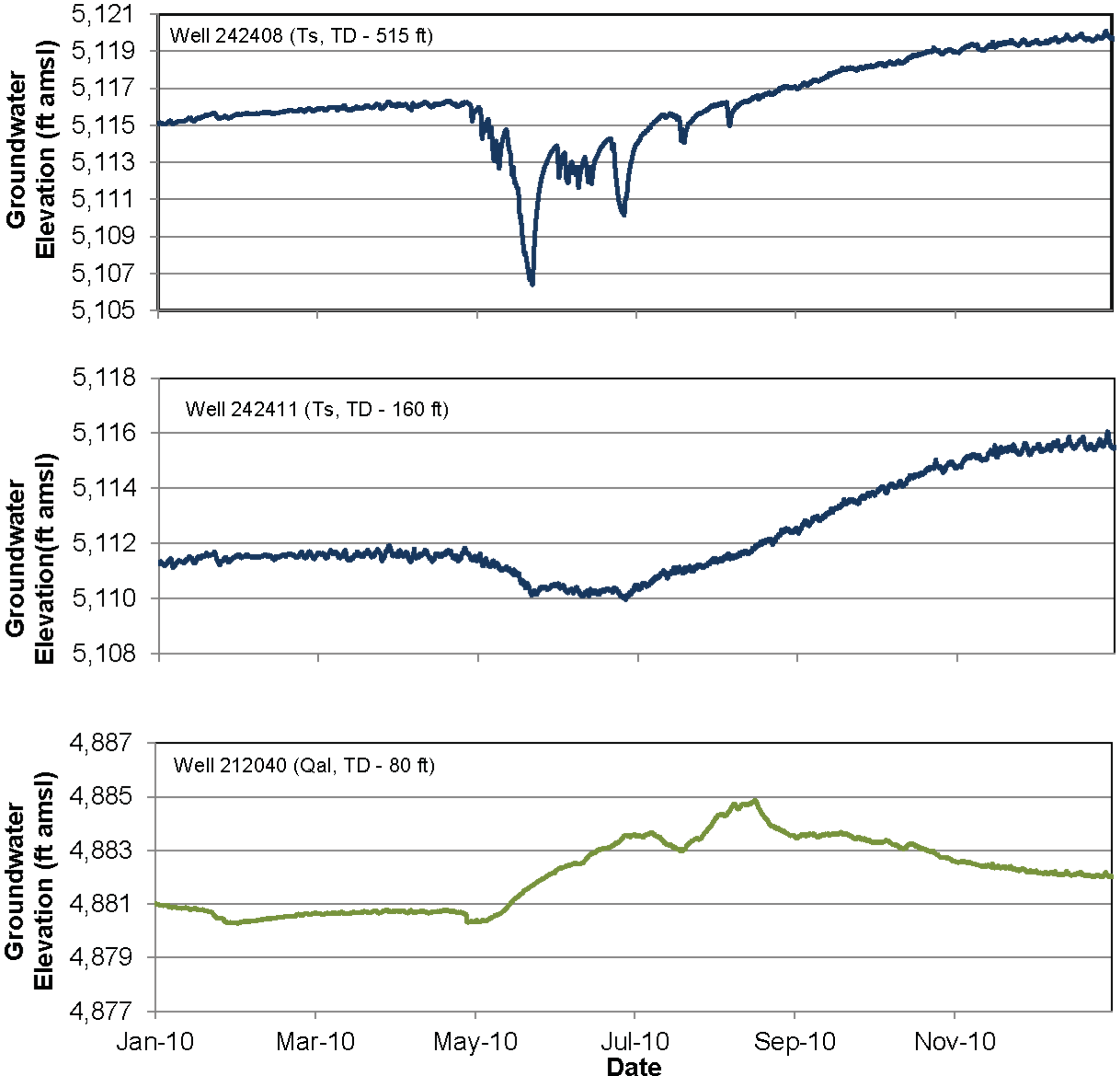


Figure 35. Groundwater hydrographs during 2010 in representative wells located on the East Bench. There was an increase in water levels in all wells from the pre- to post irrigation season.

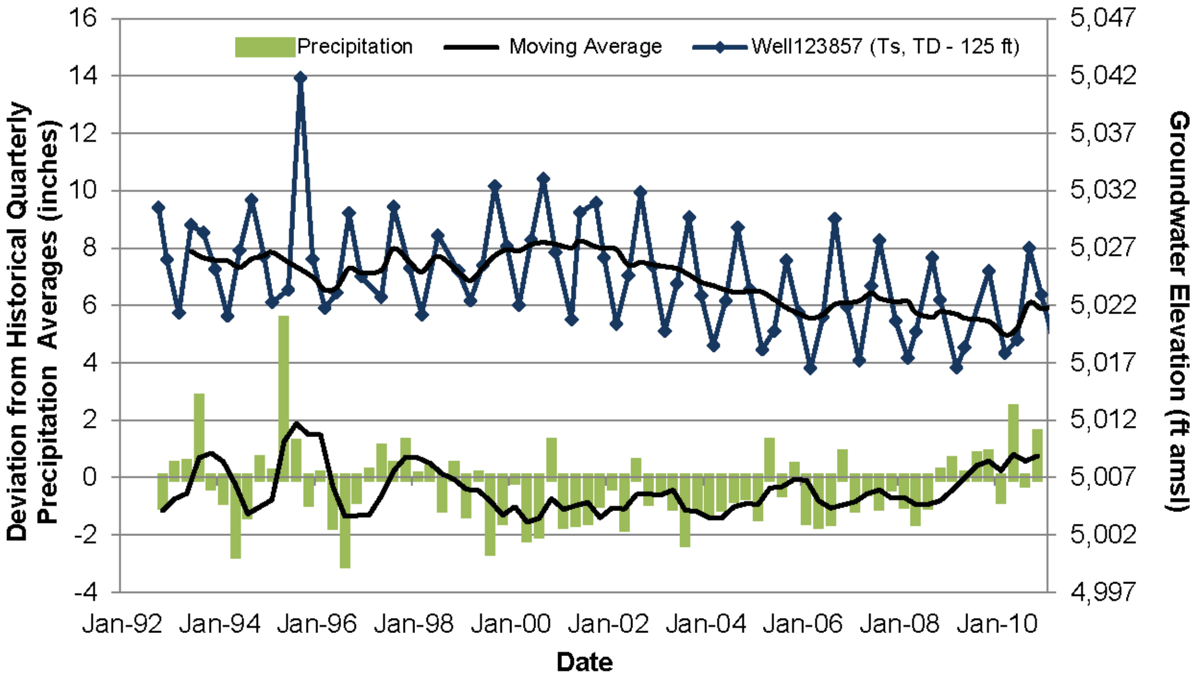
Tertiary sediments, at a depth of 160 ft. Groundwater levels in well 242411 remained fairly level until the irritation season began, and then declined by about 2 ft (fig. 36). Groundwater levels began to rise in late June and gained approximately 4 ft over pre-irrigation levels by January 2011.

Well 212040, located on the west edge of the East Bench, is 39 ft deep, completed in the alluvial sediments. Groundwater levels at this site rise shortly after the beginning of the irrigation season in early May (fig. 35). Groundwater levels rose approximately 4 ft by mid-August, and then began to decline, approaching the January levels.

Groundwater levels in the wells on the East Bench were an average of about 3.1 ft higher from January 2009 to January 2010. This is a result of the wetter year in 2010, which resulted in increased groundwater storage.

West Bench

Similar to the East Bench, groundwater levels on the West Bench responds mostly to climatic trends and irrigation. Well 123857 is located less than a tenth of a mile downgradient from the West Side Canal and is completed in the Tertiary sediments at a depth of 120 ft. Water levels in this well fluctuate seasonally, with the highest levels during the irrigation season (fig. 36) when groundwater rises in response to canal seepage and applied irrigation water. Groundwater levels remained consistent from 1993 through the late-1990s and then declined between 2000 and 2006 by about 5 ft. This decline occurs during below-average precipitation years. From 2006 to 2010, groundwater levels were more consistent and rose slightly in 2010, corre-



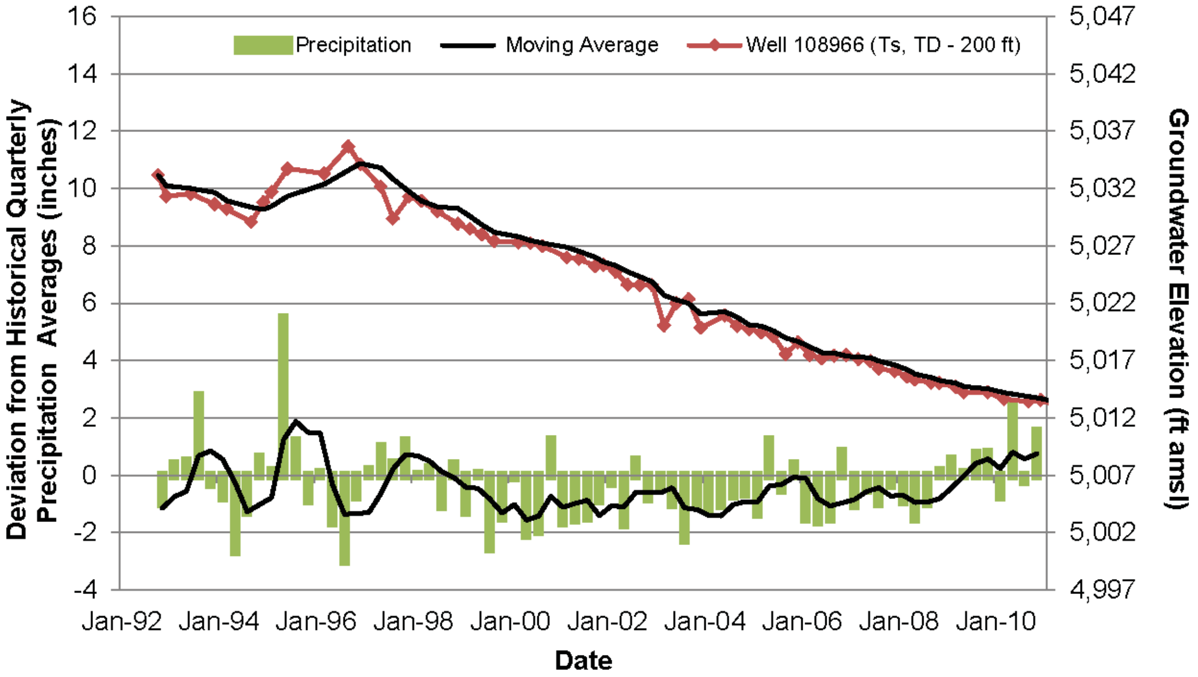


Figure 36. Groundwater levels respond differently in wells 123857 and 108966, located on the West Bench. Well 123857 (top graph) shows seasonal variation and an overall declining water-level trend of about 5 ft, while well 108966 (bottom graph) shows little seasonal variability and a decline of about 20 ft in water levels through the period of record.

sponding to an above-average precipitation year.

In contrast, groundwater levels in well 108966 showed little seasonal variability and did not appear to respond to irrigation (fig. 36). Well 108966 is located on the northern section of the West Bench (fig. 5) and is completed in the Tertiary sediments at a depth of 200 ft. From 1993 to 1997, water levels fluctuated less than 6 ft. From 1997 through 2010 water levels declined more than 20 ft. The period of decline corresponds to below-average precipitation. On the West Bench, two irrigation wells were drilled in 2003 and two more were drilled in 2005. The steady groundwater level decline began in 1998 and the trend continued at a consistent rate before and after 2003–2005. For this reason the declines are attributed to climatic influences rather than irrigation withdrawals.

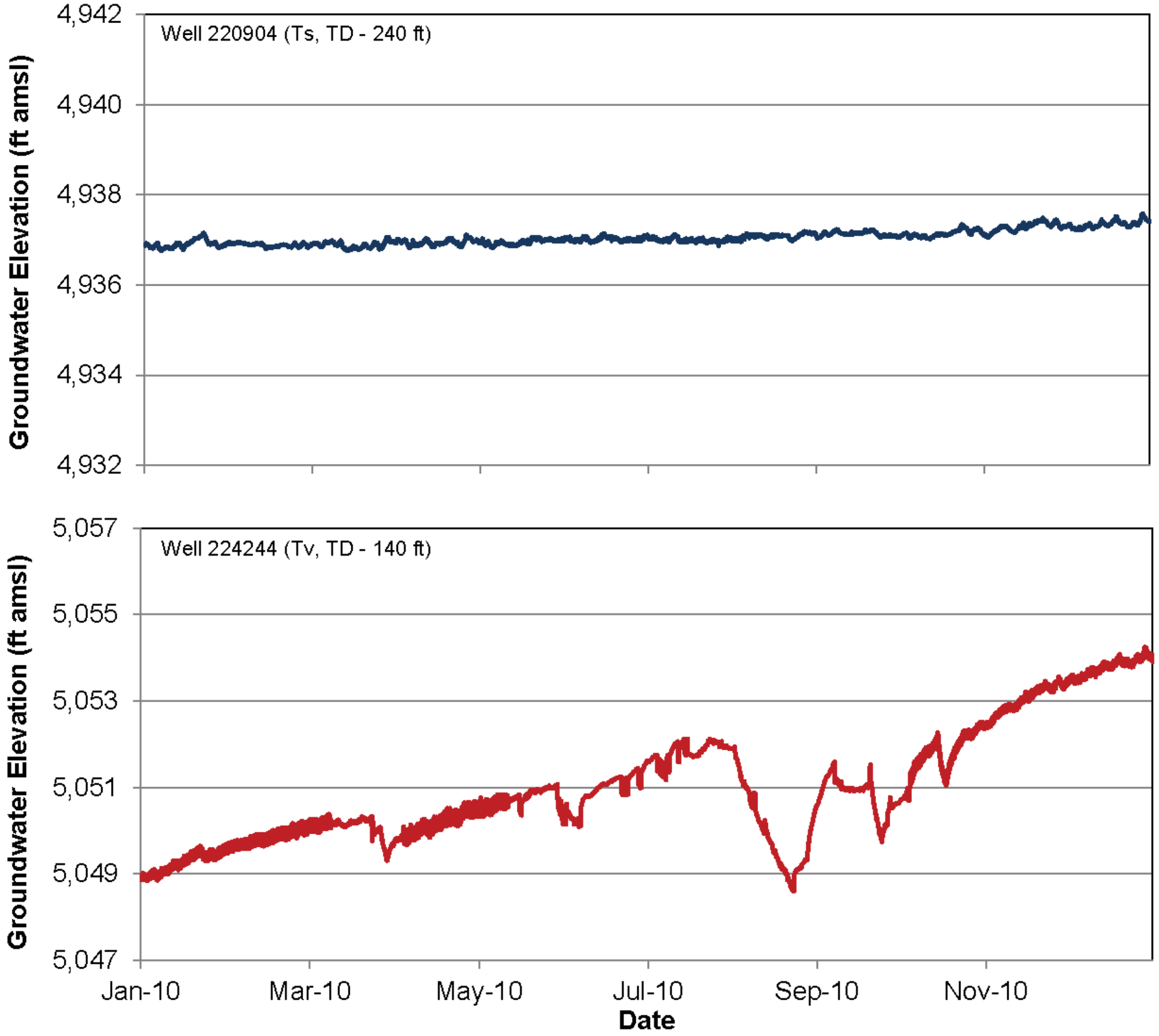


Figure 37. Groundwater levels during 2010 from select wells on the West Bench show different responses to climatic patterns and irrigation. Well 220904, completed in Tertiary sediments, showed groundwater levels that remained fairly consistent. Well 224244, completed in volcanic rock, showed an overall groundwater level rise of about 5 ft during 2010.

During 2010, groundwater levels in well 220904, completed in Tertiary sediments, showed essentially no seasonality nor response to irrigation (fig. 37), similar to the response noted in well 108966, which is about a mile from well 220904. This well is located on a non-irrigated portion of the West Bench near the floodplain and is 240 ft deep.

Well 224244, which is completed in the volcanic rock aquifer on the West Bench, shows an overall rise in groundwater levels during 2010 of approximately 5 ft (fig. 37). Groundwater levels declined during the irrigation season but then continued to rise in the fall.

On average, groundwater on the West Bench was about 0.81 ft higher in January 2009 when compared to levels from January 2010.

Canal Study

Canal Seepage Estimates

The rate of canal seepage loss is controlled by the geologic sediments underlying the canal, depth to groundwater in the canal vicinity, degree of saturation near canal sediments, stage in the canal, and the wetted perimeter in the canal. Based on published values for seepage rates in loam and sandy loam materials similar to the East and West Bench areas, these canals were expected to lose about 2 cfs per mile (Sonnichsen, 1993).

Seepage losses along the East Bench Canal were calculated from flow measurements made at six stations (fig. 9). Table 5 presents the flow measured at each station, the amount of water diverted from the canal between the stations, and the calculated seepage losses. Flow was first turned into the canal

Table 5. Results of seepage runs on the East Bench Canal. Negative loss values indicate a seepage loss in flow in the canal.

Montana Bureau of Mines and Geology, 2010													U.S. Bur. of Reclamation, 2008			
Aug 2, 2010							Aug 17, 2010						May 31, 2007		Aug 13, 2007	
Station	Station No.	Measured Flow (cfs)	Diversions (cfs)	Loss (cfs)	Distance (miles)	Loss (cfs/mile)	Station	Measured Flow (cfs)	Diversions (cfs)	Loss (cfs)	Distance (miles)	Loss (cfs/mile)	Loss (cfs)	Loss (cfs/mile)	Loss (cfs)	Loss (cfs/mile)
Diverted from River		410.0					Diverted from River	250								
Nissen Ln	1	349.1			0		Nissen Ln	217.6			0					
21.3 Check	2		31.0				21.3 Check	186.0	20.0	-11.6	4.38	**-2.7**	N/A	N/A	N/A	N/A
21.3 Check	2						21.3 Check	186.0								
Stoddard Ln	3	267.1	33.0	-18.0	8.03	**-2.2**	Stoddard Ln	163.9	18.0	-4.1	3.65	**-1.1**	-28.1	-3.5	-16.9	-2.1
Stoddard Ln	3	267.1					Stoddard Ln	163.9								
Anderson Ln	4	191.3	71.5	-4.3	2.99	**-1.4**	Anderson Ln	139.4	16.0	-8.5	2.99	**-2.8**	-14.4	-4.8	-14.1	-4.7
Anderson Ln	4	191.3					Anderson Ln	139.4								
Trout Creek	5	172.7	18.4	-0.2	3.60	**-0.1**	Trout Creek	118.0	5.0	-16.4	3.60	**-4.5**	N/A	N/A	N/A	N/A
Trout Creek	5	172.7					Trout Creek	118.0								
34.0 Check	6	141.7	18.0	-13.0	2.40	**-5.4**	34.0 Check	114.7	3.0	-0.3	2.40	**-0.1**	-7.7	-3.2	-3.4	-1.4
Average						**-2.1**						**-2.4**		**-3.8**		**-2.7**

Note. Average of two MBMG measurements is a loss of -2.2 cfs/mile

for the season on April 25. The amount of water diverted from the Beaverhead River on August 2 and August 17 was 410 and 250 cfs, respectively. The capacity of the canal at the headworks is 440 cfs (U.S. Bureau of Reclamation, 2011), so the measurements made on August 2 represent approximate bank-full conditions. Seepage was measured over a total of 17.26 miles in the study area. Measured seepage along individual sections during these two measurements ranged from 0.1 cfs per mile to 5.4 cfs per mile. The average seepage for the entire reach was 2.1 cfs on August 2 and 2.4 cfs per mile on August 17. The margin of error assumed for the diversion rates and the canal measurements was ±10%, so the actual seepage rates could range from a minimum of 0.8 cfs per mile to a high of 3.3 cfs per mile. Seepage along different sections of a canal are expected to vary due to the conditions of the canal and type of underlying geologic material. The variations reported here are not beyond those expected.

The U.S. Bureau of Reclamation performed two seepage runs on the East Bench Canal on May 31 and August 14, 2007 (U.S. Bureau of Reclamation, 2008). They measured flow at nine locations along the canal from Barretts Diversion to a distance of 39 miles downgradient from the diversion. Flow at Barretts Diversion was 231 and 160 cfs on May 31 and August 14, 2007, respectively, less than the flow for the seepage run dates in 2010. The results of their seepage investigation are similar to those of the MBMG measurements, and are included in table 5 for those measurements that were in the same reaches measured as part of this GWIP study.

Canal seepage loss from the West Side Canal was calculated from flow measured at five stations (fig. 9) on July 19 and August 16, 2010. Where the West Side Canal is diverted from the Beaverhead River, the flow was 87.4 and 54.6 cfs, on July 19 and August 16, respectively. An average seepage estimate for the West Side Canal based on the two measurement dates was 1.2 cfs/mile (table 6). The margin of error assumed for the diversion rates and the canal measurements was

Table 6. Results of seepage measurements on the West Side Canal. Negative seepage values indicate a loss in canal flow.

July 19, 2010

Station	Station No.	Flow (cfs)	Diversions (cfs)	Loss/Gain (cfs)	Distance (miles)	Loss/Gain (cfs/mile)
Cornell Park (Diverted)	1	87.4				
Frying Pan Gulch Rd.	2	74.8	6.4	-6.2	4.27	-1.4
Frying Pan Gulch Rd.	2	74.8				
Highway 93	3	63.0	10.2	-1.6	2.16	-0.8
Highway 93	3	63.0				
Anderson Lane	4	37.0	27.9	1.9	1.8	1.1
Average						**-0.7**

August 16, 2010

Station	Station No.	Flow (cfs)	Diversions (cfs)	Loss/Gain (cfs)	Distance (miles)	Loss/Gain (cfs/mile)
Diverted	1	54.6				
Frying Pan Gulch Rd.	2	46.8				
Highway 93	3	41.8	0.8	-4.2	2.16	-1.9
Highway 93	3	41.8				
Anderson Lane	4	22.9	11.4	-7.5	1.8	-4.1
Anderson Lane	4	22.9				
WSC/Black Slough	5	12.1	14.7	3.9	4.81	0.8
Average						**-1.8**

Note. The average of the two MBMG measurements (-0.7 and -1.8 cfs/mile) is an overall average loss of -1.2 cfs/mile.

±10%, so the actual seepage rates could range from a minimum of near zero cfs per mile to a high of 2.1 cfs per mile.

Canal/Groundwater Interactions

To assess the effect of canal seepage on groundwater, monitoring wells were installed at two sites along the East Bench (EBC-1 and EBC-2) and two sites along the West Bench Canal (WSC-1 and WSC-2; fig. 9). During the 2010 irrigation season, the East Bench Canal was turned on April 25 and shut down for the season on October 16. The West Side Canal was flushed on April 3, 2010, delivery began on April 7, and it was shut down on October 19.

East Bench Canal Sites

EBC-1. At this site, four monitoring wells were drilled and completed at different depths adjacent to the East Bench Canal (255491, 119 ft deep; 257998, 71 ft deep; 258009, 44 ft deep; 258012, 16 ft deep). The majority of the sediment underlying site EBC-1 are fine sand and silt, with some layers of clay, sand, and sand/gravel (fig. 38). Directly underlying the canal was silt with two interbedded layers of sand and gravel at a depth of about 28 ft. There were two silty clay layers from 80–84 ft and 104–106 ft below ground surface.

Before water was turned into the canal on April 25, the deep sand was saturated, but the intermediate and shallow sediments were not saturated (figs.

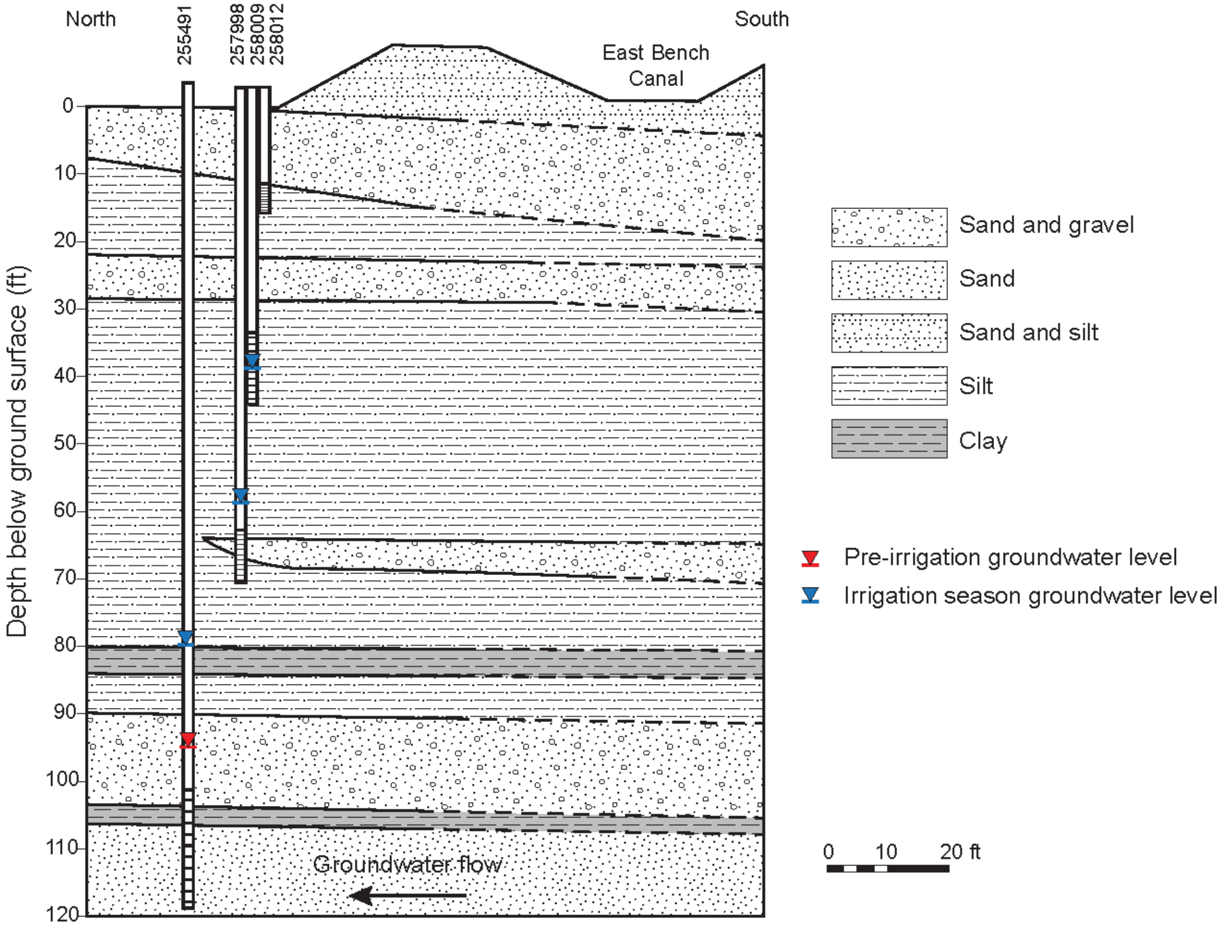


Figure 38. Schematic cross section along canal site EBC-1. Prior to the irrigation season, well 255491 was the only well that intersected groundwater. Groundwater flow at this site is generally southeast to northwest.

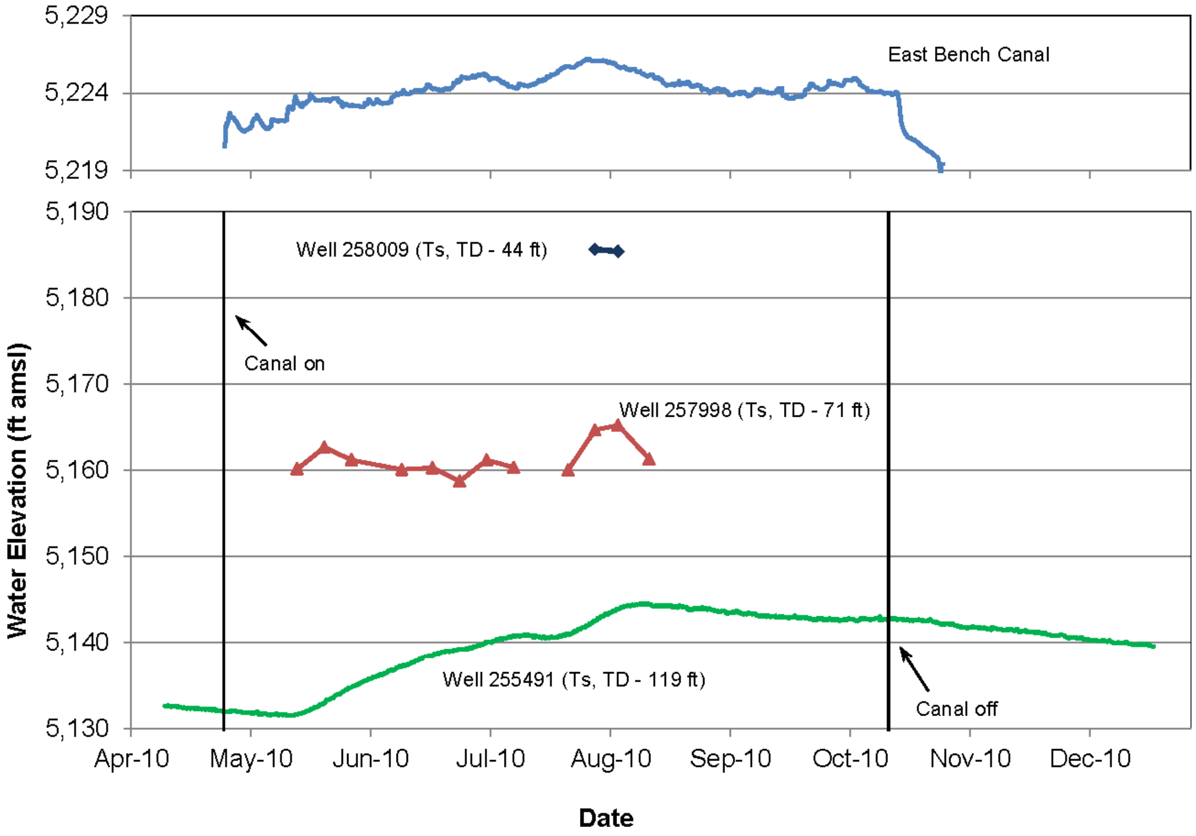


Figure 39. Groundwater levels in the monitoring wells respond to water in the canal at site EBC-1. The shallowest well (258012, TD = 16 ft) remained dry throughout the monitoring period and is not included in this graph.

38, 39). In response to flow in the canal, the water level in the deep sand rose, eventually reaching an increase of about 12 ft. The intermediate sand and silt became saturated within 2 weeks from the time the canal began flowing and rose 4.5 ft in well 257998. There were only 2 weeks in late July and early August when water levels were detected in well 258009, corresponding to the period when canal levels were highest. The shallow sand and gravel remained dry at well 258012 throughout the monitoring period indicating a shallow unsaturated zone beneath the canal.

The highest water levels in the canal were at the end of July; thereafter, flow in the canal decreased until October 16, when flow ended for the season. After August 13, the intermediate sand and silt (well 257998) went dry and water levels in the deeper sand (well 255491) began to slowly decline. By December (2 months after the canal was turned off), water levels in well 255491 had decreased by 4.4 ft from the high during irrigation. A measurement during April, 2011 (prior to turning the canal back on for the 2011 irrigation season) indicated that the groundwater level was only 0.02 ft lower than it was in December. Groundwater levels in this deeper groundwater flow system had still not fully declined to April 2010 levels.

EBC-2. At this site, monitoring wells were drilled and completed to three different depths adjacent to the East Bench Canal (well 255488, 78 ft deep; well 255489, 39 ft deep; and well 257991, 17 ft deep). The upper 20 ft of sediment underlying site EBC-2 consists of sand and gravel (fig. 40). The majority of the sediment below 20 ft is finer grained, consisting of mixtures of clay, silt, and fine sand.

Before the canal began flowing on April 25, groundwater was observed only in the deepest sand. After the canal was turned on, water levels in all monitoring wells increased (fig. 41). The shallow and intermediate zones became saturated within 5 days after flow began in the canal. Groundwater levels in the deep zone did not begin to rise until 30 days after flow began in the canal. Groundwater levels in the shallow and intermediate wells increased until the end of July, when the water level in the canal reached its maximum. Water levels in the deep well did not reach a maximum until 25 days later. The shallow groundwater level raised a total of 13.6 ft and was above the bottom of the canal during part of the summer. The intermediate water level increased 24.8 ft. In the deep zone, groundwater levels rose about 12 ft.

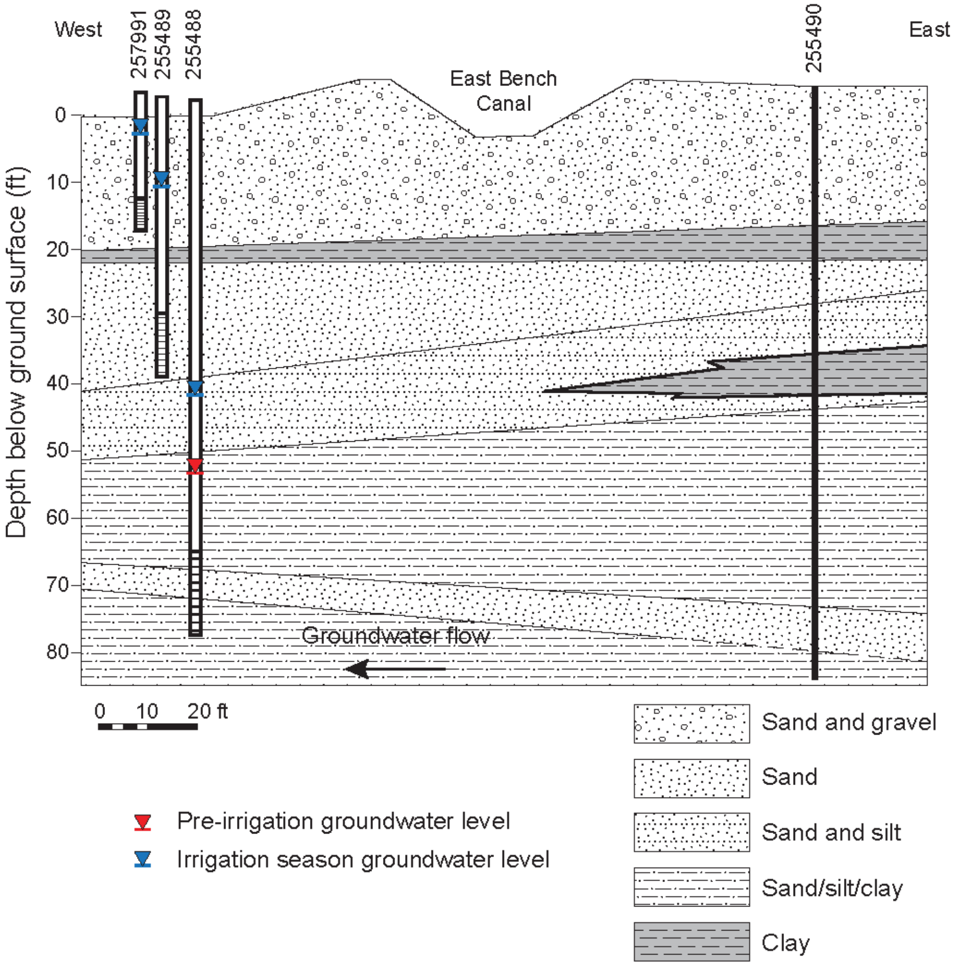


Figure 40. Schematic cross section along canal site EBC-2. Close to 20 ft of sand and gravel underlie the canal.

Water levels in the shallow and intermediate zone began to decrease when the canal water level was lowered after the peak at the end of July. The deep zone did not begin to go down until about 25 days later. When the canal was turned off

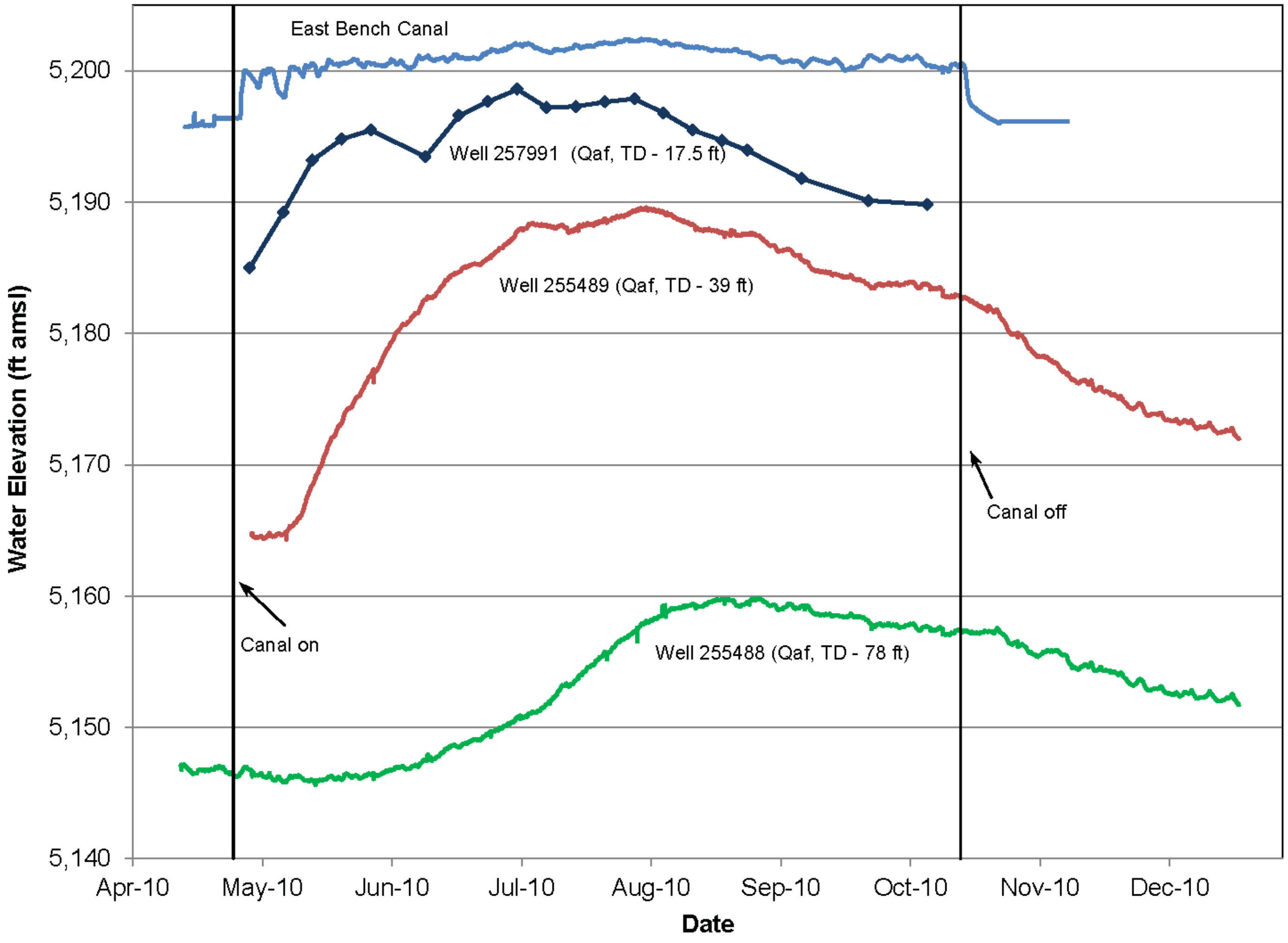


Figure 41. Water elevations in the canal and monitoring wells at site EBC-2. Groundwater began to intersect wells 257991 and 255489 between 4 to 12 days after the canal began flowing.

for the season (October 16th, 2010), the shallow zone became unsaturated and the rate of decline in water levels in the intermediate zone increased. Water levels in the deep zone began dropping at a faster rate about 8 days after the canal was turned off. As of April 2011, the intermediate groundwater level had still not receded to below the bottom of the well; the groundwater levels in the deep zone were about a foot to 1.5 ft higher than in April 2010.

Groundwater-level changes at these two sites indicate that the canal is hydraulically connected to all the zones that were monitored, but there appears to be a lag time of up to 2 weeks for groundwater in the deeper wells to respond to stage changes in the canal. Canal stage and groundwater elevations indicate a downward flow gradient. Unlike EBC-1, seepage from the canal at EBC-2 most likely saturated the underlying sediments within 2 weeks of the canal being turned on.

West Side Canal Sites

WSC-1. At this site four monitoring wells were drilled and completed in three different zones adjacent to the West Side Canal (260139, 18 ft deep; well 260133, 21 ft deep; well 260134, 46 ft deep; and 260138, 41 ft deep). The West Side Canal at site WSC-1 is directly underlain by clayey silt to depths of about 8 to 16 ft (fig. 42). Beneath the clayey silt, well-sorted sands and gravels are interbedded with finer-grained sand and clay, sand and silt, and clay and silt layers.

All monitoring wells were dry prior to the irrigation season and the beginning of flow in the canal (fig. 43). The shallow zones remained dry through the entire monitoring period. The deep zones were saturated from September 23rd until November 4th. Water levels rose about 9 ft and 3 ft from the bottom of wells 260134 and 260138, respectively. The water level in the canal was about 40 ft above the groundwater level.

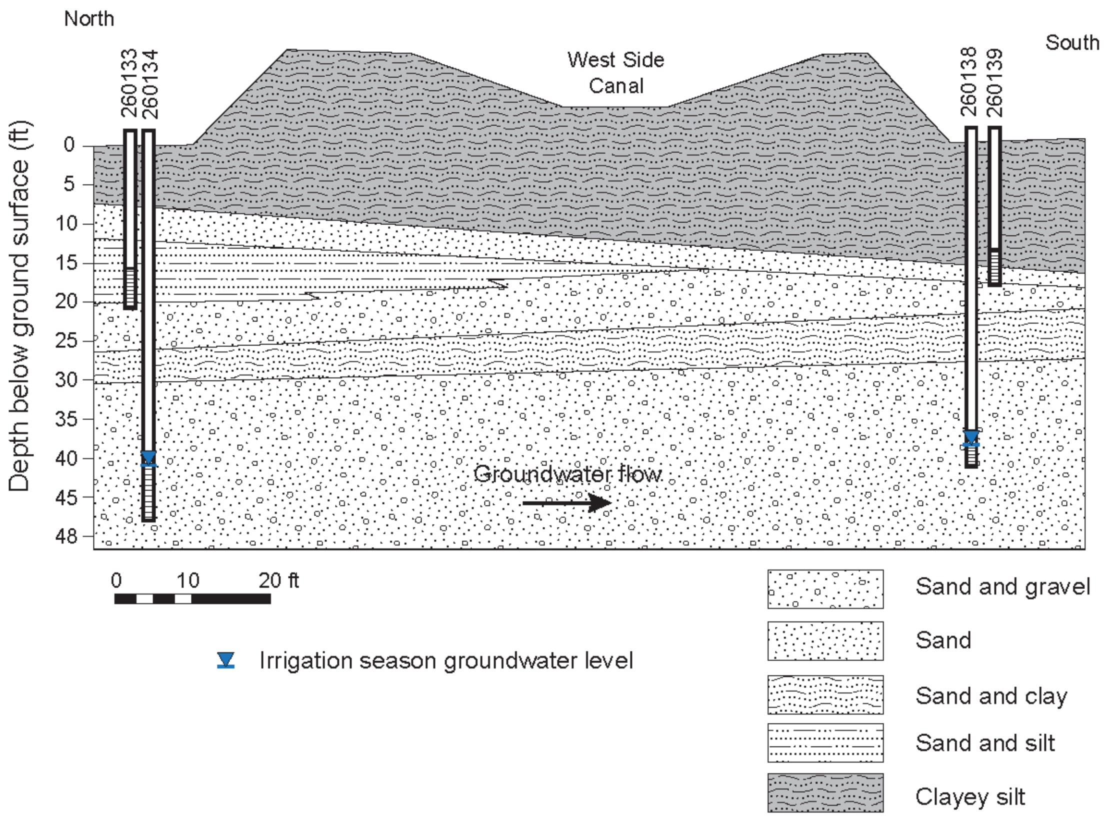


Figure 42. Cross section along canal site WSC-1. About 15 ft of clayey silt directly underlies the canal.

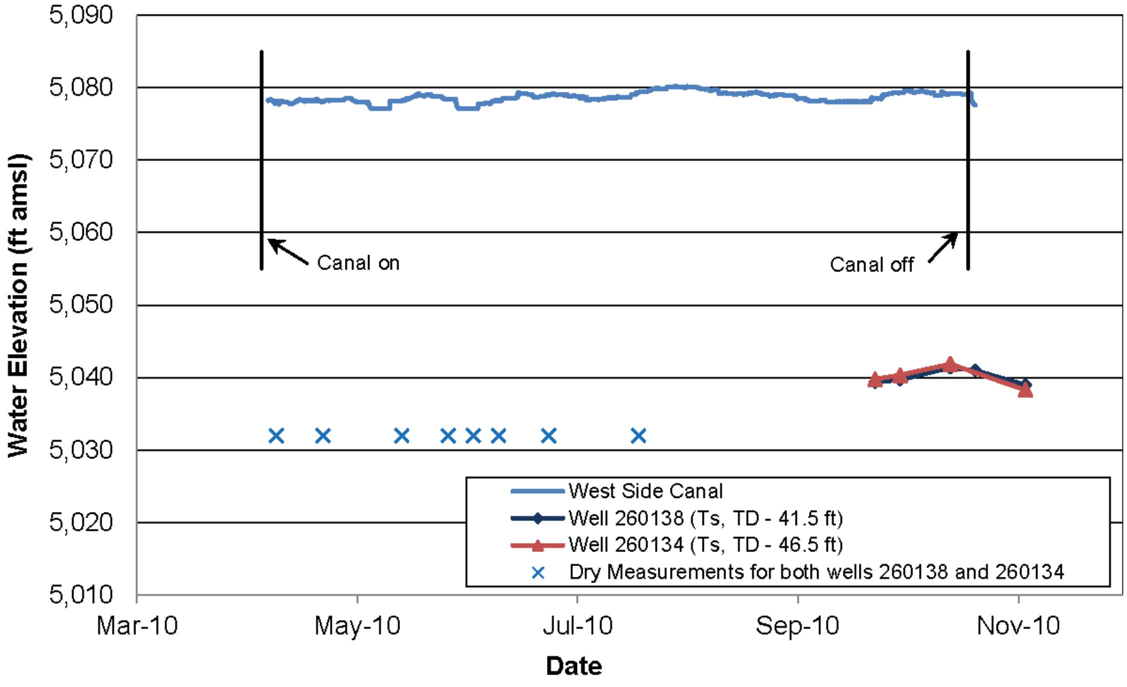


Figure 43. Water elevations in the canal and monitoring wells. The two shallow wells (260133 and 260139) remained dry throughout the monitoring period and are not shown on this graph.

WSC- 2. The monitoring network at this site includes seven wells at different depths and locations adjacent to the canal. There are two shallow wells, 257783 (17 ft deep) and 257794 (16 ft deep); three intermediate wells, 257787 (26 ft deep), 257795 (24 ft deep), and 257797 (23 ft deep); one deeper intermediate well, 257796 (31 ft deep); and one deep well, 257789 (40 ft deep). At site WSC-2, the canal is directly underlain by about 2 to 3 ft of sand and silt, which thickens to the east (fig. 44). Below this was a sand and gravel layer about 15 to 25 ft thick that is interbedded with finer-grained lenses of silt and clay. About 30 ft below ground, a silt and clay layer underlies the sand and gravels. Water was turned into the canal on April 7 and the canal was turned off during the irrigation season because of heavy precipitation from about May 5th to May 10th and again from May 30th to June 4th.

Prior to the irrigation season and flow beginning in the canal, the water level in the sand and gravel was 20 to 25 ft below ground surface (fig. 44). Groundwater levels began rising 1 to 2 days after water was turned into the canal. Approximately 1 to 2 weeks after the canal began flowing, the groundwater level had risen to near the intermediate zone of the sand and gravel, eventually reaching near the top (fig. 45). By the time of peak flow in the canal in August, the groundwater levels in the deeper wells were 12.4 ft to 14.7 ft higher

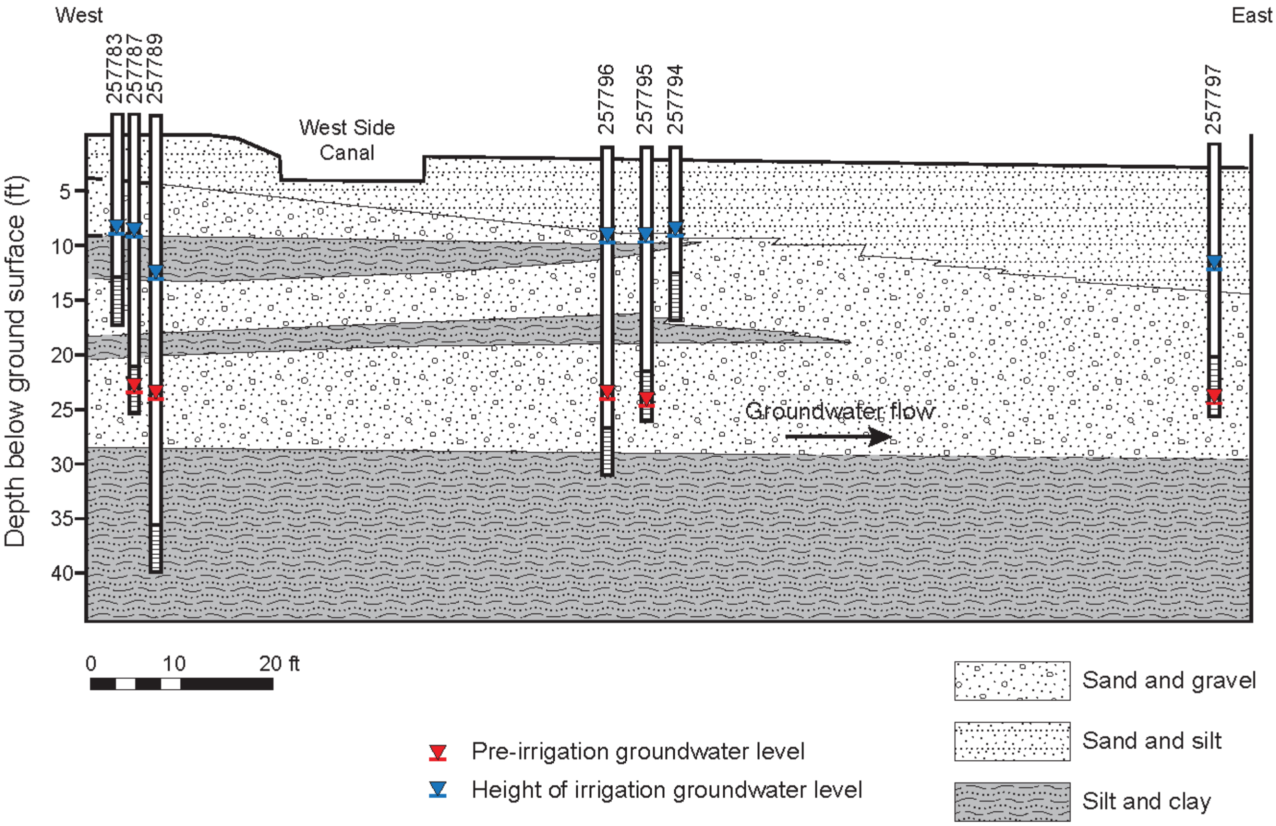


Figure 44. Cross section along canal site WSC-2. About 5 ft of sand and silt, and sand and gravel underlie the canal.

than before the irrigation season. After the canal was turned off in early and late May, for about 5 days each time, groundwater levels dropped several feet. In October, when flow to the canal was turned off, groundwater levels in the sand and gravel aquifer steadily dropped and were about 1 ft higher at the start of the 2011 irrigation season as compared to before the start of the 2010 irrigation season.

The sand and gravel responds as a single aquifer with a flow gradient from west to east. Though the monitoring wells are completed at different depths, they reflect essentially the same water levels and trends, mimicking the water-level trends in the canal.

Groundwater levels in the deep silty clay (well 257789) rose within 1 or 2 days after the canal began flowing and followed the water-level trends in the canal, with rises or declines in groundwater levels occurring within the first half-day of changes in canal flow (fig. 45).

Groundwater and Surface-Water Chemistry

Water chemistry can provide a general overview of the usability of the groundwater resources, identify possible concerns, and help evaluate the groundwater flow system including groundwater/surface-water interactions and possible sources of groundwater recharge. Water-quality data for the sites shown in figure 46 are listed in appendix C, and complete sample analyses can be accessed through the MBMG GWIC database (http://mbmg-gwic.mtech.edu/). These samples were categorized into four hydrogeologic units for purposes of this section: alluvial aquifer (Qal), Tertiary sediment aquifer east of the river (Ts east), Tertiary sediment aquifer west of the river (Ts west), and the volcanic rock aquifer (Tv).

General Water Quality

The relative concentrations of major ions, indicating the water type in milliequivalents/liter (meq/L), are presented as Stiff diagrams in figure 46. The overall width of the Stiff diagram is proportional to the total ionic content, or in this case total dissolved solids (TDS). The water types reflect the geologic material in which groundwater and surface water flow.

TDS in water originates from natural sources such as dissolution of minerals in bedrock and sediments through which water flows, and anthropogenic sources such as septic systems and agricul-

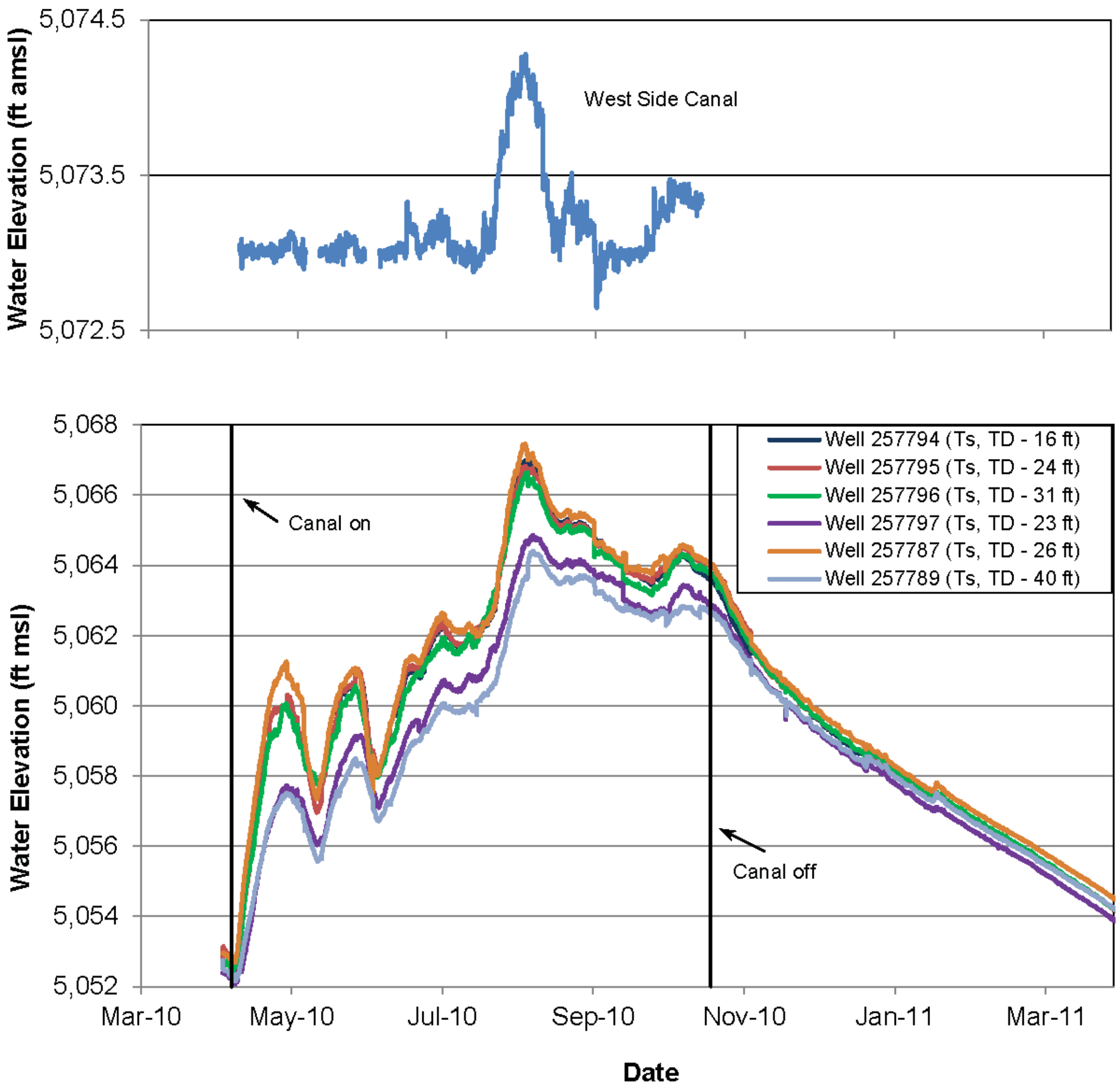


Figure 45. Water elevations in the canal and monitoring wells. Water elevation for the West Side Canal is plotted above groundwater in order to accentuate the water elevation scale.

tural activities. TDS is used as a general indicator of the quality of water. The EPA's secondary maximum contaminant level (SMCL) for TDS in drinking water is 500 mg/L. Sixteen of the 55 groundwater sites and 7 out of 16 surface-water sites sampled exceeded the SMCL for TDS.

In the study area, the dominant water type in surface and groundwater was calcium-bicarbonate (76% of all sites). Magnesium is common throughout the study area as the secondary cation. Sodium was dominant in several Tertiary west wells and volcanic rock wells. Sulfate is the most common anion after bicarbonate, and increases somewhat to the north in the Tertiary west system. Chloride is the secondary anion in several samples on the west side. Water quality in the valley was fairly consistent (calcium-bicarbonate) in the alluvial and Tertiary sediment aquifer. Sulfate and TDS were somewhat higher to the north.

Alluvium

Of the eight alluvial sites sampled, all were calcium-bicarbonate type water (fig. 46 and appendix C). TDS in the alluvium ranged from 400 to 776 mg/L. Temperature was between 5.4°C and 11.8°C. The pH ranged from 7.61 to 8.15.

Tertiary Sediment Aquifer

Based on 15 samples, water quality in the Tertiary sediments on the West Bench was more diverse than any other aquifer in the study (fig. 46). Water types included calcium-bicarbonate, calcium-sulfate, sodium-bicarbonate, and sodium-sulfate. TDS concentrations ranged from 294 to

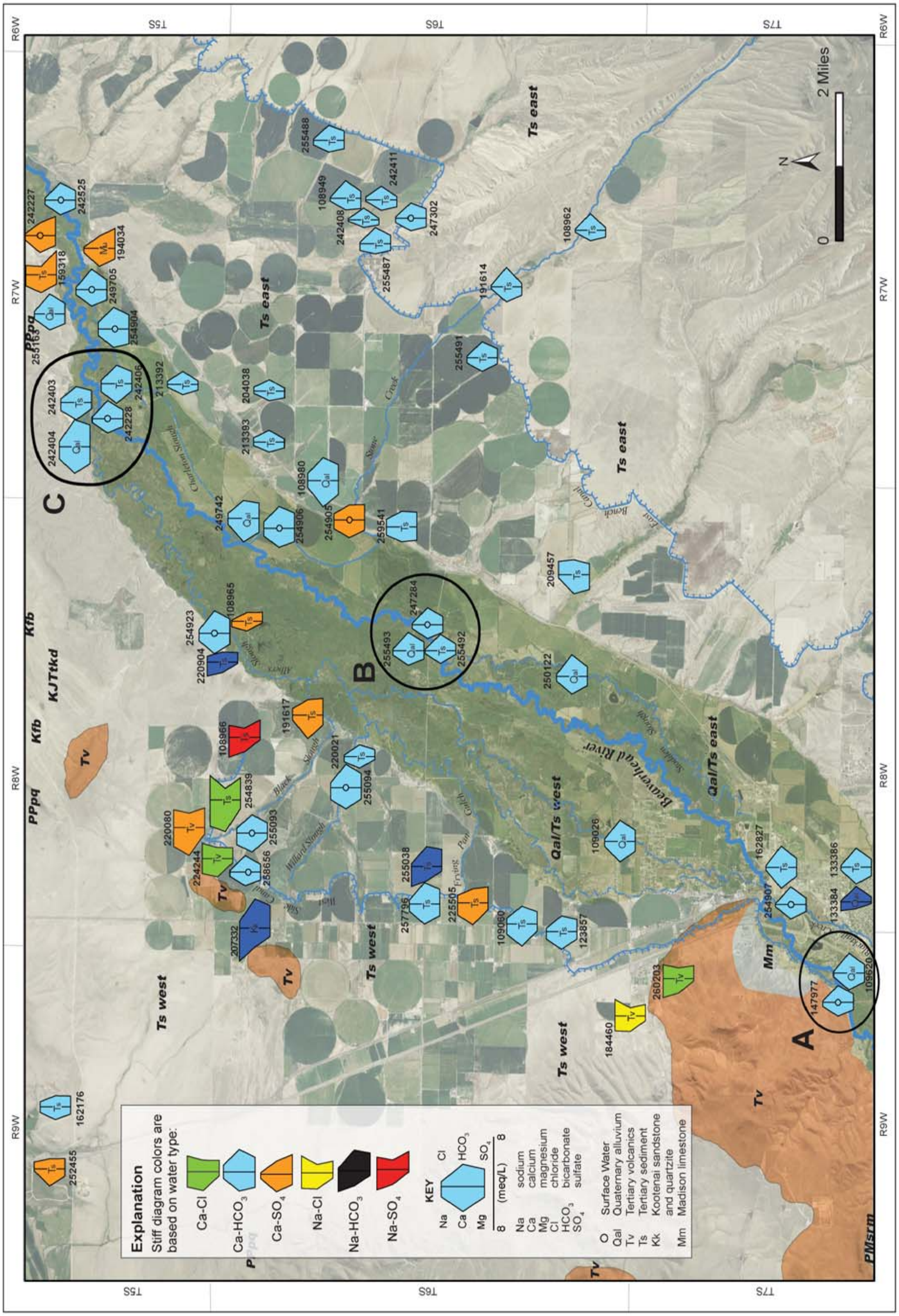


Figure 46. The dominant water type in the study area is calcium-bicarbonate. Water chemistry is more varied on the West Bench than on the East Bench or the floodplain.

901 mg/L, with the lowest values associated with calcium-bicarbonate type water and the highest TDS values associated with calcium-sulfate water. Temperature also showed variability, ranging from 5.4°C to 18.0°C. The pH was between 6.93 and 8.01.

In all 17 East Bench Tertiary sediments groundwater type was calcium-bicarbonate. TDS concentrations ranged from 230 to 626 mg/L. Temperature was between 6.9°C and 15.8°C. The pH was between 7.24 and 8.22.

Volcanic Rock Aquifer

Based on six samples, water types in the volcanic rock aquifer were calcium-sulfate and calcium-chloride. TDS in the volcanic rock ranged from 570 to 790 mg/L. Temperature was between 10°C and 13°C. The pH range was very narrow, from 7.53 to 7.88.

Surface Water

Twelve surface-water samples were collected within the study area (Beaverhead River and sloughs/creeks), and all but one contained calcium-bicarbonate type water. The Stone Creek sample collected above the floodplain was dominated by calcium with equal amounts of sulfate and bicarbonate. In surface water, TDS ranged from 370 mg/L in the East Bench Canal to 858 mg/L at the headwaters of Black Slough, located on the West Bench near volcanic outcrops. Four samples were collected from the Beaverhead River during March 2010, prior to the irrigation season so that diversions and return flows did not influence chemistry. TDS in the river increased slightly downstream during the 2010 sampling. The TDS was the same at Dillon and Anderson Lane, 483 and 482 mg/L respectively, while at Beaverhead Rock the TDS in the river was 516 mg/L. Downstream from Anderson Lane, major tributaries draining into the river include Stone Creek, Albers Slough, and Charleton Slough. These are groundwater-fed from seepage and irrigation return flow, with Stone Creek being the only drainage that is generated offsite. TDS of these tributaries ranged from 540 to 610 mg/L.

Flow Path Chemistry

Box and whisker plots of sodium and chloride concentrations for all samples in the study area indicate possible mixing along flow paths on the West Bench (fig. 47). Chloride and sodium concentrations on the West Bench are higher in the volcanic rock aquifer, lower in the Tertiary sediment and alluvial aquifers, and lowest in the Beaverhead River. Water-quality samples from aquifers under the East Bench did not show a similar pattern.

River and Groundwater Chemistry

Data show similar water quality in the Beaverhead River and nearby monitoring wells (figs. 46, 48). Water chemistry is essentially the same in both the alluvium and the river at sites A and B. At site B, water quality in the Tertiary sediments is higher in calcium and slightly higher in bicarbonate (HCO_3) than the alluvium and the river. At site C, near Beaverhead Rock, water quality in the alluvium and the Tertiary sediment samples were nearly the same, with the exception that the Tertiary aquifer groundwater was lower in magnesium. The percentage bicarbonate in the river is slightly higher than the groundwater and the percentage sodium is slightly lower.

Uranium

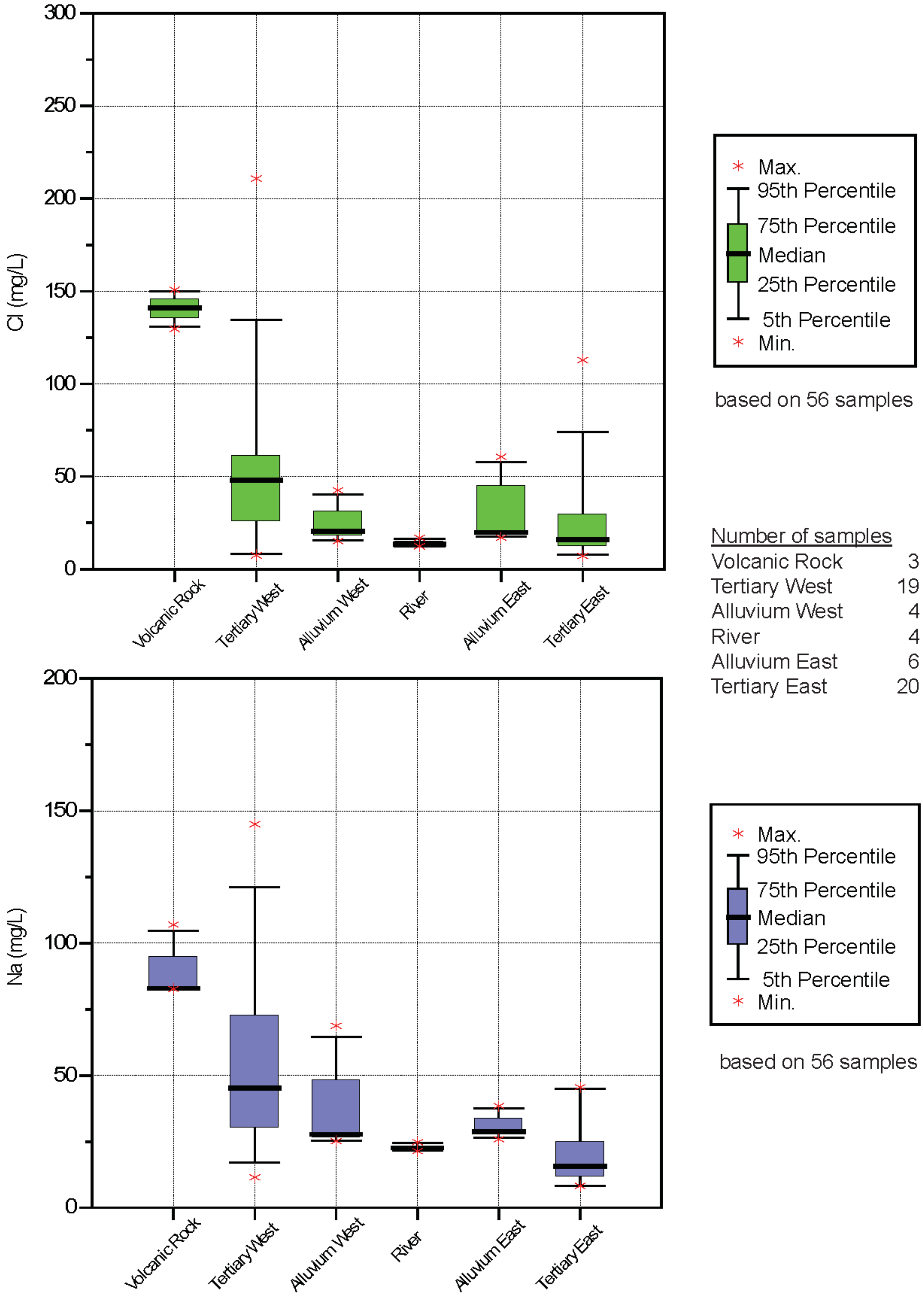
Uranium concentrations in the study area ranged from less than detection limits to 55.1 µg/L (appendix C). The drinking water maximum contaminant level (MCL) for uranium is 30 µg/L. Exceedances were found at eight locations: four in Tertiary sediments on the West Bench, two in northwestern volcanics, and two in surface water near the northwestern volcanics. There were no exceedances in water samples collected in the river valley or on the East Bench.

Arsenic

The human health MCL for arsenic in groundwater or surface water is 10 µg/L (Montana Department of Environmental Quality (MDEQ), 2010). Concentrations within the study area ranged from non-detect to 26.16 µg/L (appendix C). Arsenic concentrations over the drinking water MCL occurred at 11 locations near Beaverhead Rock and Dillon in surface water and all hydrogeologic units.

Nitrate and Chloride

Nitrate concentrations ranged from less than detection limits to 17.24 mg/L (appendix C). The



Number of samples	
Volcanic Rock	3
Tertiary West	19
Alluvium West	4
River	4
Alluvium East	6
Tertiary East	20

Figure 47. On the west side of the study area, mixing groundwater along flow paths from the volcanic rock aquifer towards the river influences water quality. Mixing is less evident on the east side of the study area.

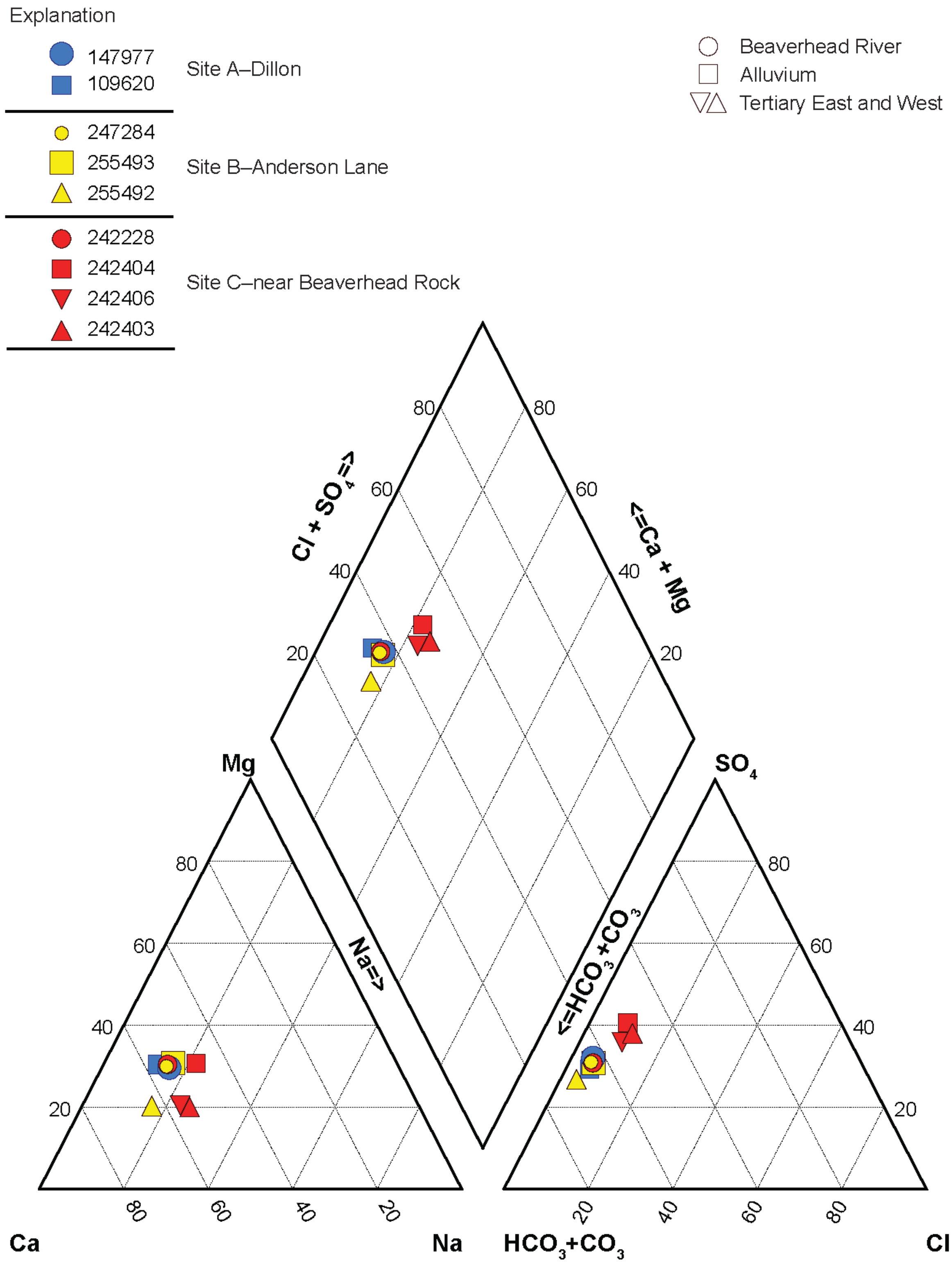


Figure 48. Surface-water and groundwater chemistry was essentially the same except at site C, where groundwater had higher concentrations of sulfate and sodium than the Beaverhead River. See figure 6 for site locations.

drinking water MCL for nitrate is 10 mg/L. The nitrate concentration was above the MCL in the volcanic rock aquifer at two wells, and in the Tertiary sediments at one well.

Elevated nitrate concentrations can indicate influences from fertilizer, animal waste, or septic systems (Katz and others, 2011). Elevated chloride concentrations can be associated with human and animal waste but typically not with fertilizers, so a comparison of chloride and nitrate concentrations can help understand sources. Those samples with nitrate values that exceeded the MCL also had high chloride concentrations (fig. 49). The combination of high nitrate with high chloride concentrations is an indicator that the source is more likely to be animal or human waste than fertilizers. Some high chloride values were associated with low nitrate, indicating natural breakdown of nitrate and/or that the nitrate was assimilated by plants.

Stable Isotopes

Stable isotopes of oxygen and hydrogen (^{18}O and D) were used to help differentiate sources of water in surface water (e.g., groundwater, overland flow, and other sources). Comparisons were made between groundwater and surface-water stable isotopes and the local meteoric water line (LMWL) to evaluate local evaporation lines (LEL). The differences between the temporal isotope records at several surface-water locations were used to characterize the relative amounts of regional groundwater input versus highly evaporated irrigation return flow in the surface water.

For this study, five snow samples were collected in the Ruby and Pioneer Mountains surrounding the study area and were compared to the Butte, Montana LMWL. δ^{18}O and δD for the local snow samples compared well with the Butte LMWL. The Butte LMWL has a more complete dataset and was therefore used in this study (fig. 50; table 7)

The plot of surface water δ^{18}O and δD samples has a slope of 4.3 with an R^2 value of 0.80 (fig. 50b). All groundwater samples, on the other hand, plot with a slope of 6.83 with an R^2 value of 0.95, closer to the Butte LMWL (fig. 50c; table 7).

Plots of δ^{18}O and δD from multiple samples from each individual location can help: elucidate groundwater/surface-water processes occurring throughout the basin; and characterize the source

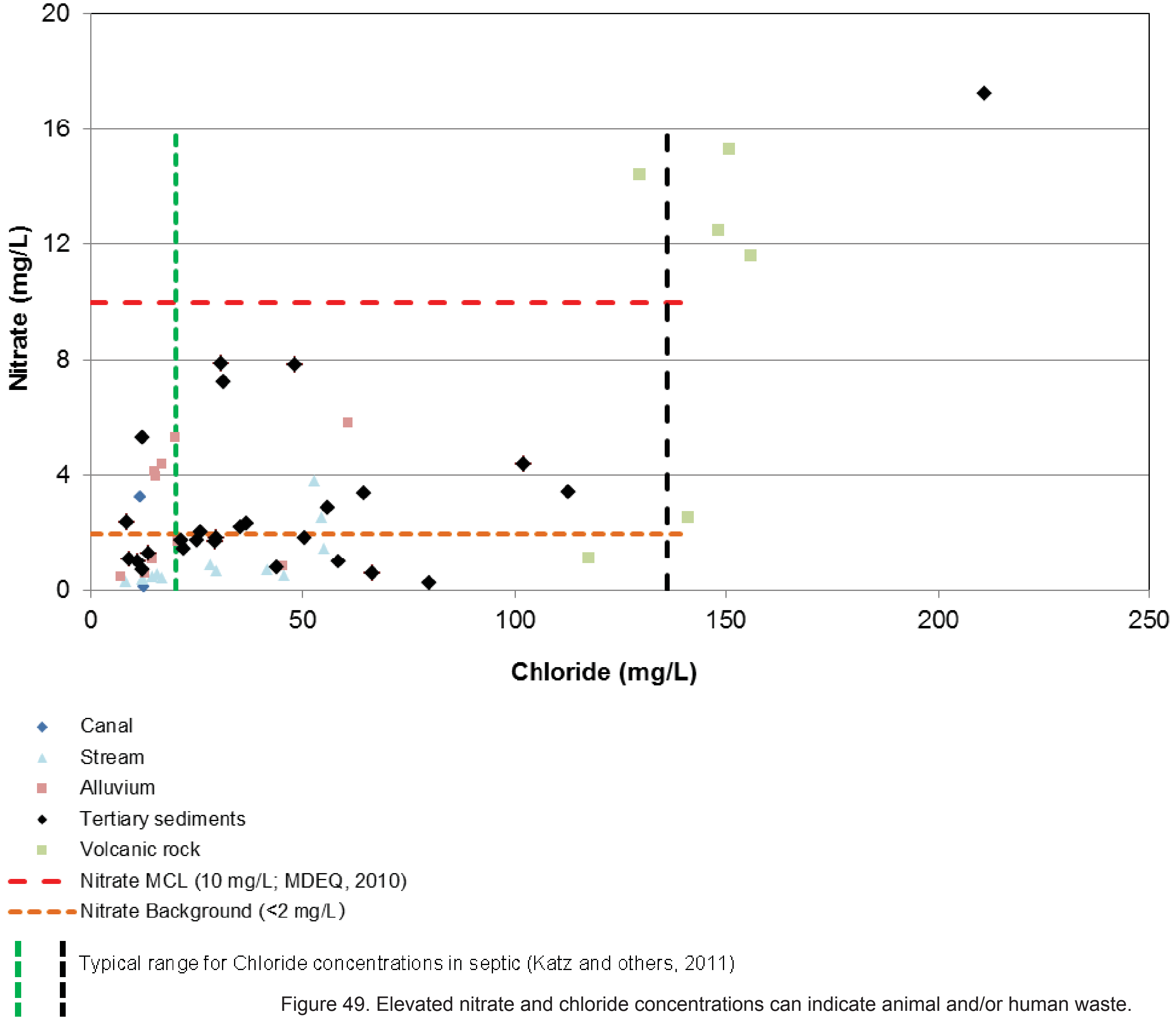


Figure 49. Elevated nitrate and chloride concentrations can indicate animal and/or human waste.

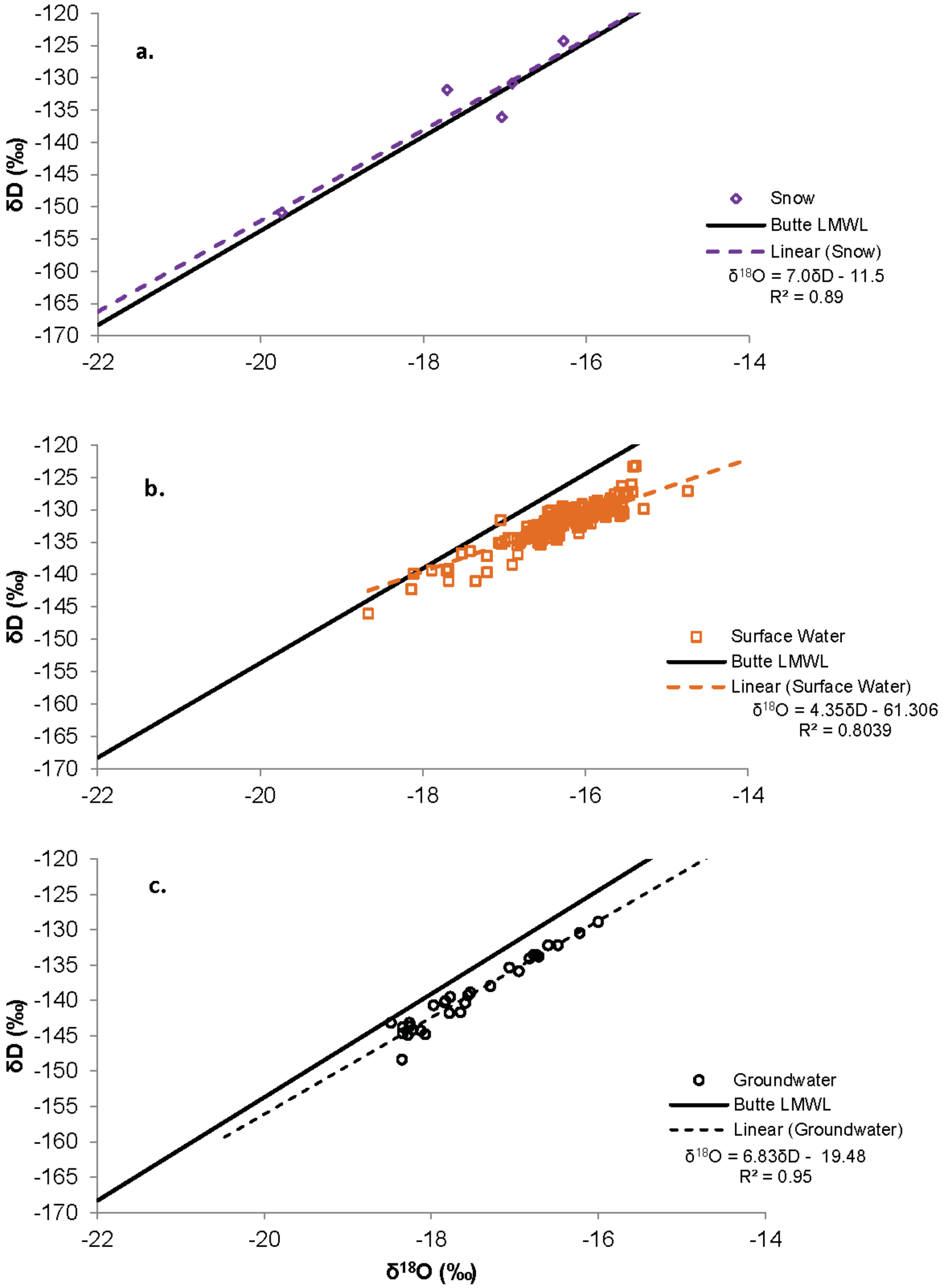


Figure 50. $\delta^{18}O$ (‰) and δD (‰) plotted with the Butte, Montana local meteoric water line (Gammons and others, 2006) for (a) snow samples, (b) surface-water samples, and (c) groundwater samples.

of evaporated water mixing with surface water. $\delta^{18}O$ and δD at each location plot along unique LELs, and the slopes of the lines indicate the degree of evaporation. Lower slopes correspond to higher rates of evaporation. Within the study area, most of the alluvial groundwater samples have an isotopic composition similar to that of surface water, while groundwater from the Tertiary sediments and volcanic rock are less evaporated and plot closer to the Butte LMWL (fig. 51).

Monitoring of isotopes at four stations along the Beaverhead River (from upstream to downstream: sites A, B, C and D, fig. 6) show that the influence of evaporation in the river does not continuously increase with downstream distance (fig. 52; table 7). Instead, sites A and D have similarly higher slopes (4.8 and 4.5, respectively) and, therefore, the least influence from evaporation. The middle sites B and C have lower slopes (3.4 and 3.7, respectively), indicating a higher influence from evaporation, likely irrigation return flows influencing the river at these sites.

There is little isotopic enrichment prior to and after the irrigation season, but significant enrichment in δD during the irrigation season (fig. 53). The influence of evapotranspiration continued for about 2 months after the end of the irrigation season, which likely is the result of delayed return flows.

The Beaverhead River and Albers Slough run parallel to each other in the floodplain, but they show very different rates of evaporation. Albers Slough shows relatively less evaporation in comparison to the Beaverhead River based on the

Table 7. Equations to the lines for $\delta^{18}O$ and δD for the Butte, MT local meteoric water line (established by Gammons and others, 2006), all snow samples (Snow), all groundwater samples (Groundwater), all surface water (Surface Water), and for individual stream locations. The slopes of the lines are bolded in each equation.

Site Name	GWIC ID	Equation	*n*	R^2
Butte LMWL	N/A	$\delta^{18}O = \mathbf{7.3}\delta D - 7.5$	42	0.99
Snow	N/A	$\delta^{18}O = \mathbf{7.0}\delta D - 11.5$	5	0.89
Groundwater	N/A	$\delta^{18}O = \mathbf{6.8}\delta D - 19.5$	31	0.95
Surface water	N/A	$\delta^{18}O = \mathbf{4.3}\delta D - 61.3$	191	0.80
BHR-Site A	147977	$\delta^{18}O = \mathbf{4.8}\delta D - 54.1$	13	0.92
BHR-Site B	247284	$\delta^{18}O = \mathbf{3.4}\delta D - 76.6$	15	0.62
BHR-Site C	242228	$\delta^{18}O = \mathbf{3.7}\delta D - 70.7$	11	0.77
BHR-Site D	242525	$\delta^{18}O = \mathbf{4.5}\delta D - 57.8$	13	0.74
Stone Ck-1	254906	$\delta^{18}O = \mathbf{3.7}\delta D - 71.7$	15	0.53
Stone Ck-2	254905	$\delta^{18}O = \mathbf{3.0}\delta D - 82.9$	13	0.58
Albers Slough-1	249749	$\delta^{18}O = \mathbf{6.0}\delta D - 34.5$	14	0.76
Albers Slough-2	254923	$\delta^{18}O = \mathbf{7.1}\delta D - 17.2$	12	0.61
Black Slough-1	255903	$\delta^{18}O = \mathbf{7.2}\delta D - 14.6$	10	0.97
Black Slough-2	261889	$\delta^{18}O = \mathbf{5.6}\delta D - 40.8$	3	0.99
Black Slough-3	257502	$\delta^{18}O = \mathbf{4.9}\delta D - 52.9$	9	0.61
Willard Slough-1	257501	$\delta^{18}O = \mathbf{8.3}\delta D + 3.1$	8	0.79
Willard Slough-2	255094	$\delta^{18}O = \mathbf{5.4}\delta D - 45.0$	9	0.77
Blacktail Deer Ck	254907	$\delta^{18}O = \mathbf{5.8}\delta D - 36.2$	13	0.87
Stodden Slough	257503	$\delta^{18}O = \mathbf{3.3}\delta D - 78.7$	12	0.65
Charleton Slough	254904	$\delta^{18}O = \mathbf{4.0}\delta D - 67.8$	13	0.74
Ditch outflow	242227	$\delta^{18}O = \mathbf{5.8}\delta D - 37.9$	8	0.93

Note. BHR, Beaverhead River. Numbers at the end of site names indicates the respective order of streams monitored at more than one location ascending from upstream to downstream sites. Each surface-water site represents a specific location with multiple temporal measurements. N/A, not applicable because there is more than one location. Numbers in **bold** represent the slope of the line.

steeper regression slopes in Albers Slough (table 7). This may indicate groundwater discharge from the West Bench area to Albers Slough.

Stone Creek, Stodden Slough, and Charleton Slough have lower regression slopes (3.0, 3.3, and 4.0) and higher evaporation influence than the Beaverhead River (table 7). Blacktail Deer Creek and the ditch near Beaverhead Rock, which are located in areas where the valley narrows, both have a higher slope of 5.8 and therefore a lower evaporation influence.

Tritium

Tritium concentrations in 22 groundwater and 11 surface-water samples were measured to gain information about residence times and groundwater/surface-water interactions. Tritium concentrations were between 0.06 and 14.5 TU, with a median value of 6.9 ± 0.47 TU (table 8).

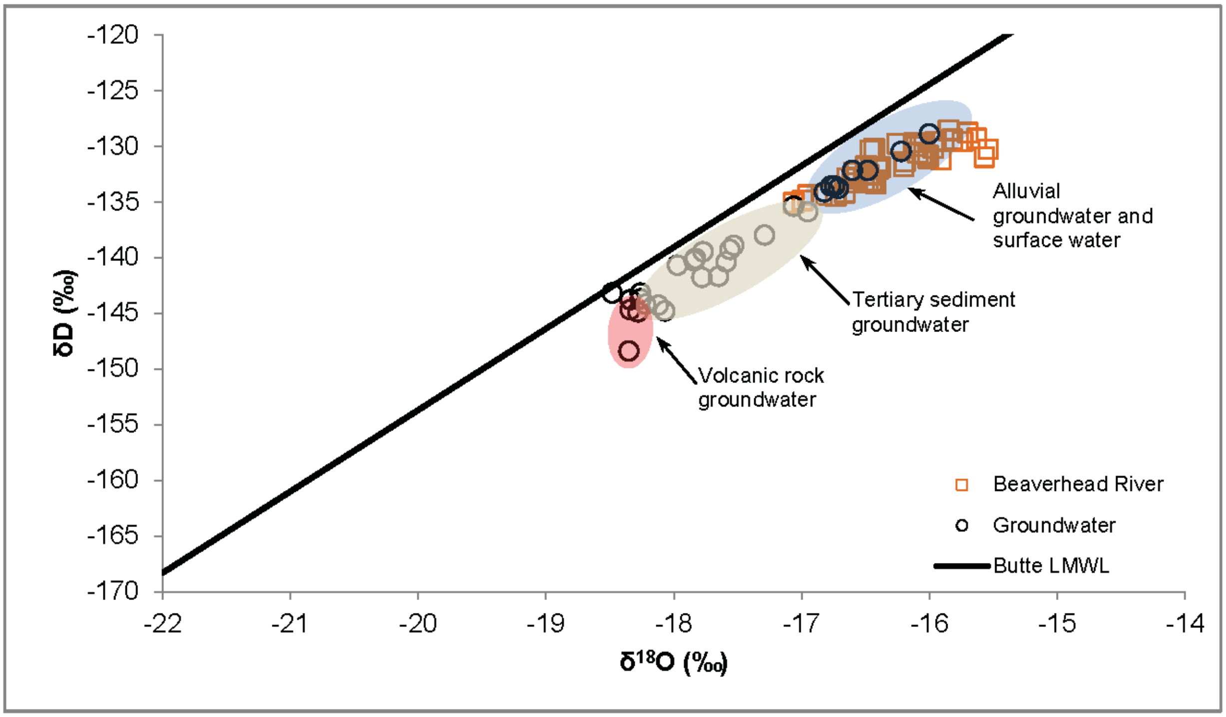


Figure 51. Most of the samples collected in the alluvial aquifer and surface water had a similar isotopic composition and indicated higher evaporation, while groundwater from the Tertiary sediments was less evaporated.

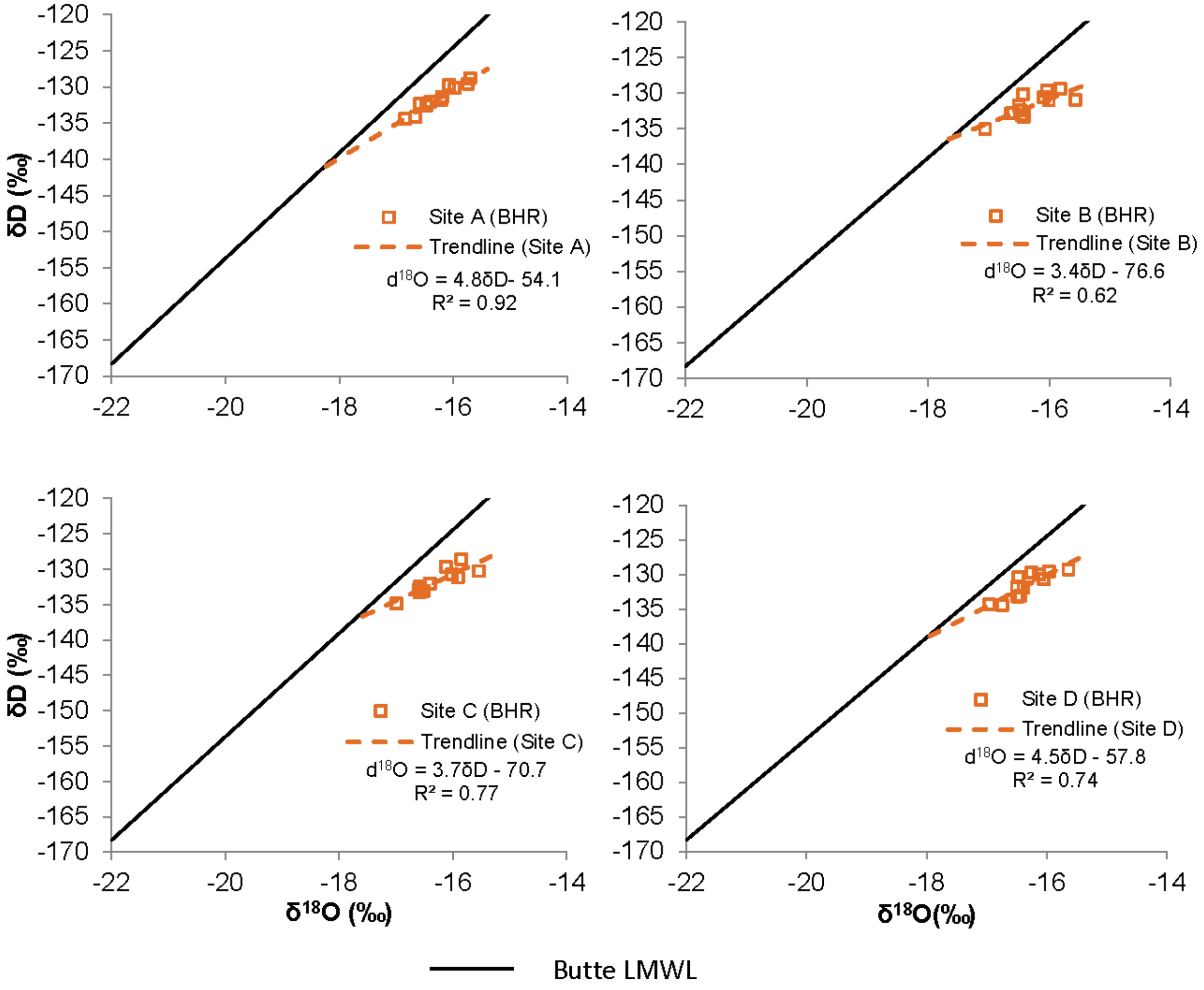


Figure 52. $\delta^{18}O$ (‰) and δD (‰) for the Beaverhead River (BHR) in four locations plotted with the Butte, MT local meteoric water line.

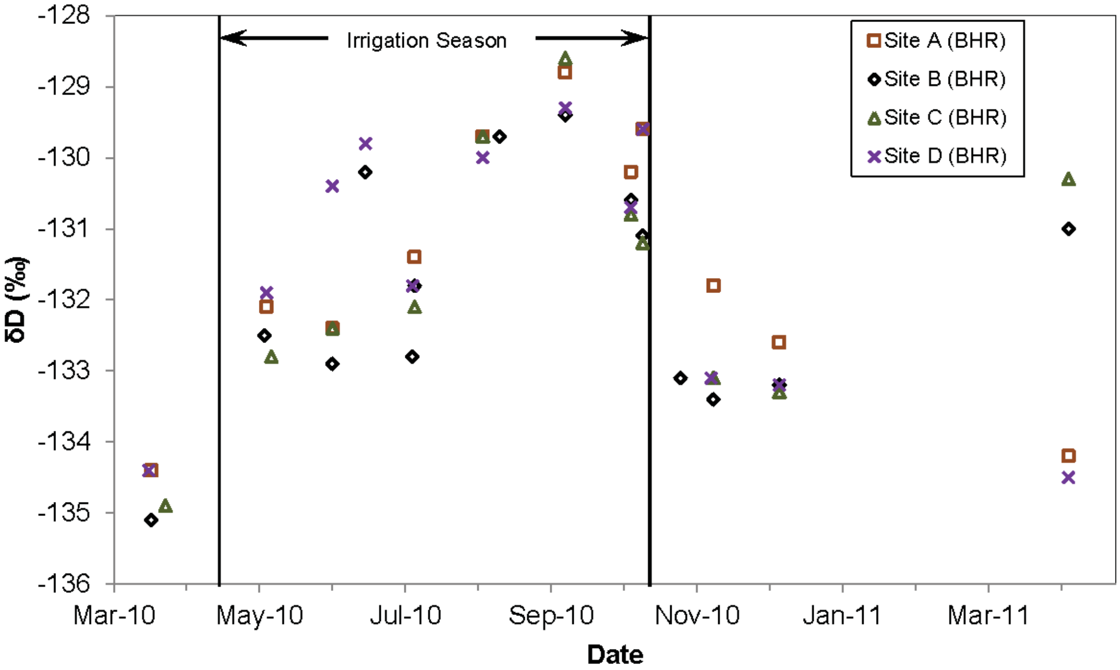


Figure 53. δD (‰) with time in the four Beaverhead River locations shows that there is little isotopic enrichment prior to and after the irrigation season. However, during the irrigation season isotopic enrichment results as more evaporated return flows reach the river.

Figure 54 displays tritium concentrations in aquifers, surface water, and a geothermal spring. Tritium concentrations in surface water ranged from 7.0 to 8.9 TU. These values were similar to the groundwater in the alluvial aquifer, which ranged between 6.47 and 8.8 TU.

Tritium concentrations in groundwater from the Tertiary sediments were lower and ranged between <0.8 and 5.18 TU (fig. 54). The oldest water (<1.0 TU) was found in the Tertiary sediments in four wells. These samples represent water that recharged the groundwater system prior to about the early 1950s, the time of nuclear testing. Samples from three sites had high tritium concentrations of 14.46, 8.92, and 9.06 TU. Sample 109060 (total depth 160 ft) is located within 150 ft of the West Side Canal, and well 255487 was located within 250 ft downgradient of the East Bench Canal. Sample 191614 (total depth 103 ft) is located within 150 ft of Stone Creek, and the drillers log indicates a prevalence of sands and gravels throughout the borehole. As such, recharge near these wells likely comes directly from surface water.

Tritium concentrations in two shallow and deep well pairs located in the floodplain show different groundwater residence times between the alluvial and Tertiary sediment aquifers. Samples from the alluvial (wells 242404 and 255493) had tritium

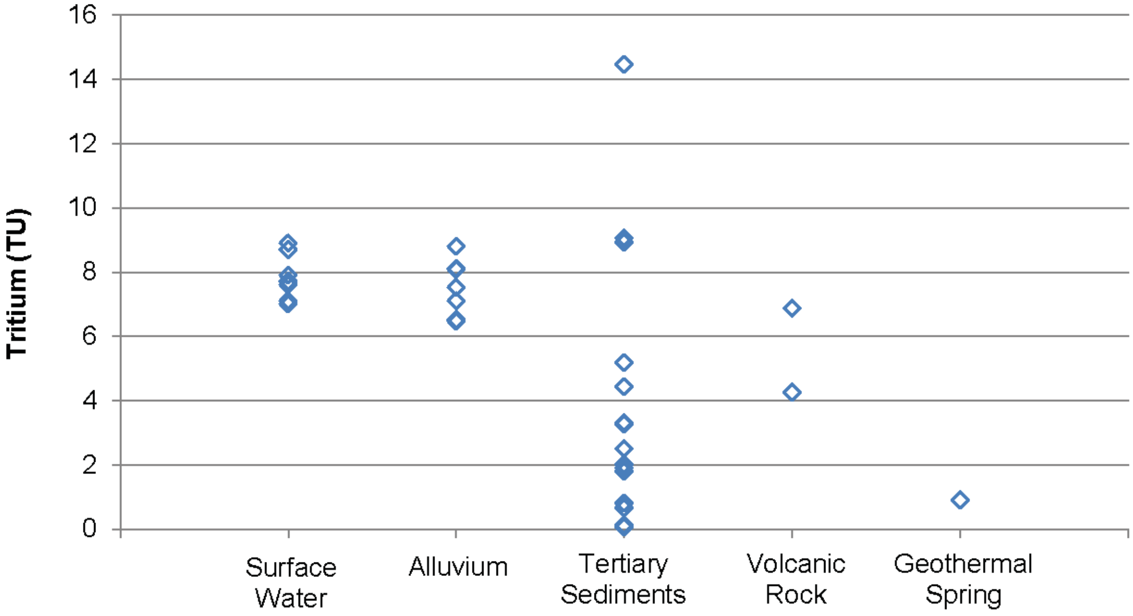


Figure 54. Tritium concentrations in surface water and by aquifer type showed that, in general, groundwater residence times in the alluvium and surface water are similar and that groundwater from the Tertiary sediments was mostly older than the shallow groundwater/surface water.

Table 8. Tritium results from 2008 and 2010 show a range between 0.06 and 14.46 TU.

GWIC No.	Collection Date	TU	TU +/-	Screen Interval (ft bgs)	Total Depth (ft bgs)	Description
242404	03/18/2008	8.80	0.80	18.5–28.5	28.5	Alluvium
249742	04/05/2010	6.47	0.23	N/A	18.50	Alluvium
108981	04/08/2010	7.11	0.26	27–32	37.00	Alluvium
250122	04/12/2010	7.52	0.25	Open bottom	18.00	Alluvium
109620	04/12/2010	8.08	0.30	20–30	30.00	Alluvium
249705	04/22/2010	6.51	0.23	N/A	14.00	Alluvium
255493	05/05/2010	8.11	0.27	14-23.5	23.50	Alluvium
247302	09/05/2008	7.60	0.90	N/A	N/A	Surface water—East Bench Canal
242227	03/18/2008	0.90	0.30	N/A	N/A	Surface water—Geothermal Seep
147977	03/17/2010	7.71	0.49	N/A	N/A	Surface water—BHR*
247284	09/05/2008	8.90	0.90	N/A	N/A	Surface water—BHR
242525	03/18/2008	7.00	0.70	N/A	N/A	Surface water—BHR
242228	03/18/2008	7.90	0.70	N/A	N/A	Surface water—BHR
242228	09/05/2008	8.70	1.00	N/A	N/A	Surface water—BHR
242525	09/05/2008	7.10	0.90	N/A	N/A	Surface water—BHR
255487	04/12/2010	9.06	0.31	98–118	118.00	Tertiary sediments
242406	03/25/2008	1.90	0.30	63-83	88	Tertiary sediments
242409	03/25/2008	<0.8	0.30	261-289	288	Tertiary sediments
213393	09/25/2008	1.80	0.60	120–420	460.0	Tertiary sediments
204038	09/25/2008	2.0	0.70	196–226, 308–328, 346–376	400.0	Tertiary sediments
213392	09/25/2008	2.5	0.70	53–78, 95–128	160.0	Tertiary sediments
220904	09/26/2008	<0.8	0.40	180–220	240.0	Tertiary sediments
109060	04/02/2010	14.46	0.93	N/A	160.00	Tertiary sediments
191614	04/09/2010	8.92	0.30	Open bottom	80.00	Tertiary sediments
108965	04/12/2010	0.06	0.10	108–115	116.00	Tertiary sediments
259541	04/13/2010	5.18	0.32	N/A	120.00	Tertiary sediments
252455	04/23/2010	3.27	0.12	70–520	540.00	Tertiary sediments
255492	05/05/2010	0.11	0.10	90.5–108	108.00	Tertiary sediments
220021	05/18/2010	0.66	0.10	183–203, 227–247, 269–329	331.00	Tertiary sediments
242408	08/4/2008	3.30	0.60	503–511	515.0	Tertiary sediments
242411	08/4/2008	4.40	0.60	143–153	160.0	Tertiary sediments
192298	09/26/2008	4.30	0.60	110–145	160.0	Volcanic rock
220080	03/28/2010	6.88	0.44	105–187, then open	200.00	Volcanic rock

Note. BHR, Beaverhead River; TU, Tritium Units; TU +/-, Analytical Error.

concentrations of 8.8 and 8.11 TU, respectively, indicating fairly recent recharge to the alluvium. Adjacent to the alluvial wells, samples from the Tertiary sediments (wells 242409 and 255492) had tritium concentrations of <0.8 and 0.11 TU, respectively. These low tritium concentrations indicate decades-old recharge to the deeper sediments, prior to the time when nuclear bombs were tested in the atmosphere.

Two samples collected in the volcanic rock aquifer had tritium values of 4.3 and 6.88 TU (wells 192298 and 220080, respectively). These values fall in the mid-range of the study area samples (fig. 54).

A geothermal spring (seep 242227) was sampled prior to irrigation impacts. This sample had a low tritium concentration, indicating relatively older water.

Water Budget

Water budgets help quantify the components of and stresses on hydrologic systems (such as irrigation wells, exempt wells, and stock wells), and are water management tools. The summary water budget is presented here; additional details are included in appendix D. The total annual budget is about 486,000 acre-ft. Surface water accounts for over 50% of both the inflows and outflows. Second to surface water, the major contributor to inflow was precipitation, and evapotranspiration for outflow (fig. 55). The monthly budget for the study area (table 9) represents the distribution of water from January 2010 through December 2010. The monthly results indicate that the total inflows and outflows were about three times higher during July than during February (table 9 and fig. 56). These two months were the extreme high and low flows for the year. A total of 145,556 acre-ft of water was applied for irrigation during 2010. Of the total irrigation application, it is estimated that 68,935 acre-ft was consumed through ET and as much as 76,621 was excess irrigation water, potentially available for groundwater recharge (appendix D, table D-1).

The water budget for the study area is based on the following equation:

<u>Inflow</u> = *<u>Outflows</u>* ± *<u>change in storage</u>*

$$P_{IN} + SW_{IN} + GW_{IN} + CAN_{IN} = SW_{OUT} + CAN_{OUT} + GW_{OUT} + ET_{TOTAL} \pm \Delta S$$

<u>Inflows:</u>

P_{IN} : Precipitation

SW_{IN}: Surface water, river and creeks, flow into the study area

GW_{IN}: Groundwater flow into the study area

CAN_{IN}: Surface-water flow into the study area via the irrigation canals

<u>Outflows:</u>

SW_{OUT}: Surface-water flow out of the study area

CAN_{OUT}: Surface-water flow out of the study area via the irrigation canals

GW_{OUT} : Groundwater flow out of the study area

ET_{TOTAL}: Evapotranspiration

ΔS: Change in storage during 2010

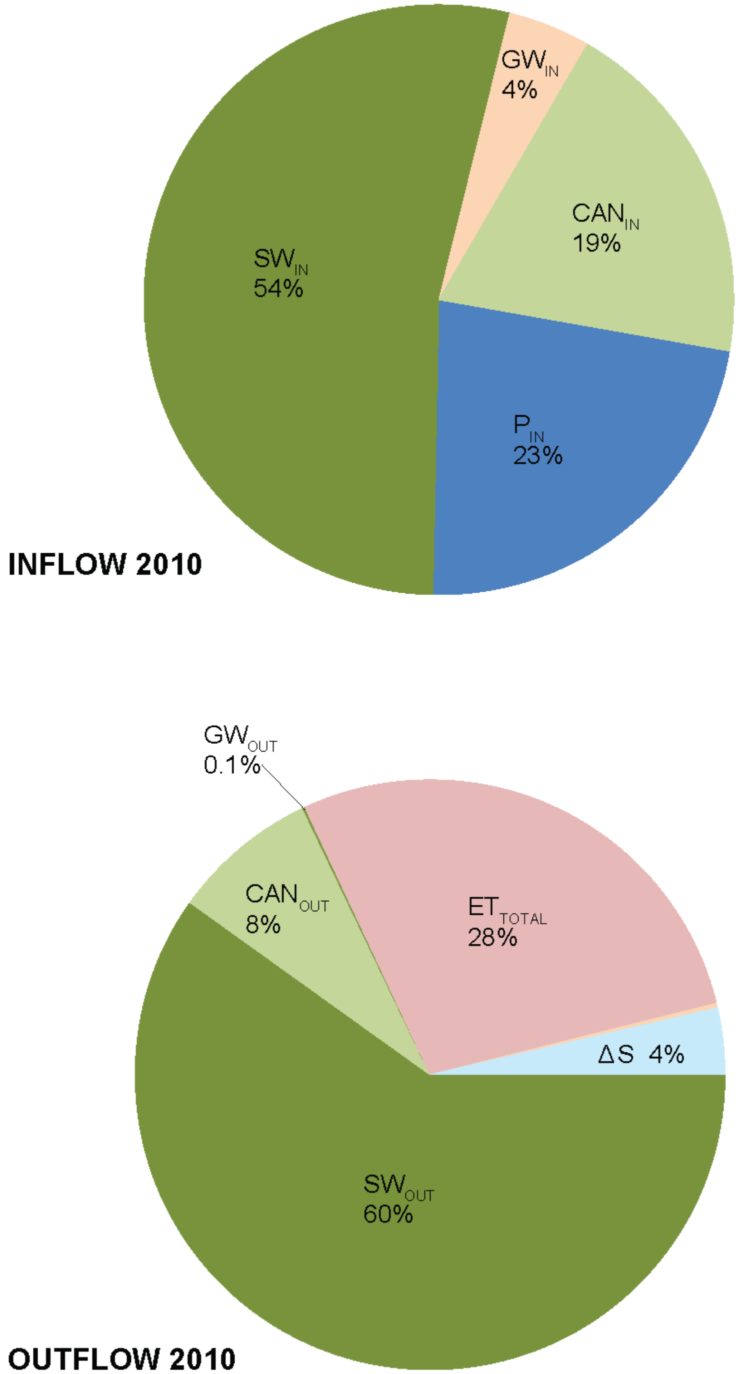


Figure 55. The water budget in the Beaverhead study area is dominated by surface water, precipitation, and evapotranspiration, shown here as annual percentages.

For some components water is withdrawn from the source and only a portion of the withdrawal is consumed through evaporation or evapotranspiration (ET); the rest returns to the source. In this case, the amount consumed was included in the water budget rather than the entire withdrawal. Irrigation wells are an example of this. More water is withdrawn and applied to the crops than is consumed through ET. The excess percolates into the soil layers and returns to the aquifer. Only the loss to evapotranspiration was included in the water budget calculations.

Table 9. Comprehensive Water Budget for the study area (2010). Monthly values are in acre-ft/month and total values are in acre-ft/yr.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Inflows	P_{IN}	1,625	1,760	3,995	21,869	17,265	16,927	6,094	7,515	8,937	3,927	10,901	8,463	**109,278**
	SW_{IN}	19,802	16,441	17,844	16,254	14,673	26,860	25,959	24,375	23,443	22,152	26,541	25,345	**259,689**
	GW_{IN}	1,941	1,753	1,941	1,878	1,941	1,878	1,941	1,941	1,878	1,941	1,878	1,941	**22,852**
	CAN_{IN}				4,691	7,367	17,991	24,696	22,336	10,499	6,428			**94,008**
	Total Inflows	**23,368**	**19,954**	**23,780**	**44,692**	**41,246**	**63,656**	**58,690**	**56,167**	**44,757**	**34,448**	**39,319**	**35,749**	**485,826**
Outflows	SW_{OUT}	24,147	18,583	22,354	19,295	15,003	23,587	23,403	18,859	26,858	25,617	32,204	29,030	**278,940**
	CAN_{OUT}	0	0	0	2,339	1,249	6,867	11,389	9,491	3,893	1,946	0	0	**37,233**
	GW_{OUT}	54	49	54	53	54	53	54	54	53	54	53	54	**641**
	ET_{TOTAL}	1,642	1,784	4,015	9,030	17,018	26,280	24,337	19,919	11,847	3,966	8,235	3,852	**131,920**
	ΔS													**16,926**
	Total Outflows	**25,843**	**20,415**	**26,422**	**30,775**	**33,324**	**56,788**	**59,184**	**48,323**	**42,650**	**31,582**	**40,491**	**32,936**	**465,660**
Net Change														**20,165**

Note. P_{IN}, total precipitation in the study area; SW_{IN}, surface water flowing into the study area includes the Beaverhead River at Dillon, Blacktail Creek, and Stone Creek; GW_{IN}, groundwater flowing into the study area; CAN_{IN}, water added to the study area through East Bench and West Side Canals; SW_{OUT}, surface water flowing out of the study area (Beaverhead River near Beaverhead Rock and Ditch Outflow); CAN_{OUT}, East Bench Canal flow leaving study area; GW_{OUT}, groundwater flowing out of the study area at Beaverhead Rock; ET_{TOTAL}, combined ET from the following sources. (1) ET from non-crop land; (2) canal irrigated land; (3) land irrigated by the Beaverhead River; (4) land irrigated with groundwater; (5) water loss from stock wells; (6) water supplied by Dillon public water supply wells; (7) from domestic usage including lawn, garden, and household (exempt wells); and ΔS, change in storage calculated from the average annual increase in water levels during 2010.

Inflows

Inflows include precipitation, surface water, groundwater, and irrigation canals that begin outside the study boundary and flow into the study area. Approximately 485,000 acre-ft of water entered the project area during 2010 (table 9).

Precipitation (P_{IN})

Precipitation for 2010 in the project area was calculated as the product of the area (81,200 acres) and the precipitation, and totaled nearly 110,000 acre-ft (Western Regional Climate Center, http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt2409). Most precipitation fell during April, May, and June. Precipitation contributed 23% of the total inflows (fig. 55).

Surface Water (SW_{IN})

Surface water entering the project area and the sources of data were: the Beaverhead River, USGS gauging station 06017000 (USGS, 2011a); Blacktail Deer Creek and Stone Creek, manual flow measurements by the MBMG; and Owen Ditch and the Dillon Canal, East Bench Irrigation District (EBID, written commun., 2011). The total surface-water inflow was roughly 260,000 acre-ft and constituted the largest inflow to the study area (54%). The river contributed 87% of the surface inflow, with the highest flows occurring from June through December (appendix D, table D-2). Blacktail Deer Creek contributed 13% of the surface inflow.

Groundwater (GW_{IN})

Groundwater flows into the project area through the alluvium near Dillon, the Tertiary sediments under both the East and West Benches, and the Tertiary sediments underlying the alluvium.

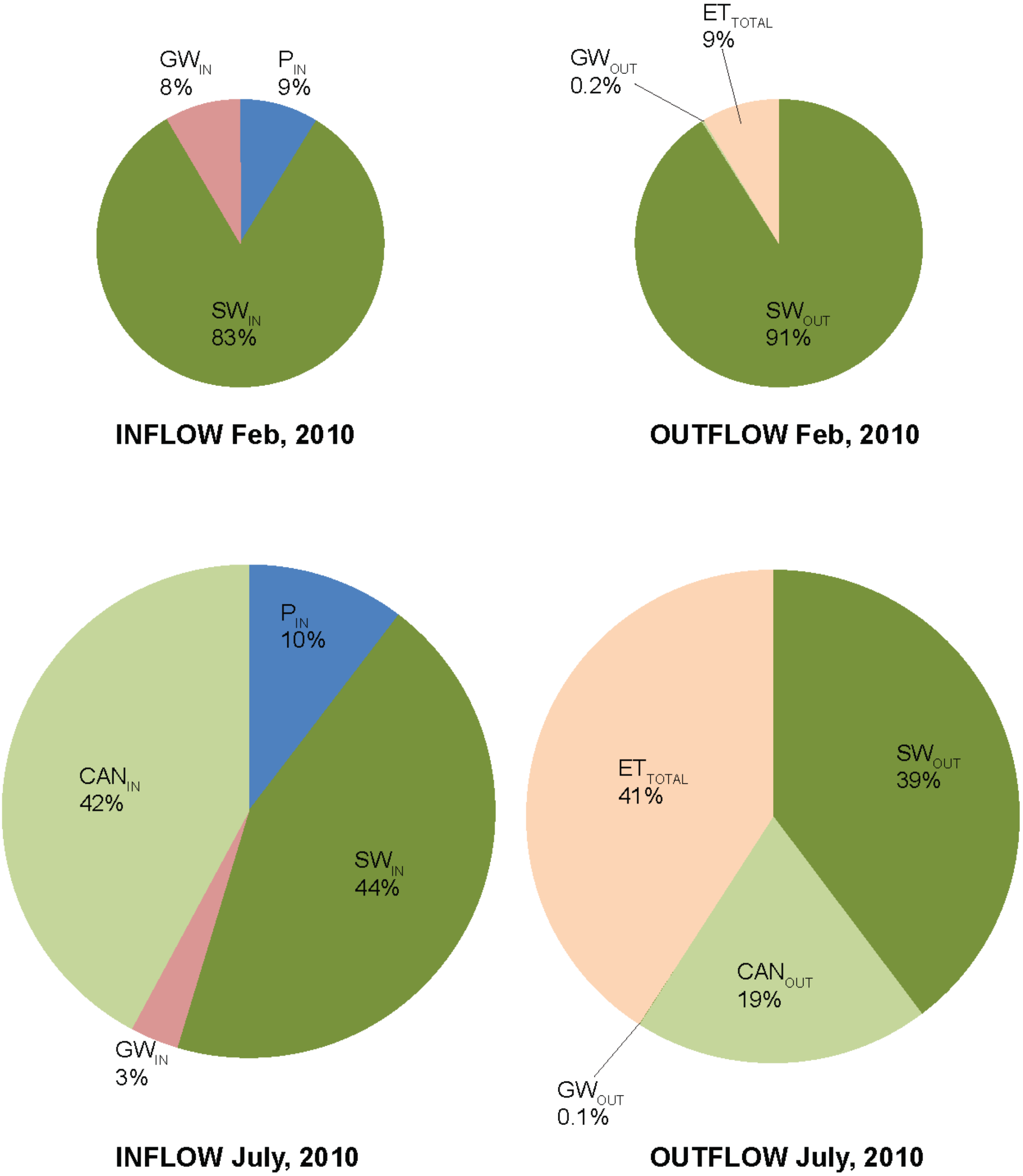


Figure 56. In the Beaverhead study area, the total water budgets for July were about three times larger than for February during 2010, as shown by the size of the graphs. The water budget for February is dominated by surface flow. In July inflows are dominated by surface water, including canals, and outflows are dominated by surface water and evapotranspiration.

The estimate of groundwater entering the site was calculated using groundwater flow nets and Darcy's law:

$$Q = KIA,$$

where

Q: Groundwater flow (cubic feet per day, ft^3/day)

K: Hydraulic conductivity (ft/day)

I: Hydraulic gradient (ft/ft)

A: Cross-sectional area, or flow tube area (ft^2)-tube width multiplied by saturated aquifer thickness.

Near Dillon, hydraulic conductivity of the alluvium ranges from 600 to 1230 ft/day with an average value of about 730 ft/day; based on the water table map, the hydraulic gradient was 0.0035 ft/ft; and the cross-sectional area was 284,200 ft^2. The average alluvial flow into the study area was about 17 acre-ft/day.

Tertiary sediments under the East Bench, West Bench, and alluvium have hydraulic conductivity values from 1.2 to 12.8 ft/day; based on the potentiometric map, the hydraulic gradient ranged from 0.006 to 0.016 ft/ft; and the saturated thickness underlying the East Bench, West Bench, and alluvium was 443, 182, and 470 ft, respectively. The calculated flow into the study area from Tertiary sediments was about 63 acre-ft/day.

Groundwater inflows contributed about 4% of the total inflow budget (table 9, fig. 55). Of that total, the East Bench Tertiary sediments were the largest contributor at 54% of groundwater inflow (appendix D, table D-3). Inflow through the alluvium near Dillon contributed 28% of the total groundwater inflow. The Tertiary sediments under the West Bench and the floodplain were fairly minor components, each contributing about 5 and 13% of the total groundwater inflow budget, respectively.

Canal Water (CAN$_{IN}$)

The East Bench and West Side canals flow into the study area and are included as inflows in the water budget (CAN$_{IN}$). Flows in the East Bench and West Side canals began in mid-April and continued into mid-October (appendix D, table D-4). During the primary irrigation months of June through August, the East Bench and West Side canals carried a combined flow of roughly 18,000 to 25,000 acre-ft/month into the project area (table 9). This flow accounted for 19% of the total inflow for the area.

Outflows

The water budget outflows represent the fate of all water that entered the project area. Water leaves the area through surface water and irrigation canal outflows, groundwater flux, and ET (table 9, fig. 55). During 2010 some of the water that entered the area was added to groundwater storage. Over long periods of time the change in groundwater storage is negligible; however, 2010 was an unusual year in that a measurable change in storage occurred. Including the change in storage, total outflow from the study area during 2010 was calculated at a total of about 466,000 acre-ft. The calculated outflow is about 4% less than the calculated inflow, which is a result of measurement errors throughout the water budget.

Surface Water (SW$_{OUT}$)

Surface-water outflow components and sources of data were similar to the surface-water inflow components. Flow data for the Beaverhead River at Beaverhead Rock were obtained from the USGS gauging station 06018500 (USGS, 2011b). One irrigation ditch diverts river water within the study area, is not applied in the area, and flows out of the area near Beaverhead Rock (site 242227). It is included in surface-water outflows since there are no irrigation applications from this ditch (EBID, written commun., 2011).

Nearly 280,000 acre-ft of water left the study area as surface flow during 2010 (table 9; appendix D, table D-2). This represents 60% of the total outflow (fig. 55). The highest surface-water flow was in late fall and the lowest at the beginning of irrigation in May.

Canal Water (CAN$_{OUT}$)

A portion of the East Bench Canal inflow continued through the study area and crossed the northern boundary as outflow. However, as no direct measurement data were available, the outflow was calculated from the inflow minus the estimated losses across the study area. An average seepage rate of 2.2 cfs/mile was calculated for the East Bench Canal, and amounts diverted from the canal obtained (EBID, written commun., 2011) were subtracted from the total amount coming into the study area (CAN$_{IN}$), in order to calculate the amount of water leaving the site. Since the West Side Canal does not leave the study area, it is not included in CAN$_{OUT}$.

The East Bench Canal was in operation from mid-April through mid-October, and outflow was calculated at a total of 37,233 acre-ft from the area during 2010 (table 9). This represents about 8% of the total outflow budget. Outflow in the East Bench Canal was highest during July and August at rates of 11,389 and 9,491 acre-ft/month, respectively.

Groundwater (GW$_{OUT}$)

Groundwater outflow exits the study area at Beaverhead Rock, based on information from groundwater potentiometric maps and knowledge of the local geology. It was assumed that flow exits primarily through the alluvial aquifer, based on a drillers log near the river that indicates the absence of Tertiary sediments (i.e., alluvium directly overlies limestone, well 194034). A negligible amount of groundwater may flow through the limestone bedrock at this pinch point but is not estimated for the water budget. The valley is narrow at this location and the alluvial aquifer is about 1,000 ft wide. Estimates of groundwater flow were made using a groundwater flow net approach and Darcy's Law as described above in the GW_{IN} section.

Total groundwater flux from the study area was calculated to be about 641 acre-ft, or about 0.1% of the calculated outflow budget (table 9, fig. 55 and appendix D, table D-3).

Total Evapotranspiration (ET_{TOTAL})

Total evapotranspiration (ET_{TOTAL}) was calculated as the sum of several ET subcategories. These subcategories include ET from: non-crop land; crop irrigation from groundwater and surface-water sources; stock water; public water supplies; and domestic wells. The details and calculated values for each category of ET are presented in appendix D (table D-5).

Evapotranspiration was estimated on irrigated and non-irrigated lands during the summer (irrigation season) and winter (non-irrigation season). Evapotranspiration from irrigated fields was further subdivided according to the type of irrigation method so the direct effects on groundwater and surface-water resources could be distinguished (fig. 57). Estimates of ET were based on data supplied by the National Resources Conservation Service (written commun., 2011) and the Dillon AgriMet Station (U.S. Bureau of Reclamation, 2011). The NRCS estimates evapotranspiration based on the Blaney-Criddle (TR21) method (U.S. Soil Conservation Service, 1970) and a Blaney-Criddle Perennial Crop Curve. AgriMet uses the Kimberly-Penman ET modeling procedure (Jensen and others, 1990).

The annual ET_{TOTAL} throughout the study area was calculated to be nearly 132,000 acre-ft during 2010, or about 28% of the total outflow of water (table 9 and fig. 55).

Groundwater Storage (ΔS)

The amount of groundwater held in storage during 2010 increased by about 17,000 acre-ft. Most of this change in stored groundwater was on the East Bench (72%) and was reflected in 3-ft higher water levels in that area.

Stream Depletion and Aquifer Drawdown

Four methods were used to evaluate stream depletion and aquifer drawdown. Both an analytical stream-depletion model and a numerical groundwater flow model were used in a small area on a site-specific scale to determine if these modeling techniques could replicate depletion of Black Slough flow observed during the aquifer test in the volcanic rock aquifer. Also, the specific conductivity values of the discharge water from that same aquifer test were used in a mass balance calculation to estimate surface water contributions. Another numerical groundwater flow model was developed to predict the effects of long-term pumping on groundwater and surface water in the overall study area.

Results from each of the four methods indicated that stream depletion would occur. Calculated rates of depletion ranged from a low of 0.001 cfs to a high of 0.3 cfs. A description of each result is below.

Analytical Model of Stream Depletion

The IDS stream-depletion analytical model is used to evaluate stream depletion for certain settings. The assumptions of the model include: homogeneous aquifer, fully penetrating pumping well, and fully penetrating stream channel (Schroeder, 1987). In practice, all asumptions are seldom met, but the model is used to provide insight to groundwater/surface-water interactions. In the vicinity of the volcanic rock aquifer test (well 220080, Results section of this report), the target aquifer is overlain by about 90 ft of saturated Tertiary sediments. Since the model assumes a homogeneous aquifer, stream depletion was modeled with this package twice: once using transmissivity values for the volcanic rock aquifer and then using values for the Tertiary sediment aquifer.

The first calculation simulated the volcanic rock conditions: transmissivity value of 49,000 ft^2/day (table 4); specific yield was 0.016; distance

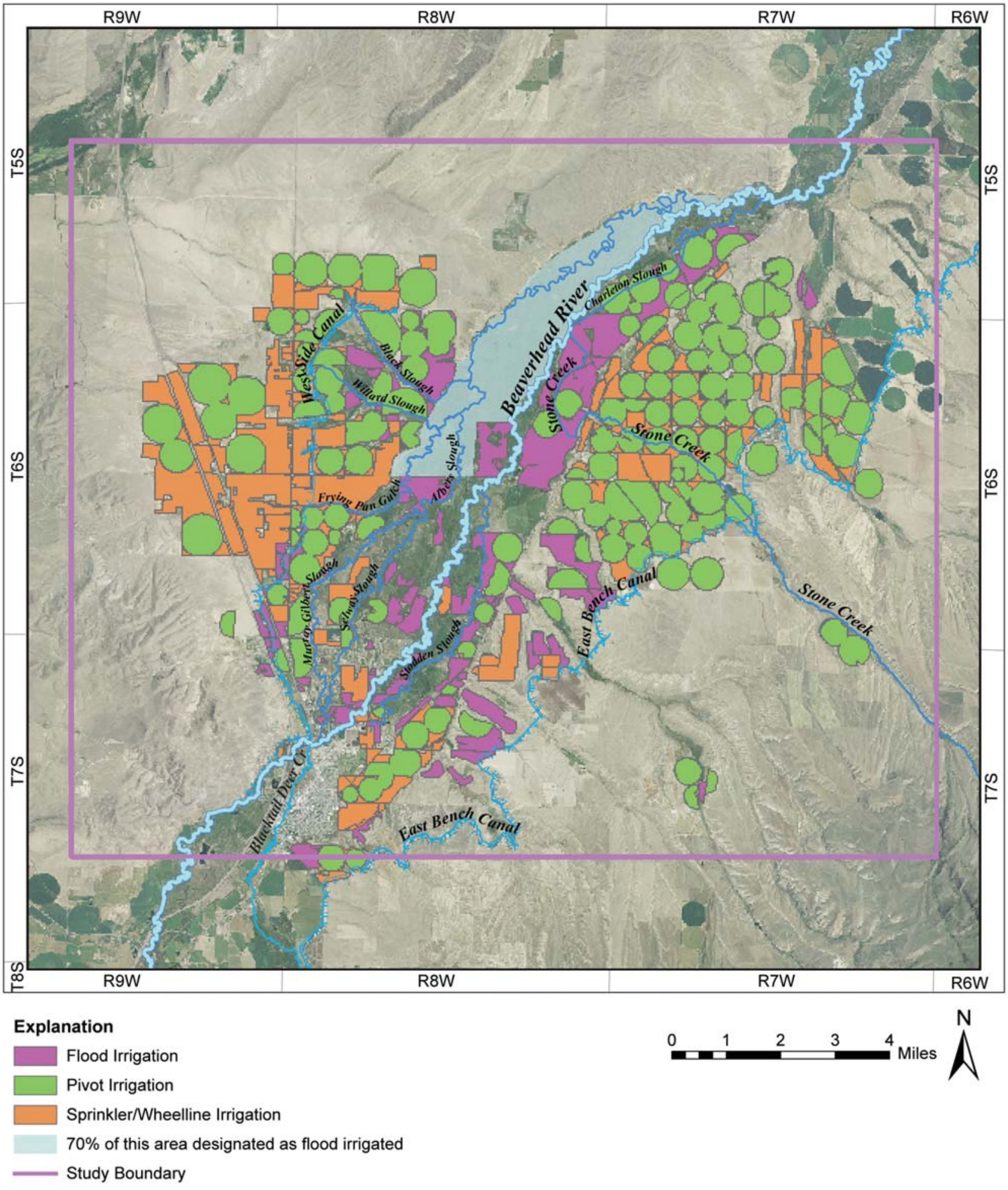


Figure 57. The irrigation method was factored into determining crop-water consumption (evapotranspiration) for the water budget. Irrigation method modified from the Montana Department of Revenue (2010). Flood irrigation for the northwest floodplain area was calculated from acres being irrigated by diversions from the Beaverhead River.

from the pumping well to the Black Slough monitoring location was 945 ft; and pumping rate was 1,422 gpm for 3 days. The analytical model calculated stream depletion at 2.16 cfs at the end of 3 days.

The second set of calculations used the above input parameters except for an average transmissivity of 463 ft^2/day, representing the Tertiary sediment aquifer (table 4). These calculations yielded a stream depletion of 0.07 cfs. Since the lower transmissivity units would control the migration of impacts, the Tertiary sediment value is probably a better overall estimate than that derived from the volcanic rock unit.

Numerical Groundwater Flow Model—Site-Specific

A two-layer, numerical groundwater flow model was used to simulate the aquifer test and evaluate related stream depletion. The model ran through three stress periods: (1) days 1 through 10, no pumping; (2) days 11 through 13, 3 days of pumping at a discharge rate of 1,422 gpm; and (3) days 14 through 43, 30 days with no pumping to simulate drawdown and recovery.

Table 10 presents the drawdown calculated by the numerical flow model and the drawdown measured during the 3-day aquifer test. Figure 58 presents the change in flux to the tributary river throughout the 43-day simulation. Effects to the stream occurred almost immediately once the pump was turned on. The reduction in groundwater flux to the stream on the third day of pumping was about 38 ft^3/day, or 0.0004 cfs (0.2 gpm). A maximum flux reduction occurred on day 22 of the simulation or 9 days after the pump was turned off; the flux was reduced by a maximum of about 81 ft^3/day or 0.001 cfs (0.4 gpm).

Table 10. Observed drawdown in monitoring wells during an aquifer test on well 220080 and numerical flow modeled generated drawdown.

GWIC ID	Observed Drawdown (ft)	Modeled Drawdown (ft)
220080 (Pumped well)	4.00	3.60
254815	2.65	1.50
254839	0.71	0.32
254767	2.38	0.50

Model Limitations—Site-Specific

The site-specific numerical model did not include vertical or horizontal anisotropy, and the areal extent of the volcanic aquifer was not limited within the model domain. Streambed conductance of the slough was based on hydraulic conductivity of the Tertiary sediment material, not the streambed material. The model was sensitive to streambed conductance, the hydraulic conductivity, and storage coefficient of the volcanic aquifer: a lower value of hydraulic conductivity and storativity for the volcanic material yielded a better match between the observed drawdown and the model drawdown and also yielded a higher stream depletion rate. Conversely, increasing streambed conductance allowed a better connection between the slough and the Tertiary sediments and consequent-

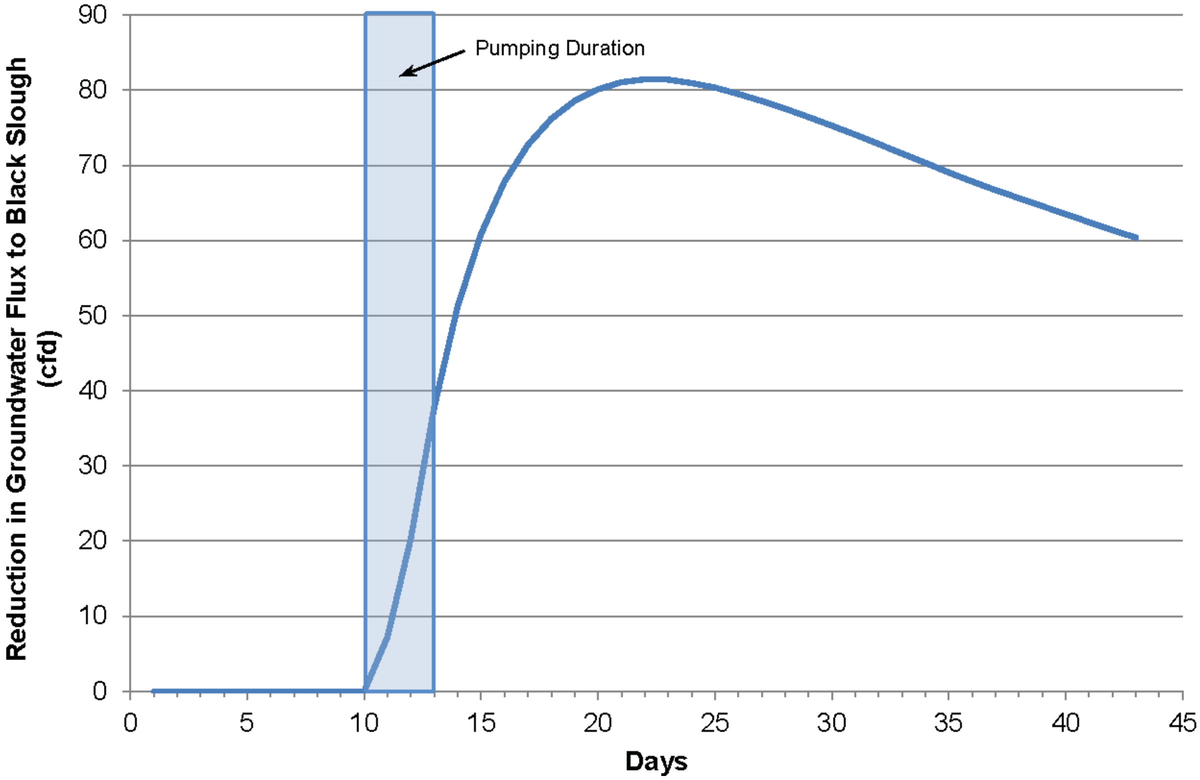


Figure 58. Reduction in groundwater flux to Black Slough during the 43-day numerical model simulation. The maximum reduction in flux occurred 9 days after the pumping ceased in the simulation.

ly with the volcanic rock, which resulted in a higher stream depletion rate, but increased the difference between the observed and modeled drawdown values.

Mass Balance Calculation

During the volcanic rock aquifer test near Black Slough, the specific conductivity (SC) of the water from the well decreased at a rate of about 9 µS/cm per day (R^2=0.74) after the first day (fig. 20). While this is a small percentage of change, it was consistent after the first day of pumping. A mass balance approach was used to estimate the ratio of water from either the West Side Canal or Black Slough to groundwater required to decrease the SC of the discharge water as observed during the aquifer test.

The following input parameters were used:

SC_{well} (end of test) * Q_{well} = ($SC_{Black\ Slough}$ * $Q_{Black\ Slough}$) + (SC_{well} (start of test)) *(Q_{well} - $Q_{Black\ Slough}$),

where

SC_{well} (end of test): 1,289 µS/cm

Q_{well} (gpm): 1,422 gpm

$SC_{Black\ Slough}$: 1,001 µS/cm (for West Side Canal, SC = 500 µS/cm)

$Q_{Black\ Slough}$: Unknown, flow captured from Black Slough to equal final discharge water specific conductivity

SC_{well} (start of test): 1,318 µS/cm.

Based on the above calculation, about 130 gpm (0.3 cfs) of surface water with an SC of 1,001 µS/cm would need to be captured from Black Slough to decrease the SC of the discharge water from 1,318 to 1,289 µS/cm. The West Side Canal is about 70 ft of the pumping well and is also considered a possible surface supply to intercept. Since the water in this canal had an SC value of 500 µS/cm, the required capture amount from it would be 50 gpm (0.1 cfs).

Numerical Groundwater Flow Model—Area-Wide

A numerical groundwater flow model was developed based on observed groundwater and surface-water conditions. The model was then used as a predictive tool to simulate the effects on groundwater and surface water from pumping wells on the West Bench completed in the volcanic rock and Tertiary sediment aquifers.

Steady-State Calibration

Model calibration was the first step in order to predict the behavior of the hydrogeologic system. Calibration involved modifying input parameters in order to match observed groundwater and surface-water data.

Boundary conditions were set to average annual values in the steady-state model. The modeled ranges of aquifer property values were comparable to those estimated during the field investigation (fig. 59, table 11), with the exception of the values assigned to the Tertiary sediment aquifer underlying the alluvium in the floodplain. The higher modeled floodplain K values were likely a result of bulk properties of the lower alluvium and the upper Tertiary aquifer. Considering the high value of the alluvial K and the limit of outflow at the pinch point, the parameter estimation process yielded a floodplain Tertiary sediment aquifer K value that was higher than the bench K values.

The steady-state model was able to replicate groundwater elevations within a reasonable error after adjustments were made to two of the model recharge components and to groundwater outflow by Beaverhead Rock. First, the East Bench Canal seepage rate was reduced from 2.8 cfs/mile (the upper range of the field range estimate of 0.8 to 3.3 cfs; see Results: Canal Study) to 1.0 cfs/mile, which resulted in lower head values and a more balanced steady-state budget. Second, the model's inflow was further decreased by reducing the amount of aerial irrigation recharge in the northern part of the floodplain where the head calibration targets had the greatest error. Aerial recharge to irrigated areas was removed in this area, which covered approximately 48% of the total floodplain area in the model (fig. 16). The water table is shallow in most of this model area, so there is limited space in the aquifer to accommodate recharge. Excess irrigation water may return to streams as direct surface water return flows via smaller drains than those included in the model. Without the incorporation of smaller drain ditches (in which limited information was available), the model could not accommodate

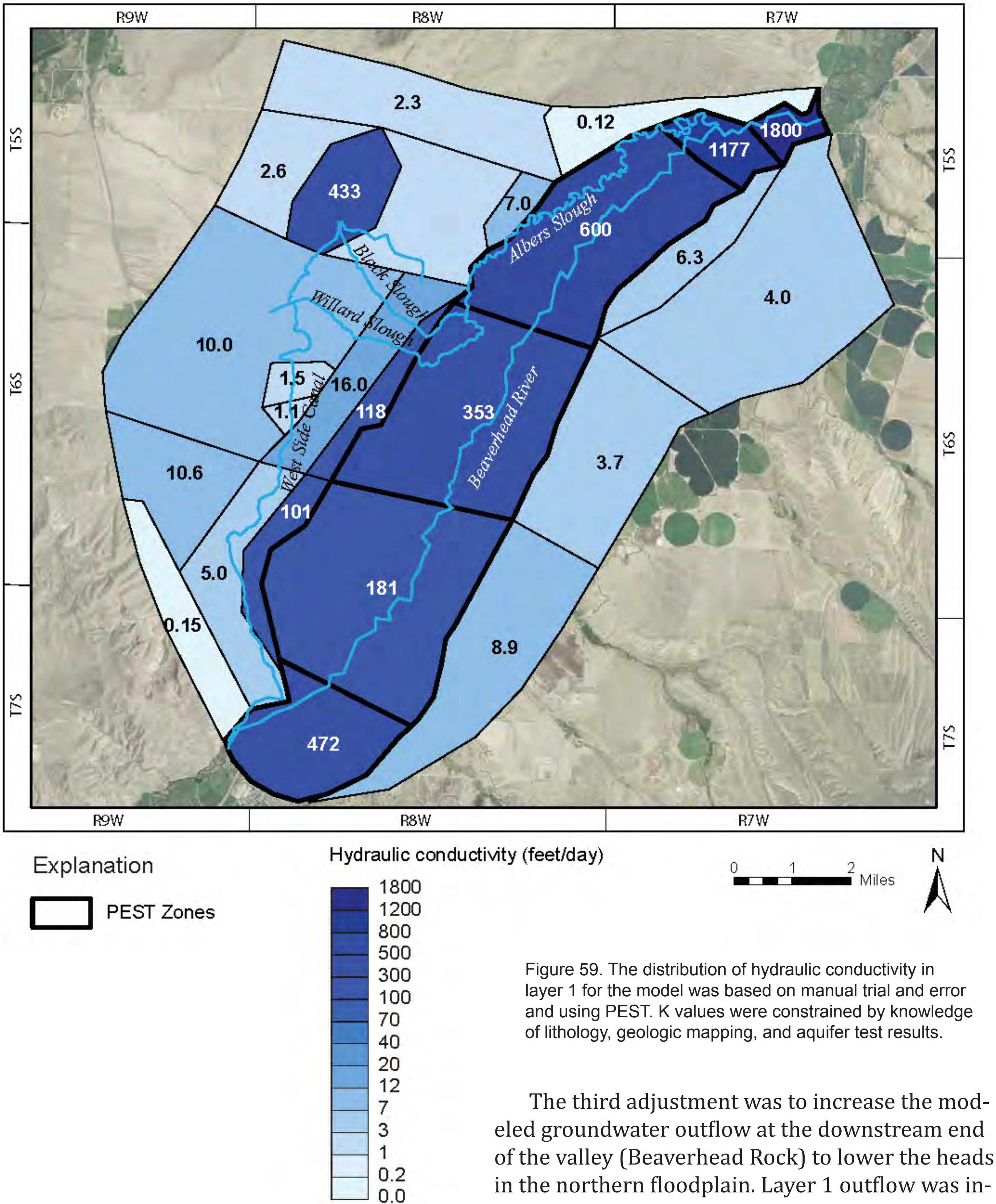


Figure 59. The distribution of hydraulic conductivity in layer 1 for the model was based on manual trial and error and using PEST. K values were constrained by knowledge of lithology, geologic mapping, and aquifer test results.

the excess water, thereby resulting in higher calibrated heads when compared to observed heads. This reduction in recharge resulted in slightly lower head values in the northern floodplain and a more balanced average annual budget.

The third adjustment was to increase the modeled groundwater outflow at the downstream end of the valley (Beaverhead Rock) to lower the heads in the northern floodplain. Layer 1 outflow was increased to match the higher alluvial K in the model (1,800 ft/day at Beaverhead Rock versus the field-estimated range of 600 to 1,233 ft/day). Furthermore, a low groundwater outflow rate (480 acre-ft/yr) was set in layer 2; the conceptual model of the system assumed that outflow is minimal beneath the alluvium at Beaverhead Rock.

Table 11. K and S Ranges from field estimates and the groundwater model results.

	Field K Range[1] (ft/day)		Model K Range (ft/day)		Model Geometric Mean[2] (ft/day)	Field Storativity Range (ft/day)		Model Storativity Range*	
	Min	Max	Min	Max		Min	Max	Min	Max
Floodplain—Alluvium	600	1,233	110	1,800	764	0.003**	0.15	0.15**	
Floodplain— Tertiary Sediments	6.2	12.8	45.2	134	95.5	NR		0.08	0.10
East Bench—Tertiary Sediments	3.5	5.8	3.74	8.92	5.74	0.004**		0.05	0.08
West Bench—Tertiary Sediments	2.3	2.9	1.50	16.5	6.47	0.001**		0.05	0.08
Northern West Bench—Volcanic Bedrock	142	252	433.5**		433.5	0.003	0.018	0.15**	
Other Bedrock	—	—	0.12	0.15	0.14	NR		0.01	0.05

Note. NR, not reported.

[1] K values obtained from transmissivity and saturated thickness (table 4)

[2] This denotes the mean of the modeled PEST zones that represented the given aquifer type.

*Storativity was not estimated using PEST. S values are discussed in the Transient Calibration section..

**Only value available for the given aquifer property.

After these adjustments were made, 59 of the 69 computed heads were within the calibration target criterion of ±15 ft (green bars, fig. 60; fig. 61). The 10 heads that still did not meet this criterion had head values that ranged from 15.9 to 25.5 ft above observed levels (average of 18.3 ft), and all fell within the north-central floodplain area (yellow bars, fig. 60). Thus, even though adjustments were made to the model, this area was the highest source of error as a result of more water entering than exiting the modeled area.

Irrigation (including canal seepage) was the predominant source of recharge to the model, contributing 88% of the inflow. The primary means of groundwater discharge from the model was baseflow to the Beaverhead River and its tributaries, which comprised 79% of the outflow (table 12).

Transient Calibration

The transient version of the model introduced the element of time in monthly increments. To calibrate the model, the steady-state set of calibration targets (i.e., observation wells) was used, except different target values were input for each month. The transient observation data set was from January 2010 through December 2010. The modeled heads are in general agreement with the observations, with the exception of the northern floodplain area (figs. 60, 62; see hydrograph well 242404). Like the steady-state model, this area exhibited heads higher than the observed levels, though the annual pattern was comparable.

The hydraulic conductivity values generated by calibration of the steady-state model were used in the transient modeling effort. Storativity was also incorporated to account for changes in aquifer storage over time. Calibration efforts were focused in the irrigated portions of the Tertiary sediment and alluvium where a large seasonal fluctuation was observed. Manual calibration resulted in storativity values ranging from 0.05 to 0.08 in the portion of the model representing the Tertiary sediment, and 0.15 in the portions representing the alluvium and West Bench volcanic rock (table 11). These values approximated the observed water-level changes. The bedrock units were assigned storativity values of 0.01 and 0.05. Because bedrock observation well data were limited and showed little to no seasonal

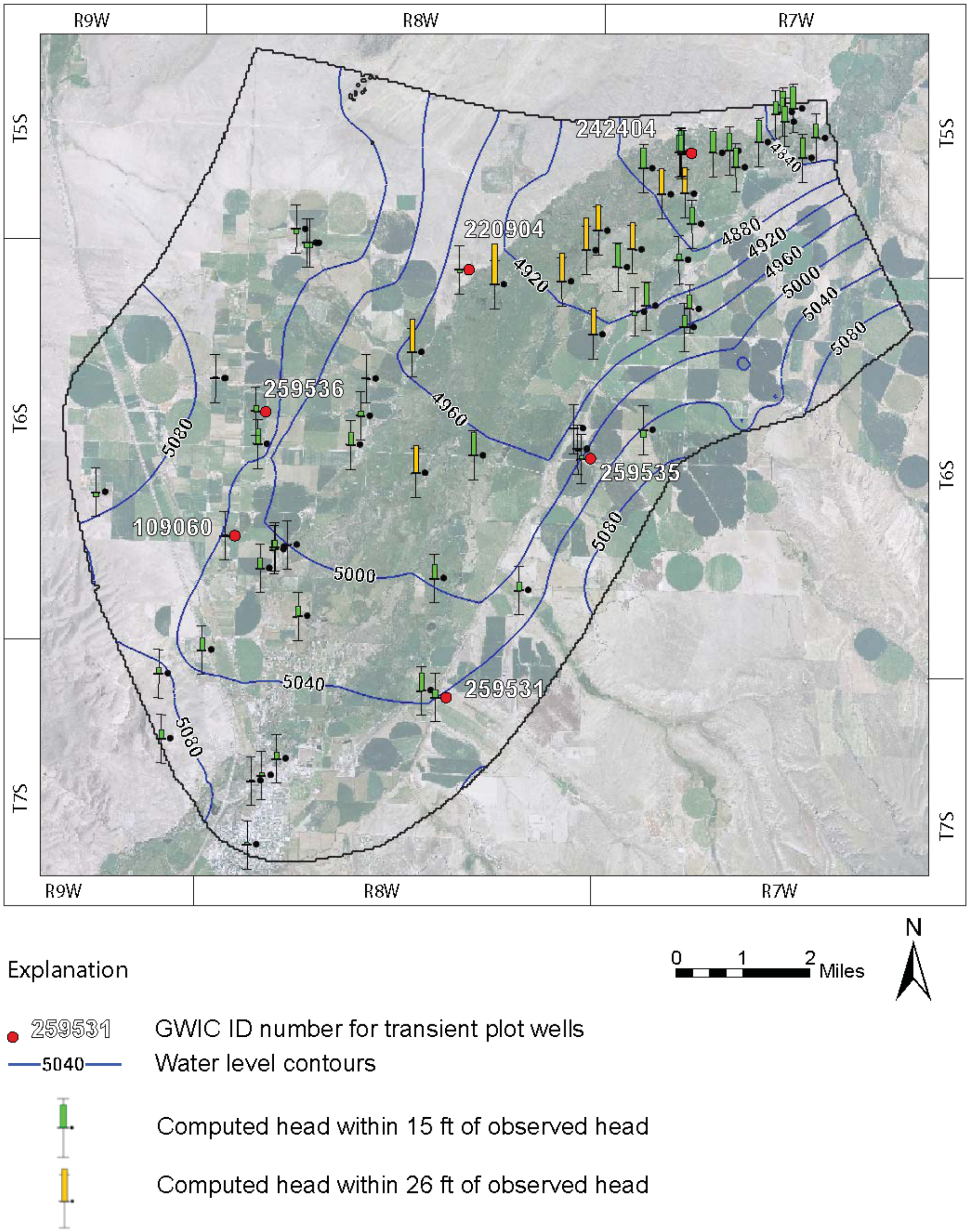


Figure 60. A potentiometric surface of both the alluvial and Tertiary sediment aquifers generated by the steady-state model. The green bars represent where the calibration targets were within ±15 ft and the yellow bars are where the calibration targets were between 16 and 25.5 ft.

change through the period of record, calibration efforts were not focused on the bedrock system.

Baseflows from Black, Willard, and Albers Slough were also used in calibrating the steady-state and 2010 transient models. Table 13 compares baseflow in the model output versus the field-based estimate for each stream. The differences between the field and model results ranged from 9 to 14%, which were within the calibration criterion of 15%.

Predictive Pumping Scenarios

Four pumping scenarios and three canal seepage scenarios were simulated in the Lower Beaverhead model (table 1, fig. 63). The results from pumping scenarios 2 through 4 and canal seepage scenario 7 are presented. Scenario 1 was the baseline scenario and is presented for comparison purposes. Details on all the scenarios are included in the modeling report (Butler and others, 2013).

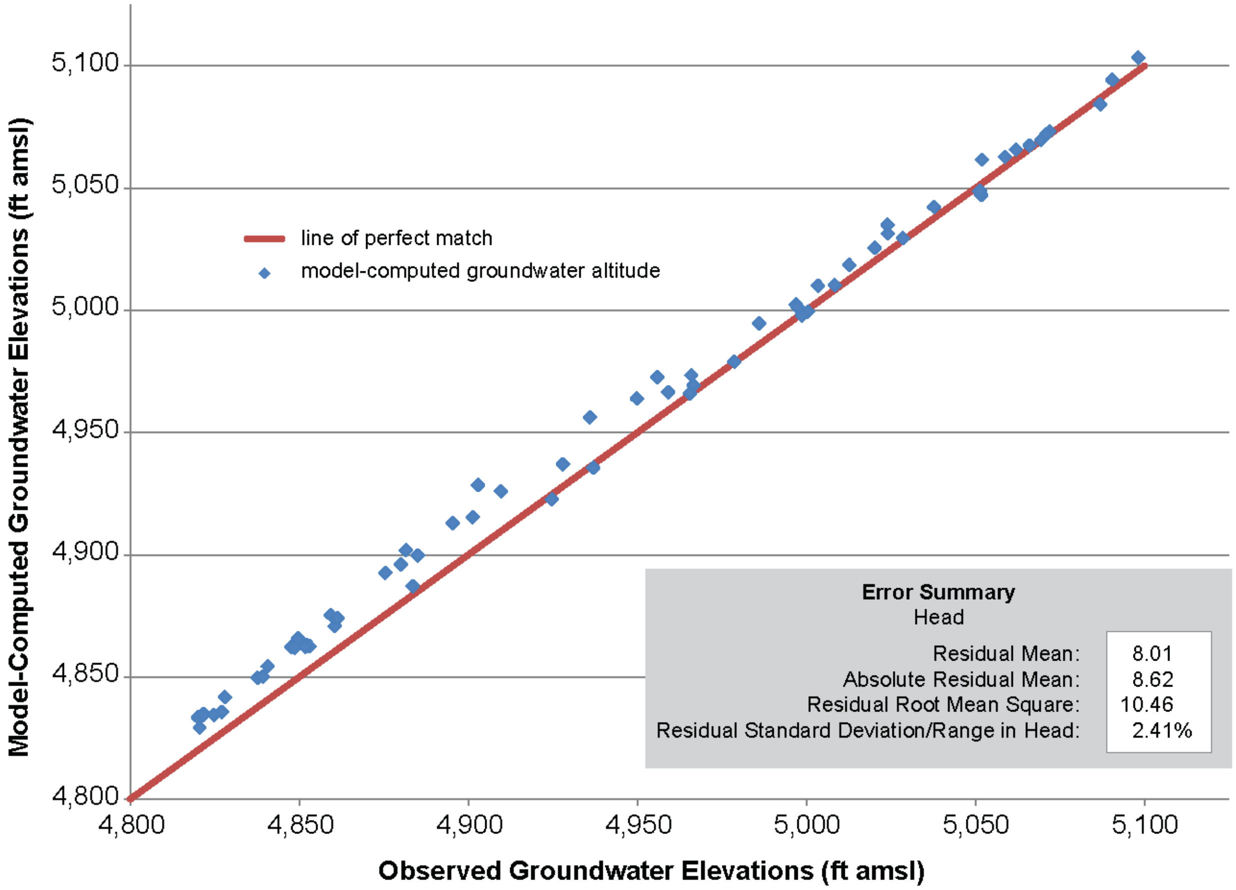


Figure 61. The residuals for the calibrated model display the difference between the observed water levels and those calculated by the model.

Table 12. Steady-state model groundwater water budget results.

	Modeled Values (acre-ft/year)
Inputs	
East Bench Inflow	3,159
Floodplain Groundwater Inflow	2,884
West Bench Inflow	103
West Side Canal Leakage	5,911
East Bench Canal Leakage	4,573
Infiltration from Applied Irrigation Water	35,994
Total Input	52,624
Outputs	
Irrigation + PWS Well Withdrawals	8,153
River (Net Gain at Beaverhead Rock, Including Sloughs)	41,631
Outflow at Beaverhead Rock Pinch Point	2,840
Total Output	52,624

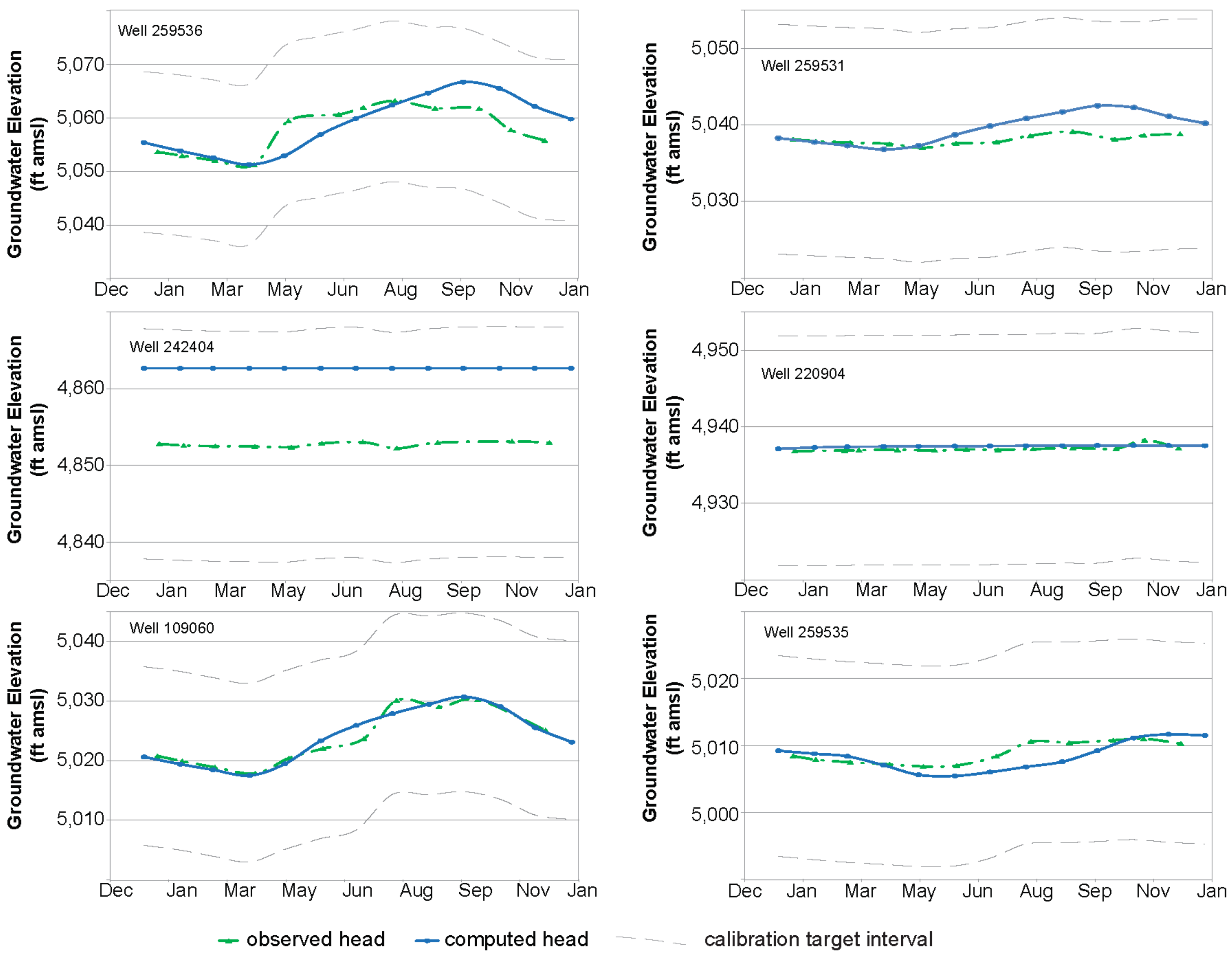


Figure 62. The observed heads and the computed heads were in general agreement. Well 242404, however, is an example of where there was about a 10 ft difference in the observed and computed heads. Well locations are shown in figure 63.

Table 13. Baseflow comparison between field estimates and model results.

Stream	Flow Measurement Events	Baseflow: Average Field Measurement (cfs)	Baseflow: Average Model Result (cfs)	Percent Difference
Willard Slough	4	2.0	2.3	14%
Albers Slough	2	12.1	13.3	10%
Black Slough	9	3.4	3.7	9%

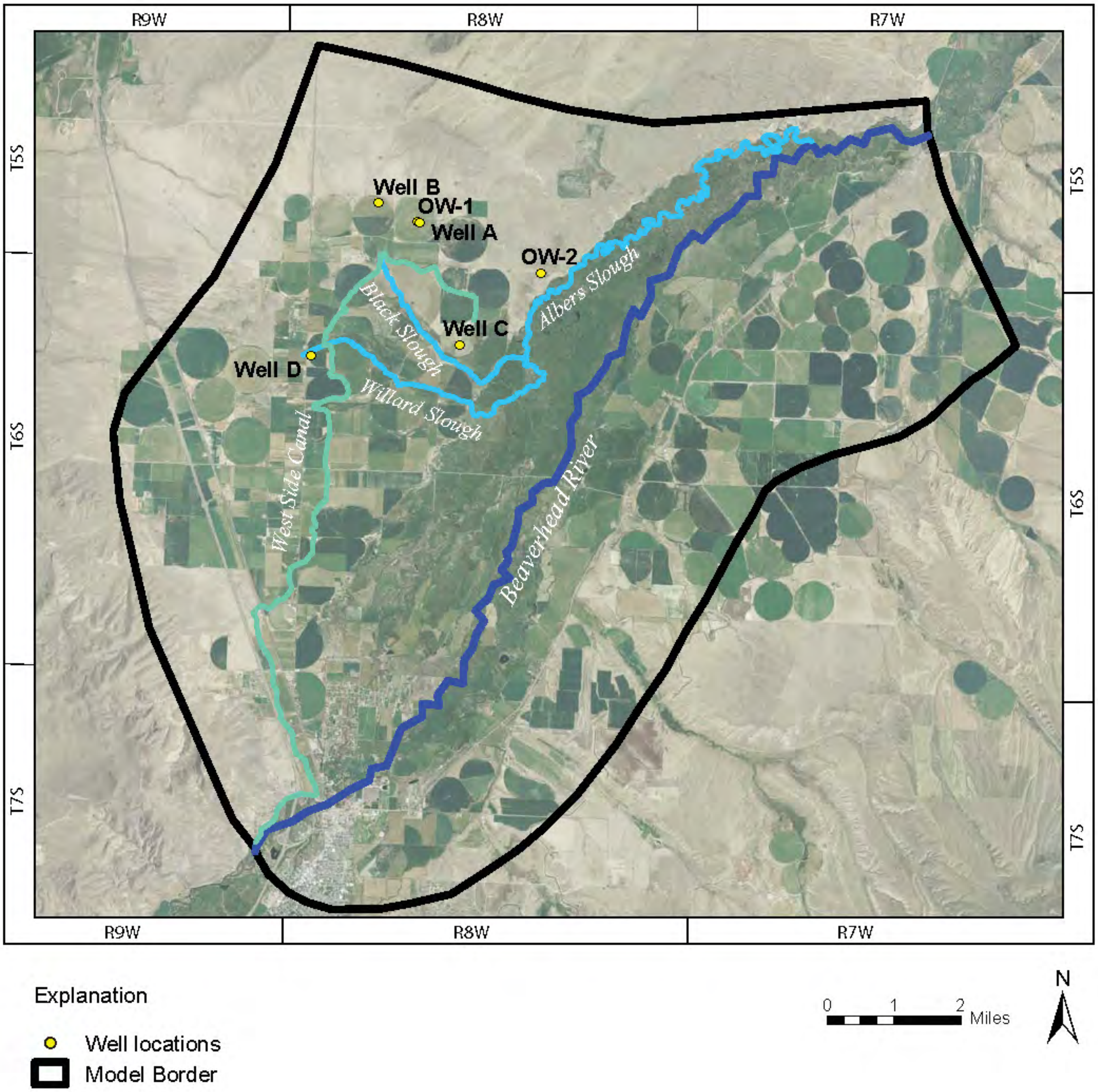


Figure 63. Location of pumping wells used in the predictive pumping scenarios. Wells A and B represent pumping from the Tertiary volcanic aquifer and wells C and D are representative of pumping from the Tertiary sediment aquifer.

Scenario 1 (Baseline). The baseline scenario featured only the pumping wells from the transient model, pumping seasonally at their assigned 2010 rates throughout the simulation and the seasonally applied recharge from canals and irrigation activities. The results of each subsequent scenario were compared to those of the baseline scenario in order to predict stream depletion and groundwater drawdown.

Scenario 2 (Well A Pumping from the Volcanic Rock Aquifer). In this scenario, well A (fig. 63) is pumped at 1,500 gpm for 2 months of each annual irrigation season. The simulation resulted in a maximum drawdown of 6.8 ft at well A, which occurred in August of the final year of pumping (year 20). The rate of drawdown decreased over time, with an additional drawdown of 0.04 ft between years 19 and 20.

The highest stream depletion rates also occurred in the final year of pumping (fig. 64). Since the model estimates the amount of groundwater flowing into or contributed to each stream, stream depletion was estimated by subtracting the amount of groundwater contributed during the baseline scenario from the pumping scenario. The amount of depletion in the river and sloughs contributed to about 19% of the total pumping rate.

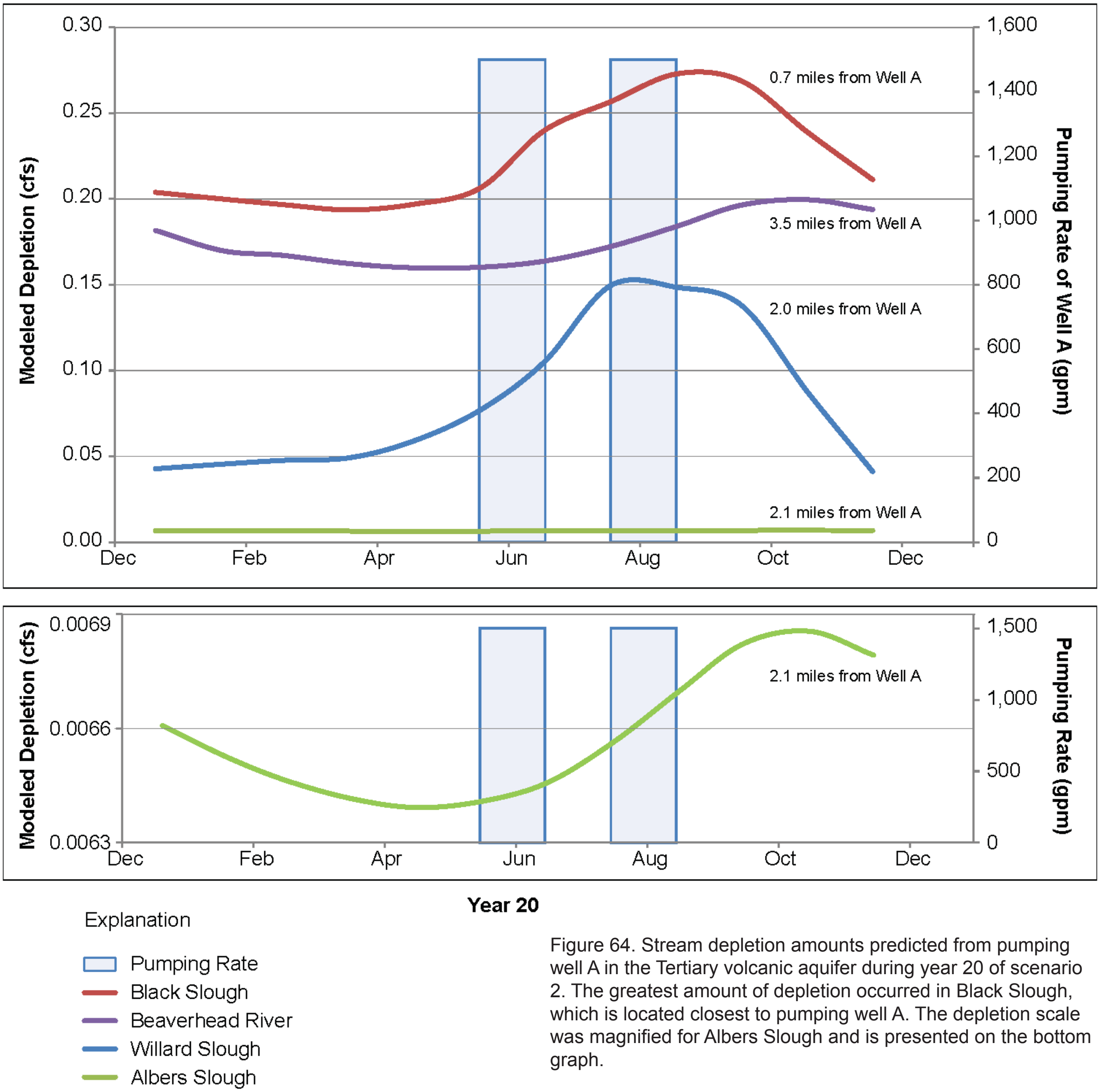


Figure 64. Stream depletion amounts predicted from pumping well A in the Tertiary volcanic aquifer during year 20 of scenario 2. The greatest amount of depletion occurred in Black Slough, which is located closest to pumping well A. The depletion scale was magnified for Albers Slough and is presented on the bottom graph.

The model results show that the highest depletion is in Black Slough, which is closest to the pumping well followed by Willard and then Albers Slough (fig. 64). The Beaverhead River had a depletion amount between that of Black Slough and Willard Slough but was also assigned a streambed conductance value three times that of the sloughs to allow for adequate water exchange with the high-transmissivity alluvial aquifer. The closest stream to well A (Black Slough) shows a rapid response. In contrast, depletion in the Beaverhead River gradually increased during the pumping period and did not reach its maximum depletion rate until 2 months after pumping ceased.

The Beaverhead River was divided into nine segments of equal lengths to examine the distribution of stream depletion. The depletion for each segment was extracted from the model output and then calculated as a percentage of the overall depletion (fig. 65). The greatest depletion occurred in the middle segments of the river, centered slightly upstream of the pumping well.

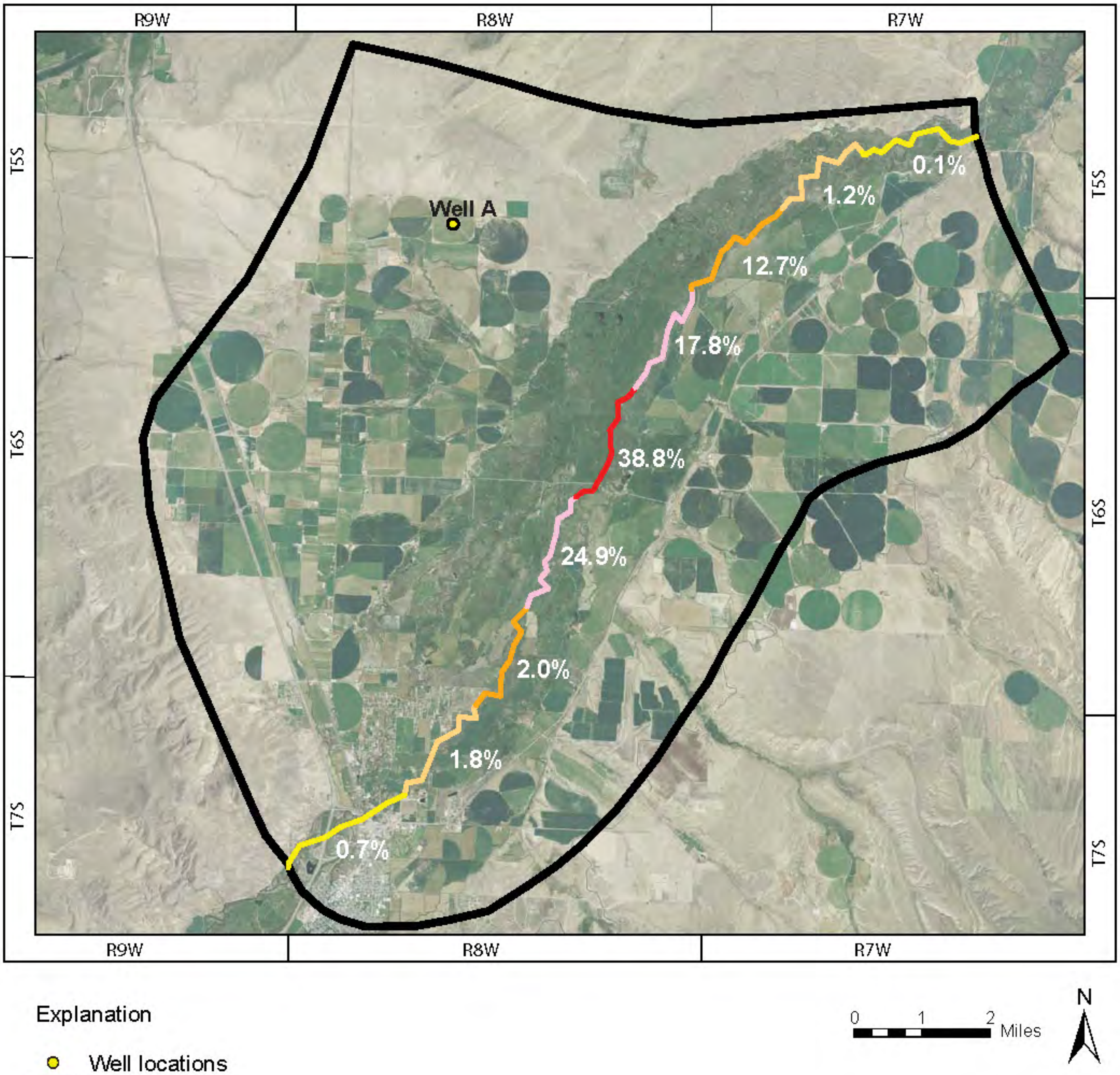


Figure 65. Stream depletion shown in percentages along segments of the Beaverhead River in year 20 of scenario 2 indicates that the greatest amount of depletion occurred in the middle segments, which were slightly upstream of the segment closest to the pumping well.

Scenario 3 (Wells A and B Pumping in the Volcanic Rock Aquifer). Both wells A and B (fig. 63) were pumped at 1,500 gpm for 2 months of each annual irrigation season. The simulation results were similar to those of scenario 2, with the only major difference being that the drawdown and depletions doubled in response to doubling groundwater withdrawals (fig. 66). As in scenario 2, the depletion rates contributed to about 19% of the total pumping rate. The distance-magnitude and distance-time relationships identified in Scenario 2 were also observed in Scenario 3.

Monthly stream depletion was calculated throughout the simulation to evaluate the change in depletion over time in the Beaverhead River (fig. 67). Although depletion increased with time, the rate of increase gradually decreased but did not stabilize within the 20-year pumping scenario. To find the ultimate depletion in the river, scenario 3 conditions were simulated in a steady-state model. The Beaverhead River depletion in this simulation was considered to be the ultimate depletion and was compared with the river depletion in the final year of the transient simulation. This comparison

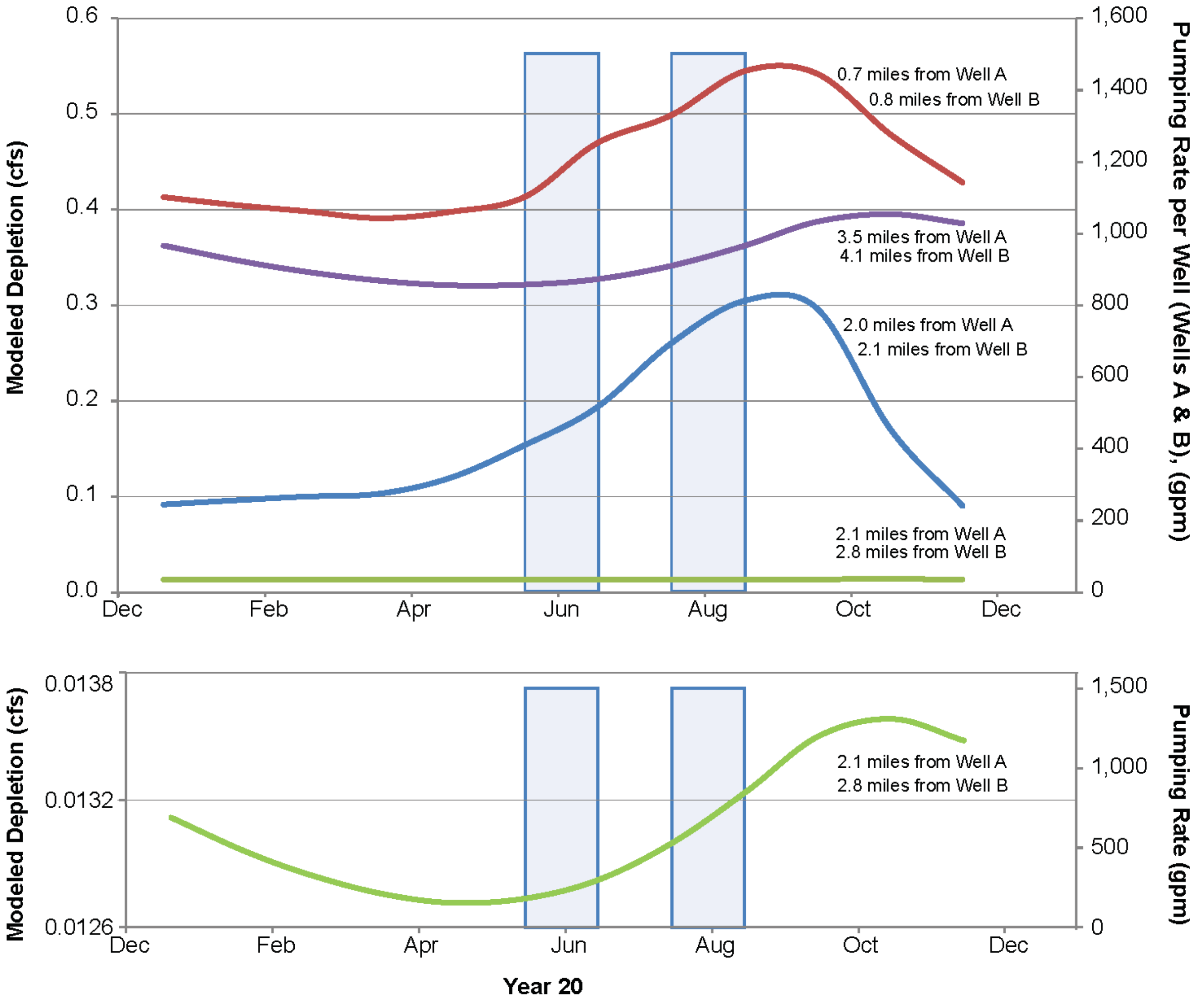


Figure 66. Stream depletion amounts predicted from pumping wells A and B in the Tertiary volcanic aquifer in year 20 of Scenario 3. The depletion scale was magnified for Albers Slough and is presented on the bottom graph.

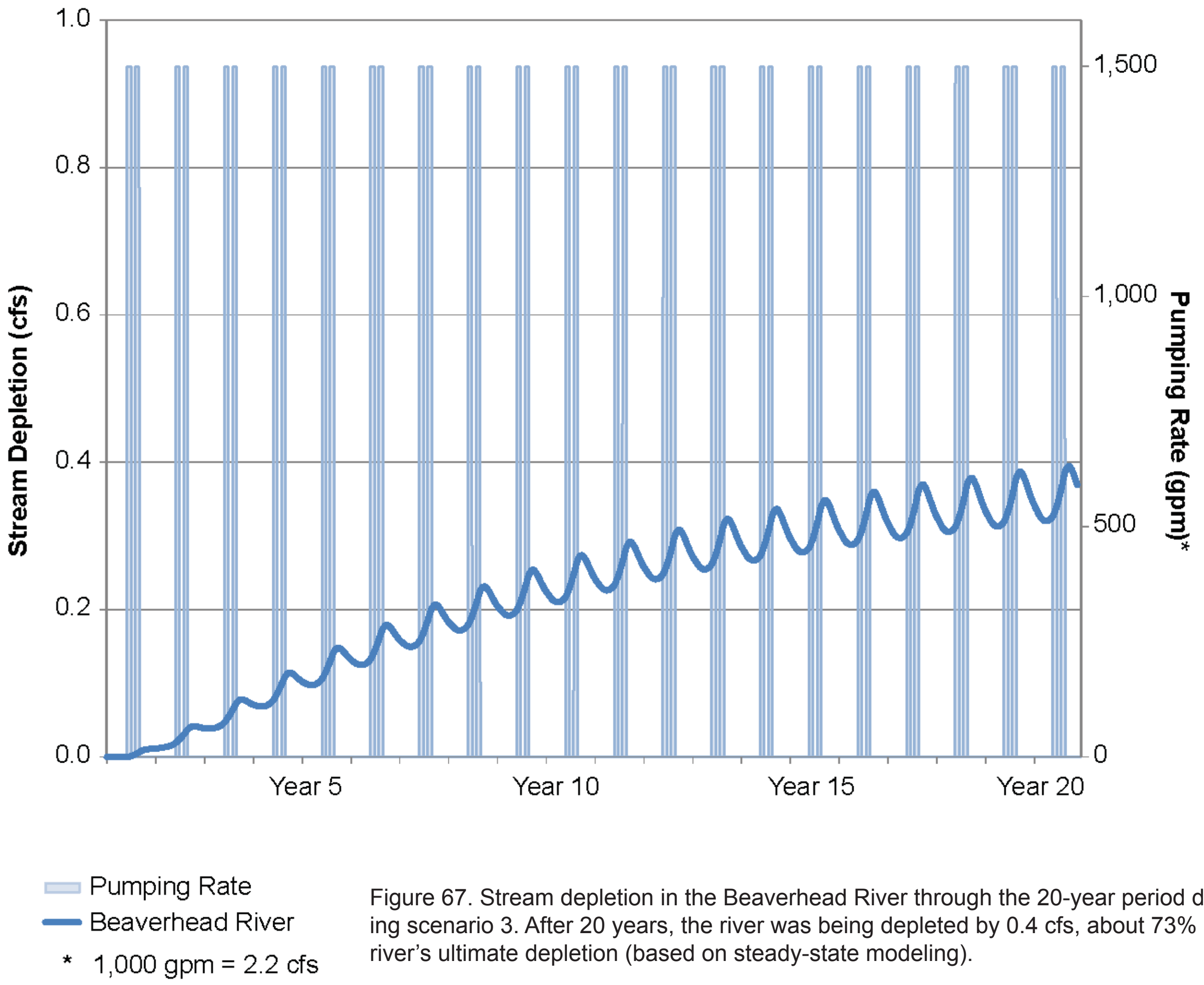


Figure 67. Stream depletion in the Beaverhead River through the 20-year period during scenario 3. After 20 years, the river was being depleted by 0.4 cfs, about 73% of the river's ultimate depletion (based on steady-state modeling).

showed the Beaverhead River had reached 0.4 cfs, or 73% of its ultimate depletion, after 20 years. This percentage does not take the sloughs' depletion effects on the Beaverhead River into account; the model calculated the direct impacts to the river mainstem only. Any slough depletion would result in additional river depletion amounts.

The effects of pumping on groundwater levels were also evaluated in scenario 3. Groundwater drawdown was compared in hypothetical wells OW-1, located adjacent to well A, and OW-2, which was 2 miles east of pumping well A (fig. 63). After 20 years, the drawdown in OW-1 had reached an annual water level about 10 ft lower than original, responding to the pumping cycles in June and August of each year. It continued to increase at the end of the 20-year simulation. In contrast, drawdown in OW-2 is more subdued, and drawdown had nearly stabilized at less than 1 ft of change after 20 years (fig. 68).

Scenario 4 (Wells C and D Pumping in the Tertiary Sediment Aquifer). Wells C and D (fig. 63) were pumped simultaneously for 2 months of each annual irrigation season, at 375 gpm. The depletion rates were lower than in scenario 3 due to the lower pumping rates of the wells (fig. 69). As in the two previous scenarios, a distance-magnitude relationship was apparent in comparing depletion in the three sloughs. The most significant differences in the scenario 4 results as compared to those of scenarios 2 and 3 were the greater relative depletion compared to the pumping rates, with about 37% of the pumping rate supplied by depletion of the river and sloughs. There was also the pronounced fluctuation in the stream depletion rates between the June and August pumping intervals.

Scenarios 5, 6, 7 (Canal Seepage Scenarios). In scenarios 5 through 7, the period of flow in the West Side Canal was extended to examine the effects of pre- and post-irrigation season seepage as a mitigation for stream depletion caused by pump-

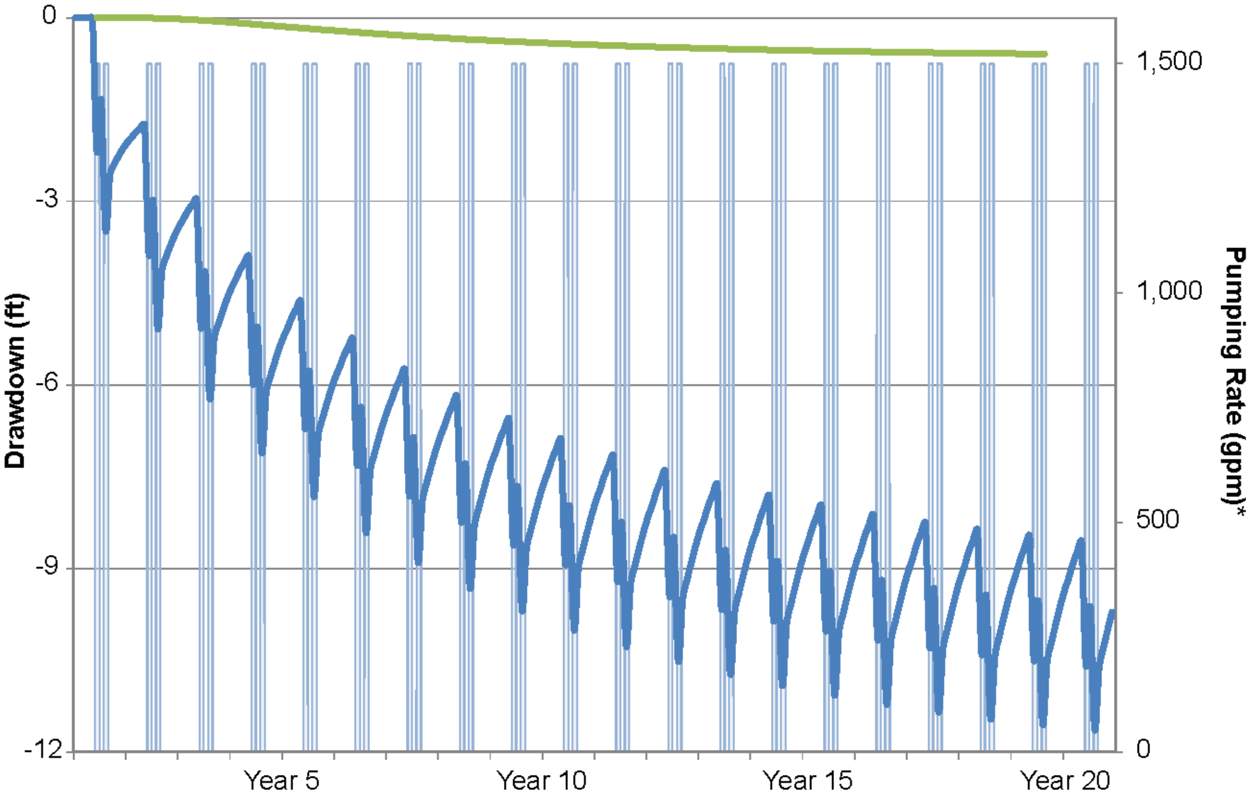


Figure 68. The drawdown in well OW-1 responded seasonally to pumping (scenario 3) and had greater drawdown then well OW-2. Well OW-1 was located in the model grid cell adjacent to pumping well A.

ing. The results of all three scenarios are presented in the modeling report (Butler and others, 2013). Scenario 7, in which the canal was simulated to flow one month before (March 15–April 15) and one month after (October 15–November 15) the irrigation season, is presented below. Scenario 3 pumping conditions were used in these canal seepage scenarios, with wells A and B pumping in the volcanic aquifer for 2 months of each irrigation season.

In scenario 7, canal seepage resulted in less stream depletion in Black Slough (fig. 70). With the additional canal recharge, the maximum Black Slough depletion in year 20 decreased by 58%. In Willard Slough, canal seepage not only offset pumping but resulted in an average increase in baseflow of 4% above baseline conditions in year 20. The same was true for the modeled reach of the Beaverhead River, which exhibited an average baseflow increase of 5% above baseline conditions in year 20 (fig. 71). However, since the canal is diverted from the river, that extra diversion would reduce stream flow accordingly. This reduction in river flow is not accounted for in figure 71.

The effects of additional canal seepage were also evaluated with respect to groundwater drawdown (fig. 72). While drawdown still occurred, it was 41% less than that of the pumping scenario.

Model Limitations

Although the groundwater models served as useful tools in refining the conceptual model and evaluating potential future scenarios, they do have limitations. For example, the models are not intended to simulate scenarios at scales larger than the design scale, i.e., taking a large area model and applying it to a smaller area.

The limitation of observation data can affect modeling results and interpretations. Uncertainty

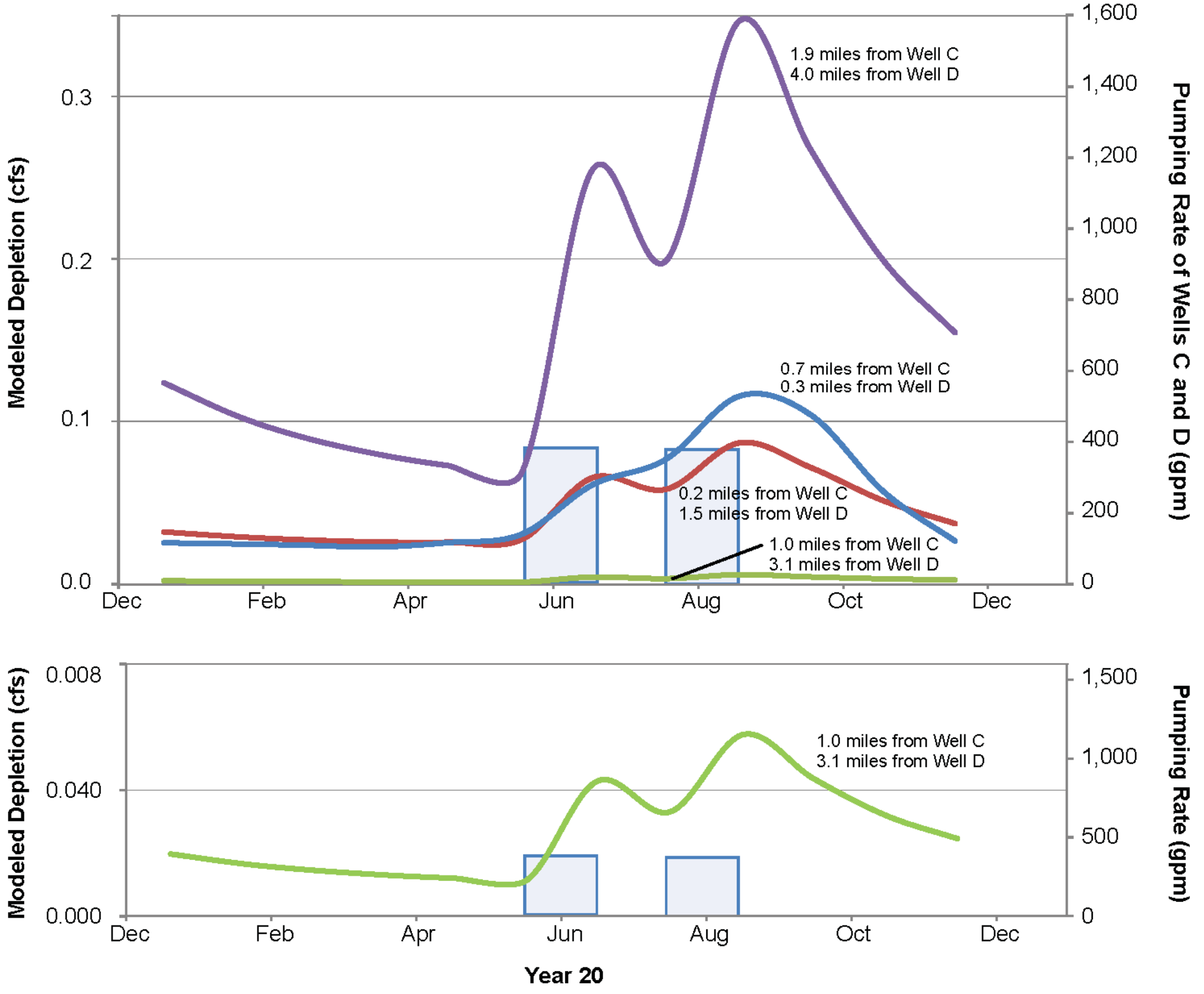


Figure 69. Stream depletion during year 20 as a result of pumping wells C and D (scenario 4) in the Tertiary sediments. Note that there was a higher responsiveness to depletion from pumping when compared to scenarios 2 and 3. The depletion scale was magnified for Albers Slough and is presented on the bottom graph.

in model input values such as streambed conductance and areas where observation well data are lacking are examples of data limitations.

The predictive scenarios represent area-wide scale estimates of applied stress effects based on the available data. The results of these modeling efforts should be considered an approximation based on the available data. Adjusting model parameters, such as hydraulic conductivity, should be adjusted to reflect new data, especially in areas where observation well data are sparse and where the model is sensitive to hydraulic conductivity (in this case the Tertiary sediment). Climatic conditions were held constant over the 20-year modeling scenarios because of the unknowns in predicting future climatic conditions. However, this approach does not include the normal variations of high recharge or drought years.

Individuals who plan to operate the model should obtain and read the model report (Butler

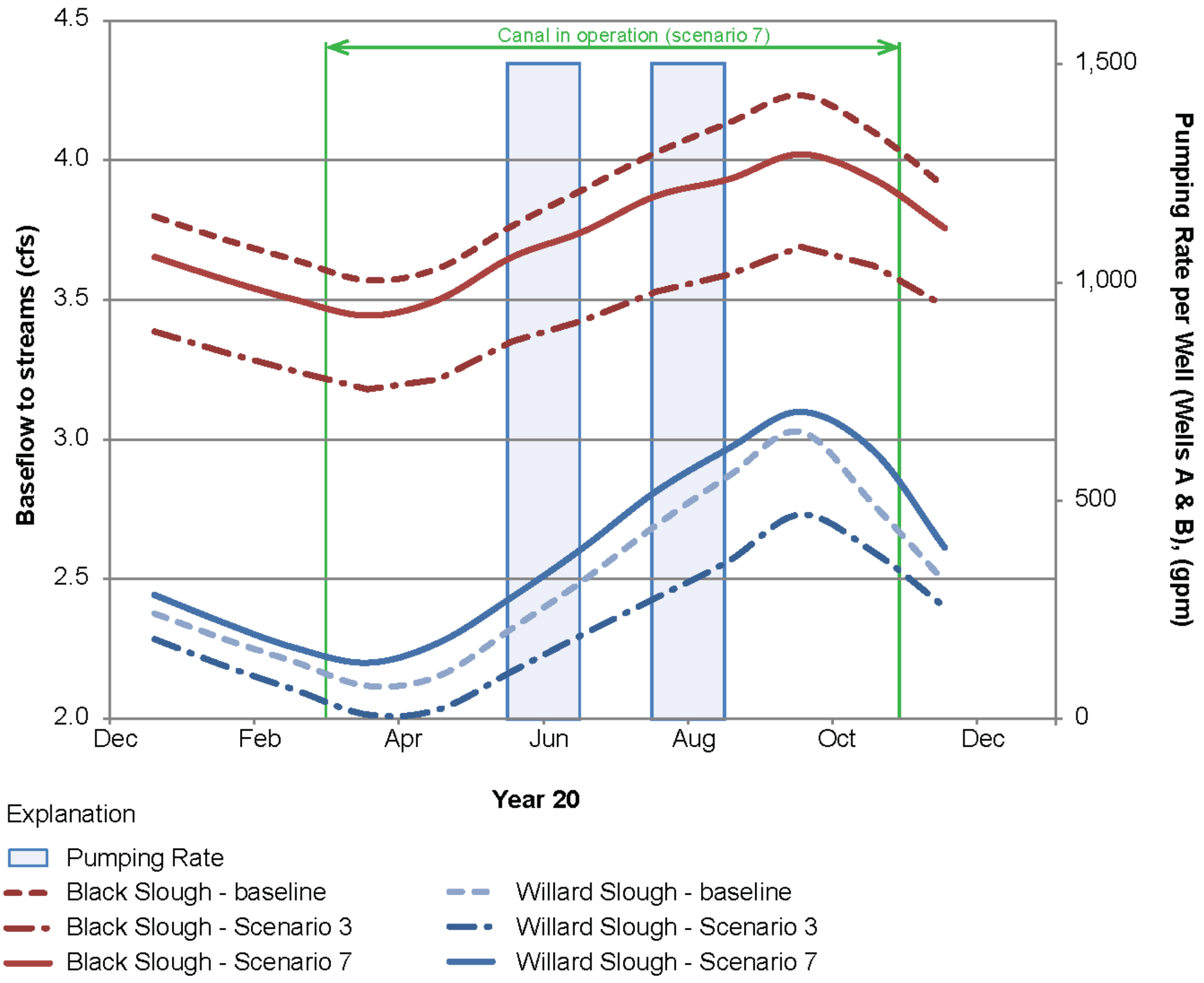


Figure 70. Modeled baseflow in Black and Willard Sloughs during year 20 of the baseline scenario (no pumping), scenario 3 (pumping wells A and B), and scenario 7 (pumping wells A and B plus extending the canal flow 1 month before and 1 month after the irrigation season). In scenario 7, baseflow in Black Slough was 58% higher than in scenario 3. The Willard Slough baseflow increased above the baseline scenario (4%) and scenario 3.

and others, 2013), review the derivation of model parameters, and use caution in interpreting results, especially if any stress is located near the model boundaries.

DISCUSSION

The Hydrogeologic System

Aquifer Properties

The three main aquifers identified in the study area are: (1) the alluvium which underlies the Beaverhead River Valley; (2) the Tertiary sediment that underlies the alluvium in the floodplain and the West and East Benches; and (3) the volcanic rock intrusions within the West Bench.

Alluvial Aquifer

The alluvial aquifer in the floodplain of the Beaverhead River is unconfined and consists of about 25 to 30 ft of sand, gravel, and cobbles. Transmissivity ranges from 18,000 to 37,000 ft^2/day. Well yields in the alluvial aquifer range from less than 1 gpm to 1,800 gpm with a median yield of 20 gpm. A clay layer of various thickness underlies the alluvium in most areas and likely provides localized separation between the alluvium and the underlying Tertiary sediments. Tritium concentrations indicate that groundwater in the alluvial aquifer is modern and has been recharged within the past 10 years. This aquifer is in direct connection with the Beaverhead River.

Tertiary Sediment Aquifer

Tertiary sediments underlie the floodplain and the West and East Benches. Typically, the Tertiary sediments consist of sand and gravel interbedded

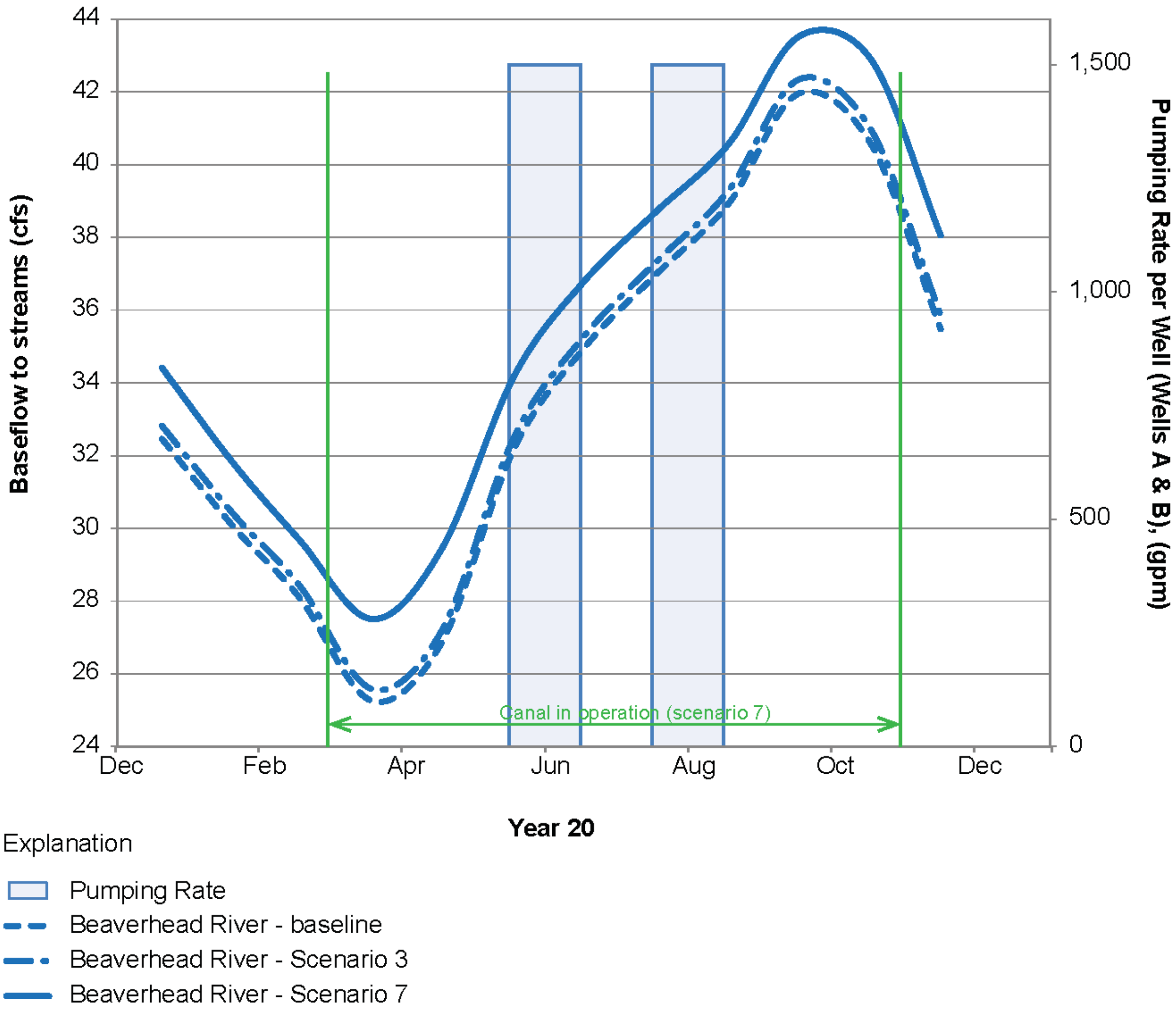


Figure 71. Modeled baseflow to the Beaverhead River during year 20 of the baseline scenario (no pumping), scenario 3 (pumping wells A and B), and scenario 7 (pumping wells A and B plus extending canal flow 1 month before and after the irrigation season). The Beaverhead River exhibited a flow increase of about 5% above baseline conditions when canal flow was extended both 1 month before and 1 month after the irrigation season (scenario 7).

with clay and silt. The thickness of the unit varies from as little as 60 ft to greater than 700 ft.

Transmissivity values in the Tertiary sediments range from about 410 to 5,890 ft^2/day, with the highest values being in the floodplain and East Bench areas. Reported well yields range from 2 to 1,800 gpm, with a median of about 20 to 25 gpm.

The Tertiary sediment aquifer test performed during this investigation in the West Bench area indicates a confined aquifer with a storativity of 0.00098. During the aquifer test pumping, there was no measurable effect on nearby Willard Slough or shallow monitoring wells. Lower permeable clay units provide, at least locally, confined to semi-confined aquifer conditions in the Tertiary sediments on the benches and the floodplain.

Overall, the groundwater in the Tertiary sediment aquifer is older than the volcanic rock and alluvial groundwater. At locations where tritium values were below 1.0 TU, groundwater was recharged prior to 1952 and little mixing has occurred with modern groundwater. In other areas, the Tertiary sediment aquifer has been recharged with groundwater since 1952 and/or has mixed with younger groundwater.

Volcanic Rock Aquifer

The volcanic rock aquifer outcrops in the northwest section of the West Bench and is the most prolific aquifer in the study area. Transmissivity ranges from 42,500 to 75,500 ft^2/day. This aquifer is capable of yielding up to 1,500 gpm with minimal drawdown. Storativity ranges from 0.0026 to 0.018,

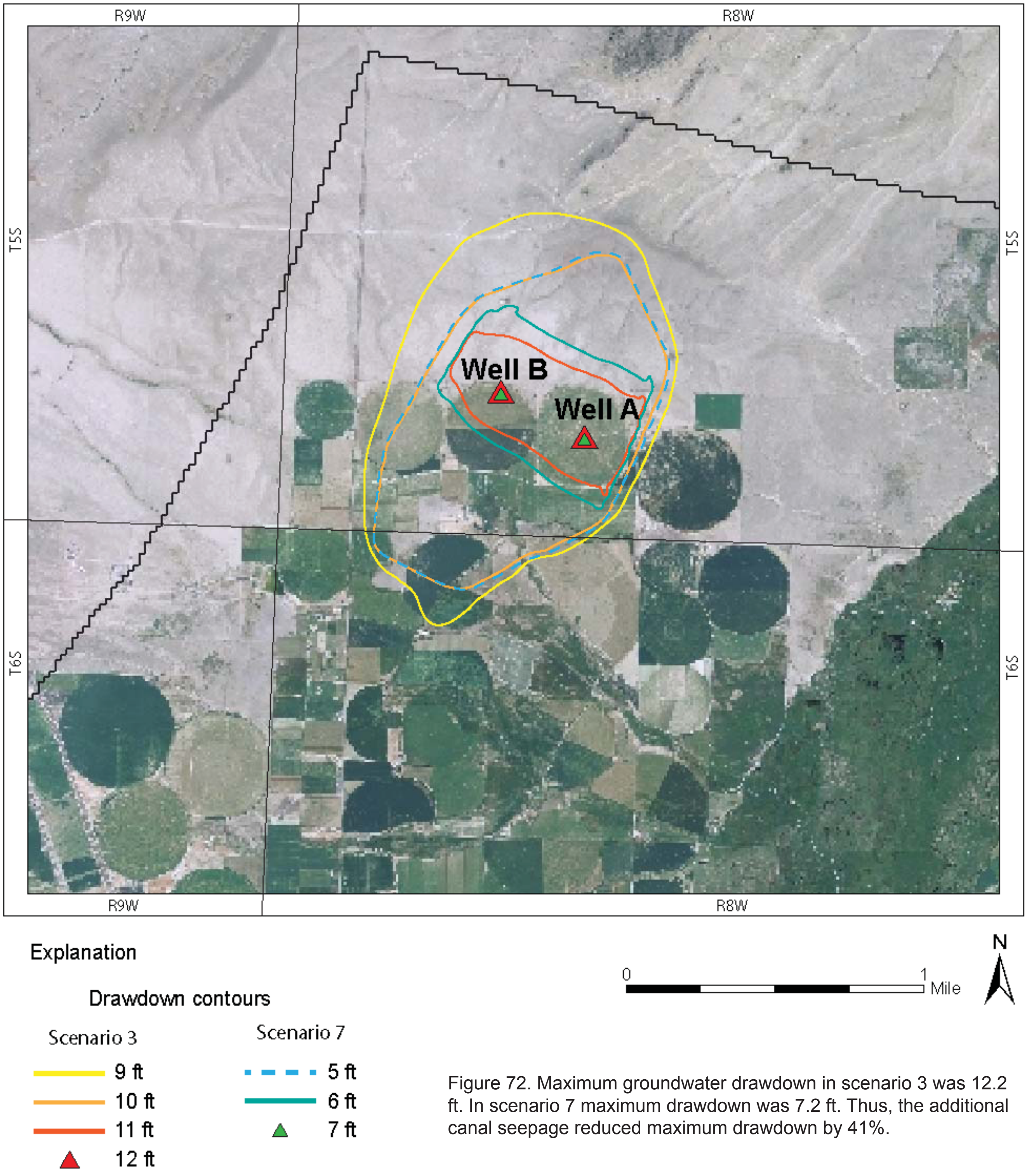


Figure 72. Maximum groundwater drawdown in scenario 3 was 12.2 ft. In scenario 7 maximum drawdown was 7.2 ft. Thus, the additional canal seepage reduced maximum drawdown by 41%.

which indicates unconfined to semi-confined conditions. Consisting mainly of rhyodacite, the high yields are attributed to the vesicular nature and fracturing of the rock. In some places the volcanic rocks outcrop on the surface, and volcanic rocks have been noted at a depth of 220 ft below ground surface on drillers logs (GWIC, 2011).

Tritium in the two groundwater samples from the volcanic rock aquifer indicate relatively young water (4.30 and 6.88 TU, table 8) and suggests that the volcanic rock aquifer receives more recent recharge than the Tertiary sediments. This recharge may occur where the volcanic rock outcrops to the west of these wells.

Groundwater Movement

Groundwater flows in the Tertiary sediments from both the East and West Benches toward the Beaverhead River Valley, providing a source of recharge to the alluvium, the underlying Tertiary sediments, and the river. Groundwater flow in the valley within both the alluvium and Tertiary sediments follows the river toward the northeast. The Beaverhead River gains water from the alluvial aquifer near Dillon, loses water as it flows out of Dillon, and gains from Anderson Lane to Beaverhead Rock.

Groundwater flow out of the volcanic rock aquifer on the West Bench recharges the Tertiary sediments during much of the year. High-capacity pumping from the volcanic rock aquifer during the irrigation season temporarily reverses the vertical gradient, causing water in the Tertiary sediments to flow to the volcanic rock aquifer.

Groundwater/Surface-Water Interaction

Interaction occurs between the alluvial aquifer and the Beaverhead River. During the irrigation season, the river gains water from the shallow alluvial aquifer when groundwater levels are elevated. During the non-irrigation season when groundwater levels are lower, the river loses water to the alluvium near Dillon and Anderson Lane. Closer to Beaverhead Rock, there was a consistent gain in the river from the alluvial aquifer throughout the year. Here the alluvium is discharging groundwater to the river at a seemingly constant rate independent of irrigation activities or precipitation. Water levels in the alluvium are likely high due to recharge from sloughs and the Tertiary sediments rather than an upwelling of deeper groundwater. This relatively constant flux is likely controlled by the effect of the pinch point at Beaverhead Rock creating both a groundwater and a surface-water spillway with a constant elevation.

Similar relative age dates (tritium) in both the alluvial groundwater and surface water suggest groundwater moves rapidly and flows to the Beaverhead River or that the river water exchanges with the shallow groundwater system.

Isotope data (^{18}O and D) from the Beaverhead River illustrate potential effects of irrigation return flows. The slopes of the river stable isotope data are lower in the central study area, likely the result of irrigation return flow which consists of highly evaporated water from both flood irrigation and pivots. However, the higher fraction of evaporated water along the center of the basin could also be due to tributary inflow into the river between Dillon and Beaverhead Rock from Stone Creek and Stodden Slough. Whether from irrigation return flows through groundwater flow paths or surface-water tributaries, the influence of irrigation returns on the Beaverhead River appears to last for about 2 months after the end of the irrigation season (fig. 53).

Flows in Willard and Black Sloughs are enhanced by shallow groundwater from irrigation return flow. Isotopic data indicate that the upper reaches of these sloughs consist of nearly all regional groundwater. Closer to the floodplain they are influenced by irrigation return flow (table 7). Although water from these sloughs flows into Albers Slough, Albers Slough is more isotopically similar to regional groundwater and composed less of irrigation return flow. Therefore, Albers Slough, which runs parallel to the Beaverhead River, receives regional groundwater discharging primarily from the West Bench. The inflow from Albers Slough could also be controlling the isotopic composition in the Beaverhead River by Beaverhead Rock, which is composed of higher quantities of regional groundwater flow.

Water Budget

The annual water budget for the Lower Beaverhead investigation area totals about 475,000 acre-ft, and is dominated by surface water for both inflows (54%) and outflows (60%; table 9 and fig. 55). The second most dominant inflow is precipitation (23%), and the second most dominant outflow is ET_{TOTAL} (28%). Irrigation canals that cross the study boundaries also represent significant inflows (19%) and outflows (8%). Groundwater is a fairly small component of the inflow to the area, accounting for 4% of the total. Near Beaverhead Rock the valley forms a hydrologic pinch point with a small cross-sectional area, forcing most groundwater into the river, which therefore exits as surface water flow. The amount of water leaving the area as groundwater flow is estimated to be less than 1% of the total outflow.

Water consumption in the study area is limited to ET, which was calculated to be nearly 132,000 acre-ft during 2010. As a percentage of total outflow from the water budget, ET from all irrigated land accounts for 15%, and ET from non-crop land for 13%. There are about 638 private wells that supply domestic water for household, lawn and garden, and stock water in the study area and they are a minor part of the overall water budget, accounting for about 0.2% or about 1,000 acre-ft/yr of the total outflow.

Groundwater Recharge from Canals and Irrigated Fields

On an annual basis, 30% (145,500 acre-ft) of the total water entering the study area was applied for irrigation. This includes water applied to irrigate fields, lost through canal seepage, groundwater pumping for irrigation, and precipitation. Of the water applied for irrigation about 69,000 acre-ft (47% of total irrigation applications) is consumed through evapotranspiration. The remaining 76,700 acre-ft (53% of applied water) either returned to the river as overland flow or became potential groundwater recharge by leakage through canals and excess water applied to fields. Groundwater supplies an estimated 5% (6,735 acre-ft) of all irrigation applications.

Recharge from Canal Seepage

Both the West Side and the East Bench Canals are a source of recharge to groundwater. Average measured seepage loss for the West Side Canal was 1.2 cfs/mile, and 2.2 cfs/mile for the East Bench Canal. During 2010, seepage losses to groundwater were calculated at about 17,000 acre-ft from the East Bench Canal and 5,900 acre-ft from the West Side Canal. This does not include the seepage losses from the lateral ditches coming off the canals.

Recharge from Irrigation Fields

Some amount of the excess irrigation water applied to fields will become aquifer recharge. The total ET demand for irrigated fields in the project area during 2010 was nearly 69,000 acre-ft. Precipitation satisfied 36,760 acre-ft of that demand, leaving a net irrigation requirement of 32,200 acre-ft. About 85,800 acre-ft of water was applied to irrigated fields, and therefore an estimated 53,600 acre-ft of water from excess irrigation was available for irrigation return flows, increases in soil moisture storage, and aquifer recharge. This excess water occurred over an irrigated area of about 36,000 acres.

Timing of Canal/Groundwater Interaction

The timing and magnitude of groundwater recharge from canal seepage is primarily dependent on the type of sediments underlying the canals and is also influenced by the depth to groundwater before the irrigation season. Conditions vary along the length of both the East Bench and West Side Canals, which can result in variable seepage amounts and delay before the water reaches the aquifer.

Groundwater-level responses were seen as soon as 4 days to as long as a month after the main canals were turned on, depending on site variability. The results of this investigation illustrate the role and importance of irrigation projects in recharging groundwater.

Reducing groundwater recharge by a decrease in canal/ditch seepage loss can occur in years when less water is available for canal conveyance or when canals are lined. Potential groundwater recharge from irrigation far exceeds groundwater withdrawn for irrigation. The combined effect of irrigation practices, therefore, is to increase groundwater levels in the area. This addition to groundwater can provide more stable baseflow to the river and maintain the water table at a level that is higher than it would have been without irrigation practices.

Current and Potential Impacts from Wells

The purpose of this investigation was to evaluate the effects of pumping high-capacity wells on surface water and groundwater in the Beaverhead River Valley downstream of Dillon, with a focus on the West Bench. Aquifer drawdown and stream depletion are concerns among senior water-rights holders, those seeking permits for wells, regulators, and other stake holders.

Stream depletion due to groundwater pumping occurs when groundwater that otherwise would discharge to surface water is intercepted by a pumping well, or when groundwater pumping induces surface-water recharge to the aquifer. Stream depletion may be rapid and measurable or may take years and be immeasurably small. The timing and magnitude depends on factors such as the distance from surface water to the well, pumping duration and amount, hydraulic characteristics of the aquifer, and streambed conductance.

Current Groundwater Trends

Within the study area, water-level records that exceed 10 years exist for nine wells. Water-level trends in most of these wells show strong correlation with either precipitation or canal flows/applied irrigation water. Long-term depletion of groundwater caused by high-capacity irrigation groundwater withdrawals are not obvious in these records. If irrigation withdrawals are causing long-term groundwater-level declines, the declines are overshadowed by other influences such as changes in irrigation recharge.

Factors that influence groundwater levels include: (1) surface-water stage changes in the Beaverhead River and its tributaries, (2) pumping, (3) applied irrigation water, (4) climate, and (5) seepage losses from the West Side and East Bench Canals. Groundwater response also depends on well depth and the type of aquifer in which the well is completed.

Pumping does cause localized, seasonal drawdown in some areas; the volcanic rock aquifer is an example of this. However, precipitation during 2010 was well above average, and most hydrographs from the study area indicate a general rising trend in groundwater levels throughout the year.

Floodplain

Groundwater elevations over the long term in both the alluvial and Tertiary sediment aquifers in the floodplain area are fairly consistent (fig. 30). This indicates that any climatic and/or groundwater pumping effects are offset by recharge. The narrow pinch point in the valley near Beaverhead Rock helps maintain the groundwater elevation by restricting discharge.

East Bench

The East Bench Canal has had a pronounced effect on groundwater on the East Bench since it began its operation in the mid-1960s. Two monitoring wells near the study area show a groundwater rise of 19 and 55 ft since the canal has been in operation. Groundwater is recharged by seepage loss from the canal and water diverted from the canal and applied to irrigate fields (fig. 34). Climate indirectly plays a role in groundwater response because the amount of precipitation drives water storage volumes in the Clark Canyon Reservoir, which ultimately affects flows in the Beaverhead River and the flow diverted for the East Bench Canal.

Although seven irrigation wells were drilled on the East Bench in 2003, the steeper declines in groundwater levels from 2004 through 2005 appear to correlate to the reduction in the amount of water allotted and subsequent shutdown of the East Bench Canal. Groundwater levels declined about an additional 1.5 to 7 ft/year in the two long-term monitoring wells (fig. 34) when the canal was shut down.

Pumping from irrigation wells in 2010 caused localized effects on the East Bench (fig. 35). However, seepage from the East Bench Canal helped offset drawdown.

West Bench

Groundwater in areas of the West Bench near irrigation influences respond to recharge during the irrigation season (fig. 36). Declines during the dry years from 2000 to 2006 indicate the influence of precipitation.

In the area of well 108966, irrigation has little direct influence on recharge as evidenced by the lack of seasonal groundwater fluctuations (fig. 36). The groundwater decline of more than 20 ft in well 108966 was not attributed to pumping from irrigation wells. The four irrigation wells on the West Bench were drilled in 2003 and 2005. Groundwater levels in this well have declined at a fairly steady rate of 1.2 ft per year since 1997, beginning 6 years before the first irrigation wells were drilled. The cause of the water-level decline in this well is not apparent. It does not follow precipitation patterns like other wells, and shows only very minor seasonal influences. Groundwater in this part of the West Bench is not well connected to shallow influences and receives little local recharge because of a thick sequence of overlying, less permeable sediments. Withdrawals from this well and/or nearby domestic and stock wells appear to be exceeding recharge and creating a very local area of drawdown that is not seen in other areas.

Pumping from the volcanic rock aquifer on the West Bench caused maximum water-level declines of about 4 ft during August 2010 (fig. 37). However, after irrigation withdrawals ceased, water levels not only recovered to pre-pumping levels, but continued to rise through the end of monitoring.

Aquifer Drawdown and Potential Stream Depletion

Numerical modeling showed that the groundwater-level response to pumping from the volcanic rock aquifer varied depending on distance from the pumped well. A hypothetical well adjacent to a pumping well showed a seasonal groundwater pattern of drawdown and recovery. After 20 years, groundwater levels were lowered by about 10 ft in this well and had still not stabilized. In contrast, a well about 2 miles from the pumping well showed no seasonal response to pumping and recovery, and groundwater levels had nearly stabilized less than 1 ft lower after 20 years (fig. 68).

Groundwater withdrawals will cause stream depletion at rates that depend on pumping rates, distance to the stream, and hydrogeologic characteristics. Relative to stream flow, depletion rates can be small and difficult to measure directly. The rate of stream depletion can even be within the margin of error for surface-water measurements. For this reason, stream depletion is more likely to be calculated than measured.

Within the study area, pumping from the alluvial aquifer will result in more immediate stream depletion than will pumping from other aquifers. A numerical model of stream depletion by an alluvial well 150 ft from the river pumping 850 gpm calculated stream depletion reaching 800 gpm (94% of the total well discharge) within 30 days (MBMG, 2008). This reflected the high transmissivity of this aquifer and close proximity to the Beaverhead River.

Pumping from confined aquifers may result in delayed, but not eliminated, stream depletion. Confining layers may not be spatially continuous and they may have varying degrees of permeability that can result in vertical leakage. The cone of depression might extend beyond the confining unit, and drawdown may induce vertical leakage.

During the 3-day aquifer test, while pumping from the confined Tertiary sediments, no measureable effects were observed in Willard Slough or in shallow monitoring wells. An aquifer test in the Tertiary sediments beneath the floodplain (MBMG, 2008) also showed no effect on the overlying alluvial aquifer due to the locally confining conditions.

The numerical model developed for this study showed that after 20 years, two wells pumping from the Tertiary sediment aquifer on the West Bench at a combined rate of 750 gpm could cause maximum seasonal stream depletion in the Beaverhead River of about 160 gpm (20% of the total well discharge). These wells were located 2 and 4 miles from the river (fig. 63). Depletions from seasonal pumping would also persist for part of the non-pumping portions of the year.

The numerical model developed for the Beaverhead Case Study (MBMG, 2008) also evaluated stream depletion caused by pumping from a confined aquifer. This simulation evaluated a well completed in the Tertiary sediments underlying the floodplain, 1,800 ft from the river. The alluvium in the model was underlain by a discontinuous clay layer. The well was pumped at 850 gpm for 90 days each year for 4 years. Stream depletion in the Beaverhead River increased each year, reaching a maximum rate of about 144 gpm, or about 17% of the total well discharge rate.

In general, modeled pumping scenario results from the current study showed the magnitude of depletion decreased, and the timing of depletion was delayed with increasing distance between the river and the pumping well. Results have also demonstrated that the stream reach with the maximum depletion was not always the one closest to the pumping well, likely due to preferential flow paths in areas of relatively high hydraulic conductivity. Although the rate of increase in depletion diminished over time during the scenarios, it did not plateau within the 20-year simulation.

The volcanic rock is the most transmissive aquifer in the study area. This aquifer is not directly connected with the alluvial aquifer or the Beaverhead River. However, the numerical model showed that after 20 years, pumping from two wells in this aquifer at a combined rate of 3,000 gpm for 2 months/yr at distances between 3 to 4 miles from the river resulted in 19% of the total well discharge being supplied by stream depletion. The Beaverhead River contributed about 180 gpm (6% of the well discharge).

Observations and modeling show that pumping from the volcanic rock aquifer could cause a calculable response in Black Slough. Results of the site-specific numerical model indicated a maximum stream depletion of about 0.5 gpm in response to pumping at 1,422 gpm at a distance of 945 ft from the slough. In the modeled scenario, the maximum response occurred 9 days after the beginning of a 3-day pumping period.

The 20-year model results showed that pumping from the Tertiary sediment aquifer resulted in a shorter response time and a higher maximum depletion rate for the Beaverhead River than pumping from the volcanic rock aquifer. These results were probably due to the closer proximity of one of the pumping wells in the Tertiary sediment aquifer to the river (1.9 miles) compared to the closest pumping well in the volcanic rock aquifer (3.5 miles from the river). The greater depletion rate could also be attributed to the larger lateral extent of the groundwater cone of depression when pumping from the Tertiary sediments, which was due to the differences in transmissivity between the two aquifers.

Results of modeling canal seepage suggest that early and late-season canal flow can be an effective method to recharge groundwater and to reduce stream depletion. The effectiveness of additional canal seepage as a mitigation depends on the proximity of the pumping well(s) and the stream(s) to the given reach of the canal. Results can vary depending on specific site conditions such as streambed and canal bed conductance values, and variations of hydraulic conductivity and storativity values of the underlying aquifer(s). In the model (scenario 3), Willard Slough was farther from the pumping center and experienced only minor depletion from pumping. As there was very little impact to mitigate, canal seepage caused its flow to exceed the baseline scenario conditions. Modeled canal seepage also appeared to successfully mitigate stream depletion in the Beaverhead River. In reality, practical issues such as weather conditions can affect extending canal operations, and therefore the amount of water that infiltrates to groundwater and is available to offset stream depletion.

RECOMMENDATIONS

The seepage loss from the West Side and East Bench Canals provides significant recharge to groundwater and should be considered in managing water resources. Extending the period of canal flow into the non-irrigation season as a means of supplementing groundwater recharge could offset some stream depletion. Modeling results indicate that extending East Bench and West Side Canal flows 1 month per year could provide additional groundwater recharge on the order of 1,135 and 500 acre/ft, respectively. Whether canal flows were extended pre- or post-irrigation season would affect the timing of when recharge is realized in surface water. The temperature during March, April, and late October should also be considered, because frozen soil would impede recharge to the subsurface. Also, knowing the quantity and the timing of the recharge moving through the system would require monitoring.

The volcanic rock aquifer is an important, high-yield aquifer with good storage capacity, but its subsurface extent is unknown. Drilling to the north and south of the volcanic outcrop would better characterize its extent and potential for development. Since the aquifer has good storage capacity, it may have potential for aquifer storage and recovery options. Enhancing groundwater recharge through artificial means could help offset the effects of pumping on stream depletion.

The rate and timing of depletion depends on the pumping rate, distance of the pumping well from the stream, and the aquifer properties. As a management tool, a numerical model can be used to generate a map delineating zones where some percentage of the maximum stream depletion might be achieved within a given timeframe. Delayed stream responses to pumping should be considered when designing a mitigation plan. Knowing the timing of stream depletion can help with developing a mitigation plan that provides the most timely and beneficial effects to the stream.

The groundwater models developed for this project were useful tools in predicting how the hydrogeologic system might respond to long-term pumping. The large area models were not intended to accurately simulate responses in smaller, focused areas within the model domain. The models should be updated as additional data become available.

Developing a monitoring program that includes measuring water levels in dedicated monitoring wells would help establish long-term groundwater trends. The wells should be strategically located to represent the different aquifers and areas of current and potential future groundwater development. Establishing several permanent surface-water sites would also help address questions on stream depletion and provide data for future numerical modeling efforts.

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APPENDIX A

Groundwater and Surface-Water Monitoring Locations

Appendix A—Groundwater and Surface-Water Monitoring Network

Groundwater Monitoring Network

GWIC	Latitude	Longitude	Township	Range	Section	Tract	Ground Surface Elevation (ft)	Aquifer**	Static Water Level (ft)[1]	SWL Date	Total Depth (ft)	Well Use	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Screen Description
108533	45.376288	-112.460450	05S	07W	27	BBDB	4841.19	120SDMS	22.21	Aug-10	150	Domestic	30	50	Skill saw slots
108949	45.324323	-112.441742	06S	07W	10	DACC	5119.17	110ALVF	23.51	Aug-10	38	Stockwater	32	38	Torch cuts
108955	45.312784	-112.508613	06S	07W	18	ADDD	5055.81	120SNGR	5.17	Aug-10	150	Stockwater	150	150	Open bottom
108956	45.304830	-112.497510	06S	07W	20	BBBA	5124.19	111ALVM	34.23	Sep-10	75	Unknown	68	73	Torch cuts
108961	45.285574	-112.480578	06S	07W	29	ADCA	5274.77	111ALVM	143.23	Apr-10	220	Domestic	210	220	Slots
108962	45.273722	-112.447142	06S	07W	34	BADA	5354.68	120SDMS	20.54	Aug-10	80	Stockwater	75	80	Slots
108965	45.344720	-112.558610	06S	08W	2	BCBD	4905.24	111ALVM	4.94	Aug-10	116	Domestic	108	115	Perforated casing
108966	45.344623	-112.593651	06S	08W	4	BDAC	5052.74	120SDMS	39.87	Sep-10	200	Domestic	189	199	Slots
108978	45.320528	-112.600828	06S	08W	9	CCCC	4982.21	111ALVM	14.75	Aug-10	33	Domestic	27	32	Slots
108981	45.334148	-112.525997	06S	08W	12	ABAB	4918.18	111ALVM	7.25	Aug-10	37	Domestic	27	32	Slots
108993	45.306800	-112.603168	06S	08W	17	DDDC	4992.58	111ALVM	27.28	Aug-10	56	Domestic	46	54	Slots
109016	45.277972	-112.630937	06S	08W	30	DCCB	5035.00	120SDMS	33.64	Aug-10	59	Domestic	59	59	Open bottom
109026	45.267389	-112.618021	06S	08W	32	CBDB	5019.00	120SDMS	6.34	Aug-10	38	Domestic	30	35	Perforated casing
109060	45.285110	-112.642662	06S	09W	25	ADDA	5078.19	120SDMS	49.58	Aug-10	160	Domestic	NR	NR	NR
109339	45.234622	-112.623234	07S	08W	7	DDDB	5063.91	112ALVM	8.10	Aug-10	160	Unknown	80	160	1/4x4
123857	45.278023	-112.642554	06S	09W	25	DDAD	5075.00	120SDMS	48.95	Sep-10	120	Domestic	90	120	Perforated casing
130176	45.451125	-112.318333	04S	06W	35	BBBB	4900.68	120SDMS	-13.44	Aug-10	275	Monitoring	NR	NR	NR
130177	45.419825	-112.339634	05S	06W	10	BCCA	5046.53	120SDMS	151.43	Aug-10	200	Monitoring	NR	NR	NR
131577	45.393689	-112.422856	05S	07W	14	DDDD	4855.73	120SDMS	26.21	Aug-10	63	Monitoring	NR	NR	NR
133382	45.208022	-112.658954	07S	09W	24	CBCA	5115.30	120SDMS	12.92	Sep-10	220	Monitoring	190	197	Air perfs
133384	45.214724	-112.631587	07S	08W	19	BADD	5085.85	120SDMS	15.20	Aug-10	325.6	Monitoring	315.5	325.5	Screen-continuous-pvc
133386	45.214724	-112.631587	07S	08W	19	BADD	5086.40	110ALVM	13.93	Aug-10	80	Monitoring	74	77.5	Air perforator
133387	45.191022	-112.672455	07S	09W	26	CDAD	5141.30	120SDMS	4.70	Sep-10	160	Monitoring	96	149	Perforated casing*
133390	45.191222	-112.673455	07S	09W	26	CDAD	5141.70	110ALVM	5.23	Sep-10	17.9	Monitoring	17.9	17.9	Open bottom
133403	45.217888	-112.655743	07S	09W	24	BABA	5104.08	110ALVM	6.91	Aug-10	32	Monitoring	22	24	Air perfs
147064	45.282413	-112.626610	06S	08W	30	DABC	5028.00	110ALVM	34.35	Aug-10	49.6	Domestic	43.6	49.6	Torch cuts
152570	45.319543	-112.639467	06S	09W	13	BBBA	5084.87	330MDSN	252.33	Aug-10	400	Domestic	300	400	NR
156784	45.238170	-112.660480	07S	09W	12	CBBD	5349.31	120VLCC	252.73	Aug-10	415	Domestic	375	415	Saw slots
159317	45.386590	-112.467382	05S	07W	21	ADDB	4864.34	320UDFD	44.64	Aug-10	260	Domestic	240	260	Saw slots
159318	45.387528	-112.464109	05S	07W	21	BCCC	4874.58	120SNGR	54.57	Aug-10	110	Domestic	10	110	Saw slots
159319	45.385934	-112.469666	05S	07W	21	DBAA	4873.21	120SDMS	53.51	Aug-10	200	Domestic	160	200	Saw slots
162827	45.230700	-112.627830	07S	08W	18	ABDB	5070.84	120SDMS	11.28	Aug-10	80	Domestic	60	80	NR
183483	45.251520	-112.577150	07S	08W	4	CBDC	5051.03	120SDMS	28.05	Aug-10	60	Domestic	41	60	Torch cuts*
184460	45.252980	-112.662110	07S	09W	1	CBCB	5306.22	120VLCC	214.01	Aug-10	526	Domestic	300	526	Torch cuts
184490	45.320752	-112.647576	06S	09W	12	DCDC	5118.88	120SDMS	58.08	Aug-10	84	Domestic	64	84	Torch cuts
191614	45.290400	-112.464950	06S	07W	28	ABAB	5239.04	120SNGR	58.07	Aug-10	103	Stockwater	95	101	Torch or plasma cuts
191617	45.328520	-112.584450	06S	08W	9	ADCA	4939.30	120SNGR	12.30	Aug-10	63	Stockwater	38	60	Saw slots
191882	45.301140	-112.581750	06S	08W	21	ADAD	4958.81	120SDMS	5.10	Aug-10	51.5	Stockwater	43.5	49.5	Saw slots
192298	45.351225	-112.625345	05S	08W	32	CCAC	5087.07	120VLCC	37.68	Aug-10	160	Stockwater	110	145	Ss telescope screen
194034	45.380970	-112.456310	05S	07W	22	CDDB	4824.66	330MDSN	4.93	Aug-10	85	Domestic	65	85	Factory slotted
204038	45.340830	-112.495120	06S	07W	5	CBAC	5032.47	120SNGR	105.99	Aug-10	400	Irrigation	196	376	Screen 70 slot*
204226	45.355141	-112.623677	05S	08W	32	CABC	5066.93	120VLCC	15.59	Aug-10	300	Irrigation	87	300	Perforated casing
207330	45.313480	-112.600340	06S	08W	16	BCCC	4985.49	120SDMS	20.87	Aug-10	45	Irrigation	43	45	Open bottom
207332	45.335528	-112.647074	06S	09W	1	DDCB	5116.96	320UDFD	247.45	Aug-10	340	Domestic	300	320	Torch or plasma cuts
209457	45.275280	-112.546880	06S	08W	35	ABAC	5062.42	120SICL	44.41	Aug-10	90	Domestic	70	90	Factory slots
212033	45.339690	-112.512840	06S	07W	6	DBDD	4975.90	120SDMS	53.68	Aug-10	90	Monitoring	88	89	Factory slotted
212035	45.367110	-112.498090	05S	07W	29	CDBD	4853.31	111ALVM	5.98	Aug-10	27	Monitoring	7	27	Torch or plasma cuts
212037	45.349722	-112.518888	06S	08W	1	AAAA	4882.52	111ALVM	11.91	Aug-10	26	Monitoring	9	26	Torch or plasma cuts

GWIC	Latitude	Longitude	Township	Range	Section	Tract	Ground Surface Elevation (ft)	Aquifer**	Static Water Level (ft)^1	SWL Date	Total Depth (ft)	Well Use	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Screen Description
212042	45.373570	-112.481940	05S	07W	28	BCAC	4837.21	111ALVM	7.02	Aug-10	25	Monitoring	7	25	Torch or plasma cuts
212044	45.353900	-112.514400	05S	07W	31	DBCC	4875.59	111ALVM	9.11	Aug-10	27	Monitoring	7	27	Torch or plasma cuts
213392	45.360880	-112.495470	05S	07W	32	BDAA	4857.83	120SNGR	4.91	Aug-10	160	Irrigation	53	128	Perforated casing*
213393	45.341180	-112.509210	06S	07W	6	CAAA	4981.79	120SNGR	81.70	Aug-10	460	Irrigation	120	420	Perforated casing
215988	45.290245	-112.652688	06S	09W	24	BAAA	5120.73	120SDMS	100	Oct-04	400	Domestic	377	381	Perforated casing
216805	45.331135	-112.421775	06S	07W	11	ACAA	5195est	120SDMS	NR	NR	520	Irrigation	NR	NR	NR
220021	45.322274	-112.600184	06S	08W	9	CCBC	4967.91	120SNGR	3.38	Jun-10	331	Irrigation	183	329	Screen-continuous-stainless*
220025	45.317950	-112.442530	06S	07W	15	ABDD	5132.06	120SDMS	15.15	Aug-10	500	Irrigation	40	465	Perforated casing*
220080	45.352535	-112.620017	05S	08W	32	CDBB	5060.47	120VLCC	11.51	Aug-10	200	Irrigation	105	200	Open hole*
220904	45.347760	-112.570120	06S	08W	3	ABCB	5005.20	120SICL	71.19	Aug-10	240	Domestic	180	220	Holte perforator slots
221582	45.349951	-112.616079	05S	08W	32	DCDC	5057.29	120SDMS	18.54	Jun-10	240	Test Well	220	240	Open hole
224244	45.355577	-112.623636	05S	08W	32	CABC	5068.61	120VLCC	19.44	Aug-10	140	Domestic	138	140	Open bottom
225505	45.297646	-112.636466	06S	08W	19	CABB	5083.68	120SNGR	40	Apr-06	130	Domestic	122	128	Torch or plasma cuts
227305	45.317950	-112.442320	06S	07W	15	ABDD	5131.83	120SNGR	15.06	Aug-10	500	Monitoring	160	500	Perforated casing
232115	45.258806	-112.648368	07S	09W	1	ABDC	5091.60	112ALVM	70.90	Aug-10	98	Stockwater	90	96	Torch or plasma cuts
234969	45.313420	-112.634108	06S	08W	18	BDDC	5073.68	120SDMS	73.31	Aug-10	340	Stockwater	320	340	Saw slots
235306	45.299543	-112.634526	06S	08W	19	BDDB	5079.72	120SNGR	50	Apr-07	136	Stockwater	116	136	Saw slots
237993	45.320860	-112.649654	06S	09W	12	DCCD	5130.14	120SDMS	299.35	Aug-10	340	Domestic	322	340	Torch or plasma cuts
238652	45.367110	-112.498090	05S	07W	29	CDBD	4853.31	111ALVM	8.89	Aug-10	11	Monitoring	7	27	Torch or plasma cuts
238653	45.367110	-112.498090	05S	07W	29	CDBD	4853.31	111ALVM	7.76	Aug-10	16	Monitoring	7	27	Torch or plasma cuts
238662	45.373570	-112.481940	05S	07W	28	BCAC	4837.26	111ALVM	7.02	Aug-10	10	Monitoring	7	25	Torch or plasma cuts
238663	45.373570	-112.481940	05S	07W	28	BCAC	4837.34	111ALVM	7.04	Aug-10	15	Monitoring	7	25	Torch or plasma cuts
238696	45.353900	-112.514400	05S	07W	31	DBCC	4875.61	111ALVM	8.34	Aug-10	10	Monitoring	7	27	Torch or plasma cuts
238698	45.353900	-112.514400	05S	07W	31	DBCC	4875.62	111ALVM	8.29	Aug-10	15	Monitoring	7	27	Torch or plasma cuts
238708	45.349722	-112.518888	06S	08W	1	AAAA	4882.53	111ALVM	7.39	Aug-10	15	Monitoring	9	26	Torch or plasma cuts
238709	45.349722	-112.518888	06S	08W	1	AAAA	4882.54	111ALVM	7.33	Aug-10	15	Monitoring	9	26	Torch or plasma cuts
242403	45.376537	-112.499812	05S	07W	29	BCAB	4846.99	120SDMS	10.96	Aug-10	95	Monitoring	74	94	Saw slots
242404	45.376579	-112.499934	05S	07W	29	BCAB	4845.65	111ALVM	5.84	Aug-10	30	Monitoring	18.5	28.5	Screen-continuous-stainless
242406	45.376040	-112.499674	05S	07W	29	BCAB	4847.14	120SNGR	8.80	Aug-10	91	Test Well	63	83	Screen-continuous-stainless
242407	45.376460	-112.499837	05S	07W	29	BCAB	4847.29	111ALVM	6.11	Aug-10	24	Monitoring	13.5	23.5	Factory slotted
242408	45.315636	-112.448649	06S	07W	15	BDAA	5181.92	120SNGR	67.62	Aug-10	515	Other	503	511	Perforated casing
242409	45.315721	-112.448685	06S	07W	15	BDAA	5181.75	120SNGR	67.14	Aug-10	290	Other	261.3	289.3	Screen-continuous-stainless
242410	45.315630	-112.448784	06S	07W	15	BDAB	5183.84	120SDMS	74.02	Aug-10	290	Other	275	285	Perforated casing
242411	45.315768	-112.448824	06S	07W	15	BDAB	5183.81	120SNGR	74.93	Aug-10	160	Other	143	153	Perforated casing
242412	45.315860	-112.449214	06S	07W	15	BDAB	5191.54	120SDMS	82.68	Aug-10	290	Other	278	288	Perforated casing
242413	45.336635	-112.496575	06S	07W	5	CCDA	5027.87	120SDMS	108.89	Aug-10	400	Other	345.6	365.8	Perforated casing
242414	45.337246	-112.495992	06S	07W	5	CCAC	5029.87	120SDMS	102.15	Aug-10	190	Other	175	185	Perforated casing
242415	45.376578	-112.499955	05S	07W	29	BCAB	4847.16	111ALVM	6.59	Aug-10	24	Monitoring	13.5	23.5	Factory slotted
242417	45.376640	-112.499786	05S	07W	29	BCAB	4848.30	110ALVM	7.52	Aug-10	24	Monitoring	13.5	23.5	Factory slotted
249640	45.372550	-112.511910	05S	07W	30	ACDB	4857.96	110ALVM	4.12	Aug-10	16	Monitoring	NR	NR	NR
249656	45.366748	-112.505606	05S	07W	30	DDAD	4857.19	111ALVM	4.10	Aug-09	13.5	Monitoring	NR	NR	NR
249705	45.382436	-112.468074	05S	07W	21	DDBA	4825.58	111ALVM	4.51	Aug-10	14	Monitoring	NR	NR	NR
249727	45.379526	-112.474796	05S	07W	21	CDDD	4831.77	111ALVM	5.28	Aug-10	14	Monitoring	NR	NR	NR
249733	45.377302	-112.484214	05S	07W	28	BBBC	4837.83	111ALVM	3.60	Aug-10	13.8	Monitoring	NR	NR	NR
249735	45.376682	-112.489478	05S	07W	29	AACB	4840.91	111ALVM	6.84	Aug-10	13.7	Monitoring	NR	NR	NR
249736	45.376512	-112.500465	05S	07W	29	BBDA	4848.24	111ALVM	7.16	Aug-10	13.9	Monitoring	NR	NR	NR
249740	45.357908	-112.525695	05S	07W	31	BCCC	4877.16	111ALVM	5.81	Aug-10	13.5	Monitoring	NR	NR	NR
249741	45.353316	-112.529270	05S	08W	36	DDBA	4884.08	111ALVM	5.99	Aug-10	18.7	Monitoring	NR	NR	NR
249742	45.345975	-112.536840	06S	08W	1	BBDC	4896.93	111ALVM	8.17	Aug-10	18.5	Monitoring	NR	NR	NR
249746	45.378941	-112.511176	05S	07W	30	ABAA	4853.22	111ALVM	3.90	Aug-10	13	Monitoring	NR	NR	NR
249747	45.377147	-112.519482	05S	07W	30	BABD	4862.30	111ALVM	7.63	Aug-10	18.5	Monitoring	NR	NR	NR
249748	45.373704	-112.525691	05S	07W	30	BCBC	4865.72	111ALVM	5.50	Aug-10	18.5	Monitoring	NR	NR	NR

GWIC	Latitude	Longitude	Township	Range	Section	Tract	Ground Surface Elevation (ft)	Aquifer**	Static Water Level (ft)[1]	SWL Date	Total Depth (ft)	Well Use	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Screen Description
249751	45.376102	-112.499802	05S	07W	29	BACC	4847.54	111ALVM	6.02	Aug-10	NR	Monitoring	NR	NR	NR
250122	45.277258	-112.574351	06S	08W	27	CDCC	4951.61	111SNGR	3.81	Aug-10	18	Stockwater	18	18	Open bottom
250167	45.372235	-112.501128	05S	07W	29	BCDD	4850.62	111ALVM	5.98	Aug-10	NR	Monitoring	NR	NR	NR
250171	45.357993	-112.521936	05S	07W	31	BCDA	4875.06	111ALVM	7.77	Aug-10	NR	Monitoring	NR	NR	NR
251003	45.283024	-112.626422	06S	08W	30	DABB	5033.00	120SDMS	37.39	Aug-10	80	Domestic	76	80	Open hole
251267	45.296151	-112.592456	06S	08W	21	CADB	5035.15	120SDMS	14.58	Aug-10	250	Domestic	250	250	Open bottom
252455	45.387689	-112.712317	05S	09W	22	DBCA	5458.24	120SICL	10.81	Aug-10	540	Domestic	70	520	Perforated casing*
254767	45.351226	-112.618812	05S	08W	32	CDAC	5061.59	120VLCC	13.68	Aug-10	280	Monitoring	143	150	Holte perforator slots
254815	45.352598	-112.619011	05S	08W	32	CDAC	5063.68	120VLCC	12.54	Aug-10	164	Monitoring	143	153	Screen-continuous-pvc
254839	45.352539	-112.619044	05S	08W	32	CDAC	5060.74	120SNGR	9.61	Aug-10	77	Monitoring	72	77	Screen-continuous-pvc
254840	45.351924	-112.620745	05S	08W	32	DCBB	5063.08	120VLCC	13.19	Aug-10	164	Monitoring	138	158	Screen-continuous-pvc
254962	45.322075	-112.601503	06S	08W	9	DDAA	4971.26	120SDMS	4.76	Aug-10	301	Monitoring	289	299	Screen-continuous-stainless
254963	45.322044	-112.598954	06S	08W	9	CCBD	4968.75	120SDMS	2.67	Aug-10	310	Monitoring	298	308	Screen-continuous-stainless
255038	45.306122	-112.633321	06S	08W	18	CDDD	5072.94	120SNGR	19.55	Aug-10	75	Domestic	75	75	Open bottom
255163	45.384407	-112.466642	05S	07W	21	DACA	4827.82	111SNGR	4.73	Aug-10	12	Domestic	NR	NR	NR
255487	45.315329	-112.449956	06S	07W	15	BDCD	5213.22	120SNGR	93.87	Aug-10	118	Monitoring	98	118	Factory slotted
255488	45.326743	-112.421457	06S	07W	11	DABB	5199.35	111SNGR	43.33	Aug-10	78	Monitoring	63	78	Factory slotted
255489	45.326731	-112.421465	06S	07W	11	DABB	5199.88	120SDMS	13.35	Aug-10	39	Monitoring	29	39	Factory slotted
255490	45.326552	-112.420943	06S	07W	11	DABB	5203.64	120SDMS	53.25	Aug-10	84	Monitoring	74	84	Factory slotted
255491	45.293532	-112.479360	06S	07W	20	DDAC	5207.44	120SNGR	82.13	Aug-10	119	Monitoring	99	119	Factory slotted
255492	45.305639	-112.563208	06S	08W	15	DDCD	4951.66	120SNGR	4.09	Aug-10	108	Monitoring	90.5	108	Screen-continuous-stainless
255493	45.305639	-112.563208	06S	08W	15	DDCD	4952.06	111SNGR	4.35	Aug-10	23.5	Monitoring	14	23.5	Screen-continuous-stainless
257783	45.306884	-112.634731	06S	08W	18	CDCA	5077.26	120SDMS	11.10	Aug-10	17	Monitoring	11.5	16.5	Screen-continuous-pvc
257787	45.306879	-112.634729	06S	08W	18	CDCA	5077.44	120SDMS	12.14	Aug-10	26	Monitoring	20.5	25.5	Screen-continuous-pvc
257789	45.306875	-112.634726	06S	08W	18	CDCA	5077.37	120SDMS	15.73	Aug-10	40	Monitoring	35	40	Screen-continuous-pvc
257794	45.306838	-112.634519	06S	08W	18	CDCA	5074.68	120SDMS	9.34	Aug-10	16.2	Monitoring	10.7	15.7	Screen-continuous-pvc
257795	45.306827	-112.634514	06S	08W	18	CDCA	5074.79	120SDMS	9.59	Aug-10	24	Monitoring	18.5	23.5	Screen-continuous-pvc
257796	45.306834	-112.634515	06S	08W	18	CDCA	5074.73	120SNGR	9.59	Aug-10	31	Monitoring	25.5	30.5	Screen-continuous-pvc
257797	45.306919	-112.634254	06S	08W	18	CDCA	5075.43	120SDMS	12.25	Aug-10	23	Monitoring	15.5	22.5	Screen-continuous-pvc
257991	45.326652	-112.421499	06S	07W	11	DABB	5200.57	110ALVM	5.81	Aug-10	17.5	Monitoring	12.5	17.5	Screen-continuous-pvc
257998	45.293511	-112.479365	06S	07W	20	DDAC	5208.16	120SDMS	60.67	Aug-10	71	Monitoring	61	71	Screen-continuous-pvc
258009	45.293511	-112.479353	06S	07W	20	DDAC	5208.11	120SDMS	40.67	Aug-10	44	Monitoring	37.5	42.5	Screen-continuous-pvc
258012	45.293511	-112.479358	06S	07W	20	DDAC	5208.06	120SDMS	dry	Aug-10	16	Monitoring	10.5	15.5	Screen-continuous-pvc
258390	45.315901	-112.593567	06S	08W	16	BDAB	4970.09	120SDMS	20.08	Jun-10	56	Domestic	40	56	Torch or plasma cuts
259531	45.250061	-112.572654	07S	08W	3	CDAB	5069.12	120SDMS	30.74	Aug-10	78	Domestic	NR	NR	NR
259534	45.293890	-112.684781	06S	09W	22	DDAB	5213.38	120SDMS	122.38	Aug-10	178.8	Stockwater	NR	NR	NR
259535	45.305821	-112.528358	06S	08W	13	DCCC	5049.55	120SNGR	39.73	Aug-10	343	Monitoring	NR	NR	NR
259536	45.313604	-112.634304	06S	08W	18	BDDC	5074.33	120SDMS	12.20	Aug-10	34.56	Unused	NR	NR	NR
259537	45.229359	-112.631046	07S	08W	18	ABCC	5073.48	110ALVM	12.25	Aug-10	26.6	Domestic	NR	NR	NR
259538	45.283590	-112.622370	06S	08W	30	DAAA	4999.21	110ALVM	3.14	Aug-10	8.2	Monitoring	NR	NR	NR
108955	45.313219	-112.499408	06S	07W	18	DDDA	5055.81	120SNGR	5.17	Aug-10	150	Stock	NR	NR	NR
259540	45.290230	-112.484366	06S	07W	29	ABAA	5233.00	120SDMS	99.30	Aug-10	473	Monitoring	NR	NR	NR
259541	45.312527	-112.531135	06S	08W	13	CAAB	5017.62	120SNGR	66.26	Aug-10	120	Domestic	NR	NR	NR
259542	45.307900	-112.529627	06S	08W	13	CDAD	5023.44	120SDMS	22.21	Aug-10	130	Stockwater	NR	NR	NR
259558	45.351598	-112.619558	05S	08W	32	CDDA	5048.23	110ALVM	1.45	Aug-10	16	Monitoring	6	16	Screen-continuous-pvc

GWIC	Latitude	Longitude	Township	Range	Section	Tract	Ground Surface Elevation (ft)	Aquifer**	Static Water Level (ft)^1	SWL Date	Total Depth (ft)	Well Use	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Screen Description
259700	45.301490	-112.478768	06S	07W	20	ADAA	5162.67	120SDMS	26.86	Aug-10	94	Stockwater	NR	NR	NR
259703	45.299945	-112.492311	06S	07W	20	BDBD	5169.14	120SDMS	94.56	Aug-10	449	Irrigation	NR	NR	NR
260203	45.256449	-112.661504	07S	09W	1	BCBC	5203est	120VLCC	NR	NR	NR	Domestic	NR	NR	NR
263935	45.284171	-112.643949	06S	09W	25	ADDC	5081.24	120SDMS	dry	Aug-10	21	Monitoring	16	21	Screen-continuous-pvc
263937	45.284173	-112.643944	06S	09W	25	ADDC	5081.31	120SDMS	43.46	Aug-10	46.5	Monitoring	41.5	46.5	Screen-continuous-pvc
263941	45.283942	-112.643704	06S	09W	25	ADDC	5080.53	120SDMS	dry	Aug-10	18	Monitoring	12.5	17.5	Screen-continuous-pvc
263943	45.283943	-112.643698	06S	09W	25	ADDC	5080.05	120SDMS	42.69	Aug-10	41.5	Monitoring	36.5	41.5	Screen-continuous-pvc

Surface-Water Monitoring Network

GWIC	Latitude	Longitude	Township	Range	Section	Quarter Section	Site Name
147977	45.217500	-112.654100	07S	09W	24	BABA	Beaverhead River at Dillon
242227	45.382760	-112.463910	05S	07W	22	CBCC	Ditch Outflow
242228	45.376440	-112.499840	05S	07W	29	BACBC	Beaverhead River near Beaverhead Rock
242525	45.383202	-112.453201	05S	07W	22	DBCC	Beaverhead River at Beaverhead Rock
247284	45.306290	-112.562660	06S	08W	15	DDDC	Beaverhead River at Anderson Lane
249749	45.343700	-112.571340	06S	08W	3	BDDA	Albers Slough up stream
254904	45.378727	-112.468382	05S	07W	28	AABB	Charleton Slough
254905	45.322850	-112.527910	06S	08W	12	DCBB	Stone Creek by Highway
254906	45.342270	-112.535420	06S	08W	1	BCCD	Stone Creek confluence with Beaverhead River
254907	45.228494	-112.632645	07S	08W	18	BDAB	Blacktail Creek
254923	45.380742	-112.498256	05S	07W	20	CDCA	Albers Slough Down Stream
255093	45.349740	-112.619750	05S	08W	32	CDDD	Black Slough up stream
255094	45.322706	-112.599126	06S	08W	9	CCBC	Willard Slough
257501	45.325050	-112.614090	06S	08W	8	CADB	Willard Slough up stream
257502	45.325560	-112.589140	06S	08W	9	DBBD	Black Slough down stream
257503	45.300450	-112.568720	06S	08W	22	ACBD	Stodden Slough
261886	45.305677	-112.598276	06S	08W	21	BBAB	Frying Pan Gulch
261889	45.335779	-112.607234	06S	08W	5	DCDD	Black Slough
261890	45.321028	-112.592098	06S	08W	9	CDDD	Willard Slough down stream
262330	45.323260	-112.601674	06S	08W	8	DDAD	Willard Slough - near Pumping well (Tertiary sediment aquifer test)

[1] Static Water Level recorded from measuring point (MP).

*Perforated at more than one screened interval

est, elevation estimated from 10m National Elevation Dataset.

NR, Not Reported;

est, elevation estimated from 10m National Elevation Dataset.

****Aquifer Codes**

110ALVF	Alluvial Fan Deposits (Quaternary)	120SNGR	Sand and Gravel (Tertiary)
110ALVM	Alluvium (Quaternary)	120VLCC	Volcanics (Tertiary)
111SNGR	Sand and Gravel (Holocene)	320UDFD	Undifferentiated rock (Pennsylvannian)
120SDMS	Sediments (Tertiary)	330MDSN	Madison Group or Limestone
120SICL	Silt and Clay (Tertiary)		

APPENDIX B

Aquifer Tests

TERTIARY SEDIMENT AQUIFER TEST

Background

A 3-day aquifer test was conducted on an irrigation well (well 220021) in May 2010 to obtain hydraulic properties of the Tertiary sediment aquifer and to examine the potential effects of pumping on nearby shallow groundwater and surface-water locations. The irrigation well is completed in Tertiary sediments at a depth of 331 ft below ground surface. Multiple clay seams were encountered in the pumped well and in two wells drilled as monitoring wells for the aquifer test (wells 254962 and 254963). The presence of clay and high hydrostatic pressure (depth to water ranges from 3 to 10 ft) indicates that the aquifer was confined.

A previous aquifer test performed in 2005 to assess the well production determined that the sustainable yield for this well is 300 gpm (Weight, written commun., 2005). The aquifer test for this GWIP study was performed to verify transmissivity estimates for the Tertiary sediments, with the added benefit of using data from two monitoring wells completed at depths similar to the pumping well. Based on the results of the 2005 aquifer test, the well was pumped at a constant pumping rate of 300 gpm.

Willard Slough is located about 100 ft from the pumped well, providing an opportunity to monitor surface water in conjunction with groundwater during the aquifer test. Surface-water flow in Willard Slough during May 2010 ranged between 0.65 and 2.17 cubic ft per second (cfs) and averaged 1.37 cfs.

Field Procedure

Groundwater was monitored in four monitoring wells and the pumping well. Two wells (254962 and 254963), drilled as monitoring wells, were completed within the same depth interval as the pumped well (301 and 310 ft deep, respectively). Two shallow domestic wells were also monitored to investigate if pumping from the deeper aquifer affected the shallow groundwater. These wells are 33 and 56 ft deep (wells 108978 and 258390, respectively). Willard Slough was monitored at two locations, about 135 ft downgradient and about 530 ft upgradient from the pumping well (sites 255094 and 262330, respectively). Figure 7 (in the main report) shows the locations of the monitoring sites, and table B-1 includes specific information on the monitoring wells/surface-water locations.

Pressure transducers with data loggers (pressure transducers) were deployed in late April 2010 in the monitoring wells and in late March at the two surface-water sites in order to monitor background groundwater levels and surface-water stage. A barometer was also deployed in order to correct for barometric pressure changes, which affect water levels. Prior to the start of the test, the pumping well, well 254962, and well 254963 data loggers were set to a 1-minute recording interval; the surface-water sites were set at a 2-minute in-

Table B-1. Specifications of monitoring sites and maximum groundwater drawdown during the Tertiary sediment aquifer test (pumping well 220021).

GWIC ID	Maximum Drawdown (ft)	Total Depth (ft)	Screened Interval (ft bgs)	Distance to Pumping Well 220021(ft)	Aquifer	Well Type/Surface Water Location
220021	233	331	183–203, 227–247, 269–329	0	Tertiary Sed	Irrigation/pumped well
254962	42	301	289–299	346	Tertiary Sed	Monitoring
254963	34.6	310	298–308	330	Tertiary Sed	Monitoring
108978	0	33	27–32	658	Tertiary Sed	Monitoring/domestic
258390	0	56	40–56	2,900	Tertiary Sed	Monitoring/domestic
255094	0	N/A	N/A	135	N/A	Willard Slough
262330	0	N/A	N/A	530	N/A	Willard Slough

terval; and wells 108978 and 258390 were set at a 10-minute interval.

An electric flow meter provided digital flow and totalizer readings. A flow meter based on water pressure, already mounted on the well's permanent discharge line, was occasionally used to verify the digital meter readings. Discharge was directed about 300 ft downstream from the pumping well and downgradient from the Willard Slough monitoring sites. A tipping-bucket rain gauge was installed on site to record precipitation before, during, and after the aquifer test.

The aquifer test started on May 18, 2010 at 12:13 and concluded on May 21, 2010 at 13:24, for a duration of 73 hours and 11 minutes. The pumping rate varied between 290 and 315 gpm, with an average rate of 296 gpm. The rate did spike up to 380 gpm at the start of the test and was adjusted as close to 300 gpm as possible.

During the aquifer test, water levels were manually measured periodically in order to calibrate the pressure transducer measurements and for backup in the event of a pressure transducer malfunction. Immediately after the aquifer test ceased, recovery water levels were manually measured for several hours and pressure transducers were kept in the monitoring locations until June 2-3 (11 and 12 days after termination of the test, respectively). All water-level data are available in GWIC (http://mbmggwic.mtech.edu/).

A groundwater sample was collected from the pumped well about 3 hours after the start of the aquifer test. The sample was analyzed for major cations/anions, trace metals, tritium, $\delta^{18}O$, and δD. Periodically, throughout the test, pH, specific conductivity (SC), and temperature of the discharge water was measured. Prior to turning off the pump, a water sample was collected and analyzed for ^{18}O and D.

Results

Drawdowns due to pumping were observed in monitoring wells 254962 and 254963 (fig. B-1). Maximum drawdown levels and their distances from the pumping well are presented in table B-1. The pumping well had about 230 ft of drawdown and the two monitoring wells had about 35 to 42 ft of drawdown. There were no observed drawdowns in the shallow wells 108978 and 258390 and no measurable impacts to surface water at both the Willard Slough locations.

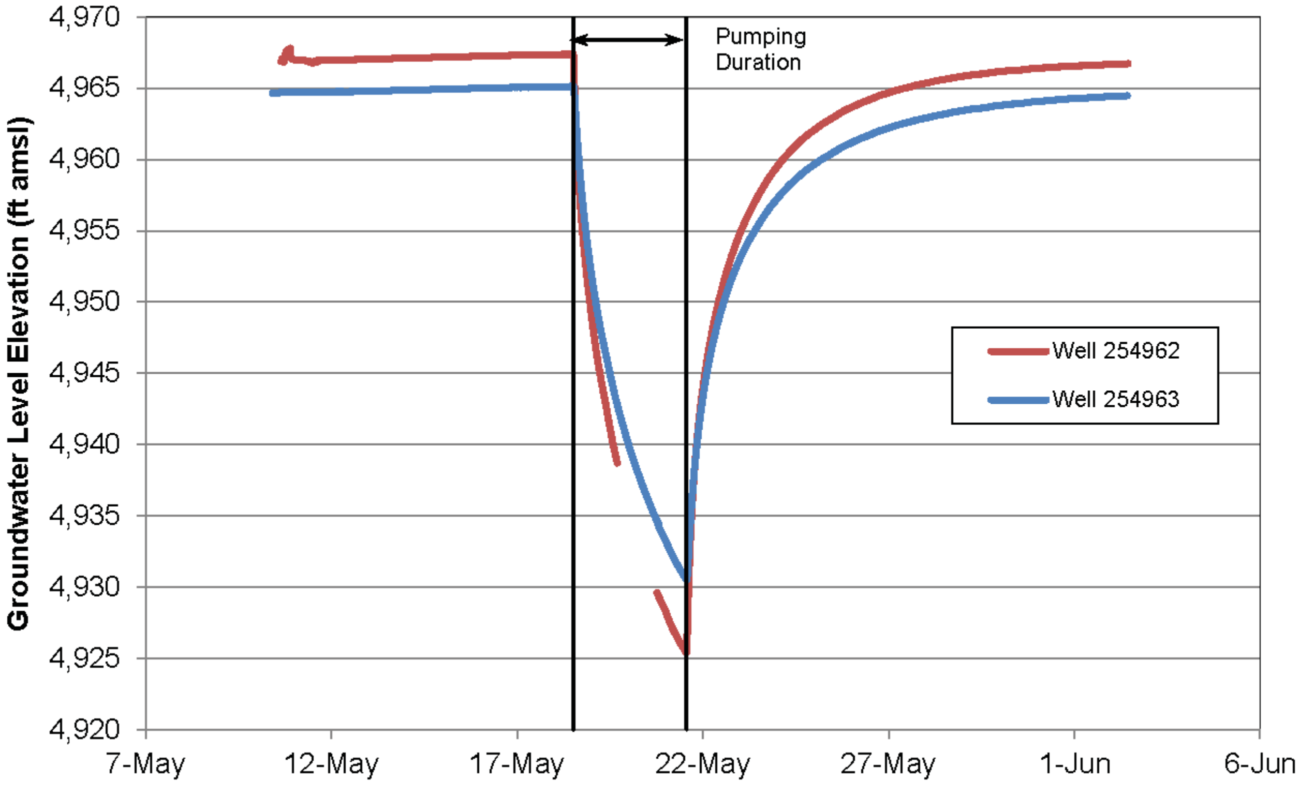

Figure B-1. Hydrographs of wells 254962 and 254963 show drawdowns due to pumping well 220021.

Water levels remained fairly consistent prior to the start of the aquifer test. Recovery data indicate that water levels recovered to over 95% of the total drawdown. This percentage is often used as a guideline to indicate adequate water-level recovery, and further monitoring is not needed. This was observed in both wells 254962 and 254963 (fig. B-1).

There was only a trace amount of precipitation (<0.01 in) for the week prior to the start of the test. During the test, 0.39 in was recorded, and 0.35 of those inches started to fall 7 hours after the start of the test and consistent rain fell for the next 10 hours. After that precipitation event, only 0.04 inches fell during the remainder of the test. Since the drawdowns were relatively large in the monitoring (35–42 ft) and irrigation (233 ft) wells, this rain event is not significant within the drawdown curves. Fluctuations observed in the irrigation-well-drawdownn plot were likely due to pumping-rate fluctuations. During the week after the aquifer test ceased, a total of about 0.87 in fell on the site. A majority of this precipitation was composed of three events: (1) 0.41 in during most of May 22, (2) 0.13 in during the morning of May 24, and (3) 0.29 in during the morning of May 28. As with the precipitation events that occurred during the aquifer test, these events that occurred during the recovery period do not seem to have affected the recovery water levels within the monitoring and irrigation wells.

Aquifer Properties

The drawdown data were then analyzed using the aquifer test analysis software, AQTESOLV™. The methods used to analyze the data were:

Cooper-Jacob (1946) Composite Plot, where all the drawdown data were normalized by plotting the data from each well versus the time divided by the distance the monitoring well is from the pumping well (t/r^2), and

Cooper-Jacob (1946) Straight-Line analysis using the recovery data and an alternative time axis. The alternative time axis was the total elapsed time since the start of the test divided by the elapsed time since the end of pumping.

The Cooper-Jacob Composite Plot analysis is a good method for estimating a single, bulk average transmissivity by using all the data available and matching a best-fit line to those data. The slope of the best-fit line is used to estimate transmissivity (T) and the x-intercept is used to calculate the storativity (S) of the aquifer. Both monitoring well's drawdown data had similar slopes, indicating that both wells are installed in similar hydrogeologic regimes. The pumping well's data were not used in the composite plot because of head losses from within the well due to pumping. The results give a transmissivity of 412 ft^2/day and a storativity value of 0.0010 (table 2, main report).

Each individual well's recovery data were also analyzed using the Cooper-Jacob Straight-Line Method using an alternative time axis. Transmissivities range from 405 to 522 ft^2/day (table 2, main report). The slope of the recovery data is the most important factor for calculating transmissivity using this method. The slope is determined by the average pumping rate and the aquifer transmissivity. Storativity cannot be obtained using this method because in the mathematical derivation storativity is factored out of the equation.

Water Quality

Specific conductivity ranged between 425 and 494 µS/cm and increased during the first 24 hours after pumping started. After this period, SC remained fairly stable at around 490 µS/cm. Temperature of the discharge water varied by about 2° (9.3 to 11.2°) and pH remained fairly stable between 7.6 and 7.9 throughout the test.

The drinking water quality standards were not exceeded in the groundwater or Willard Slough samples. In general, concentrations of inorganic constituents were higher in Willard Slough when compared to groundwater from the pumped well. Both samples are a calcium-bicarbonate water type. However, the total dissolved solids were greater in Willard Slough (591 mg/L) when compared to groundwater in well 220021 (285 mg/L).

In continental regions, a tritium value of 0.66 TU in the groundwater sample indicates that the groundwater was recharged prior to 1952 (Clark and Fritz, 1997). Figure B-2 plots δD and δO^{18} of groundwater from the pumped well during the start and near the end of the test and water samples collected of Willard Slough at multiple times

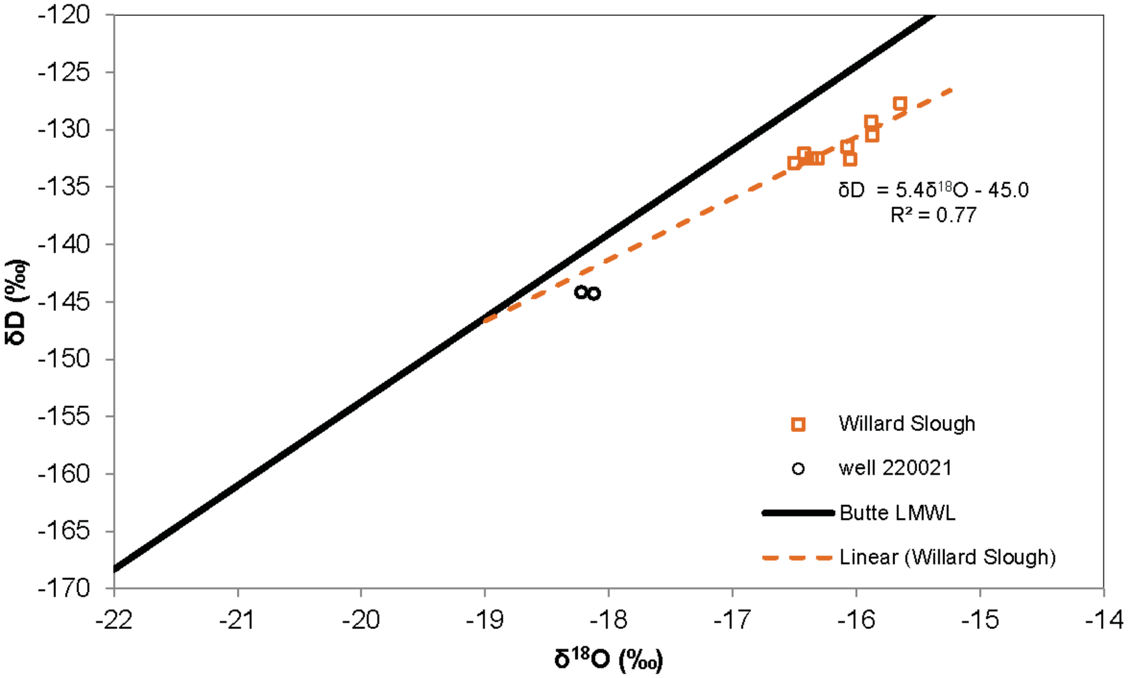

Figure B-2. δD and δ^{18}O (‰) plotted with the Butte, Montana meteoric water line (Gammons and others, 2006) for well 220021 and Willard Slough samples.

of the year. The Willard Slough samples plot on the upper right and deviate from the LMWL in a manner that suggests that the water has been subjected to evaporation. The source of this water is primarily shallow groundwater derived from precipitation and irrigation return flow. The two groundwater samples are isotopically lighter than Willard Slough samples and plot closer to the LMWL. This isotopic signature suggests a different source of recharge from surface water, mainly snowmelt and/or precipitation at higher elevations.

Summary

Analysis of the aquifer test data gives a range of transmissivities from 405–522 ft^2/day and a storativity of 0.0010 for the Tertiary aquifer. The storativity indicates a confined aquifer which is further supported by the geologic logs from the monitoring wells which indicate clay layers up to 40-ft thick in well 254962 and 20-ft thick in well 254963. In addition, drawdowns were not observed in the shallow wells 108978 and 258390 and no influences due to pumping were observed in surface water. An aquifer test conducted in 2005 also concluded a leaky-confined to confined aquifer based on the solutions used to analyze the drawdown data. The estimates of transmissivity from the 2005 test are the same order of magnitude as the estimates from the May 2010 test conducted by the MBMG.

VOLCANIC ROCK AQUIFER TEST

Background

A 3-day aquifer test was performed in October 2010 to determine the hydraulic properties of the volcanic rock aquifer. Another objective of the aquifer test was to investigate whether the Tertiary sediment aquifer is connected to the deeper volcanic rock aquifer. It had been reported that a clay layer locally confines the volcanic rock aquifer (Land & Water Consulting, Inc., written communication, 2005).

The West Side Canal is within 25 ft of the pumping well, and immediately downgradient from the canal is the headwaters of Black Slough. The aquifer test was also performed to investigate whether pumping from the volcanic rock aquifer induces a response in Black Slough.

The aquifer test was performed by pumping an irrigation well (220080) to obtain estimates of transmissivity and storativity. The sustained maximum yield of the pumping well was previously determined through aquifer tests at the time of its installation (2005, Land & Water Consulting, Inc.). The pumping rate of 1,400–1,500 gpm was known to induce an acceptable amount of drawdown in the pumping well. As a result, a step-test did not precede the constant-rate test.

Field Procedure

Water levels were monitored in seven wells and in Black Slough during the aquifer test. Figure 8 (main report) shows the location of the pumping well, monitoring wells, the Black Slough monitoring site, and the West Side Canal. Five of the wells are monitoring wells drilled specifically for the aquifer test, one is an irrigation well, and one is a stock well. The Black Slough monitoring site was located about 990 ft downgradient of the pumping well. Table B-2 provides a summary of the monitoring and pumping well specifications. All wells, except wells 254839 and 259558, were completed in volcanic rock. Well 259558 was completed in alluvial sediments and is located near Black Slough. Well 254839 was completed in the Tertiary sediments above the volcanic rock at 77 ft bgs. It is located about 10 ft from well 254815, which was completed at 158 ft bgs in the volcanic rock aquifer. This nested well set allowed for water-level observations due to pumping in the volcanic rock and the overlying Tertiary sediments.

Pressure transducers were deployed in the pumping well and monitoring wells to examine background water levels prior to the start of the test. Prior to the start of the aquifer test, the transducers were re-programmed to record on 1-minute intervals for the pumping and recovery portions of the test. All wells and the Black Slough site were instrumented with Solinst Gold Leveloggers (accuracy range of ±0.01 to ±0.06 ft), and a Solinst Gold Barologger was deployed in well 254767 to correct the water levels for changes in barometric pressure.

A staff gauge was also installed in Black Slough near the pressure transducer. Black Slough is a perennial stream that gains groundwater just below the West Side Canal (and the pumping well). During the irrigation season, flow in the slough is periodically augmented through a head gate that channels water from the West Side Canal into the slough. Flow in Black Slough prior to opening the head gate was less than 0.2 cfs. After the head gate was opened, flow increased to at least 4 cfs.

The aquifer test started on October 15, 2010 at 15:51 and concluded on October 18, 2010 at 15:53, for a test duration of 72 hours and 2 minutes. A digital flow meter was installed on the discharge line near the pumping wellhead. Flow was monitored throughout the test using the digital meter's flow rate and totalizer readings. The pumping rate varied between 1,350 and 1,463 gpm, with an average rate of 1,422 gpm. This average does not include the first 9 minutes of the test, in which the rate was considerably higher (ranging from 1,544 to 2,084 gpm), while the pressure in the discharge line equilibrated. The discharge was routed through an irrigation line that was connected to a pivot located approximately 0.5 miles northeast of the pumping well.

During the constant-rate test, water levels were manually measured periodically in order to calibrate the pressure transducer measurements and

Table B-2. Specifications of monitoring sites and maximum groundwater drawdown during the volcanic rock aquifer test (pumping well 220080).

GWIC ID	Maximum Drawdown (ft)	Total Depth (ft)	Screened Interval (ft)	Distance to Pumping Well 220080 (ft)	Aquifer	Well Type/Surface Water Location
220080	4.00	200	105–187	0	Volcanic	Pumping/irrigation
204226	0.97	300	87–300	1,335	Volcanic	Monitoring/irrigation
254767	2.38	280	143–150	569	Volcanic	Monitoring
254815	2.65	158	143–153	261	Volcanic	Monitoring
254839	0.71	77	72–77	252	Tertiary Sed	Monitoring
254840	2.65	164	138–158	294	Volcanic	Monitoring
224244	1.03	140	138–140	1,446	Volcanic	Monitoring/stock
259558	N/A	16	6–16	369	Alluvium	Monitoring
255093	N/A	N/A	N/A	989	N/A	Black Slough

for backup in the event of a pressure transducer malfunction. Immediately after the pumping test ended, on October 18, manual recovery water levels were measured for 3 hours and periodically thereafter. On the 28th (10 days after termination of the test), select data loggers were reprogrammed to a 1-hour recording interval for long-term monitoring and the remaining data loggers were removed from the site. All water-level data are available in GWIC (http://mbmggwic.mtech.edu/).

Water samples were collected to examine changes in groundwater chemistry during the aquifer test. Specific conductance, pH, and temperature of the discharge water were measured at least twice per hour during the first 3 hours of the test and at least twice per day thereafter. Groundwater samples were collected from the pumping well within 10 minutes of the start of pumping and just prior to termination of the test. Samples were collected from Black Slough and the West Side Canal mid-way through the aquifer test (October 17). All samples were analyzed for major cation/anions, trace metals, stable isotopes of the water molecule (^{18}O and D), and tritium (groundwater only).

Results

Groundwater and Surface Water Observations

Drawdowns due to pumping were observed in all monitoring wells, though the effects on the shallow well's (259558) water levels were not observed until after the pumping ceased. Maximum drawdowns and their distances from the pumping well are presented in Table B-2. The maximum amount of drawdown in the pumping well (220080) was 4 ft. The minimum amount of drawdown (0.71 ft) was observed in well 254839. This well is completed in the Tertiary sediments above the volcanic rock aquifer at a depth of 77 ft bgs and located about 250 ft from the pumping well.

Infiltration from precipitation contributed recharge to groundwater during the test. On October 16, an average of three area weather stations indicated that 0.23 inches of rain fell. This rain event is evidenced in the hydrographs shown in figure 17 (main report). This rain does not seem to have affected the overall groundwater drawdowns. The amount of water quickly moved through the system and the drawdowns continued with their previous declining trend.

Data collected from the constant-rate test were plotted temporally and indicate that the water levels were increasing before the test in all wells except wells 254839 and 259558. Figure 17 shows two hydrographs, one for well 254815, which illustrates the increasing background trend noted in most monitoring wells. This well is screened in the deeper, volcanic rock aquifer. The increasing groundwater levels may be due to recovering water levels from earlier nearby irrigation pumping, which ceased in late September. Any background groundwater trends were removed before the data were analyzed.

For well 254839, water levels were relatively constant before the start of the test, but never recovered to pre-pumping levels and showed a decreasing trend after the test was completed (fig. 17, main report). This trend was also removed before the data were analyzed. The pre- and post-aquifer test water-level trends noted in this well suggest that it may be influenced by the West Side Canal. The West Side Canal was flowing prior to and during the aquifer test. The relatively constant water level prior to the aquifer test may be the result of the West Side Canal providing recharge to the groundwater. Although 254839 is located upgradient of the canal, upgradient wells placed in the vicinity of the West Side Canal as part of the canal study show an influence from the canal (see Results: Canal Study). The West Side Canal was turned off on October 19, 1 day after the aquifer test ended. The decreasing water-level trend, after the aquifer test was completed, was most likely the result of the shutting down of the canal, thereby eliminating the canal water as a constant source of recharge.

The hydrographs in figure 17 show that water levels in the shallower well (well 254839), which was completed in the Tertiary sediments, were being influenced by the pumping well and therefore was in connection with the volcanic rock aquifer.

Surface-water observations

Figure 19 (main report) plots water levels for both Black Slough and a shallow well (well 259558) located within 5 ft of Black Slough. Changes in surface-water levels in Black Slough were due to water diverted into the slough from the West Side

Canal and pumping. In the early part of the aquifer test, water levels in both the shallow well and Black Slough were mirroring one another. Then, about 48 hours into the test, a headgate was opened to divert water from the West Side Canal to Black Slough, and water levels increased in both Black Slough and the shallow well. The water levels remained stable for the remainder of the test. After pumping ceased, water levels within Black Slough started to rise, indicating a connection of the surface water from pumping of the well. There is a slight increase in the shallow well's water levels as well, indicating the connection between Black Slough and the shallow aquifer. The headgate was closed on October 19, and a decrease in water levels in both Black Slough and the shallow well were observed.

Aquifer Properties

Since the water levels during the aquifer test did not reach steady-state, the van der Kamp (1989) method was used to enhance the drawdown data. This method uses recovery data to effectively extend the duration of pumping to aid in the aquifer test analysis. Figure B-3 gives an example of how the recovery data are used to effectively extend the pumping duration.

The drawdown data were then plotted on a log-log graph and qualitatively evaluated. Wells 254815 and 254840 show a weak unconfined/leaky confined response as indicated by an early Theis-type curve, leveling of the data, and then resuming the Theis-type curve – an "S" shape – reflecting the "delayed yield" of an unconfined/leaky confined aquifer (fig. B-4). Evaluation of these wells' geologic logs indicate that there is about a 100-ft-thick sequence of sandy clay above the volcanic rock aquifer, conducive to leaky-confined conditions. Another indication that the aquifer is a leaky-confined or unconfined aquifer is the drawdown plot for well 254839, which shows water-level declines due to pumping from well 220080 (fig. 17, main report). Well 254839 was completed in Tertiary sediments at 77 ft bgs and shallower than the other monitoring wells.

The drawdown data were then analyzed using the aquifer test analysis software, AQTESOLV™. The methods used to analyze the data were:

Cooper-Jacob (1946) Composite Plot (see above),

Cooper-Jacob (1946) Straight-Line analysis using the recovery data (see above), and

Cooper-Jacob (1946) Distance-Drawdown method, where each monitoring well's total drawdown is plotted vs their distance from the pumping well at a given time since pumping started.

The Cooper-Jacob Composite Plot can also be used as a diagnostic tool. For example, if a monitoring well's drawdown data do not match up with the curves from other wells, this is strong evidence that

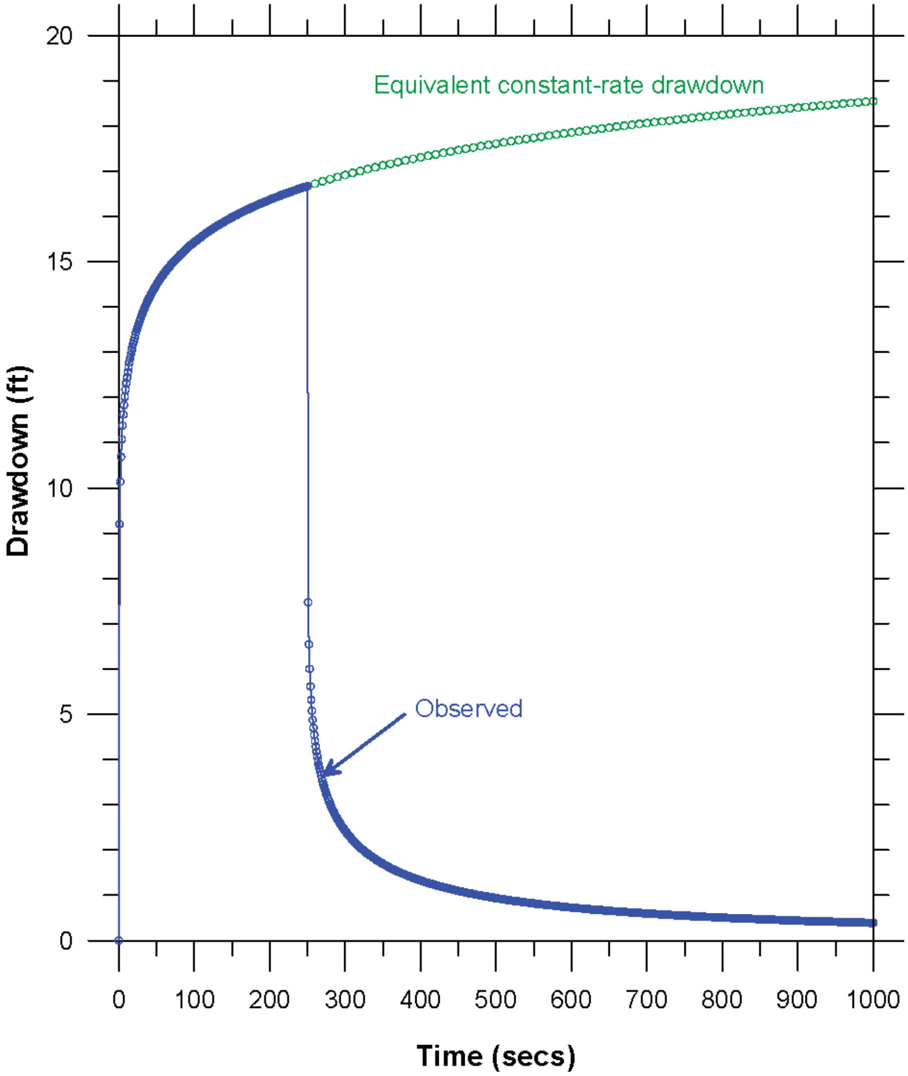

Figure B-3. Theoretical results of applying the van der Kamp method to the entire drawdown record. This method is used to effectively extend the pumping duration.

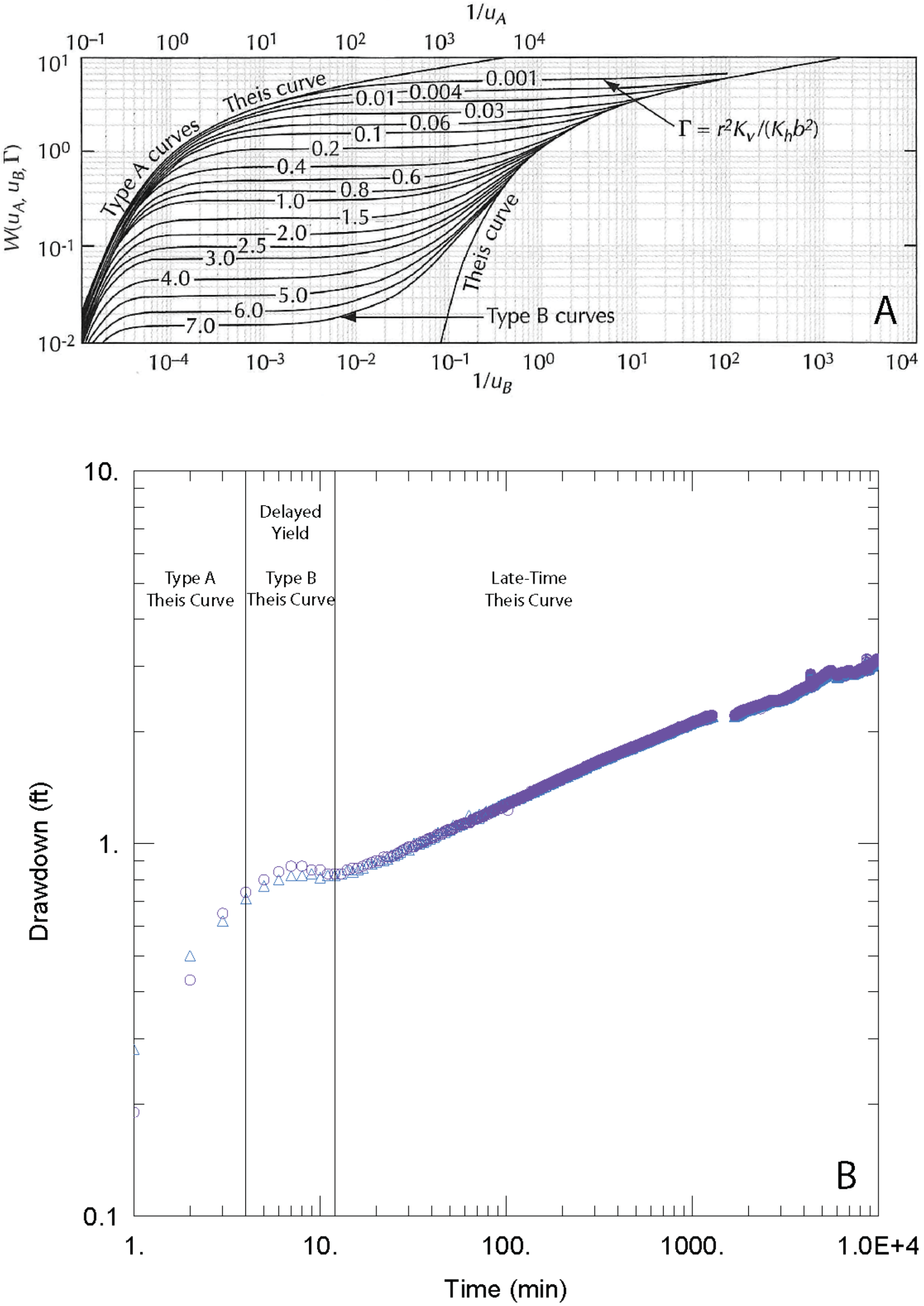

Figure B-4. (A) Theoretical response to drawdowns from an unconfined aquifer (Fetter, 2001). (B) Recorded drawdowns in wells 254815 and 254840 during the aquifer test show a pattern similar to the theoretical drawdowns.

the assumptions of the Theis solution have been violated for that monitoring well. This could indicate that the aquifer is heterogeneous or, perhaps, the monitoring well is located in a different aquifer than that which is being pumped. It could also mean that the monitoring well is located in aquifer properties significantly different than those from which the pumping well is drawing most of its water. For this test, the wells' drawdown data are plotted in four different areas on the composite plot (fig. B-5). Wells 254767, 254815, and 254840 are plotted in one area of the graph (Area 1), 204226 and 224244 plot in another area (Area 2), and both wells 254839 (Area 3) and 220080 (Area 4) are plotted separately. Area 1 wells are located generally closer to the pumping well than the other monitoring wells and are generally screened at the same depths of the aquifer. Therefore, they are located in the same area of the composite plot. Area 2 wells are located far from the pumping well in a different part of the aquifer. However, since the slope of their lines is similar to Area 1 (the slope of the line is used to calculate transmissivity), Area 2 wells are located within the same aquifer. The Area 3 well is in a different type of geologic material (Tertiary sediments). Therefore, its drawdown data cannot be used to obtain accurate aquifer properties for the aquifer in which it is located. The Area 4 well is the pumping well and will be plotted in a different part of the composite plot because of head losses that occur due to pumping. Again, for all of the wells, except well 254839, the slope of the plots are consistent and the slope of a line is used to calculate transmissivity; the x-intercept is used to calculate storativity. The results are transmissivity values ranging from 49,800 to 62,000 ft^2/day and storativ-

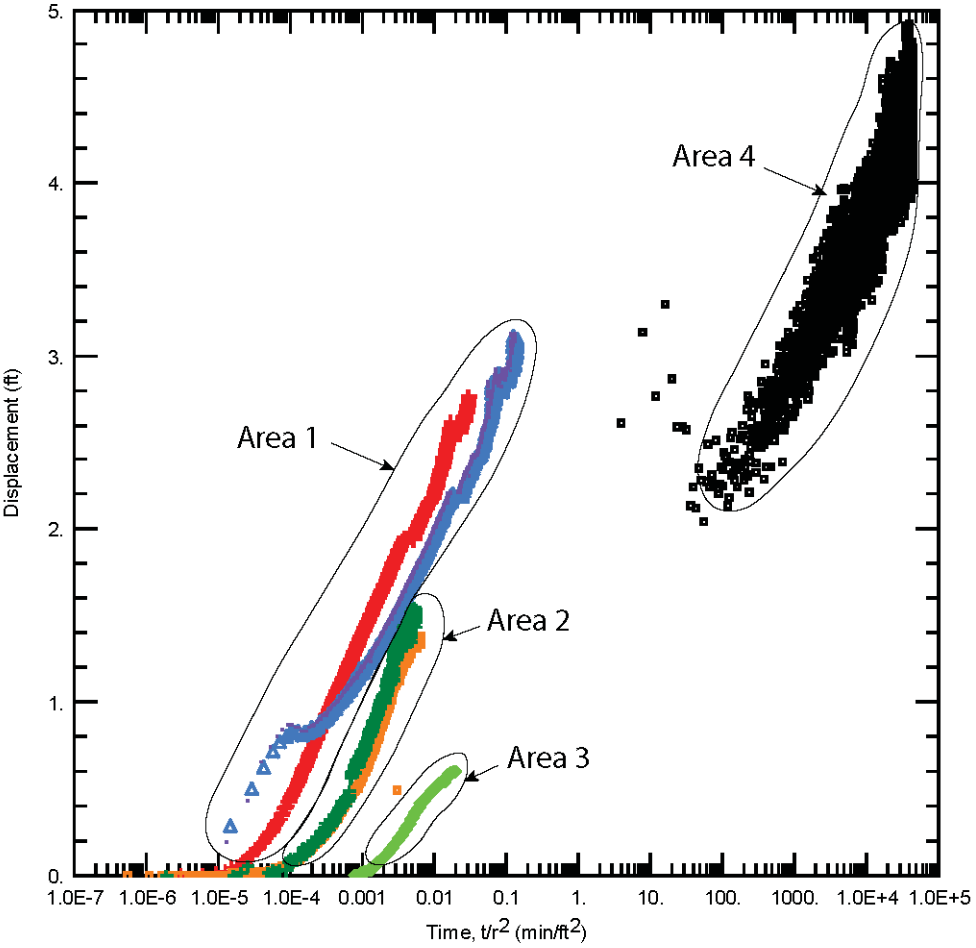

Figure B-5. Drawdown data from the monitoring wells was plotted on a Cooper-Jacob Composite Plot.

ity values ranging from 0.0026 to 0.016, except for well 254839 (table 3, main report). The different slope of well 254839 is another indication that the well is not located in the pumped aquifer and that the bulk hydraulic properties in which the well is installed are different from the pumped aquifer.

Each individual well's recovery data were also analyzed using the Cooper-Jacob (1946) Straight-Line Method, and the range of transmissivity values is consistent with transmissivity values from the Composite Plot analysis. They range from 49,500 to 75,500 ft^2/day and are presented in table 3 (main report). Similar to the Composite Method, the slope of the recovery data is the factor that is most important using this method. The slope has two main factors determining its value; one is the average pumping rate and the other is the aquifer transmissivity. As a result, storativity cannot be obtained using this method. In the mathematical derivation of this method, storativity is factored out of the final equation used to calculate transmissivity. This result indicates that late-time recovery data (which are used to match the straight-line to) are dependent only on transmissivity and not the storage coefficient.

A Distance-Drawdown plot is a plot of drawdowns, measured at the same time since pumping started, from different wells at different distances from the pumping well. The Cooper-Jacob (1946) relationship shows that drawdown varies with the log of the distance from the pumping well. Therefore, we can use this relationship as another method to obtain transmissivity and storativity. The distance drawdown analysis did not include the pumping well or well 254839. The pumping well was not used because of various headlosses and turbulent flow to the well associated with the pumped well during pumping, and well 254839 was not used because it is located in different geologic materials. Using the remaining wells for the distance drawdown analysis, transmissivity was calculated at 42,500 ft^2/day and the storativity value is 0.018 (table 3, main report). This storativity value is consistent with an unconfined aquifer.

Water Chemistry

Specific conductivity in the pumped well varied from 1,313 to 1,283 µS/cm throughout the duration of pumping. A plot of specific conductivity vs time shows a decreasing trend from the start to the end of the test (fig. 20, main report). The two specific conductivity readings measured in Black Slough on October 15 and October 17 were 1,001 and 1,116 µS/cm, respectively. Specific conductivity decreased to around 600 µS/cm after the headgate from the West Side Canal was opened, channeling water into Black Slough. The three specific conductivity readings of the West Side Canal ranged from 564 to 577 µS/cm. The decrease in specific conductivity during pumping in the discharge water may be due to induced surface water coming into the pumping well.

Water types varied between the discharge water, Black Slough, and a sample collected from well 254839 (sampled April 2010). The discharge water had a calcium–sulfate water type, Black Slough was calcium bicarbonate, and well 254839 (completed in Tertiary sediments) was a calcium–chloride type. There were no significant differences between the concentration of analytes in the sample collected in the beginning and near the end of the pumping portion of the test. Nitrate was the only analyte that decreased from 15.3 to 12.46 mg/L (close to 20% decrease). At these concentrations, nitrate exceeded the drinking water standard of 10 mg/L in both samples.

Tritium was analyzed in groundwater samples to examine potential differences in the age of the source of the water at the beginning and end of the test. The tritium concentration at the start of the test was 6.6 TU, and 6.0 TU at the end of the test. These two values are within the margin of error; therefore, the relative age of the water remained unchanged.

Figure B-6 plots δD and δO^{18} of groundwater from the discharge water during the start and near the end of the test at Black Slough, the West Side Canal and well 254839. The surface-water samples plot on the upper right and deviate from the LMWL in a manner that suggests that the water has been subjected to evaporation. The δD and δO^{18} of the groundwater samples also show evaporation equidistant from the LMWL, indicating that both sources are derived primarily from shallow groundwater derived from precipitation and irrigation return flow.

Summary

Analysis of the aquifer test data give a range of transmissivities from 49,800 to 62,000 ft^2/day and a storativity range from 0.0026 to 0.018 for the volcanic rock aquifer. These transmissivities are similar to values obtained from two other aquifer test analyses completed for water-rights applications—one test result ranging from 73,100 to 88,400 ft^2/day and the other test in a transmissivity range of 32,900 to 111,400 ft^2/day (Land and Water Consulting, written commun., 2005). These values indicate that the aquifer is very transmissive. Another indication of a very highly transmissive aquifer was the high rate of pumping (around 1,400 gpm) with a very small drawdown within the well (less than 1 ft).

The results of the aquifer test indicate that the volcanic rock aquifer is in connection with the overlying Tertiary sediment aquifer. Water levels observed in shallow well 254839, which was completed in Tertiary sediments overlying the volcanic rock, show an influence due to pumping. Drawdown hydrographs for the volcanic rock aquifer indicate both confined and unconfined conditions. This could be the result of localized confined systems as indicated in the geologic logs.

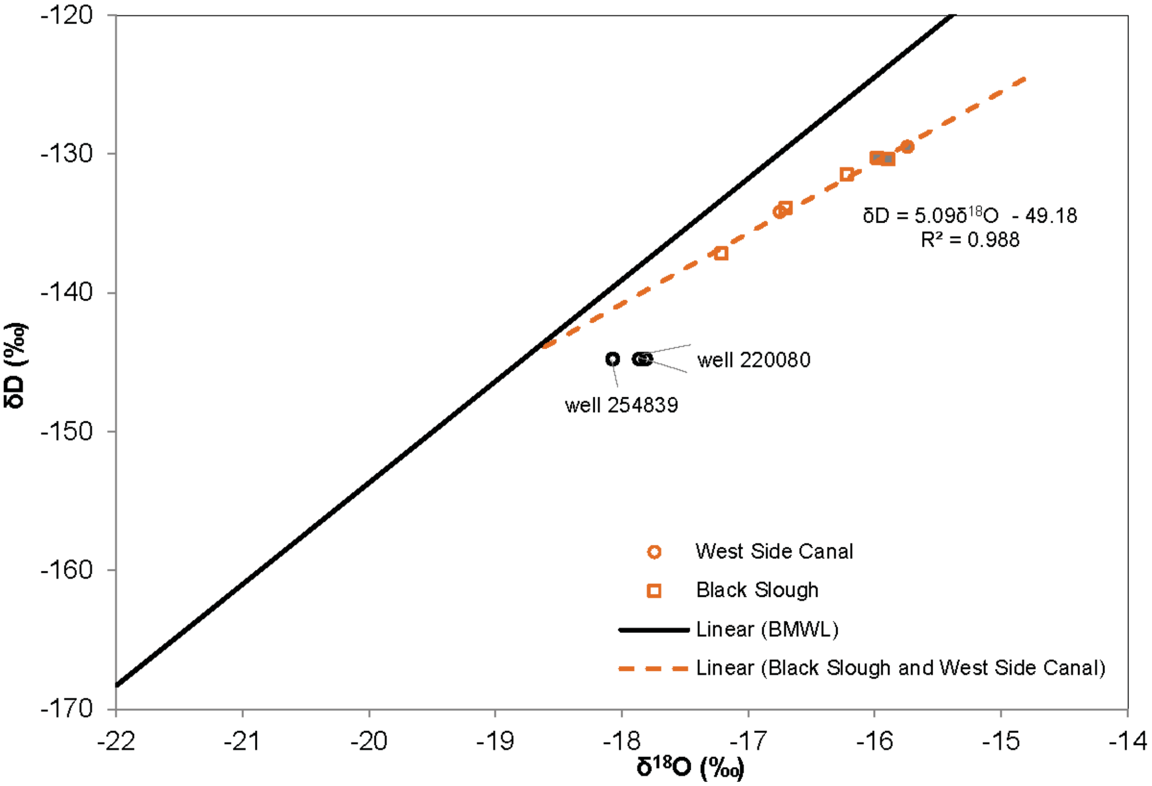

Figure B-6. Shaded symbols indicate values during aquifer test.

APPENDIX C

Water-Quality Data

Appendix C—Water Quality Data

GROUNDWATER

Gwic Id	Sample Number	Site Type	Latitude	Longitude	Aquifer	Depth (ft)	Sample Date	Water Temp (°C)	Fld pH	Fld SC	Lab pH	Lab SC	TDS (mg/L)	SAR
108949	2007Q1099	Well	45.324323	-112.441742	110ALVF	38	05/24/07	8.9	7.74	586	7.47	547	346	0.4
108962	2005Q0174	Well	45.273722	-112.447142	120SDMS	80	09/14/04	6.9	7.49	444	7.54	452	268	0.3
108965	2010Q0766	Well	45.344720	-112.558610	120SDMS	116	04/12/10	8.7	7.54	452	7.84	453	298	1.1
108966	2005Q0192	Well	45.344762	-112.593637	120SDMS	200	09/17/04	10.9	7.51	928	7.75	916	592	3.3
108980	2010Q0760	Well	45.333058	-112.526418	111ALVM	92	04/08/10	11.8		106	8.01	1060	656	0.8
109026	2010Q0762	Well	45.267389	-112.618021	111ALVM	38	04/09/10	8.2	7.7	787	8.15	774	484	0.6
109060	2010Q0723	Well	45.285110	-112.642662	120SDMS	160	04/02/10	8.5	7.75	878	7.92	863	536	1.3
109620	2010Q0764	Well	45.219916	-112.654270	111ALVM	30	04/12/10	7.9	7.4	674	7.61	653	415	0.5
123857	2007Q1133	Well	45.278023	-112.642554	120SDMS	120	06/07/07	11.8	7.41	763	6.93	748	475	1.0
131577	2002Q1250	Well	45.393689	-112.422856	120SDMS	63	05/14/02	12.7	7.96	1450	7.24	1381	1204	0.3
131577	2002R0058	Well	45.393689	-112.422856	120SDMS	63	05/14/02							
133382	2007Q0682	Well	45.208022	-112.658954	120SDMS	220	10/23/06	10.6	7.5	459	6.83	468	327	1.3
133384	2004Q0134	Well	45.214724	-112.631587	120SDMS	325.6	09/16/03	11.9	7.77	476	7.79	472	338	2.1
133386	2004Q0133	Well	45.214724	-112.631587	120SDMS	80	09/16/03	10.1	7.6	669	7.8	634	416	0.4
133387	2004Q0137	Well	45.191022	-112.672455	120SDMS	160	09/17/03	9.8	7.6	571	7.76	566	339	0.4
133390	2004Q0138	Well	45.191222	-112.673455	110ALVM	17.9	09/17/03	11.2	7.44	706	7.71	685	448	0.5
159318	2010Q0795	Well	45.387528	-112.464109	120SNGR	110	04/14/10	17.8	7.03	981	7.23	927	637	1.5
162176	2009Q0706	Well	45.392425	-112.698357	120SNGR	270	05/28/09	18	7.48	647	7.76	629	386	0.9
162827	2010Q0763	Well	45.230700	-112.627830	120SDMS	80	04/09/10	11.4	7.65	727	7.83	727	462	0.4
184460	2010Q0761	Well	45.252980	-112.662110	120VLCC	526	04/08/10	13	7.46	951	7.62	926	568	2.3
184460	2010Q0761	Well	45.252980	-112.662110	120VLCC	526	06/24/11							
191614	2010Q0759	Well	45.290400	-112.464950	120SNGR	103	04/09/10	7.9	7.8	579	8.07	567	325	0.3
191617	2010Q0765	Well	45.328520	-112.584450	120SNGR	63	04/12/10	10.4		864	7.69	844	578	0.6
194034	2009Q0096	Well	45.380970	-112.456310	330MDSN	85	07/17/08	28	7.4	719	7.41	709	497	0.5
204038	2009Q0326	Well	45.340830	-112.495120	120SNGR	400	09/26/08	15	7.76	375	7.66	477	302	0.4
207332	2010Q0867	Well	45.335528	-112.647074	320UDFD	340	04/22/10	13.2	7.67	1102	8.01	1061	642	3.8
209457	2010Q0779	Well	45.275280	-112.546880	120SICL	90	04/13/10				7.72	918	609	0.4
213392	2009Q0329	Well	45.360880	-112.495470	120SNGR	160	09/25/08	13.2	7.84	368	7.79	448	312	0.5
213393	2009Q0330	Well	45.341180	-112.509210	120SNGR	460	09/25/08	13.9	7.96	385	7.68	442	316	0.6
216805	2010Q0797	Well	45.331135	-112.421775	120SDMS	520	04/13/10				8.22	602	429	0.4
220021	2010Q0922	Well	45.322274	-112.600184	120SNGR	331	05/18/10	10.6	7.8	458	7.97	467	294	0.9
220080	2010Q0712	Well	45.352535	-112.620017	120VLCC	200	03/28/10	9.9	7.63	1280	8.14	1279	757	2.3
220080	2011Q0690	Well	45.352535	-112.620017	120VLCC	200	10/15/10	10.2	7.57	1311	7.88	1310	789	2.3
220080	2011Q0688	Well	45.352535	-112.620017	120VLCC	200	10/18/10	10	7.65	1298	7.87	1285	766	2.3
220904	2009Q0327	Well	45.347760	-112.570120	120SICL	240	09/26/08	10.9	8.05	475	7.46	592	395	2.8
224244	2009Q0328	Well	45.355577	-112.623636	120VLCC	140	09/26/08	10.3	8	745	7.53	901	554	2.2
225505	2010Q0724	Well	45.297646	-112.636466	120SNGR	130	04/05/10	9.1	7.73	905	8.01	931	563	1.6
235306	2010Q0732	Well	45.299543	-112.634526	120SNGR	136	04/05/10							
242403	2010Q0725	Well	45.376537	-112.499812	120SDMS	95	04/05/10	8.5	7.4	694	8.04	652	489	1.2

Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	F (mg/L)	OPO_4-P (mg/L)	Procedure
56.3	30.3	15.5	3.09	0.011	<0.001	22.2	261.6	0	81.7	7.11	0.47	0.289	<0.05	Dissolved
51	20.1	10.9	3.17	0.023	<0.001	23.7	243.7	0	29.4	9.19	1.06	0.084	<0.05	Dissolved
47.8	4.8	31.1	3.46	0.003	0.001	36.1	127.4	0	102.8	8.46	2.38	0.138	<0.05	Dissolved
70.1	7.65	110	5.86	0.039	0.004	28.3	134.2	0	200	102.00	4.38	0.224	<0.10	Dissolved
127	40.9	38.5	6.18	0.002	0.001	30.5	338.8	0	184.4	60.66	5.81	0.418	0.036	Dissolved
99.6	29	27.8	4.13	0.004	0.001	18.9	311.7	0	129.8	20.42	1.72	0.394	<0.05	Dissolved
107	20.1	55.9	4.77	<0.002	<0.001	27.2	262.9	0	142.3	48.07	7.84	0.165	<0.05	Dissolved
81.5	26.3	21.4	4.48	0.064	0.003	18.2	292.2	0	102.7	15.36	3.96	0.451	<0.05	Dissolved
85.2	22.1	40.8	3.87	<0.005	<0.001	34.8	231.5	0	143	29.30	1.72	0.539	<0.10	Dissolved
191	87.7	17.7	10.7	0.052	0.008	47.9	293.1	0	630	66.40	0.60	0.681	<.5	Dissolved
														Dissolved
50.5	12	38.4	7.46	0.143	0.008	30	201.5	0	79.4	9.04	<0.5	0.452	<0.05	Dissolved
33.8	5.1	49.4	12.1	0.27	0.032	62.4	226.9	0	55.6	6.40	<0.5	0.36	<0.05	Dissolved
81.2	25.1	16	6.76	0.046	0.004	38.7	282.1	0	94.8	13.80	1.27	0.153	<0.05	Dissolved
64.7	21.7	14.2	4.47	0.113	0.003	22.8	267.18	0	67.6	11.00	1.01	0.196	<0.05	Dissolved
91.2	27.8	19.3	5.21	0.041	0.001	22.5	280.6	0	128	14.60	1.09	0.419	<0.10	Dissolved
86.1	27.3	61.4	5.88	3.72	0.25	28.8	123.6	0	279.2	79.82	0.22	2.11	<0.05	Dissolved
61.7	20.9	30.4	3.32	0.005	0.001	17.9	164.7	0	125.6	43.90	0.77	<0.5	<0.5	Dissolved
101	26.2	16.2	6.15	<0.002	0.001	36.5	313.5	0	104.6	15.94	<0.5	0.339	<0.05	Dissolved
75.2	14.2	82.7	11.2	<0.002	0.035	49.3	120	0	132.7	141.10	2.54	0.269	<0.05	Dissolved
														Dissolved
73	25	11.5	3.19	<0.002	0.001	21.6	285	0	38.03	12.27	5.33	0.155	<0.05	Dissolved
114	28.7	26	3.7	0.04	0.009	41.2	228.1	0	194.1	55.89	2.89P	0.265	<0.05	Dissolved
85.6	30.1	22.9	9.21	0.176	0.013	20.9	179.3	0	228	10.30	<0.5	1.56	<0.5	Dissolved
46.8	19.7	12.6	8.05	0.008	<0.001	60.9	165.7	0	36.1	35.20	2.20	0.274	<0.05	Dissolved
68.9	18.7	137	2.47	<0.010	0.001	14.2	320.5	0	195.4	44.01	8.79	1.21	<0.05	Dissolved
92.9	43.7	18.9	10.2	0.002	0.001	95.1	219.3	0	125.6	112.80	3.43	0.233	<0.05	Dissolved
50.4	16.8	15.6	9.05	0.02	<0.001	60.6	189.3	0	38.6	25.10	1.74	0.301	<0.05	Dissolved
48.4	17.4	19.3	8.4	0.025	<0.001	62.1	173.7	0	36.7	36.70	2.32	0.305	<0.05	Dissolved
59	29.1	14.8	5.77	<0.002	<0.001	91.9	202.2	0	98.09	29.77	1.84	0.18	<0.05	Dissolved
55.6	8.83	28.8	2.62	0.011	0.001	17.4	175.4	0	81.45	12.24	0.68	0.202	<0.05	Dissolved
131	19.1	105	4.62	<0.001	<0.001	22.8	201.5	0	216.4	156.00	11.60	0.478	<0.05	Dissolved
135	20.1	107	4.58	<0.010	<0.005	24.4	211.3	0	225.4	150.80	15.30	0.42	<0.1	Dissolved
133	19.3	107	4.88	<0.010	<0.005	24.5	202.2	0	214.5	148.10	12.46	0.41	<0.1	Dissolved
50.7	3.6	77.6	4.36	0.038	<0.001	21.9	150.1	0	110	50.30	1.85	0.255	<0.05	Dissolved
88.3	12.1	82.9	5.39	0.009	<0.001	25.9	163.2	0	127	129.60	14.40	0.533	<0.5	Dissolved
106	19.5	68.3	2.63	0.024	0.004	14.1	207	0	184.8	64.40	<0.5	0.46	<0.05	Dissolved
											5.07			Dissolved
83.8	18.6	45.3	7.37	0.021	0.217	46.8	234.9	0	138.6	30.79	7.86	0.423	<0.05	Dissolved

Gwic Id	Sample Number	Site Type	Latitude	Longitude	Aquifer	Depth (ft)	Sample Date	Water Temp (°C)	Fld pH	Fld SC	Lab pH	Lab SC	TDS (mg/L)	SAR
242404	2010Q0726	Well	45.376579	-112.499934	111ALVM	30	04/05/10	7.29	6.96	1126	7.61	1143	776	1.3
242406	2008Q0409	Well	45.376040	-112.499674	120SNGR	91	03/25/08	8.7	7.79	782	7.72	762	516	1.1
242408	2009Q0137	Well	45.315636	-112.448649	120SNGR	515	08/04/08	15.3	7.74	422	7.45	594	272	0.3
242408	2010Q0748	Well	45.315636	-112.448649	120SNGR	515	04/07/10				8.06	344	230	0.3
242409	2008Q0408	Well	45.315721	-112.448685	120SNGR	290	03/25/08	15.8	6.81	331.2	7.52	343	224	0.3
242409	2010Q0747	Well	45.315721	-112.448685	120SNGR	290	04/07/10	15.8	7.84	338.2	8.16	327	237	0.3
242411	2009Q0138	Well	45.315768	-112.448824	120SNGR	160	08/04/08	14.9	6.98	471	7.45	475	305	0.3
249705	2010Q0866	Well	45.382436	-112.468074	111ALVM	14	04/21/10	5.6	7.89	730	7.9	715	449	0.7
249742	2010Q0722	Well	45.345975	-112.536840	111ALVM	18.5	04/05/10	8.13	7.28	994	7.82	1024	585	0.7
250122	2010Q0767	Well	45.277258	-112.574351	111ALVM	18	04/12/10	7.9	6.6	729	7.71	720	477	0.6
252455	2010Q0869	Well	45.387689	-112.712317	120SICL	540	04/22/10	12.7	7.75	653	8.01	632	380	0.3
254839	2010Q0727	Well	45.352539	-112.619044	120SNGR	77	04/05/10	9.2	7.4	1505	7.86	1513	901	2.9
255038	2010Q0713	Well	45.306122	-112.633321	120SNGR	75	03/31/10	9.8	7.83	878	7.91	904	583	3.2
255163	2010Q0794	Well	45.384407	-112.466642	111ALVM	12	04/14/10	5.4	7.47	736	7.76	713	473	0.7
255487	2010Q0799	Well	45.315329	-112.449956	120SNGR	118	04/12/10	12.8	7.46	574	7.99	573	434	1.1
255488	2010Q0796	Well	45.326743	-112.421457	111SNGR	78	04/12/10	11.2	7.33	592	7.91	589	427	0.7
255491	2010Q0798	Well	45.293532	-112.479360	120SNGR	119	04/12/10	13.42	7.41	594	7.96	549	418	0.8
255492	2010Q0917	Well	45.305639	-112.563208	120SNGR	108	05/04/10	8.6	7.62	522	7.99	514	332	0.6
255493	2010Q0916	Well	45.305639	-112.563208	111ALVM	23.5	05/04/10	5.7	7.54	666	7.78	651	400	0.7
257796	2010Q0714	Well	45.306834	-112.634515	120SNGR	31	03/31/10	11.2	7.68	893	7.67	884	555	0.9
259541	2010Q0800	Well	45.312527	-112.531135	120SNGR	120	04/13/10	12.4		880	8.04	864	626	1.1
260203	2011Q0951	Well	45.256449	-112.661504	120VLCC		02/11/11	3.5		1079	7.72	960	591	3.2

SURFACE WATER

Gwic Id	Sample Number	Site Type	Latitude	Longitude	Sample Date	Water Temp (°C)	Field pH	Fld SC	Lab pH	Lab SC	TDS (mg/L)	SAR	Ca (mg/L)	Mg (mg/L)
147977	2010Q0680	Stream	45.217500	-112.654100	03/16/10	4.7		580					73.5	23
147977	2010Q0679	Stream	45.217500	-112.654100	03/17/10				8.02	593	365	0.6	66.6	21.8
242227	2008Q0404	Canal	45.382760	-112.463910	03/08/08	27.8	7.52	736	7.43	699	472	0.6	84	30.5
242227	2010Q0672	Canal	45.382760	-112.463910	03/16/10	28.2	7.41	730					87	28.2
242227	2010Q0671	Canal	45.382760	-112.463910	03/16/10	28.2	7.41	730	7.95	739	487	0.6	82.1	29.6
242228	2008Q0405	Stream	45.376440	-112.499840	03/18/08	5.7	8.08	634	8.06	616	392	0.6	72.4	25.3
242228	2009Q0274	Stream	45.376440	-112.499840	09/05/08								58.9	25.6
242228	2009Q0273	Stream	45.376440	-112.499840	09/05/08	11.2	8.35	707	8.03	690	430	0.7	71.6	28.7
242228	2010Q0709	Stream	45.376440	-112.499840	03/23/10	4.9	8.52	597					74.2	23.5
242525	2008Q0407	Stream	45.383202	-112.453201	03/25/08	8.6	7.54	692	8.08	633	415	0.7	77.2	26
242525	2009Q0278	Stream	45.383202	-112.453201	09/05/08				7.96	766	498	0.8	79.3	32.1
242525	2009Q0279	Stream	45.383202	-112.453201	09/05/08	10.6	8.16	776					71.2	30.6
242525	2010Q0676	Stream	45.383202	-112.453201	03/16/10	6.4	8.27	632					76.6	23.4
242525	2010Q0675	Stream	45.383202	-112.453201	03/16/10	6.4	8.27	632	8.28	649	396	0.6	71.6	24.6
247284	2009Q0271	Stream	45.306290	-112.562660	09/05/08				7.92	650	382	0.7	71.7	26
247284	2009Q0272	Stream	45.306290	-112.562660	09/05/08	12.9	8.68	660					58.6	24.5
247284	2010Q0685	Stream	45.306290	-112.562660	03/17/10	8.6	8.46	565	8.17	563	363	0.6	66.6	21.9
247284	2010Q0686	Stream	45.306290	-112.562660	03/17/10	8.6	8.46	565			122	0.6	72.7	22.3
247302	2009Q0269	Canal	45.312937	-112.447522	09/05/08	12.7	8.56	827.6	8.07	597	360	0.7	60.8	25.7
247302	2009Q0270	Canal	45.312937	-112.447522	09/05/08	12.7	8.56	827.6					52.7	27.5
249749	2010Q0710	Stream	45.343700	-112.571340	03/23/10	3.3	8.25	846	8.04	845	544	0.9	98.3	30.3
249749	2010Q0711	Stream	45.343700	-112.571340	03/23/10	3.3	8.25	846					106	31.1

Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	F (mg/L)	OPO_4-P (mg/L)	Procedure
129	50.2	68.8	6.36	1.56	0.521	28.4	396.9	0	251.2	42.56	<0.10	0.606	<0.05	Dissolved
95.2	20.8	44.9	8.06	0.016	0.321	39.3	272.7	0	142	29.40	<0.5	0.427	<0.05	Dissolved
43.3	17	8.6	10.1	0.237	0.029	53.9	180.3	0	28	21.40	1.73	0.226	0.065	Dissolved
36.8	14.8	8.29	8.91	0.021	0.02	49.4	173.7	0	16.04	9.62	<0.5	0.272	<0.05	Dissolved
33.9	13.6	8.8	10.4	0.019	0.013	52	176.9	0	10.9	6.81	<0.5	0.38	<0.05	Dissolved
32.9	14.9	8.76	9.83	0.102	0.005	56.8	185.2	0	13.46	8.11	<0.5	0.273	<0.05	Dissolved
50.7	20.6	8.4	7.89	0.267	0.086	52	200.1	0	39.4	26.00	2.06	0.351	0.306	Dissolved
79.1	30.2	28.6	4.69	0.164	0.314	23.3	302.3	0	112.7	19.88	5.31	0.45	<0.05	Dissolved
113	40.9	34	8.59	0.004	0.082	32.2	265.1	0	178.8	45.31	0.84	0.403	<0.05	Dissolved
84.9	27.4	25.9	4.74	0.114	0.011	43.8	319.3	0	114.8	16.92	4.40	0.435	<0.05	Dissolved
83.1	22	11.5	1.91	0.813	0.087	8.86	147	0	119.7	58.55	1.00	0.104	<0.05	Dissolved
153	24.6	145	4.59	<0.009	0.049	17.2	168.4	0	258.9	210.80	17.24	0.747	<0.05	Dissolved
70.4	13	111	2.45	0.005	<0.001	17	295.6	0	199.6	21.96	1.47	0.648	<0.05	Dissolved
77.5	28.8	28.8	5.22	0.406	0.6	42.3	293.7	0	123.8	19.72	<0.5	0.607	<0.05	Dissolved
48.8	19.3	37.2	8.23	<0.002	0.039	90.2	240.3	0	97.77	13.09	<0.5	0.337	<0.05	Dissolved
56.5	24.4	25.1	7.1	<0.002	0.005	81.3	222.7	0	109.6	12.88	0.59	0.138	<0.05	Dissolved
65.9	17.2	28.1	5.91	<0.002	0.02	64.7	236.4	0	105.7	13.25	<0.5	0.19	<0.05	Dissolved
64.9	12.6	19.4	7.49	0.163	0.02	33.8	233	0	70.46	7.40	<0.5	0.214	<0.05	Dissolved
70.6	24.8	25.2	6.02	0.028	0.686	22.6	267.5	0	101.7	15.08	4.14	0.463	<0.05	Dissolved
97	34.6	39.5	5.45	<0.001	0.097	19.2	314.2	0	171.2	31.24	7.24	0.515	<0.05	Dissolved
72.1	39	45.6	13	<0.002	0.001	106	230	0	171.1	64.36	3.37	0.458	<0.05	Dissolved
70.4	7.17	106	12.4	0.006	0.037	47.4	157.1	0	149.2	117.70	1.14	0.261	0.214	Dissolved

Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	F (mg/L)	OPO_4-P (mg/L)	Procedure
24.1	4.44	0.313	0.067									Total Recoverable
22.8	3.97	0.007	0.022	16.3	247.4	0	98.55	12.31	0.32	0.468	<0.05	Dissolved
23.7	5.68	<0.005	0.002	16.6	188.6	0	204	11.60	<0.05	1.64	<0.05	Dissolved
22.6	5.34	0.037	0.003									Total Recoverable
22.9	5.19	<0.001	0.002	19.9	186.1	0	220.2	11.81	3.27	1.74	<0.05	Dissolved
23.7	5.36	0.033	0.028	14.3	252.1	0	110	15.60	0.49	0.621	<0.05	Dissolved
23.8	5.51	0.279	<0.003									Total Recoverable
27.6	6.55	0.043	0.012	18.3	309.9	0	105.6	17.91	<0.5	<0.5	<0.5	Dissolved
22.6	4.92	410	0.056									Total Recoverable
26.7	5.68	0.007	0.034	15.7	260.1	0	115	19.00	<0.5	0.6	<0.05	Dissolved
32.7	7.4	0.044	0.016	23	305	0	148.8	23.60	<0.5	0.47	<0.5	Dissolved
30.4	6.83	0.271	0.004									Total Recoverable
24.6	5.11	0.281	0.057									Total Recoverable
24.8	4.88	0.005	0.032	18.3	254.1	0	108.7	16.84	0.36	0.45	<0.05	Dissolved
25.4	4.35	0.013	<0.001	16.9	211.2	0	117.1	15.40	<0.5	0.459	<0.5	Dissolved
23.3	4.83	0.287	0.004									Total Recoverable
21.4	4.26	0.005	0.017	16.8	251.3	0	95.26	12.36	0.31	0.436	<0.05	Dissolved
21.7	4.62	0.292	0.042									Total Recoverable
24.8	4.04	0.017	0.007	13.3	223.5	0	109.1	11.30	<0.5	0.467	<0.5	Dissolved
26.9	4.52	0.279	<0.003									Total Recoverable
40.6	4.46	0.007	0.058	22.6	319.3	0	160.5	28.24	0.84	0.444	<0.05	Dissolved
41.5	4.87	0.532	0.091									Total Recoverable

Gwic Id	Sample Number	Site Type	Latitude	Longitude	Sample Date	Water Temp (°C)	Field pH	Fld SC	Lab pH	Lab SC	TDS (mg/L)	SAR	Ca (mg/L)
254904	2010Q0674	Stream	45.378727	-112.468382	03/16/10	7.7	8	942					91.7
254905	2010Q0682	Stream	45.322850	-112.527910	03/17/10	7.9	8.4	860					86.8
254905	2010Q0681	Stream	45.322850	-112.527910	03/17/10	7.9	8.4	860	8.36	863	541	1.2	86
254906	2010Q0684	Stream	45.342270	-112.535420	03/17/10	9.9	8.32	937					108
254906	2010Q0683	Stream	45.342270	-112.535420	03/17/10	9.9	8.32	937	7.9	909	610	1.0	92.7
254907	2010Q0678	Stream	45.228494	-112.632645	03/16/10	8.8	8.39	538					76
254907	2010Q0677	Stream	45.228494	-112.632645	03/16/10	8.8	8.39	538	8.21	550	339	0.3	70
254923	2010Q0706	Stream	45.380742	-112.498256	03/23/10	4.7	8.32	862	8.16	809	563	0.9	98.9
254923	2010Q0707	Stream	45.380742	-112.498256	03/23/10	4.7	8.32	862					104
255093	2010Q0729	Stream	45.349740	-112.619750	04/02/10	7.9	8.03	808					89.8
255093	2010Q0728	Stream	45.349740	-112.619750	04/02/10	7.9	8.03	808	7.89	801	489	1.6	91.4
255093	2011Q0689	Stream	45.349740	-112.619750	10/17/10	8.8	7.91	111.6	8	1107	698	1.7	124
255094	2010Q0730	Stream	45.322706	-112.599126	04/06/10	6.2		885	8.19	864	603	1.5	103
255254	2010Q0864	Snow	45.428158	-112.905173	04/02/10		6.98	17	5.91	24			<0.315
255257	2010Q0870	Snow	45.326836	-112.420605	04/13/10		6.98	33	7.61	93			5.34
258656	2011Q0687	Canal	45.352380	-112.620070	10/17/10	9.1	8.56	577	8.32	572	358	0.6	66.3

Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	F (mg/L)	OPO_4-P (mg/L)	Procedure
40.8	34.6	13.8	0.075	0.034									Total Recoverable
27.1	47.2	5.54	0.047	0.003									Total Recoverable
30.2	49.7	5.58	<0.001	0.002	26.4	221.7	3.6	177	52.58	3.77	0.161	<0.05	Dissolved
43	45.4	10.9	0.839	0.048									Total Recoverable
39.3	43.6	9.84	0.008	0.014	34.2	321.3	0	176.3	54.29	2.51	0.324	<0.05	Dissolved
20	12.2	4.74	0.649	0.043									Total Recoverable
20.4	12	4.34	0.005	0.009	19.2	260.8	0	75.35	8.21	0.23	0.304	<0.05	Dissolved
32.4	42.4	5.07	0.005	0.136	22.4	330.3	0	167.8	29.65	0.63	0.469	<0.05	Dissolved
32.7	42.7	5.41	0.351	0.179									Total Recoverable
16.4	67.7	1.6	0.129	0.076									Total Recoverable
17.1	64	1.48	0.022	0.073	19.2	272.4	0	118.1	41.53	0.64	0.577	<0.05	Dissolved
26.9	82	5.15	0.022	0.098	26.6	343.7	0	216	45.49	0.44	0.454	<0.1	Dissolved
33.5	66.4	2.93	0.021	0.109	21.6	344.3	0	164	39.53	<0.5	0.638	<0.05	Dissolved
0.15	<0.126	0.031	0.002	<0.001	<0.075	5.12	0	<2.5	0.53	<0.5	<0.05	<0.05	Dissolved
0.43	<0.126	0.312	0.005	<0.001	1.04	2.21	0	<2.5	<0.5	<0.5	<0.05	<0.05	Dissolved
23.3	23.8	4.35	0.002	0.001	14.9	241.6	1.83	90.98	12.41	0.12	0.389	<0.1	Dissolved

APPENDIX D

Water Budget Information

Table D-1. Lower Beaverhead River Study area: details of water distribution and fate for all irrigation water.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Inflows	$IRR_{DIVERSION(WSC)}$					826	2,447	3,939	5,912	1,172				**14,296**
	$IRR_{DIVERSION(EBC)}$	0	0	0	499	832	4,804	5,366	2,930	2,025	1,012	0	0	**17,468**
	$IRR_{DIVERSION(Floodplain)}$				0	4,146	11,260	10,931	12,700	8,266	0			**47,303**
	IRR_{WELLS}	0	0	0	561	1,123	1,123	1,123	1,123	1,123	561	0	0	**6,735**
	$CAN_{SEEPAGE(WSC)}$	0	0	0	588	959	928	959	959	928	588	0	0	**5,911**
	$CAN_{SEEPAGE(EBC)}$	0	0	0	589	3,044	2,945	3,044	3,044	2,945	1,473	0	0	**17,083**
	P_{IRR}				9,740	7,690	7,539	2,714	3,347	3,981	1,749			**36,760**
	Total	**0**	**0**	**0**	**11,978**	**18,619**	**31,046**	**28,076**	**30,015**	**20,440**	**5,383**	**0**	**0**	**145,556**
Outflows	$ET_{IRR(TOTAL)}$	**0**	**0**	**0**	**609**	**7,414**	**16,855**	**20,864**	**15,665**	**6,836**	**692**	**0**	**0**	**68,935**
Net (Inflows-Outflows)	Excess Irrigation Water	**0**	**0**	**0**	**11,368**	**11,205**	**14,191**	**7,211**	**14,350**	**13,604**	**4,691**	**0**	**0**	**76,621**

Note. $IRR_{DIVERSION(WSC)}$, water diverted to irrigated land from the West Side Canal; $IRR_{DIVERSION(EBC)}$, water diverted to irrigated land from the East Bench Canal; $IRR_{DIVERSION(Floodplain)}$, water diverted from the river to irrigated land on the floodplain; IRR_{WELLS}, water diverted from groundwater within the study area; $CAN_{SEEPAGE(WSC)}$, seepage from the West Side Canal; $CAN_{SEEPAGE(EBC)}$, seepage from the East Bench Canal; P_{IRR}, total precipitation on irrigated lands during the growing season; $ET_{IRR(TOTAL)}$, total ET for irrigated lands during the growing season; Excess Irrigation Water, some part of which is available for groundwater recharge.

Table D-2. Surface-water inflows (entering) and outflows (exiting) the study area. Monthly values are in acre-ft/month and total values are in acre-ft/yr.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Inflows SW_{IN}	Beaverhead River (Dillon)	17,663	13,799	14,335	13,940	12,436	18,601	20,027	20,194	19,398	17,181	21,239	21,925	**210,738**
	Blacktail Creek	1,745	2,201	3,002	1,731	834	5,776	3,493	1,530	2,441	4,359	4,671	2,789	**34,572**
	Owen Ditch					132	294	243	289	24				**982**
	Dillon Canal					516	944	1,280	1,607	987				**5,333**
	Stone Creek	394	442	508	582	754	1,246	917	755	593	612	631	630	**8,065**
	Total	**19,802**	**16,441**	**17,844**	**16,254**	**14,673**	**26,860**	**25,959**	**24,375**	**23,443**	**22,152**	**26,541**	**25,345**	**259,689**
Outflows SW_{OUT}	Beaverhead River (near Beaverhead Rock)	24,147	18,583	22,354	19,295	14,753	22,524	21,630	17,538	26,059	25,617	32,204	29,030	**273,733**
	$ET_{Flood\ Plain\ from\ BHR\ Diversions}$				351	2,276	4,247	5,345	4,285	2,133	515			**19,151**
	Ditch Outflow					250	1,063	1,774	1,322	800				**5,208**
	Total	**24,147**	**18,583**	**22,354**	**19,646**	**17,279**	**27,834**	**28,749**	**23,144**	**28,991**	**26,131**	**32,204**	**29,030**	**298,091**
NET Gain in Surface Flow		**4,345**	**2,142**	**4,510**	**3,392**	**2,606**	**974**	**2,790**	**-1,231**	**5,548**	**3,979**	**5,663**	**3,685**	**38,403**

Note. $ET_{Flood\ Plain\ from\ BHR\ Diversions}$, diversion ditches that take out from the Beaverhead River within the study area and are applied to fields within the study area with some return flow to the river.

Table D-3. Groundwater flux, Q, (inflow and outflow) to the study area during 2010.

		Q_{MIN} (acre-ft/yr)	Q_{MAX} (acre-ft/yr)	Q_{AVE} (acre-ft/yr)
Inflows GW_{IN}	$\mathrm{Alluvium}_{IN}$	5,241	7,559	6,400
	$\mathrm{West\ Bench}_{IN}$	975	1,205	1,090
	$\mathrm{East\ Bench}_{IN}$	9,472	15,385	12,429
	$\mathrm{Floodplain\ Tertiary}_{IN}$	1,915	3,946	2,931
	Total Groundwater Inflow			**22,850**
Outflows GW_{OUT}	$\mathrm{Alluvium}_{OUT}$	526	756	641
	Total Groundwater Outflow			**641**

Table D-4. East Bench and West Side Canal inflows and outflows to the study area during 2010. Monthly values are in acre-ft/month and total values are in acre-ft/yr.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
$\mathrm{CAN}_{IN(EBC)}$				3,486	5,124	14,616	19,799	15,465	8,863	4,431			**71,784**
$\mathrm{CAN}_{IN(WSC)}$				1,204	2,243	3,375	4,898	6,870	1,636	1,996			**22,223**
Total CAN_{IN}				**4,690**	**7,367**	**17,991**	**24,697**	**22,335**	**10,499**	**6,427**			**94,006**
$\mathrm{CAN}_{OUT(EBC)}$				2,399	1,249	6,867	11,389	9,491	3,893	1,946			**37,233**

Note. $\mathrm{CAN}_{IN(EBC)}$, total amount of surface water entering the site from the East Bench Canal; $\mathrm{CAN}_{IN(WSC)}$, total amount of surface water entering the site from the West Side Canal; CAN_{IN}, total water supplied to the study area by canals; $\mathrm{CAN}_{OUT(EBC)}$, total amount of surface water leaving the site from the East Bench Canal.

Table D-5. Evapotranspiration amounts for the study area during 2010. Monthly values are in acre-ft/month and total values are in acre-ft/yr.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
$\mathrm{ET}_{NON\ CROP}$	1,623	1,759	3,993	8,353	9,465	9,255	3,196	4,023	4,850	3,232	8,211	3,831	**61,791**
$\mathrm{ET}_{IRR\ CAN}$	0	0	0	258	3,930	9,457	11,569	8,056	3,262	178	0	0	**36,710**
$\mathrm{ET}_{IRR\ BHR}$	0	0	0	351	2,276	4,247	5,345	4,285	2,133	515	0	0	**19,151**
$\mathrm{ET}_{IRR\ GW}$	0	0	0	0	1,208	3,150	3,950	3,324	1,442	0	0	0	**13,074**
ET_{PWS}	-1.9	3.8	0.8	5.5	9.6	20	75	67	34	20	3.0	0.4	**237**
$\mathrm{ET}_{STOCK\ WELLS}$	19	19	19	19	19	19	19	19	19	19	19	19	**226**
$\mathrm{ET}_{DOM\ WELLS}$	1.6	1.6	1.6	43	110	132	183	145	107	1.6	1.6	1.6	**731**
ET_{TOTAL}	**1,642**	**1,783**	**4,014**	**9,029**	**17,018**	**26,281**	**24,338**	**19,918**	**11,846**	**3,965**	**8,235**	**3,851**	**131,919**

Note. $\mathrm{ET}_{NON\ CROP}$, ET for all lands during the non-growing season and non-irrigated lands during the growing season; $\mathrm{ET}_{IRR\ CAN}$, ET during the growing season on land irrigated from canals that flow into the study area; $\mathrm{ET}_{IRR\ BHR}$, ET from irrigated land supplied by river diversions within the study area; $\mathrm{ET}_{IRR\ GW}$, ET from land irrigated with groundwater; $\mathrm{ET}_{STOCK\ WELLS,}$ total volume pumped from stock wells related to exempt well class, all is lost through ET (including animal consumption); ET_{PWS}, Difference between delivered water supply and returned flow to sewage system; $\mathrm{ET}_{DOM\ WELLS,}$ ET from lawn, garden and household use related to exempt class wells; ET_{TOTAL}, total ET from the study area.