HYDROGEOLOGIC INVESTIGATION OF THE FOUR CORNERS STUDY AREA

GALLATIN COUNTY, MONTANA

Groundwater Modeling Report

Mary Sutherland, Tom Michalek, and John Wheaton

Montana Bureau of Mines and Geology
Groundwater Investigations Program

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ABSTRACT

A numerical groundwater flow model was developed for the Four Corners Groundwater Investigation. The model files are included with this report and are available online at the project website, http://www.mbmg.mtech.edu/gwip/gwip.asp. The primary purpose of the model was to evaluate the effects of the conversion of irrigated agricultural land to residential and commercial uses on the groundwater flow system and subsequently to local stream flows. Urbanization and evolving water uses precipitated a Gallatin River Basin-wide water-level evaluation by S.E. Slagle of the U.S. Geological Survey in the 1990s. Slagle concluded that little to no decline in water levels had occurred over the preceding 40 yr. However, the increasing rate of growth and land-use change through the first decade of the 21st century compelled a new study. The accompanying numerical model will aid in understanding the hydrologic system in addition to predicting future changes. The three-dimensional finite-difference model domain encompassed most of the Four Corners area west of Bozeman. The one-layer model of the alluvial aquifer incorporates an approximate grid cell size of 500 by 500 ft, and ranges in thickness from 146 to 409 ft. The model design was based on a conceptual model of the study area that was developed from previous research, analysis of water budget components, well logs, and surface-water conditions. Constant head, no-flow, river, stream, and specified flux boundaries constrain the model grid. Streams and canals cross the interior, and precipitation and irrigation provide recharge by infiltration.

The model was calibrated in steady-state and transient modes. Calibration of the steady-state version utilized the Pilot Point Parameter Estimation method as well as manual trial and error in order to estimate hydraulic conductivity and simulate observed water-level trends. The model-generated hydraulic conductivities and groundwater budget were evaluated relative to the conceptual model in order to determine their appropriateness to the physical system. The resulting hydraulic conductivity array was reasonable and fell within the range of results from previous studies in the Four Corners area. The model result gave an RMS error of 1.59 ft, which represents less than 1 percent of the range of elevations of observed water levels over the study area.

Thirteen of the 14 calibration targets were within the specified 3-ft calibration interval, and the remaining target was within 4 ft of the observed head.

The transient version of the model was utilized to simulate temporal changes in stress, such as seasonal streamflow and irrigation practices. The transient model was calibrated to 12 months of 2010 data, and compared to the observed heads. The 14 calibration targets from the steady-state model were used for transient calibration, and 5 additional wells were also included. Calibration of the transient model was performed by adjusting the storage coefficient until the observed transient water-level changes were replicated in the model. This calibration resulted in a storage coefficient range of 0.1–0.35, which is within the expected range for alluvium.

Four scenarios were simulated following calibration. Three of these were predictive scenarios that modeled possible future changes in stress on the system, including a decrease in recharge to the overall system, expansion of urban development (with decreasing agricultural use), and a hypothetical aquifer storage and recovery system. A fourth scenario replicated the historic system as described in 1960 by O.M. Hackett and others of the U.S. Geological Survey. The modeled scenarios showed little change in water-table elevations, though the overall groundwater flow volume changed significantly as compared to the 2010 model.

The model results concur with the study findings that, although groundwater elevations have not significantly changed in response to land-use changes, the groundwater flow system is highly dynamic and individual stresses likely have a greater impact than can be discerned from static water levels. If future changes reduce flow entering the study area, and development continues to increase demand on groundwater and decrease agricultural recharge, flow through the aquifer will decrease. A post-audit of the model would be beneficial in the years following the publication of this report in order to determine the accuracy of water-level fluctuations and land-use changes. Future site-specific models within the study area may benefit from using the flow characteristics of this model, but would require localized information to accurately simulate local conditions.

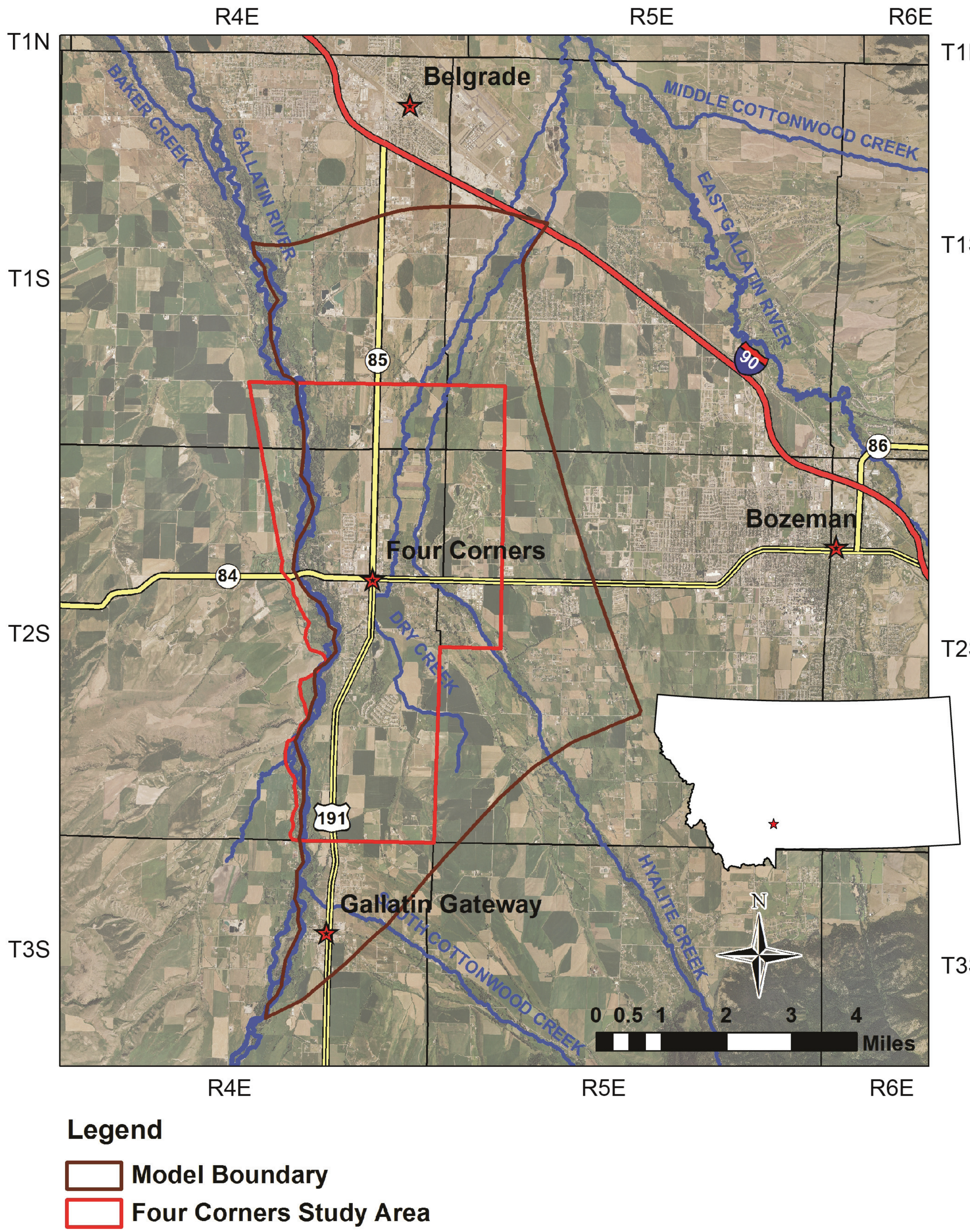

Figure 1. The Four Corners study area is located west of Bozeman and south of Belgrade. Boundaries of the model shown in brown extend beyond the study area boundary shown in red.

INTRODUCTION

In recent years the community of Four Corners has experienced substantial growth, including development of commercial and industrial businesses, rural residential neighborhoods, and suburban-style subdivisions (fig. 1). Some subdivisions and commercial interests are supplied with water and sewer services by a private utility, while other properties use conventional domestic wells and on-site septic systems. Urban and commercial growth has changed the geography of the area, which has, until recent years, remained largely agricultural in nature. In 1992, the urban and commercial acreage within the study area totaled 160 acres. By the end of 1998 there were 650 wells in the same area [Montana Bureau of Mines and Geology (MBMG)'s Ground-Water Information Center (GWIC), http://mbmggwic.mtech.edu/; fig. 2]. As of 2010, urban and commercial land in the Four Corners study area totaled over 890 acres, with approximately 1,000 wells present (fig. 3). This represents a 560% increase in urban and commercial land use, and a 150% increase in well density over a 12-yr period. Continued future development within the study area is likely.

The increase in urban use has come at the expense of agricultural acreage; large tracts of land that have historically been irrigated are now subdivided to accommodate the expansion and growing population of the Bozeman area. The 1953 *Water Resources Survey of the Gallatin Valley* (Montana State Engineer, 1953) showed limited urban development in the Four Corners area, and within the 12,400 acres of the study area, 8,500 acres were irrigated (fig. 4). Of the acreage that had not been utilized for crops, the majority was unirrigated pasture. By comparison, as of 2010, the irrigated land in the same area had fallen to just under 5,350 acres (fig. 4). Since excess irrigation water and leakage from canals contributes recharge to the groundwater system, concerns have arisen in the Four Corners area regarding the sustainability of the groundwater resource, particularly with the increasing density of wells and the overall shift in land use.

Report Purpose

This report provides documentation of the procedures and assumptions inherent in the model and communicates the findings of the model; it is intended to allow the model to be evaluated and used by others. All files needed to operate the groundwater model are posted to the program website (http://www.mbmg.mtech.edu/gwip/gwip.asp). The files are intended to enable qualified individuals to use the model developed by GWIP to test specific scenarios of interest, or to provide a starting point for site-specific analysis.

General Setting

The Four Corners study area is approximately 5 miles west of Bozeman, and 8 miles south of Belgrade (fig. 1). The study area includes about 19 square miles surrounding the community of Four Corners, located at the intersection of U.S. Highway 191 and State Highways 84 and 85. The western study area boundary follows the Quaternary/Tertiary geologic contact west of the Gallatin River, and the south and east boundaries follow section lines in Townships 1 S. and 2 S., and Ranges 4 E. and 5 E. The northern boundary runs perpendicular to Highway 85 approximately 2.8 miles north of the Four Corners intersection.

Climate

The climate of the Gallatin Valley is considered semi-arid, with cool summers and long, cold winters (Hackett and others, 1960). Climate information was compiled from the Western Regional Climate Center (WRCC) for the Belgrade Airport station (station 240622; located at Gallatin Field airport), at an elevation of 4,460 ft above mean sea level (amsl), and the Bozeman Experiment Farm station (station 241047), elevation 4,780 amsl. The Belgrade station is approximately 7 miles north of the Four Corners study area, and the Bozeman Experiment Farm station is about 3 miles east.

Between 1981 and 2010, the average annual precipitation for the Belgrade Airport Station was reported to be 14.04 in, and for the Bozeman Experiment Farm Station, 16.26 in. The majority of precipitation falls in May and June, about 5 in/month on average. The cumulative deviation for the Belgrade Airport station for the period 1951 to 2010 is (-)0.26 in and (+)1.56 in for the period

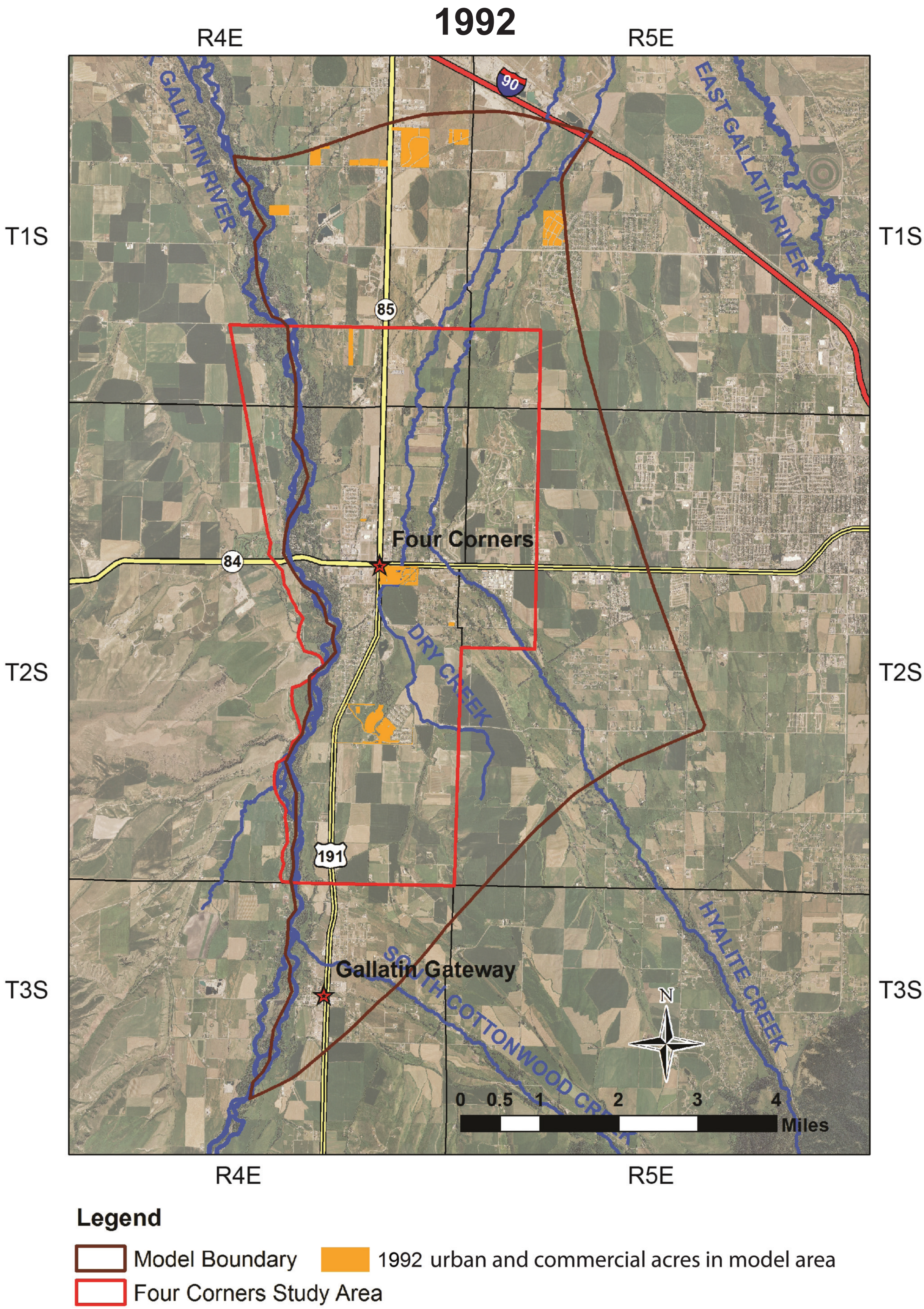

Figure 2. By 1998, the urban and commercial acreage totaled 160 acres, with 650 wells (GWIC).

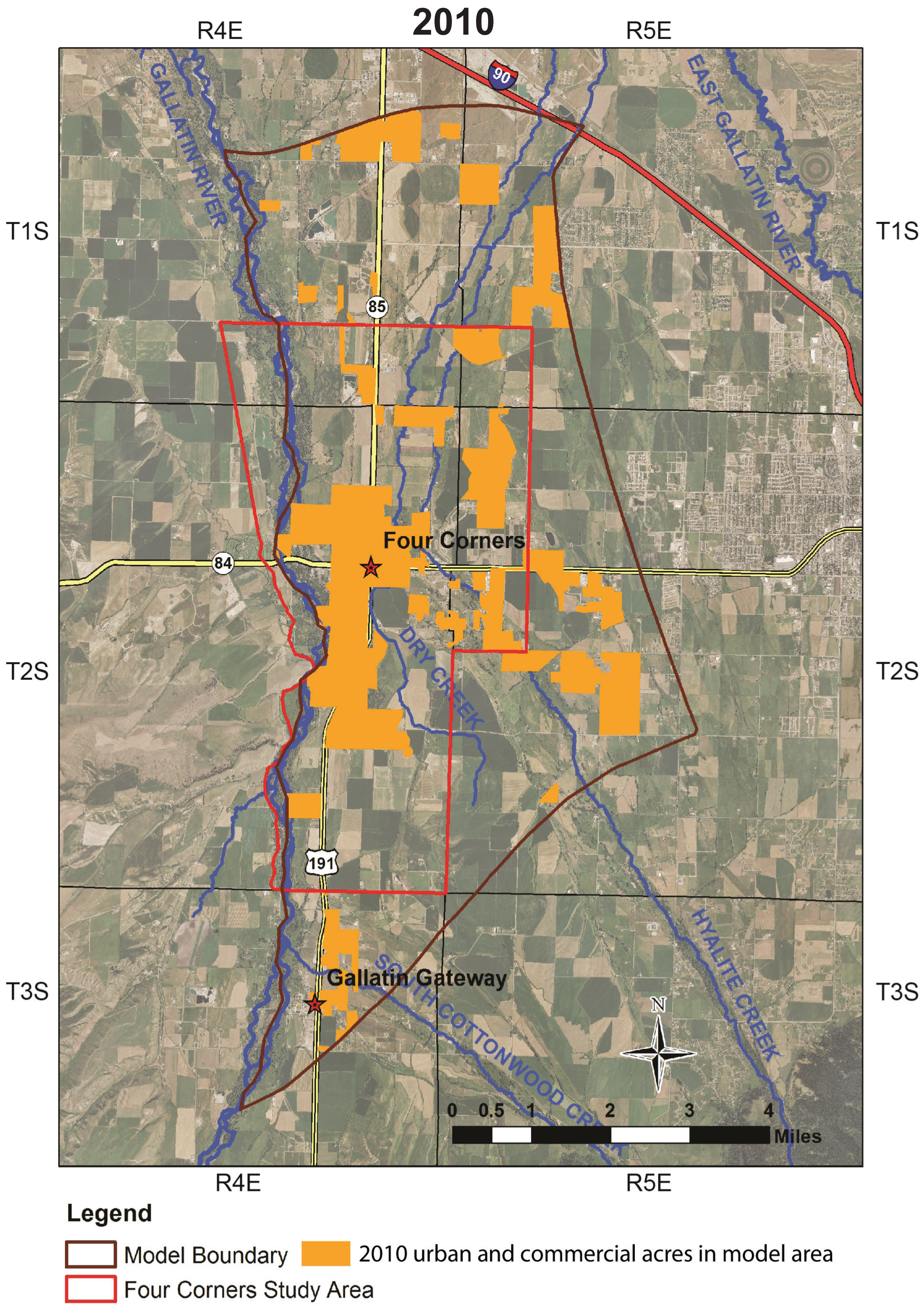

Figure 3. As of 2010, urban and commercial land in the Four Corners study area totaled over 890 acres, with approximately 1,000 wells.

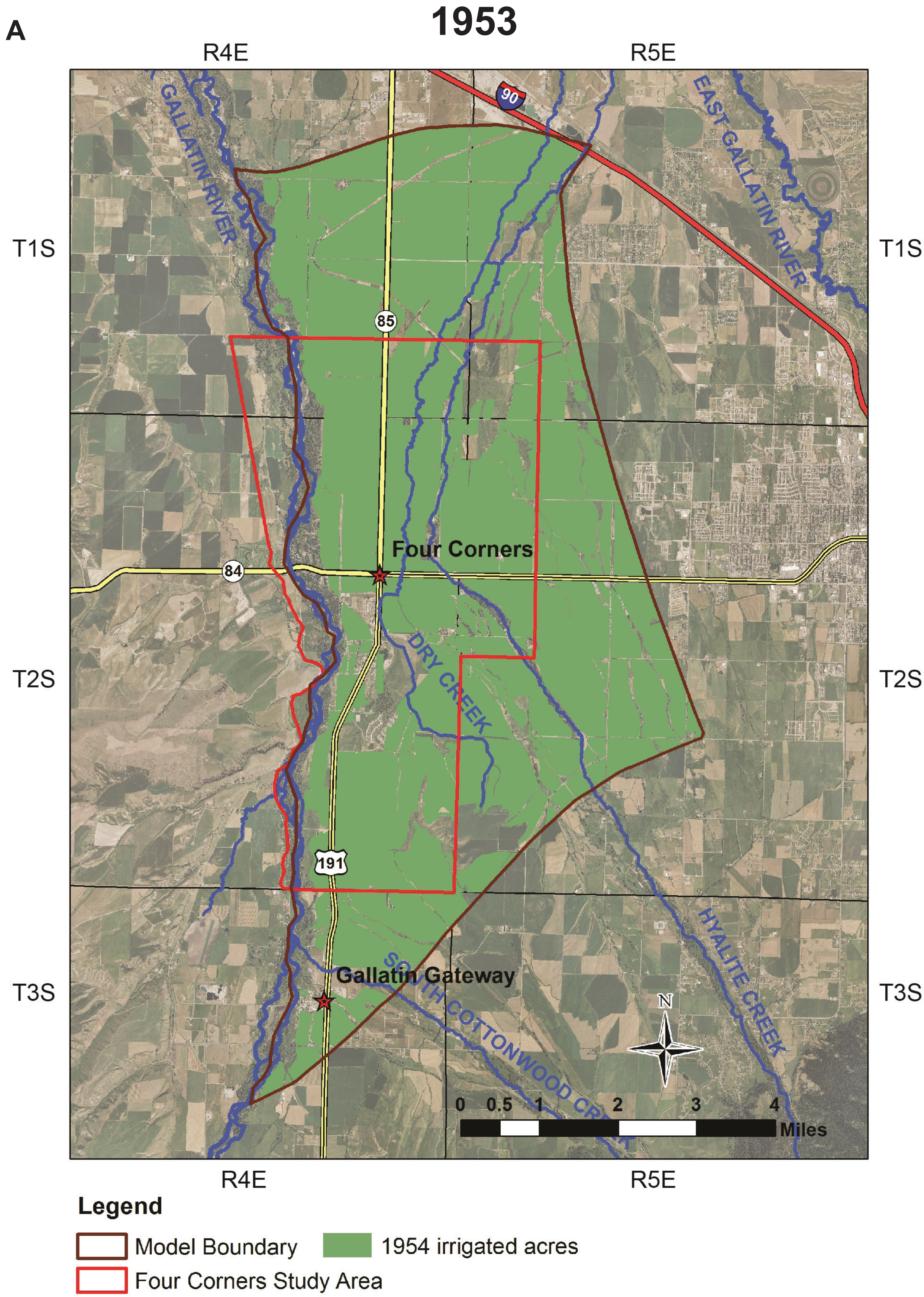

Figure 4A. The 1953 Water Resources Survey of the Gallatin Valley showed limited urban development in the Four Corners area, and within the 12,400 acres of the study area, 8,500 acres were irrigated (State Engineer's Office, 1953). Of the acreage that had not been utilized for crops, the majority was unirrigated pasture. By comparison, as of 2010, the irrigated land in the same area had fallen to just under 5,350 acres.

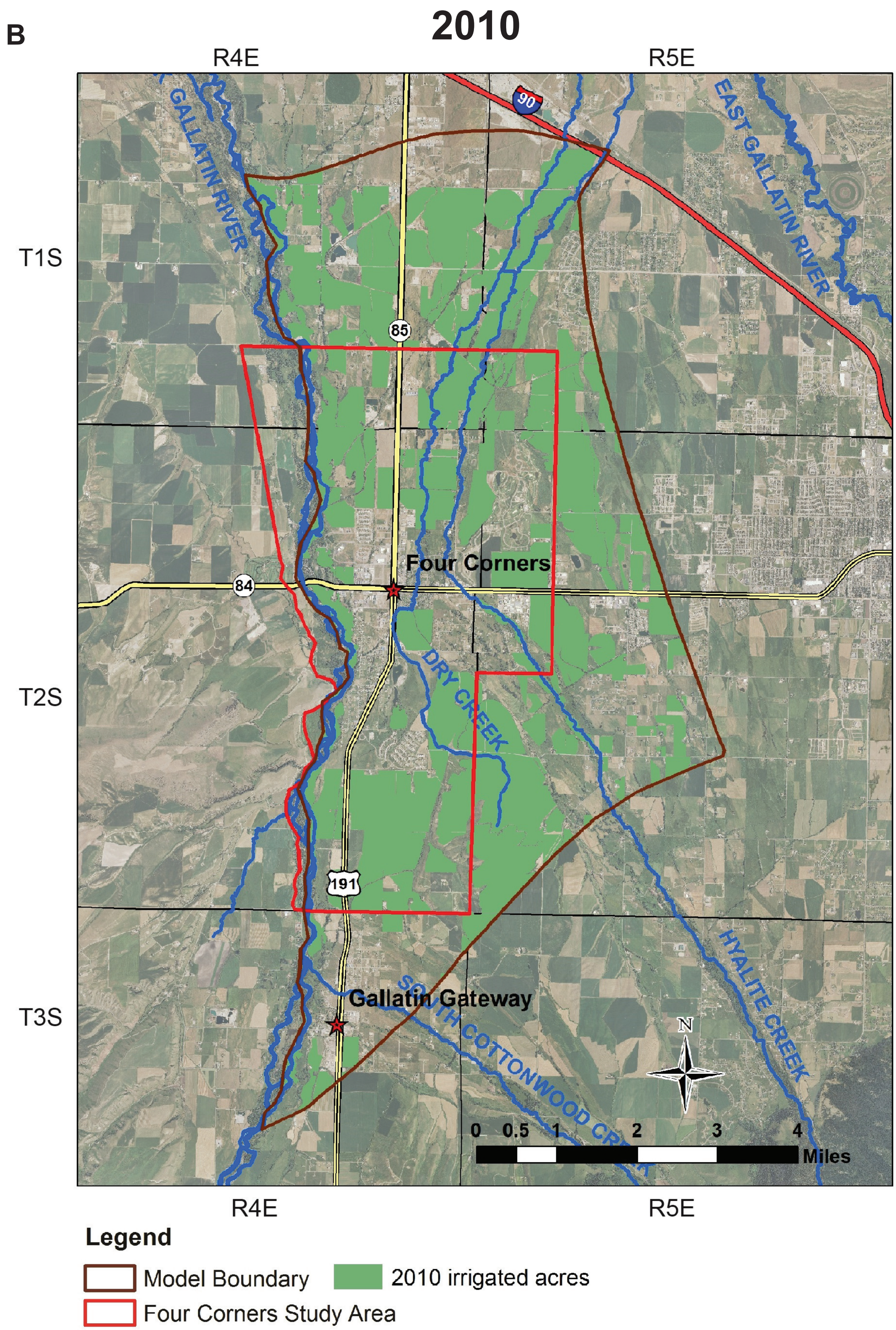

Figure 4B. The 1953 Water Resources Survey of the Gallatin Valley showed limited urban development in the Four Corners area, and within the 12,400 acres of the study area, 8,500 acres were irrigated (State Engineer's Office, 1953). Of the acreage that had not been utilized for crops, the majority was unirrigated pasture. By comparison, as of 2010, the irrigated land in the same area had fallen to just under 5,350 acres.

1981 to 2010, indicating the past 30 yr have been wetter than normal (WRCC, 2011a, b).

The average seasonal high and low temperatures were 88°F and 9°F at the Belgrade Airport station and 83°F and 12°F at the Bozeman Experimental Farm Station. The highest temperature ever recorded at the two stations was 102°F, and the lowest was -46°F. December has the coldest average temperature (7.6°F), and July has the warmest average temperature (84.9°F).

These data are deemed representative of the study area and lowlands along the Gallatin River; however, precipitation totals for the mountainous areas of the Madison, Gallatin, and Bridger Ranges typically exceed 44 in per year (Kendy and Bredehoeft, 2006). Winter snow totals in these high elevations can exceed 90 in (SNOTEL, 2013).

Physiography

The Gallatin Valley is a large, intermontane basin surrounded by rugged mountainous terrain. Encompassing an area of about 540 square miles (mi^2), it sits in the eastern half of the Three Forks structural basin. The valley is bordered on the north by the Horseshoe Hills, on the east by the Bridger Range, and on the south by the Gallatin and Madison Ranges (fig. 5). The topographic divide between the Gallatin and Madison River drainages, the Madison Plateau, bounds the valley on the west.

The principal inlets for surface water to the Gallatin Valley are the Gallatin River, which enters from the Gallatin Canyon at the upper (southern) end of the valley, and the East Gallatin River, which enters from the east. The valley is drained by the Gallatin River and its many tributaries, with the only outlet at a bedrock gorge at the town of Logan. Elevations in the Gallatin Basin range from approximately 4,100 ft amsl at Logan to about 10,000 ft amsl at the high peaks of the Gallatin Range. The highest elevations in the valley floor itself are about 6,300 ft amsl. The study area consists of the relatively flat Gallatin River floodplain and higher elevation benches that run roughly parallel to the river. These benches are typically 50 to 100 ft higher than the adjacent floodplain.

Man-Made Hydrologic Features

Engineered features important to the hydrogeology of the Four Corners study area include irrigation canals, wells, irrigation devices (pivots, sprinkler heads, etc.), septic fields, and subdivisions. The study area is irrigated primarily through a series of canals that were constructed beginning in the late 19th century and mainly date prior to 1950. The last major canal mapping project performed in the valley was part of the 1953 Water Resources Survey (WRS; Montana State Engineer, 1953). Although there have been some changes since that time, the arterial canals have been found to still exist in relatively the same locations, and it is therefore assumed that the WRS is representative of the overall system.

The 1953 survey shows a network of canals that cover nearly the entire valley, of which there are nearly 100 miles within the Four Corners study area (fig. 6). This irrigation water is diverted from the Gallatin River and Hyalite, Dry, and South Cottonwood Creeks. These canals provide recharge to the underlying groundwater both through excess irrigation application and as conveyance losses along the canals themselves (canal leakage).

Wells extract water for individual domestic use, commercial use, and irrigation (although almost all irrigation is derived from surface water within the study area). Septic systems are typically adjacent to a home, where they return a portion of the water to the aquifer to be extracted again somewhere downgradient. Irrigation devices are used for application of both surface water and groundwater, and depending on the irrigation type (pivot, sprinkler, or flood), more or less water may be applied than is transpired or evaporated; this excess water returns to the groundwater or surface-water system as return flows, runoff, or direct recharge. Gravel pits can be associated with large groundwater withdrawals through dewatering and for washing. Although the use is considered non-consumptive because the water is discharged adjacent to the pit, these pits can alter the groundwater flow system locally.

Model Objectives

The primary objective of the numerical groundwater model for the Four Corners study area was to evaluate the impacts of decreased agricultural recharge and increased urban development on groundwater levels and flow volume through the aquifer. The model was used as a predictive tool for future conditions as well as an assessment of changes since 1953 (Hackett and others, 1960), prior to significant development. Various scenarios were employed to look at long-term trends in groundwater levels based on current trends in agricultural decline and urban expansion. An important use of this model will be when future questions, currently unforeseen, are tested by other users.

This report provides detailed documentation of the procedures and assumptions inherent in the models and presents the model results, which include projected water levels, stream flow rates, and aquifer flux. This report is intended to allow the models to be evaluated and used by others. The files needed to operate the groundwater models are posted to the project website (http://www.mbmg.mtech.edu/gwip/gwip.asp), and can also be downloaded as part of this report.

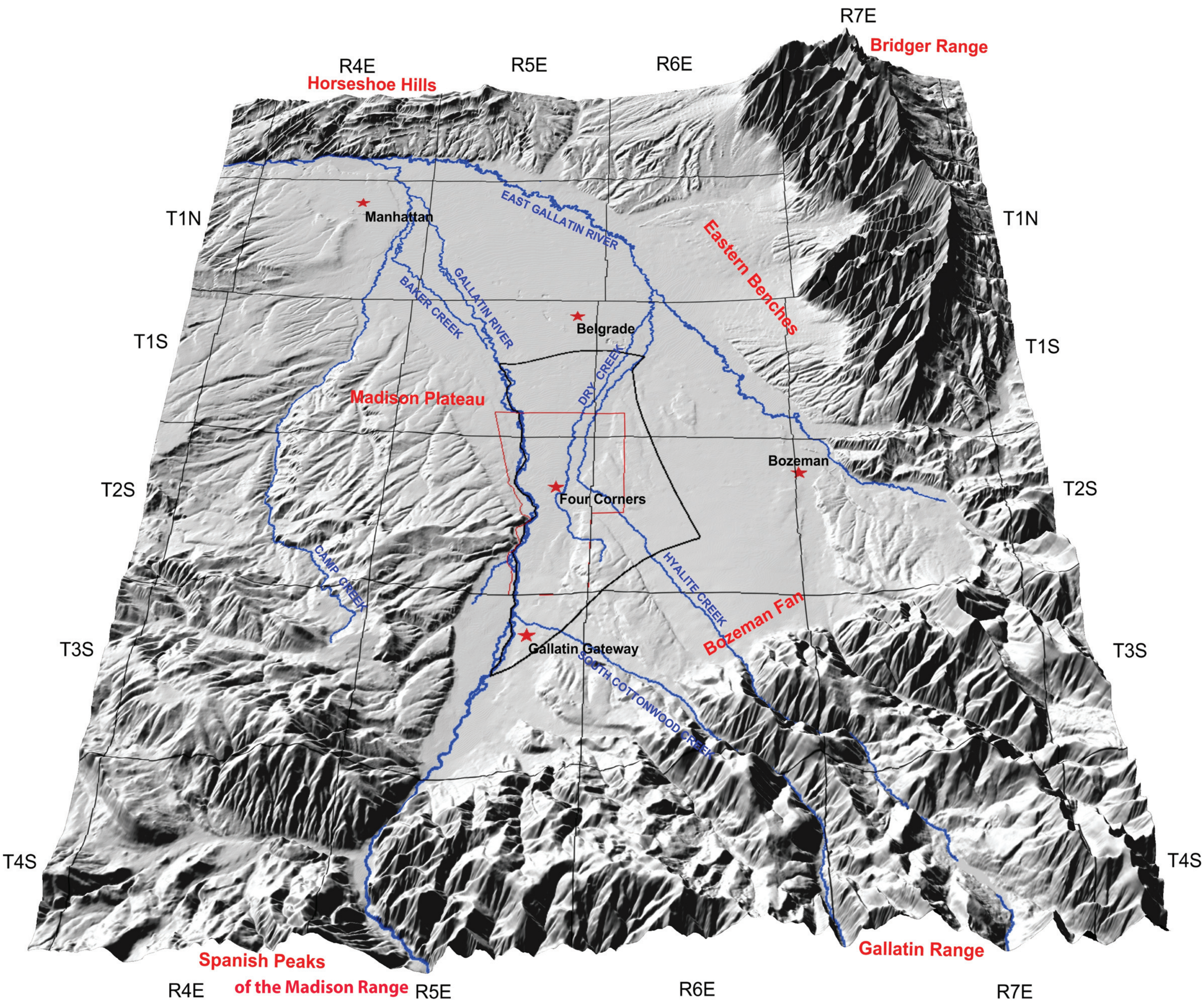

Figure 5. Elevations in the Gallatin Basin range from approximately 4,100 ft amsl at Logan to about 10,000 ft amsl at the high peaks of the Gallatin Range (vertical scale exaggerated in schematic diagram).

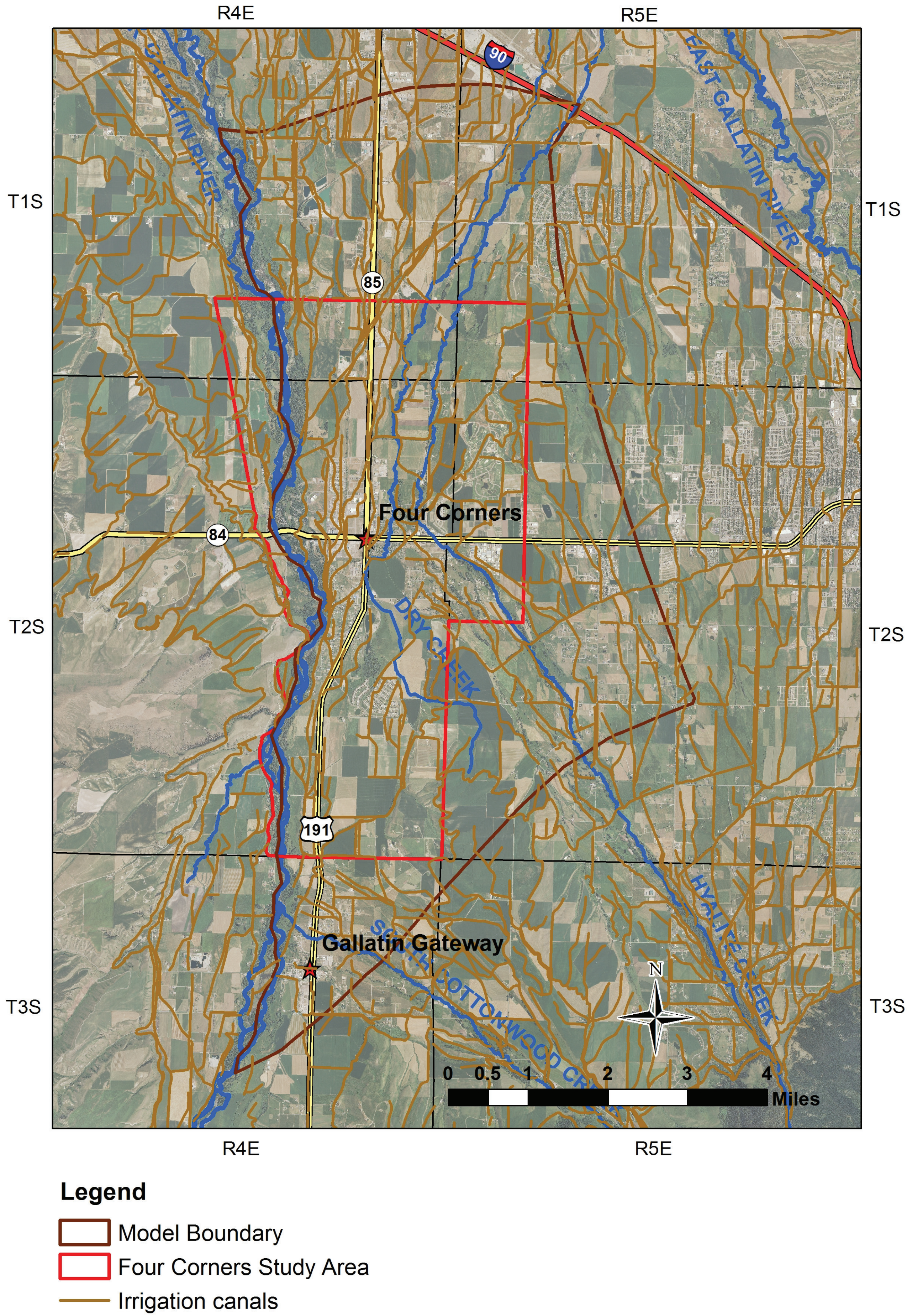

Figure 6. There are almost 2,000 miles of irrigation canals within the Gallatin Valley and nearly 200 miles of canals within the model boundary.

File explanations and details are provided in appendix A. These files are intended to enable qualified individuals to use the overall models developed by GWIP to test specific scenarios of interest, or to provide a starting point for site-specific analysis.

CONCEPTUAL MODEL

Geologic Framework

The geology of the Gallatin Basin has been mapped by Vuke and others (2014), and Lonn and English (2002); detailed descriptions are provided by Hackett and others (1960), Custer and others (1991a,b), Custer and Dixon (2002), and Slagle (1995) (fig. 7). Hackett and others (1960) and Slagle (1995) provided information on the flow regime and hydrogeology of the basin.

Two general groups of sediments were identified in the study area: (1) Quaternary alluvial sediments that cover the Gallatin Valley floor; and (2) Tertiary sediments that underlie the alluvium in the floodplain and form benches generally east and west of the floodplain. These sediments combine to form a single aquifer unit of varying characteristics.

The Quaternary-age deposits are further subdivided into separate formations, based on relative age and provenance, but are generally cobbles, sand, gravel, and silt/clay deposited by current and recent river channels and alluvial fans (fig. 7, map units Qal, Qls, Qac, Qdf, Qaf, Qab, Qafh, Qafo, Qabo, Qalo, and QTgr). These deposits can be tens to hundreds of feet in aggregate thickness.

Underlying the Quaternary deposits are Tertiary-age sediments that are grouped into the Madison Valley member of the Sixmile Creek Formation (fig. 7, map unit Tscmv). These materials are characterized by variably cemented sediments, silstones, sandstones, and conglomerates. At depth are Tertiary formations of the Dunbar Creek and Climbing Arrow Members of the Renova Formation. Together, these units can be hundreds to over 1,000 ft thick.

Hydrogeologic Units

Available water well logs, available through the GWIC database, were reviewed to determine the hydrogeologic properties of the aquifer(s) present in the Four Corners study area. Well logs are required to be submitted by water well drillers upon completion of any well in Montana, with report requirements including well location, lithological descriptions, and well completion details. Within the study area, 1,070 well logs were reviewed. Well logs used to define lithology were selected based on criteria including total depth, lithologic descriptions, and depth to water. Reported lithologies were compared to geologic maps and reports as well as well cuttings in order to aid in the stratigraphic analysis.

The stratigraphic units that define the hydrogeology of the Four Corners study area are generally lumped into two categories as defined by their respective ages: the unconsolidated Quaternary materials and the typically finer-grained and often semi-consolidated Tertiary materials. The Quaternary materials define the topography of the valley floor and dominate the surface of the Gallatin Valley. The valley-fill is alluvial in nature, ranging from clay to coarse gravel throughout the valley floor. Fluvial braid deposits, which cover much of the valley floor between the Gallatin and East Gallatin Rivers, can be as thick as 800 ft. Alluvial fan deposits exist in only a few places, primarily east of the study area, and fluvial braid and alluvium deposits generally underlie the rivers and streams.

The similarities between the compositions of the unit types, as well as the indistinct lithology of the units, often made it difficult to differentiate units in driller’s logs without a very detailed description. The eastern boundary of the study area lies over one of the few outcroppings of Tertiary sediments in the valley floor, forming the pediments surrounding the Bozeman Fan as described by Custer and others (1991a, b). Elsewhere, the Tertiary sediments are overlain by younger, Quaternary alluvial deposits.

The Quaternary and Tertiary formations are generally hydraulically connected, there being little evidence of a consistent aquitard (confining layer) to separate them. Together, therefore, they are considered one aquifer of varying conductivity with discontinuous silt/clay layers providing some local confinement in some areas. The similarities between the compositions of the unit types, as well as the indistinct lithology of the units, often make it difficult to differentiate units in driller’s logs without a very detailed description. Generally, the deeper, older sediments are finer-grained, possibly cemented, and with somewhat lower ability to transmit water to wells.

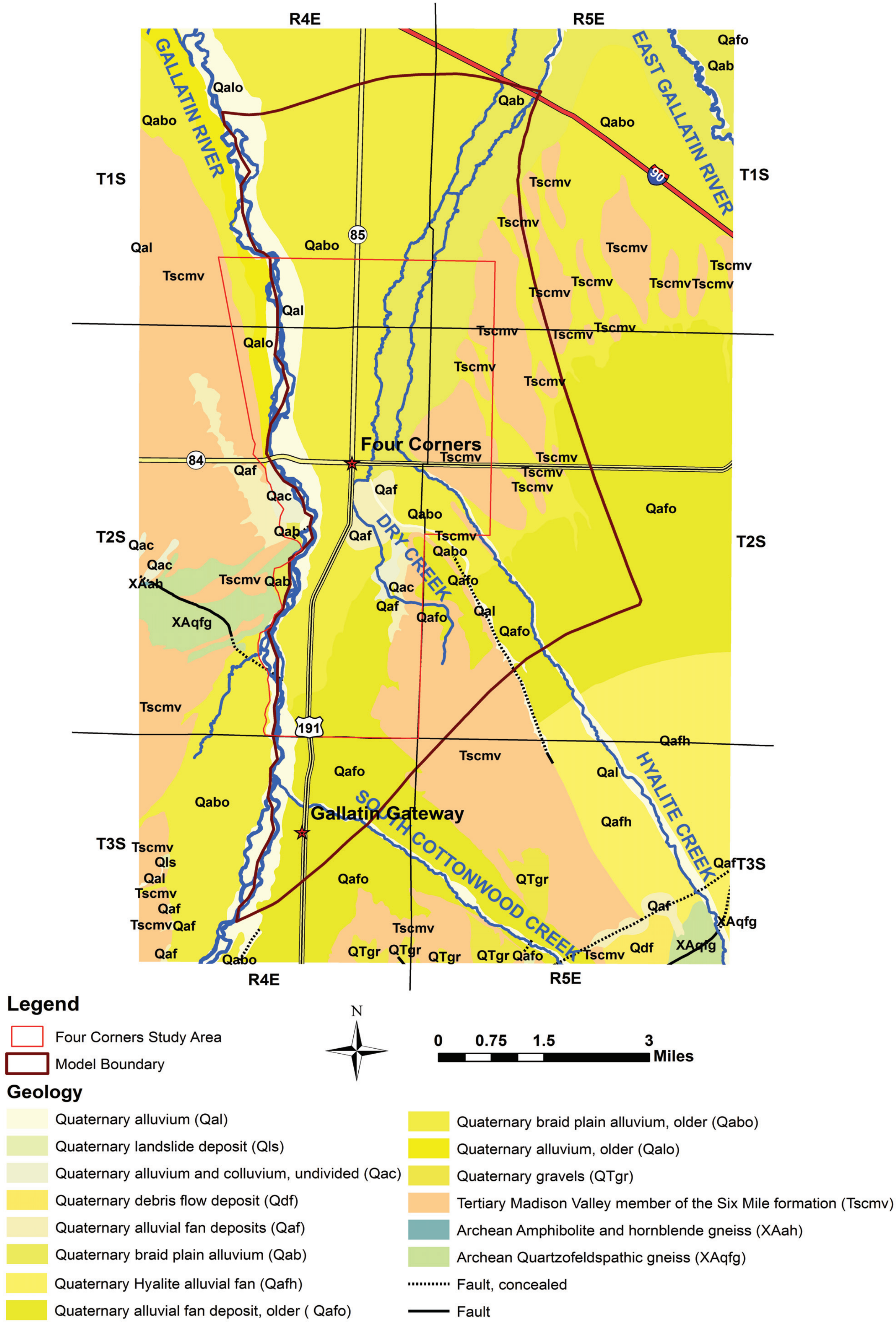

Figure 7. Surficial geologic units in the modeled area are Quaternary and Tertiary sediments.

The bedrock basement of the basin beneath the Tertiary sediments is generally over 400 to 500 ft below ground surface and was not considered hydrogeologically relevant to this effort. There are no faults that have been shown to control the groundwater flow within the study area.

Groundwater Flow System

The coarse Quaternary sediments of the Gallatin Valley are expected to have a higher transmissivity than the finer-grained underlying Tertiary deposits. These young sediments combine to form a single large aquifer, comprised of varying hydrologic units with differing hydraulic conductivities that cover the valley floor. Groundwater flow direction is controlled primarily by groundwater discharging as surface-water and groundwater recharge from the Gallatin Range. Groundwater entering the Bozeman Fan area flows northwest toward the Gallatin River, supplemented by surface-water infiltration to the unconsolidated sediments on the valley floor. The rivers and streams leaving the Gallatin Range are underlain by bedrock until they reach the range front. These streams then begin losing water to the unconsolidated Bozeman Fan and valley-fill sediments. For this reason, groundwater flow in the southern half of the study area is primarily northwest, away from the bedrock contact with the valley-fill deposits. The surface-water contribution to groundwater causes a more northward flow as groundwater leaves the Tertiary fan deposits and enters the highly conductive alluvium in the northern portions of the study area. The potentiometric map is contoured from data collected in April 2010 and shows groundwater elevations (fig. 8) and general groundwater flow direction (arrows).

The Gallatin River borders the study area to the west, and two streams flow northward through the study area, exiting through the north boundary. Hyalite Creek and Dry Creek are both perennial, though flow in Hyalite Creek is controlled by a dam upstream that creates Hyalite Reservoir. Dry Creek is a small stream that runs nearly parallel to Hyalite Creek through much of the study area, and both streams are ephemeral and intermittent. In addition, a complex network of irrigation canals is maintained throughout the entire study area. Both Hyalite Creek and Dry Creek are hydrologically connected to the irrigation network as water sources, conveyance, and receivers of return flows.

Recharge to the groundwater system is derived primarily from surface-water influx from the Gallatin River and Hyalite Creek, groundwater inflow from the Gallatin Mountains to the south, and from excess irrigation water application and leakage from the network of canals. Historically, the area has been dominated by agriculture, and a large portion of the study area is still irrigated, which provides seasonal groundwater recharge. Leakage from the irrigation network has also been found to contribute a large amount of water to the aquifer (Michalek and others, in preparation).

Groundwater exits the study area to the north through a thick package of alluvium and to surface water that exits through the Gallatin River, Hyalite Creek, Dry Creek, and irrigation canals.

Hydrologic Boundaries

The Four Corners model domain encompasses nearly the entire study area, with the exception of a small area west of the Gallatin River, extending to the Quaternary–Tertiary contact in the southeastern portion of the Madison Plateau (fig. 8). The model is bounded on the west by the Gallatin River, which acts as a dominant flow feature adjacent to the Quaternary–Tertiary contact and is defined in the model with the MODFLOW River package. On the east, a no-flow boundary runs parallel to the direction of groundwater flow determined from the potentiometric surface, until it reaches Hyalite Creek. The northernmost eastern boundary runs along Hyalite Creek for approximately 1 mile and is defined in the model as a MODFLOW Stream package. Boundaries on the north and south run parallel to potentiometric contour lines, with the northern boundary applied as a constant head boundary to reflect its relative stability throughout the year. The southern boundary fluctuates in location as the groundwater head rises and falls, though the groundwater flow into the system from the adjacent Gallatin Range provides a relatively steady influx. Therefore, this boundary was modeled as a specified-flux boundary in the numerical model.

Aquifer Properties

Several authors have estimated the aquifer properties of the Gallatin Valley, including the U.S. Geological Survey (USGS; Hackett and others,

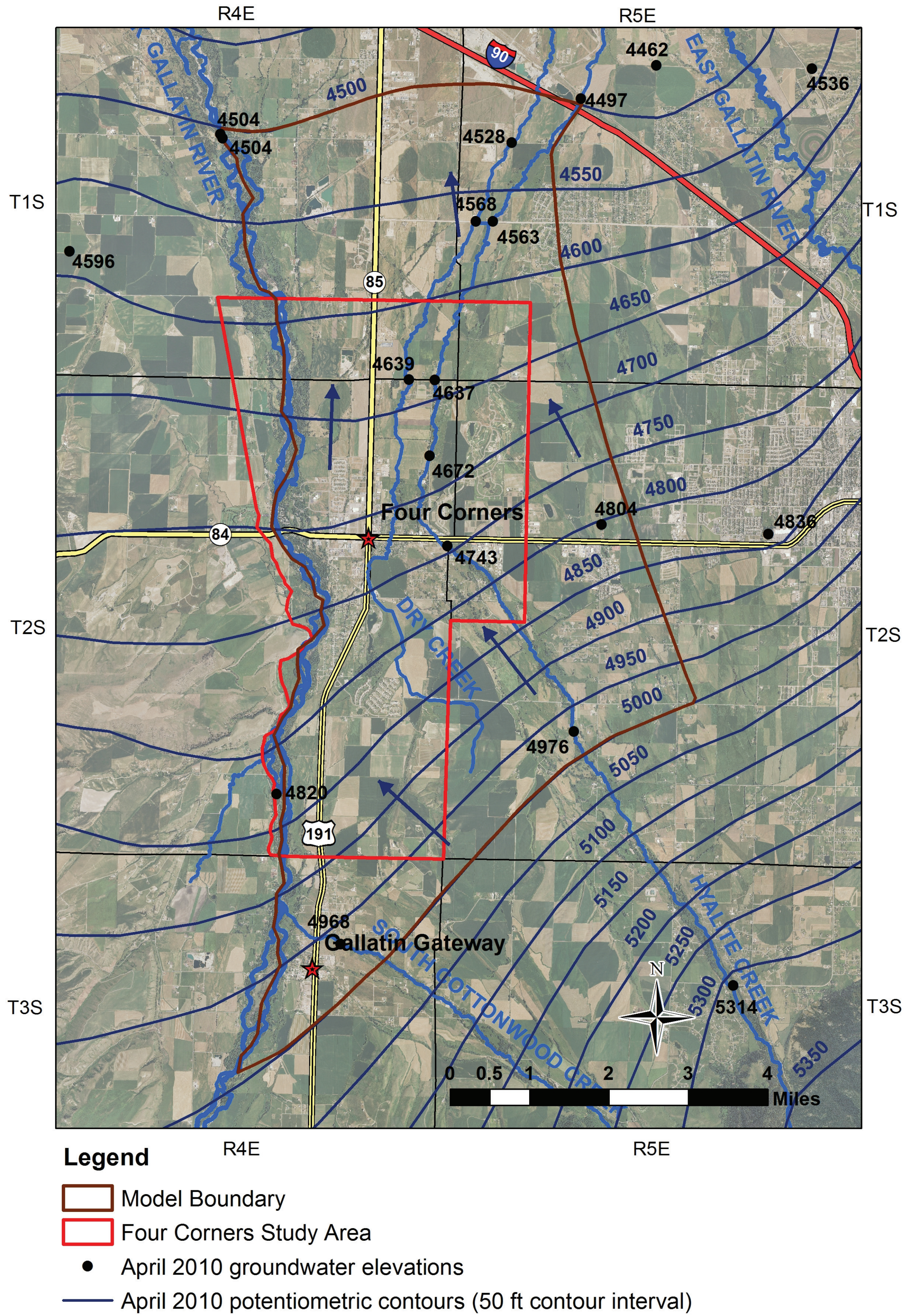

Figure 8. Potentiometric surface map indicating the approximate water levels in feet above mean sea level (amsl) based on water levels collected in April 2010.

1960; Slagle, 1995) and consultant reports, which are available through the Montana Department of Natural Resources and Conservation (Kaczmarek, 2003), and other published research (Kendy and Bredehoeft, 2006). The hydraulic conductivity of the Quaternary sediments has been estimated from aquifer testing to be between 100 and 350 ft/d, depending on the location and depth, and the Tertiary sediments have been estimated at a range of 1 to 40 ft/d. The aquifer properties used in the current model are similar to those used in another model previously developed for the Four Corners area (Kaczmarek, 2008). Aquifer properties typically reported are transmissivity (T) and storage coefficient (S); hydraulic conductivity (K) can be calculated from estimates of aquifer thickness.

In 1953, the USGS conducted a comprehensive assessment of hydrologic conditions in the Gallatin Valley, commonly referred to as the “Hackett Study” (Hackett and others, 1960); this report includes measured groundwater level and streamflow data from an extensive monitoring network and also includes pumping test data from numerous pumping tests around the Gallatin Valley (table 1).

<u>Aquifer Tests</u>

For this study three aquifer tests were conducted at three sites within the study area and an additional test site located about 3.5 miles to the northwest. Six wells were drilled at each location, five monitoring wells and one production well. Each test was conducted for approximately 7 days and water levels were measured and recorded hourly using pressure transducer data loggers. These tests were conducted and analyzed in accordance with ASTM standards (ASTM, 2010), in order to determine the horizontal and vertical flow properties of the shallow Quaternary aquifer and the underlying Tertiary sediments. These data are presented in the Four Corners Hydrogeologic Investigation Report (Michalek and others, in preparation). Existing data on aquifer properties are also available from water-rights applications obtained from the Montana DNRC (table 1).

Sources and Sinks

The sources of recharge within the model area were surficial recharge from precipitation, irrigation, and canal leakage; subsurface flow from the upgradient aquifers; and surface-water infiltration from the Gallatin River, Hyalite Creek, and Dry Creek. Hydraulic sinks included water well withdrawals, evapotranspiration (ET), discharge from the aquifer through downgradient subsurface flow, and groundwater discharge to surface water along the streams.

Groundwater Budget

Details of the components of the groundwater budget are included in appendix B. In order to describe the inputs and outputs, the equation is written as:

$$GW_{in}+R_{can}+R_{irr}+R_{pre}+RIV_{in}+STR_{DC}+STR_{Hy} = GW_{out}+R_{urb}+RIV_{out}+STR_{DC}+STR_{HY} \pm \Delta S,$$

Table 1. Various authors have reported aquifer properties on both the Quaternary (Q) and Tertiary (T) sediments in the area.

Source	Hydraulic Conductivity (ft/d)	Transmissivity (ft^2/d)	Notes
Hackett and others, 1960	low value (Q) = 1,520	38,000–670,000 (Q) 300–65,000 (T)	100 aquifer tests at 37 sites throughout the Gallatin Valley; conductivity was not determined
Kendy and Bredehoeft, 2006	200–775 (Q) 7–500 (T)	12,000–35,000 (Q) 40–2,300 (T)	Conductivity estimated from reported transmissivity values and aquifer thicknesses
Kaczmarek, 2003	260–380	12,180–12,544	Conductivity estimated as a product of reported transmissivity values and 1.5 times the screened interval
This study	510–570	20,000–22,350	Average of shallow-aquifer tests performed at two sites

where:

GW_{in}, groundwater inflow from aquifer;
R_{can}, recharge from canal leakage;
R_{irr}, recharge from infiltration from pivot, sprinkler, and flood irrigation;
R_{pre}, precipitation infiltration;
RIV_{in}, Gallatin River water leakage to aquifer;
STR_{DC} (in), Dry Creek leakage to aquifer;
STR_{Hy} (out), Hyalite Creek leakage to aquifer;
GW_{out}, groundwater outflow from aquifer;
R_{urb}, urban groundwater withdrawals from wells acting as negative recharge;
RIV_{out}, discharge to Gallatin River from groundwater;
STR_{DC}, discharge to Dry Creek from groundwater;
STR_{Hy}, discharge to Hyalite Creek from groundwater; and
ΔS, changes in storage.

In order to simplify the components of the budget within the model, the diffuse recharge from canal leakage, irrigation, and precipitation were combined into a single Recharge term (R_{in}). The diffuse extraction from multiple wells in an urban center (R_{urb}) was subtracted to simply represent net Recharge (R) over an area, the term applied to the model.

This component (R) is the difference between R_{in} (R_{can}+ R_{irr}+ R_{pre}) and R_{urb} (urban water withdrawals from wells). If R_{in} is greater than R_{urb} then recharge is positive and is expressed in the model as a single positive recharge zone. Where the urban withdrawals are in excess of the infiltration rate, R is on the right side of the equation (R_{out}). Hyalite and Dry Creeks (STR_{Hy}, STR_{DC}) were also combined to represent streamflow into (STR_{in}) or out of (STR_{out}) the model. These simplifications resulted in the following modification of the groundwater budget equation:

$$GW_{in}+R_{in}+RIV_{in}+STR_{in} = GW_{out}+RIV_{out}+R_{out}+STR_{out} \pm \Delta S.$$

Recharge is a summation of surficial inflow, including the infiltration of irrigation water, precipitation, and canal leakage as well as extraction of water through urban withdrawals. The complexity involved in quantifying the irrigation recharge created numerical uncertainties that became overly complicated for this model, and for the sake of simplicity, the irrigation season was defined as irrigation (April through September) or non-irrigation (October through March) and the irrigation rates were divided out over the irrigation months. All infiltration from canals and irrigation was set to zero during the off-season. ET is considered to be equal to or in excess of precipitation (R_{pre}) where irrigation water is not applied, and therefore in areas of no irrigation no ET water is removed or recharged, but in areas of irrigation ET is factored into the total R applied. Well withdrawals were included in the urban withdrawal uses, and calculated as a component of GW_{out}. Table 2 summarizes the values estimated for components of the groundwater budget.

Table 2. A conceptual water budget was established based on the data collected for this study and accepted hydraulic estimates.

Input Component	Value (AF/y)	Output Component	Value (AF/y)
GW_{in}	100–900	GW_{out}	30,000
R_{in}	60,000	R_{out}	Variable
RIV_{in}	20,000–40,000	RIV_{out}	20,000–50,000
STR_{in}	200–500	STR_{out}	100–500
		±ΔS	

Net recharge rates were derived from calculations, taking into account monthly precipitation throughout the irrigation season, application efficiencies for each irrigation type (DNRC, 2011), and crop requirements for grains, potatoes, alfalfa, and other hay (U.S. Soil Conservation Service, 1970) by percentage grown in Gallatin County (USDA, 2008). Recharge in these areas was held constant during steady-state calibration.

The amount of water infiltration from irrigation (R_{irr}) is dependent on the type of irrigation being employed, as determined from the 2010 Final Land Units map released by the Montana Department of Revenue (2010). Flood irrigation was calculated to be 0.00484 ft/d (21.2 in/yr), while sprinkler irrigation rates were 0.00137 ft/d (6.0 in/yr) and pivot irrigation rates were 0.004725 ft/d (20.7 in/yr).

Canal leakage (R_{can}) was found to be a difficult recharge component to quantify because it varied temporally as well as spatially. This calculation was further complicated by the fact that the canal network is quite extensive in the study area. For these reasons, canal leakage was applied to the entire model as a diffuse recharge rate of 0.00718 ft/d (31.5 in/yr) during the irrigation season; this value represents an average canal leakage rate of 1.1 cfs/mi applied over the entire model area. This leakage rate represents a best estimate of canal seepage based on multiple seepage measurements in arterial canals within several irrigation systems in the Gallatin Valley (Michalek and others, in preparation).

Urban well withdrawal (R_{out}) rates were based on a calculated average withdrawal rate for a domestic well with a household consumption rate of 0.03 acre-ft/yr in the Bozeman area (DNRC, 2011) and the average lawn and garden size in the Four Corners area (calculated as 0.8 acres) consuming 2.0 acre-ft/yr per acre (DNRC, 2011) multiplied by the number of domestic wells within the study area. Water was withdrawn at the diffuse, model-wide rates of 0.00005 ft/d (0.2 in/yr) during the irrigation season and 0.00137 ft/d (0.6 in/yr) during the off season, respectively.

Groundwater discharge into and out of the Gallatin River varies depending on the groundwater elevation adjacent to the river (hydraulic gradient) and the conductance of the river bottom sediments. The net gain to the groundwater (RIV_{in}) was estimated to be 5,000 acre-ft/yr, over the entire model area. The observed river losses proved extremely difficult to quantify due to dangerous flow-measuring conditions during the early summer months, the time period of greatest loss. Groundwater also discharges to surface water (RIV_{out}) and was estimated to be around 3,000 acre-ft/yr. This is just over half the volume that is lost from the river to groundwater (Michalek and others, in preparation).

Similar to local rivers, Hyalite Creek and Dry Creek exchange water freely between the surface and groundwater. The flow in Hyalite Creek is controlled upstream by Hyalite Dam and typically has a greater flow rate and gains and loses more water than Dry Creek. Hyalite Creek was estimated to lose (STR_{Hy}) approximately 175 acre-ft/yr, and Dry Creek was estimated to lose (STR_{DC}) approximately 25 acre-ft/yr. Conversely, Hyalite Creek gains around 8 acre-ft/yr and Dry Creek gains around 2 acre-ft/yr. After combining STR_{Hy} and STR_{DC} to create the STR components, STR_{in} was estimated to be about 200 acre-ft/yr and STR_{out} was estimated to be about 10 acre-ft/yr.

COMPUTER CODE

Groundwater Modeling Systems (GMS; Aquaveo, 2010) software was used to develop a MODFLOW 2005 groundwater flow model. MODFLOW 2005 is a widely accepted groundwater flow modeling program developed by the USGS (Harbaugh, 2005) to simulate groundwater flow through a porous medium numerically using a finite-difference method. The version of GMS used for this modeling is GMS 9.1.7, with a build date of December 6, 2013. The version of MODFLOW 2005 operated in GMS 9.1.7 is Version 1.10.00, compiled March 6, 2013.

PEST is a general-purpose parameter estimation utility developed by John Doherty of Watermark Numerical Computing (Doherty, 2010). PEST is used for automated parameter estimation in certain model runs. The version of PEST operated in GMS 9.1.7 is Version 12.3.

GROUNDWATER FLOW MODEL CONSTRUCTION

Model Grid

The model was projected in GMS using the North American Datum (NAD) 1983 Montana State Plane coordinates in U.S. Survey feet. The grid was created in GMS using a grid frame X origin of 1525170, a Y origin of 485320, and a Z origin of 4250. Overall grid size in the X, Y, and Z dimensions are 42,192 ft, 68,859 ft, and 10 ft respectively (10 ft is the initial layer thickness, later changed as part of the modeling process). The grid frame encompasses the Four Corners study area, although some cells within the grid frame were inactive in order for the model domain to correspond to flow boundaries (fig. 9). The cells are 502 x 495 ft with thicknesses between 146 and 409 ft. Table 3 provides additional details about the model grid.

The top of this single-layer model was defined using data taken from the USGS 1/3-Arc Second National Elevation Dataset (USGS, 2009). These data were converted into a scatter point dataset and imported into GMS in text format in the format of a Digital Elevation Model (DEM). The DEM scatter-

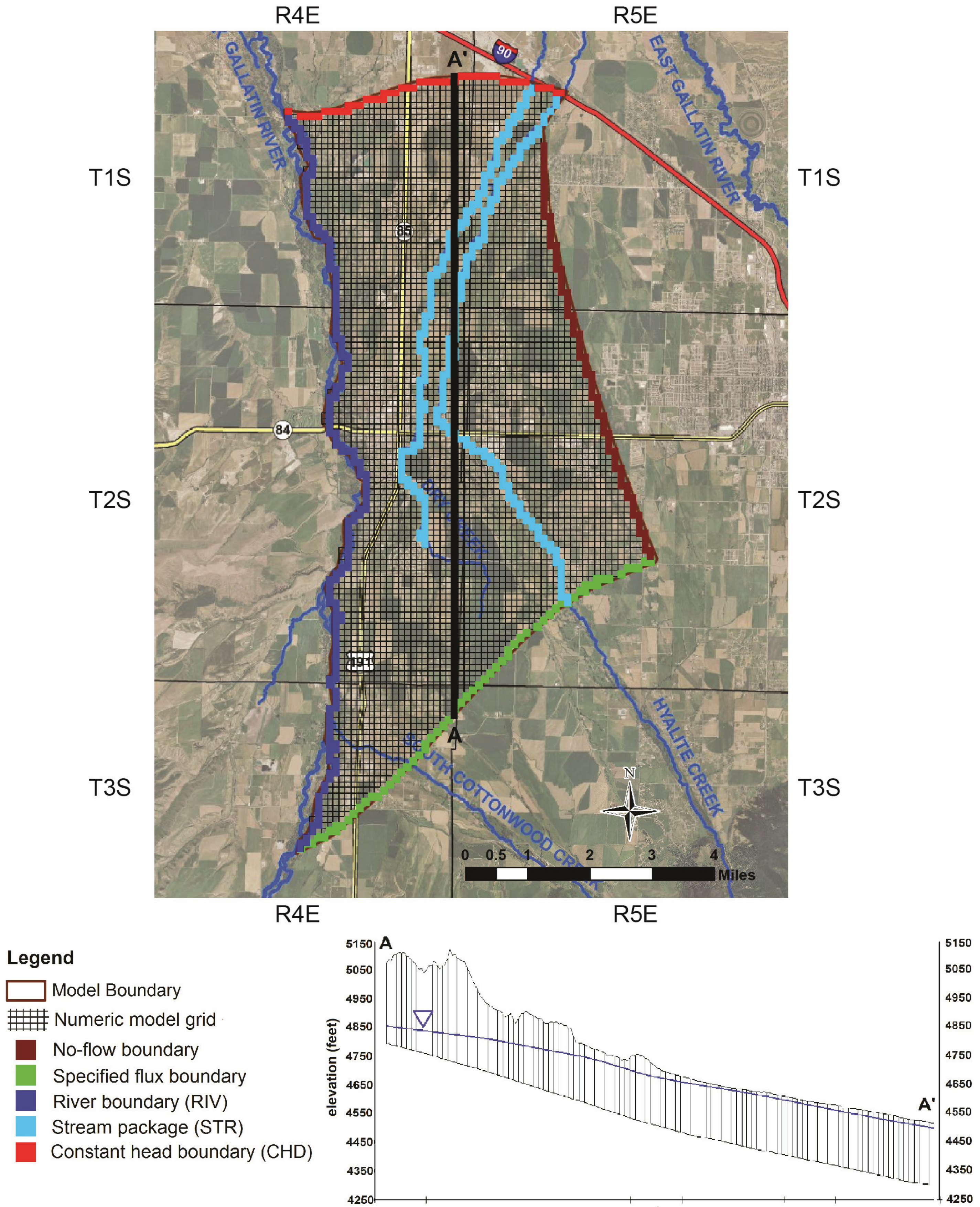

Figure 9. The model uses a single layer with uniform grid sizes of 495 by 502 ft with thicknesses ranging from 146 to 409 ft. Boundary conditions determined by groundwater flow conditions and surface-water locations are shown on the map. A cross-sectional line, drawn south to north through column 35 of the numerical model, shows the vertical profile of the single-layer model. The water table is indicated in blue.

Table 3. Details of model grid are described by the GMS software; details and definitions are provided within the GMS program.

Grid Type:	Cell Centered
X origin (ft):	1,525,170
Y origin (ft):	485,320
Z origin (ft):	4,250
Length in X (ft):	42,192
Length in Y (ft):	68,859
Length in Z (ft):	10*
Rotation angle:	0˚
AHGW X origin (ft):	1,525,170
AHGW Y origin (ft):	554,179
AHGW Z origin (ft):	4,260
AHGW Rotation angle:	90
Minimum scalar:	4,500
Maximum scalar:	5039.749
Num rows i:	139
Num columns j:	84
Num cells layers:	1
Number of nodes:	23,800
Number of cells:	11,676
Number of Active cells:	4,694
Number of Inactive cells:	6,982

* This value is the model-generated starting point. Actual thickness is 146–409 ft.

point spacing is approximately 186 ft^2, which is a greater density than the model grid. The modeling software reduced the dataset density to assign one elevation per cell. The bottom elevation of the model was a based on a composite elevation sloping from north to south. Variable vertical thicknesses reflect the surface topography changes. The layer thickness was intended to represent the shallow groundwater flow system, which is the most actively utilized aquifer zone in the Four Corners study area (fig. 9).

Two additional model configurations were evaluated prior to this final configuration. The first model included a layer designed to represent the Quaternary–Tertiary contact at depth; however, simulating the lateral continuity of the deeper layer required more information than was available. As noted, the shallow Quaternary alluvium is highly conductive due to its coarse nature, and very few wells have been drilled into the Tertiary sediments; only one or two report a clear and decisive contact margin in the well log. In addition, it was determined that a less complex model could better address the questions being posed of the model (Hill, 2006). The second model utilized a flat layer bottom; however, modeling using this bottom was abandoned due to the disproportionate layer thicknesses between the north end of the model and the south end.

The single-layer model that was adopted is a shallow-aquifer model designed to demonstrate groundwater movement in the upper aquifer, where most wells have been completed. On the time scale represented by the model, the majority of water movement and changes are believed to occur within the upper aquifer. The quantifiable and measureable groundwater gains and losses generally occur within the top 200 ft, with very few active extraction wells completed at depths greater than 100 ft.

Hydraulic Parameters

For steady-state calibration, K zones were assigned to polygons based on the geology of the study area (as described in the Geologic Framework section). Preliminary model runs were designed based on the conceptual model of the study area and utilized the groundwater budget presented above. The transient model required S inputs; due to the similar nature of the sediments, a single value was assigned throughout the model.

Groundwater inflow to the model (GW_{in}) occurs where water flows into the model domain from the Gallatin Mountains to the south. Groundwater inflow across this boundary was calculated using a flow net calculation (appendix B). The total GW_{in} component was calculated to be between 100 and 1,700 acre-ft/yr. Groundwater exits the model (GW_{out}) through the Quaternary sediments to the north.

There is an intrinsic uncertainty in all of the calculations presented that may compound when combined into the numerical model; however, a groundwater budget is necessary for understanding the impacts of the various processes within the model and determining its accuracy. The groundwater model budget combines water entering the model area through boundaries and sources, and attempts to balance that volume with water leaving the model. The balance is achieved when the water entering the model has a numerically valid source (in other words, the value is supported by hydrogeologic investigation) equal to the water leaving the model. Any excess water entering the model is placed into storage, while excess water leaving the model is drawn from storage. The steady-state model does not account for storage as it is calculated to equilibrium; that is, change in storage in (S_{in}) is equal to change in storage out (S_{out}). This can be expressed as a mass-balance equation where:

Water in = water out ± changes in storage (change in storage = 0 in steady-state).

Tables 2 and 4 show the application rates used to create recharge in the model, and the groundwater budget parameters used in the model. The calculations used to determine these rates are presented in appendix B, tables B1–B6.

As each of the elements of the groundwater budget were applied to the model as recharge influx or withdrawal, the elements occurring in each location were combined for a total recharge rate at each location. For example, an area classified as urban during the irrigation season will have a net extraction rate of -0.0007 ft/d, but it will also have a canal recharge rate of 0.00718 ft/d for a net total R of 0.0065 ft/d (28.47 in/yr).

Table 4. Recharge rates were estimated for model input. A negative value indicates a net withdrawal of water or negative recharge.

Recharge	ft/day	in/yr
Flood	0.00484	21.20
Sprinkler	0.00137	6.00
Pivot	0.00473	20.70
Urban (summer)	-0.00137	-6.00
Urban (winter)	-0.00002	-0.07
Canals	0.00718	31.45

Boundary Conditions

Model boundaries, as described by Anderson and Woessner (2002), specify the head or flux at the boundaries or perimeter of the model domain. The boundaries utilized in this model were:

- Constant head (CHD MODFLOW package) at the northern model boundary;
- Stream (STR MODFLOW package) at the northernmost portion of the eastern boundary;
- No-flow boundary on the majority of the eastern boundary;
- River (RIV MODFLOW package) on the western boundary; and
- Specified flux boundary created using the Well (WEL MODFLOW package) on the southern boundary (Harbaugh, 2005).

The boundaries for the Four Corners model correspond to the boundaries described in the Hydrologic Boundaries section. The north and south boundaries follow potentiometric contours that were developed from monthly water-level data. The southern boundary is a specified flux boundary placed along the 5,000-ft potentiometric contour, with flux into the model determined from flow net calculations across the boundary. Total flux into the model is represented by the GW_{in} component of the groundwater budget. The northern boundary is a constant head boundary (CHD), which replicates the relatively stable groundwater levels present at this location and allows water to freely leave the model domain. The eastern boundary is a no-flow boundary through most of its length, and it is parallel to the flow direction until intersecting with Hyalite Creek. The northernmost mile of the eastern boundary is represented with stream cells (STR), as it is in the approximate location of Hyalite Creek. The western boundary was drawn in the approximate location of the Gallatin River, and is therefore represented by a river boundary (RIV in fig. 9). River cells (RIV package) along the western boundary act as gaining or losing reaches depending on groundwater heads. River stages and bottoms were assigned based on surveyed monitoring locations where possible; however, where surveyed locations were not available, linear elevation changes between two surveyed locations were assumed.

Sources and Sinks

Sources and sinks represent flow into or out of the model and may use the same MODFLOW packages as boundary conditions; however, sources and sinks represent flow interior to the model. Sources and sinks in the model include:

- Recharge (RCH MODFLOW package) zones representing canal leakage, irrigation water application, and urban/commercial water withdrawals from wells acting as both sources and sinks; and

- Streams (STR MODFLOW package) representing Hyalite and Dry Creeks.

Water is contributed through canal leakage, which is applied as a diffuse recharge zone over the entire model, and irrigation zones, defined as flood, sprinkler, and pivot, which are applied in recharge polygons (fig. 10). These polygons were derived from the Statewide Final Land Unit classification database (Montana Department of Revenue, 2010).

Groundwater sinks include urban extraction zones used in place of multiple scattered wells, withdrawing water at a rate determined by calculations outlined in appendix B. These zones are applied as negative recharge in the model.

Stream cells along Dry Creek and Hyalite Creek act as water sources as well as sinks along various reaches. Where leakage recharges the aquifer, the creeks are sources, and where the STR package allows groundwater to leave the model through surficial flow, the creeks act as sinks. Stream bottoms were surveyed at several stream monitoring stations and the bottom elevation was extrapolated linearly along the stream reach between these locations. Estimates of streambed conductance, defined by McDonald and Harbaugh (1988), ranged from 10 to 160 ft/d based on sediment type, thickness, and width. Where the groundwater levels are equal to or above the stream bottom, groundwater may be lost from the aquifer to the stream, and where the groundwater elevation is below the stream bottom, water may be lost from the stream to recharge the aquifer.

CALIBRATION

Selection of Calibration Targets

Observed groundwater elevations in monitored wells were used as calibration targets for the model. Groundwater-level data were collected from an extensive area ranging from the canyon mouth south of Gallatin Gateway north to the confluence of the Gallatin and East Gallatin Rivers, north of Manhattan (table 5). These measurements extended well beyond the Four Corners study area but were crucial to determine the flow regime and potentiometric surface throughout the year. Information from 224 wells was examined and water-level data from December 2009 through December 2010 were used to produce potentiometric surface maps for each month (Michalek and others, in preparation).

Water-level monitoring data indicate that the water table fluctuates several feet annually in the model area, rising during the spring and summer and declining in the fall and winter. April was observed to have the most stable water-level conditions, and April 2010 was chosen for the steady-state model because it has the most complete dataset for the study area. Prior to calibration, 112 of the initial monitoring locations were excluded because they were outside the model domain, and 93 were excluded due to discontinuous measurements or incomplete water-level records. Nineteen wells met the criteria for calibration targets, and were included in the calibration process; 15 were utilized for steady-state calibration (table 6). Two wells, 224088 and 224089, located adjacent to the Gallatin River, were problematic throughout the calibration process. The modeled water levels for these two wells were 2 to 4 ft different from measured water levels, while other wells within the model successfully calibrated to less than 2 ft of the observed data. However, they were not removed from the model. The reason the model was unable

Table 5. Calibration targets used in the steady-state model were based on the April 2010 data.

GWIC ID	X Coordinate	Y Coordinate	Elevation	April 2010 Water Level
224068	1534530.5	509747.7	4,774.9	4,797.1
224069	1539115.2	509312.7	4,787.1	4,808.8
224082	1537766.7	512926.7	4,755.2	4,777.3
224087	1539565.7	513476.3	4,757.0	4,776.4
224088	1534412.4	515483.0	4,735.8	4,746.8
224089	1533965.0	513469.7	4,745.2	4,760.5
224091	1538576.3	516147.0	4,724.6	4,748.4
224097	1540138.0	524113.5	4,675.2	4,686.6
224099	1533428.1	526868.3	4,660.7	4,664.4
224100	1533704.5	527981.9	4,642.9	4,656.4
224103	1532470.6	526441.2	4,652.6	4,667.4
224109	1540343.9	538151.9	4,591.8	4,595.1
224110	1535653.1	536111.3	4,594.9	4,607.4
224111	1532364.4	538824.9	4,569.0	4,581.3
224177	1538470.6	522439.9	4,692.7	4,698.5

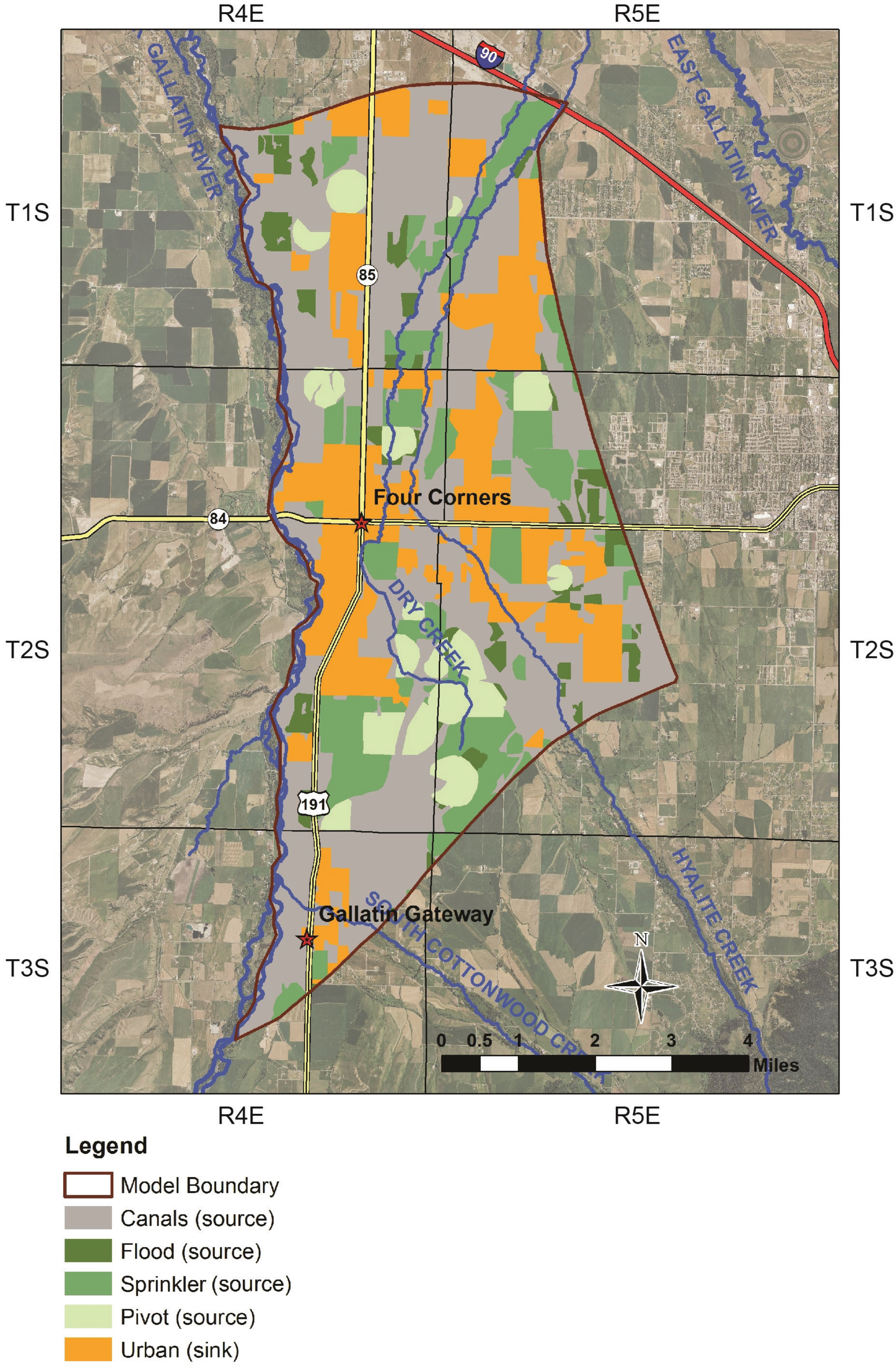

Figure 10. Sources and sinks of water flowing into and out of the model.

Table 6. Observed vs. Simulated groundwater levels and the residuals.

GWIC ID	April 2010 Measured Water Level	Modeled Water Level	Residual
224068	4,797.1	4,798.4	1.4
224069	4,808.8	4,810.2	1.4
224082	4,777.3	4,778.0	0.7
224087	4,776.4	4,777.8	1.4
224088	4,746.8	4,749.6	2.8
224089	4,760.5	4,763.9	3.3
224091	4,748.4	4,749.2	0.8
224097	4,686.6	4,688.3	1.7
224099	4,664.4	4,664.8	0.5
224100	4,656.4	4,657.7	1.3
224103	4,667.4	4,669.0	1.6
224109	4,595.1	4,595.7	0.7
224110	4,607.4	4,607.8	0.4
224111	4,581.3	4,583.1	1.8
224177	4,698.5	4,699.3	0.8

to calibrate to these two wells was not determined; it may be due to changes in the river that are not well represented in the model, an anomaly in the local lithology, or issues related to well construction.

The absolute difference between the observed head and the modeled head at a particular location is the residual head. A residual maximum of 3 ft was used as criteria for calibration; this range was selected as reasonable for a large-area model with 500 ft of head difference from the upgradient end of the model to the downgradient end. The calibration criterion is just 0.6% of the range of observed groundwater altitudes within the model domain.

In addition to the residual head calibration, three error statistics calculated by the MODFLOW software were used as calibration criteria. The statistics utilized included the mean residual error (ME), which approaches zero as the positive and negative residuals balance, indicating the model is not calibrated toward an excess or deficiency of water. Second, the root mean squared residual error (RMS), or standard deviation, is the average of the squared differences in measured and simulated heads (Anderson and Woessner, 2002), which should also decrease during the calibration process. Lastly, the mean absolute residual error (MAE) is the mean of the absolute value of the differences in measured and calculated heads (Anderson and Woessner, 2002). Calibration data files are included with the groundwater model files associated with this report.

Steady-State Calibration

The steady-state model simulates the physical system at equilibrium, where the current stresses are assumed to be balanced and representative of low flow conditions. The model was calibrated to observed water levels (calibration targets in the model) through manual manipulation of K within polygon zones representing the areas described in the Geologic Framework section. Hydraulic conductivity of the Quaternary alluvium was estimated to be between 40 and 500 ft/d, and for the Tertiary sediments between 30 and 400 ft/d. Initial manual calibration involved adjusting the parameters within this range, running the model to determine the sensitivity of each K zone, and adjusting parameters accordingly to optimize the residual errors. Typically only one parameter was changed during each calibration run.

Once a reasonable calibration had been attained manually, automated parameter estimation was used to determine the best mathematical solution for the zonal K distribution. The range of K for model cells within the polygons was held to the distribution in the manual method, but was subdivided into smaller polygons in order to allow a greater K distribution throughout the model. The zones were held to within the values found to be optimal by the manual calibration and the estimated K ranges for the sediment type. The initial attempt at calibration resulted in K distributions that were not a good fit with the conceptual model and deemed an unrealistic representation of the physical setting. Thus, an array was constructed to determine a more likely K distribution. The zonal method was not wholly abandoned in the estimation of the K distribution, but rather a composite solution was devised to determine the optimal realistic solution. Within the geologically defined zones, an array of spatially distributed targets, or pilot points, were used to adjust the K distribution to create the optimal calibration.

Pilot points were used to construct the array that calibrated to a series of specified points rather than zones. Kriging techniques were used to determine the K value of each cell between pilot points that would best optimize the residual error. The use of pilot points eliminated the sharp contrasts between K zones and the potential for irregular solutions unrepresentative of the geology. A grid of points was overlaid on the K zones to create pilot points that were calibrated within the given range of K. The constraints on K had to be applied manually because the pilot point method does not allow for zonal constraint of K; the optimal distribution of K caused some areas to fall outside of the known range.

Each pilot point was assigned a numerical identity, so the MODFLOW input file could be edited. Pilot points found to be within a particular geologic zone were constrained using the input file to reflect the limits of the desired range. K values for Tertiary zone sediments were constrained to the desired range of 30–400 ft/d and the K values for Quaternary sediments were constrained to 40–500 ft/d rather than assigning the entire pilot point array range as 30–500 ft/d. This was done in order to create the desired composite PEST input between the grid array of pilot points and the geologic K zones (fig. 11).

The modeled potentiometric surface generated from the array compared well to the observed potentiometric surface (fig. 12). Fourteen of the 15 calibration targets were within the 3-ft calibration criteria; 1 was within 4 ft of the observed head (fig. 13, table 6). The RMS error was 1.59 ft, which represents less than 1 percent of the elevation range in the observed water levels (500 ft). The ME was -1.38 and the MAE was 1.38, all deemed to be within the range of reasonable calibration criteria (Anderson and Woessner, 2003).

The range of K values predicted by the model was within the expected range for the geologic setting. The simulated groundwater rates, however, were higher than initially estimated (table 7), which may be due to the lack of direct measurements. The model predicted that the river and the streams both contributed more water than estimated. Because the river and stream bound the physical flow system, it is likely that surface-water elevation and leakage from the Gallatin River and Hyalite Creek act to control groundwater elevation in the Four Corners area.

Recharge was simulated in the model at a lower rate than the initial estimate; the largest component of recharge, canal leakage, was applied at a constant rate over the entire model. As discussed, simulating canal leakage as recharge was chosen because quantifying the canal leakage proved extremely difficult. Canal leakage rates were found to be highly variable in both timing and location. The method of applying canal recharge as described in the Conceptual Model section may have overestimated the effects of seepage from the canals, as the model has shown that surface-water leakage contributes significantly to water levels in the model domain. Applying the spatially distributed volume at a steady rate caused a muted effect on groundwater levels.

Given the assumptions and limitations of the estimated budget, the steady-state model's budget was considered reasonable. The individual components compared well with initial estimates, but the overall budget was more than twice the estimated total flow volume. As noted, the objective of the steady-state simulation was to determine the best distribution of the water-budget components constrained by the volumetric budget. Comparison of the surface-water and groundwater budgets suggests that the measurement limitations encountered for calculating the groundwater budget caused an underestimation of the canal leakage and the effect the surface-water bodies have on the system.

Transient Calibration

The transient model is an extension of the steady-state model that takes into account the temporal variations in the hydrologic system. The Four Corners model includes 24 months, from January 2009 through December 2010. Each month is a stress period with five time steps, though the first year simply replicates the stresses of the steady-state model (table 8). In order to calibrate the model, 19 wells were used with a monthly water-level elevation, including the original 15 wells from the steady-state model. Transient calibration was achieved by adjusting the storage (S) value as constrained by the geology until the water-level changes were reasonably replicated throughout the year. Figure 14 presents the comparison between modeled and observed heads at four targets.

An optimum S value was determined for the model using the zonal constraints on geology as described in the Steady-State Calibration section. This was done as a necessary assumption and simplification for the modeling process. The

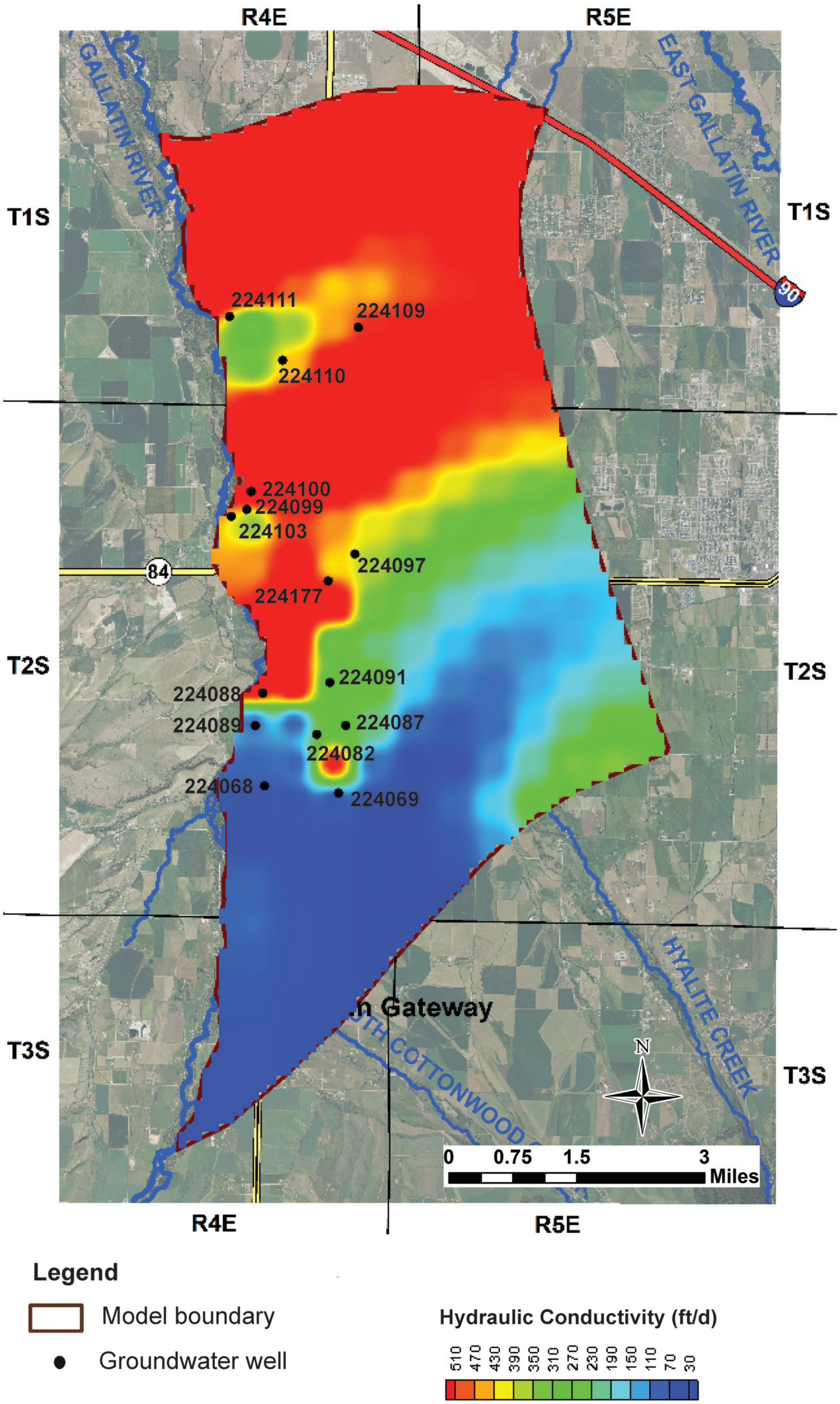

Figure 11. Final array of horizontal hydraulic conductivity determined by parameter estimation in the numerical groundwater model. Calibration targets (wells) used for steady-state calibration are identified by the GWIC ID number.

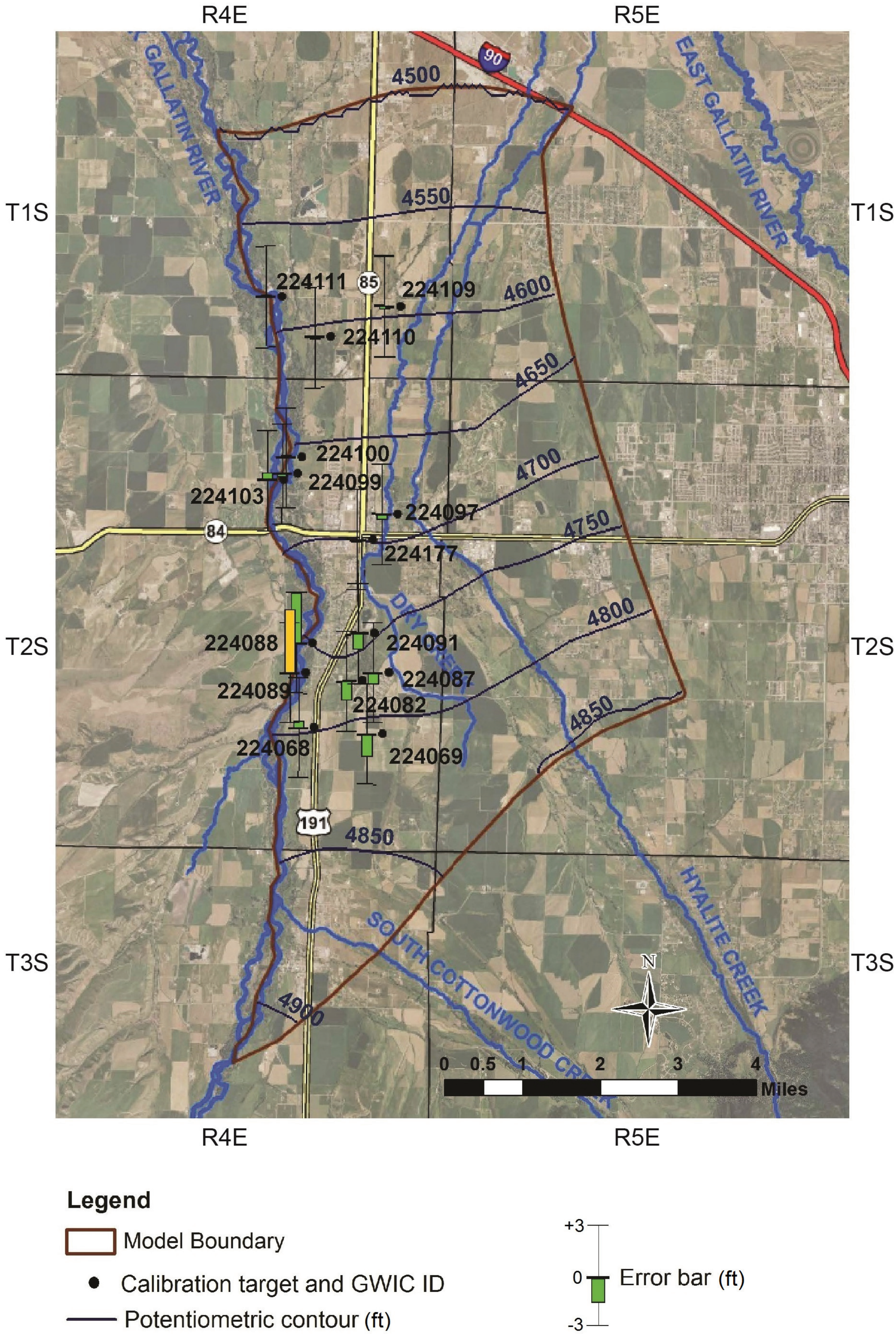

Figure 12. Calibration targets have a 3 ft error interval; green targets indicate calibration within 3 ft and yellow targets are between 3 and 6 ft.

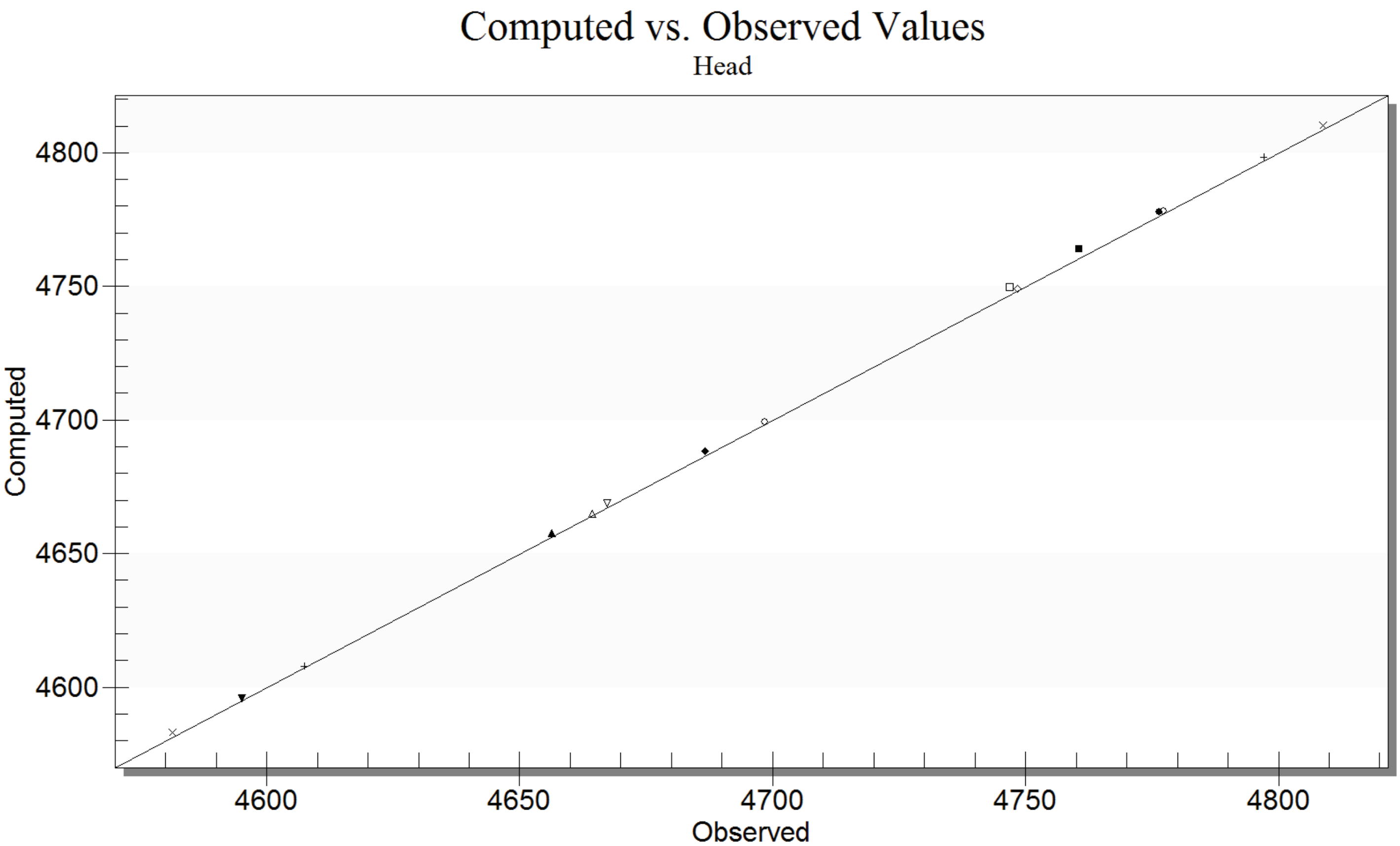

Figure 13. Thirteen of the 14 calibration targets were within the 3 ft calibration criteria and the 4th was within 4 ft of the observed head.

model was generally sensitive to small changes in the storage value; changing the storage coefficient by a few percent caused an unacceptable departure from observed values for head. Moreover, the model was also sensitive to spatial distribution of S over the model domain; small differences of the storage coefficient value between hydrologic units also caused large departures from calibration target values. Thus, an S range of 0.1–0.35, which is reasonable for an unconfined aquifer composed of sand and gravel (Fetter, 2001), was assigned to the model domain. Transient calibration focused primarily on replicating a seasonal head increase throughout the model that occurred during the irrigation season, when flows are higher in the Gallatin Valley due to seasonal snowmelt runoff. The total annual recharge rates are the same as those in the steady-state model, but are applied during the irrigation season only rather than throughout the year.

Table 7. Comparison of the conceptual groundwater budget with the steady-state model simulation.

	Conceptual Model (Table 2)		Steady-State Model	
	In (AF/y)	Out (AF/y)	In (AF/y)	Out (AF/y)
Rivers	20,000–40,000	20,000–50,000	41,997	59,870
Streams	200–500	100–500	110	237
Recharge	60,000	Variable	66,864	0
Groundwater	100–900	30,000	93,660	142,525
TOTAL FLOW	90,000	90,000	202,632	202,632

Table 8. Stress periods and time steps used in the transient model.

Date	Stress Period Length	No. of Time Steps
1/1/2009	365	10
1/1/2010	31	5
2/1/2010	28	5
3/1/2010	31	5
4/1/2010	30	5
5/1/2010	31	5
6/1/2010	30	5
7/1/2010	31	5
8/1/2010	31	5
9/1/2010	30	5
10/1/2010	31	5
11/1/2010	30	5
12/1/2010	31	5

Sensitivity Analysis

A sensitivity analysis was performed to assess the error associated with the calibrated model that may be created by uncertainty in applied parameters. The two parameters, hydraulic conductivity and recharge, were adjusted systematically and individually in order to determine the model's response to deviations from the calibrated values. The magnitude in change from the calibrated parameter is an analysis of the model's sensitivity to the solution of that parameter (Anderson and Woessner, 2002).

The analysis was performed on the steady-state model because the transient model was limited to 13 months of data. Both hydraulic conductivity and recharge were altered, individually, by +25%, +50%, -25%, and -50%, establishing eight sensitivity simulations. Deviation from the starting RMS error in water levels was used to judge the model's sensitivity to the parameter.

The modeled heads proved to be the most sensitive to decreases in recharge, varying considerably from the baseline calibration values. When recharge was decreased 50%, the RMS error exceeded16 ft. Comparison of other modeled values with calibration criteria was not improved through increasing or decreasing either recharge or hydraulic conductivity parameters. When recharge was increased 50%, the RMS error value increased over 4.5 ft. The model proved less sensitive to decreases in conductivity, as can be seen in figure 15. As conductivity decreased, the departure from calibration grew slowly, while increasing K followed a similar trend in RMS error as increasing recharge.

In order to determine where areas of sensitivity might lie, a spatial analysis of calibrated heads was also considered when performing each simulation. Decreases in the recharge caused most central wells to fall out of calibration as heads fell below the observed values, and, as the R value was further decreased, the simulated heads continued to decrease near the town of Four Corners and just south of that area (fig. 16). Decreasing the conductivity had a similar effect, though not as pronounced. This suggests that the central part of the model and the area around Four Corners is most sensitive to the modeled parameters in this simulation, which gives higher confidence to this area of the model domain. The model is least sensitive to changes adjacent to the river, suggesting groundwater levels are heavily influenced by the river elevation.

Model Verification

Model verification allows for the model parameters to be tested, frequently through the use of reproducing a second set of field data. The verification process is performed in order to provide greater certainty in the model parameters and confidence in the model's prediction capabilities. The model was verified through the first predictive scenario, which replicated conditions that existed in the study area during the 1950s. The data available from the 2010–2011 study period were included in the model where possible, although continued data collection in the study area should be utilized for a later verification of the model in the future. In particular, additional data would be needed for inclusion in the model if the stresses on the system changed similar to the predictive simulations, such as if a municipal system were to be developed or land-use changes occur at the predicted rates. Reasonable agreement between the modeled results and any future changes in stress will increase confidence in the model as an appropriate representation of the system.

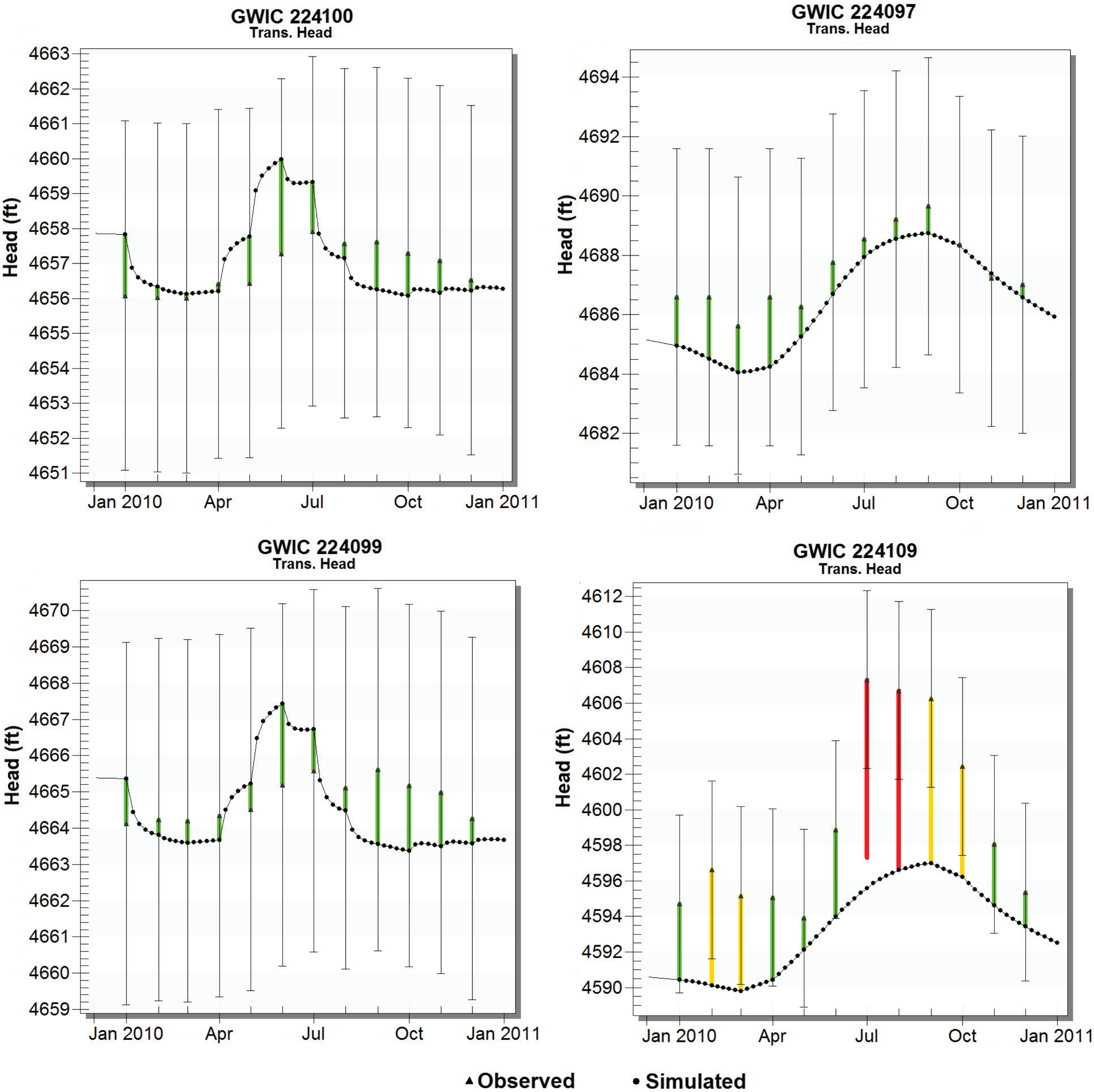

Figure 14. Four selected calibration targets were used in the calibration of the transient model. Error bars included 3 ft of head change from the observed values. Calibrations are shown in green to indicate a calibration interval of 0 to 3 ft, yellow indicates 3 to 6 ft, and red indicates greater than 6 ft deviation from the observed value.

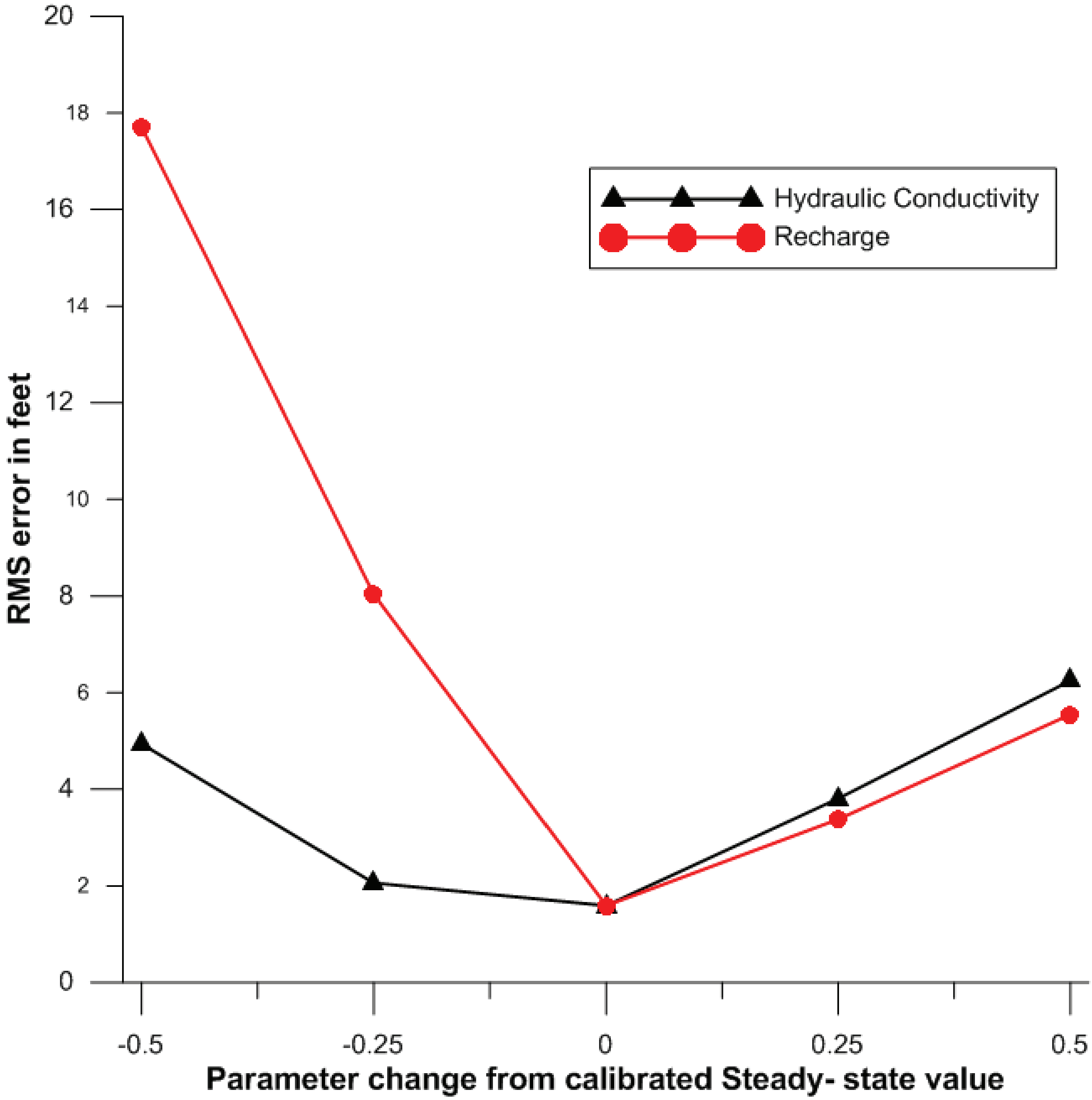

Figure 15. The sensitivity analysis indicates the model is sensitive to hydraulic conductivity, but not to recharge.

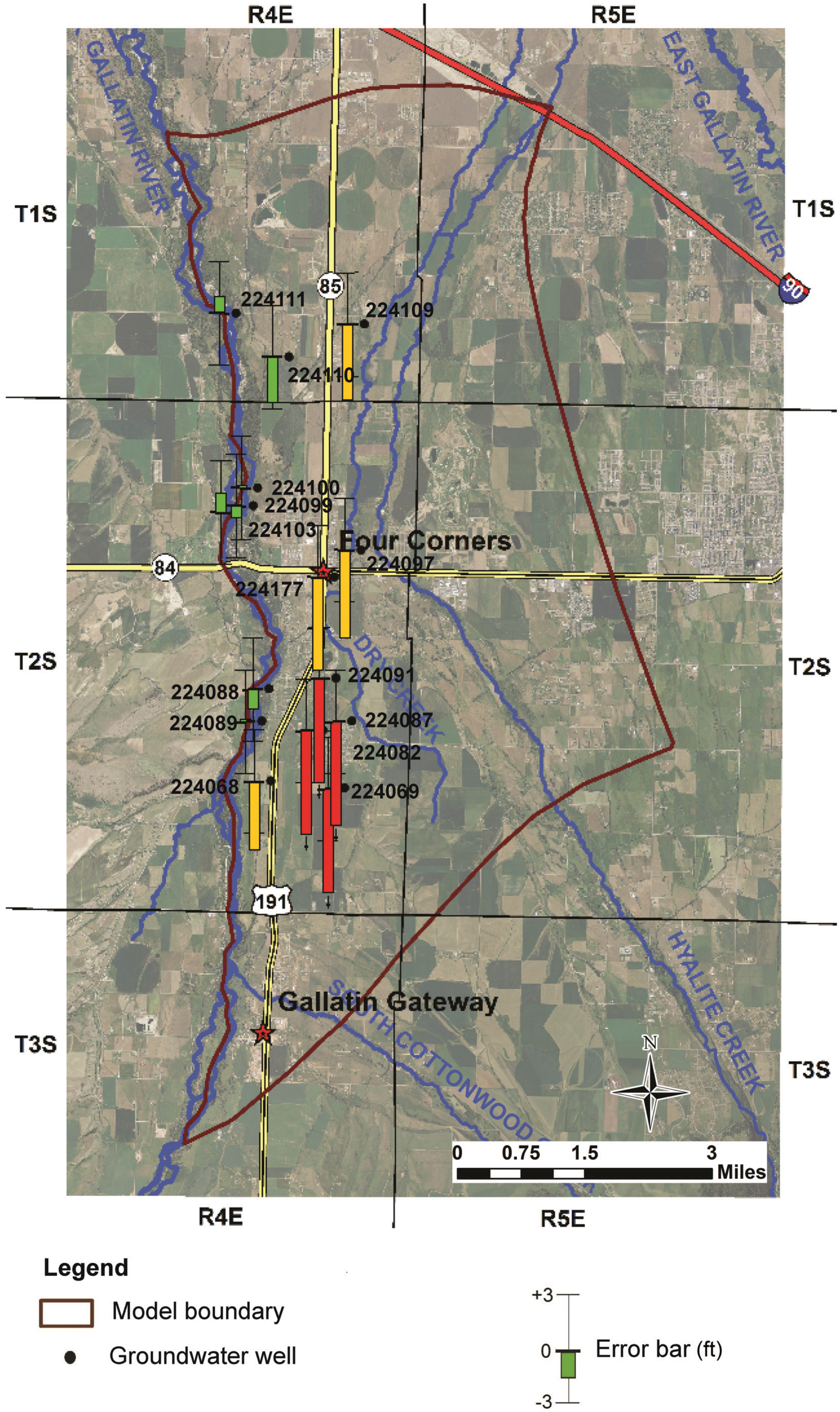

Figure 16. As part of the sensitivity analysis conducted on the model, hydraulic conductivity was decreased by 50%, resulting in poor calibration (compare to fig. 12). Calibration targets have a 3 ft error interval, green targets indicate calibration within 3 ft, yellow targets are between 3 and 6 ft, and red targets exceed 6 ft.

PREDICTIVE SIMULATIONS

Models are frequently utilized as predictive tools to understand the impacts of a change in stresses on the physical system. Though the model is purely a mathematical simulation, it can be useful in understanding the possible outcomes of an action. For the Four Corners model, four hypothetical scenarios were modeled. These simulations were not meant to represent actual future changes, but are intended to predict trends and illustrate the interconnected responses to stresses that might not otherwise be considered. The simulations were intended to be useful in understanding the current hydrologic system's dependence on the various water-budget components and their possible impacts.

The baseline models from which each scenario was altered were the steady-state model described in the Steady-State Calibration section, a 25-yr transient model that replicated the stresses of the 1-year transient model out for 25 yr in order to assess the future impacts, and one simulation that was extended to 50 yr.

There has been notable concern about urban development and the related use of multiple domestic/exempt wells and municipal water systems that are causing different stresses on the hydrologic system. Additionally, as stresses on the streams and rivers change due to increasing water consumption or changing flow directions from large-scale urban development, the groundwater flow system changes as well.

In order to evaluate these changes, four simulations were constructed:

(1) pre-urbanization of the Four Corners study area,
(2) drier climate changes causing reduced inflow into the valley,
(3) land-use changes including the increased development of urban land and decreased agricultural use, 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 stress changes from the 2010–2011 baseline condition.

Scenario 1: Hackett Study, Pre-Urbanization of the Four Corners Area

A study of the Gallatin Valley groundwater flow system was conducted by Hackett and others (1960). Hackett's study covered a much larger area than the Four Corners study, and the land-use changes and the climatic influences since the 1950s have been extensive. This model attempted to recreate the historic flow system using the current understanding of irrigation practices and the information reported in the USGS publication on groundwater elevations and streamflow. During the 1950s, most of the valley floor was flood-irrigated agricultural fields, and there were few domestic wells.

The key assumptions made for the 1953 and 2010 model included:

1. Irrigation water applied to the valley may be overestimated for 1953, possibly by a large amount. Current flood irrigation practices and efficiencies may not be accurate proxies for past practices.
2. All lands classified as irrigated in 1953 may not have been actively irrigated during the modeled 6-month irrigation season. This assumption may lead to the over-allocation of irrigation water and may cause a significant increase in source water applied to the model; however, without a more accurate accounting of the irrigation season and water application on irrigated lands, the assumptions are necessary.

This model was run in steady-state, using the calibrated steady-state model described in the previous section as the baseline model. The changes in stress included a change in the recharge to simulate leakage occurring throughout almost the entire valley from flood irrigation. The irrigated lands were assigned the same recharge value used in the baseline model, which was estimated based on our current understanding of flood irrigation aquifer recharge. The non-irrigated lands were assigned the recharge rate specified for canals. Calibration targets selected were wells measured for the April 1953 dataset, although stream and river elevations were not included in the report. The northern constant head boundary was adjusted to reflect the potentiometric surface presented by Hackett and others (1960), and the influx through the southern boundary was adjusted for the potentiometric surface from 1953 and the same K and thickness as used in the modern steady-state model.

For the purposes of this simulation, river stages were assigned to be 5 ft above the channel bottom and streams were 2 ft above the channel bottom. Based on the USGS discharge summaries at Gallatin Gateway (http://waterdata.usgs.gov/nwis/nwisman/?site_no=06043500) and Logan (http://waterdata.usgs.gov/nwis/uv?06052500), flow in the Gallatin River was somewhat higher during the early 1950s than it is today, so this assumption was needed to make sufficient flow available to recharge the aquifer. The Hackett report adequately describes the flow system of the Gallatin Valley at that time; however, that report described a much larger area and the parameters necessary to constrain this model could not be used directly. The input parameters for this simulation are therefore extrapolated.

The purpose of this simulation was to replicate the flow conditions with the information available and to compare the baseline model conditions to the past conditions. The model input parameters (hydraulic conductivity, thickness, storage, etc.) were not adjusted to reduce error, and head-residual criteria were held to 10 ft rather than 3 ft (fig. 17). Two of the 12 residuals fell outside this range, though only one observation well was considered an outlier. Table 9 shows the results of this simulation. The RMS error value of this simulation was 14.8 ft, though when well D2-5-5ba (using well designation described by Hackett and others, 1960) was removed as an outlier, the RMS error value was reduced to 6.7 ft. A comparison of the potentiometric surfaces created by Hackett compared favorably throughout most of the model with the simulated potentiometric surface for this scenario (fig. 18). The simulation of 1953 conditions was reasonable given the limitations on the available information for modeling purposes.

Table 9. Results of Scenario 1, simulation of USGS 1953 study of Gallatin Valley (Hackett and others, 1960).

Well	Observed head (ft-amsl)	Simulated Head (ft-amsl)	Residual (ft)
D1-4-13ad	4,503	4,508.90	5.9
D1-4-25ba1	4,569	4,557.20	-11.8
D1-4-25aa1	4,571	4,562.70	-8.3
D1-4-25aa3	4,570	4,563.50	-6.5
D1-5-19cd	4,563	4,558.90	-4.1
D1-5-30aa	4,558	4,564.10	6.1
D1-5-30cd	4,593	4,596.00	3.0
D2-5-5ba	4,694	4,647.60	-46.4
D2-4-10dd	4,697	4,691.70	-5.3
D2-4-11cd1	4,697	4,693.80	-3.2
D2-4-13cc	4,738	4,735.00	-3.0
D2-4-25bd	4,813	4,803.20	-9.8

Comparison of the simulated water budget for the 2010–2011 steady-state model and the simulated 1953 budget show a greater groundwater flow volume through the model in 1953 (table 10). The river and stream cells contribute significantly more water to the aquifer in the 1953 model, though this may be, at least in part, a factor of the estimated stages for surface water. The groundwater recharge is significantly higher under 1953 conditions, primarily due to the replacement of flood irrigation with more efficient methods. Urban withdrawals found in the current system were lacking during

Table 10. Simulated groundwater budgets for the 1953 and 2010 model scenarios.

	Steady-State Model 1953 Simulation		Steady-State Model 2010 Simulation	
	In (AF/y)	Out (AF/y)	In (AF/y)	Out (AF/y)
Rivers	71,785	42,984	41,997	59,870
Streams	14	14	110	237
Recharge	104,615	0	66,864	0
Groundwater	59,748	193,165	93,660	142,525
TOTAL FLOW	236,162	236,163	202,632	202,632

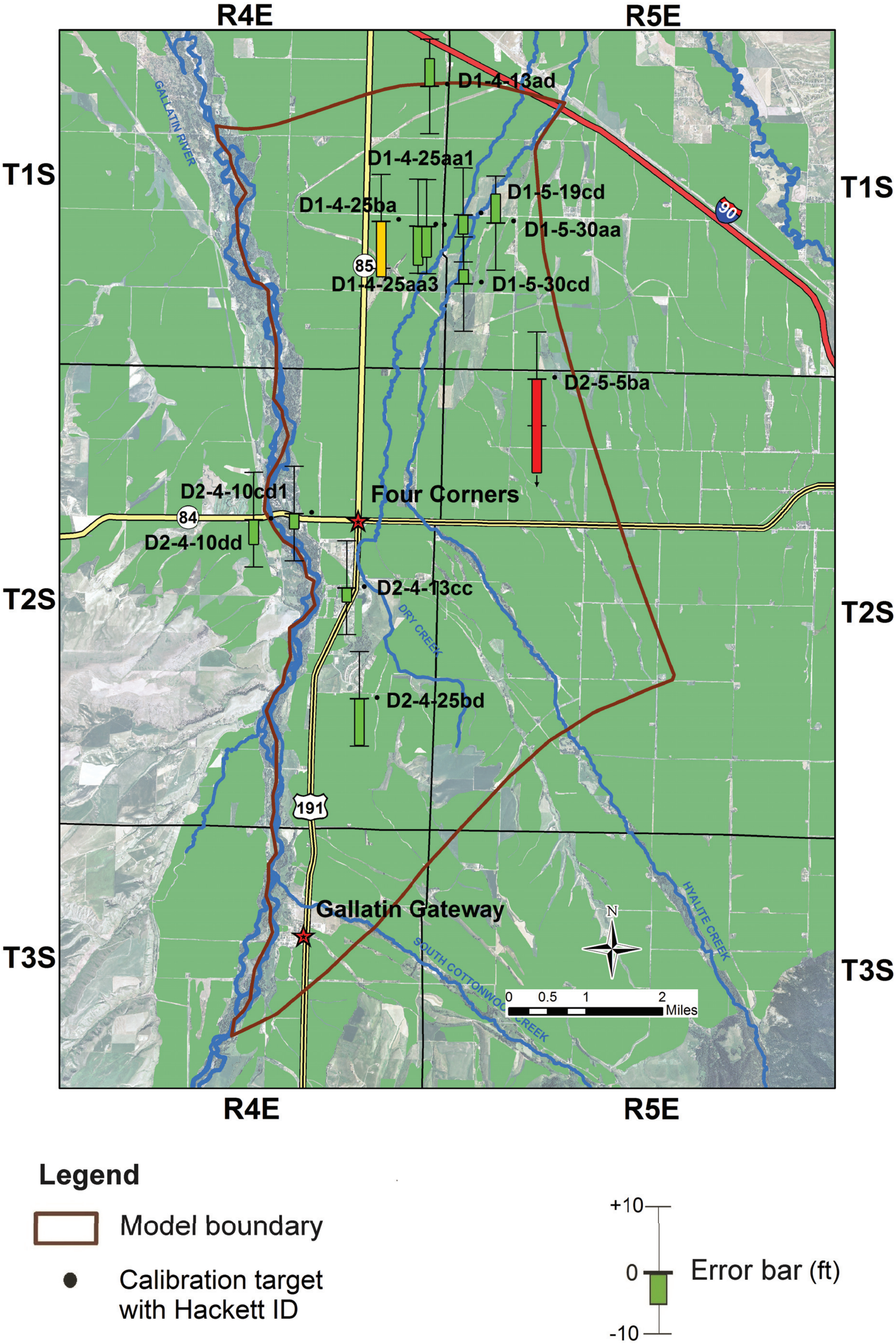

Figure 17. Calibration results of Hackett Scenario (Scenario 1). Areas in green indicate flood-irrigated lands. Calibration targets have a 5 ft error interval, green targets indicate calibration within 5 ft, yellow targets are between 5 and 10 ft, and red targets exceed 10 ft.

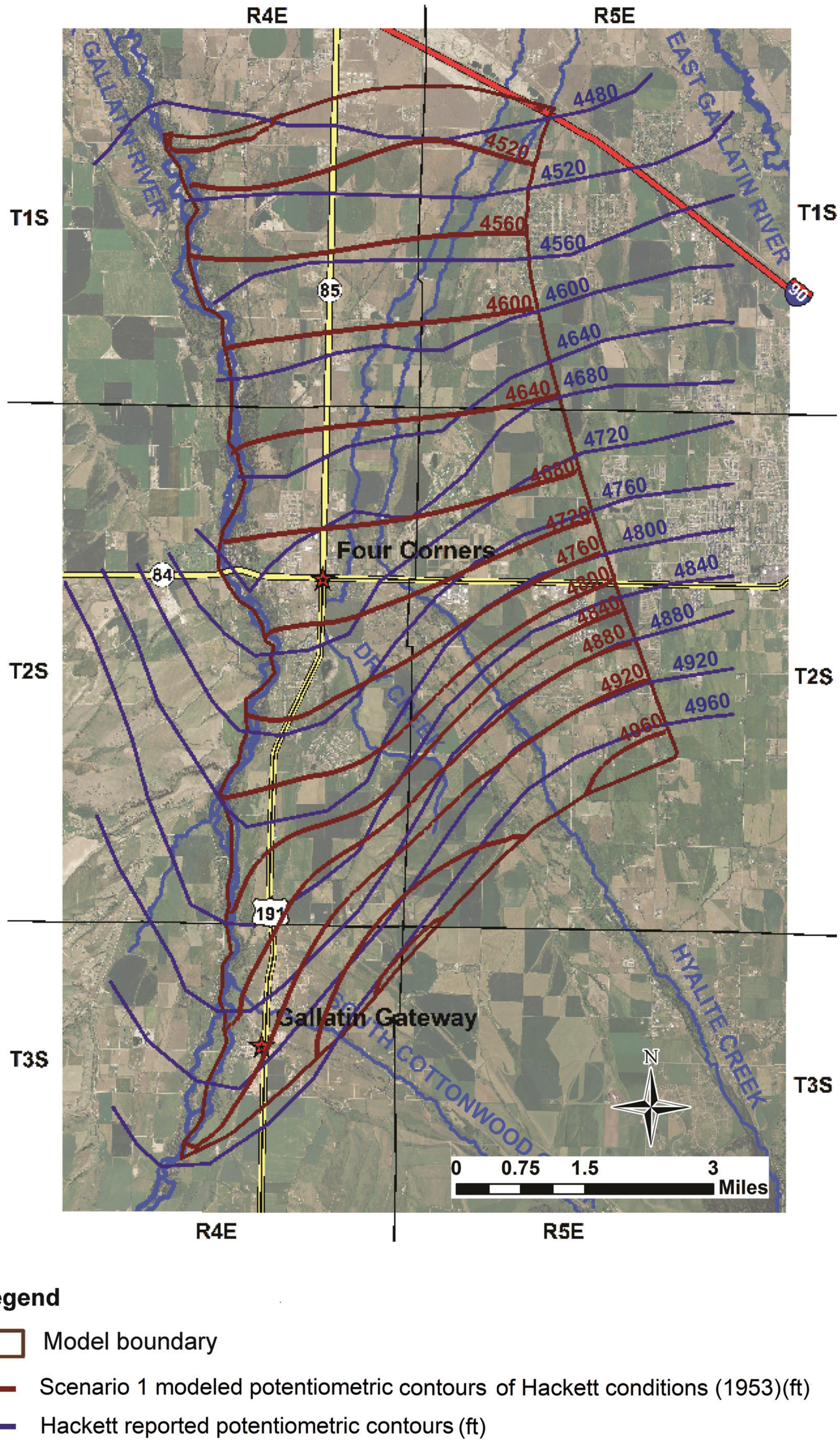

Figure 18. Potentiometric surface contours comparing Hackett's water-level surface to the water-level surface simulated in Scenario 1 show a similar trend in water movement.

the period of Hackett's study, and this results in more groundwater flow in 1953. These findings suggest that although the groundwater levels within the study area have not changed significantly since the early 1950s, the groundwater flow volume in the study area has decreased as groundwater gradients changed. Groundwater flow gradients and heads are higher today, south and east of the study area, contributing to the higher groundwater influx into the modeled area.

Groundwater in the central area of the valley is highly interactive with surface water. Groundwater levels in the peripheral areas of the valley fluctuate seasonally more than those near surface-water bodies. Therefore, in the study area, small changes in groundwater levels correspond to large changes in water volume. Considering the high connectivity of the groundwater and surface water within the modeled area, minor decreases in head not only create large decreases in the volume of groundwater, but can also reduce surface-water flow through two mechanisms: (1) lowering the water table decreases the groundwater contribution to surface-water flow; (2) sufficiently decreased groundwater levels may reverse the gradient, causing surface water to contribute to groundwater flow. To summarize, comparing the simulations for 1953 and 2010 hydrologic conditions demonstrated that:

(1) groundwater-level changes in the modeled area have been small;
(2) there was a lower rate of groundwater flow into the area and a higher rate of groundwater flow out of the area in 1953; and
(3) there was a larger rate of recharge from irrigation to groundwater in the study area during 1953.

Scenario 2: Drier Climate

Scenario 2 was designed to simulate lower precipitation rates for the area where snowpack is decreasing, causing a reduction to the water entering the system. In the first scenario, all inputs were reduced and stream and river stages were decreased. In the second simulation, recharge within the model boundaries was the same as baseline conditions, but inflow from the south was reduced and stream and river stages were decreased. These simulations used the steady-state model as a baseline condition and stresses were modeled assuming steady-state conditions.

In Simulation 2a, recharge was decreased throughout the model by 25%, except where recharge was negative to simulate urban withdrawals, which are assumed to remain the same. Influx into the model through the south boundary was also decreased by 25%, and the stream and river stages were decreased by 0.5 and 1.5 ft, respectively. The simulated results all showed a decrease in head. The overall flow through the system decreased by approximately 28,200 acre-ft/yr, which is slightly less than a 20% decrease in outflow.

Simulation 2b used the same recharge as current conditions; however, no decrease in recharge from irrigation was simulated. Influx into the model through the south boundary was decreased by 25%, and the stream and river stages were decreased by 0.5 and 1.5 ft, respectively. In this simulation, the decrease in water levels is less than in the first drier-climate simulation as a result of continued recharge from irrigation. Groundwater losses amount to approximately 14,700 acre-ft/yr, or a 10% decrease in flow volume.

Table 11 documents the original observed water level and the simulated heads in both of the drier climate simulations, and the accompanying residual difference between the modeled and observed heads. The dry-climate simulation budget indicates a loss of over 50% of the groundwater influx from the river and all of the recharge from the streams when inflows are decreased by 25%.

In both simulations, the greatest water-level decreases were interior to the model, while the wells adjacent to the river stayed closer to baseline than the rest (figs. 19, 20). This suggests that the river as modeled is recharging the aquifer as water levels decline, which may be of concern if maintaining baseflow conditions is desired. One of the assumptions necessary for calibration of the steady-state model was that the irrigation recharge may be muted or underestimated due to the diffuse application throughout the model, especially in the application of canal leakage. If this assumption is correct, the simulated water levels may be artificially muted in Simulation 2b, as recharge from canal leakage and flood irrigation practices could cause greater mounding locally.

Table 11. Simulated heads and residuals for Scenario 2.

GWIC No.	Obs. Head (ft)	Simulation 2a Head (ft)	Residual (ft)	Simulation 2b Head (ft)	Residual (ft)
224068	4,797.1	4,785.0	-12.1	4,792.6	-4.5
224069	4,808.8	4,785.1	-23.7	4,797.8	-11.0
224082	4,777.3	4,754.1	-23.2	4,766.9	-10.4
224087	4,776.4	4,752.4	-24.0	4,765.7	-10.7
224088	4,746.8	4,728.9	-17.9	4,740.5	-6.3
224089	4,760.5	4,745.9	-14.6	4,756.4	-4.1
224091	4,748.4	4,725.8	-22.7	4,738.4	-10.0
224097	4,686.6	4,670.0	-16.6	4,680.2	-6.4
224099	4,664.4	4,660.2	-4.2	4,662.2	-2.2
224100	4,656.4	4,653.3	-3.1	4,655.2	-1.2
224103	4,667.4	4,666.2	-1.2	4,667.0	-0.4
224109	4,595.1	4,584.8	-10.3	4,591.6	-3.5
224110	4,607.4	4,600.0	-7.4	4,604.5	-2.9
224111	4,581.3	4,575.8	-5.5	4,578.9	-2.5
224177	4,698.5	4,681.0	-17.5	4,691.1	-7.5

Scenario 3: Land-Use Changes

This simulation was performed to compare possible future changes to the groundwater flow system caused by land-use changes, particularly those caused by the conversion of irrigated land to non-irrigated and urban uses. The stresses that were analyzed in Scenario 3 were increased pumping by domestic wells, reduced aerial recharge within the model, and reduced recharge from irrigated fields converted to subdivisions in the final simulation. The 25-yr transient model was used as the baseline, and the only new stresses to this model were placed on the recharge. Urban groundwater extraction zones were systematically increased in size every 5 yr to reflect the expansion trends found in the Four Corners study area between 1998 and 2010. An average urban expansion of 535 acres per year was seen during this time frame, for a total of 2,675 predicted acres of urbanization every 5 yr. This created four simulations, 5-yr, 10-yr, 15-yr, and 20-yr models. In order to fully assess the 20-yr model, the time frame was extended out to 50 yr, though no additional changes were made beyond the 20-yr change. A fifth simulation was included to determine the impact of removing canal leakage within the urbanized areas created at 20 yr using the steady-state model as a baseline.

Urban expansion in the study area has historically not only been on unused land, but has also taken irrigated lands out of production to be turned into subdivisions or urban centers. In order to simulate the projected future urban growth and adequately portray this in the model, the 5-yr growth was applied in each simulation as an iterative decrease in recharge during the 5-yr period, and only the final trends were assessed (fig. 21).

The first simulation (Simulation 3a) applied urban expansion to acreage that was identified as non-irrigated for 2009 (Montana Department of Revenue, 2010). The acreage selected was in the center of the model and adjacent to the largest urban centers already existing; over the 5-yr period 2,796 acres were expanded upon to replicate urbanization. The same method was applied for the 10-yr simulation (Simulation 3b), increasing the urban recharge zones by another 2,677 acres. The third simulation (Simulation 3c), representing 15 yr of urban expansion, increased the acreage by another 2,656 acres, though this simulation expanded into only irrigated lands, essentially filling in the central part of the model domain and creating a single large urban area. The fourth simulation (Simulation 3d), which was expanded out to year 50, expanded another 2,687 acres and included both irrigated and non-irrigated lands (fig. 22). The last simulation (Simulation 3e) recreated the urbanization of Simulation 3d with the exception of removing all canal leakage within the urbanized zones.

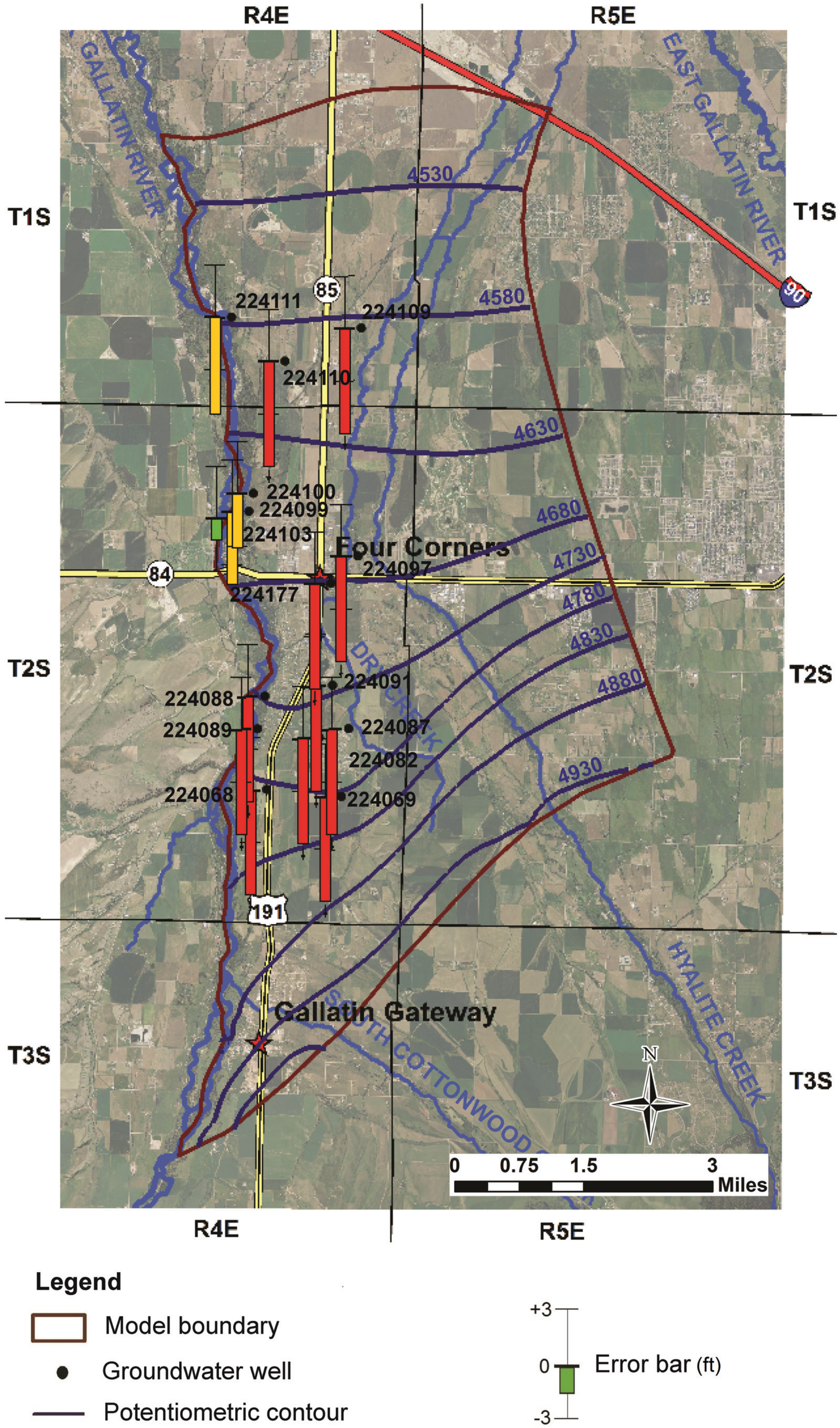

Figure 19. Potentiometric surface and the well head residuals are shown for the drier-climate scenario (Scenario 2a). A stream and river stage decrease of 0.5 and 1.5 ft, respectively, is seen, and a 25% decrease in groundwater influx as well as a 25% decrease in recharge from irrigation. Simulation targets have a 3 ft error interval, green targets indicate results within 3 ft, yellow targets are between 3 and 6 ft, and red targets exceed 6 ft.

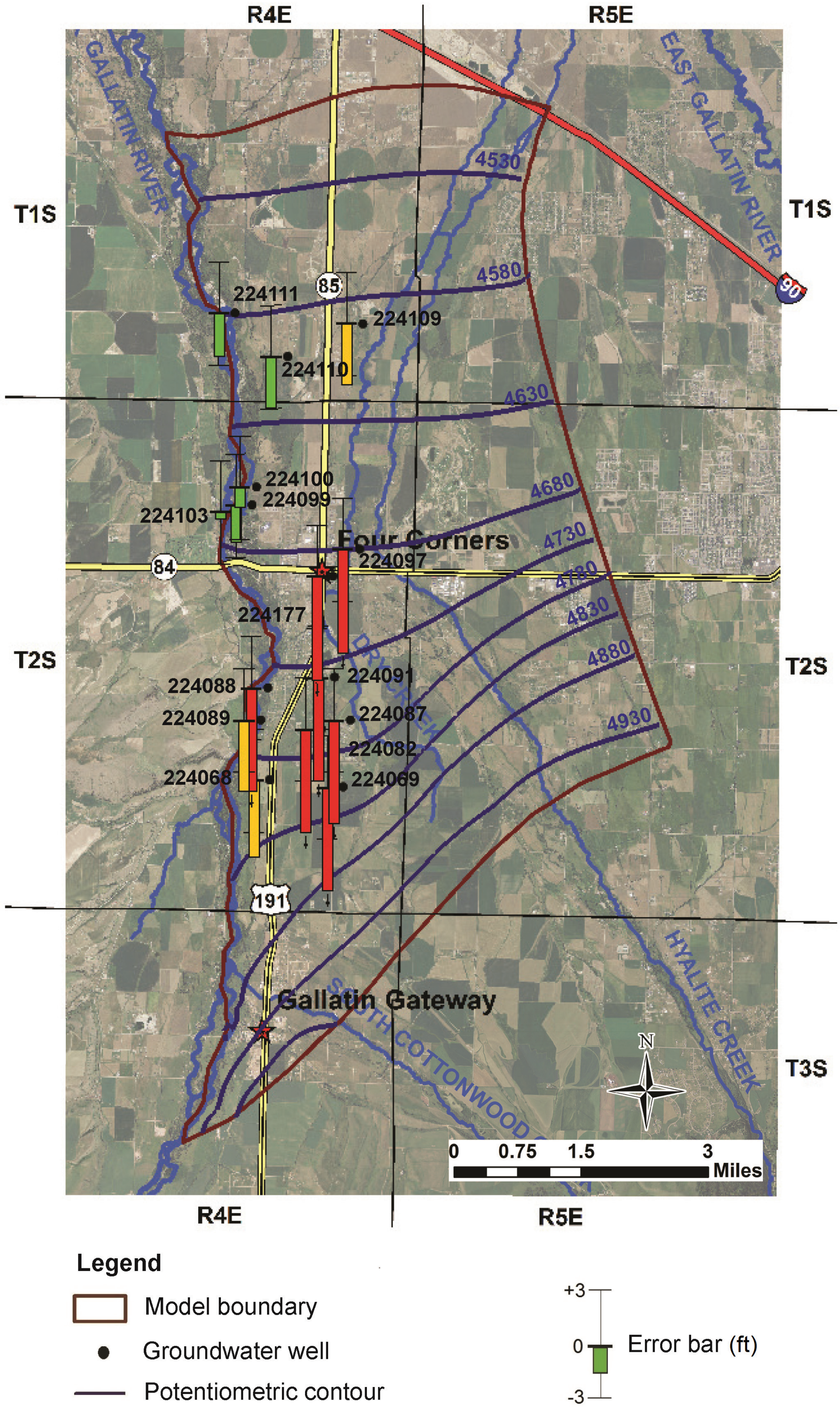

Figure 20. Potentiometric surface and the well head residuals are shown for the drier-climate scenario (Scenario 2b). A stream and river stage decrease of 0.5 and 1.5 ft, respectively, is seen, and a 25% decrease in groundwater influx. Simulation targets have a 3 ft error interval, green targets indicate results within 3 ft, yellow targets are between 3 and 6 ft, and red targets exceed 6 ft.

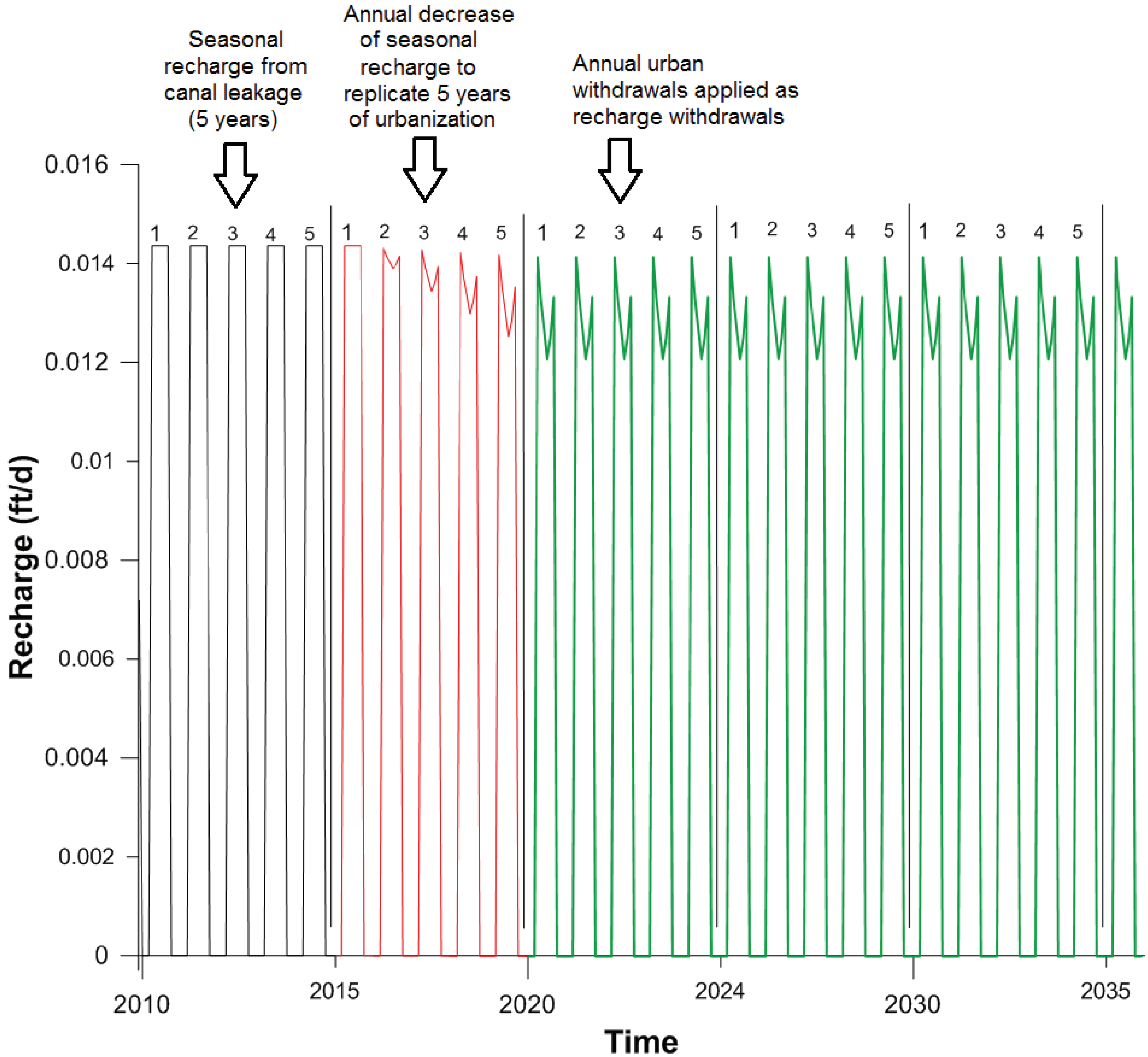

Figure 21. In Scenario 3 recharge is decreased in 5-yr intervals for 25 years. In order to adequately portray further urban growth in the model, the 5-yr growth was applied in each simulation as an iterative decrease in recharge during the 5-yr period and only the final trends were assessed. This graph displays the incremental decline in recharge to the predicted future rate of recharge.

To summarize:

- *Simulation 3a:* applies land-use changes between 2015 and 2020, including an urban/ commercial expansion onto 2,796 acres of non-irrigated lands.
- *Simulation 3b:* further expands the urban/ commercial land uses to an additional 2,677 acres of non-irrigated land over the years 2020–2025.
- *Simulation 3c:* further expands the urban/ commercial land uses to an additional 2,656 acres of irrigated land over the years 2025–2030.
- *Simulation 3d:* further expands the urban/ commercial land uses to an additional 2,687 acres of both irrigated and non-irrigated lands over the years 2030–2035 using a 50-yr transient model.
- *Simulation 3e:* a steady-state simulation that removes all agricultural recharge (irrigation water recharge from canal leakage) from the urbanized zones using the recharge conditions described in Simulation 3d.

Water-level changes in each of the four urban expansion simulations showed similar trends. Some wells indicated water-level decreases while

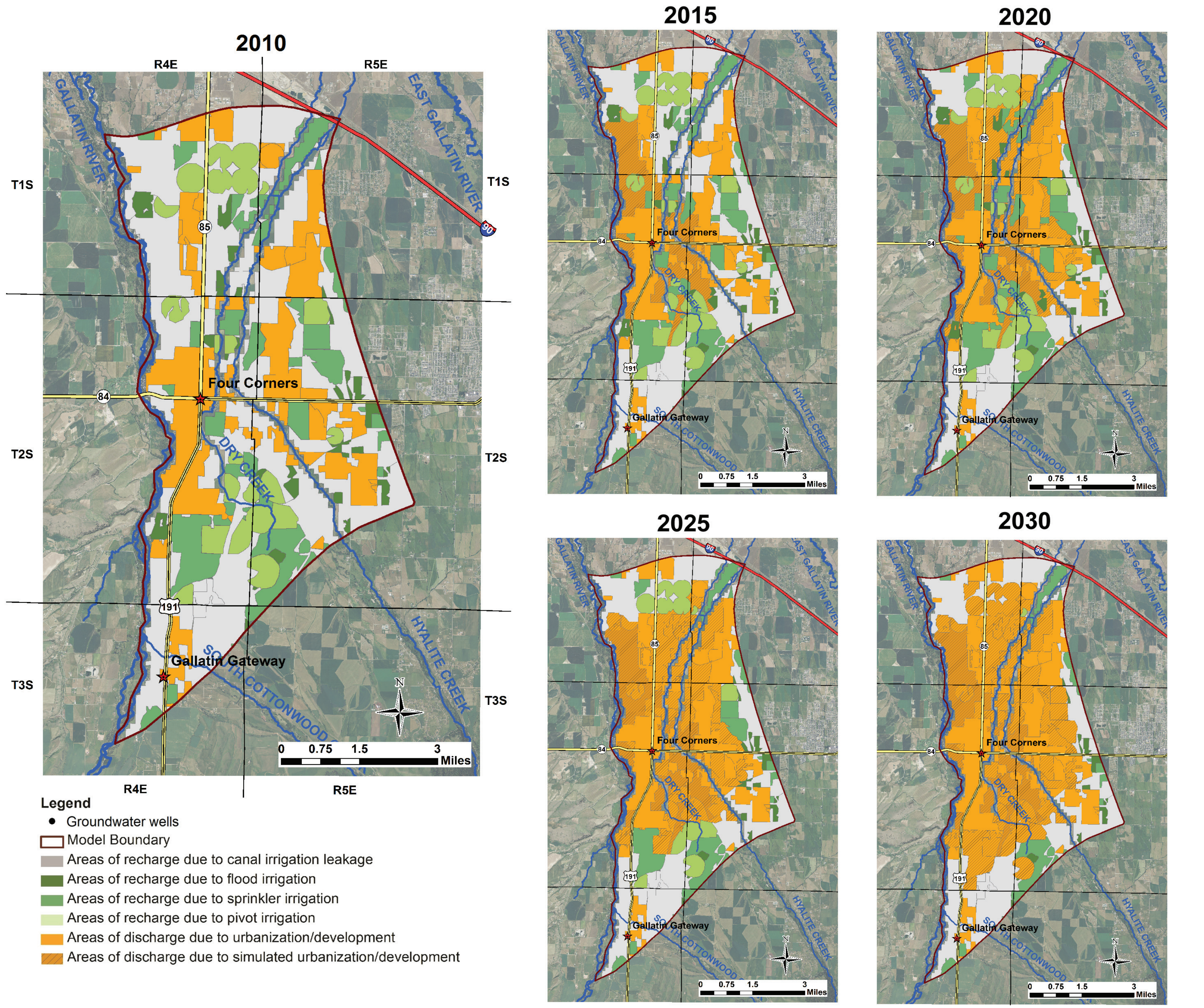

Figure 22. In Scenario 3, future growth is simulated through expansion of urban areas. Five maps show the simulated recharge zones in the baseline model and the expansion of urban development at 5, 10, 15, and 20 yr.

other wells did not. Three wells (GWIC IDs 224092, 224097, and 224177) were utilized to show the annual fluctuations of the water levels (figs. 23, 24).

Overall, water levels in the wells adjacent to the river were less affected by the decreasing recharge, as river leakage maintained the aquifer level. As recharge decreased and urbanization expanded, greater flow volumes were depleted from the river to maintain groundwater levels. This effect was also shown in Scenario 2, where the decrease in recharge caused increasing stream and river depletions in order to maintain water levels.

Wells that were not located adjacent to the river showed varying degrees of water-level decline. The water levels in all wells reached equilibrium almost immediately after the pumping stresses reached a constant rate. This suggests that the relatively high transmissivity of the aquifer responds to stresses very quickly, and water-level fluctuations due to new stresses will be rapid. Looking at well GWIC ID 224097 in Simulation 3d (fig. 25), equilibrium is not reached until over 5 to10 yr after the pumping rates have become constant. This suggests that the system may show a partial, immediate response to a stress, but the full response is long-term and can take years to fully realize.

This scenario assumes recharge from canal leakage will continue throughout the urban expansion. If the canal network were to be removed from the system, the impacts of pumping may be exacerbated. A steady-state simulation (Simulation 3e) was run that removed agricultural recharge (i.e., canal leakage and surficial diffuse recharge from irrigation) from the model and simulated the 20-yr urban expansion (fig. 26). The resulting water level declined as much as 13 ft in wells located in the interior of the model, indicating again that the groundwater levels are heavily reliant on river and stream stages as well as recharge. The overall flow volume leaving the system, however, decreased by over 9,000 acre-ft/yr, and induced infiltration from the river created a loss of over 5,000 acre-ft/yr from surface water. Three wells located adjacent to the river showed an increase in head, indicating the increased dependence of the groundwater system on surface water, which was artificially held constant at 2010 elevations. Greater losses would be likely should the river stages reflect the declining groundwater trends that would occur in this simulation.

Scenario 4: Aquifer Storage and Recovery

This scenario simulated the effects to surface water of a new subdivision supplied with groundwater that also mitigates or offsets its water use with an injection well that is supplied by a water source that is outside the model domain. This scenario was simulated using the transient 25-yr model as the baseline, adding a pumping well and an injection well. The wells were placed adjacent to the Gallatin River in the northern section of the model.

Two locations were used to simulate the aquifer storage and recovery system, and switching the locations of the pumping and injection wells for each location resulted in four total simulations (fig. 27, table 12). Simulations 4a and 4b were chosen to examine the difference in responses to the positions of the pumping and injection wells relative to groundwater flow direction. In Simulation 4a the pumping well was located approximately 2,030 ft upgradient from the injection well. In Simulation 4b the locations of the pumping and injection wells were reversed. Simulations 4c and 4d were designed to examine the difference in responses to the locations of the wells relative to the river. In Simulation 4c, the injection well was nearer the river and the pumping well was 2,020 ft east. Simulation 4d reversed the locations of the pumping and injection wells in Simulation 4c.

Using the average consumption rate for Bozeman as reported by the DNRC (2011), individual households use 0.03 acre-ft (3.6 ft^3/d) throughout the year and consume an additional 0.8 acre-ft (190.8 ft^3/d) per half-acre watered for lawn and garden maintenance during the summer. This includes the inherent assumption that the difference between the actual diverted use and the consumed use is returned to the aquifer near enough to the withdrawal source as to cause no impact to surface water. Therefore, a 100-lot subdivision with half-acre lawn/garden lots will consume 80 acre-ft

Table 12. Well locations for Scenario 4.

	Well Locations	
Scenario	Pumping Well	Injection Well
4a	Z	X
4b	X	Z
4c	Y	X
4d	X	Y

Note. Locations X, Y, and Z are indicated on fig. 23.

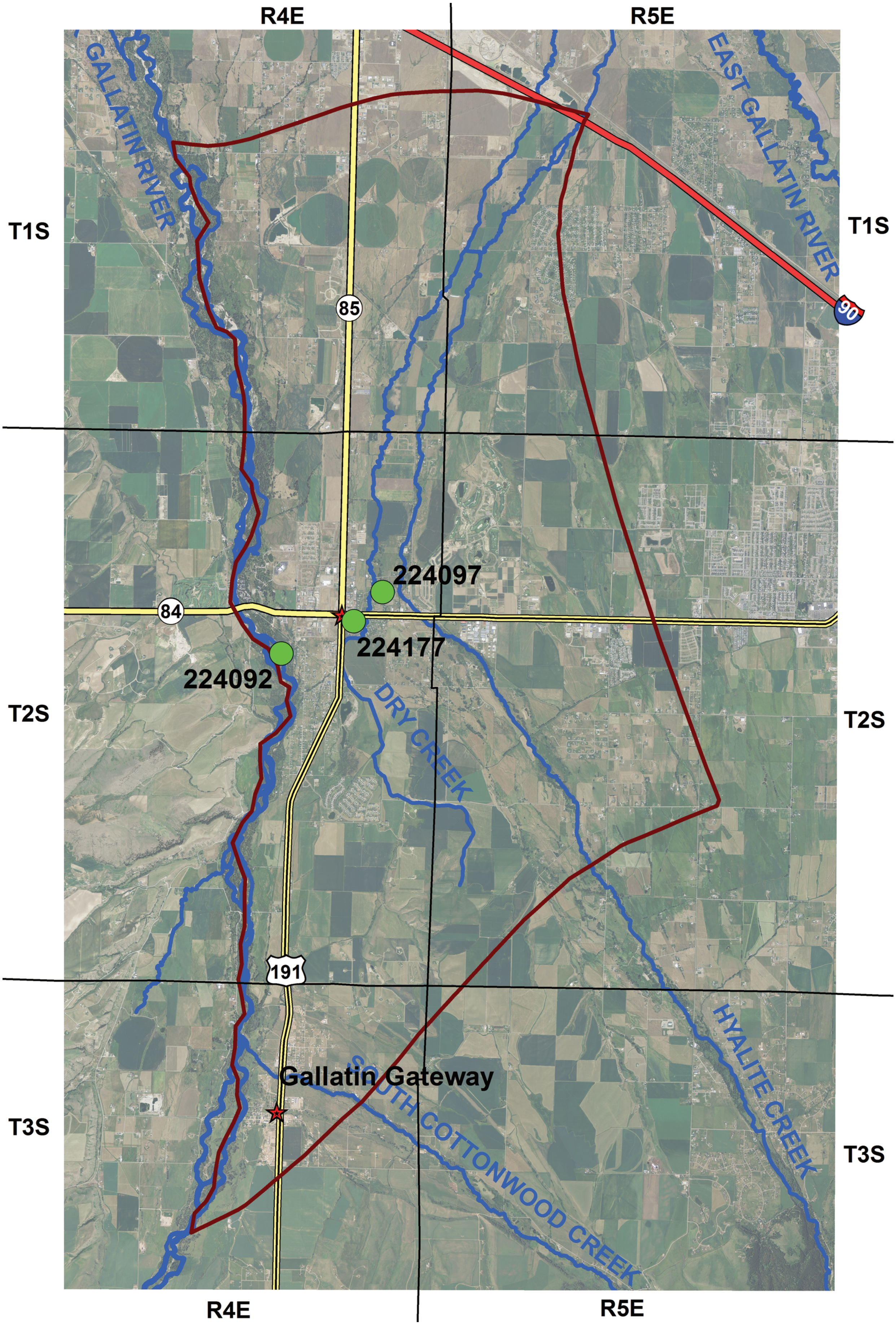

Figure 23. Locations for wells 224097, 224092, and 224177 are shown for the land-use change scenario (Scenario 3). The water-level trends for these three wells are shown in figure 24.

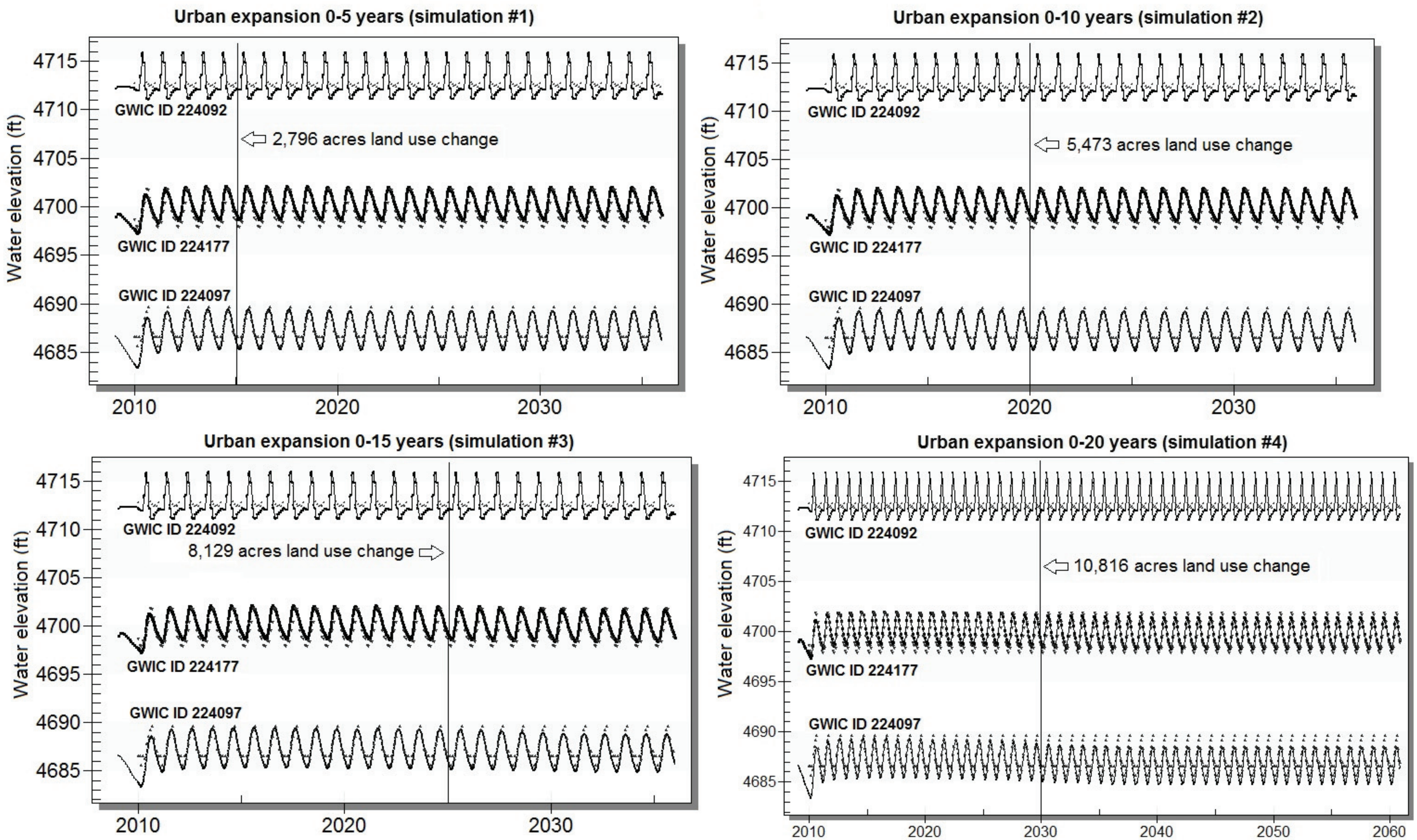

Figure 24. Three selected wells showing the groundwater elevation changes resulting from four urban expansion scenarios (Scenario 3). The first three scenarios predict 25 yr into the future; the final scenario extends to 50 yr.

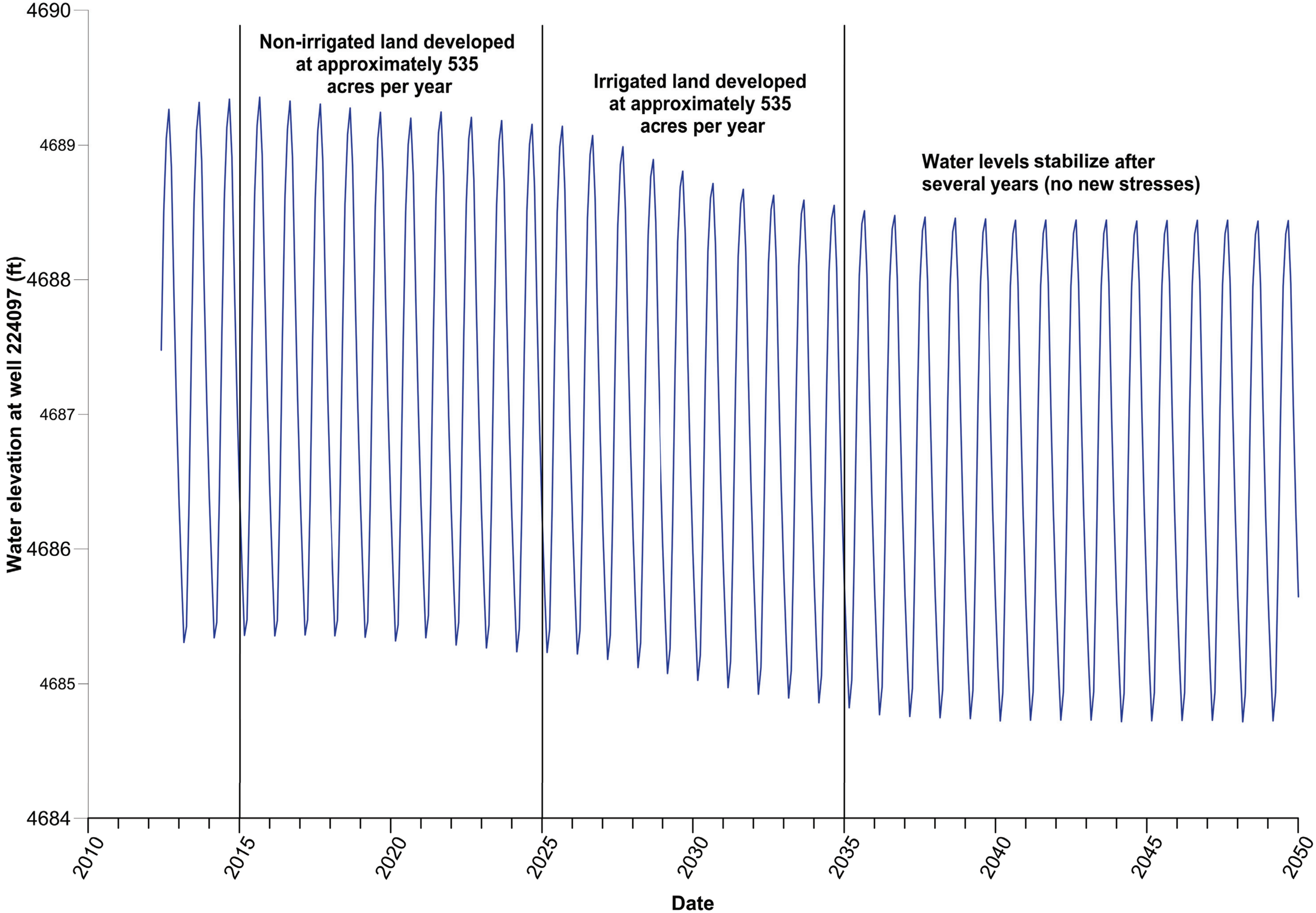

Figure 25. This well (GWIC ID 224097) shows greater declines in water-level trends when recharge from irrigation is removed for urbanization than when non-irrigated lands are urbanized (Scenario 3).

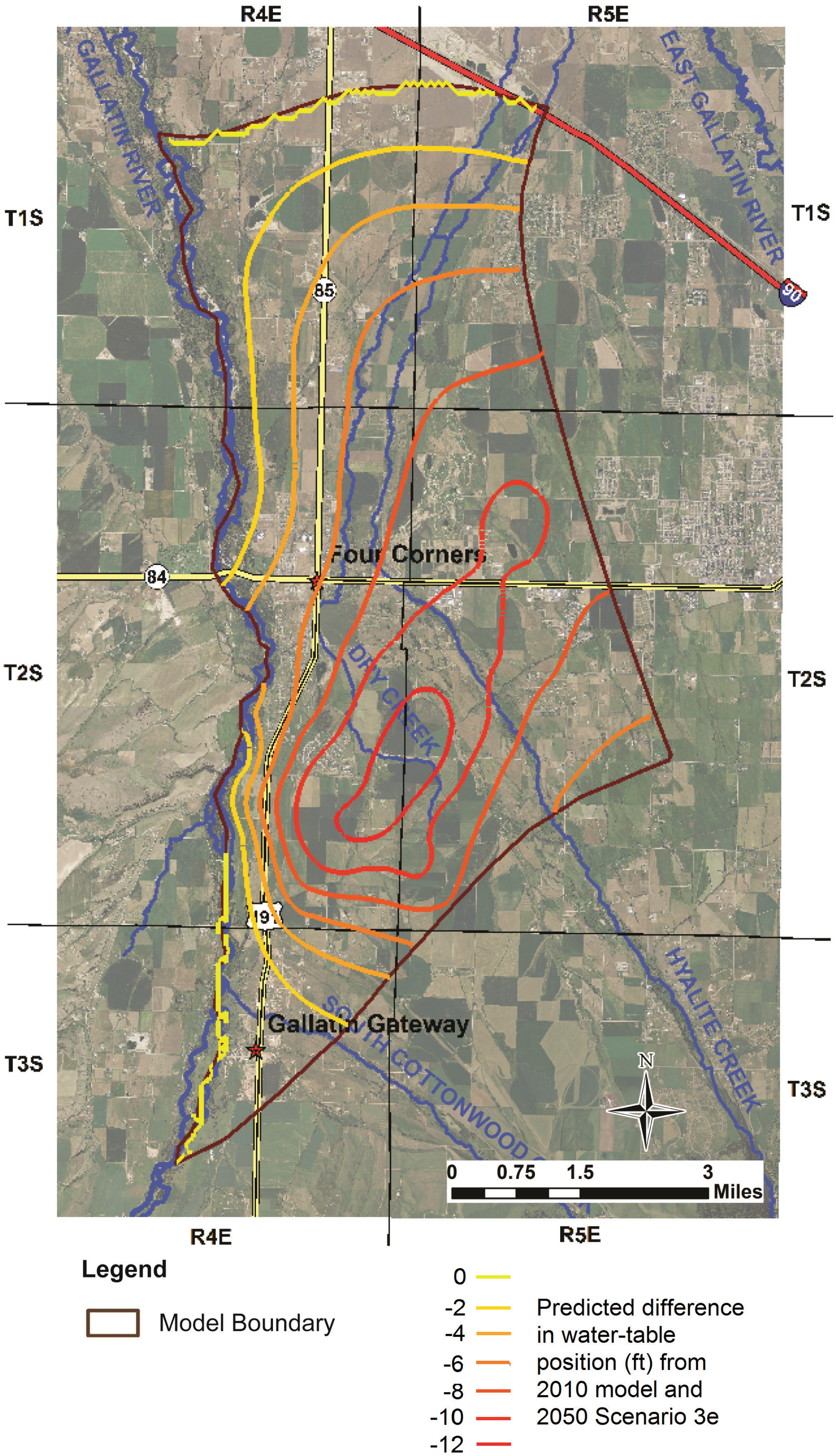

Figure 26. Potentiometric surface contours comparing the 2010 water-level surface to the water-level surface simulated in Scenario 3e shows a general decline in water levels once irrigation recharge and canal seepage have been removed from the urbanized zones.

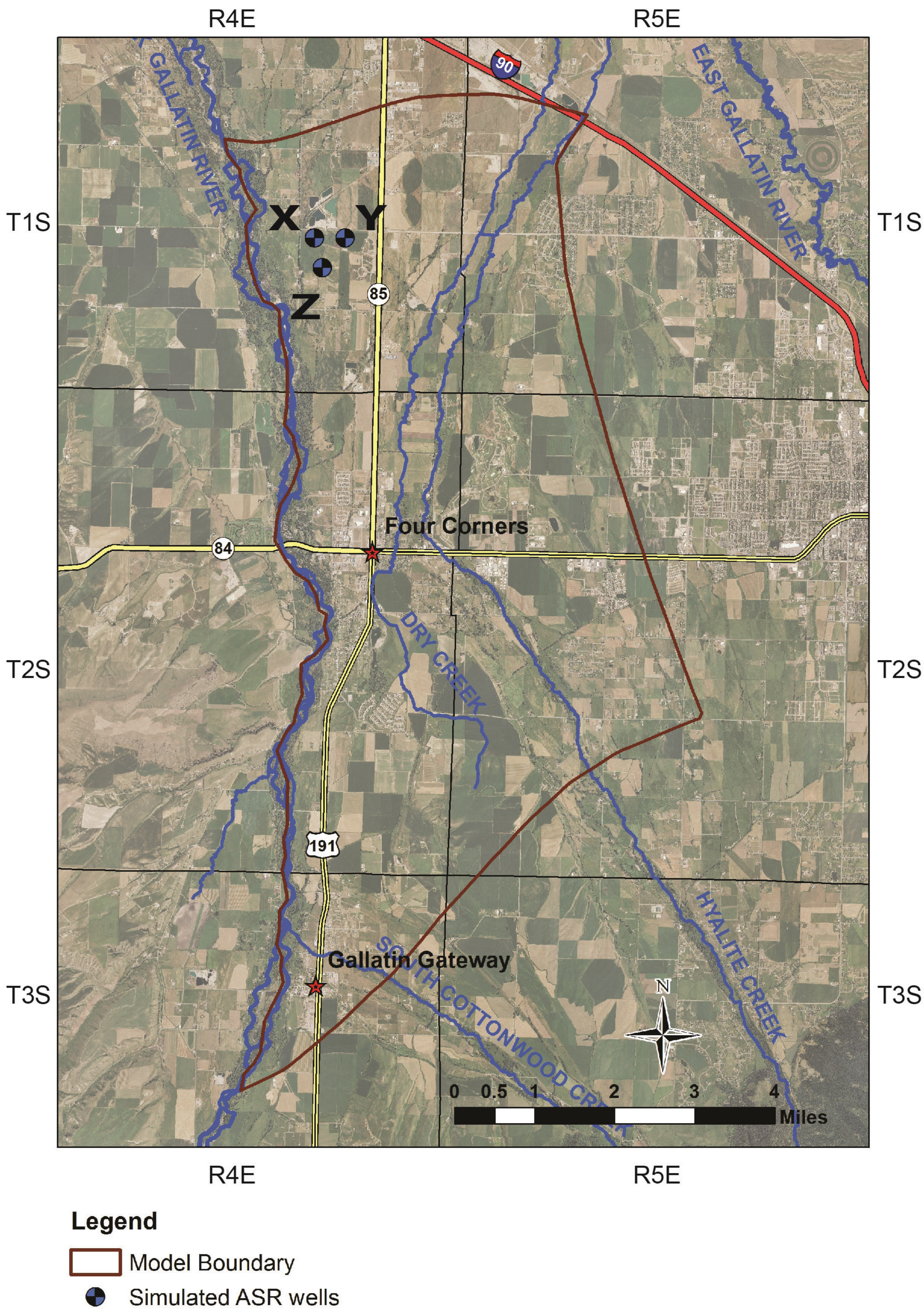

Figure 27. Scenario 4 employs three simulated pumping locations to identify the impacts of an aquifer storage and recovery (ASR) style municipal system.

during the 6-month irrigation season for lawn irrigation, and 3 acre-ft throughout the year for household use. As this hypothesis assumes water during high-spring river flow is used to offset groundwater depletions, the injection period simulated was for 3 months starting in April, the beginning of the irrigation season. The injection rate was 39,700 ft^3/d during the 3-month irrigation season for an annual total of 83 acre-ft, which is designed to offset the entire annual consumptive use of the 100-lot subdivision. The injected water is numerically created from outside of the model in order to offset the annual withdrawal of water from the model. The annual pumping and injection rates are shown in figure 28, as they apply to each year of the simulations.

The analysis of these simulations compared the deviation from baseline storage and the deviation from baseline (no pumping or injection) simulated river leakage and storage. It should be noted that stream depletion is specific to the reach of the Gallatin River most likely to be impacted, while storage is calculated for the entire model. None of the four simulations showed any impact to either river leakage or aquifer storage in the model. The limited variability in these simulations is likely due to the high transmissivity of the aquifer and the selection of well locations, allowing for the rapid offset of withdrawn water by injected water. This simulation indicates the effects on river leakage and storage are limited, even when a pumping and injection site is placed adjacent to the river. Distance from the river may be important for determining timing and magnitude of effects; however, the overall volume of change appears to be completely offset within the model domain. Well locations other than those tested here may produce different modeled responses.

SUMMARY AND CONCLUSIONS

Assumptions and Limitations

The numerical groundwater model is a useful and informative tool for developing, testing, and refining our understanding of the hydrologic system. The numerical model also helps investigate the effects of possible future stresses. There are some inherent limitations to computer-based modeling in general, and this model specifically, that must be kept in mind. The accuracy with which a model represents a system is heavily reliant on the information used to parameterize the model and the objectives for which the model is designed. For example, in this model a uniform rate of recharge from canal leakage over the entire model domain was assumed, which is a reasonable representation of canal leakage on the scale of this model. If the objective of the model had been to look at groundwater mounding or flow at a specific location, a smaller-area model with linear canal recharge that varied laterally as well as temporally would be needed for accurate resolution at the desired scale. The model is more sensitive to changes in recharge than changes in hydraulic conductivity. This may be indicative of non-uniqueness in recharge, and more detailed information on canal seepage, locations, and timing may be necessary to further refine the model. Assumptions about aquifer depth may also have placed artificial limits on the range of K, as conductivity was calculated based on transmissivity and aquifer thickness values derived from aquifer tests. Additional information on the elevation of the subsurface Quaternary–Tertiary contact could improve the model, possibly by creating a layer bottom that is more reflective of the physical system. Additional information on water levels along the perimeter of the model domain could also help to refine the calibration.

The lack of long-term monitoring records presented a problem for projecting the model into the future. Typically, a model should not be considered valid for projecting future conditions beyond twice the calibration interval (Anderson and Woessner, 2002). The most complete data set available was for 1 year, 2010, and therefore those conditions were projected into the future as an acceptable and necessary approach. This model is not calibrated for replicating flow conditions that are dissimilar to 2010; for example, a high snowpack year may cause excessive flows in the Gallatin River and the creeks and a higher than average influx into the groundwater through the southern boundary. As the model has demonstrated a great dependence on river leakage, this could cause a significant shift in the flow budget and water-table elevations.

These simulations are intended to represent system-scale approximations of the physical response to applied stresses. As more information becomes available, this model may be modified to better reflect physical conditions.

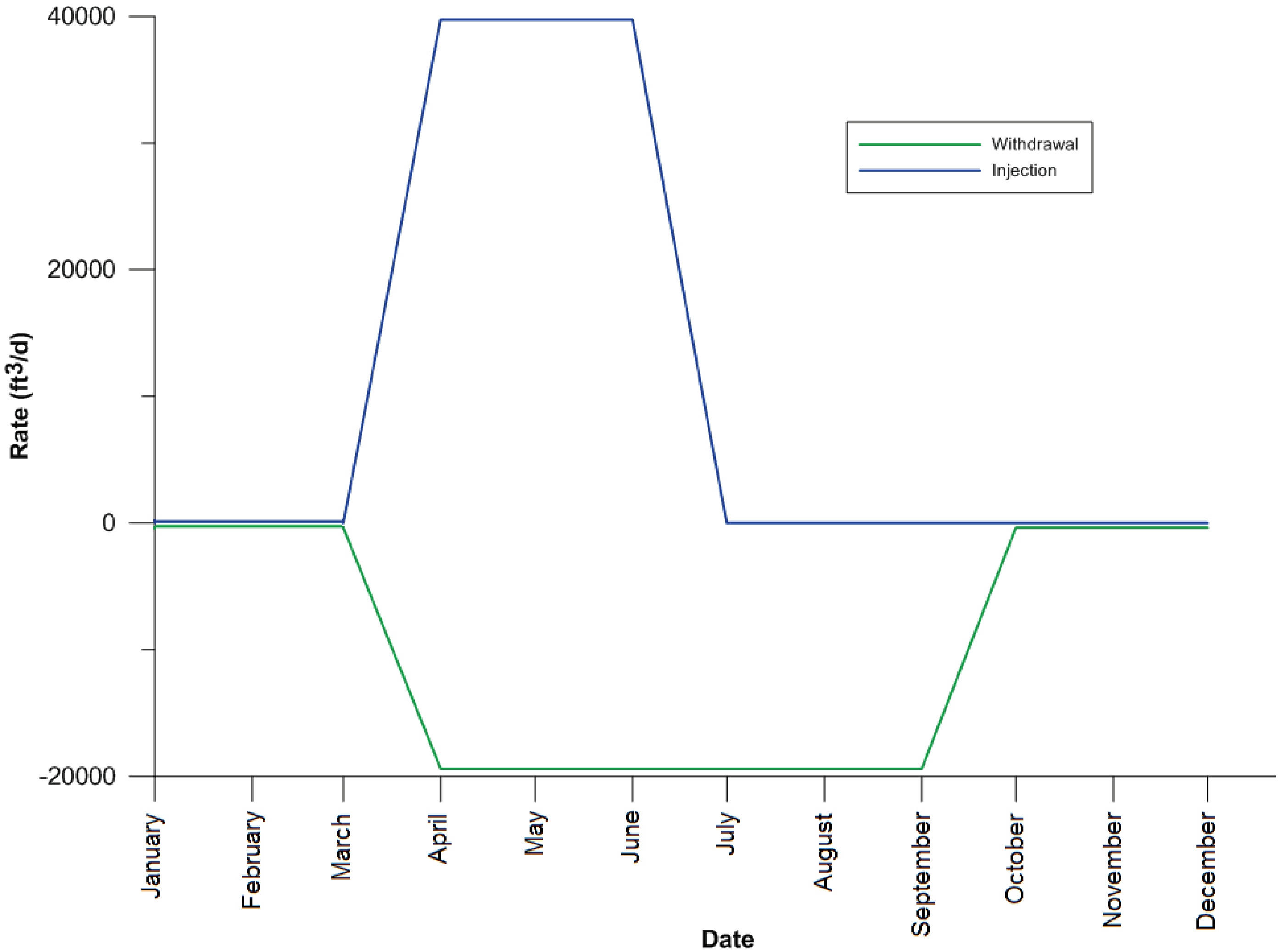

Figure 28. Scenario 4 pumping and injection rates for the simulated ASR wells.

Model Predictions

The model was used to simulate several possible future stresses, and each simulation suggested the model is sensitive to river leakage (table 13). The Gallatin River, and to a lesser degree Hyalite Creek, are directly connected to the aquifer and, alternately, recharges and discharges to groundwater. The simulation of historic conditions suggested that although recharge plays a role in groundwater elevations, the flow volume through the aquifer is a more sensitive indicator of stress than the actual water levels. This was exhibited again in Scenarios 2 and 3, where decreased recharge caused a slight drop in water-table elevations, but a significant decrease in groundwater flow volume. As the water table and the surface-water elevations are very closely tied, minor decreases in head can cause significant decreases to the river and streams. Groundwater elevation changes may be minor as they are distributed over a large area or show little to no impact in a 200-ft-deep well, but the river and streams are sensitive to this drop and stream discharge will correspondingly decrease. Just as the decreasing water levels in the aquifer reflect a decrease in flow volume, a minor decrease in surface water is equivalent to a larger decrease in the flow volume of the river and streams.

Recommendations

In the future, a post-audit of this 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. A reasonable prediction would validate the model. If conditions are found to be somehow different from the current understanding, the model should be modified to better represent these conditions. Particularly, a better understanding of canal leakage (variability in leakage rates temporally and spatially) throughout the model domain would be useful, as the dif-

Table 13. Four predictive scenarios were run on the model in order to determine the possible outcome of different stresses.

	Model	Simulation Design	Results
Scenario 1: Hackett's 1953 study	Steady-State	Flood irrigation on most of valley floor, higher stream and river stages, no urban/domestic well withdrawals	Compared to 2010, minor changes in groundwater elevation, significantly greater flow volume in the aquifer, significant contributions to groundwater from flood irrigation and surface water
Scenario 2: Drier Climate	Steady-State	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	Recharge remained constant, stream and river stages decreased, southern boundary influx decreased 25%	Head slightly decreased throughout the aquifer, overall flow volume decreased approximately 14,700 acre-ft/yr, groundwater levels indicate sensitivity to surface water
Scenario 3: Future Growth	25-yr transient	Urban expansion of 535 acres/yr for 5 years, no irrigated acreage removed	No decrease in aquifer levels, river and streams maintain water levels at model boundaries
	25-yr transient	Urban expansion of 535 acres/yr for 10 years, no irrigated acreage removed	Very slight decrease in aquifer levels, river and streams maintain water levels at model boundaries—equilibrium reached immediately after stresses applied
	25-yr transient	Urban expansion of 535 acres/yr for 15 years, only irrigated acres urbanized last 5 years	Very slight decrease in aquifer levels, flow volume decreases slightly, equilibrium reached immediately after stresses applied
	50-yr transient	Urban expansion of 535 acres/yr for 20 years, irrigated lands removed years 10–15, mixed un-irrigated and irrigated removed years 15–20	Very slight decrease in aquifer levels, equilibrium reached immediately after stresses applied, minimal impact to aquifer
	Steady-State	Urban expansion of areas in 50-yr transient model, all water from irrigation 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	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	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

Note. Though these scenarios may not reflect actual outcomes, they are useful for determining which components of the system are highly sensitive or for examining trends.

fuse application of recharge may be underestimating the influence of surficial recharge throughout the model and forcing other parameters to compensate for this deficiency. It is also recommended that this model be refined in the future as more detailed information related to land-use changes, water use, and well placement that cannot be predicted are collected. The model will serve as a starting point for further analysis as understanding of the system evolves and additional issues arise.

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APPENDIX A

MODEL FILE INDEX

FOUR CORNERS GROUNDWATER INVESTIGATION—GROUNDWATER MODEL

This appendix lists the files of the simulations that served as final modeling products. The files include the GMS project file and MODFLOW input and output files. Background map files were not included but are widely available through other sources for the area. This information is sufficient for a third party to rebuild the model, reproduce the model results, and use the model for future purposes. Details on the model's grid, boundary conditions, and parameters are provided in the body of this report. The following simulations are included in the index:

Calibration

1. Steady-State Calibration: Calibrated heads and water budget in steady-state mode
2. Transient Calibration: Calibrated heads and water budget in transient mode from January 2010 to January 2011

From these simulations, other simulations presented in this report were generated. Where a 25- or 50-yr transient model is described, the annual conditions from the 1-yr transient model were repeated to create an extended transient model. Those simulations are summarized below.

Sensitivity Analysis

- K+25%: Tested the model's sensitivity to an increase of K by 25%
- K-25%: Tested the model's sensitivity to an decrease of K by 25%
- K+50%: Tested the model's sensitivity to an increase of K by 50%
- K-50%: Tested the model's sensitivity to an decrease of K by 50%
- R+25%: Tested the model's sensitivity to an increase of R by 25%
- R-25%: Tested the model's sensitivity to an decrease of R by 25%
- R+50%: Tested the model's sensitivity to an increase of R by 50%
- R-50%: Tested the model's sensitivity to an decrease of R by 50%

Predictive Scenarios

- **Scenario 1, Hackett Study, Pre-Urbanization of the Four Corners Area:** This scenario uses a steady-state simulation to re-create historic irrigation practices and compare pre-urbanization aquifer conditions to the current system.
- **Scenario 2, Drier Climate:** This scenario uses two simulations to predict possible future climate change conditions using the steady-state model.

  Simulation 2a: This simulation decreases any influx into the model (groundwater boundary flow in or applied recharge internal to the model) by 25% and decreased river and stream stages by 1.5 ft and 0.5 ft, respectively.
  Simulation 2b: This simulation decreases influx into the model through the southern boundary by 25% and decreased river and stream stages by 1.5 ft and 0.5 ft, respectively. This simulation does not decrease internal model recharge as in simulation 2a.

- **Scenario 3, Land-Use Changes:** This scenario uses baseline 25-yr and 50-yr models to create five simulations applying current land-use changes to predictive future changes in 5-yr intervals. The land-use changes are applied by adjusting recharge values to match the land uses modeled. The first 5 yr of each simulation replicate the 1-yr transient model with no annual changes from 2010 to 2015.

  Simulation 3a: applies land-use changes between 2015 and 2020, including an urban/commercial

expansion onto 2,796 acres of non-irrigated lands.
Simulation 3b: further expands the urban/commercial land uses to an additional 2,677 acres of non-irrigated land over the years 2020–2025.
Simulation 3c: further expands the urban/commercial land uses to an additional 2,656 acres of irrigated land over the years 2025–2030.
Simulation 3d: further expands the urban/commercial land uses to an additional 2,687 acres of both irrigated and non-irrigated lands over the years 2030–2035 using a 50-yr transient model.
Simulation 3e: a steady-state simulation that removes all agricultural recharge (irrigation water recharge from canal leakage) from the urbanized zones using the recharge conditions described in Simulation 3d.

- **Scenario 4, Aquifer Storage and Recovery (ASR):** This scenario uses a baseline 25-yr model to create four simulations identifying the impacts on river leakage and aquifer storage of a theoretical pumping and injection well system.

  Simulation 4a: places the pumping well upgradient from the injection well, with both wells parallel to the river.
  Simulation 4b: reverses the location of simulation 4a, placing the injection well upgradient from the pumping well, with both wells parallel to the river.
  Simulation 4c: places the pumping well some distance from the river, with the injection well situated between the river and the pumping well.
  Simulation 4d: reverses the location of simulation 4c, placing the injection well some distance from the river, with the pumping well situated between the river and the pumping well.

Table A-1 provides the file name and type for the steady-state and transient calibrations; the required supporting files are also included.

Table A-1. Four Corners groundwater model file organization.

Simulation ID	Primary Action	File Name	Supporting files
Steady-state calibration	Final run of steady-state calibration	4C_Steadystate	4C_SS_obs_wells.csv
Transient calibration	Final run of transient calibration	4C_Transient	4C_T_obs_wells.csv

Table A-2 provides the input and output file types for each simulation, including those specific to GMS. These files are available for download from the Groundwater Investigations Program website (http://www.mbmg.mtech.edu/gwip/project-fourcorners.asp). MODFLOW files were generated using the "Export Native MF2K text" function in GMS. The MODFLOW 2000 files were tested using MODFLOW downloaded from the USGS website: http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html. The downloaded version of MODFLOW was 1.19.01, compiled on March 25, 2010.

Table A-2. Input and output files for the Four Corners model.

File type	File extension	GMS specific
Input files		
GMS project file	GPR	Y
Advanced Spatial Parameterization	ASP	
Basic	BA6	
Constant Head Package	CHD	
Discretization	DIS	
River Package	RIV	
Stream Package	STR	
Head and Flow HDF5 (binary data)	H5	Y
Layer-Property Flow	LPF	
Name	MFN	
Obs-Sen-Pes Process	OBS	
	CHOB	
	DROB	
	HOB	
	SNN	
Output control	OC	
Parameter Estimation	PARAM	
Pre-Conjugate Solver Package	PCG	
Recharge Package	RCH	
MODFLOW Super file	MFS	Y
MODFLOW world file	MFW	Y
Projection file	PRJ	Y
Well Package	WEL	
Output files		
Cell-by-cell flow	CCF	
Global	GLO	
Head	HED	
Head and Flow	HFF	
Link-MT3D Package	LMT	
Output List	OUT	
Obs-Sen-Pes Process	_NM	
	_OS	
	_R	
	_W	
	_WS	

APPENDIX B

CALCULATION TABLES FOR SELECTED MODEL INPUTS

Table B-1. Conversion of canal leakage to diffuse aerial recharge (R_{can}).

	Model Area	**1.1 cfs/mi canal leakage**					
		Maximum*			**Minimum***		
	ft^2	Miles	ft^3/d	**R_{can} ft/d**	Miles	ft^3/d	**R_{can} ft/d**
January	1,151,290,800	215	0	**0**	174	0	**0**
February	1,151,290,800	215	0	**0**	174	0	**0**
March	1,151,290,800	215	0	**0**	174	0	**0**
April	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
May	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
June	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
July	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
August	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
September	1,151,290,800	215	20,433,600	**0.018**	174	16,536,960	**0.014**
October	1,151,290,800	215	0	**0**	174	0	**0**
November	1,151,290,800	215	0	**0**	174	0	**0**
December	1,151,290,800	215	0	**0**	174	0	**0**
Average annual (SS)				**0.009**			**0.007**

Note. SS, steady-state model; ft/d, feet/day; R_{CAN} ft/d, diffuse canal recharge in feet/day over the entire model area; miles of canals within the study area. Model input units are feet and days; therefore, R values and all other data used for modeling are reported in feet and days.

Formula:

R_{CAN} = (canal length x leakage rate) / area.

*Minimum recharge rates are calculated for the 20 largest canals only; maximum recharge rates include all mapped canals within the model area.

Table B-2. Water requirements for major crops grown in Gallatin County.

Crop requirements (ET)				
Monthly	Spring grains (ft)	Potatoes (ft)	Afalfa (ft)	Other hay (ft)
Apr	0.000	0.000	0.0325	0.0475
May	0.073	0.000	0.284	0.234
Jun	0.497	0.163	0.444	0.356
Jul	0.723	0.576	0.634	0.504
Aug	0.105	0.558	0.512	0.410
Sept	0.000	0.300	0.319	0.220
Total	1.398	1.596	2.226	1.772

Note. Spring grains includes oats, spring wheat, and barley. The water demands of each crop, each month, were determined by the United States Soil Conservation Service (1970) and the average monthly precipitation (WRCC, 2011).

Table B-3. Average precipitation during the 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 taken from the two nearest weather stations (WRCC 2011,).

Table B-4. Irrigation efficiency of three typical irrigation systems.

Irrigation Efficiency (IE)	
Flood	0.35
Sprinkler	0.65
Pivot	0.80

Note. Application efficiencies for irrigation types were determined to be 35% efficient for flood irrigation, 65% efficient for sprinkler irrigation, and 80% efficient for pivot irrigation by the Montana DNRC (2011).

Table B-5. Percentages of four largest crops grown in Gallatin County.

Crops grown by percentage (CP)	
Spring grains	0.560
Potatoes	0.030
Alfalfa	0.348
Other hay	0.062

Note. Crop percentages grown in the Gallatin Valley are taken from the USDA National Agriculture Statistics Service (2008) and assumed to be evenly distributed based on land percentages. Grains represent 56%, Potatoes represent 3%, Alfalfa represents 34.8%, and other hay represents 6.2%.

Table B-6. Calculation of monthly recharge from flood (R_{FLD}), sprinkler (R_{SPR}), and pivot (R_{PIV}) irrigation.

April	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	-0.1269872	-0.0589583
Potatoes	N/A	-0.1269872	-0.0589583
Alfalfa	N/A	-0.1094872	-0.0508333
Other hay	**-0.3497619**	-0.1014103	-0.0470833
by %	N/A	**-0.1191844**	**-0.0553356**

May	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	-0.0354487	-0.0164583
Potatoes	N/A	-0.0749359	-0.0347917
Alfalfa	N/A	0.0780769	0.0362500
Other hay	**0.1764286**	0.0511538	0.0237500
by %	N/A	**0.0081599**	**0.0037885**

June	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	0.1498718	0.0695833
Potatoes	N/A	-0.0300641	-0.0139583
Alfalfa	N/A	0.1216026	0.0564583
Other hay	**0.2553571**	0.0740385	0.0343750
by %	N/A	**0.1292447**	**0.0600065**

July	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	0.2638462	0.1225000
Potatoes	N/A	0.1848718	0.0858333
Alfalfa	N/A	0.2162821	0.1004167
Other hay	**0.5045238**	0.1462821	0.0679167
by %	N/A	**0.2371349**	**0.1100983**

August	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	-0.0134615	-0.0062500
Potatoes	N/A	0.2301923	0.1068750
Alfalfa	N/A	0.2055128	0.0954167
Other hay	**0.5200000**	0.1507692	0.0700000
by %	N/A	**0.0809779**	**0.0375969**

September	Applied (ft)		
	Flood (R_{FLD})	Sprinkler (R_{SPR})	Pivot (R_{PIV})
Spring grains	N/A	-0.0242308	-0.0112500
Potatoes	N/A	0.1373077	0.0637500
Alfalfa	N/A	0.1476282	0.0685417
Other hay	**0.3250000**	0.0942308	0.0437500
by %	N/A	**0.0482758**	**0.0224138**

Note. R_{FLD} ft/d, flood irrigation recharge in feet/day over the entire model area; R_{SPR} ft/d, sprinkler irrigation recharge in feet/day over the entire model area; R_{PIV} ft/d, pivot irrigation recharge in feet/day over the entire model area; N/A, not applicable. 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. Calculations in bold represent the final R_{CAN}, R_{SPR}, and R_{PIV} applied to the model, except where negative. Negative applied totals were zeroed.

Formulas:

Monthly recharge from flood irrigation (R_{FLD}) = precipitation (P) + irrigation (I) - crop requirements (ET)

Monthly recharge from sprinkler (R_{SPR}) and pivot (R_{PIV}) irrigation = [precipitation (P) + irrigation (I) - crop requirements (ET)] x crop percentage (CP)

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

where

Crop requirements (ET) calculated in table B-2

Preciptitation (P) calculated in table B-3

Irrigation efficiency (IE) calculated in table B-4

Crop percentages (CP) calculated in table B-5

Table B-7. Calculation of the irrigation recharge rate over time.

	days	Flood		Sprinkler		Pivot	
		R_{FLD} ft	**R_{FLD} ft/d**	R_{SPR} ft	**R_{SPR} ft/d**	R_{PIV} ft	**R_{PIV} ft/d**
January		0	**0**	0	**0**	0	**0**
February		0	**0**	0	**0**	0	**0**
March		0	**0**	0	**0**	0	**0**
April		0	**0**	0	**0**	0	**0**
May	31	0.176	**0.006**	0.008	**0.000**	0.004	**0.000**
June	30	0.255	**0.009**	0.129	**0.004**	0.060	**0.002**
July	31	0.505	**0.016**	0.237	**0.008**	0.110	**0.004**
August	31	0.520	**0.017**	0.081	**0.003**	0.038	**0.001**
September	30	0.325	**0.011**	0.048	**0.002**	0.022	**0.001**
October		0	**0**	0	**0**	0	**0**
November		0	**0**	0	**0**	0	**0**
December		0	**0**	0	**0**	0	**0**
Average Annual (SS)			**0.00484**		**0.00137**		**0.00064**

Note. Areas designated within the model as Flood, Sprinkler, or Pivot irrigation have been identified as such by the Montana Department of Revenue (2010) Final Land Unit survey for the 2010 coverage. For Scenario 1 (Hackett), land use designations were identified by the Montana State Engineer's Water Resource Survey (1953) for the 1953 (Hackett and others 1960) coverage.

Table B-8. Calculation of groundwater removed and consumed by household and lawn/garden demands (R_{URB}).

	Average Annual Domestic Consumption								
	Urban acres	# of wells	House	Lawns				Total volume consumed	**R_{URB}**
			0.03 AF/m/house	0.8 A	Monthly ET %	Monthly ET AF/A-m	ET AF/m	AF/m	**ft/d**
January	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
February	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
March	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
April	6860	1334	3.34	1067.2	0.03	0.043	46	49	**-0.0002**
May	6860	1334	3.34	1067.2	0.13	0.211	226	229	**-0.0011**
June	6860	1334	3.34	1067.2	0.20	0.321	343	346	**-0.0017**
July	6860	1334	3.34	1067.2	0.28	0.455	486	489	**-0.0023**
August	6860	1334	3.34	1067.2	0.23	0.370	395	398	**-0.0019**
September	6860	1334	3.34	1067.2	0.12	0.199	212	215	**-0.0010**
October	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
November	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
December	6860	1334	3.34	1067.2	0	0	0	3	**0.0000**
Average Annual (SS)			3.34						**-0.0007**

Note. AF, acre-feet; mo, month; RURB, urban or domestic wells extracting water-applied as a negative recharge or extraction rate over the entire model area. The average household consumptive use rate in the Four Corners area is 0.03 AF/y (DNRC 2011) and the number of household wells in the model area is 1,334, for a total of 40.02 AF/y consumed. The average lawn and garden size in the Four Corners area was calculated to be 0.8 A based on a 10% random sampling of lot sizes in the study area. The average total consumptive use for the area is 1.6 AF/y/1A (DNRC 2011). Each of the 1,334 wells includes an adjacent 0.8 A lawn/garden, and the consumptive use is calculated during the April-September irrigation months based on local ET data (Total volume consumed AF).

Table B-9. Calculated recharge values for land use and irrigation types used for model input in the steady-state and transient one year models.

		Recharge Zones (ft/d)					Combined Recharge zones						
	Days	R_{CAN}	R_{URB}	R_{FLD}	R_{SPR}	R_{PIV}	$R_{CAN}+R_{URB}$	$R_{CAN}+R_{FLD}$	$R_{CAN}+R_{SPR}$	$R_{CAN}+R_{PIV}$	$RC_{AN}+R_{URB}+R_{FLD}$	$R_{CAN}+R_{URB}+R_{SPR}$	$R_{CAN}+R_{URB}+R_{PIV}$
Jan	31	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Feb	29	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Mar	31	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Apr	30	**0.01436**	-0.00024	0	0	0	**0.01413**	**0.01436**	**0.01436**	**0.01436**	**0.01413**	**0.01413**	**0.01413**
May	31	**0.01436**	-0.00108	0.00569	0.00026	0.00012	**0.01329**	**0.02006**	**0.01463**	**0.01449**	**0.01898**	**0.01355**	**0.01341**
June	30	**0.01436**	-0.00168	0.00851	0.00431	0.00200	**0.01268**	**0.02288**	**0.01867**	**0.01636**	**0.02119**	**0.01699**	**0.01468**
July	31	**0.01436**	-0.00230	0.01627	0.00765	0.00355	**0.01206**	**0.03064**	**0.02201**	**0.01792**	**0.02834**	**0.01971**	**0.01561**
Aug	31	**0.01436**	-0.00187	0.01677	0.00261	0.00121	**0.01249**	**0.03114**	**0.01698**	**0.01558**	**0.02926**	**0.01510**	**0.01370**
Sept	30	**0.01436**	-0.00105	0.01083	0.00161	0.00075	**0.01332**	**0.02520**	**0.01597**	**0.01511**	**0.02415**	**0.01493**	**0.01406**
Oct	31	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Nov	30	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Dec	31	**0**	-0.00002	0	0	0	**-0.00002**	**0**	**0**	**0**	**-0.00002**	**-0.00002**	**-0.00002**
Average Annual (SS)		**0.00718**	-0.00069	0.00484	0.00137	0.00473	**0.00649**	**0.01202**	**0.00855**	**0.00782**	**0.01133**	**0.00786**	**0.00713**

Note. Combined recharge rates in areas that have overlapping land use types (Department of Revenue, 2010) are used in the model; however, if zones are distinguished by only one land use, the recharge rate calculated for that zone is used. All areas of the model receive diffuse canal recharge (R_{CAN}), and are combined with the designated land use recharge. In areas of no land use designation the diffuse canal recharge is applied.

Table B-10. Calculated recharge values for land use and irrigation types used for model input in the 25- and 50-year models to simulate stress periods.

		Recharge Zones					Combined Recharge zones						
	Days	R_{CAN}	R_{URB}	R_{FLD}	R_{SPR}	R_{PIV}	$R_{CAN}+R_{URB}$	$R_{CAN}+R_{FLD}$	$R_{CAN}+R_{SPR}$	$R_{CAN}+R_{PIV}$	$RC_{AN}+R_{URB}+R_{FLD}$	$R_{CAN}+R_{URB}+R_{SPR}$	$R_{CAN}+R_{URB}+R_{PIV}$
Jan to Apr	91	0	-0.00002	0	0	0	-0.00002	0	0	0	-0.00002	-0.00002	-0.00002
Apr to Sept	153	0.01436	-0.00137	0.00968	0.00274	0.00127	0.01299	0.02404	0.01710	0.01564	0.02267	0.01573	0
Oct to Jan	122	0	-0.00002	0	0	0	-0.00002	0	0	0	-0.00002	-0.00002	-0.00002

Note. The 25- and 50- year models used transient stress periods of 91 days (no irrigation), 153 days (irrigation), and 122 days (no irrigation).

Table B-11. GW_{in} calculations based on a constructed flow net along the southern boundary of the model.

Flownet	Q low (ft/d)	Q high (ft/d)	Q Ave (ft/d)	w (ft)	b (ft)	A (ft^2)	Δh (ft)	L (ft)	i	K low (ft/d)	K high (ft/d)	T low (ft^2/d)	T high (ft^2/d)
FT1 (50%)	404,761	8095221	**4,249,991**	5696	200	1139200	100	5629	0.017765145	40	800	8000	160000
FT2	793,799	15875989	**8,334,894**	6145	200	1229000	100	6193	0.016147263	40	800	8000	160000
FT3	706,548	12339708	**6,523,128**	6140	200	1228000	100	6170	0.016207455	35.5	620	7100	124000
FT4	605,600	8074672	**4,340,136**	6380	200	1276000	100	6321	0.015820282	30	400	6000	80000
FT5	801,933	15794408	**8,298,170**	7425	200	1485000	100	7296	0.01370614	39.4	776	7880	155200
FT6	730,375	13250522	**6,990,448**	8990	200	1798000	100	9010	0.011098779	36.6	664	7320	132800

Note. Q, groundwater discharge; w, flow tube width; b, saturated flow tube thickness, A, flow tube cross-sectional area; Δh, flow tube change in head; L, flow tube length; i, flow tube gradient (unitless); K, hydraulic conductivity; T, transmissivity. The estimated range for hydraulic conductivity from literary reviews and aquifer testing for this study was 30-400 ft/d in the Tertiary sediments (K_T) and 40-500 in the Quaternary sediments (K_Q). Low and high conductivities were determined by the percentage of the area mapped as Quaternary and Tertiary sediments.

Formulas:
Discharge (Q) = hydraulic conductivity (K) x gradient (i) x area (A)
Area (A) = width (w) x thickness (b)
Gradient (i) = change in head (Δh) / length (L)

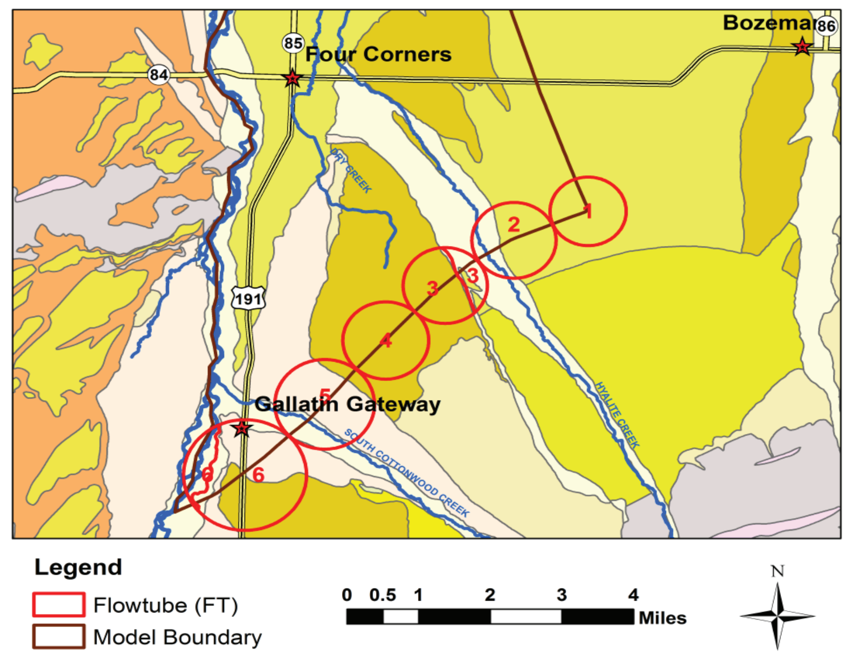

Table B-12. GW_{in} calculations based on a constructed flow net along the southern boundary of the model for Scenario 1.

Flownet	Q low (ft/d)	Q high (ft/d)	w (ft)	b (ft)	A (ft^2)	Δh (ft)	L (ft)	i	K low (ft/d)	K high (ft/d)	T low (ft^2/d)	T high (ft^2/d)
FT1	576,000	7,200,000	4,953	180	891,540	80	4,953	0.016	40	500	8,000	100,000
FT2	576,000	7,200,000	4,962	180	893,160	80	4,962	0.016	40	500	8,000	100,000
FT3	432,000	5,760,000	4,438	180	798,840	80	4,438	0.018	30	400	6,000	80,000
FT4	432,000	5,760,000	3,445	180	620,100	80	3,445	0.023	30	400	6,000	80,000
FT5	432,000	5,760,000	3,054	180	549,720	80	3,054	0.026	30	400	6,000	80,000
FT6	576,000	7,200,000	2,906	180	523,080	80	2,906	0.028	40	500	8,000	100,000
FT7	576,000	7,200,000	3,748	180	674,640	80	3,748	0.021	40	500	8,000	100,000
FT8	576,000	7,200,000	5,713	180	1,028,340	80	5,713	0.014	40	500	8,000	100,000

Note. Q, groundwater discharge; w, flow tube width; b, saturated flow tube thickness, A, flow tube cross-sectional area; Δh, flow tube change in head; L, flow tube length; i, flow tube gradient (unitless); K, hydraulic conductivity; T, transmissivity. The estimated range for hydraulic conductivity from literary reviews and aquifer testing for this study was 30-400 ft/d in the Tertiary sediments (K_T) and 40-500 in the Quaternary sediments (K_Q). Low and high conductivities were determined by the percentage of the area mapped as Quaternary and Tertiary sediments.

Formulas:
Discharge (Q) = hydraulic conductivity (K) x gradient (i) x area (A)
Area (A) = width (w) x thickness (b)
Gradient (i) = change in head (Δh) / length (L)

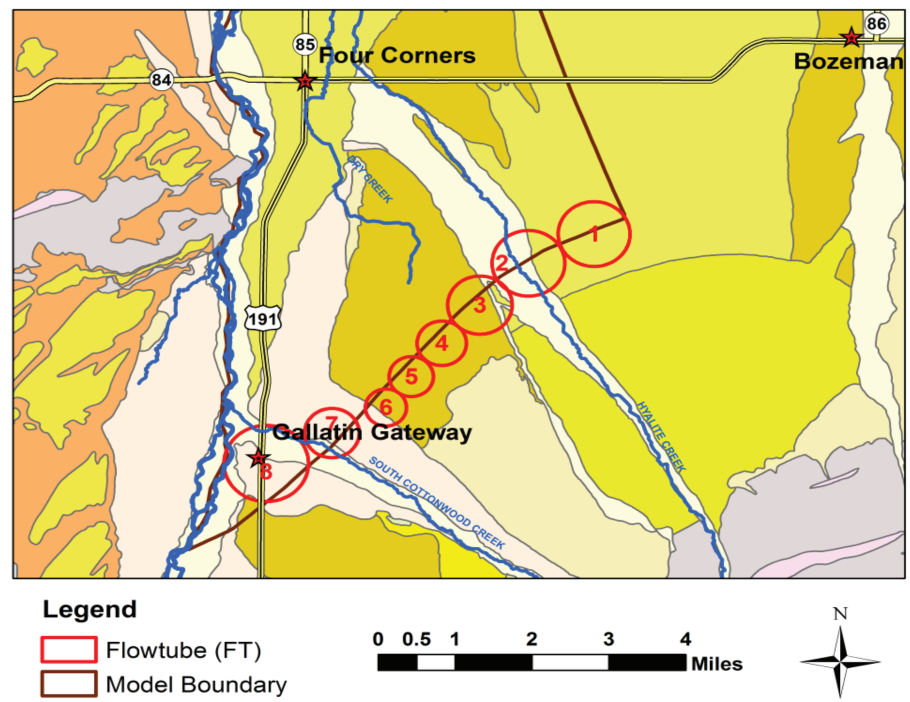

Table B-13. Pumping and injection schedule for ASR Scenario (Scenario 4)

Month	Withdrawal (ft^3/d)	Injection (ft^3/d)
Jan	-358	0
Feb	-358	0
Mar	-358	0
Apr	-19,401	39,739
May	-19,401	39,739
June	-19,401	39,739
July	-19,401	0
Aug	-19,401	0
Sept	-19,401	0
Oct	-358	0
Nov	-358	0
Dec	-358	0