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HYDROGEOLOGIC INVESTIGATION OF THE FOUR CORNERS AREA, GALLATIN COUNTY, MONTANA: INTERPRETIVE REPORT

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Montana Bureau of Mines and Geology Ground Water Investigation Program

MBMG Montana Bureau of Mines and Geology

Cover: Agricultural land in the Gallatin Valley, Montana is being converted to accommodate increasing residential and commercial growth. From GoogleEarth.

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TABLE OF CONTENTS

FIGURES

TABLES

ABSTRACT

The purpose of the Four Corners groundwater investigation was to evaluate the effects of land-use conversion from irrigated agriculture to high-density residential and commercial development on groundwater and surface-water resources in the study area. Historically, agricultural use dominated the landscape, and a portion of the study area remains irrigated. Subdivisions, rural residential buildings, and commercial development are transforming agricultural land in this area. Neighborhoods with individual well and septic systems, municipal water distribution, and wastewater treatment systems are developing on previously irrigated parcels.

Water for domestic and commercial use in the Four Corners area primarily comes from the alluvial aquifer, composed of unconsolidated Quaternary sand and gravel deposits, and the underlying finer-grained Tertiary sediments. This study uses the term Gallatin Valley Aquifer System (GVAS) to describe this groundwater system (English and Baker, 2004).

The Gallatin River and local tributaries are the primary sources for irrigation water. The streams and river interact with the groundwater system; in some locations streams receive groundwater discharge, while in other locations, streams provide recharge to groundwater. Canal leakage and surplus irrigation water applied to fields infiltrate into the subsurface and recharge groundwater. This enhanced recharge increases groundwater stored in the aquifer, which subsequently bolsters late-season surface-water flows.

An annual groundwater budget for the project area developed for 2010 used a monthly time step. The total annual budget was about 170,000 acre-ft/yr. Groundwater flow into the study area and canal leakage dominate budget inflow. Additional inflows include stream losses from the Gallatin River, tributary streams, and surplus water applied to irrigated fields. Groundwater budget outflows include groundwater flow out of the study area, discharge to rivers, riparian evapotranspiration, and domestic consumptive use.

Changes in groundwater levels through time in the study area are attributed to changes in irrigation recharge and variation in precipitation. Water levels measured at two wells through a year or more during the 1950s were compared to those of recent decades. One of these wells decreased by about 1 ft while the other showed no overall change. Water-level data collected at four wells between 1993 and 2018 showed a mixed response. One well had an upward trend of less than 1 ft, possibly due to decreased evapotranspiration demand from agricultural land. Two wells showed no trends in water levels, while the fourth well had an overall decrease of 3 to 4 ft during these years. This decline is attributed to irrigation system conversions at nearby fields. Domestic consumptive water use is minimal, accounting for only 2% of the groundwater budget outflow, and its influence on groundwater-level changes through time is not evident in the monitoring data.

Numerical modeling showed that future changes in land use, irrigation practices, and potential drought conditions are likely to decrease groundwater availability. Long-term urbanization, decreased irrigation-related recharge, and climatic variables may decrease groundwater flow through the area and ultimately influence river flow. Specifically, a reduction in canal leakage may affect groundwater quantity and water levels.

PREFACE

The Ground Water Investigation Program (GWIP) at the Montana Bureau of Mines and Geology (MBMG) investigates areas prioritized by the Ground-Water Assessment Steering Committee (2-15-1523 MCA) based on current and anticipated growth of industry, housing, and commercial activity, or agriculture. Additional program information is available at: http://www.mbmg.mtech.edu/gwip/gwip.html.

The final products of the Four Corners investigation include:

An **Interpretive Report** that presents data interpretations and summarizes the project results. This report's main focus addresses potential effects to groundwater from land-use changes, increased residential development, and potential future changes to the groundwater system. This report is available from MBMG's Publications page: (http://www.mbmg.mtech.edu/mbmgcat/catMain.asp)

A **Groundwater Modeling Report** (Sutherland and others, 2014) documents development of groundwater flow models, including a detailed description of the procedures, assumptions, and results of the models. Groundwater modelers and other qualified individuals can evaluate and use the models as a starting point to test additional water-use scenarios and for site-specific analyses. The MBMG publications website includes the model files under the report citation https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=31655&.

MBMG's Groundwater Information Center (GWIC) online database (http://mbmggwic.mtech.edu/) provides a permanent archive for the data from this study.

INTRODUCTION

The Four Corners area, Gallatin County, Montana has experienced conversion of land from irrigated and non-irrigated agriculture to residential, commercial, and industrial development over the past several decades. This study examines the effects of these changes on groundwater and surface-water resources. The study area includes approximately 42 mi^2 of developed and agricultural areas around the unincorporated community of Four Corners (fig. 1).

The population of Gallatin County, which is representative of the growth in the Four Corners area, grew by 32% between 2000 and 2010, and the number of housing units increased by almost 10,000, making it the fastest growing county in Montana (U.S. Census Bureau, 2011) during this period. This rapid growth has led to conversion of agricultural land to housing and commercial uses, reducing the amount of irrigated farmland in the county by 20% between 1953 and 2010 (State Engineer's Office, 1953; U.S. Census Bureau, 2011).

In the Four Corners area, irrigated acreage decreased by 55% from 1953 to 2010 (fig. 2). Newer, more efficient methods of irrigation have replaced much of the traditionally flood-irrigated land. For the same period, rural residential development resulted in an increase in the number of wells in the county and in the study area (fig. 3). The area also saw a growing reliance on groundwater-sourced municipal systems for residential water use. The decrease in flood irrigation recharge due to changes in irrigation practices and a conversion of irrigated land to rural residential development has raised questions concerning both the availability and the quality of groundwater.

Purpose and Scope

The purpose of this project was to assess whether large-scale land-use conversion from irrigated and non-irrigated agriculture to residential, commercial, and industrial development has altered local groundwater and surface-water conditions. This project included the following objectives:

- Evaluate effects to the groundwater system in the Four Corners area over the past 60 yr related to changes in irrigation practices and land use.
- Document the effects of irrigation application and canal leakage on groundwater recharge.
- Evaluate potential effects of future changes in land use, irrigation, and groundwater development, and potential effects of drought, using a numerical groundwater flow model.

The study included stream flow and groundwater elevation monitoring, sampling of groundwater and surface water, geologic descriptions, and aquifer testing. Data collection for this project started in 2010 and continued through 2015. A numerical computer model constructed for the project (Sutherland and others, 2014) simulates surface-water and groundwater interactions and was used to evaluate aquifer system response to specific stresses, such as changes in pumping and climate.

Previous Investigations

Information from previous studies provided a framework for this investigation. Murdoch (1926) completed an early study of the connection between groundwater, surface water, and the effects of irrigation in the Gallatin Valley, identifying groundwater recharge from irrigation and poor drainage as the cause of inundation of agricultural land in the northern part of the valley.

Hackett and others (1960) provided one of the most comprehensive assessments of hydrologic conditions in the Gallatin Valley. Hackett's report presented geologic mapping, groundwater level, and stream flow data from 1952 and 1953, from an extensive monitoring network. The report served as a basis for comparing hydrologic conditions in the early 1950s to current conditions described in this study. Hackett and others (1960) concluded that groundwater could supplement

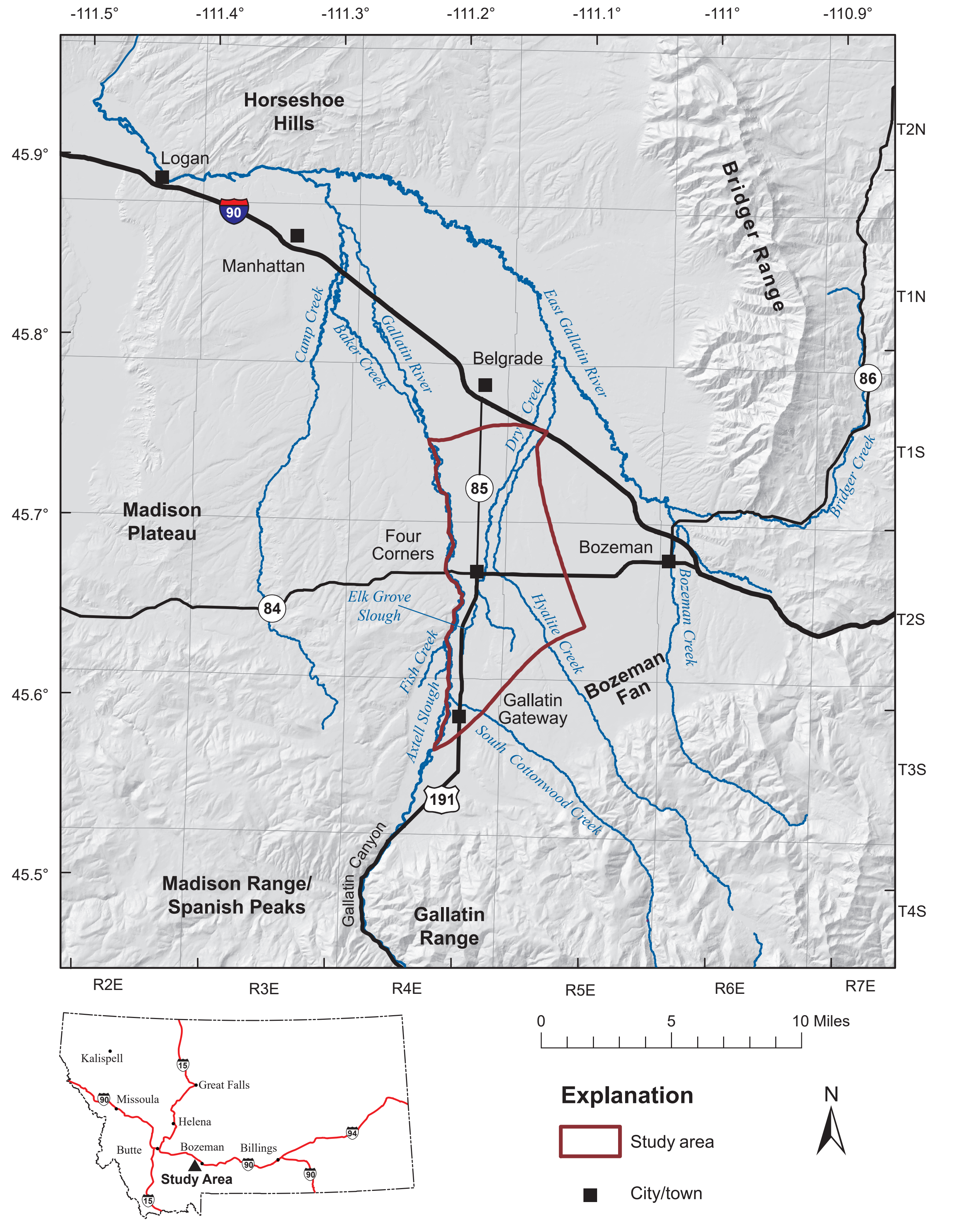

Figure 1. The Four Corners study area is located surrounding the town of Four Corners, Montana in Gallatin County.

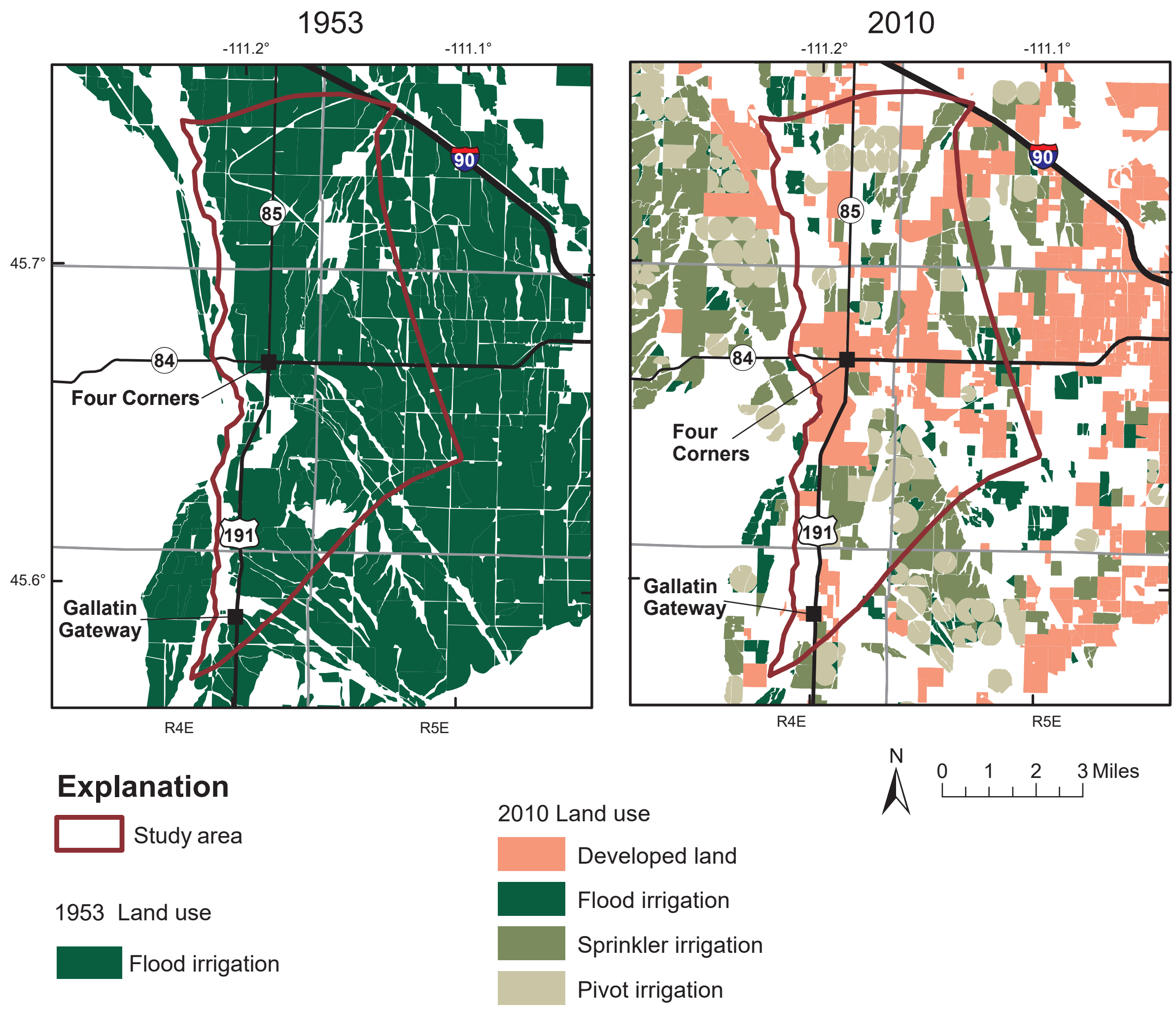

Figure 2. Land use in the study area in 1953 (left) compared to 2010 (right).

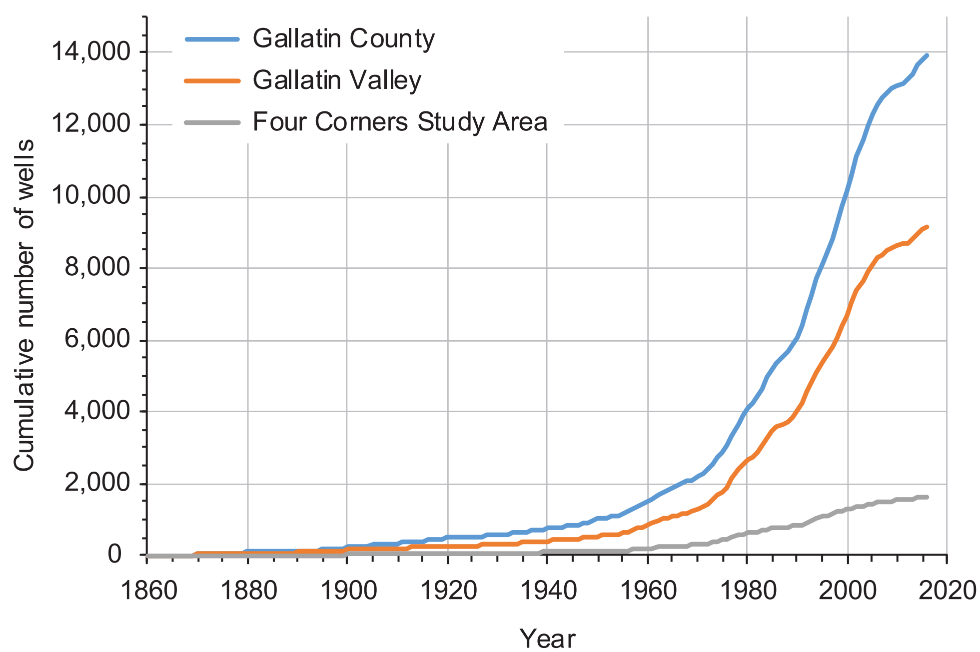

Figure 3.The total number of water wells in the region and study area grew rapidly between 1950 and 2010.

surface-water irrigation during dry years and be used to expand irrigation to uncultivated acres.

Dunn (1978) sampled and collected groundwater-level data to evaluate conditions since the 1960 Hackett report was completed. Slagle (1995) examined hydrologic conditions in the Gallatin Valley to assess the effects of land-use change. Neither Dunn nor Slagle reported notable changes to local water supplies. Kendy (2001) investigated nitrate in groundwater within the Gallatin Local Water Quality District (which includes Four Corners) and found generally low levels of nitrate and good water quality.

Custer and others (1991a,b) evaluated the hydrogeologic properties of the Bozeman Fan (fig. 1). Dixon (2002) examined aquifer properties based on drillers' log information and categorized local hydrogeologic units. Custer and Schaffer (2009) and Schaffer (2011) assessed groundwater/surface-water interaction, describing the close connection between the two. These studies provided details of the geology and hydrogeology near Four Corners.

English (2018) used existing information to evaluate the hydrogeology of the Gallatin Valley and identify areas that have the greatest potential for developing wells that yield greater than 950 gallons per minute (gpm). Using a framework of 12 "hydrogeologic subareas" identified by Hackett and others (1960), English compiled previously published geologic and hydrogeologic information, aquifer test data, and well log information from the Montana Bureau of Mines and Geology Ground Water Information Center (GWIC) to identify potential high-yield areas. The Four Corners study area reported on here is at the southern end of Hackett's Belgrade subarea, which is one of the most promising areas for producing sustainable high well yields.

Numerous other, smaller-scale hydrogeologic studies completed in the Gallatin Valley and the Four Corners area include theses and consultant reports submitted for water-rights applications. Although not widely available, these materials were reviewed as a part of this study.

Physiography

The Gallatin Valley covers about 540 mi^2 and occupies the eastern half of the Three Forks structural basin (Robinson, 1961). The valley is bounded by the Horseshoe Hills to the north, the Bridger Range on the east, and the Gallatin Range and the Spanish Peaks of the Madison Range to the south. The Madison Plateau forms the western boundary of the Gallatin Valley, and forms a topographic divide between the Gallatin and Madison River Basins (fig. 1).

The principal inlet for surface water to the Gallatin Valley is the Gallatin River, which enters from Gallatin Canyon at the southern (upper) end of the valley. The Gallatin River forms the western boundary of the study area, and includes water from South Cottonwood Creek. The Gallatin River's largest tributary, the East Gallatin River, receives flow from many smaller tributaries, including Hyalite Creek and Dry Creek, which flow through the study area and meet the East Gallatin east of Belgrade. The drainage outlet for both surface water and groundwater is a bedrock notch near the town of Logan.

The study area consists of a relatively flat valley floor consisting of the Gallatin River floodplain and the higher-elevation benches, referred to collectively as the Bozeman Fan area. These benches are typically 50 to 100 ft higher than the adjacent floodplain. The area slopes approximately north–northwest following the overall orientation of the Gallatin Valley. Elevations range from approximately 4,490 ft at the northwestern boundary to 5,210 ft on the plateau of the Bozeman Fan (USGS, 2009). The Bozeman Fan forms a hilly area encompassing the southeastern portion of the study area and consists of mounded depositional sediments. Topographic lows fall along the streambeds of the Gallatin River and Hyalite and Dry Creeks.

Dry Creek is spring-fed and originates within the study area near the southern boundary. Hyalite Creek flows roughly parallel to Dry Creek, but originates outside of the study area in the Gallatin Mountains. South Cottonwood Creek, which transects the southwestern portion of the study area prior to flowing into the Gallatin River, originates in the Gallatin Mountain range. Other surface waters adjacent to the study area include Fish Creek, a spring-fed creek to the west; Axtell Slough, directly adjacent to Fish Creek; and Elk Grove Slough, a former river channel that directs water for irrigation just south of Four Corners (fig. 1).

Climate

Gallatin Valley's climate is semiarid, with cool summers and cold winters. Climate data from the Western Regional Climate Center (WRCC) for the Belgrade Airport station (elevation of 4,460 ft), the Montana State University station (elevation of 4,913 ft), and the Bozeman Experiment Farm station (elevation of 4,780 ft) were compiled for this study (WRCC, 2018a,b,c: stations 240622, 241044, and 241047, respectively).

The Belgrade Airport station is approximately 7 mi north of Four Corners; the Montana State University station is approximately 7 mi east. While the Experiment Farm station falls within the study area (approximately 1.5 mi east of Four Corners), its period of record begins in 1967, which is shorter than the other stations. Temperature and precipitation records for the Experiment Farm station fall within the range of 1967–2018 data for the two nearby climate stations.

Average annual precipitation was 13.8 in at the Belgrade climate station and 19.1 at the Montana State University station between 1950 and 2018 (table 1). Average monthly precipitation is highest from April to June (fig. 4). The warmest temperatures occur in July–August and coolest temperatures during December–January. The annual deviation from average precipitation (13.3 in) at the Belgrade Airport station shows mostly drier years in the 1950s, wetter years from the 1960s through the mid-1990s, and predominantly drier years since 1998 (fig. 5). The data indicate that 14 of the past 18 yr were drier than average (fig. 5). During the data collection period for this project, 2010–2015, 2010 and 2015 were about 1 to 1.5 in above average precipitation, whereas 2011, 2012, and 2013 were 2 to 4.5 in below average.

The data from these climate stations are representative of the climate in Four Corners and lowlands along the Gallatin River; however, precipitation totals for the mountainous areas of the Madison, Gallatin, and Bridger Ranges exceed 44 in per year. Most of this precipitation occurs as snow, with snow depths exceeding 60 in common at higher elevations (Shower Falls SNOTEL station 754; SNOTEL, 2013).

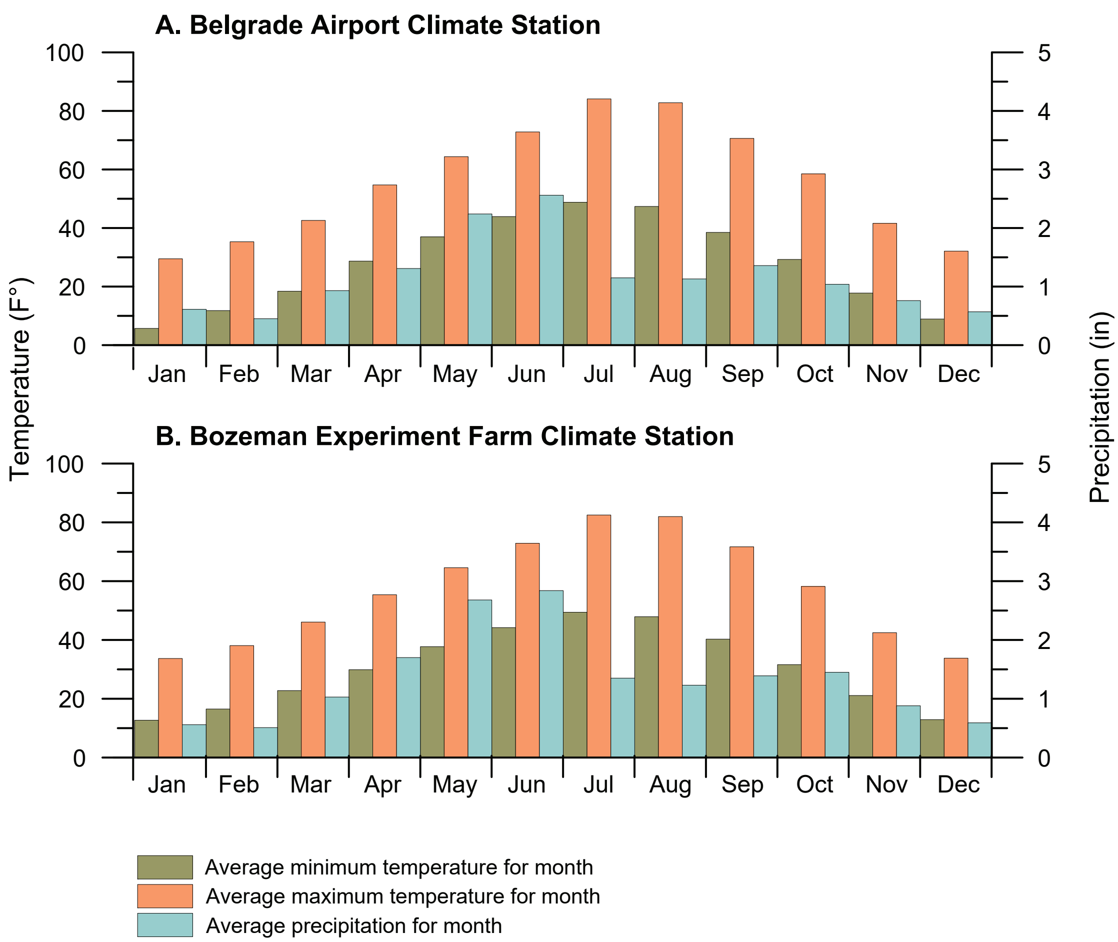

Figure 4. The average monthly precipitation is highest from April to June and lowest from December to February, based on the 1980–2010 30-yr average (source: www.wrcc.dri.edu).

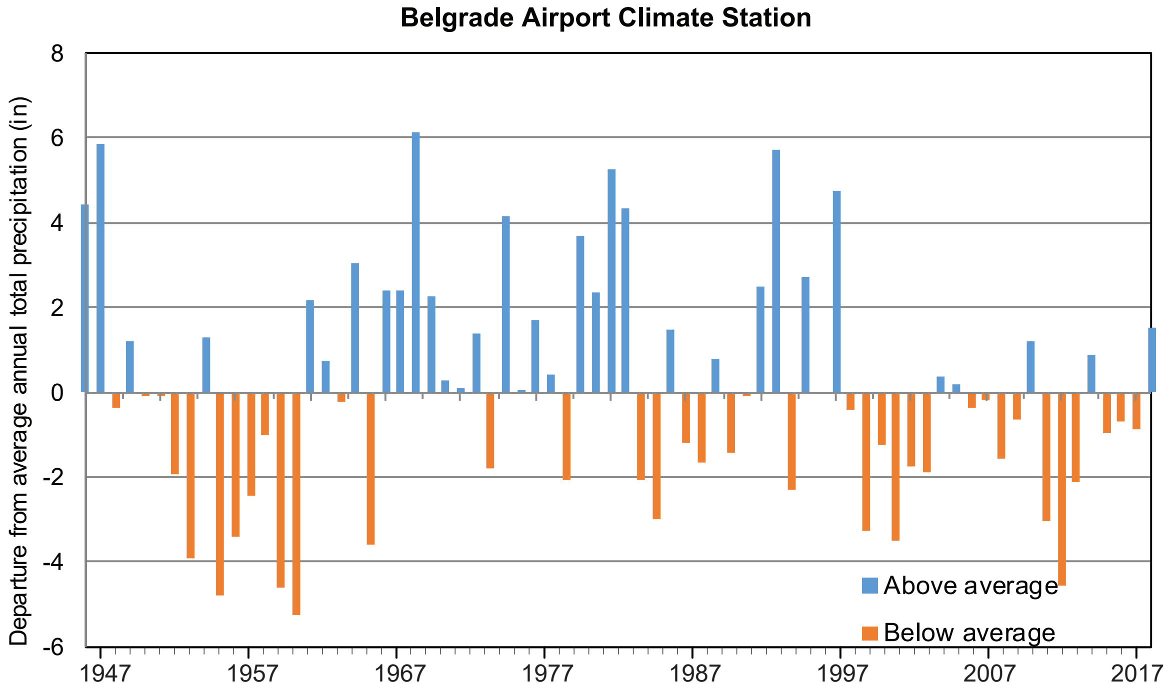

Figure 5. Since 1946, annual precipitation has ranged from about 5 in below to about 6 in above the annual average (13.8 in).

Table 1. Primary climate statistics for the three stations near the study area.

Station	Average Annual Precipitation	Average Annual Minimum Temperature	Average Annual Maximum Temperature
Belgrade Airport	13.8 in	28.4° F	56.2° F
Montana State University	19.1 in	32.0° F	56.6° F
Bozeman Experiment Farm	16.1 in	30.8° F	56.9° F

Note. Statistics reported for the period 1950–2018 for the Belgrade Airport and the Montana State University climate stations. The Bozeman Experiment Farm includes the period 1967–2018.

Water Supply Infrastructure

Water infrastructure includes water wells, irrigation canals, irrigated fields, and subdivisions with water distribution and wastewater collection systems (fig. 6). The golf courses, parks, and septic systems (not shown in fig. 6) in the area may affect groundwater quantity and quality, but were not included in this study. The Four Corners County Water and Sewer District serves most properties developed since 2003, but older properties rely on individual well and septic systems.

Almost 2,000 mi of irrigation canals and laterals distribute irrigation water throughout the valley. The main source of irrigation water in the valley is the Gallatin River, with smaller irrigation diversions from Hyalite, Dry, and South Cottonwood Creeks. These creeks also serve as conveyances for some canal companies. Infiltration of water in excess of crop demand and canal leakage recharges groundwater. The study area includes 172 mi of irrigation canals, on-farm laterals, and drains (fig. 6B). As of 2010, irrigated acres totaled 5,350 (fig. 2).

The Four Corners Water and Sewer District (2019) operates a public water supply system and a public wastewater treatment system that infiltrates treated wastewater back to the aquifer. The sewer and water district also operate a groundwater recharge system to mitigate the impacts from public water supply wells (public supply wells shown in fig. 6). This recharge system is outside of the study area and is not accounted for further in this report.

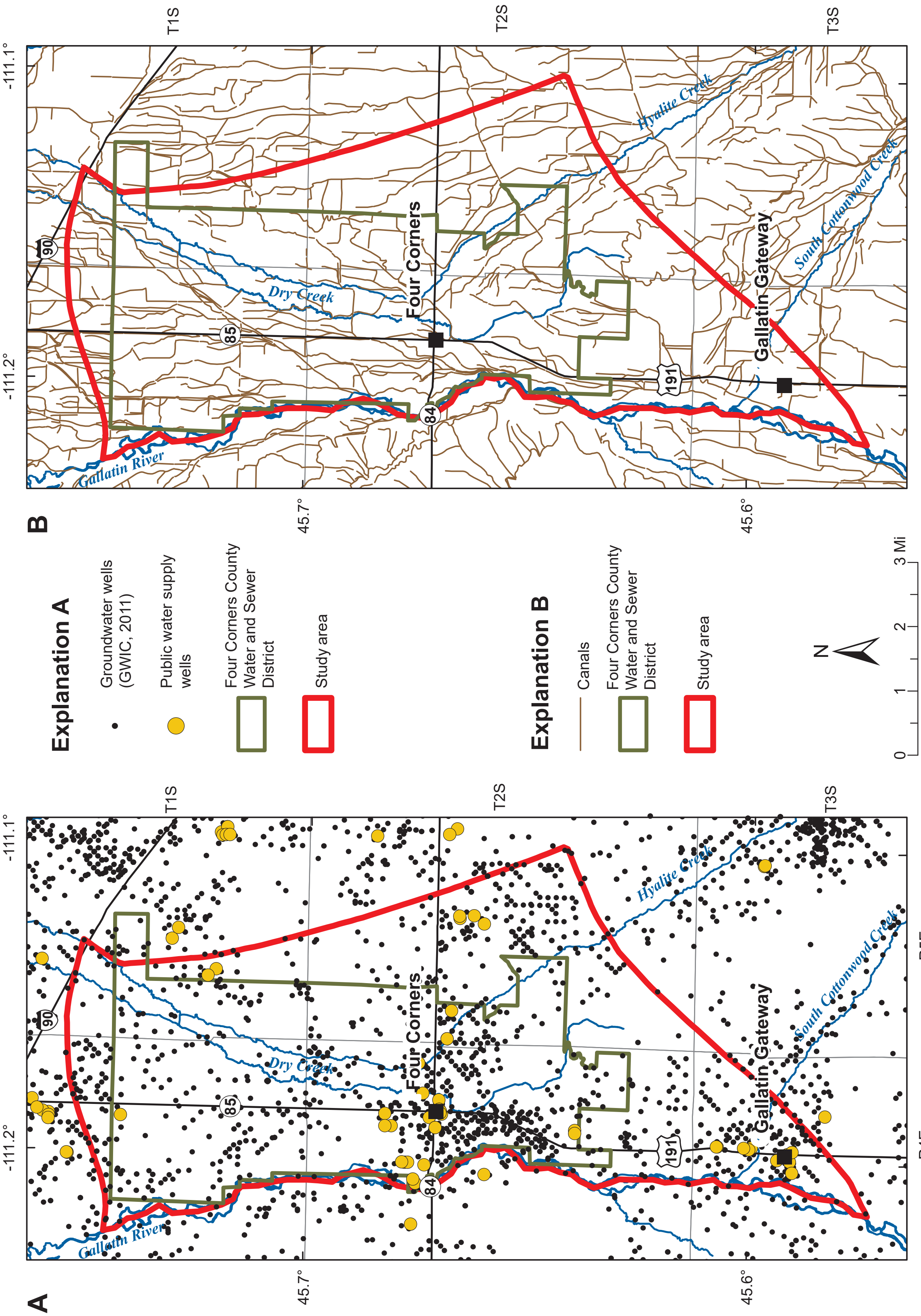

Figure 6. Locations of 21 public supply wells, the Four Corners County Water and Sewer District (FCCWSD, 2019) over 1,334 wells with records in GWIC (A), and irrigation canals, including on-farm laterals and drains (B).

In Montana, wells that pump 35 gpm or less, and do not exceed 10 acre-ft per year, are exempt from the water-right permitting process. Most of the 1,300 domestic wells within the study area (GWIC, 2011) are exempt wells, including domestic wells that withdraw groundwater for household, lawn, and garden uses. The accompanying septic systems return a portion of the extracted water back into the ground.

Geologic Setting

The Gallatin Valley is an intermontane basin formed by Basin and Range style extension. The valley floor dips to the northwest. Underlying bedrock structures dip to the east, with steeply dipping normal faults along the front of the Gallatin and Bridger Ranges; these define the eastern and southern margins of the valley (Vuke and others, 2014).

Hackett and others (1960) described the geology of the Gallatin Basin in detail. Vuke and others (2014) mapped the surficial geology (fig. 7) at a scale of 1:100,000. Vuke (2003) provided a more detailed 1:50,000 surficial map of the western Gallatin Valley. Additional geologic mapping has been done by Custer and others (1991a,b), Slagle (1995), Dixon (2002), and Lonn and English (2002).

Bedrock underlying the study area consists of Archean metamorphic basement rocks composed mainly of schist and gneiss. The basement rocks crop out west of the Gallatin River and southwest of Four Corners (fig. 7, map unit XAqfg). Above the bedrock, two general types of sediments are: (1) Tertiary sediments that form benches generally east and west of the modern floodplain; and (2) Quaternary alluvial sediments deposited by the Gallatin River as it eroded into the Tertiary sediments that cover the Gallatin Valley floor and floodplain.

The contact between the Tertiary sediments and the bedrock is poorly defined in the study area, as only a few wells are drilled to bedrock. Well logs indicate the Tertiary sediments range from about 200 to 400 ft in thickness. Tertiary sediments make up the Madison Valley Member of the Sixmile Creek Formation (fig. 7, map unit Tscmv). Variably cemented sediments, siltstones, sandstones, and conglomerates characterize these materials. At depth are Tertiary formations of the Dunbar Creek and Climbing Arrow Members of the Renova Formation (Vuke, 2003; Vuke and others, 2014).

Quaternary sediments overlying the Tertiary sediments range from non-existent (in the case of the Tertiary exposures on the southern benches) to over 100 ft thick in areas of river deposition. Collectively, these sediments exceed 1,000 ft in thickness in other parts of the valley (Vuke and others, 2014). Vuke and others (2014) further subdivided the Quaternary sediments into separate units, based on relative age and provenance, but the sediments generally contain cobbles, sand, gravel, and silt/clay deposited by current and recent river channels and alluvial fans (fig. 7, map units Qal, Qls, Qdf, Qac, Qaf, Qab, Qafh, Qafo, Qabo, Qalo, QTgr).

METHODS

Data Management

Data collected for the Four Corners investigation are stored in MBMG's GWIC database (http://mbmg-gwic.mtech.edu/). GWIC contains information on well completions, groundwater levels, water chemistry, aquifer tests, and other information. GWIC identification numbers reference locations and sites where data were collected for this report. The data associated with this study are presented at: http://mbmggwic.mtech.edu/sqlserver/v11/menus/menuProject.asp?mygroup=GWIP&myroot=BWIP4C&ord=1&. Appendices A, C, and D contain summaries of the data cited in this report.

Groundwater and Surface-Water Monitoring

Ninety-five wells were used to obtain water-level and water-quality data for this study (fig. 8; appendix A, table A-1). Existing wells were selected based on availability, well owner cooperation, historical record, geographic location, and hydrogeologic setting. Twenty-four monitoring wells were installed for this project at four test sites, one of which (Stagecoach Trail) was located outside of the study area (fig. 8). Water levels from these wells were used to calculate hydraulic gradients and compile potentiometric surface maps used to develop the groundwater budget. Wells and data were also included from the MBMG's Ground-Water Assessment Program (GWAP) monitoring network. Some of these wells were installed by the Gallatin Local Water Quality District (GLWQD), and some in association with a Montana State University study (Schaffer, 2011). Wells and surface-water sites were monitored generally monthly from the spring of 2010 through July 2014.

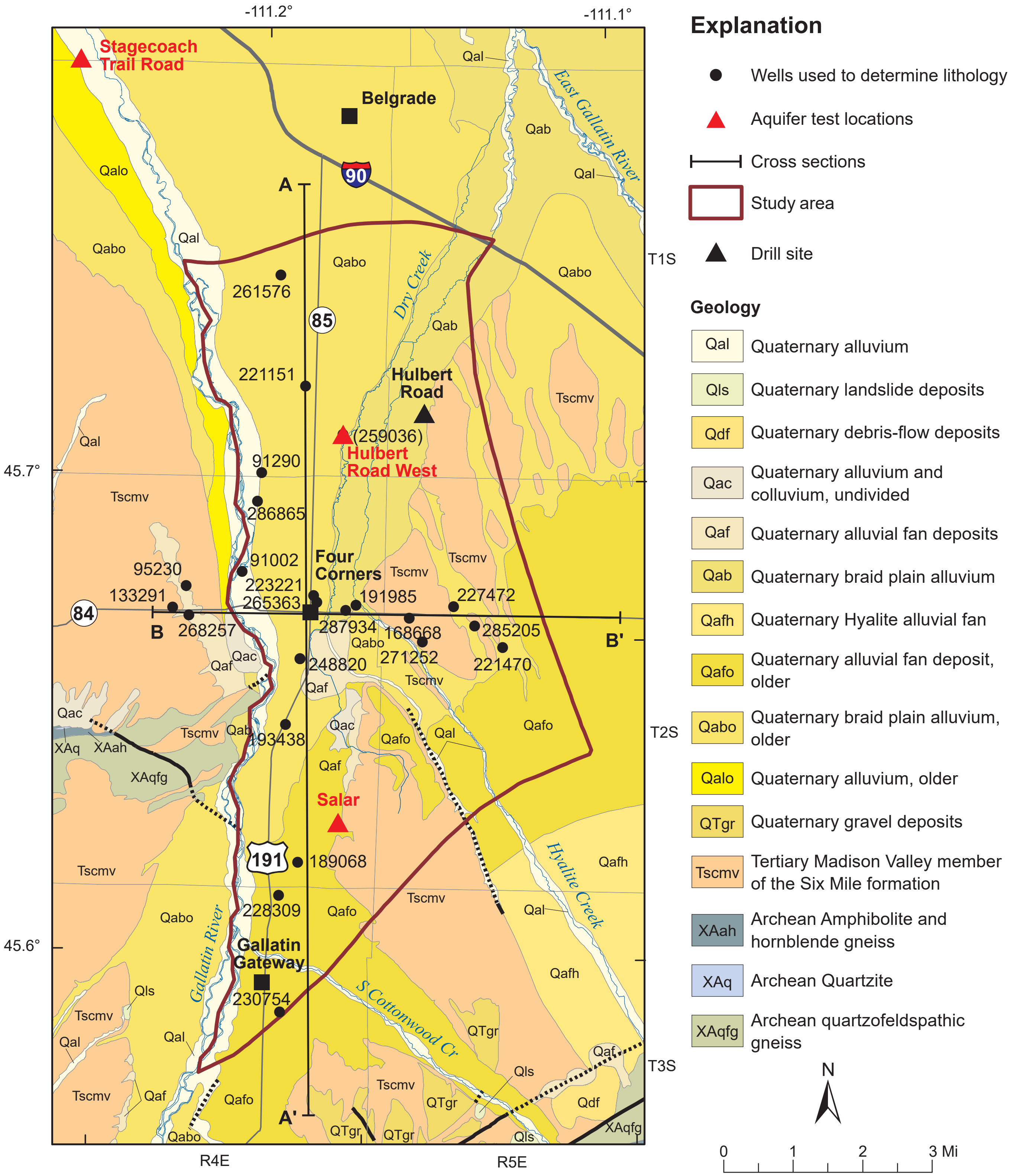

Figure 7. The surficial geology of Four Corners is mainly composed of Quaternary alluvial deposits in floodplains with Tertiary sediments underlying and forming lateral benches (from Vuke and others, 2014; see figs. 11 and 12 for cross sections A–A´ and B–B´).

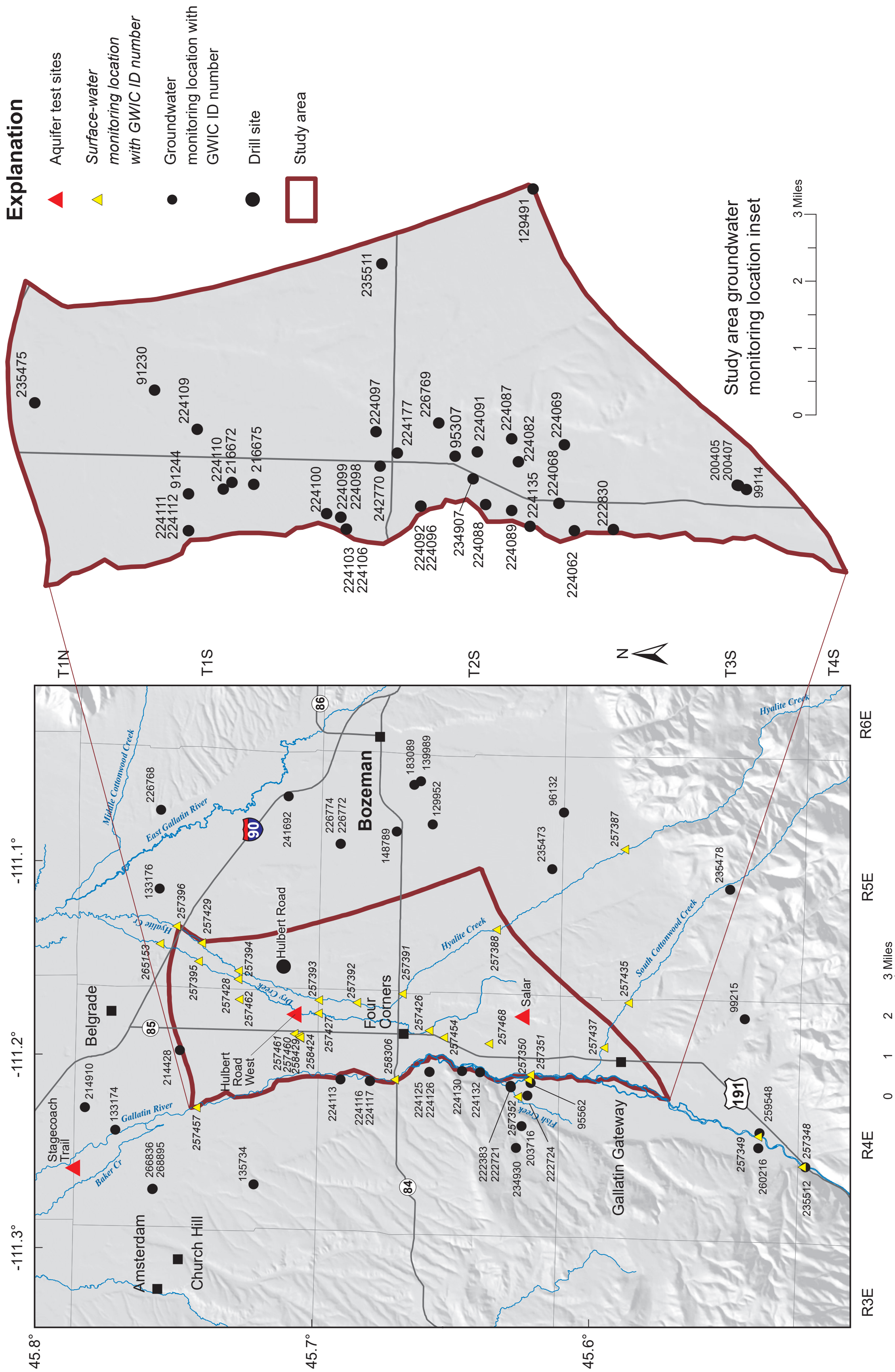

Figure 8. Locations of 95 wells and 29 surface-water sites monitored during this study.

Water levels were measured in wells using an electric tape. Forty-seven wells in the monitoring network were equipped during different periods with pressure transducers and data loggers that recorded measurements hourly.

GWIP investigators monitored discharge and stage at 29 surface-water sites in and around the study area, including the Gallatin River; South Cottonwood, Hyalite, Dry, and Fish Creeks; Axtel and Elk Grove Sloughs; and Mammoth Ditch (fig. 8; appendix A, table A-2). A Sontek River Surveyor Acoustic Doppler Current Profiler (ADCP), a Sontek FlowTracker Acoustic Doppler Velocimeter (ADV), and an OTT MF-Pro electromagnetic current meter were used to measure instantaneous discharge. Stage levels were recorded at staff gages, from surveyed locations on bridges, and from stilling wells equipped with water-level data loggers.

A licensed professional surveyor surveyed almost all groundwater and surface-water sites for location and elevation. Appendix A details the wells and surface-water sites.

Aquifer Testing

Aquifer tests were conducted at three sites (including Stagecoach Trail, north of the study area) to evaluate aquifer properties in the shallow Quaternary alluvium and the underlying Tertiary sediments (fig. 8). The Hulbert Road drill site, developed as a fourth aquifer test site, experienced challenges related to artesian flow conditions. Although not aquifer tested, wells at this site provided water levels to assess hydraulic gradients. One production well and five monitoring wells were drilled at each location. Each test consisted of at least 1 week of pre-test water-level monitoring, approximately 7 days of pumping, and water-level measurements through recovery to pre-pumping conditions. Manual measurements verified water-level data recorded with transducers and data loggers. A digital flow meter recorded pumping rates and the total volume of water pumped during the tests.

GWIP personnel conducted and analyzed aquifer tests in accordance with ASTM standards (ASTM, 2010). Data on aquifer properties were also obtained from water-rights applications held by the Montana DNRC, and from previous studies. Details of, and data collected for, aquifer tests completed during this study are available in GWIC using the pumping well identification numbers: Stagecoach Trail Road, 255476; Hulbert Road West, 259052; and Salar, 259053 (figs. 7, 8).

Canal Leakage

GWIP personnel investigated canal leakage on six canal systems (fig. 9) to quantify water loss, aid in development of a water budget, and provide data for the numerical groundwater flow model developed by Sutherland and others (2014).

The Sonnichsen (1993) inflow–outflow method was used to estimate canal seepage. Canal flow was measured at two locations between 1 and 5 mi apart on reaches with no known active diversions. A Flowtracker Accoustic Doppler Velocimeter was used to collect flow measurements at all locations. With the exception of Farmers Canal, flow measurements were taken after initial wetting, when canal flow was relatively stable and before end of season shut off. The difference in flow is the amount of loss (seepage) estimated to recharge the underlying aquifer. Evaporation was considered negligible over the reaches of canal measured as the volume would fall within the measurement error. Although presented in appendix C for completeness, the Farmers Canal measurement was not used to estimate the average canal seepage rate because wetting conditions during measurement were not ideal. Measured flow rates were generally within a ±5 percent margin of error (Montana Department of Natural Resources and Conservation, 2018).

Lack of detailed maps hindered evaluation of the extent of the canal system, although the network of canals appears to be largely intact since it was described in 1953, based on comparison with aerial imagery (State Engineers Office, 1953; NAIP, 2015). Estimates of the length of the canal network ranged from 121 mi, based on a ranking of the largest flowing canals (G. Alberda, written commun., 2012), to 215 mi, based on the 1953 maps (State Engineers Office, 1953).

Long-Term Groundwater-Level Trend Analysis

We evaluated historic water-level data to assess changes between water levels during the 1950s (Hackett and others, 1960) and more recent years (1990s–2018) and to examine water-level trends from the 1990s through 2018. Long-term water-level records from the study area included only one 15-ft-deep hand-dug well that was abandoned in 2001(well

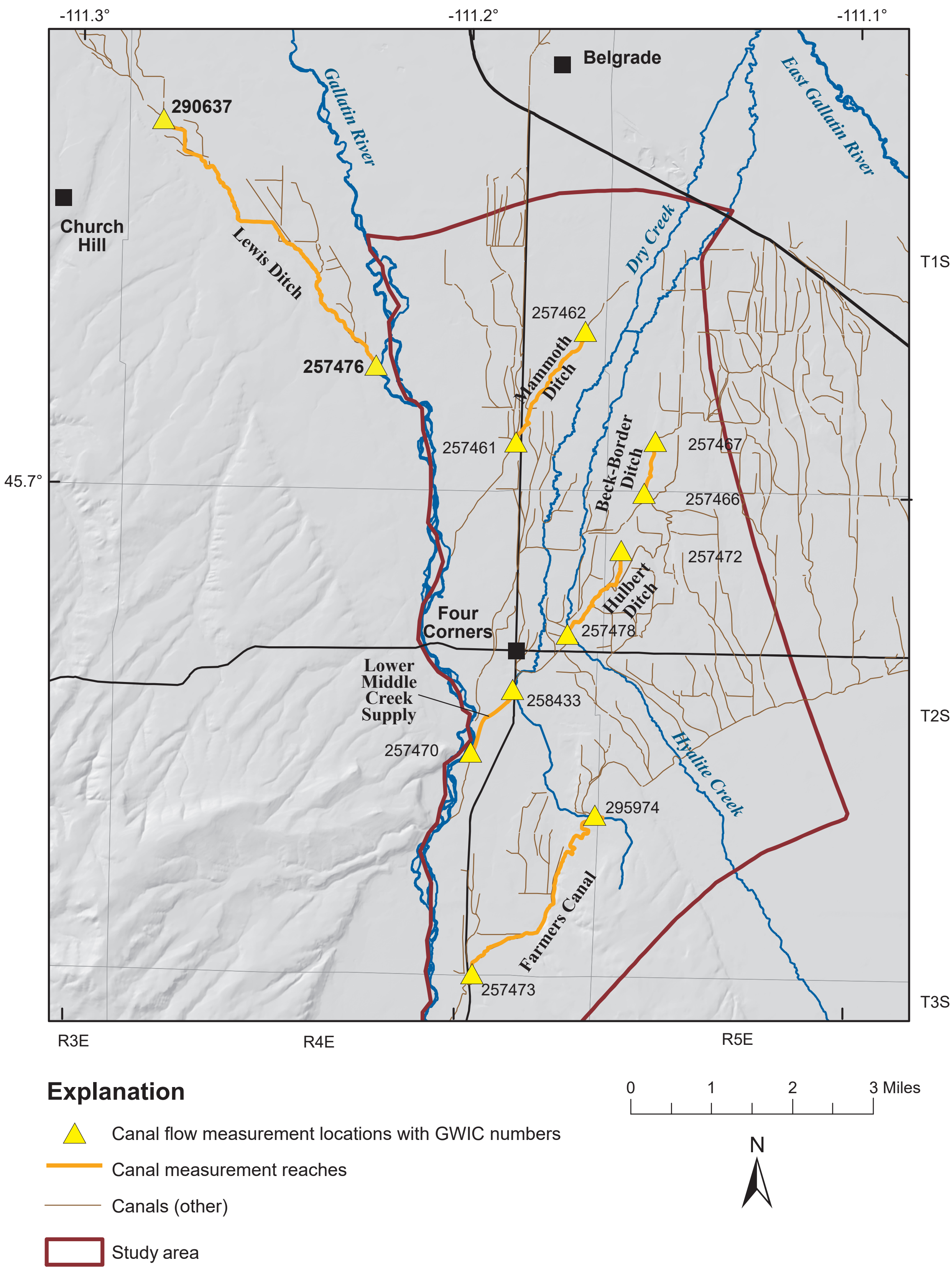

Figure 9. Flow measurements were made on six canals to estimate leakage rates.

95307). For that reason, we included four wells within 3 mi of the study area (fig. 8). At wells with just one to three measurements from the 1950s, we present these limited data for visual comparison to more recent decades. For wells with larger data sets, one of two statistical tests were applied, depending on the number of water-level measurements and their temporal distribution: the Wilcoxon–Mann–Whitney rank sum test, and the seasonal Mann–Kendell monotonic test (table 2; Helsel and Hirsch, 2002). The Hodges–Lehmann estimator (Helsel and Hirsch, 2002) established the magnitude of the trend. The XLSTAT add-on package for Excel (Addinsoft, 2018) was used to perform this analysis.

Water-level comparison between the 1950s and recent decades

The seasonal Mann–Kendall test was applied to the record from well 95307, which has measurements from the 1950s through 2001. The data were assigned to calendar quarters (Jan–Mar; Apr–Jun; Jul–Sep; and Oct–Dec) so that like seasons were compared throughout the period of record to evaluate water-level changes. At some wells and during certain periods, groundwater was measured once during the quarter, and these measurements were used to represent levels during that quarter. At sites or times where more frequent levels were measured (monthly or hourly data), the water level closest to the middle of the quarter (referred to as the quarterly mid-point water level) was used in the analysis (i.e., for Jan–Mar, the water level closest to Feb 15).

The data available from well 129491 included 393 water levels measured between March 1953 and April 1954 followed by a gap in measurements until 1992. We used the nonparametric Wilcoxson–Mann–Whitney rank sum test to compare the two periods.

Water-level comparison 1990s to 2018

The seasonal Mann–Kendall trend test was applied to wells 96132, 129491, 133174, and 133176 using the most recent 25 years (1990s–2018). The data were assigned to calendar quarters for this analysis, as described above.

Groundwater and Surface-Water Chemistry

Water samples were collected and analyzed for major ions, trace elements, and nitrate–nitrite N (appendix B, table B-1). Water samples from 24 surface-water sites and 22 wells were examined (fig. 10). Data from earlier studies (pre-2009) from eight wells were also used (appendix B, table B-2). Surface-water samples were collected from four locations on the Gallatin River, four creeks (South Cottonwood, Dry, Fish, and Hyalite Creeks), two sloughs (Elk Grove and Axtell), and one canal (Farmer's Canal; appendix B, table B-3).

Field personnel measured specific conductance, pH, and temperature during sampling events. The MBMG Analytical Laboratory analyzed samples for major cations, anions, and trace elements using methods described by Timmer (2020). Complete results of these analyses are available through the GWIC database.

Samples were also collected during this study for analysis for pharmaceuticals and personal care products. Interpretation of these data was hindered by contamination of field and laboratory quality control samples, and the data are not presented in this report.

Table 2. Number of water-level measurements made during each decade and the method used to compare 1950s to recent water levels.

Site	1940	1950	1960	1970	1980	1990	2000	2010	Statistical Analysis
96132		1				1160	32000	75437	Visual comparison
133176		1				36	57	79	Visual comparison
133174		3				39	56	80	Visual comparison
95307	18	103	102	104	26	31	5		Seasonal Mann Kendall
129491		403				20	25	77	Wilcoxon–Mann–Whitney rank sum

Note. Each column is SWL per decade.

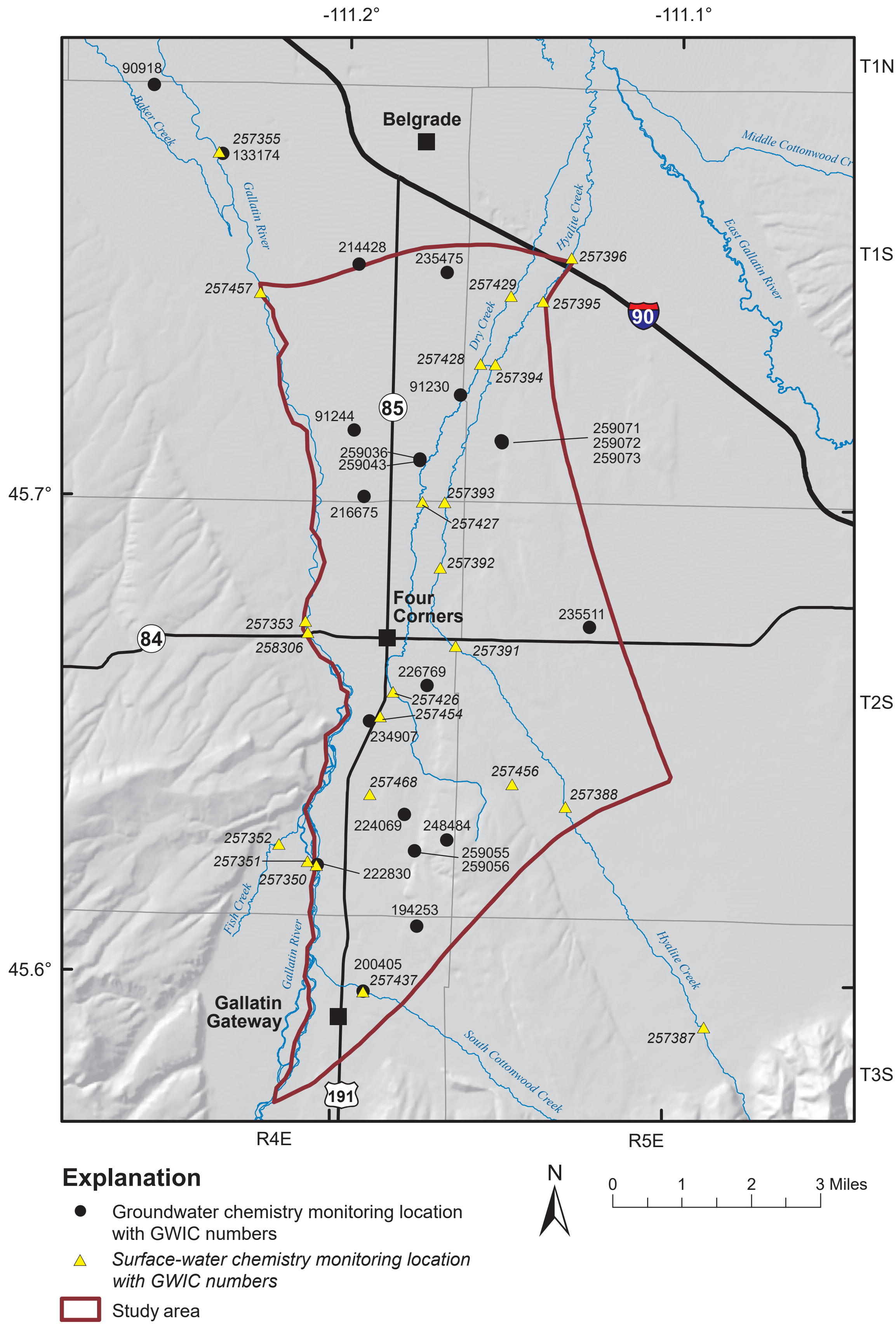

Figure 10. Water chemistry samples were collected from 20 wells and 20 surface-water sites.

Groundwater Budget

A groundwater budget provides a quantitative estimate of each component of the groundwater system. For this project, we developed a groundwater budget based on numerical modeling (Sutherland and others, 2014), and interpretation of the data collected during this study. Fetter (2001) presents a general equation for such a budget:

$$\text{Inputs} = \text{Outputs} \pm \text{Changes in storage.}$$

For this study, the general equation was expanded to:

$$GW_{in} + R_{can} + R_{irr} + STC_{in} = GW_{out} + DW_{out} + ET_r + STC_{out} + STR_{out} \pm \Delta S,$$

where: GW_{in} is groundwater inflow from upgradient; R_{can} is groundwater recharge from canal leakage; R_{irr} is groundwater recharge by infiltration from pivot, sprinkler, and flood irrigation; STC_{in} is leakage to the aquifer from South Cottonwood Creek, Dry Creek, and Hyalite Creek; GW_{out} is groundwater outflow from the aquifer; DW_{out} is domestic consumptive use of groundwater; ET_r is evapotranspiration by riparian vegetation; STC_{out} is groundwater discharge to South Cottonwood Creek, Dry Creek, and Hyalite Creek; STR_{out} is net groundwater discharge to Gallatin River; and ΔS is change in groundwater storage. Negative values represent reduction in the volume of water in storage.

All terms in this equation are expressed in acre-feet per month (acre-ft/mo) or per year (acre-ft/yr).

Appendix C includes the details on the derivation of the water budget components.

Groundwater inflow and outflow (GW_{in} and GW_{out})

Groundwater flow into and out of the project area was calculated in monthly time steps for the year 2010 using Darcy's Law (Fetter, 2001), applied across volumes of the aquifer referred to as "flow tubes." Inflow across the southern boundary was calculated in six flow tubes (appendix C, table C-1). Outflow across the northern boundary was calculated through two flow tubes. The groundwater flux was taken as the sum of these flows for each boundary.

Darcy's Law states:

$$Q = KiA \frac{dh}{dl},$$

where: Q is volumetric flux (ft^3/d); Ki is horizontal hydraulic conductivity (ft/d); A is cross-sectional area (ft^2); and $\frac{dh}{dl}$ is hydraulic gradient (ft/ft, or unitless).

Hydraulic conductivity values for these calculations were from the ranges used to calibrate the steady-state model (Sutherland and others, 2014) and were within the ranges reported from aquifer testing in the Gallatin Valley. We applied a range of K values to the monthly flux calculations to generate a range of aquifer flux into and out of the aquifer.

The width (w), or diameter, of each tube was measured in ArcGIS. The aquifer thickness (b) was the saturated thickness along each boundary. Area (A) was calculated by multiplying the width and thickness. We selected three wells nearest to each tube and used the monthly water levels from those wells to determine the horizontal hydraulic gradients within each flow tube.

Groundwater recharge from canal leakage (R_{can})

The canal leakage rate was estimated from multiple flow measurements in some of the largest canal systems in and near the study area (appendix C, table C-2). Canal leakage rates vary temporally as stages change throughout the season, and spatially as the sediment lining shifts or the canal passes over various geologic units. A single average leakage rate, based on measurements from large arterial canals and small lateral canals, was applied uniformly to three estimates of total canal length in the study area (121, 168, and 215 mi). This range represents a low, average, and high estimate of existing canals (appendix C, table C-3).

Groundwater recharge from irrigation (R_{irr})

The term *groundwater recharge from irrigation* in this report refers to irrigated land in the study area, and accounts for direct precipitation on that land in addition to applied irrigation water. The estimated R_{irr} is the sum of applied irrigation water and monthly precipitation minus crop use (ET).

The amount of groundwater recharge from irrigation (R_{irr}) depends on the irrigation method, the consumptive use (evapotranspiration, or ET) by specific crops, and the precipitation record. For this study, we based crop consumption on the number of irrigated acres (Montana Department of Revenue, 2010), percentage of specific crops grown in Gallatin County (USDA, 2008), and water requirements of each crop type (United States Soil Conservation Service, 1970). Irrigation water requirement and precipitation were included as applied water in irrigated areas throughout the growing season. The distribution of various irrigation methods was determined from the 2010 Final Land Units map (Montana Department of Revenue, 2010) and verified with aerial imagery.

Irrigation water requirement is the crop water requirement (ET) minus precipitation and then adjusted for irrigation application efficiency. Monthly water requirements estimated for the four primary crops grown in the valley were multiplied by the number of acres of each crop. ET measurements are accurate to within 15% (Kelsey Jensco, written commun., February 15, 2019), and that percent error was applied to develop a range of values for this budget term.

Groundwater recharge from and groundwater discharge to streams (STC_{in} and STC_{out})

Groundwater/surface-water interactions between the aquifer and South Cottonwood Creek, Dry Creek, and Hyalite Creek were averaged over the length of the creeks within the study area. In order to minimize the effects that irrigation withdrawals have on stream flows during the irrigation season, we averaged streamflow measurements from non-irrigation months (March, April, and October) and applied this value to all months in the budget. On each of the three streams, the flow leaving the study area (the gaging station nearest the northern boundary) was subtracted from the flow entering the study area (the gaging station nearest the southern boundary) to estimate stream loss to groundwater or stream gain from groundwater. We generated a range of values for this budget term by applying a multiplier of 15%, based on the accuracy of flow measurements for less than ideal settings.

Domestic consumptive use of groundwater (DW)

Residential and municipal wells provide water for indoor use and associated lawn and garden irrigation. Most indoor domestic water returns to the subsurface via septic or other wastewater systems. In this report, this term does not include that water, but accounts for consumptive water use at residences in the study area. Indoor domestic consumption (DW) was based on the estimated 2,500 houses in the project area and an average indoor consumption rate of 0.03 acre-ft/yr per household (DNRC, 2011). The approximate average lawn and garden size was determined by measuring the irrigated portion of lots in a randomly selected 10% sample of single-family properties within the project area. The average lawn and garden size was 0.8 acres, and in the Bozeman area, lawns and gardens consume about 1.6 acre-ft/yr per acre (DNRC, 2011).

All houses rely on groundwater, through either private domestic wells or connections to the Four Corners County Water and Sewer District. We did not distinguish between these two potential sources because the effect on the aquifer is the same.

Lawn evaporation accounted for most of domestic consumptive use, and the accuracy in the ET estimate is about 15% (Kelsey Jensco, written commun., February 15, 2019). We applied this estimate of 15% to develop a range of values for domestic groundwater consumption.

Evapotranspiration by non-irrigated lands and riparian vegetation (ET_r)

In the Gallatin Valley, potential ET for non-irrigated land typically exceeds precipitation rates throughout the growing season (Wight and others, 1986; USDA, 2015; Mueggler and Stewart, 1980). The potential ET for non-agricultural plants exceeded precipitation rates for 2010. In addition, from November through February, average temperatures were below freezing, which impeded infiltration. Therefore, we assumed precipitation in non-irrigated lands did not recharge groundwater.

Riparian vegetation in the project area is primarily cottonwood trees and willows, which typically consume about 2 ft of water during the growing season (Hackett and others, 1960; Lautz, 2008). ArcGIS aerial imagery was used to estimate the total area of riparian zones, which was then multiplied by the ET rate for cottonwood trees. Monthly distribution was based on the monthly variation of reference ET rates from AgriMet data for 2010 (U.S. Bureau of Reclamation, 2014). The accuracy of ET measurements is about ±15% (Kelsey Jensco, written commun., February 15, 2019), and this value was applied to develop a range of values for ET on non-irrigated land.

Groundwater discharge to Gallatin River (STR_{out})

The Gallatin River is characterized by braided channels, turbulent flows, and many irrigation diversions. These factors complicate collecting flow measurements on the river. Therefore, groundwater discharge to the river, and river leakage to the aquifer, were estimated with results from the steady-state model (Sutherland and others, 2014). In order to simplify the gains and losses that occur over limited reaches, the flow volumes were quantified as river gains (negative) and river losses (positive). The river forms the western boundary of the model, and the model results, therefore, only include groundwater/surface-water interactions along the eastern side of the river. We used annual discharge to (negative term) and recharge from (positive term) the river simulated by the steady-state model to estimate this budget term. We developed the minimum and maximum estimates of groundwater interactions with the Gallatin by applying minimum and maximum streambed conductance values published for similar hydrogeologic settings (Calver, 2001).

The model results showed: (1) groundwater discharge to the river in the southern one-third of the study area, (2) alternating reaches of discharge and recharge at low rates through the middle area, and (3) groundwater recharge from the river in the northern one-third. We used the annual net change for the entire river reach within the study area and divided it equally between the 12 monthly time steps in the budget.

Change in groundwater storage (ΔS)

Water levels from 32 wells were used to develop a potentiometric surface for each month of 2010 using the Spline algorithm in ArcGIS (ESRI, 2017). The selected wells were those completed at comparable depths in the groundwater system to avoid use of water levels measured in locally confined areas, and those that had a monthly manual water measurement. We calculated the change in volume between surfaces from the beginning to the end of each month. This served as an estimate of the monthly gain or loss of storage from the aquifer, using a representative aquifer porosity (n) of 0.15 for the entire study area (26,820 acres). Positive values represent estimated increases in storage, whereas negative numbers represent estimated loss from groundwater storage.

Numerical Modeling

Sutherland and others (2014) developed a numerical groundwater flow model to evaluate effects on the groundwater flow system and local stream flows from the conversion of irrigated agricultural land to residential and commercial uses. The model reproduced aquifer conditions and characteristics interpreted from this and other studies, and the model was used to test scenarios involving development and land-use change. The Four Corners Groundwater Investigation Modeling Report (Sutherland and others, 2014) provides a more detailed description of the model. The MODFLOW-2005 (Harbaugh, 2005) program solved the groundwater flow equation, and Groundwater Modeling System (GMS, Aquaveo, 2010) provided the user design interface. The model represents the aquifer system using a single-layer, numerical grid. Hydraulic properties and stresses assigned to the model grid mathematically represent the groundwater flow system. The modeling effort utilized PEST (a general-purpose parameter estimation utility) for model calibration (Doherty, 2010).

Model design

Boundary conditions represent the sources of recharge and/or discharge to the groundwater flow system (specified flux boundaries), and/or the groundwater elevations at the edges of the model domain (constant head). The Gallatin River, a natural boundary on the west side of the alluvial system, is defined in the model with the MODFLOW River package. On the east, a no-flow boundary was modeled parallel to the direction of groundwater flow determined from the potentiometric surface, until it reached Hyalite Creek. The MODFLOW Stream package simulated the northernmost eastern boundary along Hyalite Creek for approximately 1 mi. Boundaries on the north and south were parallel to potentiometric contour lines (fig. 11). A constant head boundary designated the northern boundary to reflect its relative stability throughout the year. The potentiometric surface is more spatially variable to the south, though the groundwater flow into the system from the adjacent Gallatin Range provides a relatively steady influx. Therefore, the southern boundary was modeled as a specified-flux boundary in the numerical model.

The single-layer model represents the unconfined aquifer system, which is the most used portion of the aquifer near Four Corners.

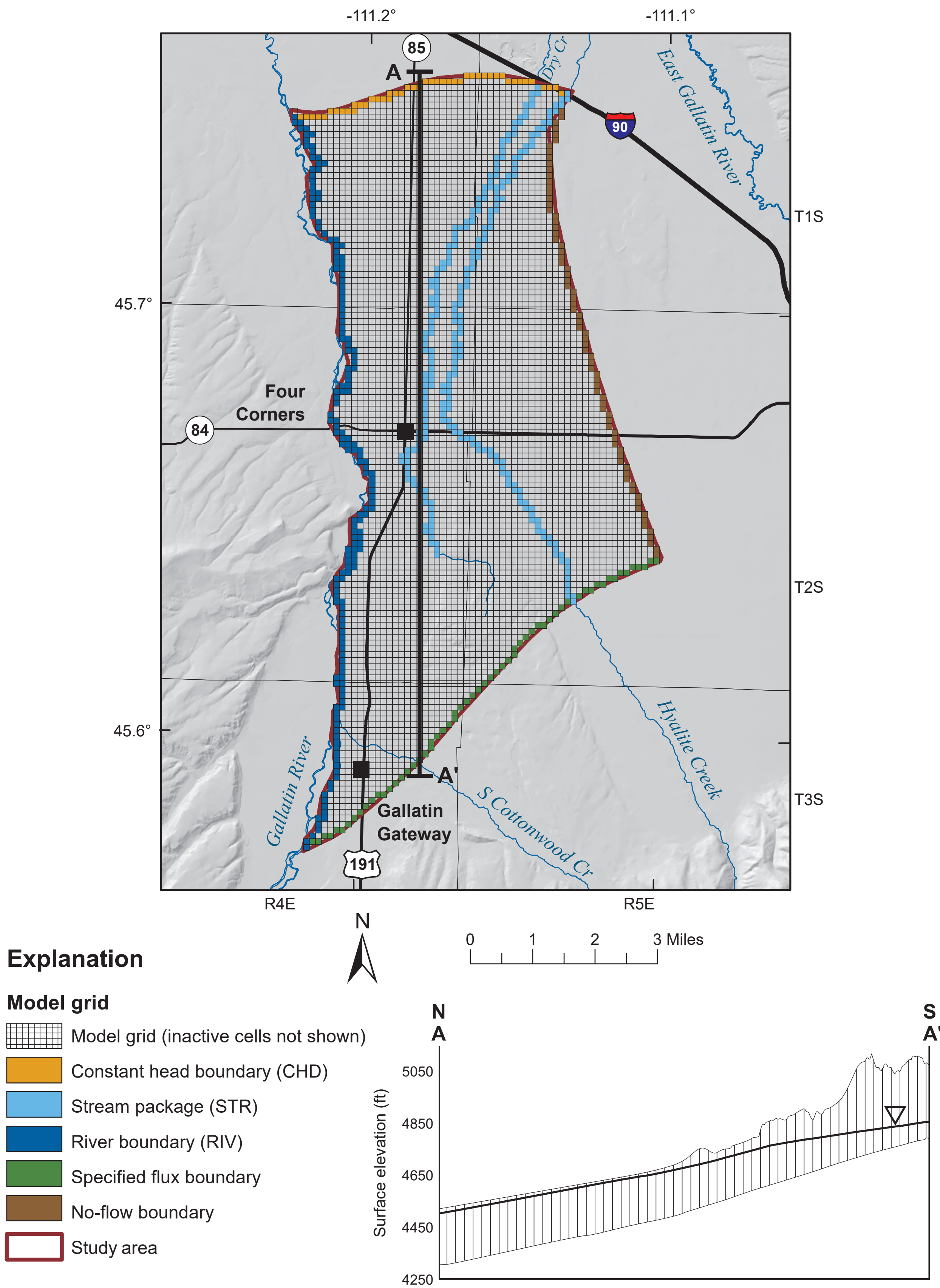

Figure 11. The numerical model of the Four Corners area is a single-layer model, encompassing 42 mi^2.

RESULTS

Hydrogeologic Setting

The aquifer system in the Four Corners study area consists of two aquifer materials: (1) coarse-grained Quaternary alluvial sediments, and (2) finer-grained Tertiary sediments (fig. 7). The Quaternary alluvium deposited by the Gallatin River and its tributaries, and the underlying finer-grained Tertiary sediments, combine to form a single unconfined aquifer system of varying characteristics.

Silt and clay lenses and layers within both the Quaternary and Tertiary sediments are typically not laterally extensive; however, they can cause local confinement (hydraulic separation between water-bearing zones).

Geologic cross sections presented in figures 12 and 13 show the interrelationships of the various geologic units in the area. The Quaternary deposits are subdivided based on relative age and source. Modern and recently abandoned (Holocene) river channels and alluvial fan deposits consist of well-sorted cobbles, gravels, and sands. Within these units are some silt and clay lenses and layers. Thickness of these Quaternary deposits ranges from 60 to 80 ft in the central and southern portion of the area to 200 ft to the north and closer to the Gallatin River.

Most wells in the study area are less than 100 ft in depth, completed in Quaternary alluvium (Qal) or older Quaternary deposits (fig. 7). Well yields are adequate for their intended use (domestic, municipal, and stock). Some domestic well logs report yields greater than 100 gpm for 6-in-diameter completions. Several larger diameter municipal wells reported yields greater than 1,000 gpm. English (2018) identified 26 wells in the Four Corners study area that had driller-reported well yields between 500 and 1,500 gpm. Driller-reported yields are typically higher than sustained yields after well completion.

Based on aquifer tests performed for this study (documented within GWIC), the hydraulic conductivity of the Quaternary sediments was between 20 and 1,000 ft/d and transmissivity ranged from 6,000 to as high as 107,000 ft^2/d. These ranges are similar to reported values from previous studies (table 3).

The Quaternary and Tertiary sediments are similar in appearance. During drilling completed for this study, the presence of cementation was a marker of the Tertiary sediments. When cementation was not present, grain size, compaction, color, clay content, and the presence of worm castings were used to determine the contact with Tertiary sediments.

The Tertiary sediments of the Madison Valley Member of the Sixmile Creek Formation (fig. 7, Tscmv; figs. 12, 13) consist of unconsolidated to variably cemented silts, clays, sandstones, and conglomerates. Tertiary sediments can be hundreds of feet thick, and in the study area, some well logs reported

Table 3. Aquifer properties for both the Quaternary and Tertiary sediments in the Gallatin Valley area from this and previous studies.

Source	Hydraulic Conductivity (ft/d)		Transmissivity (ft^2/d)		Notes
	Quaternary	Tertiary	Quaternary	Tertiary	
Hackett and others, 1960	N/A	N/A	5,080–89,566	40–8,689	100 aquifer tests at 37 sites throughout the Gallatin Valley; conductivity was not determined.
Kendy and Bredehoeft, 2006	200–775	7–500	12,300–35,000	40–2,300	Conductivity estimated from reported transmissivity values and aquifer thicknesses.
Kaczmarek, 2003	260–380	N/A	12,180–12,544	N/A	Conductivity estimated as a product of reported transmissivity values and 1.5 times the screened interval.
This study	20–1,000	50–350	5,900–107,100	10,140–23,250	Results of shallow aquifer tests conducted at four sites.

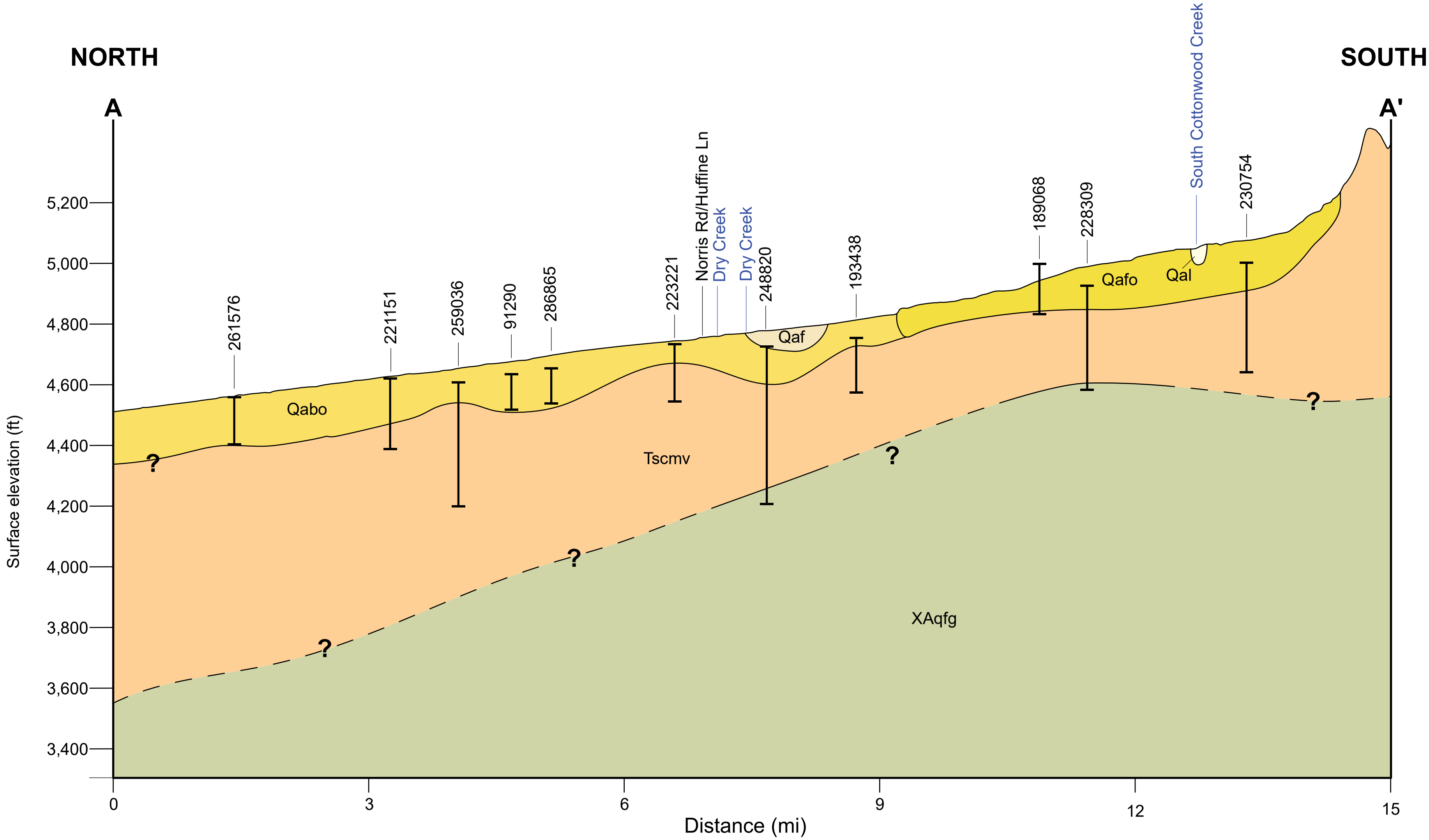

Figure 12. The north to south (A–A´) cross section through the Four Corners area shows Quaternary deposits at the surface, underlain by older Tertiary sediments with bedrock at depth (see fig. 7 for cross section location). Note the vertical exaggeration on units Qal, Qaf, and Qac.

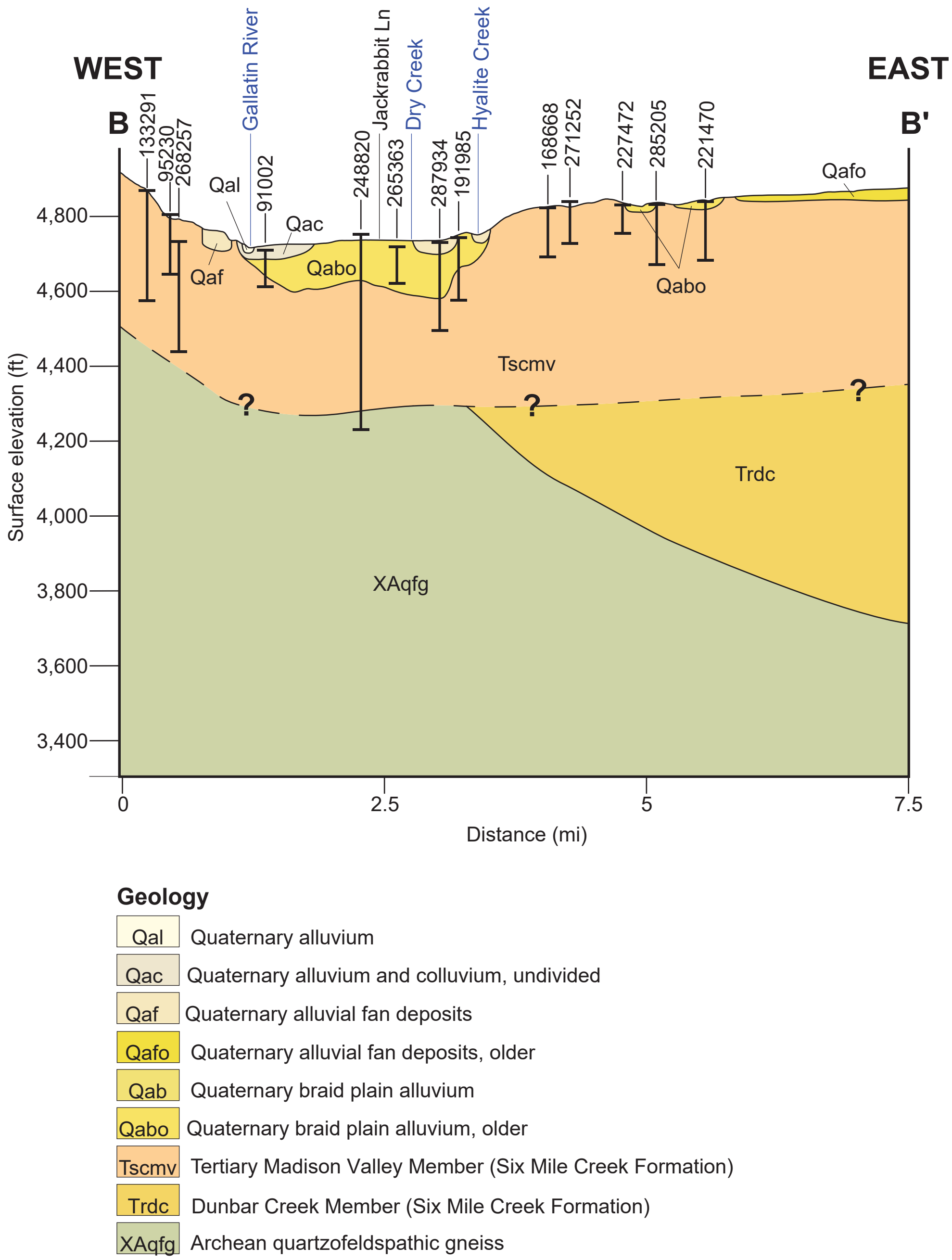

Figure 13. The east to west cross section (B–B´) through the Four Corners area shows older Tertiary sediments adjacent to and underlying Quaternary deposits (see fig. 7 for cross section location). Note the vertical exaggeration on units Qal, Qaf, and Qac.

underlying bedrock (figs. 7, 12, 13; map unit XAqfg) near the western and southern margins of the GVAS. The driller's log for well 248820, located about 0.7 mi south of Four Corners, reported metamorphic rock at a depth of about 500 ft. The driller's log for well 228309, about a mile south of the study area, reported bedrock at about 300 ft. The deepest well drilled for this study was completed in the Tertiary sediments (259036) at a depth of 401 ft (figs. 7, 12).

Hydraulic conductivity and transmissivity are generally lower in the Tertiary sediments compared to the overlying Quaternary deposits. Based on aquifer tests, we calculated a range in hydraulic conductivity between 50 and 350 ft/d, and transmissivities ranged from 10,100 to 23,250 ft^2/d (table 3). This range of hydraulic conductivity falls within that reported by Kendy and Bredehoeft (2006; table 3) although the range of transmissivity (10,100 ft^2/day) is an order of magnitude higher than the highest values reported by Kendy and Bredehoeft (2006) and Hackett and others (1960).

Canal Leakage

Canal leakage estimated for this study is based on measurements on six canal systems along reaches with no known active withdrawals or inflows at the time of data collection (fig. 9). Leakage ranged from about 0.4 to 2.5 cfs/mi, with an average leakage rate of 1.1 cfs/mi. Table C-2 (appendix C) provides details on the measurements and an average leakage rate.

The volume of flow in the canal and leakage rate were positively correlated based on limited measurements. Higher flows have larger wetted perimeters and cross-sectional areas that can allow more leakage. Higher flows also have greater head and increased vertical gradient that drives leakage.

Groundwater Flow

Potentiometric surfaces

The general groundwater flow direction in the study area is to the north (fig. 14). The horizontal hydraulic gradient is about 0.017 along the Tertiary bench in the southeast part of the study area, where groundwater flows from the lower hydraulic conductivity benches of the Bozeman Fan towards the river. The gradient is lower, 0.004, where groundwater flows through the coarse deposits that form the valley bottom. Groundwater exits the study area to the north through a thick package of aquifer sediments, and as discharge to surface water through the Gallatin River, Hyalite Creek, Dry Creek, and irrigation canals.

Vertical gradients

Vertical gradients evaluated in the project area reflect the hydraulic conductivity of sediments and the hydraulic influences of nearby irrigation infrastructure (canals and ponds) and other surface water. Vertical gradients indicate areas of upward or downward groundwater flow within the GVAS and were examined at four test sites (figs. 7, 8). Water-level monitoring at these sites began in 2010 and continued to 2014. These data reveal a complex vertical flow system within the GVAS.

Surface water influences vertical groundwater gradients in the shallow groundwater system, while characteristics of aquifer sediment affect the rate and volume of groundwater flow. In general, groundwater gradients in the Quaternary alluvium are downward in locations where nearby streams lose water to the subsurface. Downward gradients become more pronounced during the irrigation season when irrigation water recharges groundwater. In areas where the vertical gradient is upward during the non-irrigation season, the gradient decreases or reverses during the irrigation season. The following sections describe conditions at each of the test sites.

Stagecoach Trail Road site

The Stagecoach Trail Road site is in an unirrigated pasture adjacent to an ephemeral channel of the Gallatin River, about 650 ft from the main channel. The wells at this site are completed in Quaternary deposits consisting of coarse sands and gravels (fig. 7; map units Qal and Qalo). The vertical gradient is consistently downward between 0.09 and 0.10 at this site, with higher head in the 60-ft-deep well (259064) compared to that in the 273-ft-deep well (259062; fig. 15A).

Hulbert Road site

The Hulbert Road site is located near the boundary of the Quaternary braided plain alluvium, with wells completed in Tertiary sediments (Tscmv) that form the adjacent bench (fig. 7). The monitoring wells are in a flood-irrigated pasture supplied with water from an unnamed stream 200 ft to the west. On the bench above the wells to the east, an alfalfa field is sprinkler irrigated with water from a canal located on the bench about 1,000 ft southeast of the well site.

There is a deep, locally confined zone at this site, demonstrated by artesian conditions at well 259069 (250 ft depth). The head in this well is about 12 ft above the ground surface (fig. 15B), with an upward gradient of 0.100 between the deep confined zone and the shallower portion of the aquifer.

Aquifer test data showed hydraulic separation between the intermediate well (well 259072, 70 ft depth) and shallow well (well 259073, 30 ft depth), which reflects approximately 30 ft of clay between them (fig. 15B). During most of the year, the wells have similar water levels, or an upward gradient on the order of 0.02 or less. During the flood irrigation season, a downward gradient of 0.07 to 0.50 is attributed to local recharge from flood irrigation at the site and sprinkler irrigation on the bench.

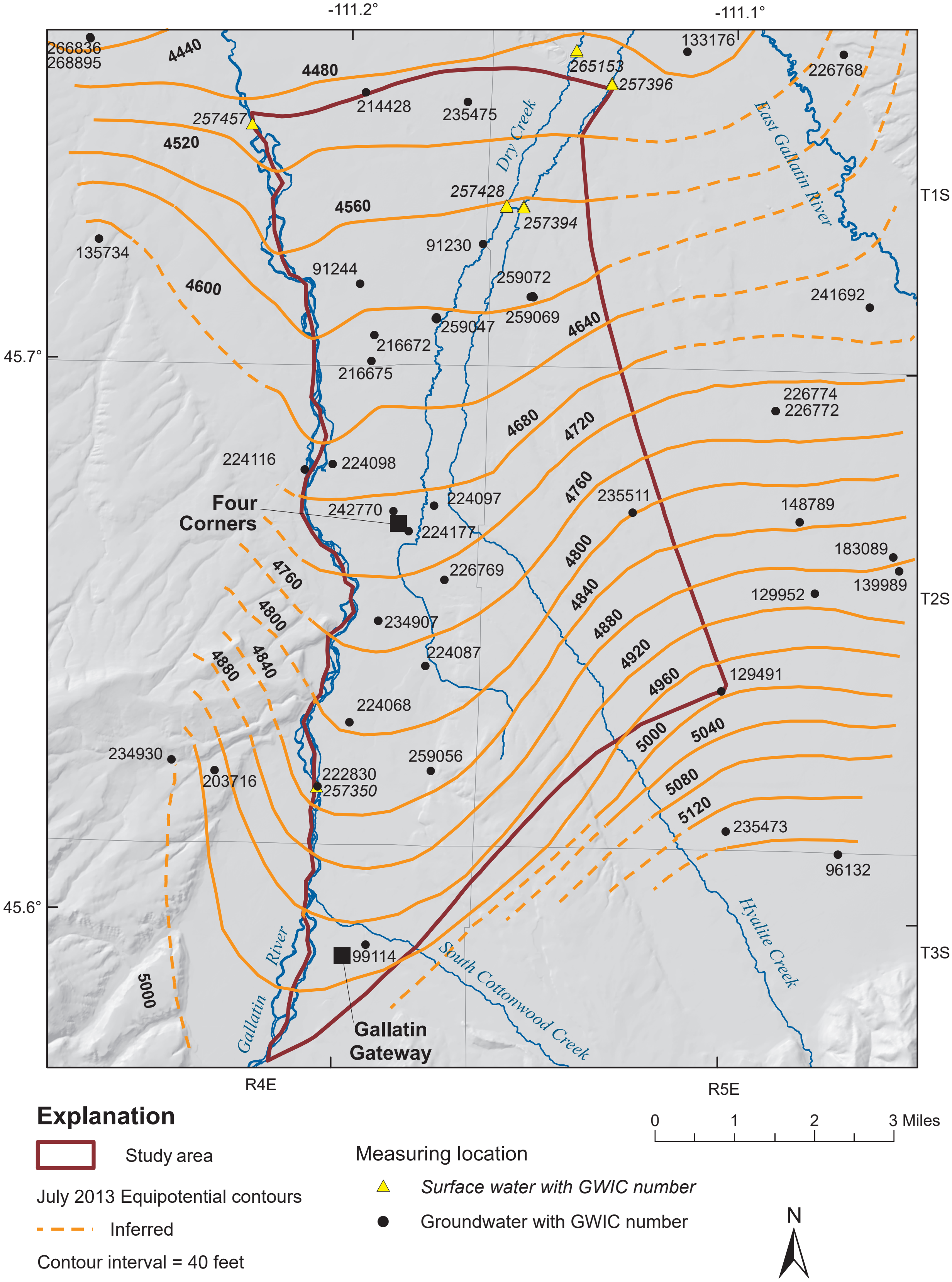

Figure 14. The potentiometric surface map for Four Corners and the surrounding area, July 2013. Dashed contours used in areas with few data points.

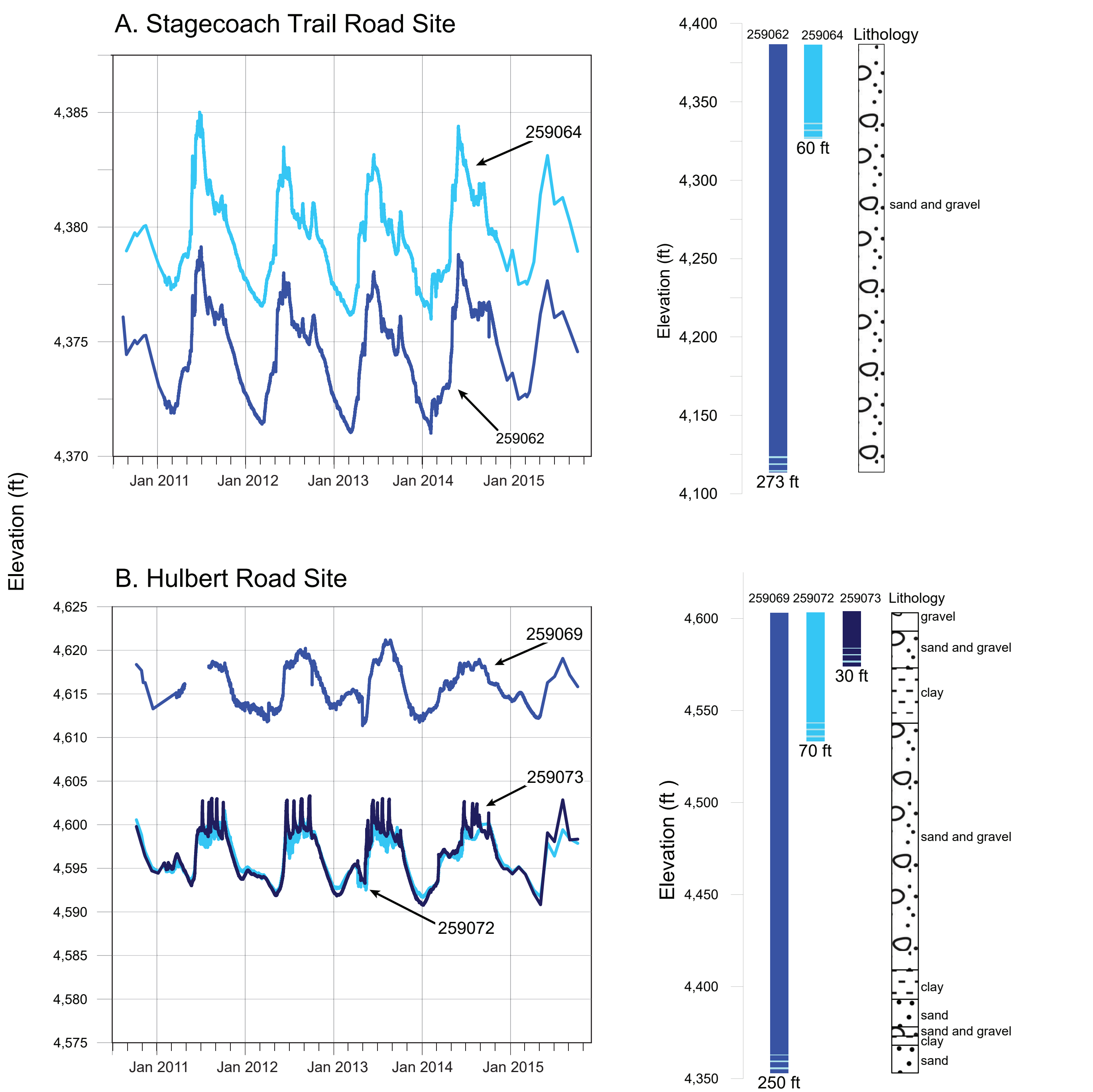

Figure 15. A downward vertical gradient is present year-round at the Stagecoach Trail Road test site (A). The Hulbert Road site (B) is under confined conditions at depth and is affected by local flood irrigation recharge to the water table.

Hulbert Road West site

The Hulbert Road West site is in alluvial braid plain sediments (Qabo) of the Gallatin River's terrace and occupies a flood-irrigated pasture about 300 ft west of Dry Creek, from which irrigators divert and convey water. The gradient is consistently downward at 0.016 during the irrigation season peak in July and August (fig. 16A) and is reduced or reversed during other times of the year.

The deeper Tertiary sediments at this location (Tsc-mv) show annual water-level trends that are typical of aquifers recharged by springtime runoff of snowmelt. Water levels rise about 5 ft during the summer and decline during the winter and early spring (fig. 16A, well 259036). The shallow wells have a flashier response (fig. 16A, well 259047) and about twice the magnitude of fluctuation due to the wells' proximity to recharge from flood irrigation. Well 259036 also showed a pulse of recharge from snowmelt and precipitation

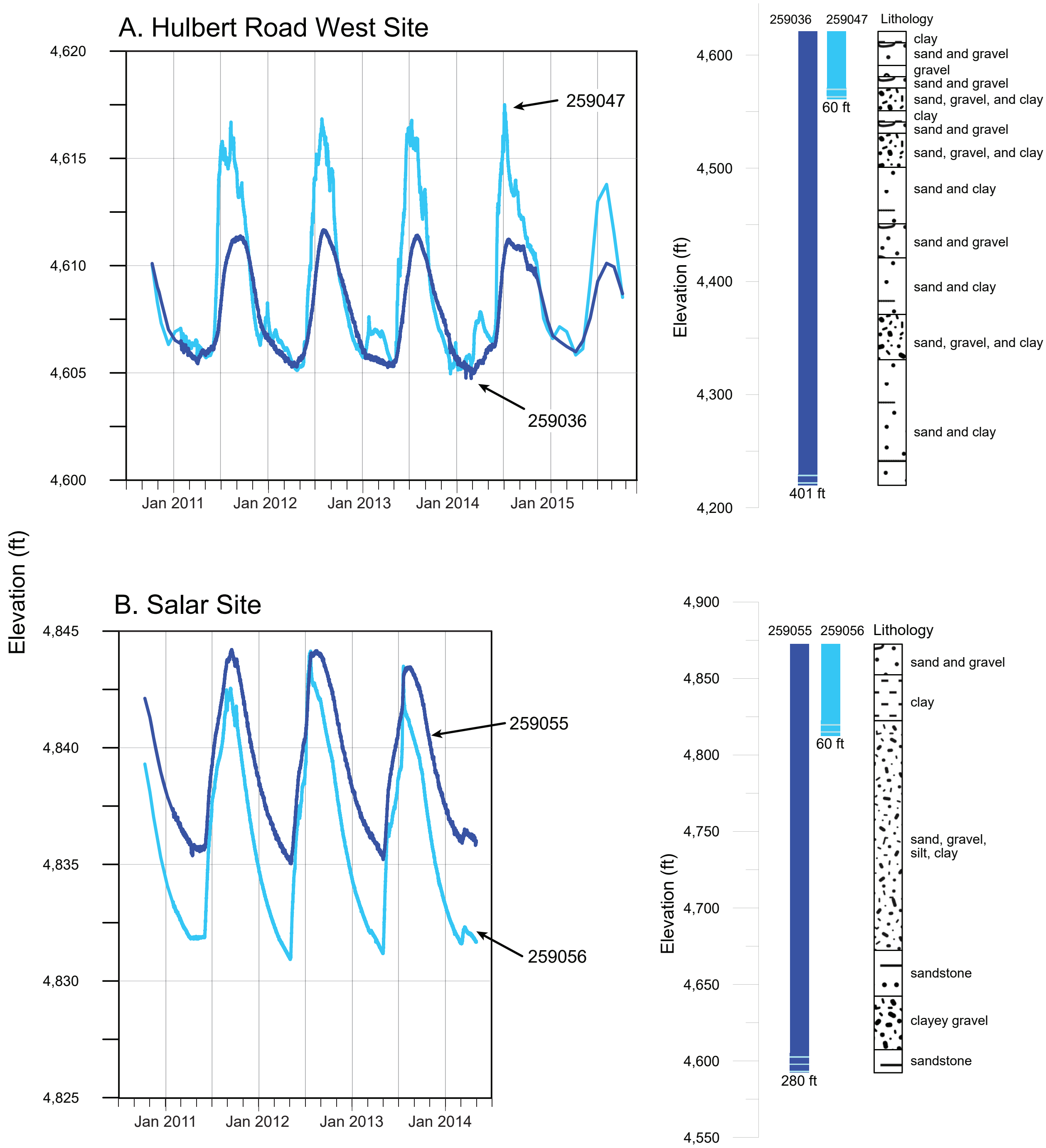

Figure 16. The Hulbert West site (A) shows an increasing downward gradient caused by seasonal irrigation water. An upward groundwater flow gradient is indicated at the Salar site (B). Water levels at both sites are influenced by recharge from nearby irrigation canals.

preceding the irrigation season, which is muted deeper in the groundwater system (fig. 16A, well 259036)

Salar properties site

The Salar site is on the contact between older Quaternary alluvial fan (Qafo) sediments and the underlying Tertiary sediments, which also form a bench just east of the site. The Farmers Canal is approximately 100 ft uphill (east) of the site. Although there is no irrigation onsite, sprinkler-irrigated fields bound the area to the north and west.

Three years of data from two wells showed a primarily upward gradient (fig. 16B), indicating the site is in or adjacent to a groundwater discharge area. The upward gradient is about 0.018 during the lowest water-level period (April). Water levels rise more in the shallow well than in the deep well during the spring and summer, from a combination of canal leakage and increased groundwater flow from the higher elevation bench. This causes the gradient to decrease. The hydraulic head in the deep well has an annual range of about 8 ft, compared to a range of about 13 ft per year in the shallow well.

The Salar site hydrographs show that during the non-irrigation season, recharge entering the study area from the higher elevation Tertiary bench and Bozeman Fan sediments affect the head deeper in the aquifer. During the irrigation season, increased local recharge from canal leakage and upgradient excess irrigation water cause a reduction and, at times, a reversal of the vertical gradient.

Hydrograph Trend Analysis

Since the 1970s, flood-irrigated acreage in the Gallatin Valley and the Four Corners area has been decreasing, and the use of more efficient irrigation methods has increased. In addition, commercial and residential development have replaced some irrigated agriculture (figs. 2A, 2B). Irrigated acreage decreased by up to 55% between the 1950s and 2010 in the Four Corners study area. Conversion from flood to more efficient sprinkler and pivot irrigation has occurred on more than 65% of the remaining irrigated land (Montana Department of Revenue, 2010). Residential development has increased throughout the valley, including the Four Corners area, as indicated by the number of wells drilled since the 1970s (fig. 3). We assessed long-term and seasonal changes in water levels to investigate effects of land-use change on the groundwater system.

Comparison of 1950s to modern water levels

Throughout the 1950s, historic irrigation practices were near their peak in the study area, with many acres of flood-irrigated land and associated water diversions (fig. 2). We examined groundwater-level changes since the 1950s to investigate aquifer response to land-use conversion from flood-irrigated land to residential areas and more efficient means of irrigation.

Overall, the few data available from the 1950s fell within or close to those observed in subsequent years. In well 96132, the sole measurement from the 1950s was within the range of values measured since 1992 (fig. 17A). The single water-level measurement in well 133176 from the 1950s was about 1 ft higher than measurements made since 1993 (fig. 17B). The March 1953 water level measured in well 133174 exceeded those measured since 1998 by about 1 ft, while measurements from April and October 1953 were within the range of the past several decades (figs. 17C–17E). Although the scarcity of 1950s data precludes an evaluation of trends, the limited number of measurements indicate that water levels at these locations in the 1950s were comparable to subsequent decades.

Well 95307 was a 15-ft-deep hand-dug well that was abandoned in 2001 (table 4; fig. 18A). The annual high water levels were similar (within 1 to 3 ft) between 1947 and 1983 during both dry and wet years, suggesting that recharge from flood irrigation exerted the predominant influence on the hydrograph (fig. 18A). Analysis of quarterly data from well 95307 for the period 1947 through 2001, with a data gap from 1983 to 1991, indicates a declining trend of about 1 ft. Increased irrigation efficiency or decreased irrigation and a prolonged drought between 1997 and 2001 may have decreased aquifer recharge in this area.

Prior to 1983, the difference between annual low and annual high water levels in well 95307 was about 4 to 6 ft. Since 1991, when regular groundwater measurements resumed, the annual fluctuations decreased to between 2 and 3 ft (fig. 18A), indicating less annual variability in the water table than the earlier period of record. An increase in irrigation efficiency may be responsible for this difference. Low-efficiency flood irrigation increases recharge in the spring, causing higher annual water levels. Consequently, a decrease in irrigated acres and an increase in irrigation efficiency may be responsible for the lower annual highs,

Table 4. Comparison of data collected in the 1940s and 1950s to data collected between the 1990s and 2018.

Well Number	p-Value	Result[1]	Method
95307[2]	0.001	Lowered levels (1990s–2001 data)	Seasonal Mann–Kendall test
129491	0.171	No change	Wilcoxson–Mann–Whitney rank sum test

[1]p-Values <0.05 indicate that there was a trend in the water-level data.

[2]Data from well 95307 was collected until 2001.

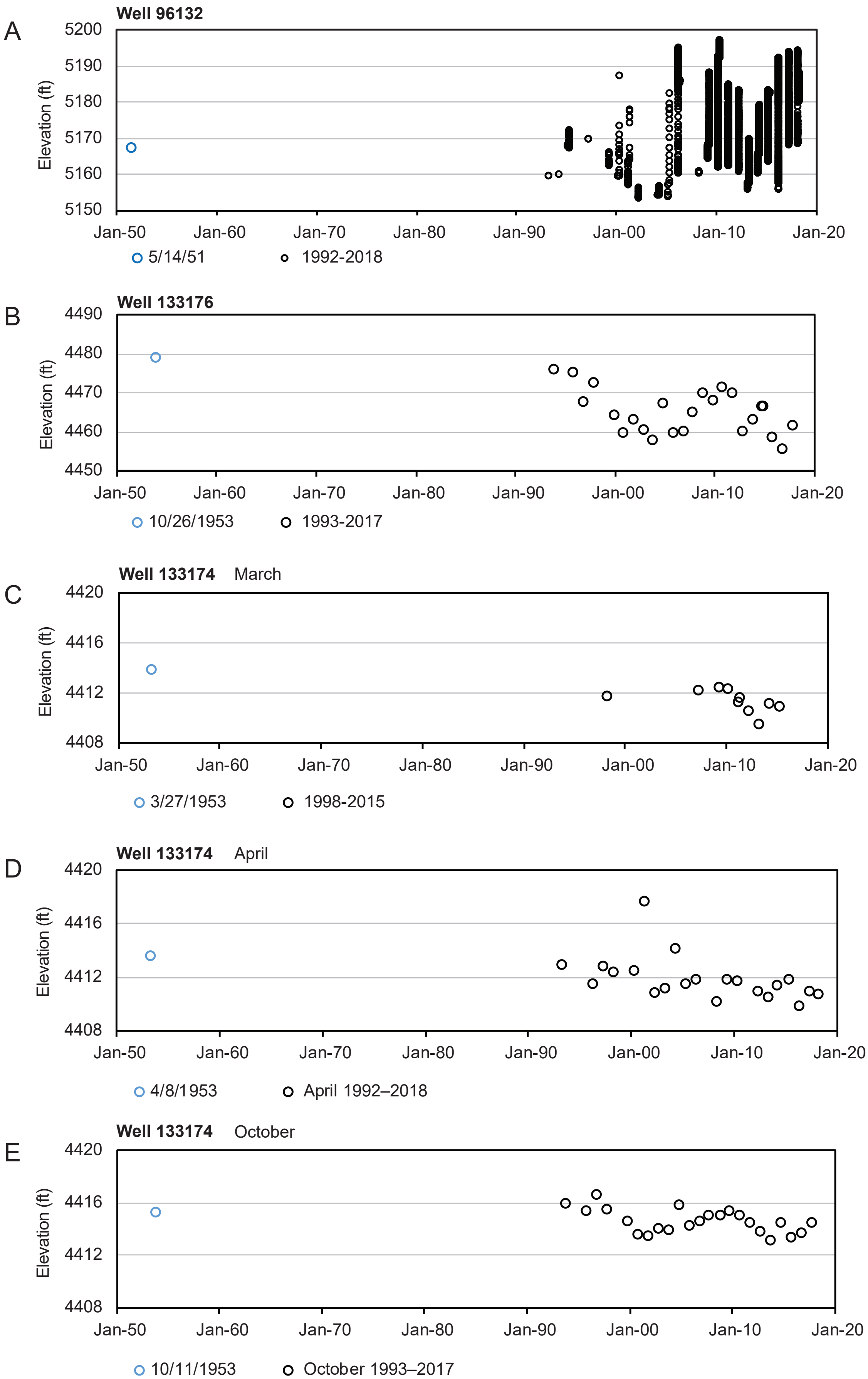

Figure 17. Measurements from several wells during the 1950s compared to measurements from more recent decades. Data are limited to 1–3 points for wells 133176 and 133174 while more continuous data were available for well 96132.

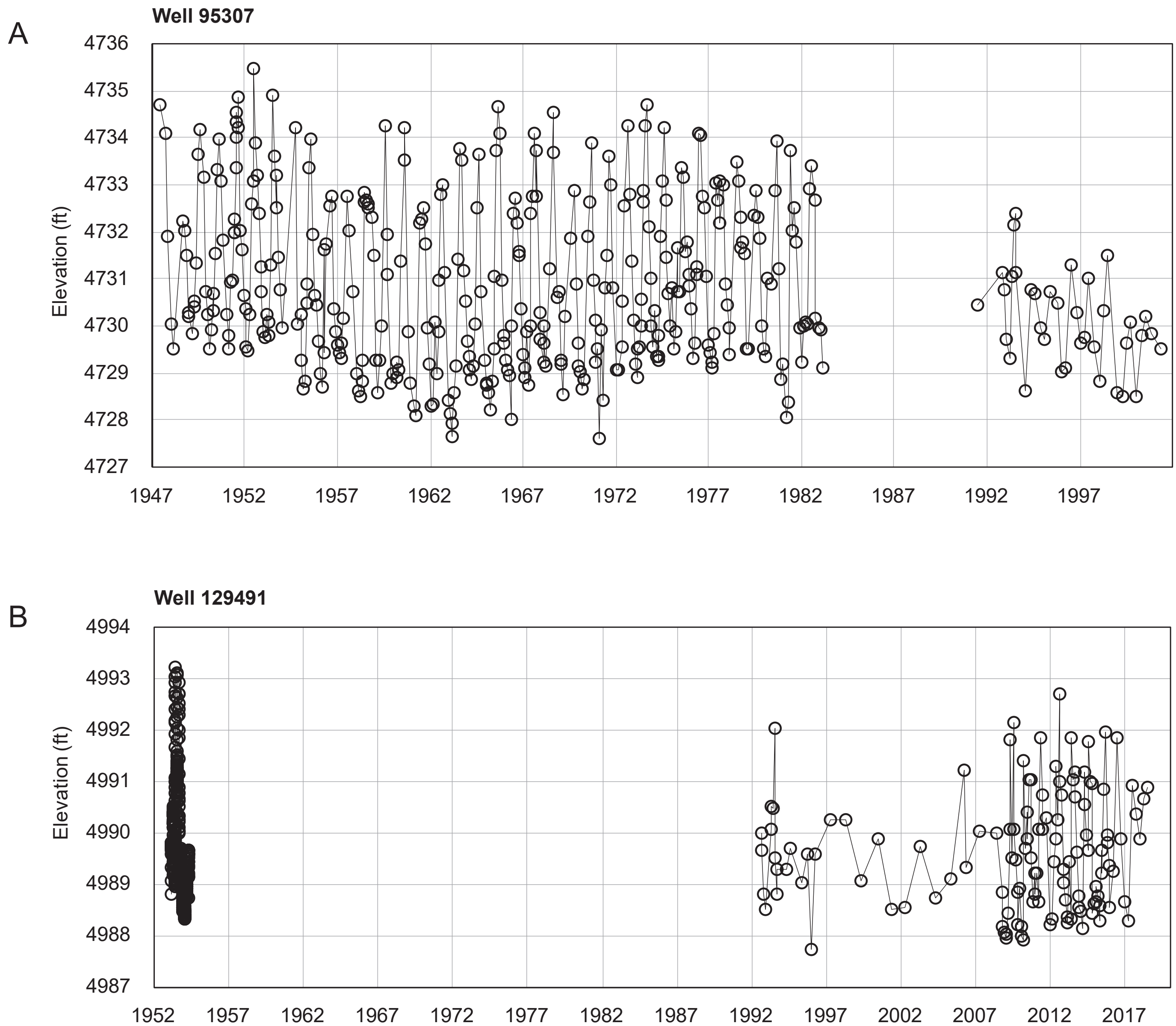

Figure 18. Measurements from well 95307 (A) indicate a declining trend of about 1 ft and a decrease in the magnitude of annual fluctuations in the 1991–2001 data compared to 1947–1984. Daily groundwater levels in well 129491 (B) were not significantly different in the 1950s compared to recent data. All available data are shown on the graph.

while drought conditions may have decreased the overall water levels.

Well 129491 showed no statistical difference between the 393 daily water-level measurements from 1953 and 1954 and recent monthly data (fig. 18B).

Water-level trends from 1993 through 2018

Four wells (129491, 133176, 96132, and 133174) with regular groundwater-level data since 1993 are within 3 mi of the study area (fig. 8). These wells document the water-level trends during the most recent 25 years. Table 5 and figure 19 summarize the results of the seasonal Mann–Kendall test on quarterly data from the four wells.

Visual examination of the hydrograph at well 129491 indicates a consistent range in heads between 1993 and 2018, although data was sparsely collected in some years (fig. 19A). A statistical analysis of quarterly mid-point data shows water levels rising less than a foot at this location (fig. 19A). Near the southeastern corner of the study area, there is no obvious change in irrigated area or methods. There are, however, several new private ponds. The effect of small ponds on groundwater levels was not part of this study, because their number and surface area were much smaller than irrigated areas. However, like irrigation ditches, they may enhance recharge locally.

Table 5. Summary for seasonal Mann-Kendall trend test of quarterly water level data (1993–2018). Additional details in appendix D-2.

Site	p-Value[1]	Implied Change
129491	0.015	Upward trend, <1 ft
133176	0.034	Downward trend, 3–4 ft
96132	0.07	No apparent trend
133174	0.078	No apparent trend

[1]p-Values <0.05 indicate that there was a trend in the water-level data.

Visual examination of well 133176, in figure 19B, shows four separate patterns, some of which relate to the precipitation record in figure 5. From 1993 to 1997, no increasing or decreasing pattern was visible. From 1998 to 2002, water-level decline likely reflected a prolonged drought. From 2003 to 2011, heads rose as the drought lifted and precipitation was nearer average. The years 2012–2018 suggest little to no pattern overall but are reflective of an annual basis of precipitation. A statistical analysis of quarterly average water levels shows a downward trend of about 3 to 4 ft during 1993 through 2018 (table 5). This well is adjacent to three fields that have been pivot irrigated throughout the period of record, and the water-level response is largely attributed to precipitation patterns rather than land-use trends.

Visual inspection of the hydrograph for well 96132 shows four patterns that also reflect the precipitation trends (figs. 5, 19C). Heads increased from 1993 to 1997, and showed an overall decrease from 1998 to 2002. Another increase followed, from 2003 to 2010, followed by a relatively flat pattern from 2010 to 2018. Analysis of quarterly mid-point water level data indicated no overall trend in well 96132 during the period of record (table 5). Water levels in well 133174 showed a similar response to well 96132 (fig. 19D). Statistical analysis of quarterly water levels in well 133174 also indicates no apparent trend (table 5). Well 96132 is in an area that has seen a decrease in flood-irrigated agricultural land and an increase in subdivisions, but with no apparent effect on water levels at this well. Compared to well 96132, well 133174 is in an area that has undergone relatively little change in land use.

Seasonal groundwater-level trends

Groundwater in the study area typically responds on a seasonal basis to canal seepage, excess water applied to fields, snowmelt, and precipitation. Snowmelt and precipitation cause water levels to rise in the late spring and early summer, with peaks due to irrigation recharge in the mid to late summer. Once irrigation ceases, groundwater levels decline toward late winter/early spring.

Well 259056, completed at 60 ft in Quaternary sediment, shows an example of typical groundwater response in the Four Corners area. Water levels rise in May with the onset of the irrigation season and peak in late July. Overall, water levels rise approximately 11 ft throughout the season, and decrease to low conditions after irrigation ceases (fig. 20A). Groundwater in well 259055, completed at 280 ft in Tertiary sediments, was located within 40 ft of well 259056. Groundwater in the Tertiary well showed a similar trend, with a muted response and flattened peaks, rising about 8 ft throughout the irrigation season.

Well 259056, completed at 30 ft in a flood-irrigated field, shows the rapid response of groundwater levels to irrigation. Groundwater levels peak multiple times throughout the irrigation season due to episodic application of flood irrigation water (fig. 20B). Early spring melt events appear to cause an early seasonal water-level rise at this well, in late March–early April (fig. 20B).

Groundwater/Surface-Water Interactions

As in most hydrologic settings, groundwater and surface water interact in the Four Corners area. The near-surface sediments are coarse alluvium, imposing restrictions to the flow of water between streams and the unconfined aquifer. The Gallatin River, Hyalite Creek, South Cottonwood Creek, and to a lesser extent Dry Creek all lose to, and gain from, groundwater along various reaches depending on the location and time of year.

Along its course near Four Corners, the Gallatin River alternately gains and loses, as demonstrated by comparing surface-water stage to groundwater elevations in nearby wells. Hydrographs of stream stage and nearby groundwater elevations show that where the Gallatin River enters the study area from the south, at Axtell Bridge, the river gains flow from groundwater throughout the year (fig. 21). Farther north at Cameron Bridge Road and Amsterdam Road, the river consistently loses flow to groundwater (fig. 21).

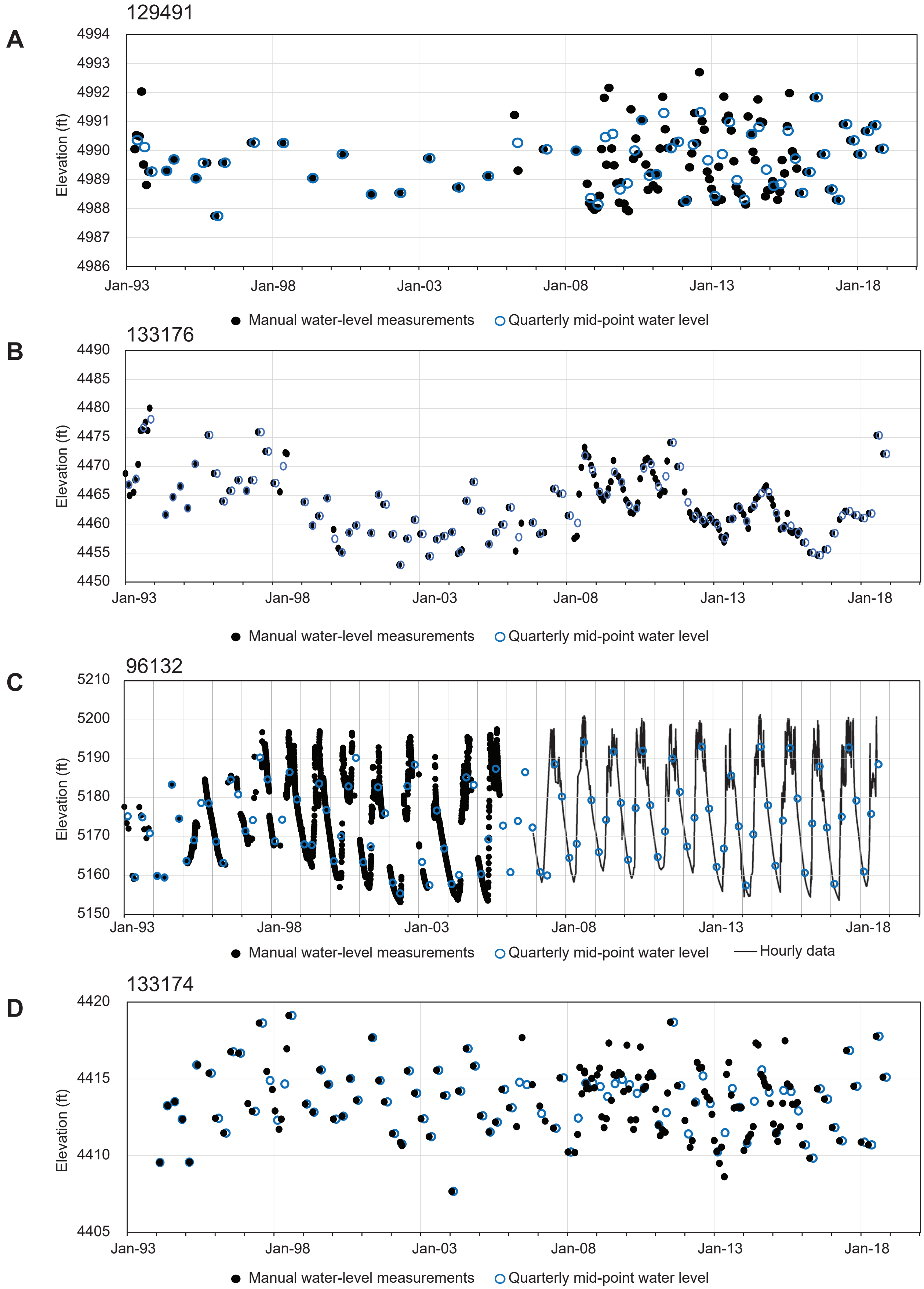

Figure 19. Water-level measurements in four wells monitored quarterly since 1993 show long-term trends that are attributed to climate and local irrigation practices.

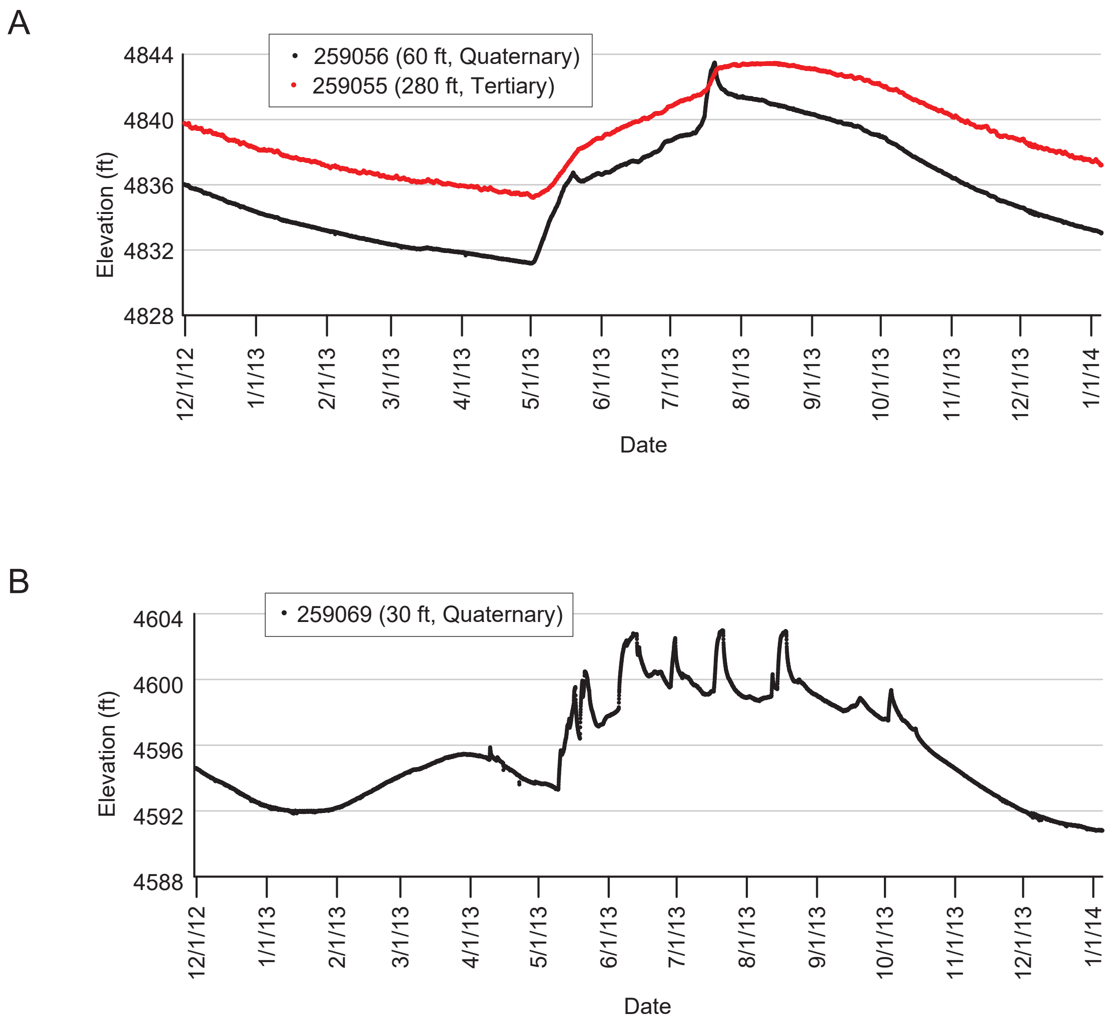

Figure 20. Seasonal water-level fluctuations illustrate an annual recharge cycle. Water-table elevations decline through the fall, winter, and early spring and rise in response to snowmelt and precipitation. Groundwater levels remain elevated through the irrigation season.

South Cottonwood, Hyalite, and Dry Creeks behave much the same as the Gallatin River. Hyalite Reservoir, irrigation diversions, and irrigation returns control the flow in Hyalite Creek and therefore affect the timing and locations of losses and gains along Hyalite Creek. This results in complex temporal changes in the groundwater/surface-water relationship. Dry Creek, which is adjacent to Hyalite Creek, is a smaller, slower-moving spring-fed creek. The low-flow conditions have led to deposition of fine-grained sediment that may reduce stream–aquifer interaction.

In addition to the streams, many irrigation canals flow through the area. Leakage from these canals, which are unlined, recharges water to the aquifer during the irrigation season (May–September) and artificially raises groundwater levels. The rate of leakage to the aquifer was spatially variable (appendix C, table C-2). These results are presented below in the Groundwater Budget section.

Water Chemistry

Groundwater

Thirty-nine groundwater analyses from 22 wells were used to characterize the groundwater chemistry of the GVAS (see fig. 10 for location; appendix B, table B-2). Historic samples and those collected during this project range over the period from 1992 to 2013. Sampled wells included those completed in Quaternary (well depths ranging from 5 to 273 ft below land surface) and underlying Tertiary sediments (well depths ranging from 9 to 401 ft below land surface). Results were compared to the U.S. Environmental Protection Agency’s primary, health-based standards for drinking water (maximum concentration limits, or MCLs) and their secondary standards (SMCLs), which are based on aesthetic qualities such as taste and smell (U.S. EPA, 2019).

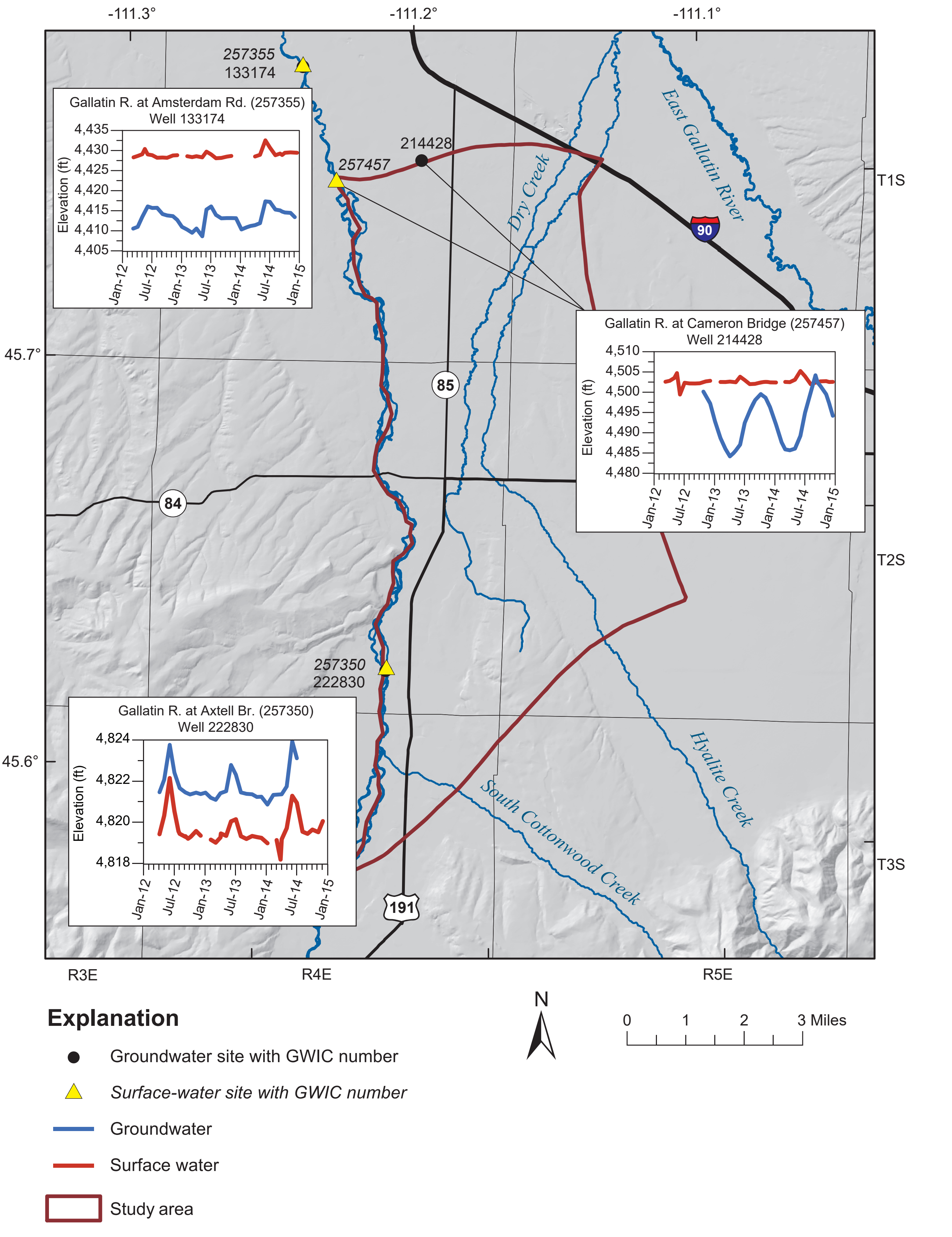

Figure 21. The relationship between the Gallatin River and groundwater varies. At Axtell Bridge, the groundwater elevations are higher than surface water; further north at Cameron Bridge and Amsterdam Road, the surface-water elevations are higher than groundwater.

Major ion chemistry was similar in both the Quaternary and Tertiary portions of the aquifer. All groundwater samples were calcium–magnesium–bicarbonate type, and the total dissolved solids (TDS, a measure of water salinity) ranged between 177 and 301 mg/L (fig. 22; appendix B, table B-2). These concentrations are well below the SMCL of 500 mg/L.

Samples were collected in the spring and fall from two wells: 133174 (Quaternary sediments, 97 ft depth, sampled three times) and 259073 (Tertiary sediments, 250 ft depth, sampled twice). Results from this small sample set indicate that groundwater chemistry at wells is similar across seasons during snowmelt and the start of the irrigation season (April) as compared to during or just after the irrigation season (October; appendix B, table B-2).

Quaternary Alluvium. With few exceptions, the shallow alluvium supplies local residents with good quality, low-salinity drinking water; the average TDS is 241 mg/L, with a high of about 290 mg/L (fig. 22; appendix B, table B-2). The water is considered “hard” to “very hard” because of the high calcium and magnesium concentrations in relation to sodium (Hem, 1985). Hard water can cause scaling in plumbing and cause soaps to lose effectiveness. Water softeners commonly lessen the problems associated with hard water in domestic settings.

Nitrate concentrations in groundwater from Quaternary sediments ranged from below detection limits, at less than 1.0 mg/L, to 2.07 mg/L (appendix B, table B-2), well below the MCL of 10 mg/L. Arsenic occurs naturally within many groundwater systems due to dissolution of arsenic-bearing sediments. The average concentration from wells completed in Quaternary sediments was 0.89 µg/L, with the highest concentration at 2.68 µg/L, well below the MCL of 10 µg/L.

The EPA’s SMCLs for iron and manganese are 0.3 mg/L and 0.03 mg/L, respectively. Iron and manganese can influence the color, taste, and smell of water and can cause staining on clothing and plumbing fixtures. Concentrations in samples collected during this study from shallow wells were low, with maximums of 0.110 mg/L and 0.058 mg/L for iron and manganese, respectively. Two samples collected from 2002–2008, prior to this study, exceeded the manganese SMCL at 0.088 and 0.241 mg/L, at wells 235475 and 91230 (appendix B, table B-2). These wells were not resampled for this study.

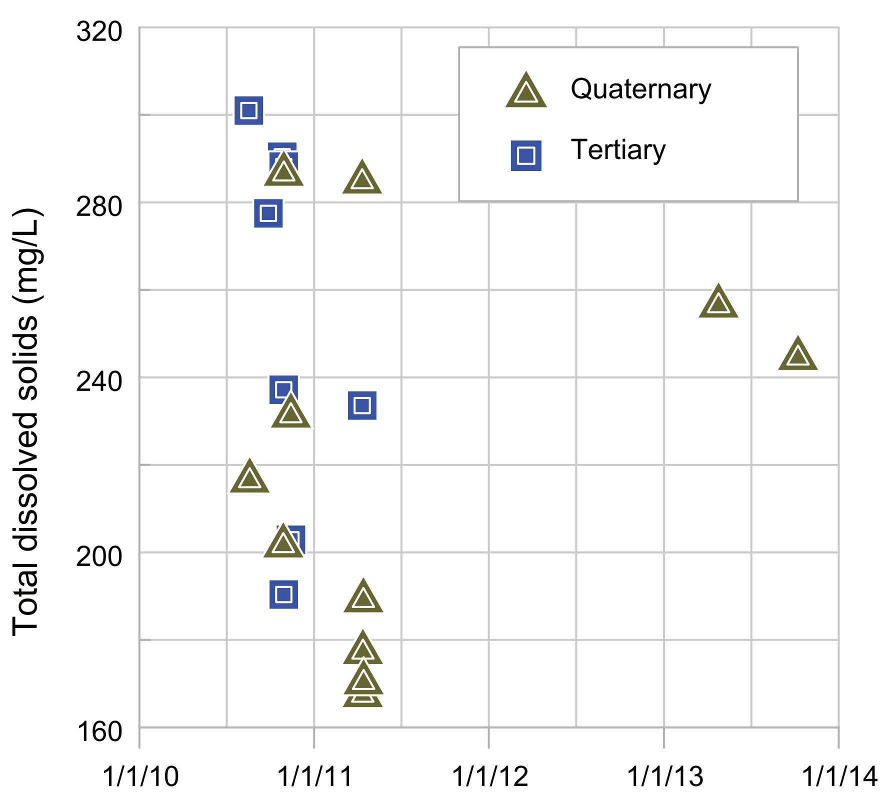

Figure 22. Total dissolved solids in groundwater from wells completed in Quaternary and Tertiary deposits have similar ranges, falling between 177 and 301 mg/L, well below the EPA’s SMCL of 500 mg/L.

Tertiary Sediments. Groundwater from seven wells (ranging in depth from 9 to 401 ft) completed in the Tertiary sediments and adjoining benches showed similar water chemistry compared to those completed in the Quaternary sediments (fig. 23; appendix B, table B-2). Groundwater from the Tertiary sediments indicated low salinity, with an average TDS of 253 mg/L and a maximum TDS of 301 mg/L. Hardness ranged from hard to very hard.

The maximum nitrate concentration measured in the deep wells was below the MCL at 1.7 mg/L. Arsenic concentrations averaged 1.23 µg/L, with a maximum of 2.40 µg/L. The maximum concentrations of iron and manganese in sample wells in the Tertiary were very low, at 0.050 mg/L and 0.010 mg/L, respectively (appendix B, table B-2).

Surface water

Surface-water sites were sampled periodically from the summer of 2010 through the summer of 2013. Overall, 38 samples were collected from 22 locations. These included sites along a group of eight streams and one slough; six smaller streams were sampled at one location, and five larger streams, such as Hyalite Creek and the Gallatin River, were sampled at up to eight locations (fig. 10; appendix B, table B-3).

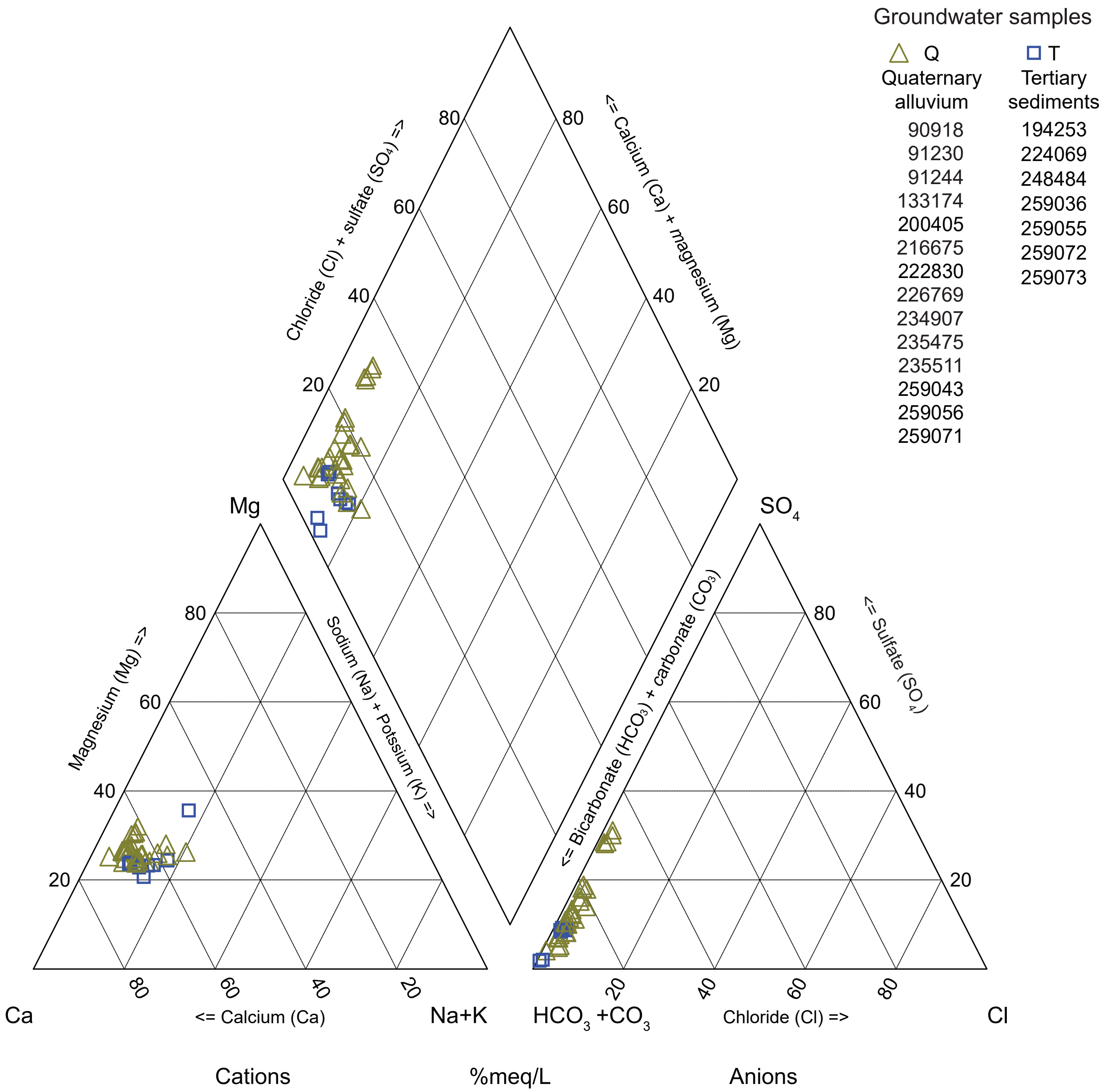

Figure 23. Calcium–magnesium–bicarbonate water dominates the groundwater chemistry in the Four Corners area.

The chemistry of surface water in the study area is similar to the overall chemistry of the groundwater: low TDS, dominantly calcium–magnesium–bicarbonate type water (fig. 24). TDS concentration in surface-water samples ranged from 78 to 323 mg/L and averaged 180 mg/L, lower than groundwater, which averaged 243 mg/L (appendix B, table B-3). TDS in the Gallatin River is lower during high flows because of dilution from low TDS springs, snowmelt, and tributaries that increase river flow volume, as illustrated in figure 25. Hyalite Creek and the Gallatin River have markedly lower TDS concentrations than other streams in the area, typically under 200 mg/L and occasionally under 100 mg/L (appendix B, table B-3).

Groundwater Budget

Groundwater budgets quantify the groundwater flow system. While some uncertainty is inherent in the calculations, a groundwater budget is useful for determining the relative importance of different processes affecting the system.

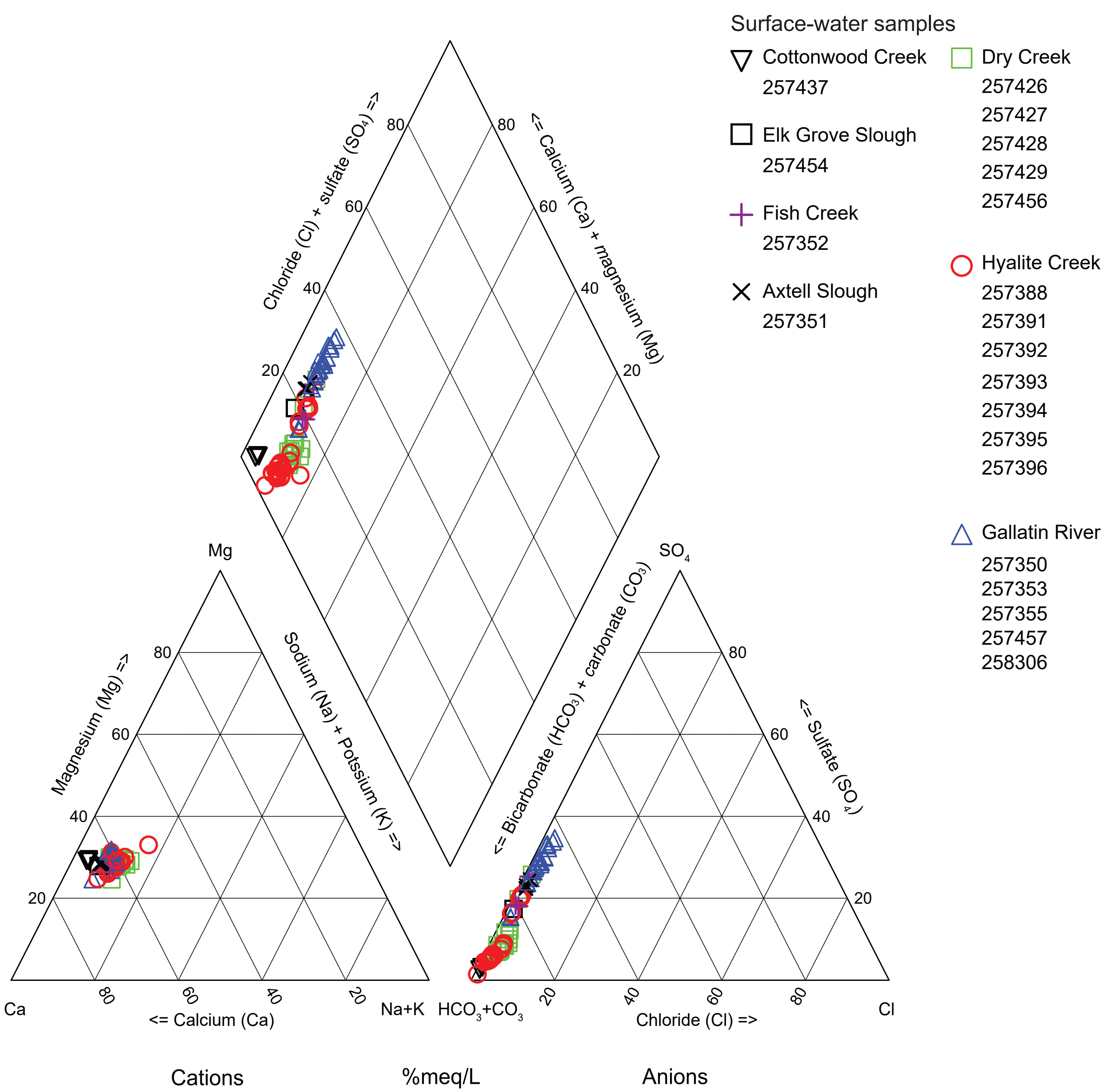

Figure 24. Calcium–magnesium–bicarbonate and calcium–magnesium–bicarbonate–sulfate water types dominate surface-water chemistry in the Four Corners area.

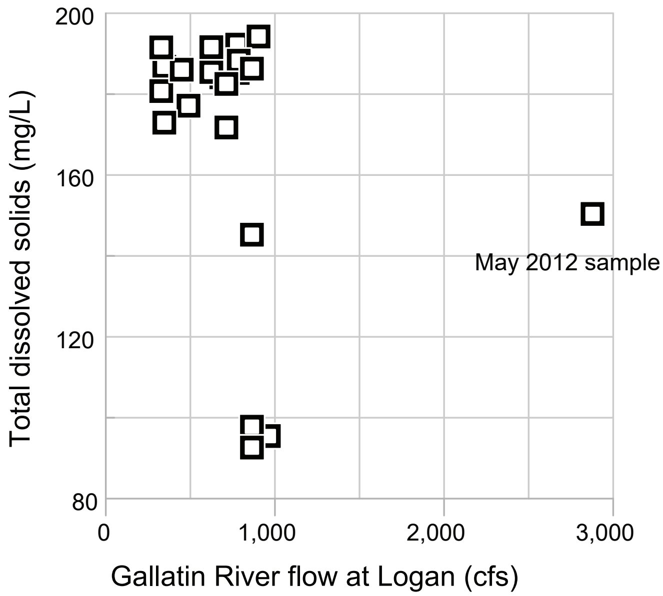

Figure 25. Gallatin River TDS remains below 200 mg/L through the seasonal flow fluctuations. Due to dilution, TDS is generally lower during periods of high flow on the Gallatin River. Data reflect March–May and July–August collection events (appendix B, table B-3).

The 2010 groundwater budget compiled for this project was interpreted from numerical modeling (Sutherland and others, 2014), field measurements, and referenced information. The hydrologic interactions described in the budget are variable in both time and location. For example, groundwater discharge to streams varies seasonally and with locations along various reaches of the stream. Here, we used monthly time steps and summed these into an annual budget (table 6). For each term, we developed an expected amount and minimum and maximum values based on uncertainty in estimates and measurements (see appendix C for detail).

Net recharge, defined as total of inflows to the groundwater system, exceeds net discharge (total of outflows from the system) during the spring and summer months (fig. 26). The recharge associated with irrigation diversions starts during April and continues through September, as reflected in seasonally high groundwater levels (fig. 20). Once the irrigation systems terminate for the season, recharge decreases below discharge through the fall and winter months (fig. 26).

The groundwater budget for the study area is expressed in terms of sources of water to the aquifer (inflows) and discharge from the aquifer (outflows), expressed in acre-feet/month for monthly time steps and per year for the annual summary (acre-ft/yr). The groundwater budget equation used for this study was:

$$GW_{in} + R_{can} + R_{irr} + STC_{in} = GW_{out} + DW_{out} + ET_r + STC_{out} + STR_{out} \pm \Delta S.$$

Groundwater flow (GW_{in} and GW_{out})

For each month, there was a range of inflows and outflows through aquifer sediments, into and out of the study area. Calculations were divided into two subsections along the northern boundary and five subsections along the southern boundary (appendix C, table C-1). The monthly groundwater inflow over the 12 mo of 2010 ranged from 6,740 acre-ft to 8,270 acre-ft (table 6; appendix C, table C-1). The annual total inflow ranged from a minimum of 70,270 acre-ft to a maximum 117,110 acre-ft. Over the 12 mo of 2010, aquifer outflows ranged from 10,580 acre-ft/mo to 13,150 acre-ft/mo. The estimated total outflow for the year ranged from 106,680 to 177,800 acre-ft.

Groundwater recharge from canal leakage (R_{can})

The total volume of recharge from canal leakage (R_{can}) was based on the estimated length of the largest canal systems that flow through or near the area (Farmers, Mammoth, Beck-Border, Hulbert, and Lower Middle Creek Supply canals; fig. 9). This length excluded small canals and ditches such as on-farm laterals. This is a reasonable simplification because these laterals are narrow, have low flows, and many are lined with silt, and therefore unlikely to recharge groundwater. For large canals in the study area, the average leakage rate of 1.1 cfs/mi (appendix C, table C-2) is similar to previous studies in similar hydrogeologic settings (Abdo and others, 2013; Hobza and Andersen, 2010). The total annual R_{can} calculated for the study area was 56,080 acre-ft, with a range of 40,380 and 71,780 acre-ft/yr based on the range of canal length in the study area (table 6; appendix C, table C-3).

Groundwater recharge from irrigation (R_{irr})

Groundwater recharge from irrigation accounts for applied irrigation water and direct precipitation on irrigated acres that are not used by crops. Irrigation application depends on crop type, weather, and applica-

Table 6. Monthly and annual water budget estimates.

	Percent of Total Recharge/ Discharge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Estimated Minimum Annual	Annual Estimate	Estimated Maximum Annual
Groundwater inflow (Gw_{in})	55%	7,730	6,740	7,640	7,390	8,000	7,830	8,090	8,090	8,180	7,730	8,000	8,270	**70,270**	**93,690**	**117,110**
Groundwater recharge from canal leakage (R_{can})	33%	0	0	0	0	11,363	10,996	11,363	11,363	10,996	0	0	0	**40,380**	**56,080**	**71,780**
Groundwater recharge from irrigation (R_{irr})	3%	0	0	0	0	171	1,390	2,553	1,045	630	0	0	0	**4,920**	**5,790**	**6,660**
Groundwater recharge from South Cottonwood and Hyalite creeks (STC_{in})	8%	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	1,120	**11,420**	**13,440**	**15,460**
Total inflow	**100%**	**8,850**	**7,860**	**8,760**	**8,510**	**20,654**	**21,336**	**23,126**	**21,618**	**20,926**	**8,850**	**9,120**	**9,390**	**140,720**	**169,000**	**197,280**
Groundwater outflow (Gw_{out})	85%	12,330	10,580	13,150	11,140	13,150	11,930	11,510	12,330	11,140	11,510	11,140	12,330	**106,680**	**142,240**	**177,800**
Domestic consumption (Dw_{out})	2%	6	6	6	92	429	649	917	747	404	6	6	6	**2,790**	**3,280**	**3,770**
Riparian evapotranspiration (Et_r)	1%	0	0	0	53	382	426	642	528	322	73	0	0	**2,070**	**2,430**	**2,790**
Groundwater discharge to Dry Creek (STC_{out})	1%	190	190	190	190	190	190	190	190	190	190	190	190	**1,940**	**2,280**	**2,620**
Groundwater discharge to Gallatin River (STR_{out})	11%	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	**3,350**	**18,000**	**34,850**
Total outflow	**100%**	**14,026**	**12,276**	**14,846**	**12,975**	**15,652**	**14,695**	**14,759**	**15,294**	**13,556**	**13,279**	**12,836**	**14,026**	**129,750**	**168,220**	**207,580**
Change in storage assuming a 0.15 porosity		-2,833	-2,875	2,028	1,535	6,229	8,710	4,733	4,012	-3,960	-7,907	-5,919	-5,729	**-1,580**	**-1,980**	**-2,380**

Note. Values in acre-feet. Values may not add for totals due to rounding. General groundwater budget equation:

$GW_{in} + R_{can} + R_{irr} + STC_{in} = GW_{out} + DW + ETr + STC_{out} + STR_{out} \pm \Delta S$,

where GW_{in}, groundwater inflow from aquifer; GW_{out}, groundwater outflow from aquifer; R_{can}, groundwater recharge from canal leakage; DW, domestic consumption from wells; R_{irr}, groundwater recharge from infiltration by pivot, sprinkler, and flood irrigation; ET_r, evapotranspiration by riparian vegetation; STC_{in}, stream leakage to aquifer from Cottonwood, Dry and Hyalite Creeks; STC_{out}, discharge to Cottonwood, Dry and Hyalite Creeks from groundwater; STR_{in}, stream leakage to aquifer from Gallatin River; and ΔS, changes in groundwater storage.

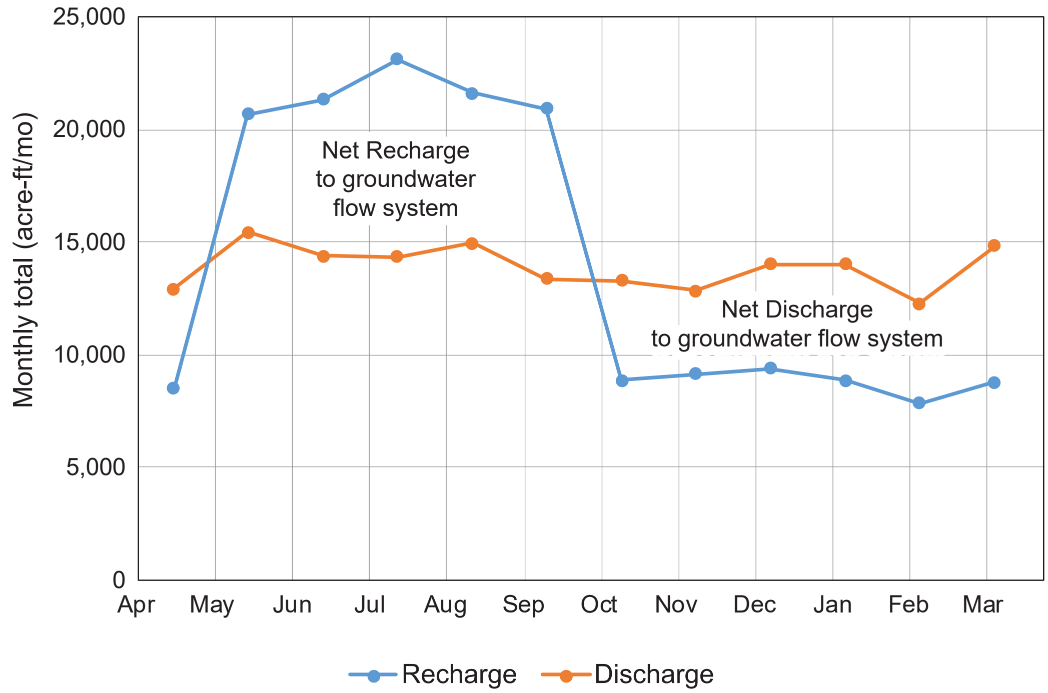

Figure 26. The total estimated monthly inflows and outflows show irrigation-driven recharge during the spring and summer and net groundwater discharge during the fall and winter.

tion methods (appendix C, tables C-4–C-8). Total estimated recharge from irrigation application was 5,790 acre-ft/yr with a range of 4,920 to 6,660 acre-ft/yr, and applied in the budget from May through September (table 6; appendix C, table C-8). Flood (686 acres), sprinkler (8,691 acres), and pivot irrigation (2,059 acres) contributed recharge amounts of 1,222 acre-ft/yr, 4,116 acre-ft/yr, and 452 acre-ft/yr, respectively.

Groundwater recharge to and discharge from streams (STC_{in} and STC_{out})

Stream leakage recharges the aquifer (STC_{in}), and aquifer discharge increases streamflow (STC_{out}; table 6; appendix C, table C-9). Some factors that affect surface flow, such as irrigation diversions and overland return flows, are difficult to measure, and identifying the magnitude and locations of all diversions was beyond the scope of this study. Estimates presented in this section were developed from measurements made outside of the irrigation season. Groundwater/surface-water interactions are considered the most difficult and imprecise part of the water budget.

Based on flow measurements during March, April, and October 2010 (non-irrigation months), South Cottonwood Creek recharges the aquifer, on average, about 120 acre-ft/mo, or about 1,440 acre-ft/yr, and Hyalite Creek loses about 1,000 acre-ft/mo, or about 12,000 acre-ft/yr. This yields a total for these creeks of 13,440 acre-ft/yr (table 6; appendix C, table C-9).

Groundwater discharges from springs within the project area to form the headwater of Dry Creek. The stream then flows north and crosses the study area boundary. All flow in the creek is considered groundwater discharge. Based on three measurements, the aquifer discharges about 190 acre-ft/mo (2,280 acre-ft/yr) to Dry Creek (table 6; appendix C, table C-9).

Domestic consumptive use of groundwater (DW)

Domestic and municipal wells provide water for indoor residential use and for lawn and garden irrigation (table 6; appendix C, table C-10). Based on an estimate of domestic, indoor consumptive use of 0.03 acre-ft/yr (26 gpd) in the Bozeman area (DNRC, 2011) and about 2,500 houses in the study area, annual domestic indoor consumptive use was about 75 acre-ft/yr in the project area. Average lawn and garden consumption, based on an ET rate of 1.6 ft of water (DNRC, 2011) and an average area of 0.8 acres per home, was 3,200 acre-ft/yr. Total indoor and outdoor domestic use was estimated at 3,280 acre-ft/yr.

Indoor use is relatively consistent year-round, at 6.3 acre-ft/mo for the total number of domestic wells and units. Outdoor use varies seasonally from nearly zero during the winter months with a maximum of about 900 acre-ft/mo during July.

Evapotranspiration by riparian vegetation (ET_r)

Riparian vegetation, primarily cottonwood trees and a few willows, typically consumes about 2 ft of water during the growing season (Hackett and others, 1960; Lautz, 2008). The total of cottonwood riparian areas estimated from ArcMap was 1,213 acres (NAIP, 2015). Therefore, the annual evapotranspiration estimate for riparian areas (ET_r) was 2,430 acre-ft. Monthly distribution ranged from zero in the winter months (November through March) to a high of nearly 650 acre-ft/mo during July (appendix C, table C-11).

Groundwater discharge to Gallatin River (STR_{out})

Gradients between river stage and groundwater (fig. 21) and computer modeling (Sutherland and others, 2014) indicated groundwater discharges to the Gallatin River in the southern part of the study area, and the river recharges groundwater in the north. To develop this term of the water budget, river recharge to groundwater simulated in the steady-state model was subtracted from simulated groundwater discharge to river cells to estimate an overall annual discharge of 18,000 acre-ft/yr (1,500 acre-ft/mo; table 6). We applied reasonable streambed hydraulic conductivity values to develop a range in total aquifer discharge to the river. This range (3,350 to 34,850 acre-ft/yr) is large due to the uncertainty in streambed hydraulic conductivity.

Change in groundwater storage (ΔS)

We applied a representative porosity and the difference in the potentiometric surface elevation from month to month to estimate the volume of water going into and out of groundwater storage. Positive values represent estimated increases in storage, and negative numbers represent estimated loss from groundwater storage.

The total change in storage during 2010 was an overall decrease in stored groundwater of nearly 2,000 acre-ft. This decrease is attributed to low annual precipitation since 1998 (fig. 5). The greatest increases in storage occurred in May and June, at the start of the irrigation season, and the largest decrease was in October, following the irrigation season (table 6).

Numerical Modeling Scenarios

Sutherland and others (2014) developed four model scenarios to simulate the hydrogeologic system response to a variety of situations. The simulations include:

(1) Pre-urbanization of the Four Corners area,

(2) Drought conditions that cause reduced groundwater inflow into the valley,

(3) Land-use changes, including an increase in urban land and a decrease in agricultural acres, and

(4) An aquifer storage and recovery (ASR) simulation for a 100-home subdivision.

Some of the scenarios include more than one simulation to address multiple changes from the 2010–2011 baseline condition. The modeling report (Sutherland and others, 2014) includes detailed descriptions of each scenario. Table 7 includes a summary of the scenarios and the results.

Pre-Urbanization (Hackett) Scenario 1

This scenario compared conditions in the 1950s as reported by Hackett (1960) to current conditions. However, this scenario necessitated significant assumptions about prior conditions that could not be verified with the historical dataset. Although not reported on further here, Sutherland and others (2014) provide more information about this scenario.

Drier Climate Scenario 2 (Two Simulations)

This scenario simulated reductions in water entering the groundwater system and streams to represent effects related to less precipitation and less snowpack. Two simulations implemented changes to surface-water and groundwater inflows (table 7). In simulation 2a, groundwater inflow along the model boundaries, irrigation recharge, and stream and river stages were reduced by 25%. In simulation 2b, irrigation recharge within the model boundaries was restored to 2010 conditions, but groundwater inflow from the south, stream, and river stages were decreased by 25%. This simulated less drastic conditions, as simulation 2b assumes sufficient water for continued irrigation.

This scenario (fig. 27, table 7; simulations 2a, 2b) showed that the greatest water-level decreases were to the east, farther from the influence of boundary condi-

Table 7. Scenarios and simulations completed with the model.

	Model	Simulation Design	Results
Scenario 1: Pre-Urbanization (Hackett)	Steady-State	Comparison of groundwater conditions in 1953 and 2013.	Scenario 1 results presented in Sutherland and others (2014).
Scenario 2: Drier Climate	Steady-State (2a)	Irrigation recharge decreased 25%, stream and river stages decreased, southern boundary influx decreased 25%.	Head decreased throughout the aquifer, overall flow volume decreased approximately 28,200 acre-ft/yr.
	Steady-State (2b)	Irrigation recharge remained constant, stream and river stages decreased, southern boundary influx decreased 25%.	Head slightly decreased throughout the aquifer, overall flow volume decreased by approximately 14,700 acre-ft/yr, groundwater levels indicate sensitivity to surface water.
Scenario 3: Land-Use Changes	25-yr transient (3a)	Urban expansion of 535 acres/yr for 5 yr, no irrigated acreage removed.	No decrease in aquifer levels, river and streams maintain water levels at model boundaries.
	25-yr transient (3b)	Urban expansion of 535 acres/yr for 10 yr, no irrigated acreage removed.	Less than 1 ft decrease in aquifer levels, river and streams maintain water levels at model boundaries—equilibrium reached immediately after stresses applied.
	25-yr transient (3c)	Urban expansion of 535 acres/yr for 15 yr, only irrigated acres urbanized last 5 yr.	Less than 1 ft decrease in aquifer levels, flow volume decreases slightly, equilibrium reached immediately after stresses applied.
	50-yr transient (3d)	Urban expansion of 535 acres/yr for 20 yr, irrigated lands removed years 10–15, mixed unirrigated and irrigated removed years 15–20.	Less than 1 ft decrease in aquifer levels, equilibrium reached immediately after stresses applied, minimal impact to aquifer.
	Steady-State (3e)	Urban expansion of areas in 50-yr transient model, all water from irrigation and canals removed within urbanized areas.	Aquifer levels decrease in model interior, flow volume decreases approximately 6.5%, induced leakage from Gallatin River.
Scenario 4: ASR Project	25-yr transient (4a and b)	New 100-lot subdivision, wells perpendicular to potentiometric contour; 4a pumping well upgradient, 4b injection well upgradient.	River leakage and storage completely offset within the model domain.
	25-yr transient (4c and d)	New 100-lot subdivision, wells parallel to potentiometric contour; 4c injection well adjacent to river, 4d pumping well adjacent to river.	River leakage and storage completely offset within the model domain.

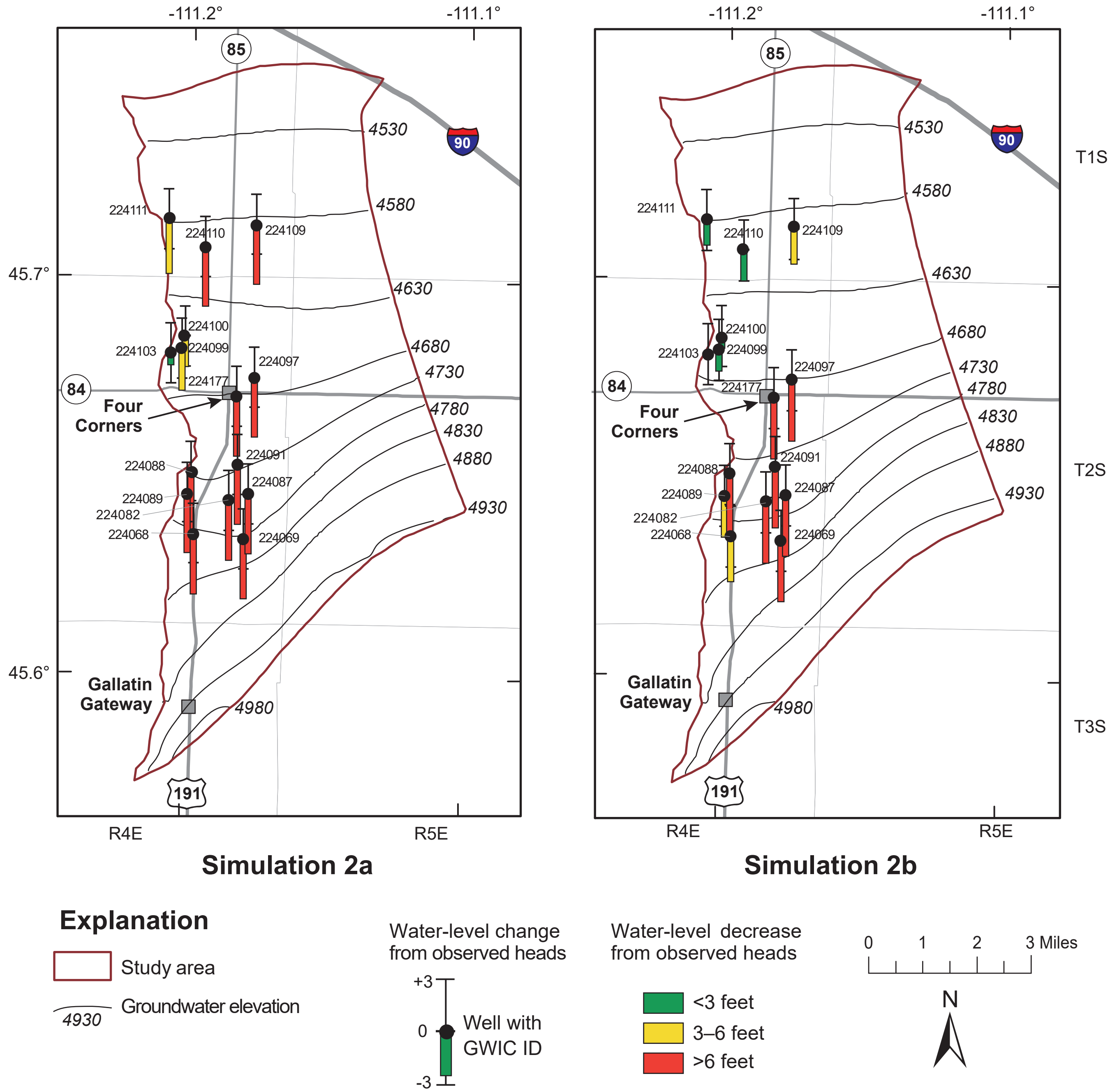

Figure 27. Scenarios 2a and 2b reduce groundwater inflow by 25% and lower stream stage due to a drier climate. Scenario 2a further reduces recharge from irrigation by 25%. Both scenarios show decreases in water levels throughout the model.

tions, such as the Gallatin River. Water levels in wells adjacent to the river stayed closer to non-drought, or 2010 conditions, because the groundwater system was supported by recharge from streams and river leakage (fig. 27). Simulated changes in groundwater levels are relatively small, on the order of 1 ft.

Recharge from canal leakage was important in simulation 2b because it provides recharge across much of the domain and diminishes local water-level changes. Groundwater flow (the total volume of water entering the model domain) in simulation 2a decreased from the baseline amount of 202,632 acre-ft/yr by 28,200 acre-ft/yr and in 2b by 14,700 acre-ft/yr.

Land-Use Changes Scenario 3 (One Simulation)

This scenario used a 50-yr transient model run to simulate a progression in development. The simulation compared effects to the groundwater system from the conversion of irrigated land to non-irrigated and urban uses (fig. 28, scenarios 3a–3d; table 7, scenarios 3a–3e). The first 20 yr included increased residential water use (scenarios 3a–3d), reduced irrigation re-

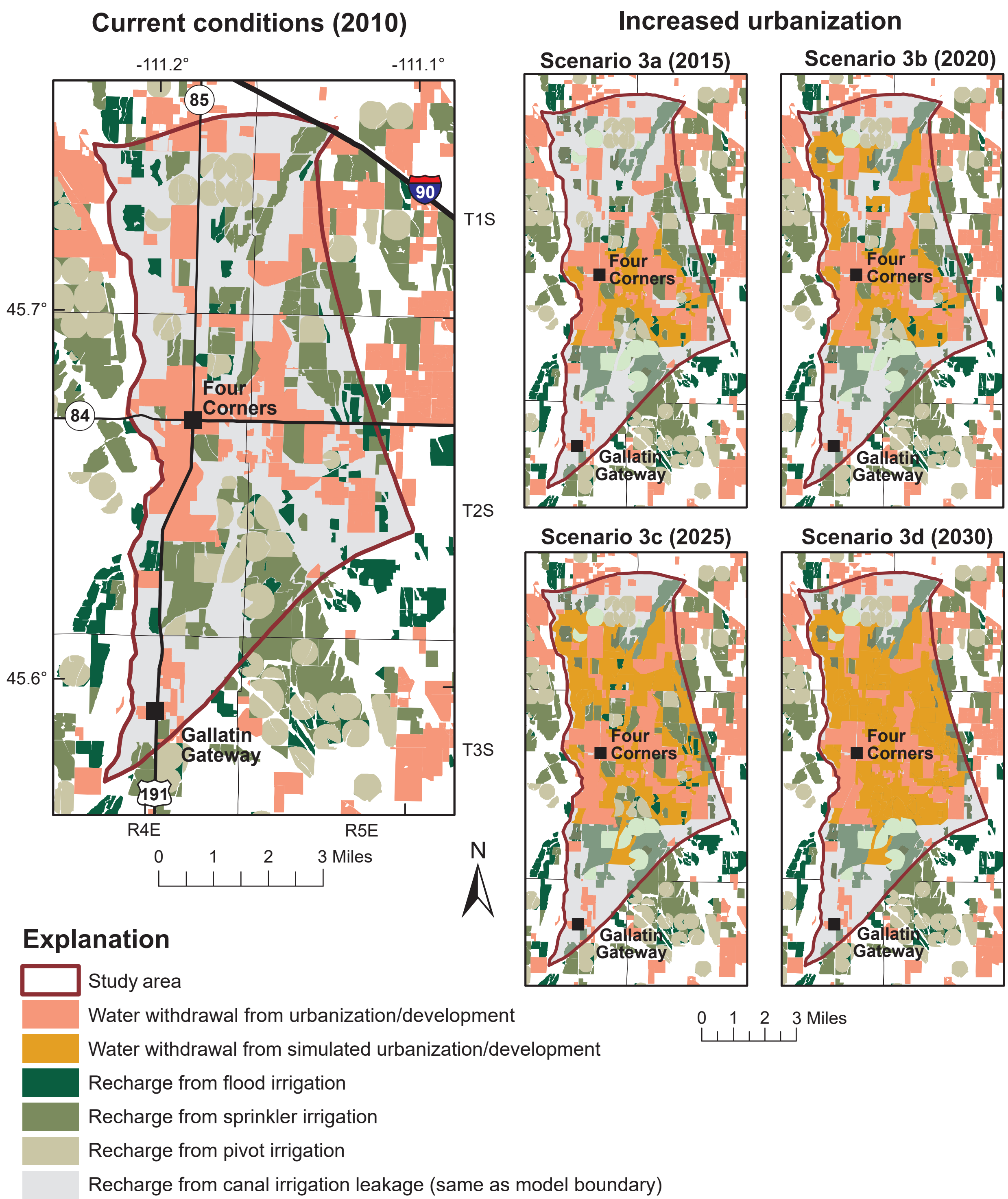

Figure 28. Scenarios 3a through 3d modeled increasing development. Each simulation (3a, 2015; 3b, 2020; 3c, 2025; 3d, 2030) includes a cumulative decrease in recharge during the 5-yr period for 20 yr.

charge within the model (scenarios 3c–3d), and, in the final 5-yr period, removal of all irrigation recharge (scenario 3e). Details on implementing these changes are presented by Sutherland and others (2014). Simulated groundwater pumping for urban areas systematically increased every 5 yr to reflect the development trends in Four Corners between 1998 and 2010 (scenarios 3a–3d).

Over the past several decades, urban expansion led to conversion of both irrigated and fallow land into subdivisions or urban centers. The simulations included a cumulative decrease in recharge during 5-yr periods for 20 yr (fig. 29). The first 20 yr held canal leakage constant but years 20 to 25 removed canal leakage from the model. No subsequent changes were made for model years 25 to 50 to investigate the long-term effects of these changes.

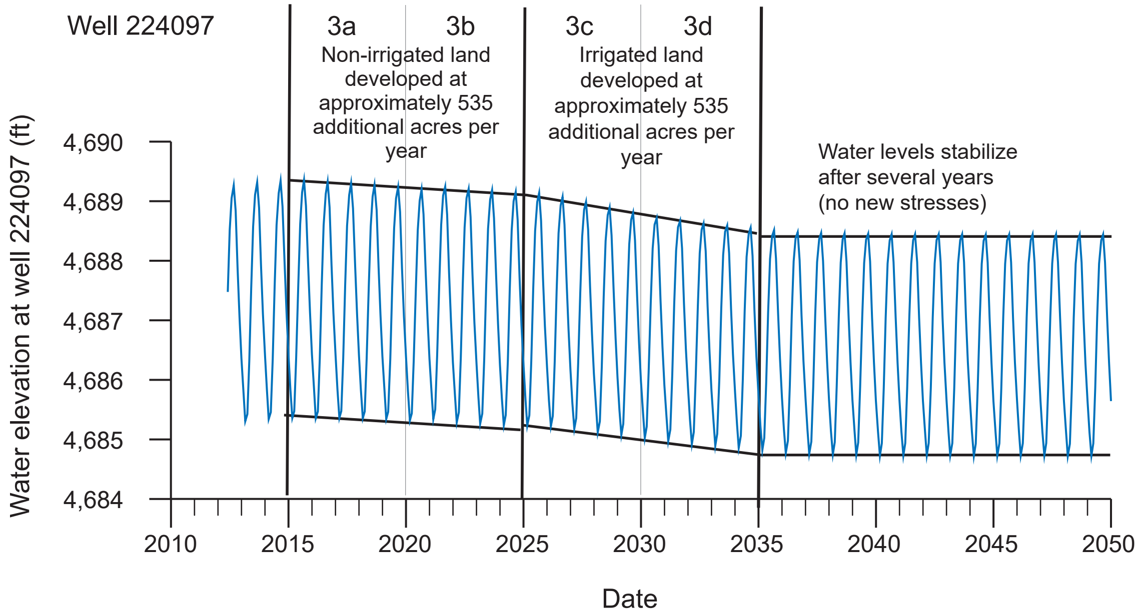

Figure 29. Scenarios 3a through 3d modeled future development and predicted a slight decline (about a foot). Groundwater levels stabilized 5 to 10 yr after 2035 when new changes were no longer introduced.

The results of scenario 3 indicate that wells in the center of the model had the greatest degree of water-level decline. Water levels reached equilibrium in under a month after the increased residential water use reached a constant rate, indicating that the high transmissivity of the aquifer responds to stresses quickly, and water-level fluctuations resulting from new stresses will be rapid. One well (224097) near Four Corners (fig. 8) did not reach equilibrium until 5 to 10 yr after the pumping rates had become constant, in 2035 (fig. 29). This shows an immediate response to a stress, but that a new equilibrium may take years to establish. Additionally, response across the aquifer differs; wells closest to a surface-water feature stabilized more quickly than distant wells. The connectivity of the system allows surface-water leakage to groundwater to mitigate drawdown from increased withdrawals. This suggests that in-stream flows supply groundwater recharge to support pumping, but given the simulated change in land use, less irrigation diversion would also affect in-stream flow.

Overall, groundwater-level declines were more sensitive to the removal of irrigation recharge than to urban development and subsequent domestic water withdrawals (table 7, scenarios 3a–3e). When non-irrigated lands were developed (fig. 28, scenarios 3a–3b), the water-level declines were minimal, in the range of one-tenth of a foot after 5 and 10 yr. Removal of irrigation recharge (fig. 28, scenarios 3c–3d) induced a decline 5 to 10 times greater than increased domestic withdrawals. The final simulation (scenario 3e) showed the greatest impacts, with water-level decreases after 50 yr greater than 10 ft after canal leakage was removed (fig. 30). Scenario 3e indicates the groundwater system depends on recharge from the network of leaking canals throughout the valley. The simulation without canal leakage resulted in drawdown reaching the model boundaries.

Aquifer Storage and Recovery (ASR) Scenario 4 (Four Simulations)

This scenario simulated the effects on surface water of a hypothetical subdivision supplied with groundwater that also mitigates or offsets its water use with an injection well, similar to the Four Corners County Water and Sewer District design. As most surface-water diversions are located to the south, the injection well added water from a location outside of the model domain. Four simulations predicted the effects of placing the pumping and injection wells adjacent to the river (table 7, scenarios 4a–4d). Scenarios 4a and 4b placed the pumping and injection wells in the direction of groundwater flow, south to north, within 4,000 ft of the Gallatin River (fig. 31). In scenario 4a, the pumping well was 2,000 ft south of the injection well, and in scenario 4b, the wells were reversed. Scenarios 4c and 4d explored the relationship between distance from the river and the location of the wells. Scenario 4c placed the injection well closer to the river than the pumping well, about 2,000 ft to the east, and scenario 4d reversed the positions of the pumping and injection wells.

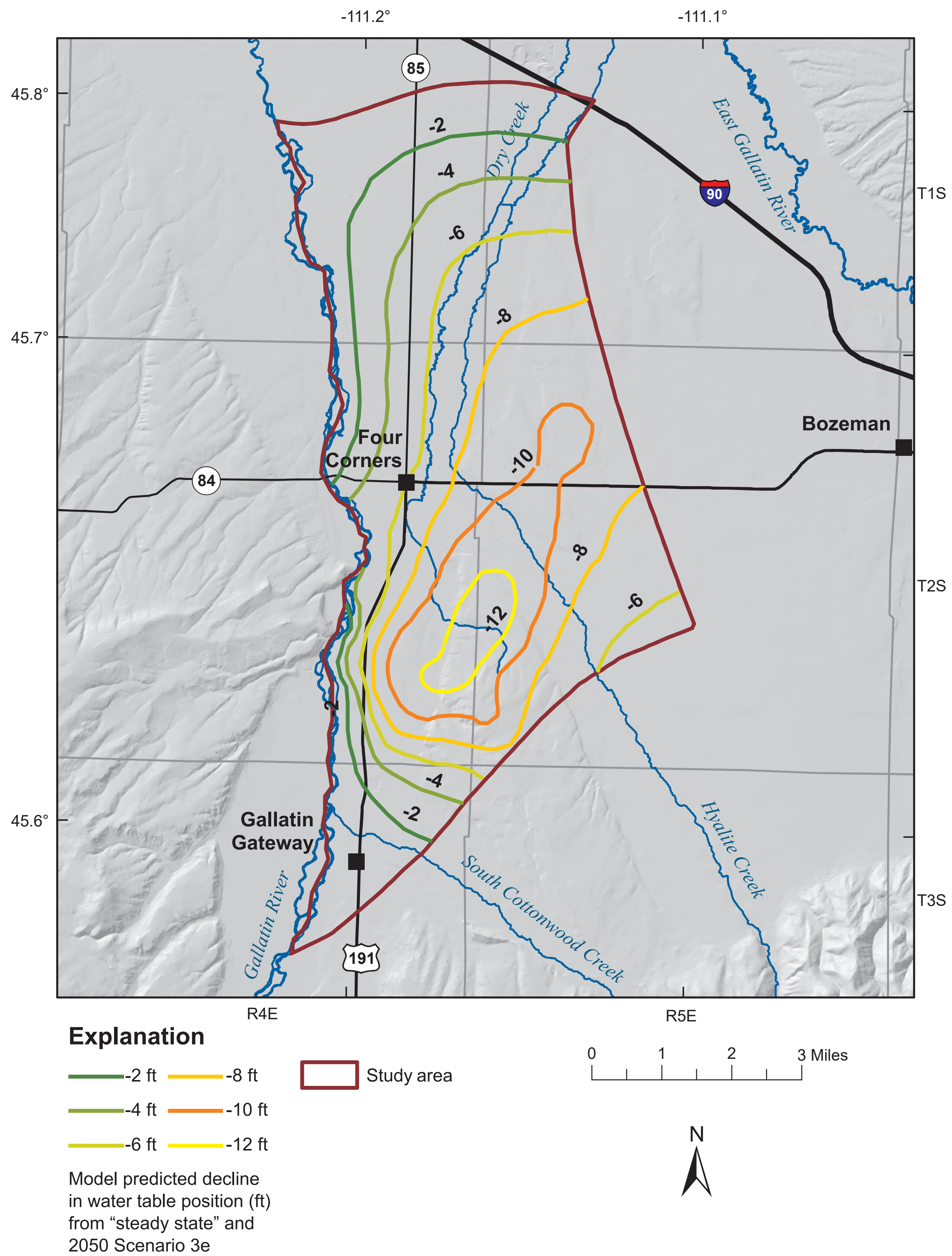

Figure 30. The simulation without canal leakage or irrigation produces declines in groundwater levels on the order of 10 ft (scenario 3e).

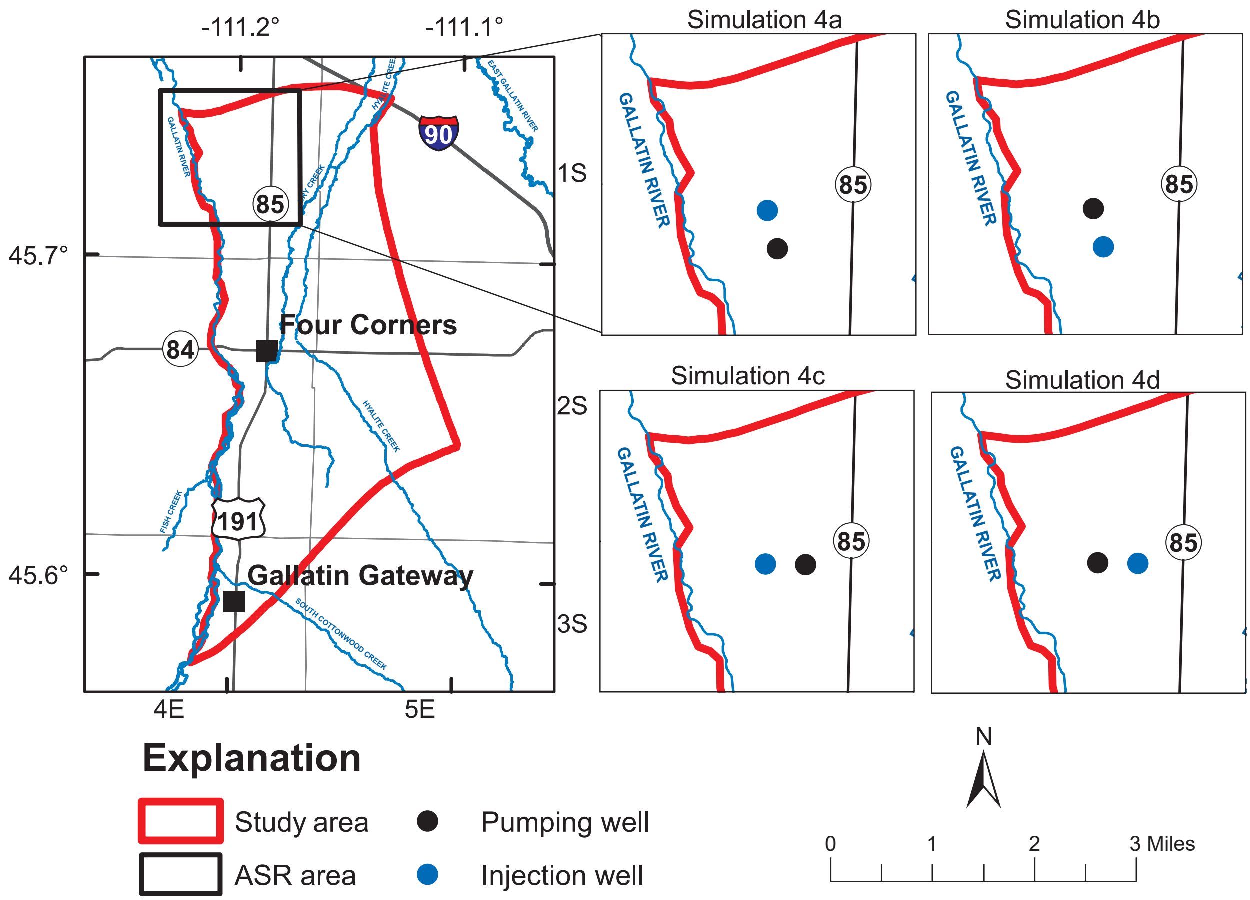

Figure 31. In scenario 4, injection and withdrawal of groundwater are simulated at specified times and rates in various ASR configurations.

The simulated wells were within a mile of the Gallatin River, in the northern section of the model, and use a hypothetical 100-lot subdivision to replicate the average consumption of a supply well. Injection was simulated during the high surface water flow months (March–June), when water is most readily available. Domestic consumptive use is lower during the non-irrigation months (0.03 acre-ft/yr), when there is only indoor water use. Ninety-seven percent of water used indoors returns to the aquifer after treatment by either a municipal sewage treatment facility or a septic tank. During the summer (June–September), however, lawn and garden maintenance consumes nearly 100% of water applied, and consumptive use increases (1.63 acre-ft/yr).

The results of these four simulations were compared to baseline (no pumping or injection) simulated river leakage and groundwater storage. None of the four simulations affected either river leakage or aquifer storage in the model. The limited variability of the results is likely the result of the high transmissivity of the aquifer, the low volume of simulated water withdrawal/injection, and the selection of well locations, which allows for the rapid offset of pumping by injected water. The simulation shows that rather than supplying pumped water from river leakage, groundwater comes from storage and injection when pumping and injection wells are close to one another.

The model results suggest that the hypothetical subdivision would have only a small effect on the hydrologic system. This is attributed to the high aquifer transmissivity, the high recharge rate, and the relatively low rate of groundwater use. Distance from the river is an important control on the timing and magnitude of effects.

DISCUSSION

Effects of Land-Use Changes on the Groundwater System

The groundwater budget illustrates the relative importance of the inflow (recharge) and outflow (discharge) components of the hydrogeologic system. The estimated annual groundwater budget for the project area during 2010 was about 169,000 acre-ft/yr (plus or minus about 5,000 acre-ft/yr; table 7). Groundwater inflow and outflow through the aquifer dominated the budget, constituting 55% and 85% of the totals, respectively. The second largest component of groundwater inflow is irrigation recharge from canal leakage, totaling about 33%.

Approximately 45% of the Four Corners study area is irrigated. In 2010, flood irrigation, which is the least efficient of irrigation methods and provides the most recharge to groundwater, made up only 10% of the irrigated area. More efficient sprinkler and pivot irrigation methods are used on 90% of the irrigated area. Canal leakage contributes more groundwater recharge than recharge from irrigated fields (table 7). This is important as it indicates that retaining the unlined canal system could decrease the effects to groundwater from development on previously irrigated land more than maintaining irrigated lands.

Although there has been an increase in residential housing since the 1950s, consumptive groundwater use for domestic lawn and garden irrigation was only 3,770 acre-ft/yr, or about 2% of annual groundwater outflow. Recharge to the aquifer from agricultural applications is a greater proportion of the water budget, suggesting the loss of applied irrigation (3% of inflow) and canal leakage (33% of inflow) would have a greater impact on groundwater levels than additional pumping for residential development.

Groundwater-level trends examined as a means of evaluating land-use changes since the 1950s showed mixed results in statistical analyses. While the wells evaluated are not located within the study, they give an indication of how groundwater may respond to land-use changes and other stresses in the Four Corners area (fig. 18; table 4). Water levels either increased since the 1990s–2000s or no statistical change was found (table 4). Visual examination of the 1950s water-level data indicates water levels were similar to the more recent water-level data overall (fig. 19).

Analysis of water-level trends over the past 25 yr also shows mixed statistical results, but these trends are considered more relevant to water managers than comparisons to the 1950s (table 5). Groundwater trends analyzed in four wells (table 4) indicate that there is not an overall declining or increasing trend in the study area, but rather that groundwater responds to localized changes in land use and/or climate.

Changes in irrigation recharge resulting from water conservation practices cause greater changes in groundwater levels than does conversion of land to residential and commercial development. This is also evident in the water budget, which shows that inflows related to irrigation dwarf the withdrawals from residential and commercial wells.

Potential Future Effects

Seventy years ago, all crop irrigation was by flood. Today, flood irrigation accounts for less than 10% of irrigated land in the Gallatin Valley. Small changes in groundwater levels have been documented over that time. Groundwater elevations today are generally similar to those of the 1950s, but future changes in land use and irrigation practices can be managed with an understanding of the role of canals and other components of irrigation recharge in maintaining the valley's hydrologic system. Changes in climatic conditions such as drought or changes in seasonal patterns of precipitation will affect groundwater and surface-water availability, and the model is a useful tool to explore these scenarios.

We used the groundwater flow model developed for this study to simulate changing conditions in the study area. These simulations showed that river leakage and canal leakage maintain groundwater levels. The Gallatin River and Hyalite Creek are directly connected to the aquifer system and alternately provide recharge to the aquifer and receive discharge from the aquifer. The model scenarios indicated decreased recharge caused a drop in groundwater levels on the order of 1 ft (scenarios 3a–3d). Because of the groundwater/surface-water connection, decreases of as little as 1 ft in groundwater levels can cause decreases in groundwater discharge to the river and streams; however, maintaining flow in unlined canals provides groundwater recharge that generally offsets the effects of pumping.

RECOMMENDATIONS

We established an extensive surface-water- and groundwater-monitoring network for this project and recommend that the Gallatin Local Water Quality District continue monitoring at several wells and some surface-water-monitoring sites. Such monitoring would yield data useful for detecting changes in the groundwater system and its interaction with streams.

This interaction is complex, and spatially and temporally variable. Changes that occur in one part of the Gallatin Valley may not affect all parts of the valley, or may not be immediately apparent in other areas. Monitoring will help identify changes, and inform decisions about water use and development. Continued monitoring at wells with long-term records will increase understanding of the effects of converting land from agriculture to residential and commercial uses.

A key conclusion of this investigation is the importance of irrigation water to the GVAS flow system and subsequent contribution to late-season stream flows. Canal seepage provides recharge by increasing groundwater levels during the irrigation season and augments late season stream flows. A recommendation that follows is for water managers to consider the hydrogeological effects of lining canals. Although lining canals improves delivery efficiency, and eliminating canals could be considered as residential and commercial development increases, the canal system is a critical part of the current hydrologic regime in the valley. Although irrigation methods have less of an effect on recharge compared to canal seepage, changes to more efficient irrigation methods will affect the GVAS and stream flows. These effects can be considered and evaluated to understand the consequences related to such changes, especially if the changes are large scale.

In the future, a post-audit of the groundwater model would be advantageous to its users. The post-audit should include new long-term water-level data to test the model's predictive capabilities. If conditions differ from the current understanding of the aquifer system, updating the model can improve representation of these conditions.

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APPENDIX A

SITE LISTS

Table A-1. Groundwater sites.

GWIC ID	Type	Latitude	Longitude	Geomethod	Township	Range	Section	Ground-Surface Altitude (ft-amsl)	Total Depth (ft)	Aquifer
91230	WELL	45.7227	-111.1651	SUR-GPS	01S	04E	25	4,587	32.5	110SNGR
91244	WELL	45.7149	-111.1968	SUR-GPS	01S	04E	26	4,599	45	110SNGR
95307	WELL	45.6602	-111.1841	MAP	02S	04E	13	4,738	15	111ALVM
95562	WELL	45.6228	-111.2093	SUR-GPS	02S	04E	34	4,832	40	111SNGR
96132	WELL	45.6129	-111.0698	SUR-GPS	02S	05E	35	5,206	156	120SDMS
99114	WELL	45.5948	-111.1917	SUR-GPS	03S	04E	11	4,968	125	112ALVF
99215	WELL	45.5460	-111.1742	TRS-SEC	03S	04E	25	5,296	50	111SNGR
129491	WELL	45.6421	-111.1009	SUR-GPS	02S	05E	22	5,000	165	110ALVM
129952	WELL	45.6602	-111.0771	SUR-GPS	02S	05E	14	4,914	117	120SNGR
133162	WELL	45.8353	-111.2015	SUR-GPS	01N	04E	15	4,321	315	120SNGR
133174	WELL	45.7725	-111.2380	SUR-GPS	01S	04E	9	4,437	97.5	110SNGR
133176	WELL	45.7583	-111.1131	SUR-GPS	01S	05E	9	4,495	141	111SNGR
135680	WELL	45.9152	-111.1195	SUR-GPS	02S	05E	21	4,967	33.8	110SNGR
135734	WELL	45.7221	-111.2649	SUR-GPS	01S	04E	29	4,671	120	120SDMS
135735	WELL	45.8022	-111.1653	SUR-GPS	01N	04E	25	4,389	101	110SNGR
139989	WELL	45.6647	-111.0553	SUR-GPS	02S	05E	13	4,895	184	120SNGR
148789	WELL	45.6732	-111.0814	SUR-GPS	02S	05E	11	4,846	40	110SNGR
183089	WELL	45.6671	-111.0569	SUR-GPS	02S	05E	13	4,884	315	120SNGR
200405	WELL	45.5968	-111.1905	SUR-GPS	03S	04E	11	4,967	56	111ALVM
200407	WELL	45.5965	-111.1906	SUR-GPS	03S	04E	11	4,969	56	111ALVM
203716	WELL	45.6258	-111.2318	SUR-GPS	02S	04E	33	5,032	180	120SNGR
214428	WELL	45.7498	-111.1963	SUR-GPS	01S	04E	14	4,522	80	111ALVM
214910	WELL	45.7838	-111.2269	SUR-GPS	01S	04E	4	4,420	58	111SNGR
216672	WELL	45.7056	-111.1929	SUR-GPS	01S	04E	35	4,627	40	111SNGR
216675	WELL	45.7009	-111.1934	SUR-GPS	01S	04E	35	4,639	40	111ALVM
222383	WELL	45.6300	-111.2119	SUR-GPS	02S	04E	27	4,818	30	111ALVM
222721	WELL	45.6301	-111.2112	SUR-GPS	02S	04E	27	4,806	19.5	111ALVM
222724	WELL	45.6239	-111.2160	SUR-GPS	02S	04E	34	4,839	28	111ALVM
222830	WELL	45.6233	-111.2050	SUR-GPS	02S	04E	35	4,827	28	111ALVM
224062	WELL	45.6317	-111.2056	SUR-GPS	02S	04E	26	4,803	5.2	111ALVM
224068	WELL	45.6351	-111.1971	SUR-GPS	02S	04E	26	4,804	29.2	111ALVM
224069	WELL	45.6342	-111.1792	SUR-GPS	02S	04E	25	4,813	26.1	120SNGR
224082	WELL	45.6440	-111.1848	SUR-GPS	02S	04E	23	4,781	25.75	111ALVM
224087	WELL	45.6456	-111.1778	SUR-GPS	02S	04E	24	4,786	29.2	120SNGR
224088	WELL	45.6508	-111.1981	SUR-GPS	02S	04E	23	4,753	17	111ALVM
224089	WELL	45.6453	-111.1997	SUR-GPS	02S	04E	23	4,765	19.5	111ALVM
224091	WELL	45.6529	-111.1819	SUR-GPS	02S	04E	24	4,750	25.3	111ALVM
224092	WELL	45.6648	-111.1989	SUR-GPS	02S	04E	14	4,717	19.5	111ALVM
224096	WELL	45.6648	-111.1989	SUR-GPS	02S	04E	14	4,717	10	111ALVM

GWIC ID	Type	Latitude	Longitude	Geomethod	Township	Range	Section	Ground-Surface Altitude (ft-amsl)	Total Depth (ft)	Aquifer
224097	WELL	45.6749	-111.1764	SUR-GPS	02S	04E	12	4,705	30	111ALVM
224098	WELL	45.6820	-111.2029	SUR-GPS	02S	04E	11	4,669	14.5	111ALVM
224099	WELL	45.6820	-111.2029	SUR-GPS	02S	04E	11	4,669	8	111ALVM
224100	WELL	45.6851	-111.2019	SUR-GPS	02S	04E	11	4,664	21.5	111ALVM
224103	WELL	45.6808	-111.2066	SUR-GPS	02S	04E	10	4,672	19.5	111ALVM
224106	WELL	45.6808	-111.2066	SUR-GPS	02S	04E	10	4,671	9.8	111ALVM
224109	WELL	45.7134	-111.1768	SUR-GPS	01S	04E	36	4,610	18.5	111ALVM
224110	WELL	45.7075	-111.1950	SUR-GPS	01S	04E	35	4,617	21.65	111ALVM
224111	WELL	45.7147	-111.2081	SUR-GPS	01S	04E	27	4,587	17.5	111ALVM
224112	WELL	45.7147	-111.2081	SUR-GPS	01S	04E	27	4,586	10	111ALVM
224113	WELL	45.6916	-111.2097	SUR-GPS	02S	04E	3	4,644	11	111ALVM
224116	WELL	45.6810	-111.2102	SUR-GPS	02S	04E	10	4,672	12.2	111ALVM
224117	WELL	45.6810	-111.2102	SUR-GPS	02S	04E	10	4,672	8.5	111ALVM
224125	WELL	45.6595	-111.2048	SUR-GPS	02S	04E	14	4,726	20	111ALVM
224126	WELL	45.6595	-111.2048	SUR-GPS	02S	04E	14	4,726	10	111ALVM
224130	WELL	45.6478	-111.2040	SUR-GPS	02S	04E	23	4,762	29	111ALVM
224132	WELL	45.6412	-111.2045	SUR-GPS	02S	04E	26	4,777	19.5	111ALVM
224135	WELL	45.6412	-111.2045	SUR-GPS	02S	04E	26	4,777	10	111ALVM
224177	WELL	45.6702	-111.1828	SUR-GPS	02S	04E	13	4,713	20.24	111ALVM
226768	WELL	45.7584	-111.0724	SUR-GPS	01S	05E	14	4,581	90	120SNGR
226769	WELL	45.6614	-111.1733	SUR-GPS	02S	04E	13	4,756	50	111ALVM
226772	WELL	45.6933	-111.0882	SUR-GPS	02S	05E	3	4,748	56.5	111SNGR
226774	WELL	45.6933	-111.0882	SUR-GPS	02S	05E	3	4,748	23	111SICL
234907	WELL	45.6537	-111.1902	SUR-GPS	02S	04E	23	4,754	28	111SNGR
234930	WELL	45.6277	-111.2430	SUR-GPS	02S	04E	28	5,060	158	500GNSC
235473	WELL	45.6167	-111.0990	SUR-GPS	02S	05E	34	5,156	36	112SNGR
235475	WELL	45.7485	-111.1698	SUR-GPS	01S	04E	13	4,527	73	112SNGR
235478	WELL	45.5523	-111.1079	SUR-GPS	03S	05E	28	5,581	80	500GNSC
235511	WELL	45.6743	-111.1248	SUR-GPS	02S	05E	9	4,807	36	111SNGR
235512	WELL	45.5231	-111.2496	SUR-GPS	04S	04E	5	5,125	57	111SNGR
241692	WELL	45.7125	-111.0644	SUR-GPS	01S	05E	35	4,669	8.9	120SNGR
242770	WELL	45.6738	-111.1869	SUR-GPS	02S	04E	11	4,705	23	111SNGR
255476	WELL	45.7876	-111.2585	SUR-GPS	01N	04E	32	4,381	63	111ALVM
259036	WELL	45.7091	-111.1768	SUR-GPS	01S	04E	36	4,621	401	121SXCK
259041	WELL	45.7089	-111.1770	SUR-GPS	01S	04E	36	4,622	60	112ALVM
259043	WELL	45.7087	-111.1768	SUR-GPS	01S	04E	36	4,622	59	112ALVM
259046	WELL	45.7089	-111.1766	SUR-GPS	01S	04E	36	4,621	60	112ALVM
259047	WELL	45.7091	-111.1768	SUR-GPS	01S	04E	36	4,621	60	112ALVM
259052	WELL	45.7089	-111.1768	SUR-GPS	01S	04E	36	4,621	60	112ALVM
259053	WELL	45.6266	-111.1756	SUR-GPS	02S	04E	36	4,873	80	112ALVF

GWIC ID	Type	Latitude	Longitude	Geomethod	Township	Range	Section	Ground-Surface Altitude (ft-amsl)	Total Depth (ft)	Aquifer
259055	WELL	45.6266	-111.1758	SUR-GPS	02S	04E	36	4,872	280	121SXCK
259056	WELL	45.6266	-111.1758	SUR-GPS	02S	04E	36	4,873	60	112ALVF
259058	WELL	45.6265	-111.1756	SUR-GPS	02S	04E	36	4,874	60	112ALVF
259059	WELL	45.6266	-111.1754	SUR-GPS	02S	04E	36	4,874	60	112ALVF
259061	WELL	45.6268	-111.1756	SUR-GPS	02S	04E	36	4,872	60	112ALVF
259062	WELL	45.7877	-111.2587	SUR-GPS	01N	04E	32	4,387	273	111ALVM
259064	WELL	45.7878	-111.2587	SUR-GPS	01N	04E	32	4,387	60	111ALVM
259066	WELL	45.7878	-111.2584	SUR-GPS	01N	04E	32	4,386	60	111ALVM
259067	WELL	45.7875	-111.2584	SUR-GPS	01N	04E	32	4,388	60	111ALVM
259068	WELL	45.7875	-111.2587	SUR-GPS	01N	04E	32	4,387	60	111ALVM
259069	WELL	45.7131	-111.1516	SUR-GPS	01S	05E	31	4,604	30	111ALVM
259070	WELL	45.7134	-111.1520	SUR-GPS	01S	05E	31	4,603	72	111ALVM
259071	WELL	45.7129	-111.1521	SUR-GPS	01S	05E	31	4,604	30	111ALVM
259072	WELL	45.7132	-111.1524	SUR-GPS	01S	05E	31	4,603	70	121SXCK
259073	WELL	45.7132	-111.1522	SUR-GPS	01S	05E	31	4,603	250	121SXCK
259074	WELL	45.7131	-111.1520	SUR-GPS	01S	05E	31	4,603	90	111ALVM
259548	WELL	45.5399	-111.2326	SUR-GPS	03S	04E	33	5,073	55	111SNGR
260216	WELL	45.5402	-111.2403	SUR-GPS	03S	04E	33	5,084	100	NA
266836	WELL	45.7585	-111.2683	SUR-GPS	01S	04E	8	4,446	100	112ALVM
268895	WELL	45.7587	-111.2684	SUR-GPS	01S	04E	8	4,446	40	112ALVM

Note. NA, not available. Aquifer codes are as follows:

110ALVM	Alluvium (Quaternary)
110SNGR	Sand and gravel (Quaternary)
111ALVM	Alluvium (Quaternary)
111SICL	Silt and clay (Quaternary)
111SNGR	Sand and gravel (Quaternary)
112ALVF	Alluvial fan deposits (Pleistocene; Quaternary or Tertiary)
112ALVM	Alluvium (Pleistocene; Quaternary or Tertiary)
112SNGR	Sand and Gravel (Pleistocene; Quaternary or Tertiary)
120SDMS	Sediments (Tertiary)
120SNGR	Sand and gravel (Tertiary)
121SXCK	Sixmile Creek Formation (Tertiary)
500GNSC	Gneiss and Schist (Early Proterozoic or Achean)

Table A-2. Surface-water sites.

GWIC ID	Type	Site Name	Latitude	Longitude	Geomethod	Township	Range	Section	Ground-Surface Altitude (ft-amsl)
257348	STREAM	Gallatin River (Hwy. 191)	45.5243	-111.2496	SUR-GPS	04S	04E	5	5,100
257349	STREAM	Gallatin River (Williams Bridge)	45.5404	-111.2345	SUR-GPS	03S	04E	28	5,049
257350	STREAM	Gallatin River (Axtell Bridge)	45.6231	-111.2053	SUR-GPS	02S	04E	35	4,831
257351	STREAM	Axtell Slough (Axtell-Anceny Rd.)	45.6239	-111.2080	SUR-GPS	02S	04E	34	4,819
257352	STREAM	Fish Creek (Axtell-Anceney Rd.)	45.6274	-111.2167	SUR-GPS	02S	04E	27	4,826
257355	STREAM	Gallatin River (Amsterdam Rd.)	45.7727	-111.2391	SUR-GPS	01S	04E	4	4,435
257387	STREAM	Hyalite Creek (S. 19th st.)	45.5907	-111.0881	SUR-GPS	03S	05E	10	5,314
257388	STREAM	Hyalite Creek (Gooch Hill Rd.)	45.6364	-111.1310	SUR-GPS	02S	05E	29	4,975
257391	STREAM	Hyalite Creek (Cobb Hill Rd.)	45.6699	-111.1649	SUR-GPS	02S	04E	13	4,741
257392	STREAM	Hyalite Creek (Monforton Sch. Rd.)	45.6863	-111.1700	SUR-GPS	02S	04E	1	4,670
257393	STREAM	Hyalite Creek (Baxter Ln.)	45.7001	-111.1690	SUR-GPS	02S	04E	1	4,636
257394	STREAM	Hyalite Creek (Valley Ctr Rd.)	45.7293	-111.1547	SUR-GPS	01S	05E	19	4,562
257395	STREAM	Hyalite Creek (Cameron Bridge Rd.)	45.7427	-111.1408	SUR-GPS	01S	05E	20	4,521
257396	STREAM	Hyalite Creek (Frontage Rd.)	45.7520	-111.1325	SUR-GPS	01S	05E	17	4,496
257426	STREAM	Dry Creek (Cobb Hill Rd.)	45.6599	-111.1834	SUR-GPS	02S	04E	13	4,733
257427	STREAM	Dry Creek (Baxter Ln.)	45.7000	-111.1758	SUR-GPS	02S	04E	1	4,638
257428	STREAM	Dry Creek (Valley Center Rd.)	45.7293	-111.1592	SUR-GPS	01S	05E	19	4,566
257429	STREAM	Dry Creek (Cameron Bridge Rd.)	45.7437	-111.1504	SUR-GPS	01S	05E	19	4,527
257435	STREAM	Cottonwood Creek (Law Bridge)	45.5881	-111.1672	NAV-GPS	03S	04E	12	N/A
257437	STREAM	Cottonwood Creek (near Gooch Hill Rd.)	45.5968	-111.1905	SUR-GPS	03S	04E	11	4,966
257454	STREAM	Elk Grove Slough (near Hwy. 191)	45.6547	-111.1870	SUR-GPS	02S	04E	23	4,745
257457	STREAM	Gallatin River (Cameron Bridge Rd.)	45.7434	-111.2257	SUR-GPS	01S	04E	16	4,510
257460	CANAL	Mammoth Ditch	45.7065	-111.1887	SUR-GPS	01S	04E	35	4,625
257461	CANAL	Mammoth Ditch	45.7087	-111.1868	SUR-GPS	01S	04E	35	4,618
257462	CANAL	Mammoth Ditch	45.7289	-111.1695	SUR-GPS	02S	04E	2	4,572
257466	CANAL	Beck Border Ditch (Baxter Rd.)	45.6999	-111.1535	NAV-GPS	02S	05E	6	N/A
257467	CANAL	Beck Border Ditch (Gaffkey Ranch)	45.7093	-111.1509	NAV-GPS	01S	05E	31	N/A
257468	STREAM	Elk Grove Slough (Blackwood Rd.)	45.6383	-111.1896	NAV-GPS	02S	04E	26	N/A
257470	CANAL	Middle Creek Supply Ditch	45.6527	-111.1966	NAV-GPS	02S	04E	23	N/A
257472	CANAL	Hulbert Ditch	45.6895	-111.1591	NAV-GPS	02S	05E	6	N/A
257473	CANAL	Farmers Canal (Zachariah Lane)	45.6149	-111.1932	NAV-GPS	02S	04E	35	N/A
257478	CANAL	Hulbert Ditch	45.6743	-111.1725	NAV-GPS	02S	04E	12	N/A
258306	STREAM	West Gallatin (near Norris Rd. bridge)	45.6720	-111.2093	SUR-GPS	02S	04E	10	4,686
258424	CANAL	Mammoth Ditch	45.7069	-111.1877	NAV-GPS	01S	04E	35	N/A
258429	CANAL	Middle Creek Supply Ditch	45.7065	-111.1886	NAV-GPS	01S	04E	35	N/A
258433	CANAL	Middle Creek Supply Ditch	45.6641	-111.1863	NAV-GPS	02S	04E	23	N/A
265153	STREAM	Dry Creek (Frontage Rd.)	45.7579	-111.1418	SUR-GPS	01S	05E	17	4,490
295974	CANAL	Mammoth Ditch (Blackwood Rd.)	45.6419	-111.1655	NAV-GPS	02S	04E	24	5,630

Note. N/A, not available.

Table A-3. Lithology sites.

GWIC ID	Type	Latitude	Longitude	Geomethod	Township	Range	Section	Ground-Surface Altitude (ft-amsl)	Total Depth (ft)	Static Water Level (ft)	Aquifer
91002	WELL	45.6795	-111.2065	MAP	01S	04E	10	4685	103	42	110ALVM
91290	WELL	45.7006	-111.2011	TRS-SEC	01S	04E	35	4635	111.5	40.5	110ALVM
95230	WELL	45.6796	-111.2148	MAP	02S	04E	10	4720	300	100	122MDSV
133291	WELL	45.6717	-111.2272	TRS-SEC	02S	04E	9	4855	295	60	122MDSV
168668	WELL	45.6703	-111.1555	TRS-SEC	02S	05E	18	4815	140	60	122MDSV
189068	WELL	45.6180	-111.1877	TRS-SEC	02S	04E	35	5000	175	121	110ALVF
191985	WELL	45.6728	-111.1716	TRS-SEC	02S	04E	12	4722	158	27	122MDSV
193438	WELL	45.6472	-111.1923	TRS-SEC	02S	04E	23	4775	158.5	14	122MDSV
221151	WELL	45.7192	-111.1884	NAV-GPS	01S	04E	26	4600	240	24	122MDSV
221470	WELL	45.6645	-111.1271	NAV-GPS	02S	05E	17	4851	160	16	122MDSV
223221	WELL	45.6748	-111.1846	NAV-GPS	02S	04E	12	4747	208	20.3	122MDSV
227472	WELL	45.6730	-111.1422	TRS-SEC	02S	05E	8	4795	87	35	122MDSV
228309	WELL	45.6109	-111.1932	TRS-SEC	03S	04E	2	4893	340	22	500GNSC
230754	WELL	45.5861	-111.1922	NAV-GPS	03S	04E	11	4997	360	44	122MDSV
248820	WELL	45.6612	-111.1883	NAV-GPS	02S	04E	14	4735	525	-12.17	500GNSC
259036	WELL	45.7091	-111.177	NULL	01S	04E	36	4621	13	401	121SXCK
261576	WELL	45.7426	-111.1966	TRS-SEC	01S	04E	23	4542	135	18	110ALVM
265363	WELL	45.6733	-111.1836	TRS-SEC	02S	04E	12	4710	100	12	110ALVM
268257	WELL	45.6700	-111.2222	NAV-GPS	02S	04E	15	4790	160	59	122MDSV
271252	WELL	45.6653	-111.1515	NAV-GPS	02S	05E	18	4835	112	52	122MDSV
285205	WELL	45.6689	-111.1357	SUR-GPS	02S	05E	17	4815	162	8.48	122MDSV
286865	WELL	45.7820	-111.2028	TRS-SEC	01S	04E	2	4650	118.5	70	110ALVM
287934	WELL	45.6717	-111.1748	MAP	02S	04E	12	4720	240	28.5	122MDSV

Note. Aquifer codes are as follows:

110ALVF Alluvial fan deposits (Quaternary)

110ALVM Alluvium (Quaternary)

121SXCK Sixmile Creek Formation (Pleistocene; Quaternary or Tertiary)

122MDSV Madison Valley Formation (Tertiary)

500GNSC Gneiss and Schist (Early Proterozoic or Achean)

APPENDIX B

WATER CHEMISTRY TABLES

Table B-1. Analytical parameters for water samples reported in the study area.

Major Ions (mg/L)	
Calcium	Ca
Magnesium	Mg
Sodium	Na
Potassium	K
Silica	SiO_2
Bicarbonate	HCO_3
Sulfate	SO_4
Chlorine	Cl
Nitrate	as N
Iron	Fe
Manganese	Mn

Field Parameters		
Water Temperature	Temp	ºC

Other Parameters		
Total Dissolved Solids	TDS	mg/L
Lab Conductivity	Lab SC	µmhos
Lab pH	Lab pH	—
Nitrate	as N	mg/L
Hardness/Alkalinity	as $CaCO_3$	mg/L

Trace Elements (µg/L)[1]	
Arsenic	As

[1]Other parameters may be available from the GWIC database.

Note. Measurements performed by the MBMG adhere to quality guidelines set forth by Timmer, 2020. µmhos = micromhos per centimeter at 25ºC.

Table B-2. Groundwater chemistry results (for selected parameters).

GWIC ID	Well Depth (ft)	Sample Date	Sediment Age	Temp °C	Lab pH	Lab SC (µmhos)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)
90918	40	4/13/11	Quaternary	7.5	7.3	356	177	38.1	11.0	4.78	1.46	13.3	125.8	44.7	2.00	0.12	0.051	0.001	0.398
90918	40	4/14/11	Quaternary	7.3	8.4	326	189	42.1	12.4	5.46	1.73	5.5	136.8	46.3	2.80	<0.5	<0.005	0.002	0.853
91230	32.5	5/13/02	Quaternary	8.5	7.01	347	214	46.5	11.5	7.71	2.87	21.8	205.2	19.4	2.51	.7 P	0.013	<0.001	<1.00
91230	32.5	8/14/08	Quaternary	8.3	7.11	335	193	37.7	10.1	7.00	9.44	20.2	184.5	13.6	4.04	0.8 P	<0.003	0.241	0.410
91244	45	9/10/92	Quaternary	9.6	7.72	449	275	64.4	14.9	10.00	2.60	22.8	256.0	29.8	3.62	0.5	<0.003	<0.002	<0.80
91244	45	7/13/93	Quaternary	9.4	7.77	444	263	61.1	13.9	10.10	3.00	21.8	243.0	30.2	3.20	0.3	0.008	<0.002	<1.00
91244	45	5/13/02	Quaternary	9.9	7.79	366	255	57.0	12.6	9.19	2.60	21.3	228.4	35.7	3.67	.5 P	0.015	<0.001	<1.00
91244	45	8/25/08	Quaternary	11.7	7.47	482	269	60.0	14.7	10.20	2.81	22.0	239.6	32.6	8.13	1.3 P	<0.003	<0.001	0.810
133174	97.5	5/14/02	Quaternary	8.1	6.94	250	185	39.0	11.1	4.50	1.44	12.5	142.5	43.7	1.45	<0.5 P	0.105	0.017	<1.00
133174	97.5	8/21/08	Quaternary	7.9	7.08	297	171	34.3	10.8	4.43	1.35	12.9	131.5	40.8	2.17	<0.5 P	<0.003	<0.001	0.523
133174	97.5	4/14/11	Quaternary	6.9	7.63	346	170	36.8	10.9	4.69	1.45	12.1	128.5	38.8	1.82	0.2	<0.005	0.002	0.459
200405	56	4/12/11	Quaternary	NR	7.77	314	167	45.7	9.9	2.34	1.22	12.4	182.3	6.2	0.90	0.1	0.007	<0.001	0.400
214428	80	4/25/13	Quaternary	11.9	7.3	428	256	59.1	14.5	5.97	3.50	21.1	228.6	33.5	4.41	1.4	<0.015 U	<0.002 U	0.850
214428	80	10/8/13	Quaternary	11.1	7.21	385	244	57.2	14.3	5.91	3.38	20.6	227.0	25.8	4.03	1.0	<0.015 U	<0.002 U	0.910
216675	40	10/23/07	Quaternary	NR	7.48	433	290	63.8	15.0	14.00	3.11	22.1	248.9	44.4	5.19	1.7 P	0.007	<0.001	0.828
216675	40	10/24/08	Quaternary	13.9	7.32	467	271	60.2	13.5	11.40	2.07	24.1	255.5	26.6	6.44	1.7 P	0.006	<0.001	0.700
222830	28	8/19/10	Quaternary	17.5	8.02	326	216	47.1	11.5	4.23	2.21	35.8	168.4	31.3	2.18	0.3	<0.002	<0.001	0.712
222830	28	10/28/10	Quaternary	11.0	7.87	288	202	47.6	11.7	4.71	2.03	16.5	173.4	31.1	2.18	0.3	<0.002	<0.001	0.785
226769	26.1	6/7/06	Quaternary	10.4	7.32	423	276	51.2	15.3	19.80	4.69	31.3	248.1	26.3	3.72	1.1	0.023	0.013	2.420
234907	28	4/25/07	Quaternary	9.4	7.63	378	220	60.6	14.8	5.24	4.01	<0.5	232.5	15.8	3.08	2.1	0.009	0.002	0.855
234907	28	10/23/07	Quaternary	NR	7.45	391	247	61.2	14.6	4.55	3.55	20.3	250.1	15.5	2.96	1.2 P	<0.005	<0.001	1.720
234907	28	10/23/07	Quaternary	NR	7.26	411	243	60.9	14.6	4.54	3.54	20.2	245.0	15.2	2.93	1.2 P	<0.005	<0.001	1.000
234907	28	10/21/08	Quaternary	13.0	7.46	419	246	61.0	14.8	5.11	3.00	21.9	247.7	15.0	3.39	1.1 P	0.008	<0.001	0.895
235475	73	4/26/07	Quaternary	11.4	7.63	453	292	68.3	15.7	13.10	4.27	24.1	275.5	27.0	3.18	0.9	0.012	0.088	0.576
235475	73	10/23/07	Quaternary	NR	7.32	501	300	74.9	16.8	7.95	3.35	22.2	294.0	26.4	3.63	1.3 P	0.006	0.002	0.603
235475	73	8/20/08	Quaternary	12.2	7.52	518	292	73.6	15.7	7.74	3.19	21.9	282.8	26.4	4.41	1.7 P	<0.001	<0.003	0.534
235511	36	10/23/07	Quaternary	NR	7.44	436	264	61.0	15.8	6.30	3.62	30.5	263.5	11.0	5.19	0.8 P	<0.005	<0.001	0.889
235511	36	9/8/08	Quaternary	11.3	7.23	465	271	62.9	15.4	6.55	3.66	32.0	267.7	12.3	5.62	0.7 P	0.033	0.004	0.734
259043	59	10/29/10	Quaternary	NR	7.75	419	286	68.8	16.2	10.90	3.10	21.2	275.3	25.1	4.71	1.2	<0.002	<0.001	0.544
259056	60	11/13/10	Quaternary	NR	7.98	334	231	44.8	13.4	11.20	4.31	34.1	202.6	20.6	2.68	0.2	<0.002	<0.001	2.680
259071	30	4/11/11	Quaternary	NR	7.26	575	285	65.0	17.2	14.80	5.25	22.4	271.4	20.1	5.31	2.0	<0.005	<0.001	0.982
194253	140	9/27/10	Tertiary	9.9	8.23	407	277	45.1	20.3	15.00	4.72	37.7	260.3	20.8	3.65	0.8	<0.020	<0.001	2.400
224069	26.1	10/26/10	Tertiary	8.3	7.87	390	290	65.5	15.0	15.70	4.10	27.2	279.9	20.4	3.84	1.4	<0.002	<0.001	1.030
248484	273	8/17/10	Tertiary	9.8	7.83	442	301	60.1	13.4	12.70	3.78	52.0	273.3	20.4	3.47	1.4	0.009	<0.001	0.725
259036	401	10/29/10	Tertiary	NR	7.93	216	190	37.0	7.1	5.86	5.41	48.0	168.9	2.5	0.55	0.1	<0.002	0.013	1.730
259055	280	11/13/10	Tertiary	NR	8.07	288	203	40.2	8.5	4.96	5.83	49.6	181.1	3.0	1.28	0.3	<0.002	0.010	1.150
259072	70	10/29/10	Tertiary	NR	7.61	396	288	60.4	15.3	17.80	4.85	26.7	273.2	21.1	5.40	1.7	<0.002	<0.001	0.635
259073	250	10/29/10	Tertiary	NR	7.87	312	237	53.4	11.4	5.62	4.90	33.2	219.8	16.8	2.37	0.6	<0.002	<0.001	1.100
259073	250	4/11/11	Tertiary	NR	7.66	457	234	54.3	11.8	5.93	5.03	32.6	208.3	17.0	2.50	0.6	<0.005	<0.001	1.070

Note. See table B-1 for parameter abbreviations. U, not detected at the method detection limit shown; P, preserved sample; J, detected above the method detection limit, but below the method reporting limit.

Table B-3. Surface-water chemistry results (for selected parameters).

GWIC No.	Surface Water Site	Sample Date	Temp °C	Lab pH	Lab SC (µmhos)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)
257350	Gallatin River	8/18/10	20.9	8.37	267	170	34.4	10.0	4.2	1.6	23.9	112.2	34.8	1.4	0.1	0.005	0.002	0.71
257350	Gallatin River	10/16/10	7.2	8.32	292	177	36.4	11.7	4.6	1.7	12.5	130.2	42.7	1.5	0.1	<0.002	0.001	0.77
257350	Gallatin River	3/10/11	5.2	8.39	295	188	38.5	12.1	4.8	1.5	12.5	125.1	50.2	1.9	0.1	<0.002	<0.001	0.86
257350	Gallatin River	4/12/11	7.9	8.46	334	184	37.0	11.1	4.8	1.5	10.6	125.7	48.7	2.6	0.1	<0.002	0.002	0.86
257350	Gallatin River	7/26/12	16.4	8.28	308	145	31.2	9.4	4.1	1.4	11.0	114.7	31.2	1.3	0.1	<0.015 U	<0.002 U	0.74
257350	Gallatin River	9/21/12	13.5	8.56	318	180	39.9	11.9	4.5	1.5	11.1	118.8	46.9	1.6	0.1	<0.015 U	<0.002 U	0.92
257350	Gallatin River	4/5/13	7.4	7.80	319	187	39.1	11.1	5.1	1.7	12.3	134.7	47.5	2.8	0.1	<0.015 U	<0.002 U	0.83
257350	Gallatin River	10/8/13	7.3	8.02	268	172	36.3	11.0	4.5	1.6	11.4	133.1	40.3	1.7	0.1	<0.015 U	<0.002 U	0.81
257351	Axtell Slough	8/19/10	10.1	7.98	395	252	52.7	13.9	4.9	2.8	36.3	189.1	44.2	2.8	0.6	0.005	0.004	0.75
257351	Axtell Slough	10/23/10	10.8	8.19	350	226	51.1	13.6	5.1	2.8	17.6	182.2	44.3	2.3	0.3	<0.002	0.003	0.81
257351	Axtell Slough	4/11/11	9.9	8.00	344	213	46.2	12.5	4.7	2.6	14.7	170.0	44.9	2.5	0.3	<0.002	0.003	0.89
257352	Fish Creek	8/18/10	12.6	8.17	352	227	51.4	13.6	7.0	3.9	21.3	187.9	33.9	2.5	0.3	0.004	0.004	1.93
257352	Fish Creek	10/23/10	10.0	8.48	311	203	44.6	12.7	5.5	2.3	15.0	152.8	41.5	2.0	0.2	<0.002	0.003	1.14
257352	Fish Creek	4/11/11	12.7	8.21	427	221	46.1	12.6	7.0	3.6	19.0	190.5	34.0	3.7	0.4	<0.002	0.004	1.56
257353	Gallatin River	10/22/10	8.9	8.70	277	185	41.1	11.8	5.0	1.8	12.4	124.6	42.5	1.6	0.1	<0.002	<0.001	0.84
257355	Gallatin River	10/23/10	NR	8.17	292	185	40.6	11.7	5.0	1.8	12.1	144.3	41.3	1.7	<0.05	<0.002	0.002	0.73
257355	Gallatin River	4/13/11	5.7	7.95	389	192	42.3	12.5	5.4	1.7	11.2	142.9	46.3	2.8	0.1	<0.005	0.003	0.85
257355	Gallatin River	4/15/11	4.4	8.23	402	194	43.6	12.7	5.9	1.8	11.7	142.0	45.0	3.1	0.1	<0.005	0.002	0.80
257355	Gallatin River	5/18/12	10.1	7.76	169	95	20.6	5.4	3.3	1.5	10.5	82.2	11.8	1.2	0.1	0.029	0.005 J	0.59
257355	Gallatin River	7/26/12	16.4	7.97	254	150	33.1	9.6	4.2	1.6	11.2	120.3	29.7	1.5	<0.01 U	<0.015 U	0.002 J	0.75
257355	Gallatin River	9/21/12	NR	8.25	312	181	41.0	11.7	4.4	1.9	10.9	133.9	42.7	1.8	<0.01 U	<0.015 U	<0.002 U	1.76
257387	Hyalite Creek	10/26/10	3.8	7.97	116	98	20.2	6.3	2.7	1.5	14.9	96.2	3.8	<0.5	<0.05	<0.002	0.002	0.55
257387	Hyalite Creek	4/12/11	3.6	7.88	147	80	16.0	4.7	2.6	1.5	15.5	74.4	3.3	<0.5	<0.05	0.021	0.002	0.46
257387	Hyalite Creek	4/14/11	2.1	7.89	146	78	15.4	4.5	2.5	1.4	14.8	74.2	3.2	<0.5	0.1	0.025	0.002	0.45
257388	Hyalite Creek	10/26/10	4.2	7.96	123	103	21.1	6.4	2.8	1.7	15.5	100.0	3.7	0.6	<0.05	<0.002	0.003	0.55
257388	Hyalite Creek	4/13/11	3.2	8.00	168	90	18.2	5.1	2.9	1.6	15.8	84.6	3.4	0.8	0.1	0.011	0.003	0.46
257391	Hyalite Creek	10/26/10	4.2	7.94	129	104	23.1	6.7	3.0	1.7	15.7	106.3	<2.5	0.5	<0.05	<0.002	0.002	0.57
257391	Hyalite Creek	4/12/11	6.1	8.30	179	95	20.1	5.5	2.9	1.7	15.0	88.4	3.7	1.1	<0.05	<0.005	0.003	0.50
257391	Hyalite Creek	4/13/11	3.4	8.16	184	95	20.0	5.5	2.8	1.6	15.2	91.0	3.7	1.0	<0.05	<0.005	0.002	0.49
257392	Hyalite Creek	10/25/10	1.4	8.32	216	165	36.4	10.8	7.0	2.5	15.8	166.5	7.2	2.2	0.5	<0.002	0.001	0.72
257392	Hyalite Creek	4/14/11	4.0	8.44	191	99	21.5	5.9	3.4	1.8	15.5	88.5	3.8	1.1	0.1	<0.005	0.001	0.47
257393	Hyalite Creek	10/25/10	5.2	8.32	211	163	36.3	10.7	6.9	2.5	16.2	165.4	7.1	2.2	0.4	<0.002	0.001	0.71
257393	Hyalite Creek	4/14/11	4.1	8.29	187	100	21.8	6.0	3.5	1.7	15.8	93.1	3.8	1.1	<0.05	<0.005	0.001	0.48
257394	Hyalite Creek	10/25/10	5.4	8.18	287	168	37.4	11.1	7.2	2.6	15.1	173.7	7.3	2.2	0.4	<0.002	0.002	0.69
257394	Hyalite Creek	5/2/12	9.0	7.75	160	82	16.7	4.2	2.2	1.4	15.7	76.2	3.7	0.9	<0.01 U	0.042	0.002 J	0.64
257394	Hyalite Creek	7/17/12	21.3	8.27	245	151	32.9	9.7	4.8	2.0	11.9	134.9	21.4	1.5	0.1	<0.015 U	0.003 J	0.71
257394	Hyalite Creek	9/5/12	15.0	8.33	310	186	42.1	12.3	6.4	2.6	12.4	154.3	32.2	2.0	<0.01 U	<0.015 U	0.002 J	0.72
257394	Hyalite Creek	10/8/13	9.1	8.24	360	219	43.0	17.0	13.7	3.9	4.1	220.7	16.6	5.0	0.3	<0.015 U	<0.002 U	0.72
257395	Hyalite Creek	8/27/10	18.7	8.35	290	177	42.0	9.4	4.9	1.9	11.6	138.3	29.3	1.9	0.1	<0.002	0.002	0.82
257395	Hyalite Creek	10/27/10	5.1	8.35	271	165	36.3	10.8	6.6	2.4	15.4	163.5	8.9	2.3	0.3	0.002	<0.001	0.74

Table B-3. *Continued.*

GWIC No.	Surface Water Site	Sample Date	Temp °C	Lab pH	Lab SC (µmhos)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3 (mg/L)	Fe (mg/L)	Mn (mg/L)	As (mg/L)
257395	Hyalite Creek	4/13/11	10.1	8.56	206	107	24.1	6.6	4.0	1.9	15.3	90.4	4.4	1.4	0.1	<0.005	0.002	0.58
257396	Hyalite Creek	8/27/10	NR	8.27	291	177	39.3	11.3	6.0	2.1	13.1	149.1	29.6	1.9	0.1	<0.002	0.003	0.81
257396	Hyalite Creek	10/21/10	NR	8.46	352	219	50.0	14.8	9.0	3.4	16.7	202.9	16.3	4.5	0.2	<0.002	0.001	0.82
257396	Hyalite Creek	4/13/11	NR	8.55	214	112	25.5	6.3	3.6	1.8	13.2	95.1	4.9	1.6	0.1	<0.005	0.002	0.56
257396	Hyalite Creek	4/27/12	6.4	7.55	158	80	17.2	4.5	2.3	1.5	15.2	71.6	3.8	0.9	<0.01 U	0.128	0.008 J	0.70
257396	Hyalite Creek	7/18/12	15.6	7.94	256	155	33.8	10.1	5.3	2.1	11.1	140.2	21.6	1.6	<0.01 U	<0.015 U	0.003 J	0.72
257396	Hyalite Creek	9/7/12	11.5	8.23	317	192	42.5	12.7	6.8	2.7	13.3	159.8	32.6	2.3	<0.01 U	<0.015 U	<0.002 U	0.77
257396	Hyalite Creek	10/9/13	4.5	8.06	443	274	58.5	18.4	11.6	4.3	18.5	278.5	18.6	6.4	0.1	0.021 J	<0.002 U	0.93
257426	Dry Creek	10/27/10	6.9	8.18	414	309	69.2	19.9	14.0	3.3	25.0	295.6	22.2	7.8	1.9	<0.002	0.004	1.09
257426	Dry Creek	4/11/11	17.4	8.46	512	287	59.7	17.5	13.9	3.3	21.5	250.2	28.3	5.5	1.3	<0.002	0.004	1.22
257427	Dry Creek	10/27/10	4.3	8.30	484	287	66.8	18.6	11.4	3.2	21.1	277.2	21.1	6.2	1.4	0.002	0.002	0.96
257427	Dry Creek	4/14/11	5.5	8.50	550	264	62.7	18.2	13.0	3.2	18.5	230.9	15.3	5.1	1.5	<0.005	0.004	0.83
257428	Dry Creek	10/27/10	4.5	8.29	467	280	63.6	18.5	11.5	3.5	20.4	267.7	21.5	6.4	1.3	0.004	0.003	1.08
257428	Dry Creek	5/2/12	9.7	8.45	521	234	48.0	14.8	10.2	2.8	17.8	216.7	13.5	4.6	1.2	0.020 J	0.004 J	1.07
257428	Dry Creek	7/17/12	18.1	7.88	233	143	31.6	9.2	4.1	1.7	10.8	123.2	24.4	1.3	0.1	<0.015 U	0.005 J	0.73
257428	Dry Creek	9/5/12	12.9	8.02	317	188	42.4	12.6	5.3	2.6	12.4	144.1	40.3	1.9	0.1	<0.015 U	0.003 J	0.81
257428	Dry Creek	4/4/13	11.2	8.22	481	259	57.1	15.8	10.7	3.2	19.5	255.5	15.3	4.7	1.5	<0.015 U	0.004 J	1.02
257428	Dry Creek	10/8/13	9.0	8.16	399	255	55.8	16.0	9.7	3.2	17.6	239.0	25.7	3.7	0.8	<0.015 U	<0.002 U	1.03
257429	Dry Creek	8/18/10	15.6	8.07	456	323	62.7	17.5	11.6	3.6	49.6	286.7	23.6	8.5	1.6	0.00	0.01	1.08
257429	Dry Creek	10/25/10	5.0	8.28	362	258	58.1	16.2	10.4	3.4	17.6	245.4	24.9	5.9	0.9	0.00	0.00	0.98
257429	Dry Creek	4/11/11	11.8	8.66	423	236	51.6	16.0	12.8	3.1	13.5	198.3	18.1	5.5	1.2	0.00	0.00	0.93
257437	Cottonwood Creek	4/11/11	9.0	8.48	328	158	38.8	10.4	1.9	1.1	10.6	172.8	4.5	1.0	<0.05	<0.002	<0.001	0.55
257437	Cottonwood Creek	4/12/11	3.5	8.39	352	165	44.1	11.6	2.4	1.2	11.3	175.6	4.5	1.2	0.1	<0.005	0.00	0.59
257454	Elk Grove Slough	8/17/10	17.3	8.48	300	201	44.0	11.4	4.2	2.1	27.9	147.4	24.8	1.6	0.4	0.01	0.01	0.82
257456	Dry Creek	8/17/10	10.2	7.84	425	290	59.9	14.0	10.6	3.6	50.0	256.9	19.4	3.3	1.9	<0.002	0.00	0.92
257457	Gallatin River	8/27/10	19.6	8.70	279	173	43.0	9.4	4.2	1.7	10.4	124.7	36.3	1.7	0.1	0.01	0.00	0.87
257457	Gallatin River	10/23/10	7.5	8.24	287	186	41.7	11.9	5.0	1.8	11.4	143.3	41.6	1.7	<0.05	<0.002	0.00	0.77
257457	Gallatin River	4/12/11	10.7	8.68	336	188	40.2	10.9	4.9	1.6	11.2	113.5	47.5	2.8	0.1	0.00	0.00	0.91
257457	Gallatin River	5/18/12	7.8	7.69	179	93	20.4	5.3	3.1	1.3	10.5	81.5	11.9	1.0	0.1	0.03	0.004 J	0.56
257457	Gallatin River	7/26/12	15.6	7.95	255	151	33.2	9.7	4.4	1.6	11.2	121.0	30.2	1.5	<0.01 U	<0.015 U	0.003 J	0.80
257457	Gallatin River	4/5/13	8.4	7.94	349	192	40.7	11.4	5.4	1.9	12.3	142.7	47.0	2.8	<0.01 U	<0.015 U	0.003 J	0.89
257457	Gallatin River	10/8/13	7.4	7.89	298	183	39.1	11.5	4.8	1.9	12.0	146.0	39.0	2.1	<0.01 U	<0.015 U	0.003 J	0.76
258306	Gallatin River	4/12/2011	9.5	8.50	383	192	41.7	12.4	5.5	1.7	11.5	132.6	46.3	3.0	0.1	<0.005	0.02	0.89
258306	Gallatin River	4/12/2011	NR	8.67	354	186	39.1	11.0	4.9	1.6	11.1	108.0	47.0	2.7	0.1	0.00	0.00	0.92

Note. See table B-1 for parameter abbreviations. U, not detected at the method detection limit shown. See figure 10 for site locations. P, preserved sample. J, detected above the method detection limit, but below the method reporting limit.

APPENDIX C

WATER BUDGET TABLES

Table C-1. Monthly Groundwater In (GW_{in}) and Groundwater Out (GW_{out}) calculations based on a constructed flow net (subsections) along the upgradient and downgradient boundaries of the area. All units in acre-feet unless otherwise indicated.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
GW_{in}	Min*	5,800	5,050	5,730	5,550	6,000	5,870	6,070	6,070	6,130	5,800	6,000	6,200	**70,270**
	GeoMean	7,730	6,740	7,640	7,390	8,000	7,830	8,090	8,090	8,180	7,730	8,000	8,270	**93,690**
	Max*	9,660	8,420	9,550	9,240	10,000	9,790	10,110	10,110	10,220	9,660	10,000	10,340	**117,110**
GW_{out}	Min	9,250	7,930	9,860	8,350	9,860	8,950	8,630	9,250	8,350	8,630	8,350	9,250	**106,660**
	GeoMean	12,330	10,580	13,150	11,140	13,150	11,930	11,510	12,330	11,140	11,510	11,140	12,330	**142,240**
	Max	15,410	13,220	16,440	13,920	16,440	14,910	14,380	15,410	13,920	14,380	13,920	15,410	**177,800**

Note. Min and max GW_{in} was calculated from the range of hydraulic conductivities (see K zone ranges below).

Table C-2. Canal flow measurement data used to calculate leakage.

Reach	Upstream Lat	Upstream Lon	Downstream Lat	Downstream Lon	Length (mi)	Date	Upstream Flow (cfs)	Downstream Flow (cfs)	Change in Flow (cfs)	Loss per mile (cfs/mi)	Geology
Mammoth	E. side floodplain (relative to W. Gallatin River.)										
Jackrabbit to	45.70866968	-111.1867657	45.72886227	-111.1694912	1.78	5/21/2010	5.64	4.92	0.73	**0.41**	Qab
E. Valley Center						8/9/2010	5.18	4.08	1.09	**0.61**	
Lower Middle Creek Supply	E. side floodplain										
Reach	**Upstream Lat**	**Upstream Lon**	**Downstream Lat**	**Downstream Lon**	**Length (mi)**	**Date**	**Upstream flow (cfs)**	**Downstream flow (cfs)**	**Change in flow (cfs)**	**Loss per mile (cfs/mi)**	**Geology**
Flume to Hwy191	45.652747	-111.196625	45.664128	-111.186268	1.01	5/28/2010	21.38	20.06	1.32	**1.31**	Qal, Qab
Hulbert	E. side floodplain										
Reach	**Upstream Lat**	**Upstream Lon**	**Downstream Lat**	**Downstream Lon**	**Length (mi)**	**Date**	**Upstream flow (cfs)**	**Downstream flow (cfs)**	**Change in flow (cfs)**	**Loss per mile (cfs/mi)**	**Geology**
Headgate (Hyalite Cr.) to Black Bull Lake	45.674328	-111.172484	45.689513	-111.159149	1.48	5/25/2010	8.03	6.41	1.62	**1.09**	Tscmv (Qab minor)
Beck-Border	E. side bench/floodplain transition										
Reach	**Upstream Lat**	**Upstream Lon**	**Downstream Lat**	**Downstream Lon**	**Length (mi)**	**Date**	**Upstream flow (cfs)**	**Downstream flow (cfs)**	**Change in flow (cfs)**	**Loss per mile (cfs/mi)**	**Geology**
Baxter to siphon	45.699906	-111.153537	45.709293	-111.150937	0.71	5/26-27/2010	7.46	5.71	1.75	**2.46**	contact of Qab, Tscmv
Lewis	W. side floodplain										
Reach	**Upstream Lat**	**Upstream Lon**	**Downstream Lat**	**Downstream Lon**	**Length (mi)**	**Date**	**Upstream flow (cfs)**	**Downstream flow (cfs)**	**Change in flow (cfs)**	**Loss per mile (cfs/mi)**	**Geology**
Flume to Taylor	45.72194444	-111.2230556	45.76546	-111.27906	4.70	4/27/2011	16.47	11.779	4.69	**1.00**	Qab
										1.1	**AVERAGE (cfs/mi)**
Farmers	E. side benches										
Reach	**Upstream Lat**	**Upstream Lon**	**Downstream Lat**	**Downstream Lon**	**Length (mi)**	**Date**	**Upstream flow (cfs)**	**Downstream flow (cfs)**	**Change in flow (cfs)**	**Loss per mile (cfs/mi)**	**Geology**
Hwy 191 (Zachariah) to Hyalite	45.614864	-111.193244	45.652463	-111.143505	5.43	5/13/2010	18.54	0.71	17.83	3.28	Qat, Tsuc, Qal canal in wetting stage

Note. These measurements were collected on reaches with no known diversions or inflows. Farmers Canal measurements were not included in the average as the canal was in wetting conditions.

Table C-3. Conversion of canal leakage to groundwater recharge (R_{can}).

	Active Days per month	Canal (mi)			Estimated Canal Leakage (acre-ft/mo)[4]		
		Minimum[1]	Mid-range[2]	Maximum[3]	Minimum	Mid-range[2]	Maximum
January	0				0	0	0
February	0				0	0	0
March	0				0	0	0
April	0				0	0	0
May	31	121	168	215	8,184	11,363	14,542
June	30	121	168	215	7,920	10,996	14,073
July	31	121	168	215	8,184	11,363	14,542
August	31	121	168	215	8,184	11,363	14,542
September	30	121	168	215	7,920	10,996	14,073
October	0				0	0	0
November	0				0	0	0
December	0				0	0	0
Total Annual					40,390	56,080	71,771

[1]Based on 2006 ditches flowing 3–60 cfs (G. Alberda, written commun., 2012).

[2]Conditions used in the Four Corners Modeling Report (Sutherland, 2014).

[3]Based on all ditches mapped (Montana State Engineer, 1953).

[4]Average canal leakage 1.1 (cfs/mi).

Note. R_{can} = (leakage rate) x (canal length) x (days per month during irrigation season).

Table C-4. Average monthly precipitation during 2010 irrigation season.

Precipitation (P) (ft)					
Apr	May	Jun	July	Aug	Sept
0.236	0.139	0.218	0.233	0.130	0.045

Note. The average precipitation each month was based on the two nearest weather stations (WRCC, 2011).

Table C-5. Water requirements (ET) for major crops grown in Gallatin County.

Crop	Apr	May	Jun	Jul	Aug	Sept	Total
Spring grains (ft)	0.000	0.073	0.497	0.723	0.105	0.000	1.398
Potatoes (ft)	0.000	0.000	0.163	0.576	0.558	0.300	1.596
Afalfa (ft)	0.033	0.284	0.444	0.634	0.512	0.319	2.226
Other hay (ft)	0.048	0.234	0.356	0.504	0.410	0.220	1.772

Note. Spring grains includes oats, spring wheat, and barley. Source*:* The water demands of each crop, each month, were determined by the Agrimet station (U.S. Bureau of Reclamation, 2014) and the average monthly precipitation (WRCC, 2011).

Table C-6. Percentages and areas of four largest crops grown in Gallatin County.

	Flood Irrigation (acres)	Sprinkler Irrigation (acres)	Pivot Irrigation (acres)	Total Area (acres)
Irrigation Efficiency (IE)[1]	35%	65%	80%	
Area Applied (acres)	686	8691	2059	11436

[1]Source: DNRC, 2011.

Table C-7. Calculation of potential monthly recharge (ft) from flood (RFLD), sprinkler (RSPR), and pivot (RPIV) irrigation in ft/month.

April	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	-0.127	-0.059
Potatoes	3%	0.000	-0.127	-0.059
Alfalfa	35%	0.000	-0.110	-0.051
Other hay	6%	-0.350	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**-0.350**	**-0.113**	**-0.053**

May	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	-0.036	-0.017
Potatoes	3%	0.000	-0.075	-0.035
Alfalfa	35%	0.000	0.078	0.036
Other hay	6%	0.176	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**0.176**	**0.005**	**0.002**

June	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	0.150	0.070
Potatoes	3%	0.000	-0.030	-0.014
Alfalfa	35%	0.000	0.122	0.056
Other hay	6%	0.256	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**0.256**	**0.126**	**0.058**

July	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	0.264	0.123
Potatoes	3%	0.000	0.185	0.086
Alfalfa	35%	0.000	0.216	0.100
Other hay	6%	0.503	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**0.503**	**0.229**	**0.106**

August	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	-0.013	-0.006
Potatoes	3%	0.000	0.230	0.107
Alfalfa	35%	0.000	0.206	0.095
Other hay	6%	0.520	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**0.520**	**0.071**	**0.033**

September	Crop Percentage (CP)	Monthly Recharge (ft)		
		Flood	Sprinkler	Pivot
Spring grains	56%	0.000	-0.024	-0.011
Potatoes	3%	0.000	0.137	0.064
Alfalfa	35%	0.000	0.148	0.069
Other hay	6%	0.325	0.000	0.000
Total recharge by crop % (R_{FLD}, R_{SPR}, R_{PIV})		**0.325**	**0.042**	**0.020**

Note. RFLD ft, flood irrigation recharge; RSPR ft, sprinkler irrigation recharge; RPIV ft/d, pivot irrigation recharge. Crops are assumed to be evenly distributed based on land percentages and irrigation type except in the case of “Other hay,” which is assumed to be flood irrigated. Where negative values indicate ET was greater than recharge; these values were zeroed.

Formulas:

Irrigation application:

Irrigation (I) = [crop requirements (ET) - precipitation (P)] / irrigation efficiency (IE)

Monthly recharge from sprinkler and pivot irrigation:

(RFLD), (RSPR) and (RPIV) = [precipitation (P) + irrigation (I) - crop requirements (ET)] x crop percentage (CP),

where: preciptitation (P) calculated in table C-4; crop requirements (ET) calculated in table C-5; irrigation efficiency (IE) listed in table C-6; irrigation method areas listed in table C-6; crop percentages (CP) calculated is based on agricultural statistics for Gallatin County (USDA 2008).

Table C-8. Calculation of the daily irrigation groundwater recharge rate and annual total for 2010 (R_{irr}).

		Flood			Sprinkler			Pivot			R_{irr}	**R_{irr}**	R_{irr}
	Acres	686			8691			2059			Min[1]	**Calculated**	Max[1]
	Days	R_{FLD} (ft)	R_{FLD} (AF)	R_{FLD} (ft/d)	R_{SPR} (ft)	R_{SPR} (AF)	R_{SPR} (ft/d)	R_{PIV} (ft)	R_{SPR} (AF)	R_{PIV} (ft/d)	(AF)	**(AF)**	(AF)
January		0			0			0					
February		0			0			0					
March		0			0			0					
April		0			0			0					
May	31	0.176	121	0.006	0.005	45	0.0002	0.002	5	0.0001	145	**171**	197
June	30	0.256	176	0.009	0.126	1,094	0.0042	0.058	120	0.0019	1,182	**1,390**	1599
July	31	0.503	345	0.016	0.229	1,989	0.0074	0.106	219	0.0034	2,170	**2,553**	2936
August	31	0.520	357	0.017	0.071	620	0.0023	0.033	68	0.0011	888	**1,045**	1202
September	30	0.325	223	0.011	0.042	367	0.0014	0.020	40	0.0007	536	**630**	725
October		0			0			0					
November		0			0			0					
December		0			0			0					
Total Annual (acre-ft/year)			1,222			4,115			452		4,920	**5,790**	6,660

[1]Minimum and maximum irrigation recharge is 15% of the calculated value. This is based on professional judgment by the author and personal communication (Kelsey Jensco, Montana Climate Office, 2019)

Note. Source: Areas designated as flood, sprinkler, or pivot irrigation from Montana Department of Revenue (2010). R_{FLD}, groundwater recharge from flood irrigation; R_{SPR}, groundwater recharge from sprinkler irrigation; R_{PIV}, groundwater recharge from pivot irrigation.

Table C-9. Calculation of groundwater recharge and discharge from stream losses and gains (STC_{in} and STC_{out}, 2010).

Month	Cottonwood Creek (acre-ft/mo)	Hyalite Creek (acre-ft/mo)	Dry Creek (acre-ft/mo)	STC_{in} (acre-ft/mo)	STC_{out} (acre-ft/mo)
January	120	1,000	190	1,120	190
February	120	1,000	190	1,120	190
March	120	1,000	190	1,120	190
April	120	1,000	190	1,120	190
May	120	1,000	190	1,120	190
June	120	1,000	190	1,120	190
July	120	1,000	190	1,120	190
August	120	1,000	190	1,120	190
September	120	1,000	190	1,120	190
October	120	1,000	190	1,120	190
November	120	1,000	190	1,120	190
December	120	1,000	190	1,120	190
Total Annual (acre-ft/yr)	1,440	12,000	2,280	13,440	2,280

Note. Minimum and maximum values for these components that are presented in table 5 are 10% of the calculated values. STC_{in}, groundwater recharge from South Cottonwood and Hyalite Creeks; STC_{out}, groundwater discharge to Dry Creek. Annual total is based on average of available flow measurements taken during non-irrigation months. Monthly estimates are the annual total divided by 12.

Table C-10. Calculation of groundwater consumption from wells (DW, 2010 conditions).

	No. Household Wells	In-House Consumption (AF/m)	Lawn and Garden Consumption				Total Volume Consumed
			Area (0.8 A/ unit)	Monthly ET %	Monthly ET AF/A	ET AF/m	**DW (AF/m)**
January	2,500	6.3	2,000	0%	0	0	**6.3**
February	2,500	6.3	2,000	0%	0	0	**6.3**
March	2,500	6.3	2,000	0%	0	0	**6.3**
April	2,500	6.3	2,000	3%	0.043	86	**92.0**
May	2,500	6.3	2,000	13%	0.211	423	**429.2**
June	2,500	6.3	2,000	20%	0.321	643	**649.0**
July	2,500	6.3	2,000	28%	0.455	911	**916.9**
August	2,500	6.3	2,000	23%	0.370	741	**746.8**
September	2,500	6.3	2,000	12%	0.199	397	**403.6**
October	2,500	6.3	2,000	0%	0	0	**6.3**
November	2,500	6.3	2,000	0%	0	0	**6.3**
December	2,500	6.3	2,000	0%	0	0	**6.3**
Total Annual		80		100%	1.6	3200	**3,280**

Note. AF, acre-feet; A, acre; m, month; ET, evapotranspiration; DW, domestic well consumption. The average in-house consumptive use rate in the Four Corners area is 0.03 AF/y (DNRC, 2011). The average lawn and garden size in the Four Corners area was calculated to be 0.8 A based on a 10% random sampling and measurement of lot sizes in the area. The Monthly ET rate for turf is from the Bozeman AgriMet station for each irrigation month (U.S. Bureau of Reclamation, 2014). The annual lawn and garden consumption for the Bozeman area is 1.6 AF/y/A (DNRC, 2011) and is used with the monthly ET rate to calculate a monthly lawn and garden consumption. On average, each residential lot includes an adjacent 0.8 A lawn/garden, and the consumptive use is calculated for the irrigation months (Total volume consumed AF). Residential lots include 1,334 domestic wells and 1,176 municipally supplied residences in the Four Corners County Water and Sewer District (FCCSD, 2019).

Table C-11. Riparian evapotranspiration for the study area.

	Riparian Area (acres)	Monthly Portion of Annual (%)[1]	Riparian ET[2] (acre-ft/mo)
January	1,213	0.0%	0
February	1,213	0.0%	0
March	1,213	0.0%	0
April	1,213	2.2%	0
May	1,213	15.7%	0
June	1,213	17.6%	0
July	1,213	26.5%	0
August	1,213	21.8%	0
September	1,213	13.3%	0
October	1,213	3.0%	0
November	1,213	0.0%	0
December	1,213	0.0%	0
Total Annual (acre-ft/yr)			0

[1]Based on monthly distribution ET rates of cottonwood from Hackett and others (1960) and Lautz (2008).
[2]Annual cottonwood ET (ft) = 2.