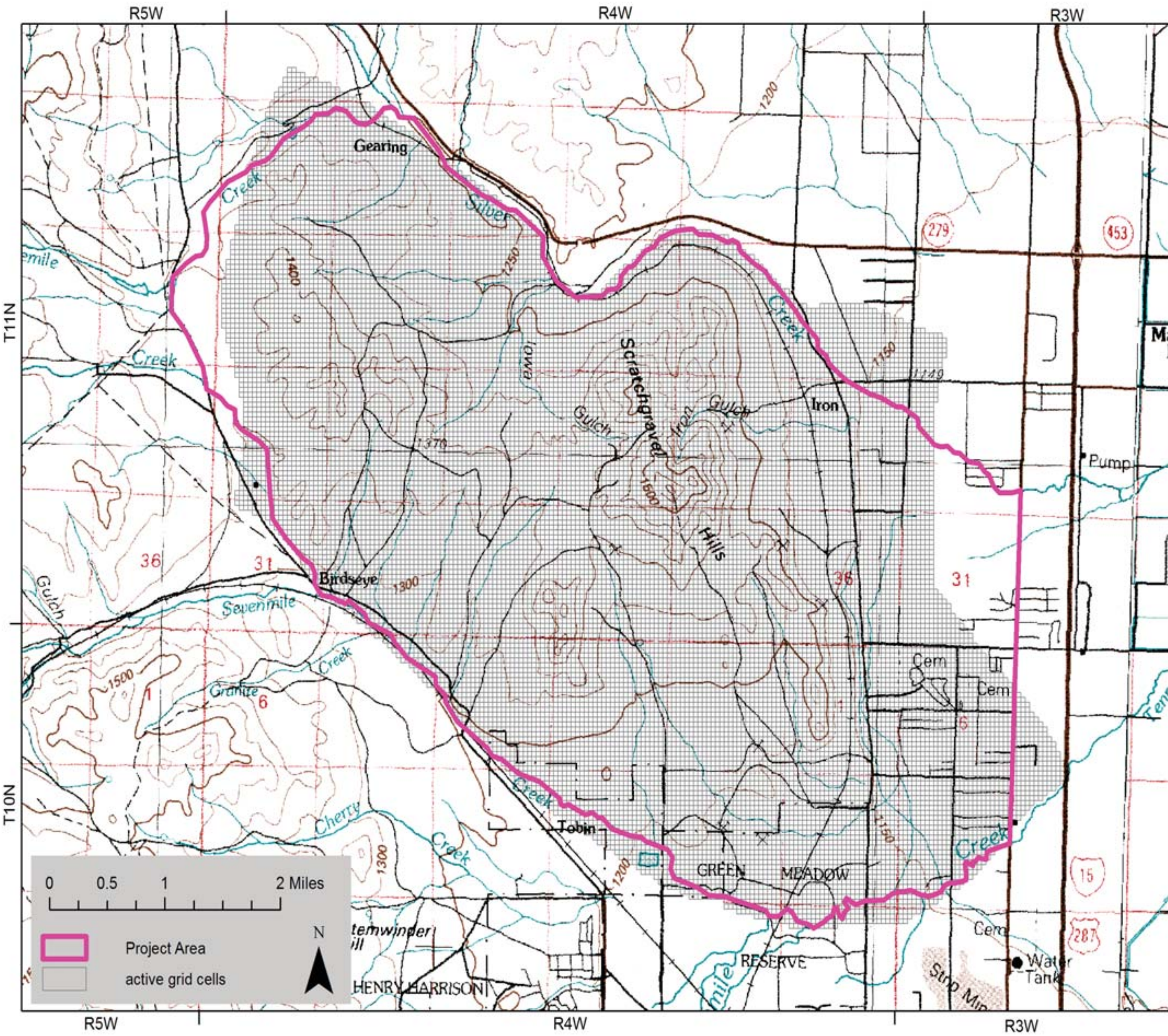
HYDROGEOLOGIC INVESTIGATION OF THE SCRATCHGRAVEL HILLS STUDY AREA, LEWIS AND CLARK COUNTY, MONTANA GROUNDWATER MODELING REPORT



Julie A. Butler, Andrew L. Bobst, and Kirk B. Waren
Montana Bureau of Mines and Geology
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Open-File Report 643
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GROUNDWATER MODELING REPORT

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PREFACE

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

The final products of the Scratchgravel Hills study include:

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

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

- A collection of stand-alone chapters are presented as a Technical Data Report that provides detailed data and information about study components, such as aquifer tests and analyses. This report provides the technical foundation for the Interpretive and Modeling reports.

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

ABSTRACT

A groundwater flow model was developed for the Scratchgravel Hills Groundwater Investigation. This model was operated in both steady-state and transient modes. The primary modeling objective was to predict impacts of potential future groundwater withdrawals. Due to ongoing development, particularly a proposed high-density subdivision known as Cornerstone Estates, area residents became concerned about the long-term capacity of aquifers to supply water within the Scratchgravel Hills.

MODFLOW-2000 was used as the modeling code, while GMS served as the graphical user interface. The domain of the three-dimensional finite-difference model encompassed the study area and consisted of two layers. The model design was derived from analysis of groundwater and surface-water monitoring, aquifer tests, water budget components, and well logs. Constant-head and no-flow boundary conditions bordered the model grid, while drains and injection wells were used within the grid to represent alluvial drainages and canal seepage, respectively. Recharge was applied aerially in areas where precipitation and/or irrigation water infiltrates to groundwater.

In the steady-state version of the model, pilot point parameter estimation and manual trial-and-error were used to estimate hydraulic conductivity (K) values, which produced hydraulic heads similar to observed water levels (i.e., calibration targets). The resulting K distribution and water budget were consistent with the conceptual model. The resulting array of head values had an RMS error of 7.7 ft, which represents about 1% of the modeled groundwater elevation range (750 ft).

The transient version of the model was used to simulate time-dependent stresses, such as seasonal irrigation activities. It was calibrated to 13 months of recently collected data. Calibration was conducted by adjusting storativity (S) values until observed water-level fluctuations were reasonably replicated by the model. The calibration resulted in S values of 0.01 in the bedrock aquifers, 0.05 near the interface between the bedrock and unconsolidated sediments, and 0.08 throughout most of the unconsolidated sediments.

Predictive scenarios were simulated following calibration and sensitivity analysis. The proposed Cornerstone Estates Subdivision was the focus area. Results suggested that if wells in the granitic bedrock were used to supply water for a development similar to that originally proposed (~0.4 acre lots), widespread drawdown would occur. Model results also indicated that using bedrock wells for the currently proposed development (10 acre lots) would produce minimal drawdown. Furthermore, use of a single public water supply (PWS) well located in the unconsolidated sediments resulted in less drawdown than pumping single-home domestic wells, most of which were completed in the granite aquifer; this difference was primarily due to the selective placement of the PWS well in a more productive aquifer.

The model results showed that groundwater availability in the bedrock aquifer system is variable and can be very limited, particularly in the granitic core of the Scratchgravel Hills. If future subdivisions are developed with lot sizes of less than 10 acres, establishing minimum groundwater-level targets would aid management of well withdrawal rates.

INTRODUCTION

General Setting

The Scratchgravel Hills study area is located approximately 3 miles northwest of Helena, Montana, and west of the Helena Valley (figs. 1, 2). The study area covers approximately 20 square miles. The study area boundary follows Tenmile Creek, Sevenmile Creek, and Park Creek on the south, Silver Creek and Threemile Creek on the north, Birdseye Road on the west, and Montana Avenue on the east.

Development in this area has been controversial at least since the subdivision of Green Meadow Ranch in 1972, which included 2,900 acres of 10-acre tracts. This subdivision precipitated the Green Meadow Study by Lewis and Clark County (1977), which recommended a minimum lot size of 10 acres per dwelling unless specific criteria for septic systems, building sites, and water availability were met. If those criteria were indeed met, the recommended minimum lot size was 2 acres per dwelling. The Green Meadow Study also recommended the use of community sewage systems and community water systems.

In recent years, subdivisions have been developed in the Scratchgravel Hills study area, particularly on the western edge of the Helena Valley, outside the area covered by the Green Meadow Study. Within the Green Meadow Study Area, the Cornerstone Estates subdivision was proposed in 2005 for the area southeast of the junction of Head Lane and Franklin Mine Road (the former Franklin Mine area; fig. 2). Originally, up to 800 homes on 320 acres (0.4 acres per dwelling) were proposed

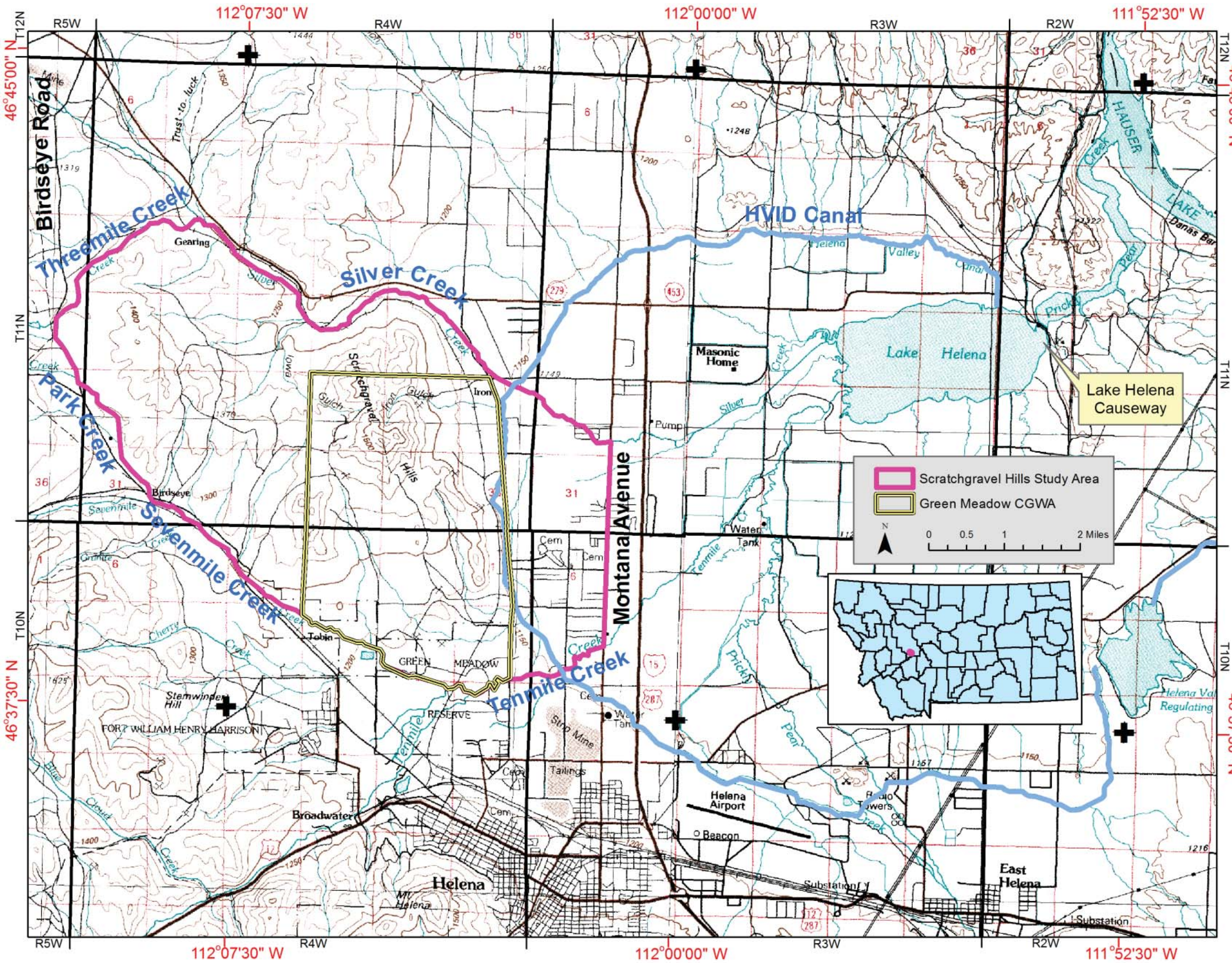


Figure 1. The Scratchgravel Hills study area is located north and west of Helena, on the western edge of the Helena Valley. The Green Meadow Controlled Groundwater Area is located in the central portion of the study area.

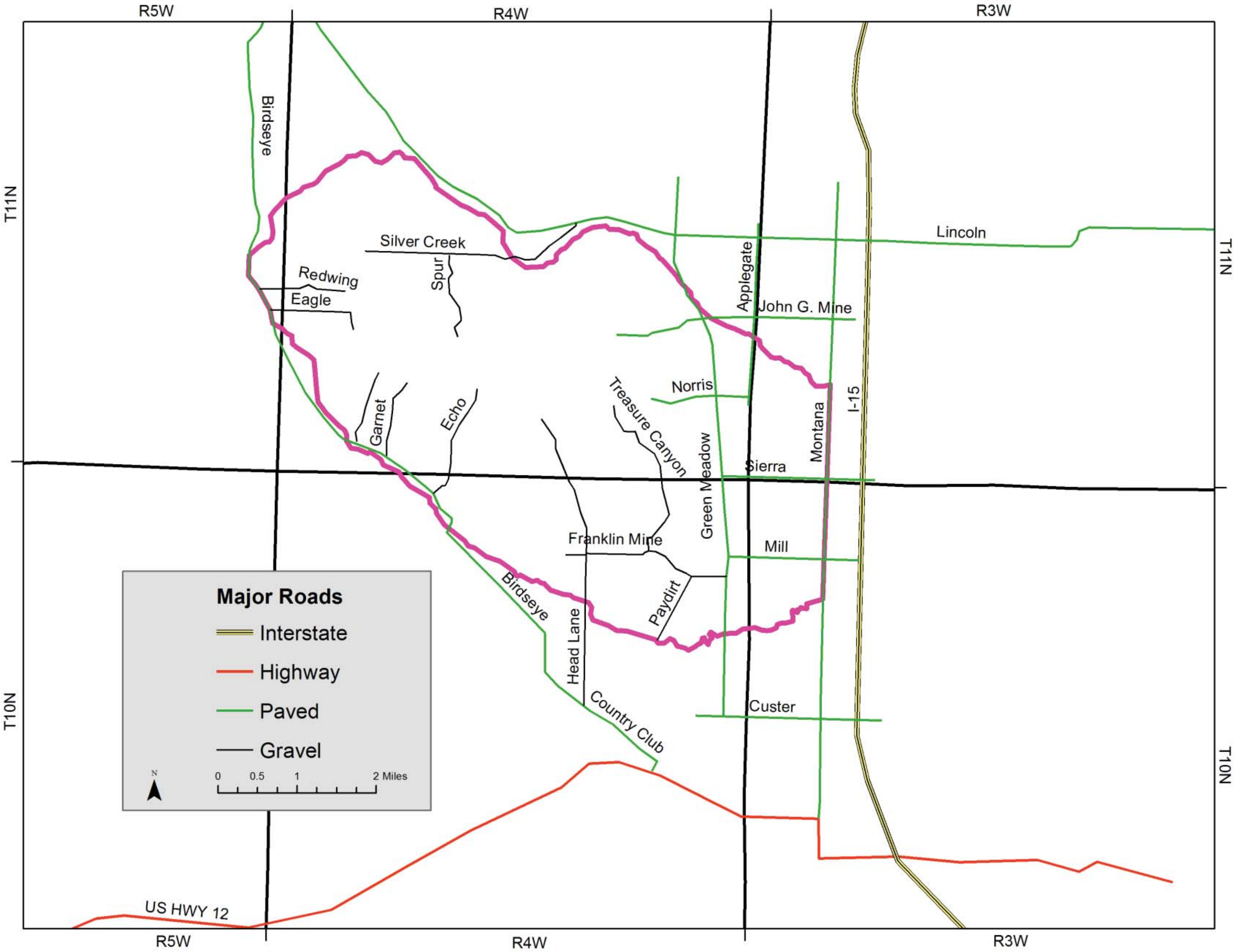


Figure 2. Major roads in and near the Scratchgravel Hills study area.

for the subdivision, as well as community water and sewage. This application has since been withdrawn and a subdivision with 10-acre lots is now proposed. This lower density development would likely use individual wells and septic systems. In 2010, zoning requirements in this area were changed to require a 10-acre minimum lot size.

Of the 1,910 lots within the Scratchgravel Hills study area in 2009, 79.3 percent were less than 10 acres (NRIS, 2009; fig. 3); however, because they are small, these lots constituted only 17.7 percent of the total study area. Analysis of aerial photographs indicated that between 1995 and 2009, the number of dwellings within the study area increased from 1,285 to 1,608 (fig. 4). Many of these homes use individual water wells and septic systems. Because of this ongoing development, in particular the proposal for the Cornerstone Estates subdivision, there are concerns regarding both the long-term capacity of area aquifers to supply water and the potential for aquifer contamination from septic effluent. These issues prompted the Montana Department of Natural Resources Conservation (DNRC) to designate the Green Meadow Temporary Controlled Groundwater Area (CGWA) in April 2008. The CGWA is focused on the central granitic core of the Scratchgravel Hills (figs. 1, 5).

Climate

The Scratchgravel Hills study area has a semi-arid climate, typical for areas east of the Continental Divide in Montana. It is generally characterized by cold winters, mild summers, and low precipitation (Kendy and Tresch, 1996).

Weather data have been recorded at the Helena Weather Service Office station (altitude 3,830 ft)

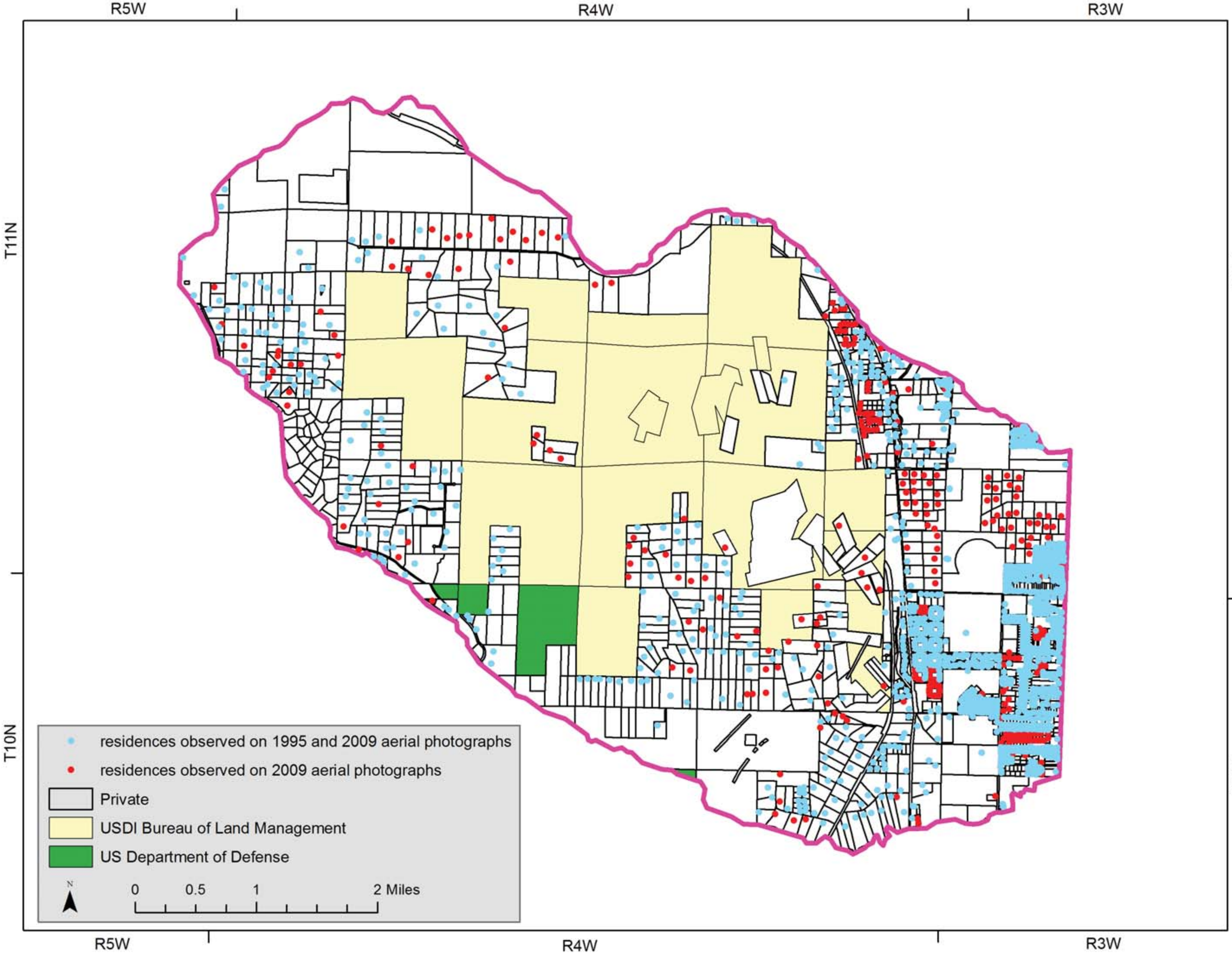


Figure 3. The number of homes within the Scratchgravel Hills study area increased from 1,285 to 1,608 between 1995 and 2009. The core of the study area is dominated by Federal lands. The rest of the study area is predominantly private land, much of which has been subdivided. Lot sizes in most of the area are greater than 10 acres. Smaller lots are found on the eastern side, in the Helena Valley.

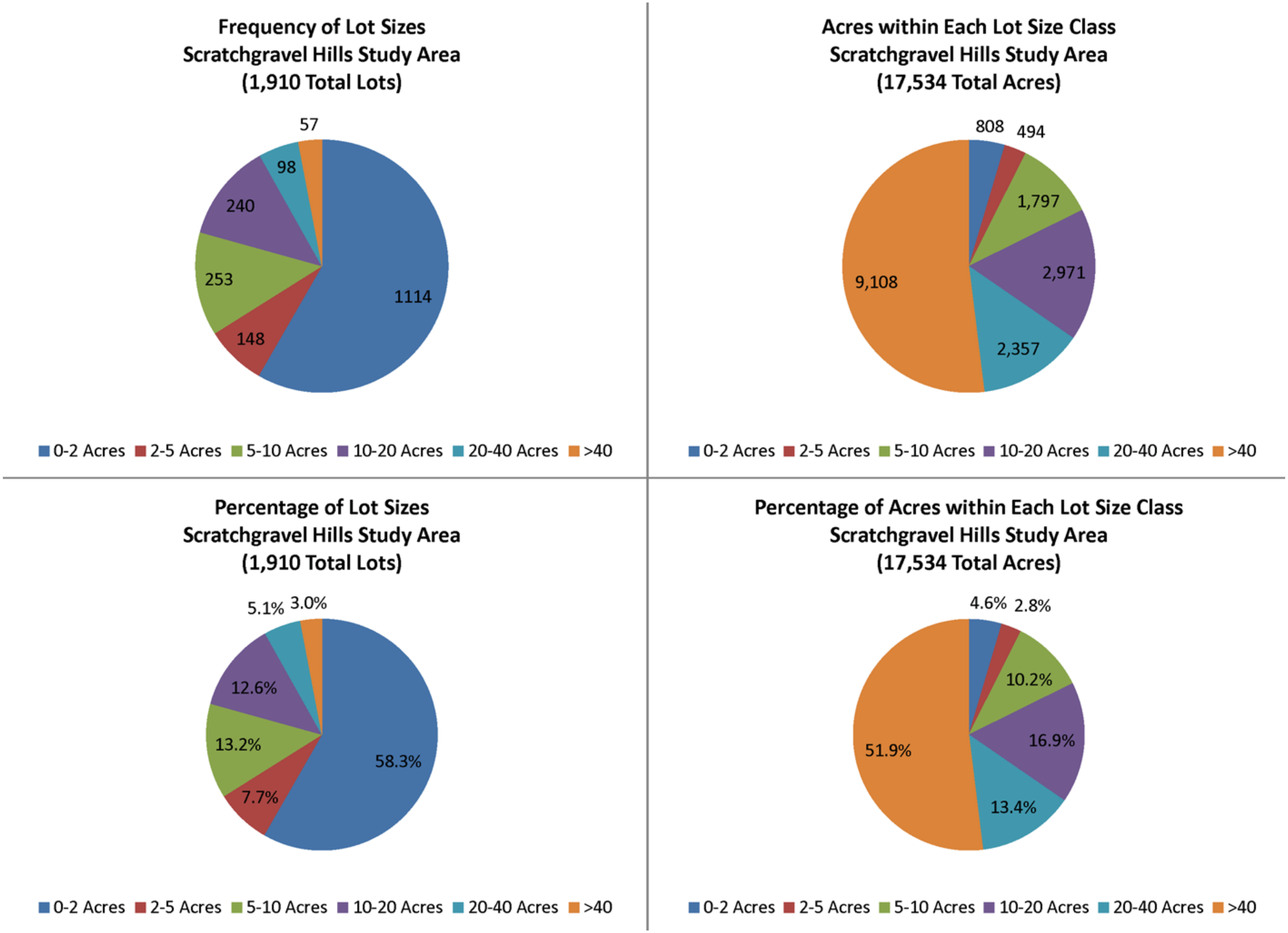


Figure 4. Cadastral data for the Scratchgravel Hills study area (NRIS, 2009; http://nris.mt.gov/gis) indicates that lots less than 10 acres make up 79.3 percent of the lots, and 17.7 percent of the study area.

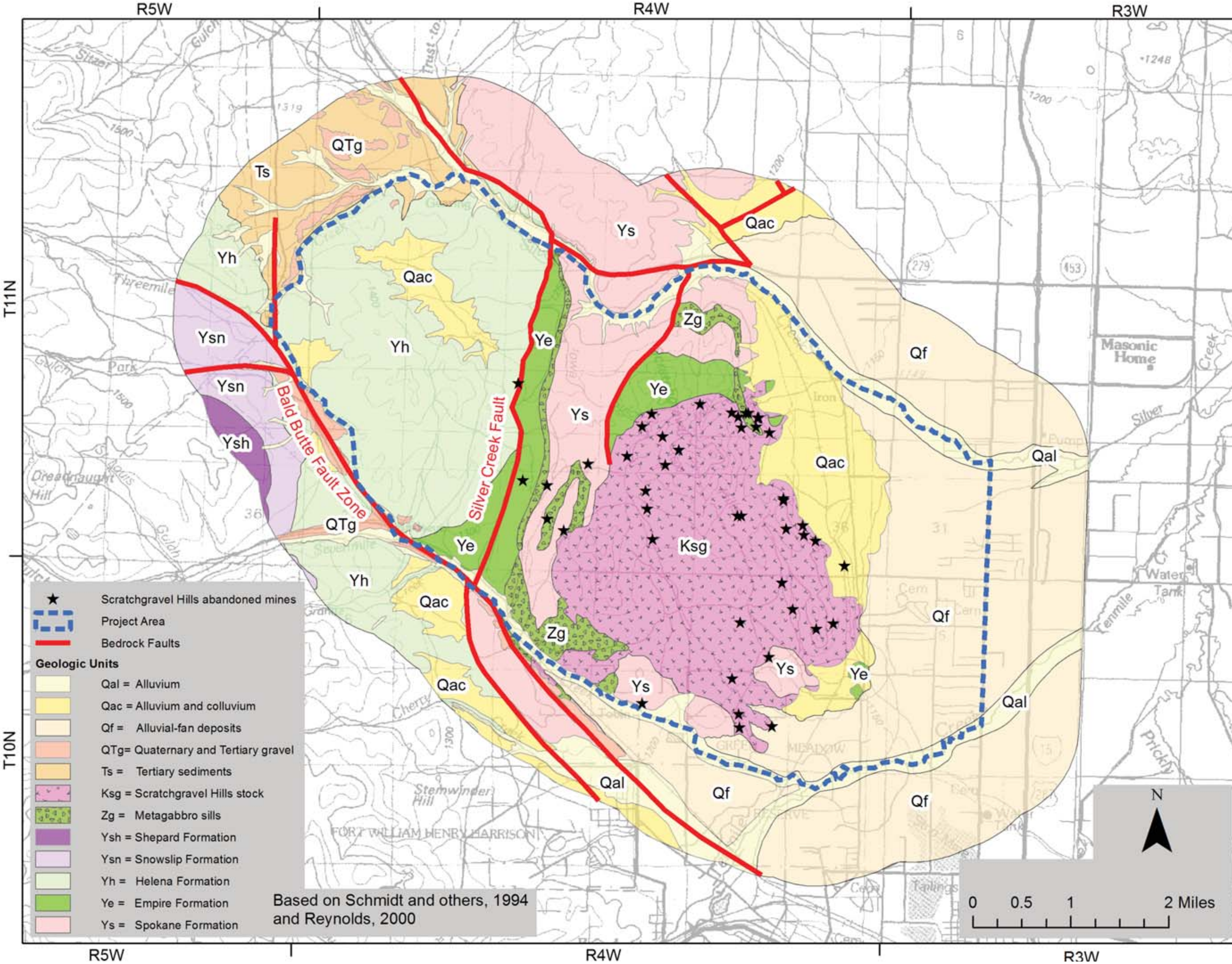


Figure 5. The core of the Scratchgravel Hills is a granitic stock. Argillite bedrock of the Spokane and Empire Formations outcrops to the west of the stock. The Helena Formation overlies the argillite and is found in the western portion of the study area. Metagabbro sills are found in bands within the Proterozoic units. The Helena Valley aquifer, rich in sand and gravel, is located in the eastern portion of the study area. Quaternary alluvium is found along modern streams and overlies bedrock. Several bedrock faults are also present in the study area (geologic map from Schmidt and others, 1994).

since 1893, the longest record in the area (NOAA, 2011). From 1893 through 2010 the mean annual temperature at this station was 43.9°F. The coldest temperature recorded at this station was -42°F, and the warmest was 105°F. January had the coldest average temperature (20.6°F) and July had the warmest average temperature (68.3°F). Over the same period of record, the average annual precipitation at this station was 11.87 in. On average the most precipitation occurred in June (2.12 in) and the least in February (0.46 in). During the period 1990 through 2010, precipitation was cumulatively 18.37 in below average. However, 1993 was a particularly wet year; that year's precipitation was 6.94 in above average, while the standard deviation of the entire record was 3.0 in (fig. 6). The amount of precipitation generally correlates with elevation, with higher elevations receiving higher precipitation rates. Average annual precipitation within the Scratchgravel Hills study area ranges from under 10 in/yr to over 16 in/yr (P. Farnes, written commun., 2010; fig. 6A).

Physiography

The Scratchgravel Hills study area is in the Northern Rocky Mountains physiographic province, on the boundary between the Helena Valley and the mountains that border it to the west. The relatively flat alluvial plain of the Helena Valley is on the eastern side of the study area, and extends to the east. The rest of the Scratchgravel Hills study area is semi-mountainous terrain (fig. 7). The highest altitude in the study area is the peak of the Scratchgravel Hills, at 5,252 ft above mean sea level (amsl). The lowest point is along Silver Creek at Montana Avenue, at 3,700 ft amsl. Surface water in this area drains to the Missouri River via Silver Creek and Tenmile Creek. The Missouri River (in the form of Hauser Lake) is approximately 10 miles east of the study area.

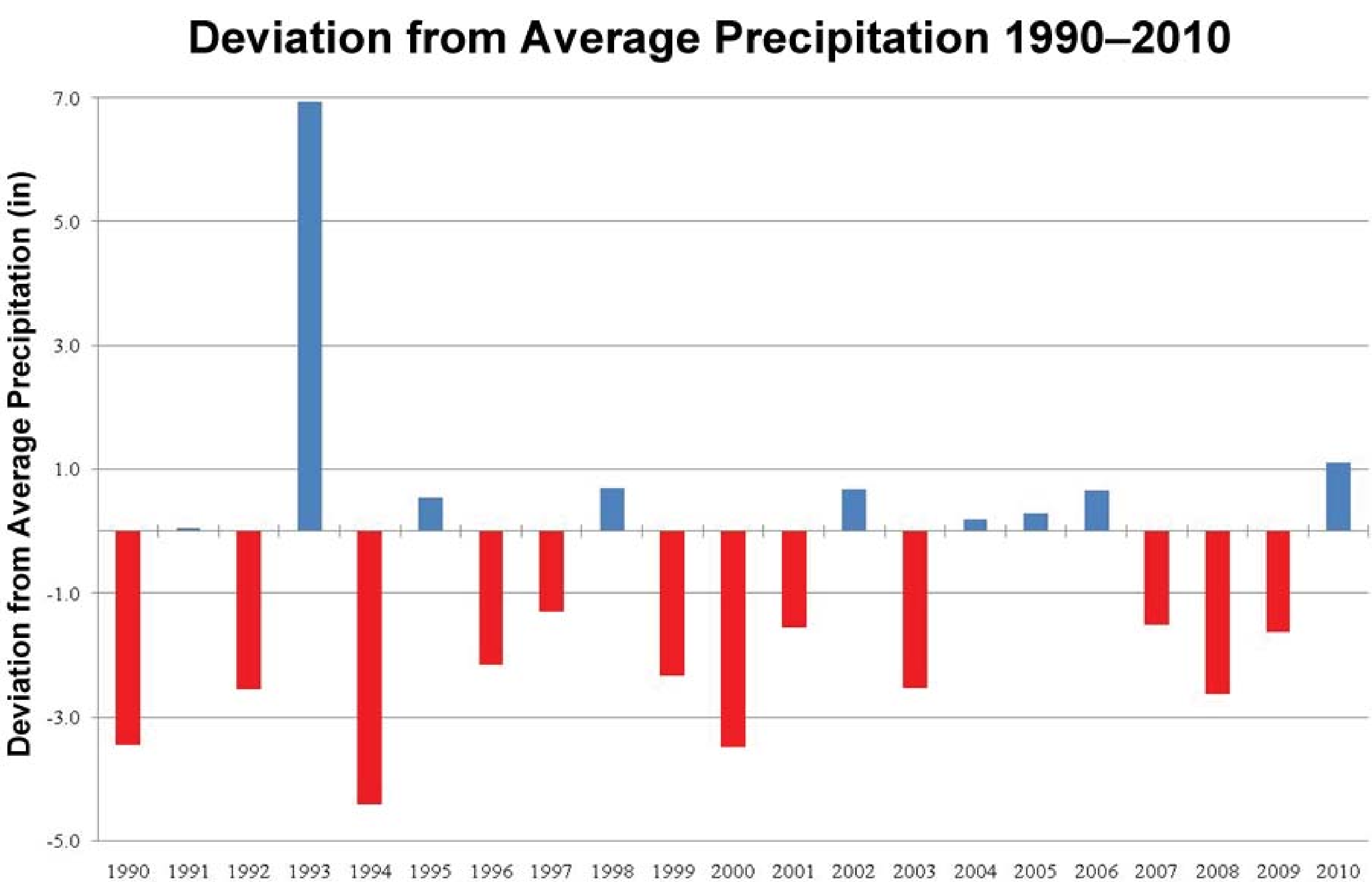


Figure 6. Annual precipitation data at the Helena Airport Weather Service Off ce (HLN–244055; Helena WSO) from 1990 to 2010 show a cumulative departure from average annual precipitation (11.78 in) of -18.37 in; 1993 was a particularly wet year (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt4055, accessed 6/27/11).

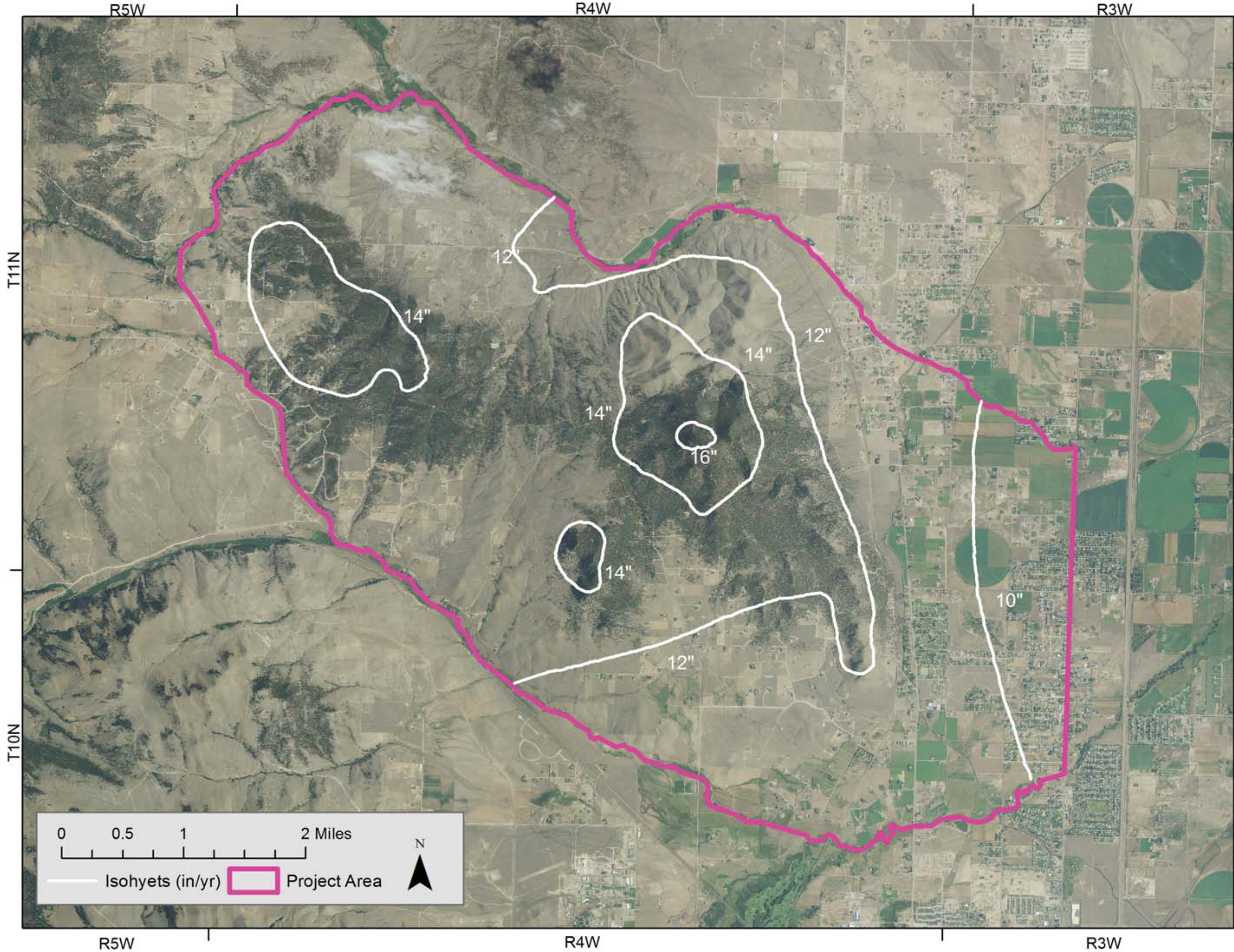


Figure 6A. Average annual precipitation isohytes in the Scratchgravel Hills study area (1970–2000; P. Farnes, written commun., 2010) show that precipitation ranges from less than 10 in. in the Helena Valley to over 16 in. in the hills. The highest precipitation rates occur at the highest elevations.

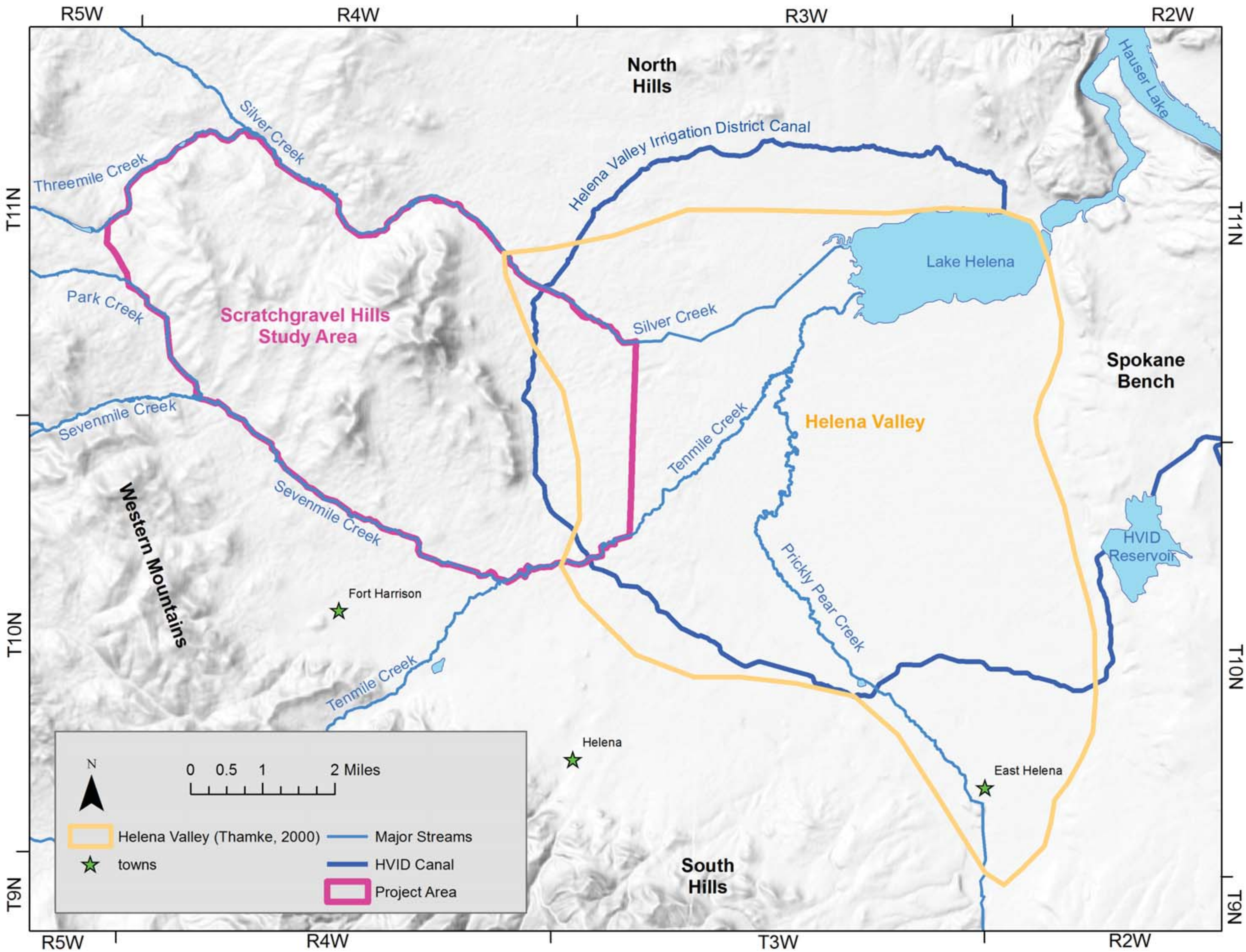


Figure 7. The Scratchgravel Hills study area drains to the Missouri River via Lake Helena. The Continental Divide is located approximately 11 miles to the west. Most of the study area features semi-mountainous terrain; however, the Helena Valley is relatively f at.

Man-Made Features

Hydrogeologically significant man-made features within the Scratchgravel Hills study area include irrigation ditches, irrigated fields, drains, wells, and septic systems. The main source of irrigation water in the Helena Valley is from the Missouri River, by way of the Helena Valley Irrigation District (HVID) Canal (fig. 8). Less irrigation occurs along Silver Creek, Sevenmile Creek, Tenmile Creek, and Threemile Creek. The canals and irrigated fields recharge the underlying groundwater through canal leakage, and through infiltration of water applied to fields in excess of crop demand. Drains were installed in the Helena Valley during the installation of the HVID Canal in order to prevent waterlogging the land; the drains limit the altitude to which groundwater may rise. Wells and septic systems are located adjacent to homes (fig. 3). Wells extract water from the aquifer system, while septic systems return a portion of the extracted water to it.

Model Objectives

The primary objective of groundwater modeling in the Scratchgravel Hills study area was to evaluate impacts of future subdivision development on groundwater levels, most notably in terms of drawdown extent. The model thus served as a predictive tool. Various scenarios were simulated to examine the effects of pumping from single domestic wells and public water supply wells.

This report provides detailed documentation of the procedures and assumptions inherent in the model and presents the model results. This report is intended to allow the model to be evaluated and used by others. All files needed to operate the groundwater model are posted on the program website (http://www.mbmg.mtech.edu/gwip/), and file details are provided in appendix A. These files 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.

CONCEPTUAL MODEL

A conceptual model is an interpretation or working description of the characteristics and dynamics of the physical groundwater flow system. It is based on the analysis of all available hydrogeologic data for the study area. The conceptual model includes the system's geologic framework, aquifer properties, groundwater flow directions, locations and rates of recharge and discharge, and the locations and hydraulic characteristics of natural boundaries (ASTM, 1995; Mandle, 2002).

Geologic Framework

Schmidt and others (1994; fig. 5) provided detailed descriptions of the geology in the Scratchgravel Hills. Additional descriptions of the geologic units in this area were provided by Reynolds (2000) and Reynolds and Brandt (2005). These data were supplemented with hydrogeologic concepts presented in Thamke (2000).

Water well logs were reviewed to establish hydrogeologic units for the Scratchgravel Hills study area (fig. 9); all of the reviewed logs are in the Ground Water Information Center (GWIC) database. Well logs are required to be submitted by water well drillers upon completion of each well (MCA 85-2-516) and include well location, lithologic descriptions, and well-completion details. The well logs were reviewed for such attributes as total depth, depth to bedrock, depth to water, and lithology. A total of 506 logs were available for wells completed in bedrock, and all 506 were reviewed. More than 1,500 well logs were available for the area along the western edge of the alluvial Helena Valley; about 200 of these well logs were used to characterize the unconsolidated sediments. Initially, logs for wells drilled to at least 200 ft were considered; additional well logs for wells of shallower depths were later reviewed in areas where only shallower wells were present. Lithologic descriptions on each well log were compared with surrounding well logs, which aided in deducing the most likely geologic formation present. Additionally, the lithologic descriptions were compared with geologic maps to determine whether the lithologies agreed with the mapped geologic formations. Field observations, including drill cuttings and field reconnaissance, also aided in well log analysis.

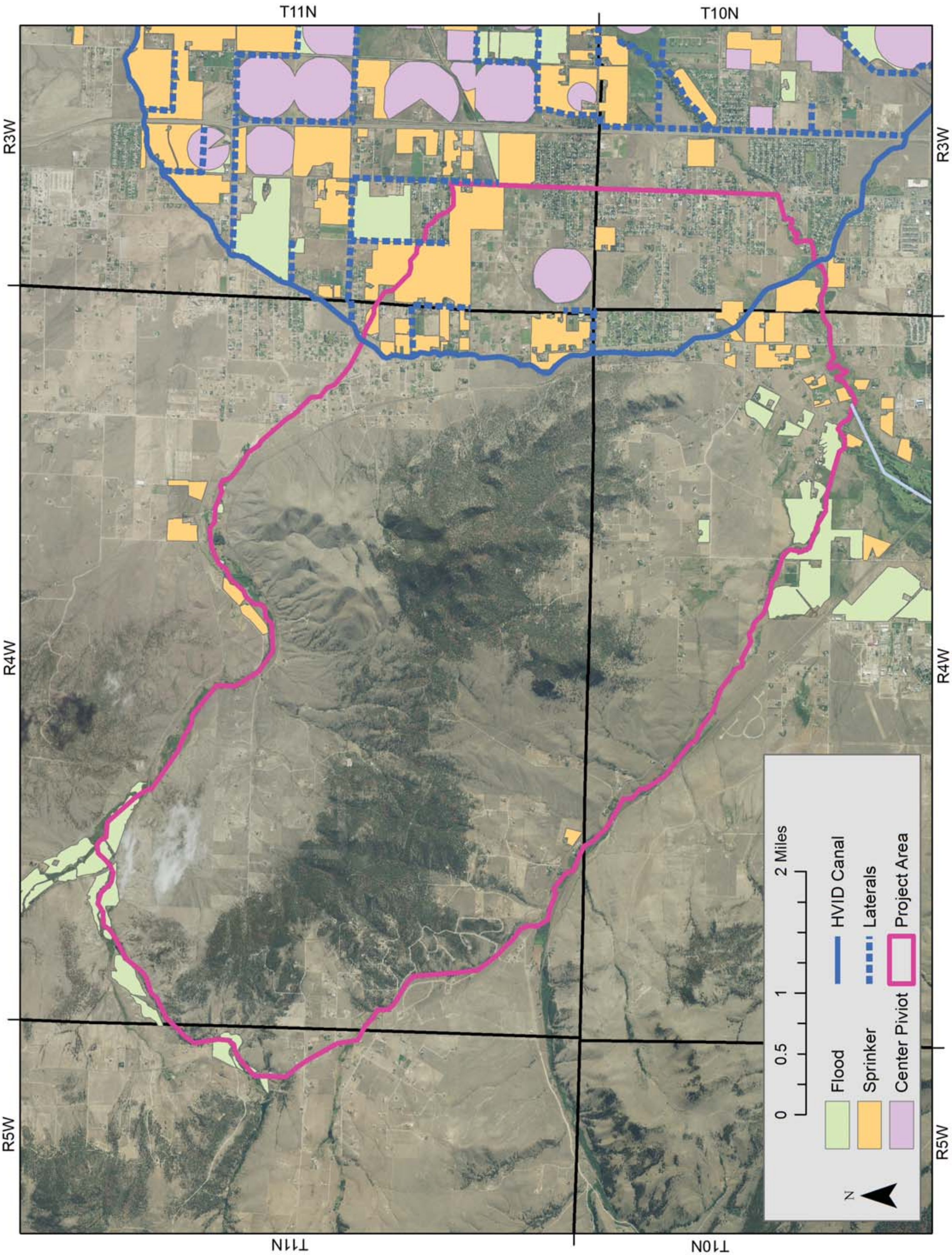


Figure 8. Irrigation canals and irrigated fields along the east side of the Scratchgravel Hills study area recharge alluvial and valley-fill groundwater with water diverted from the Missouri River and from smaller streams (fields from Montana Department of Revenue, 2009; Canals and laterals from HVID, written commun., 2009).

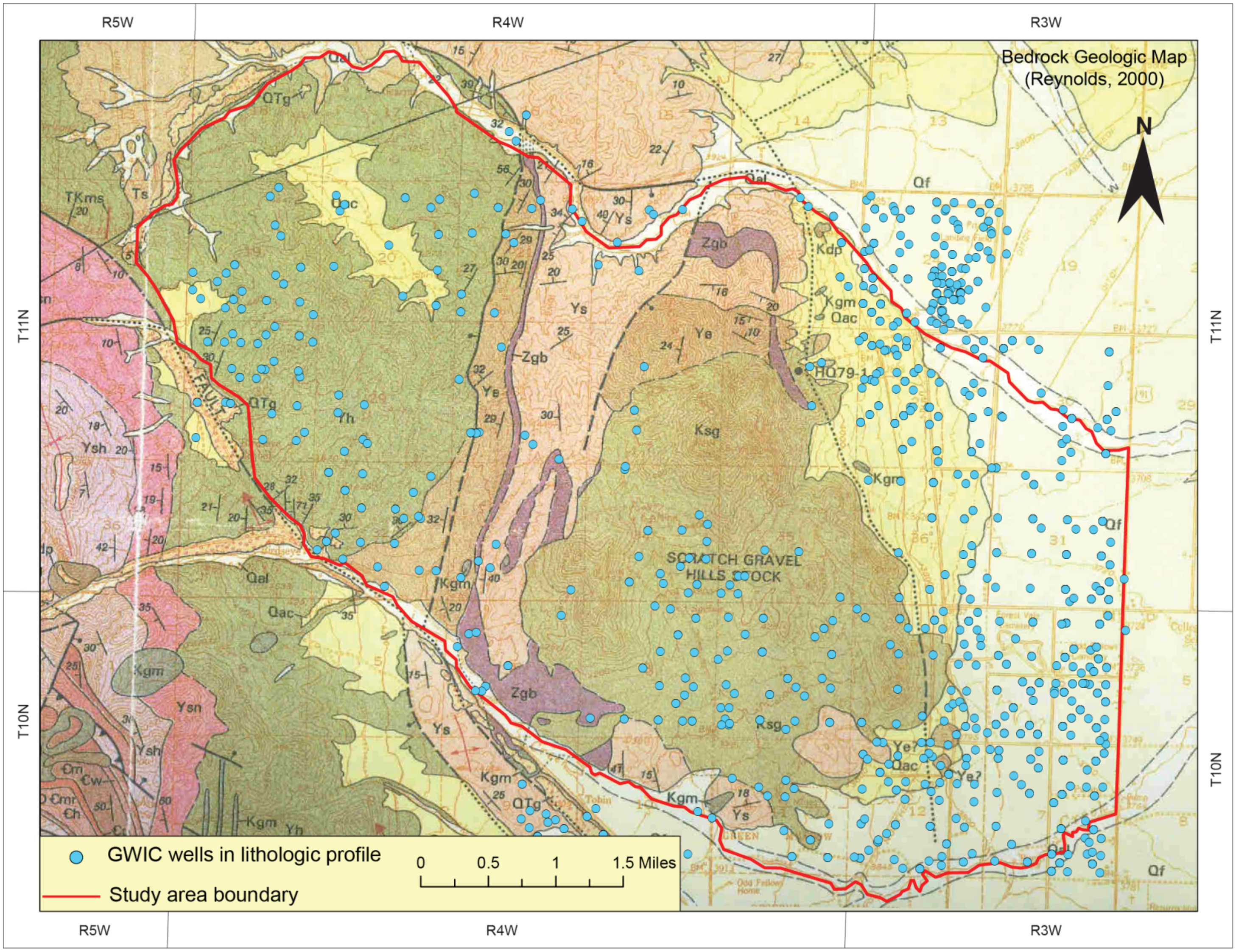


Figure 9. Location of wells with GWIC logs that were used in the lithologic analysis.

The well logs within the Scratchgravel Hills indicated very shallow bedrock, which was consistent with field observations where bedrock was often seen exposed at the surface. Regarding bedrock composition, there was general agreement between the logs and geologic maps. Due to certain lithologies being shared among different formations (e.g., argillite, limestone), the specific geologic formation could not always be discerned from a given log's lithologic description.

Hydrogeologic Units

Significant formations in the study area were grouped into the following five hydrogeologic units or aquifers: (1) unconsolidated alluvium and colluvium of the Helena Valley aquifer; (2) the Scratchgravel Hills Stock (granite); (3) metagabbro; (4) the Helena Formation; and (5) argillite bedrock (fig. 5).

- *Unconsolidated Sediments (Qac, Qf, Qal):* Unconsolidated sediments cover the bedrock along streams and in the Helena Valley. These relatively young sediments include Tertiary and Quaternary colluvium and alluvium. The colluvium at the surface is generally thin and unsaturated. The alluvium is composed of sand, gravel, silt, and clay. The units are typically much more productive than the bedrock aquifers. Within the Helena Valley, these materials are referred to as the Helena Valley aquifer. The surficial portion of the Helena Valley aquifer is Quaternary in age; however, the deeper portion of the Helena Valley aquifer is Tertiary. Briar and Madison (1992) reported that the Quaternary and Tertiary deposits of the Helena Valley aquifer are indistinguishable in well logs. The unconsolidated materials in the Helena Valley are up to 6,000 ft thick (Noble and others, 1982). Along streams, the unconsolidated materials are typically Quaternary in age. On the western edge of the Helena Valley, the logs show that bedrock underlies the unconsolidated Helena Valley sediments at increasing depth from west to east. At the bedrock–colluvium interface, depth to bedrock ranges from 3 to 50 ft. Along the eastern border of the study area, where the unconsolidated sediments are relatively thick, bedrock is reported at depths as shallow as 90 ft, but it is not encountered in some wells deeper than 200 ft.

- *Scratchgravel Hills Stock (Kg):* In the Middle Cretaceous the Scratchgravel Hills Stock intruded through the east-central portion of the study area (Schmidt and others, 1994). The Stock is a quartz monzonite, which is similar to granite but contains less quartz. It is commonly described by drillers and others as granite, and it will be referred to as granite in this report. The formation is central to the Scratchgravel Hills and forms the core of the Green Meadow CGWA. It stands out as the formation of highest topographic relief in the study area and is variably fractured.
- *Metagabbro (Zgb):* The units of the Belt Supergroup (see below) were intruded by gabbro sills in the Late Proterozoic. Subsequent metamorphism altered these sills to metagabbro. Relative to the older formations, the extent of the metagabbro is very limited. The gabbro composition includes plagioclase feldspar, augite, and olivine, and trace amounts of quartz. When compared with relatively fine-grained basalt, gabbro is rather coarse grained due to its intrusive slow-cooling formation.
- *Helena Formation (Yh):* The Middle Proterozoic Helena Formation stratigraphically overlies the argillite (see below) and is part of the Belt Supergroup. This formation is primarily composed of cyclic layers of clastics, dolomite, and limestone, with some quartzite beds. It is located in the western portion of the study area. In terms of aquifer types, the Helena Formation is distinguished from the Spokane and Empire Formations by the greater prevalence of carbonates. Carbonates are more susceptible to chemical weathering, which may increase or decrease the secondary porosity of a bedrock aquifer due to the dissolution and re-precipitation of carbonate minerals (e.g., calcite). Where dissolution occurs, the aperture of fractures becomes greater. Where re-precipitation occurs, porosity (both primary and secondary) is decreased.
- *Argillite bedrock (Ys, Ye):* The Middle Proterozoic Spokane and Empire Formations, which are part of the Belt Supergroup, are the oldest rocks in the study area. They are present at the surface in the west-central portion of the study area and as small exposures along the southern and eastern edges of the granite. The two formations are composed primarily of argillite and siltite, and to a lesser extent, limestone and quartz sandstone. These units are often described as "shale" in water well logs and are typically reddish brown or greenish gray in color.
- *Intrusive Contacts:* The contacts between intrusive rocks and older country rocks are an important part of the geologic framework, because they can strongly affect the occurrence and movement of groundwater. When igneous rocks intrude, the country rock is altered, often causing its structure to become denser and less permeable. Similarly, the plutons themselves are often more finely crystalline along their contacts with the country rock (Thamke, 2000). The Scratchgravel Hills contain two types of intrusive bodies that may have such an impact: the Scratchgravel Stock (granite) and the metagabbro sills. The margins of both of these rock types have the potential to impede groundwater flow.
- *Faults:* Within the Scratchgravel Hills study area there are at least two major faults, and likely others that have not been identified (Schmidt and others, 1994; Reynolds, 2000). The Silver Creek Fault runs roughly north–south and is located on the eastern edge of the Helena Formation (fig. 5). Another unnamed fault runs east of and sub-parallel to the Silver Creek Fault and is truncated where it has been

cut by the intruded granite. The Bald Butte Fault Zone passes along the southwestern boundary of the study area, roughly paralleling Sevenmile and Park Creeks. While some geologic maps show the "Iron Gulch Fault" (Stickney, 1987), also known as the Scratchgravel Hills Fault, running along the eastern edge of the Scratchgravel Hills, more recent work by Stickney (2007) shows that this feature is an escarpment produced by erosion rather than faulting. Zones of high secondary permeability can be created within a fracture zone due to shear (i.e., highly fractured rocks); however, at the fault plane where the units slip past each other, the rock can be finely ground and form clay-sized particles (fault gouge) that plug pore spaces and act as a barrier to flow. According to Freeze and Cherry (1979), faults "…can play many roles. Faults that have developed thick zones of sheared and broken rock with little fault gouge may be highly permeable, while those that possess a thin (but continuous) layer of gouge may form almost impermeable barriers."

Groundwater Flow System

The hydrogeologic units within the study area readily exchange water with each other, so they can be treated as one aquifer system, with each unit exhibiting different aquifer properties. In the bedrock aquifers, groundwater moves through and is extracted from fractures. These units have little primary porosity, but they are variably fractured and may have significant secondary permeability (Thamke, 2000). The fractures are extensive enough that when the bedrock aquifer is viewed at the level of the study area, it can be treated as equivalent porous media. Locally, the geometry of fractures may strongly affect groundwater flow and aquifer properties. The productivity of a well completed in bedrock is mainly a function of the number of saturated fractures encountered, the aperture of those fractures, and their connectivity to the larger system.

Groundwater flow in the Scratchgravel Hills is mainly a localized, radial flow system. Groundwater recharge to most of the study area is primarily from local precipitation in the Scratchgravel Hills. The potentiometric map (fig. 10) indicates some inflow of groundwater from the bedrock west of the study area; however, groundwater flow is predominantly radial and moves from the core of the Scratchgravel Hills through the bedrock aquifers to the alluvial creek drainages and to the Helena Valley aquifer.

Silver Creek, Sevenmile Creek, and Tenmile Creek are perennial streams that border the study area. These creeks are primarily losing streams, and so infiltration from the stream beds recharges the groundwater system. A few ditches are diverted off of these creeks and are used for irrigation in summer months. The HVID Canal runs north–south along the western edge of the Helena Valley and services an area between the bedrock–alluvium interface and the eastern edge of the study area. The canal and associated irrigation activities are a significant source of groundwater recharge to the unconsolidated sediments. Estimated groundwater fluxes are provided in the Groundwater Budget section.

Hydrologic Boundaries

The Scratchgravel Hills model domain encompasses almost the entire study area, extending north and south to the creeks that border the Scratchgravel Hills (fig. 11). The study area boundaries on much of the north and south edges were located at alluvial drainages along creeks. Groundwater flow lines parallel these drainages, making them no-flow boundaries (fig. 10).

The eastern edge of the study area is within the Helena Valley aquifer. Groundwater flows in an approximately west-to-east direction near the eastern study area boundary based on the potentiometric surface mapped for this study (fig. 10) and the potentiometric surface of the Helena Valley aquifer as mapped by Briar and Madison (1992).

Some groundwater inflow is expected to enter the study area from the west. However, as the flow lines in figure 10 suggest, the majority of this westerly flow is diverted to the alluvial drainages to the north and south of the bedrock aquifer system.

Aquifer Properties

The U.S. Geological Survey (Briar and Madison, 1992) estimated the effective hydraulic conductivity of the upper part of the Helena Valley aquifer to be approximately 200 ft/d. Other sources of data for aquifer properties in the vicinity of the study

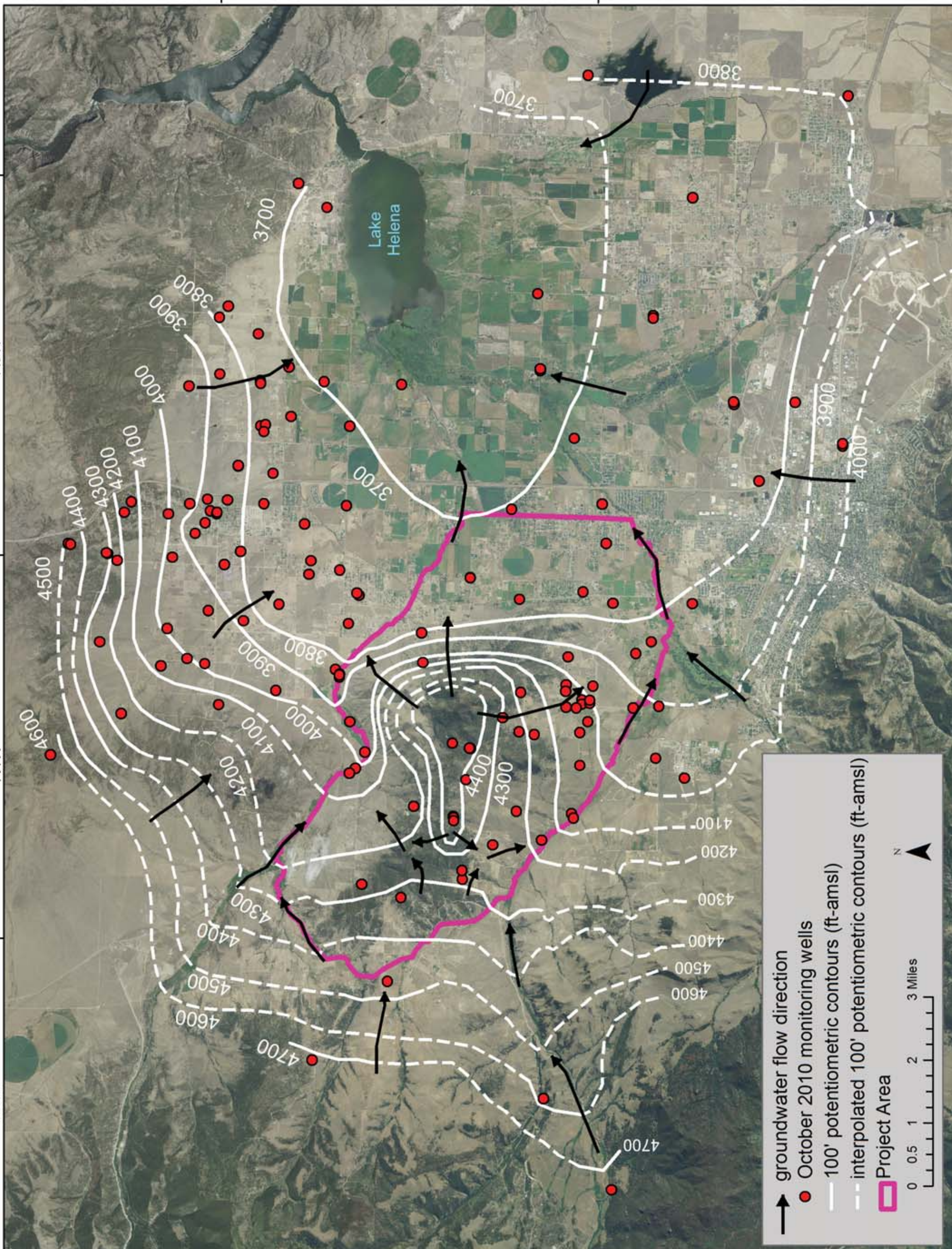


Figure 10. This composite potentiometric surface map from October 2010 shows that groundwater f ow is generally from the hills toward Lake Helena. Local recharge from precipitation and low-permeability bedrock at the top of the Scratchgravel Hills cause a local mound in the potentiometric surface.

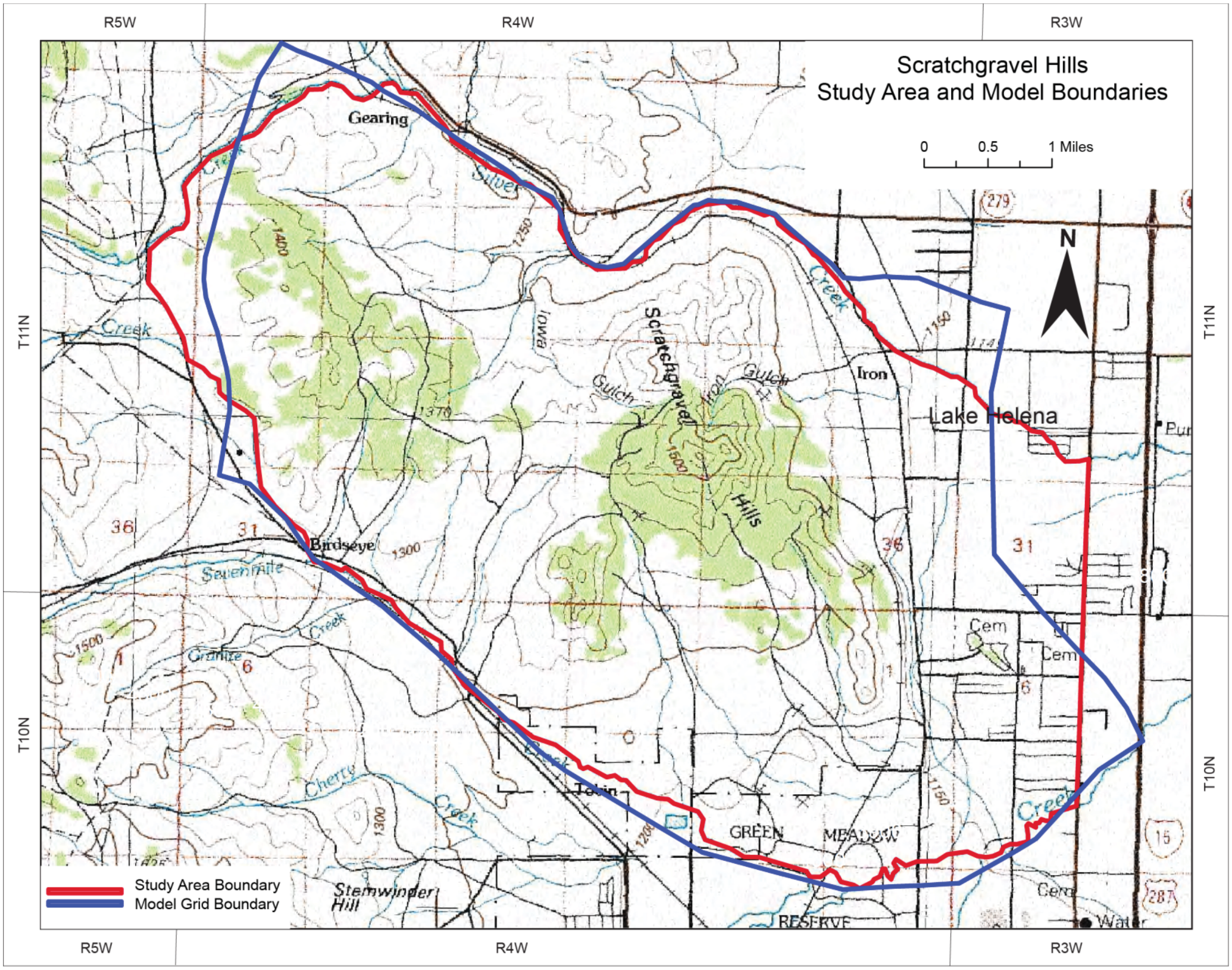


Figure 11. Scratchgravel Hills study area and model boundaries.

area included aquifer test data from reports obtained from DNRC. The reported values were compiled for the North Hills and Scratchgravel GWIP study areas by Patrick Faber (P. Faber, written commun., 2010). Data sources also included aquifer tests conducted as part of this study, previous hydrogeologic reports for the Helena vicinity, and values from similar groundwater studies and flow models in western Montana. Aquifer properties typically generated by aquifer tests are transmissivity (T), hydraulic conductivity (K), and storativity (S). The range of property values exhibited in the aquifer system was evaluated using these available data (tables 1, 2). The aquifer system was divided into the five hydrogeologic units discussed in the Geologic Framework section: the unconsolidated sediments, Scratchgravel Hills Stock (granite), metagabbro, Helena Formation, and argillite bedrock.

Aquifer Test Reports

Aqua Bona Consulting (P. Faber, written commun., 2010) compiled results of previous aquifer tests for the Scratchgravel Hills study area, which are available from DNRC (table 1). The following descriptions use only the data listed for single aquifers; aquifer test data listed for more than one aquifer were not considered.

Thirteen tests were available for the unconsolidated sediments aquifer. T values for the unconsolidated sediments ranged from 108 to 52,300 ft^2/d. Estimated K values ranged from 1 to 803 ft/d, with geometric mean and average values of 73 and 215 ft/d, respectively. S values for four tests with observation wells ranged from 0.0008 to 0.046; such values reflect a semi-confined to unconfined system.

Four tests were available for the Scratchgravel Hills Stock aquifer. Results indicated transmissivity values that ranged from 14 to 72 ft^2/day. K values

Table 1. Aquifer properties determined from aquifer tests conducted in the Helena area for DNRC or by the MBMG.

	Aquifer Tests				
	K (ft/day)			S	
Hydrogeologic Unit	Min	Max	Geometric Mean	Min	Max
Argillite bedrock	0.24	18	4.2	0.002	0.03
Helena Formation	0.09	0.11	0.10[#]	—	—
Metagabbro	1.95	2.69	2.23	0.0007	0.0011
Scratchgravel Hills stock	0.0009	1.5	0.66	—	—
Unconsolidated sediments	1.0	916	73	0.0008	0.05

Note. K, hydrologic conductivity; S, storativity.

[#]The Helena Formation's geometric mean is based on only two values.

Table 2. Hydraulic conductivity values used in other western Montana large-area groundwater models.

Upper Beaverhead—Uthman and Beck (1998), DNRC transient simulation	
Layer 1 (Quaternary alluvium) 25 to 170 ft thick	10–1,800 ft/day
Layer 2 (Tertiary basin-fill)	5–10 ft/day
Hayes Creek—Waren (1998), DNRC limited transient simulation	
Belt Argillite—Missoula Group, Mount Shields Fm., Member 3	0.1-0.75 ft/day
Helena Valley Aquifer—Briar and Madison (1992), USGS steady-state simulation	
Layer 1, Upper 35 ft thickness of aquifer	80 ft/day
Layer 2, Next 75 ft thickness	40 ft/day
Layer 3, 170 to 1,000 ft thickness beneath layers 1 and 2	40 ft/day
Lower Beaverhead—MBMG (2007), transient simulation	
Alluvium	75 ft/day
Mesozoic bedrock	1–2 ft/day
Gallatin Valley and Madison Plateau—MBMG (2007), transient simulation	
Alluvium	82–131 ft/day
Drummond Valley—Kauffman (1999), Montana State University Graduate Thesis, transient simulation	
Alluvium	26–45 ft/day

ranged from 0.14 to 0.74 ft/day. S values were unavailable due to a lack of observation wells. PBS&J (2008) also conducted an aquifer test in the granite bedrock, which resulted in a calculated transmissivity of 253 ft^2/day and a hydraulic conductivity value of 0.8 ft/day. PBS&J also estimated transmissivity in the granite based on specific capacity (Driscoll, 1986), which resulted in transmissivity values of 11.3 to 27.3 ft^2/day and hydraulic conductivity values of 0.04 to 0.38 ft/day (PBS&J, 2008).

Three reported tests were conducted in what is likely the metagabbro aquifer. The wells at the test sites were determined to be completed in the metagabbro based on their location and well log lithology ('black andesite'). Reported T values ranged from 306 to 322 ft^2/d. Estimated K ranged from 1.95 to 2.69 ft/d. S was reported for two of the tests, at values of 0.0007 and 0.0011. These data suggest that the metagabbro aquifer properties are comparable to those of the older argillite bedrock, likely as a result of a similar history of deformation and fracturing.

Two aquifer tests were available for the Helena Formation. Like the metagabbro sites, the wells at these two test sites were determined to be completed in the Helena Formation based on location and well log lithology ('limestone' and/or 'shale'). Transmissivity values of 8.3 and 33 ft^2/d were reported. Estimated K values were 0.09 and 0.11 ft/d. No S values were available from these tests.

Seven aquifer tests were available for the argillite bedrock aquifer. T values reported for argillite bedrock generally ranged from 43 to 6,410 ft^2/d, resulting in estimated K values of about 1 to 19 ft/d. There was one unusual T value of 11,100 ft^2/d for one well, GWIC ID 222881. This well may be completed in gravels derived of argillite fragments or in a zone of brecciated bedrock. The K value for that test was 163 ft/d, which is considered an outlier. The geometric mean and average of the K values for argillite bedrock, not including the value for well 222881, were 3.7 and 8.2 ft/d, respectively. S values available for argillite bedrock were 0.0002 and 0.0006, which reflect semi-confined conditions. These S values were determined for tests located where the bedrock was overlain by Tertiary deposits containing silt and clay.

<u>Aquifer Tests Conducted</u>

Six aquifer tests were conducted for this study (fig. 12). The details of these tests and the data analysis are discussed in the Aquifer Test section of the Scratchgravel Hills Technical Report (Bobst and others, 2013b).

Five of the six tests were located in the granitic core of the Scratchgravel Hills and were intended to estimate the aquifer properties of the granite. Test results indicated T values ranging from 0.15 to 225 ft^2/d and K values ranging from $8.8x10^{-4}$ to 1 ft/d. S values were not calculated due to a delayed response or lack of response in observation wells. A lack of response occurs when the pumping well and observation wells are not directly hydraulically connected. The fracture pattern determines the response, and when the scale becomes relatively local, the aquifer does not function as an ideal porous media.

The sixth aquifer test was conducted on the Silver Creek Fault west of the Scratchgravel Hills granite. The test was intended to determine the hydrogeologic function of the fault (i.e., if it forms a boundary to flow). At this site, four wells were installed, two on each side of the fault (fig. 12, site WF). The fault location was determined based on changes in soil composition, and on observed fault gouge in outcrops. Long-term groundwater-level monitoring was conducted at this site. Groundwater-surface elevations showed a marked change across the fault (fig. 13). This finding suggests that the fault and the associated gouge act as a barrier to groundwater flow.

A 24-hour, constant-rate aquifer test was also conducted at this site. During the test, water levels were drawn down 228 ft in the pumping well (WF2; east side of fault) and 63 ft in WF1 (east side of fault), while no change was seen in water levels of the wells west of the fault (WF3 and WF4). The results supported the idea that the fault functions as a barrier to flow at this location. The results were also consistent with other fault investigations in the nearby North Hills (Waren and others, 2012).

Aquifer tests conducted in the argillite bedrock aquifer of the nearby North Hills (northeast of the study area) by the Montana Bureau of Mines and Geology (MBMG; Waren and others, 2012) were also considered. The Valley Excavating site in the North Hills was deemed most representative of

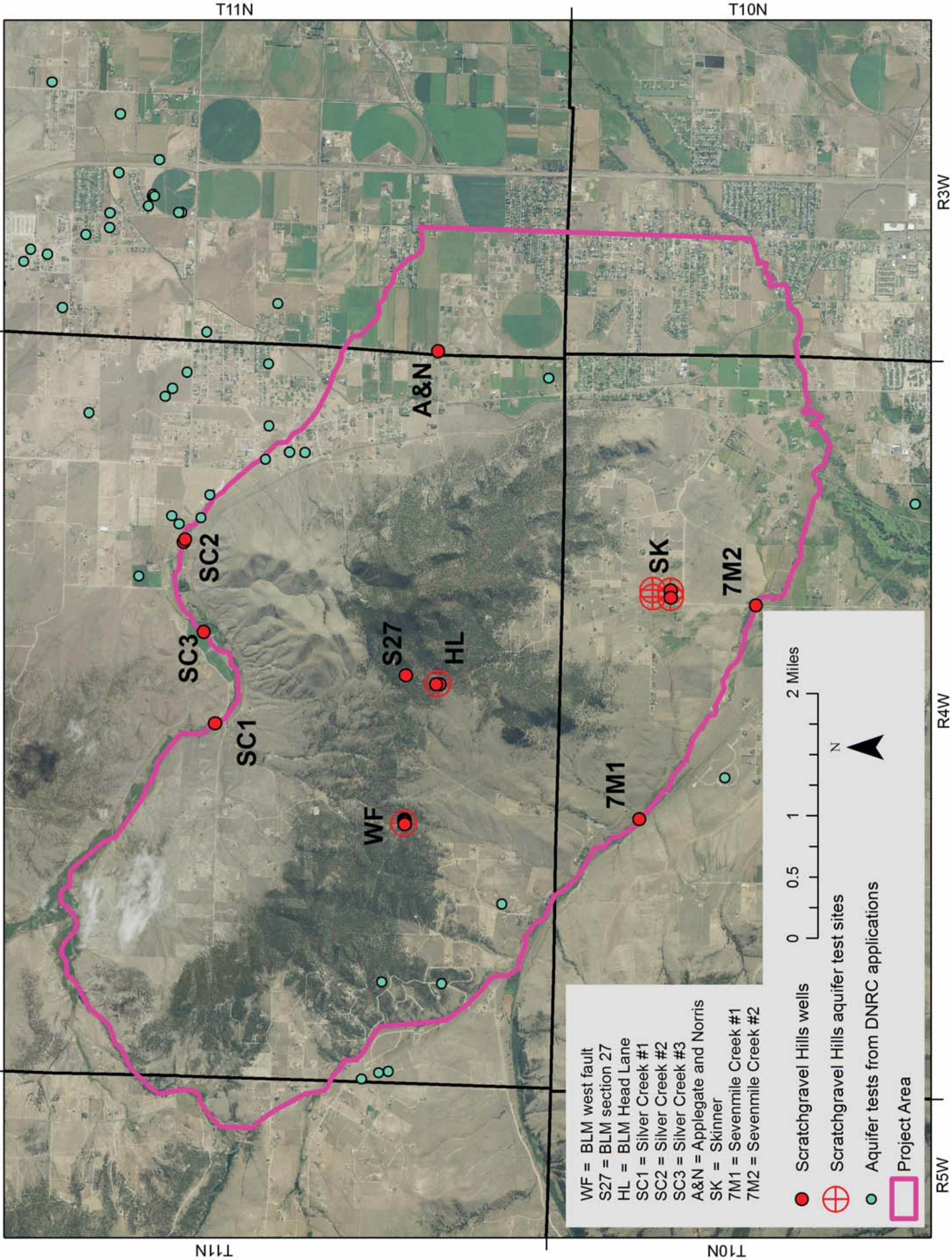


Figure 12. Wells were installed at 10 locations and aquifer tests were conducted at 6 locations within the Scratchgravel Hills study area to acquire water-level information and evaluate aquifer properties. Aquifer test data from DNRC applications (P. Faber, written commun., 2010) also provided information on aquifer properties.

Figure 13. This well-installation site is located on the Silver Creek Fault. Static groundwater elevations from November 9th, 2010 (ftamsl, in yellow) showed an abrupt water-level change across the fault. A 24-hour pumping test was conducted at this site, and resulting drawdowns (ft) are shown in green. This site is located in T. 11 N., R. 4 W., sec. 28 SWSW. WF2 (well 257370) is at 46.6774301° N, 112.1230996° W.

argillite bedrock, as it was away from major fault zones. The hydraulic conductivity determined at that site was 2.9 ft/d, and the storage coefficient was 0.02. Three other bedrock aquifer tests yielded hydraulic conductivities of 0.8, 3.2, and 7.5 ft/d, and two of these tests yielded storage coefficients of 0.001 and 0.03.

Summary of Hydraulic Properties

Aquifer property ranges and geometric mean values for each aquifer were evaluated (table 1). These values were derived from reported data in the area and the aquifer tests conducted during this study. The ranges of aquifer property values were used in groundwater flow calculations and groundwater modeling; they were all within the range of expected values, as described in numerous groundwater textbooks for similar materials.

Sources and Sinks

Sources of groundwater recharge within the Scratchgravel Hills study area include diffuse infiltration, bedrock inflow, Silver Creek and Tenmile Creek infiltration, water leakage from the HVID Canal and laterals, and irrigation water applied in excess of crop demand. The sinks for the Scratchgravel Hills study area include well withdrawals and discharge to the Helena Valley aquifer (including the alluvium along the study area creeks, which flow into the Helena Valley).

Groundwater Budget

A groundwater budget quantitatively summarizes the processes within the conceptual model. While some uncertainty is inherent with the calculations, a groundwater budget is useful for determining the relative importance of different processes affecting the groundwater flow system. A groundwater budget accounts for water entering and leaving the study area from boundaries, sources, and sinks. The idea of a water budget is the same as the more general law of mass balance. That is, matter cannot disappear or be created spontaneously. Thus, the amount of water which enters over a period of time must be equal to the amount of water that leaves over that same time period, plus or minus any water that is removed from, or put into, storage. In a groundwater system, changes in storage are directly related to changes in groundwater levels. The general form of the mass balance equation is:

Inputs = Outputs ± Changes in storage.

A detailed report on the Scratchgravel Hills groundwater budget is included in the Scratchgravel Hills Technical Report (Bobst and others, 2013b). A brief summary of the major components is discussed below. The mass balance equation can be expanded for the Scratchgravel Hills study area to:

$$BR + DI + 10M + SC + CL + IR = WL + HVA \pm \Delta S,$$

where:
BR, bedrock inflow;
DI, diffuse infiltration;
10M, Tenmile Creek infiltration;
SC, Silver Creek infiltration;
CL, irrigation canal leakage;
IR, irrigation recharge;
WL, withdrawals from wells;
HVA, discharge to the Helena Valley aquifer and the alluvium along creeks; and
ΔS, changes in storage.

Groundwater inflow from bedrock (BR) occurs on the western side of the study area, where groundwater flows in from the western mountains. It should be noted that local radial groundwater flow from the Scratchgravel Hills causes this western inflow to be deflected to the north and south, and it is drained by the alluvium of Silver Creek and Sevenmile Creek (fig. 10); therefore, none of this inflow enters the Green Meadow CGWA. Groundwater inflow to the study area was calculated to be approximately 482 acre-ft/yr.

Diffuse infiltration (DI) occurs when the amount of precipitation exceeds runoff, evaporation, and plant consumption (Lerner and others, 1990; DeVries and Simmers, 2002; Ng and others, 2009). Diffuse infiltration was evaluated for the parts of the study area that are not irrigated, as irrigation recharge accounted for diffuse infiltration in irrigated areas (see below). Because runoff was determined to be minimal in the study area, diffuse recharge was considered to be equal to precipitation minus evapotranspiration (ET). As discussed in the Scratchgravel Hills Technical Report (Bobst and others, 2013b), the pediment and forested hills both have an ET rate of about 13 in/yr. Subtracting ET from the annual average precipitation values (fig. 6a) resulted in a total diffuse infiltration in non-irrigated areas of 2,184 acre-ft/yr.

Infiltration from perennial streams to groundwater occurs along Silver Creek (SC) and Tenmile Creek (10M). GIS analysis showed that approximately 2.8 miles of Tenmile Creek border the study area. Briar and Madison (1992) monitored Tenmile Creek and estimated an infiltration rate of 2.14 cfs/mile; assuming that half of this flows north into the study area (while the other half flows south), the total Tenmile Creek infiltration estimate for the study area was 1,742 acre-ft/yr. Measurements of surface-water discharge in Silver Creek indicated that about 490 acre-ft/yr infiltrated to groundwater. It should be kept in mind that, because this infiltration is to the alluvium, the water is only available to wells completed along the creek drainages or in the Helena Valley aquifer. This recharge has no effect on the availability of groundwater in the uplands.

Canals in the study area are not lined, so canal leakage (CL) to the underlying groundwater occurs. GIS analysis of canals showed that 4.3 miles of the HVID Canal and 7.8 miles of smaller canals were present in the study area. Water from the Missouri River feeds the HVID Canal and its laterals, while Silver Creek, Sevenmile Creek, Tenmile Creek, and Threemile Creek feed the smaller canals. Groundwater levels under the canals are often greater than 20 ft below ground surface before the ditches are turned on. Leakage is quite evident in several hydrographs (e.g., wells 254309 and 239913). Briar and Madison (1992) estimated that the HVID Canal infiltrates water at a rate of about 0.63 cfs/mile, and smaller canals infiltrate at about 0.21 cfs/mile. Therefore, a total of 1,821 acre-ft/yr was estimated to infiltrate from canals during the irrigation season. Because most of the canals are located on or near the unconsolidated sediments, this water was only available to wells completed in the alluvial creek drainages or in the Helena Valley aquifer. The exception was the Sunny Vista Canal, which crosses Head Lane about 0.9 miles north of Sevenmile Creek. Leakage from the Sunny Vista Canal recharges the underlying granite bedrock aquifer.

When water (irrigation water plus precipitation) is applied to a field in excess of crop demand and evaporation, the excess must either runoff or infiltrate to the underlying aquifer. On irrigated fields, the water that recharges groundwater is termed irrigation recharge (IR). Briar and Madison (1992) calculated irrigation recharge in the Helena Valley using the amount of water applied by irrigation, the amount of precipitation, and crop demand, with alfalfa as the primary crop in the area. The result was an average irrigation recharge rate of 1.5 ft/yr. GIS analysis showed approximately 1,078 acres were irrigated in the Scratchgravel Hills study area; thus, irrigation recharge accounted for an input of about 1,622 acre-ft/yr. Because most of the irrigated areas are located on or near the unconsolidated sediments, this water was only available to wells completed in the alluvial creek drainages or in the Helena Valley aquifer. The exception was the area supplied by the Sunny Vista Canal (~120 acres).

In the northern portion of the Helena Valley, 20 years of monthly water-use data from Townview Estates were assessed (Bobst and others, 2013a). This analysis estimated that an average home with a septic system near Helena consumptively used about 435 gallons of water per day (gpd). Approximately 98 percent of this water was consumed as ET by landscaping (lawns and gardens) during the growing season. Most in-house diversions were returned to the groundwater by the septic system. This 435-gpd figure is in good agreement with the estimate made by Stahly Engineering (2008) for the proposed Cornerstone Estates subdivision (438 to 445 gpd per lot). Given that there were 1,608 homes in the Scratchgravel Hills study area in 2009, it was estimated that a total of about 781 acre-ft/yr of water was consumptively used by homes (WL).

Using Darcy's Law, the rate of groundwater flow to the Helena Valley aquifer (HVA) was calculated. The result was an outflow of about 3,270 acre-ft/yr to the alluvium along the creeks, and an outflow of about 4,290 acre-ft/yr directly to the Helena Valley aquifer. All of this alluvial water flows towards Lake Helena.

Evaluation of groundwater hydrographs in the Scratchgravel Hills did not reveal any evidence of regional changes in groundwater levels during the study period (Bobst and others, 2013a); thus, a significant change in storage (ΔS) did not occur.

The groundwater budget analysis indicated that overall inputs to the Scratchgravel Hills study area were between 7300 and 9400 acre-ft/yr. Outputs were estimated to be between 7400 and 9400 acre-ft/yr. Given the fact that there was no evidence of regional changes in groundwater levels, and thus no appreciable change in groundwater storage, the budget is in balance (table 3). The probable range of inflows and outflows shown in table 3 take into account the estimated uncertainty with each calculation.

The results of this water budget and the model budget (operated in steady-state mode) are compared in table 3. The values are generally similar; differences are due to minor variations in the model area versus the study area, and to how certain components were modeled. These differences are discussed further in the Steady-State Calibration section of this report.

COMPUTER CODE

Groundwater Modeling Systems (GMS) software was used to develop a MODFLOW 2000 groundwater flow model (Aquaveo, 2010). MODFLOW-2000 is a widely accepted groundwater flow program developed by the U.S. Geological Survey (Harbaugh and others, 2000). The program simulates groundwater flow numerically using a finite-difference method. The version of GMS used for this modeling was GMS 7.1.2, with a build date of April 16, 2010. The version of MODFLOW-2000 operated in GMS 7.1.2 was Version 1.18.01, compiled June 20, 2008.

PEST is a general-purpose parameter estimation utility developed by John Doherty of Water-

Table 3. The Scratchgravel Hills study area groundwater budget calculated values (acre-ft per year).

	Best Estimate	Probable Range		Modeled Values
		Min	Max	
INPUTS				
Bedrock inflow	482	241	723	378
Diffuse infiltration	2,184	1,966	2,403	1,330
Tenmile Creek infiltration	1,742	1,565	1,913	N/A
Silver Creek infiltration	490	438	535	N/A
Irrigation canal leakage	1,821	1,638	2,001	1,410
Irrigation recharge	1,622	1,455	1,778	3,098
TOTAL INPUT	8,342	7,303	9,355	6,216
OUTPUTS				
Well withdrawals	781	721	901	N/A
Outflow to alluvial drainages	3,270	2,767	3,759	3,117
Outflow to Helena Valley aquifer	4,290	3,887	4,751	3,100
TOTAL OUTPUT	8,342	7,376	9,411	6,217

Table 4. Details of the model grid as listed in GMS.

Grid type	Cell Centered
X origin (ft)	1295373
Y origin (ft)	875560
Z origin (ft)	3250
Length in X (ft)	45917
Length in Y (ft)	42890
Length in Z (ft)	500
Rotation angle	0^0
AHGW X origin (ft)	45917
AHGW Y origin (ft)	918450
AHGW Z origin (ft)	4500
AHGW rotation angle	90
Minimum scalar	3728
Maximum scalar	4598
Number of rows (i)	215
Number of columns (j)	230
Number of layers (k)	2
Number of nodes	149688
Number of cells	98900
Number of active cells	39130
Number of inactive cells	59770

mark Numerical Computing (Doherty, 2010). PEST was used for automated parameter estimation in certain model runs. The version of PEST operated in GMS 7.1.2 was Pest Version 12.0.

GROUNDWATER FLOW MODEL CONSTRUCTION

Model Grid

The GMS project was operated using the North American Datum (NAD) 1983 Montana State Plane coordinates, in units of U.S. Survey Feet. The model grid was created in GMS using a uniform grid frame. Lengths of the grid in the X, Y, and Z dimensions were 45,917, 42,890, and 1,463 ft, respectively. The rectangular grid frame encompassed the Scratchgravel Hills study area; some cells within the frame were inactivated in order for the model domain to best correspond with the study area (fig. 14). Cells measured 200 ft x 200 ft, and the model had two layers, 215 rows, and 230 columns. The model thickness ranged from 400 to 1,460 ft thick, while the saturated thickness ranged from about 400 to 800 ft. Table 4 provides additional numeric details about the model grid.

The top of layer one was defined using data derived from the U.S. Geological Survey 1/3-Arc Second National Elevation Dataset (U.S. Geological Survey, 2009). These data were converted into scatter points and imported into GMS. This scatter point set is referred to here as the Digital Elevation Model (DEM) scatter point set. The DEM scatter point spacing was about 186 ft, which was similar to the cell size of 200 ft. The bottom of layer one was a surface defined by two approaches. The first method involved a composite of flat surfaces that changed elevation in a west-to-east direction. The shifts in elevation of the bottom surface corresponded with large shifts in elevation of the top surface (i.e., the land surface). The layer's bottom elevation ranged from 3,900 to 3,250 ft. The sec-

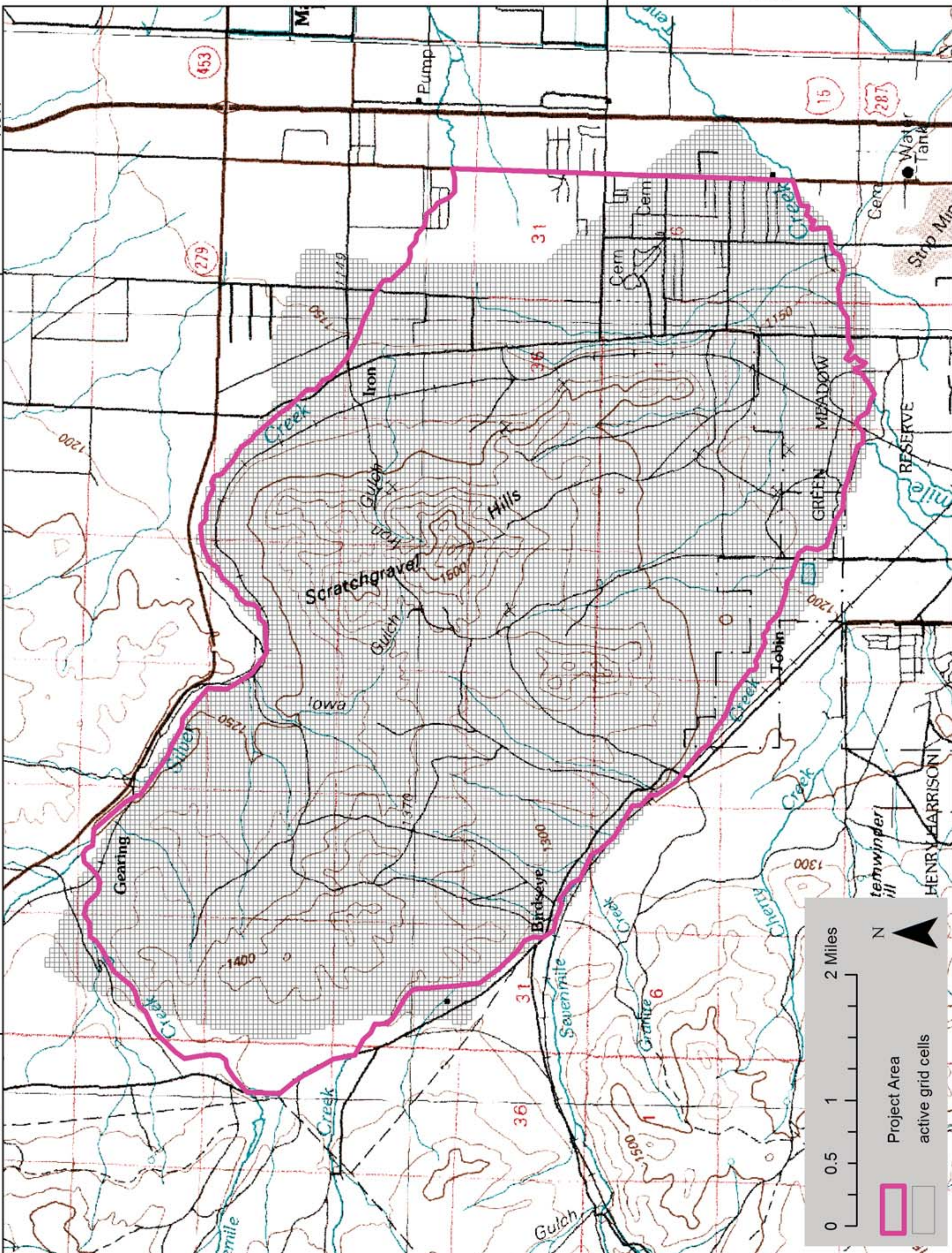


Figure 14. The Scratchgravel Hills groundwater f ow model is composed of 200 ft by 200 ft square cells and two layers.

ond approach defined a surface by subtracting 200 ft from the elevation of the DEM scatter point set. This second approach was used in areas where the top surface of the model dropped precipitously, causing layer one to become very thin or pinch out altogether; this occurred at the northern and southern slopes of the granite hills. Layer one varied in thickness from 200 ft to 1,260 ft. The thicker cells corresponded to areas of high topographic relief and relatively deep water levels (e.g., in the central Scratchgravel Hills Stock). The thickness of layer one was intended to approximate the productive zone of the aquifer system, which ranged from about 300 to 600 ft of saturated thickness in the bedrock aquifers and 100 to 400 ft in the alluvial aquifer (fig. 15).

Two alternative surface configurations were also tested. The first involved a simple subtraction of 500 ft from the top surface of layer one. The resulting bottom surface was problematic due to the sharp increase in elevation in central areas of the Scratchgravel Hills. Many cells were dry beneath these high-relief areas because the elevation change was so steep, and the head gradient became insurmountable. The second version of the layer one bottom surface was a flat, constant elevation. This version was determined to be undesirable as well, because the saturated zone beneath high-relief areas became disproportionately thick in relation to the rest of the model. For instance, the alluvial saturated zone was only 200–300 ft thick, while that of the granite hills was over 1,200 ft thick.

The bottom surface of layer two was defined by subtracting 200 ft from the elevation of the bottom of layer one; it therefore had a uniform thickness of 200 ft (fig. 15). This bottom layer was included to simulate bedrock beneath the unconsolidated sediments on the east side of the study area and the deeper, less productive bedrock in the hills. This allowed the aquifer thicknesses to be adequately represented, which was needed to properly reflect transmissivity values and groundwater budget estimates.

Hydraulic Parameters

For steady-state simulations, initial values of K were assigned to polygons based on the results of preliminary runs of the Scratchgravel Hills model, in which each polygon defined a K zone. The preliminary runs operated on the basic premises of the conceptual model and the groundwater budget for the study area. The extents of the K zones were based on the five hydrogeologic units described in the Geologic Framework section. As discussed in the Calibration section, the initial K values were modified during the calibration process.

The transient model required input of storativity (S) values. As with K, S values were assigned to polygonal zones and were based on study estimates discussed in the Aquifer Properties section (table 1).

Boundary Conditions

The boundaries of a model specify the head or flux at the horizontal edge of the problem domain (Anderson and Woessner, 2002, p. 97). The boundary conditions for the Scratchgravel Hills model followed those discussed in the Hydrologic Boundaries section. The western and eastern borders of the model were constant-head boundaries, which allowed for groundwater inflow from the western mountains, and for groundwater outflow to the Helena Valley aquifer. The boundaries were placed along the potentiometric surface map contours developed for this study. The western constant-head boundary followed the map's 4,350-ft potentiometric contour, which approximated the western study area boundary. Likewise, the eastern constant-head boundary followed the 3,730-ft potentiometric contour and approximated the eastern study area boundary. These constant-head boundaries replicated the relatively stable groundwater setting observed in these areas. No-flow boundaries were placed along the northern and southern borders of the grid and ran parallel to groundwater flow lines on the potentiometric surface map (fig. 16). The no-flow boundaries fell along the creeks' alluvial drainages, which act as drains that cause the flow lines to parallel them.

Sources and Sinks

Sources and sinks are similar to boundaries, in that they specify head or flux; however, they occur in the interior of the model (Anderson and Woessner, 2002, p. 146). The sources of water for the Scratchgravel Hills model included bedrock inflow along the western edge of the model, which was simulated using the constant-head cells

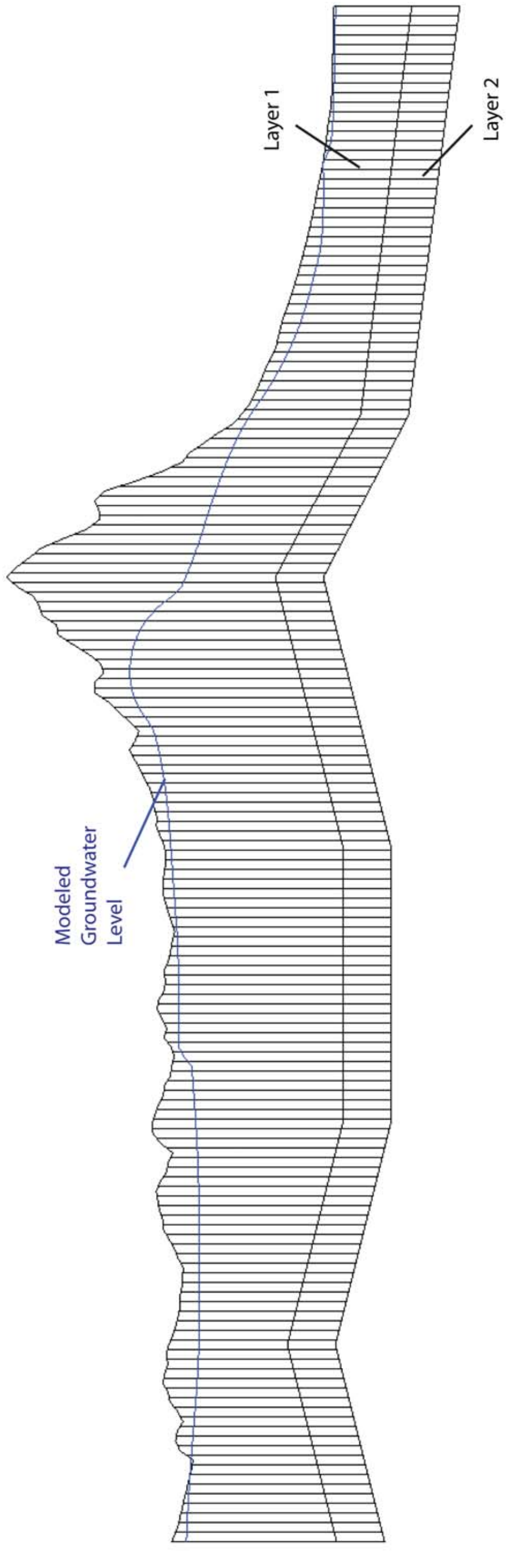


Figure 15. Cross section through Row 118 of the model. Both layers one and two are shown.

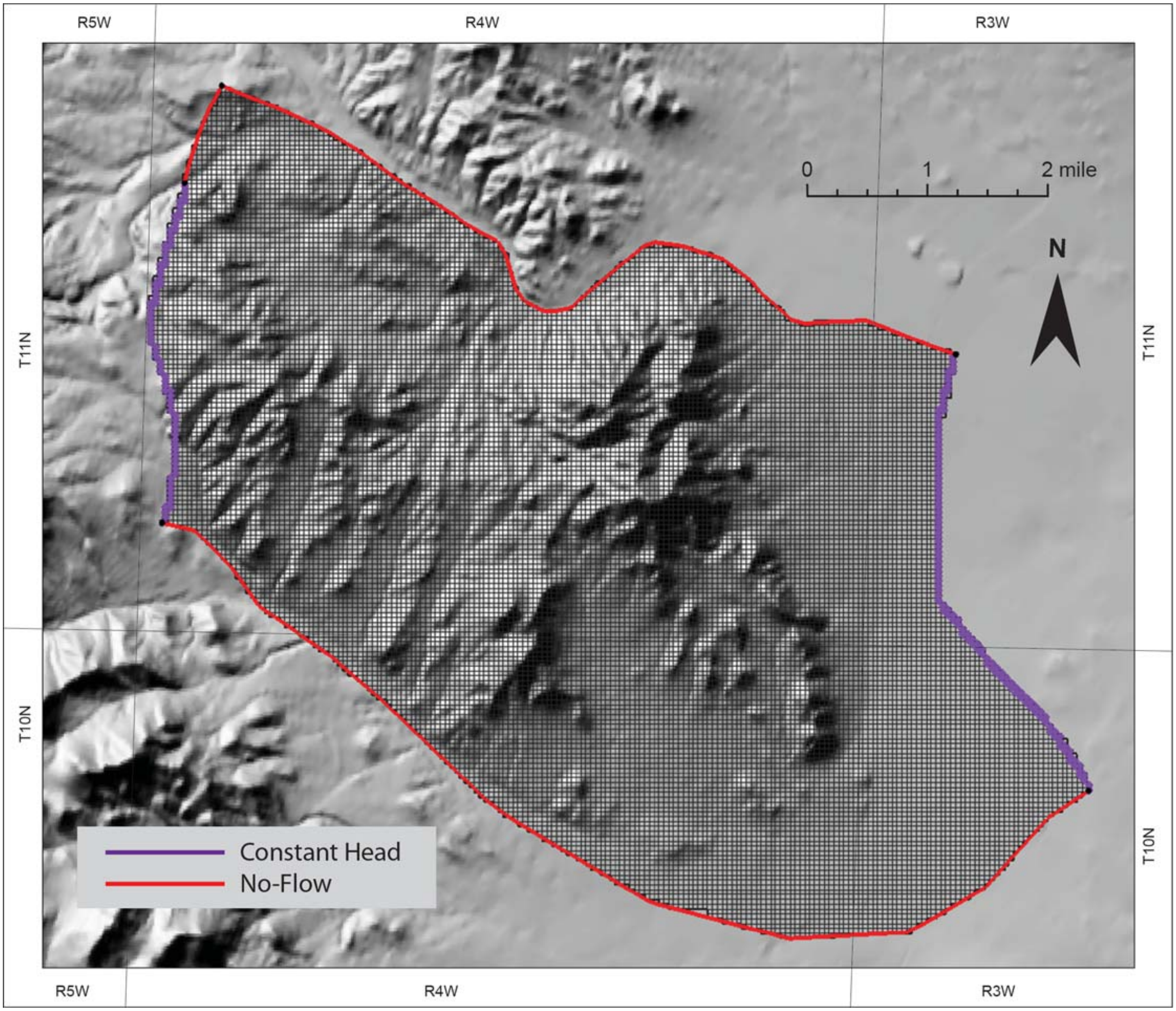


Figure 16. Constant-head and no-f ow boundaries were applied to the edges of the Scratchgravel Hills Model.

discussed in the Boundary Conditions section. Diffuse infiltration (precipitation minus ET) and irrigation field recharge were applied using the Recharge Package (fig. 17). The maximum diffuse infiltration recharge was limited to the peaks of the Scratchgravel Hills, while a smaller amount of recharge was assigned to the hills' lower elevations. Irrigation field recharge was limited to the portions of the grid below the HVID Canal and the Sunny Vista Canal. The irrigation polygons were derived from the Statewide Final Land Unit classification database (Montana Department of Revenue, 2009). Recharge was held constant at the indicated values during steady-state calibration. HVID Canal leakage was explicitly simulated using the Well Package, which is a specified-flux boundary. Sunny Vista Canal, one of the ditches diverted off of Sevenmile Creek, was also simulated using this method. It was explicitly modeled due to its local influence within the Green Meadow Groundwater Control Area.

The sinks in the model included the constant-head cells along the eastern edge of the model, as discussed in the Boundary Conditions section; these cells allowed for the eastward outflow of groundwater into the Helena Valley aquifer. The Drain Package was used to simulate groundwater flow from the bedrock into the alluvium along streams (fig. 16). Drain elevations were set at the approximate alluvial–bedrock interface (based on well log data) and ranged from 10 to 30 ft below

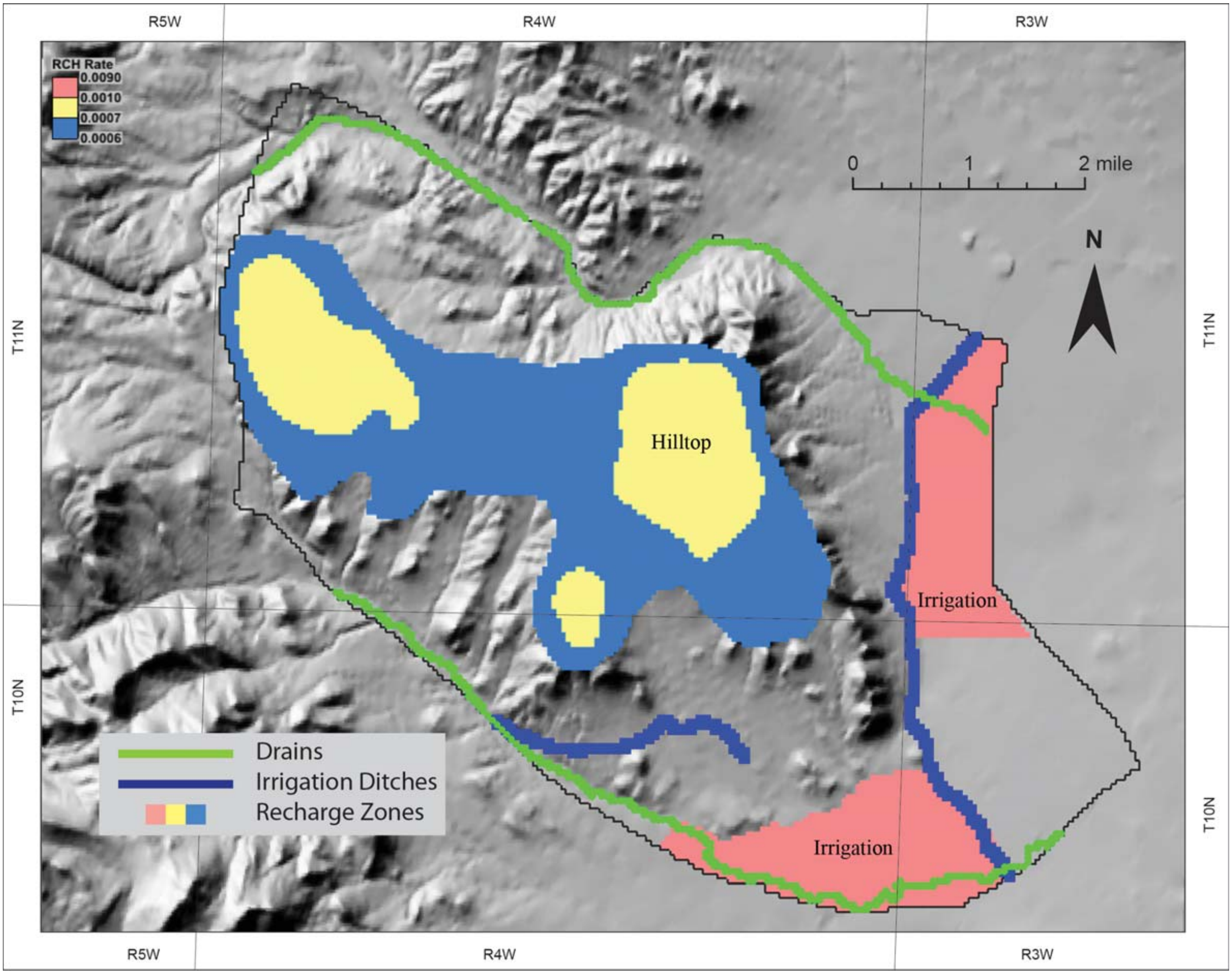


Figure 17. Within the model domain, recharge was applied to three areas: in the higher portions of the hills, where precipitation is greatest; along irrigation ditches to represent ditch leakage; and on irrigated f elds to represent irrigation recharge. Water was removed from the model through drains along alluvial drainages, and through constant-head boundaries along the model borders (f g. 16). Wells were not included in the steady-state or 1-year transient simulations, but were added for the predictive scenarios. Recharge rates (RCH Rate) are in ft/day.

land surface. Drain bed conductances ranged from 0.1 to 10 ft^2/d. As noted in the Conceptual Model section, well withdrawals have relatively little effect on the groundwater flow system. Most of the wells within the study area are domestic and pump at relatively low rates; moreover, they are spaced at a low density. For these reasons, current well withdrawals were omitted from the model.

CALIBRATION

Selection of Calibration Targets

Observed groundwater elevations were used as calibration targets in the model. Groundwater-level data were collected monthly at selected area wells during the project, beginning at various times during the fall of 2009 and winter of 2010, and continuing until June 2011. Static water-level records from 71 sites were adequate for potentiometric map generation. Without modification, the monthly 2010 data sets yielded quite similar potentiometric surfaces when contoured using the default kriging method in Surfer Version 9 (Golden Software, Inc.; Bobst and others, 2013b). Because there was no major shift in contours from month to month, it was concluded that the most abundant monthly dataset should be used for the steady-state calibration. The month with the most abundant dataset was October 2010.

Prior to steady-state calibration, 14 of the 71 wells were removed from the October 2010 data set because they were located outside the model domain. Another well was also removed from the dataset because it was a non-static water level. During calibration, four wells were deleted from the calibration data set due to the inability to calibrate the model successfully based on the polygon array. These wells included well 254227, which was shallow relative to surrounding wells. The second and third wells removed, 257370 and 257560, were two of the four wells drilled along the Silver Creek Fault for this project. Because the fault impedes groundwater flow, the differences in water-level elevations on either side of the fault are large. Wells 257561 and 257562, located only about 100 ft to the west on the other side of the fault, remained as targets in this vicinity. As discussed in the next section (Steady-State Calibration), the model successfully calibrated to conditions at all four wells by the insertion of a narrow low-K zone to represent the fault (fig. 18). The fourth well removed, well 706044, fell along the western edge of the model grid domain. It was removed from the calibration data set due to its anomalously low water levels relative to the four wells surrounding it (254247 to the southeast, 254948 to the northeast, 65696 to

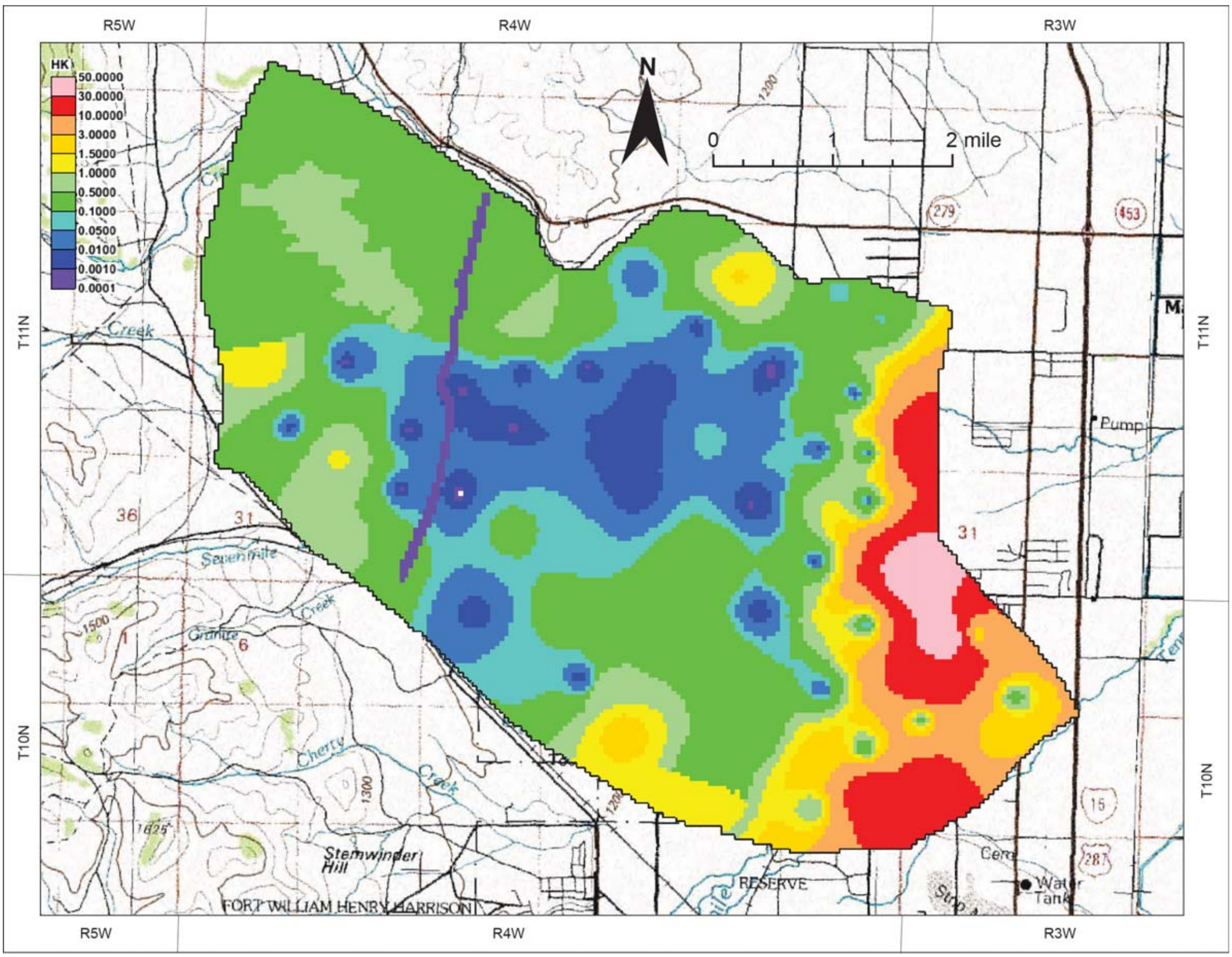


Figure 18. The modeled distribution of hydraulic conductivity is consistent with the conceptual model of the area. The bedrock in the core of the Scratchgravel Hills has the lowest permeability, with slightly higher values for bedrock near the edges of the study area. The Quaternary alluvium is the most permeable. Hydraulic conductivity is labeled as HK in the legend, and values are in ft/day. Individual cells have independent values within the specif ed range.

the southwest, and 155613 to the northwest). The cause for the anomaly is unknown. One possibility is a highly localized change in lithology; however, as a driller's log could not be obtained for this well, its borehole lithology is uncertain.

Also during calibration, control points (i.e., imaginary observations wells) were added to better fit heads to observed water levels. A total of seven points were added after preliminary PEST runs generated an unrealistic hydraulic gradient in certain areas due to a lack of observation data. The majority of control points were placed in the unconsolidated sediments near their interface with the granite hills, where initial PEST K configurations produced a uniform gradient. In reality the gradient is very steep on the eastern slope of the granite hills and then lessens considerably to the east, as groundwater flows into the more transmissive alluvial aquifer. In such locations, the position of the potentiometric surface was estimated and control points were entered to guide the model calculations toward a realistic result.

The removal of observation points and addition of imaginary points resulted in a total of 60 calibration targets, 53 of which were real monitoring sites. The calibration criterion was set as a ±15 ft head residual; the head residual is the difference between the modeled head value and the observed value. This value was selected based on the results of models of similar scale in Montana and Utah (Kauffman, 1999; Uthman and Beck, 1998; Waren, 1998). This calibration criterion was approximately 2 percent of the range of observed groundwater elevations within the modeled area.

In addition to the head residual criterion of ±15 ft, error statistics were used during calibration. Statistics of concern included the residual mean, which should be close to zero in a well-calibrated model (i.e., the positive and negative residuals balance one another); the mean of the absolute value of the residuals, which is a measure of the average error in the model; and the root mean square (RMS) error, which is the square root of the average of the squared residuals. Calibration data files are provided with each set of groundwater model files in appendix A. Note that the calibration statistics were based only on data measured from the 53 actual observation wells and did not take the seven control points into account.

Steady-State Calibration

The steady-state version of a model simulates average annual conditions for all components of recharge and discharge, and it represents the system in equilibrium with a specified set of stresses. A steady-state model is useful for predicting the ultimate impact to the groundwater flow system from a new stress, such as a pumping well, and for evaluating the overall groundwater budget.

The steady-state model was calibrated to observed values (i.e., the calibration targets) through manual trial and error as well as two forms of automated parameter estimation (PEST). Only the top layer (layer one) was calibrated, as no observation wells were screened deep enough to penetrate layer two. Layer two was uniformly assigned a low hydraulic conductivity value (0.05 ft/d), which was intended to represent the lower permeability of the bedrock at depth.

Manual calibration was performed first and involved adjusting input parameters (hydraulic conductivity and recharge) until MODFLOW converged on a solution and produced reasonable head and water-budget values. Typically, only one parameter was adjusted per model iteration in order to isolate its influence relative to other input parameters.

Automated parameter estimation was used following the manual calibration approach. In this first type of parameter estimation, polygonal hydraulic conductivity zones were defined, and recharge values were held constant. Polygons were drawn to allow hydraulic conductivity to vary about the model. Polygonal extents were based on known or suspected geologic boundaries, such as those discussed in the Geologic Framework section. The zones were assigned initial values based on manual calibration results and on the aquifer property estimates discussed in the Aquifer Properties section (table 1). PEST model runs were repeated and adjustments made to the polygon configurations and values in order to minimize the difference between computed heads and observed water levels.

The pilot point PEST method was used to further refine the hydraulic conductivity assignments in the model. In this method, recharge rates were held constant as in the polygonal zone approach. The pilot point method generates hydraulic conductivity values for each model cell, and these values optimize the objective function. This approach eliminates the potentially sharp contrasts in hydraulic conductivity values that can occur at polygon boundaries. The resulting hydraulic conductivity values and groundwater budget were evaluated relative to the conceptual model, the results of aquifer tests, and the manually calculated groundwater budget to ensure that they were reasonable.

The pilot point method was inadequate in two locations due to the isolated and distinct nature of the actual K values at these sites. In the northwest portion of the study area, a small zone of relatively permeable material (Qac; fig. 5) overlies the less permeable Helena Formation. Similarly, the Silver Creek Fault zone exhibits low permeability and acts as a barrier to flow, as noted in the Hydrogeologic Units section of this report. Extreme contrasts in K within a discrete area make pilot point parameter estimation difficult without a sufficiently dense array of observation wells. In each of these areas, K values were defined via manual adjustment. The K values generated by these methods appear reasonable relative to the conceptual model (table 1; fig. 18).

The resulting modeled potentiometric surface was similar to the observed surface, and errors were reasonably small (figs. 19, 20). The steady-state model used a calibration criterion of ±15 ft. Forty-nine of 52 wells were within the calibration

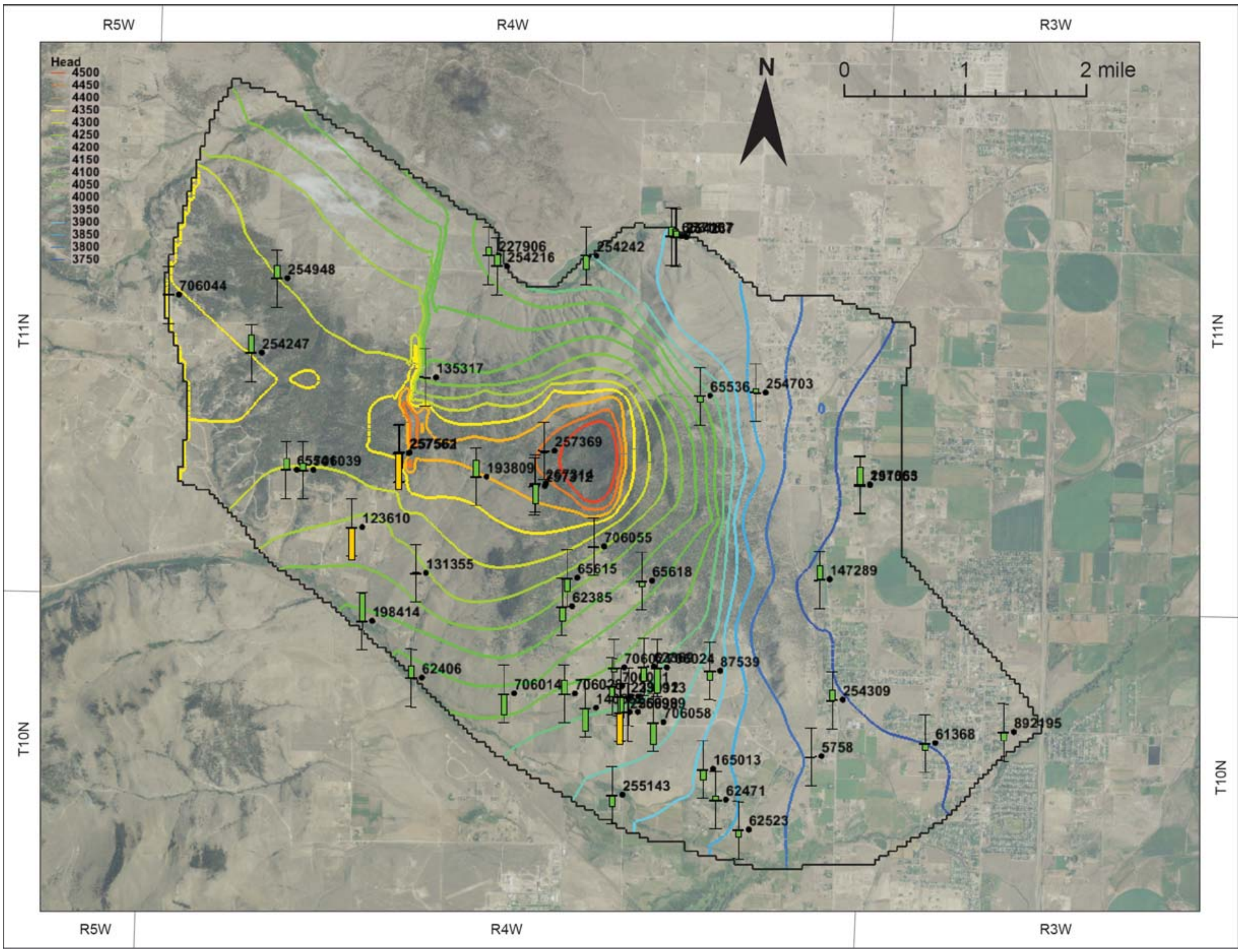


Figure 19. The pilot point method and manual trial and error were used to calibrate the steady-state version of the Scratchgravel Hills model. The resulting calculated potentiometric surface is shown above. Calibration targets are the monitoring well sites shown by the dots. The dots are labeled with the GWIC well identif cation number for the site. The vertical scales illustrate the target elevation (middle hachure), with colored bars showing the vertical difference between the target elevation and the computed head value. Green indicates the head value was within the set calibration criterion (15 ft), and yellow indicates the value was within twice the calibration interval (30 ft).

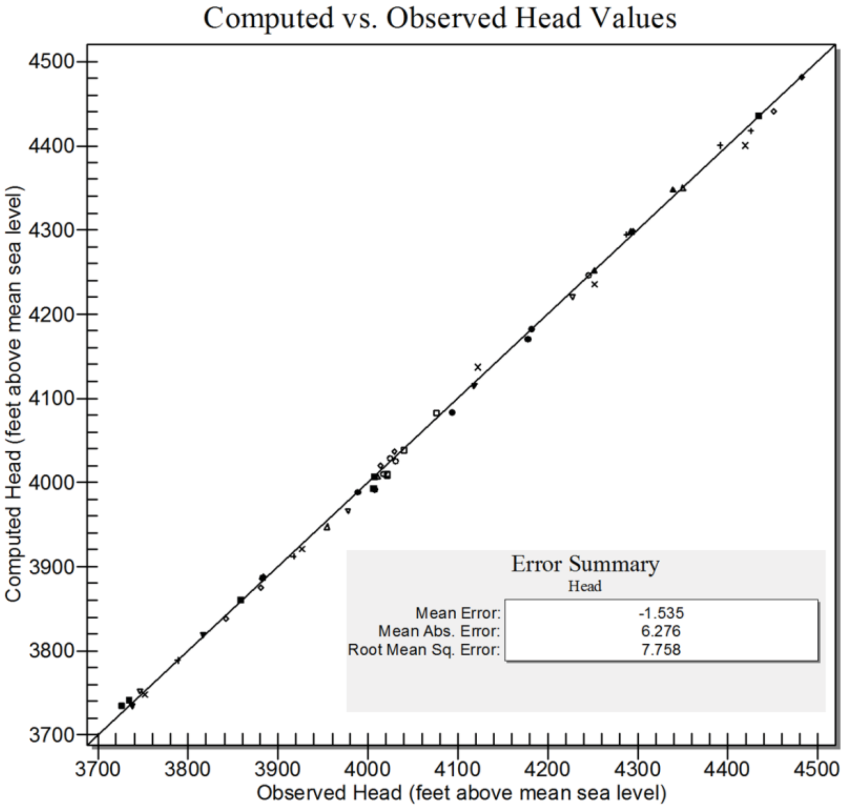


Figure 20. Comparison of computed head values vs. observed head values at calibration target wells in the Scratchgravel Hills model showed a root mean square error of 7.7, with no systematic deviation from unity. A total of 53 observations were used.

criterion of ±15 ft. The other three wells were within ±20 ft. The RMS error for the steady-state simulation was 7.7 ft (figs. 19, 20). This error represents about 1 percent of the modeled groundwater elevation range (750 ft). Because the RMS error was small relative to the overall change in head, it represented a small part of the overall model response (Anderson and Woessner, 2002, p. 241) and was considered to be reasonable.

The range of K values resulting from calibration was greater than aquifer test estimates, and model values on average tended to be lower than aquifer test values. The greater range was due to a larger coverage area in the model, and the lower overall value was due to the effects of faults and igneous contacts (barriers to flow) on bulk hydraulic conductivity. Decreasing recharge would further lower K values, pushing them further from the estimated range. Therefore, the applied recharge rate was considered reasonable and was perhaps a conservative estimate of recharge from precipitation in the Scratchgravel Hills. As noted later in this section, groundwater outflow from the model was at the low end of our estimates made in the water budget, which further supported the notion that precipitation-derived recharge could not be much lower than the values selected.

The steady-state model groundwater budget was reasonably similar to the groundwater budget estimated from the field investigation performed for this study. Comparison of the groundwater budget estimates to the modeled values illustrates that, while individual budget components were comparable, the total input and output values were noticeably smaller (table 3). This discrepancy was due to the lack of certain budget components in the model.

One omitted component was domestic well withdrawals. As noted in the Sources and Sinks section, the withdrawals have relatively little impact on the groundwater flow system. Similarly, infiltration from Tenmile Creek and Silver Creek was not modeled due to their small zone of influence. Because the creeks lie within the alluvial drainages along the study area boundary, the recharge they provide is confined to the alluvium and has little impact on the bedrock aquifer system, which was the focus of this study.

The canal leakage component shown in table 3 was higher than the modeled value because it represented water leaking from both the HVID Canal and ditches diverted off the creeks. The 1,410 acre-ft/yr simulated in the model represented only the HVID Canal and the Sunny Vista Canal. Other canals were not simulated because they impact the alluvial drainage rather than the bedrock system and are outside the primary focus area (i.e., the Green Meadow CGWA). The Lower Ditch off Sevenmile Creek also was not simulated explicitly; instead, it was considered sufficient to cover the broader irrigated area with aerial recharge to represent irrigation recharge.

The contrast between irrigation recharge estimates vs. modeled values was due in part to the model's application of 1.5 ft/yr of recharge to a bulk polygon, rather than exact irrigated acreages. The model's larger recharge estimate was also due to the fact that the model encompassed additional irrigated lands to the north and south of the study area border.

Transient Calibration

The transient version of the model used the aquifer properties from the steady-state model and added the element of time. The transient model was used to simulate time-dependent stresses, such as seasonal irrigation activities. The model was calibrated to 13 months of recently collected data, from February 2010 through February 2011. This period of record was modeled as monthly stress periods, each of which had one time step (table 5). To calibrate the model, the steady-state set of calibration targets (i.e., observation wells) was used, except different target values were input for each month. Transient calibration was conducted by adjusting S values until observed transient water-level changes were reasonably replicated by the model.

The fractured bedrock aquifers were assigned an S value of 0.01. Because bedrock observation well data showed little to no seasonal change through the period of record, calibration efforts were not focused on the bedrock system. Instead, efforts were focused where a clear and relatively large seasonal fluctuation was observed in the irrigated portions of the colluvium and alluvium. Manual calibration produced an S value of 0.05 in the portion of the model representing the unconsolidated sediments aquifer near the bedrock. This value approximately rendered the observed water-level changes caused by seasonal changes in irrigation recharge. S values were increased to 0.08 for the unconsolidated sediments farther from the bedrock (figs. 21, 22).

Irrigation recharge and canal leakage were modified from the steady-state version of the model; recharge was applied from April 15 to October 15 to approximate the irrigation season. Diffuse recharge rates in the Scratchgravel Hills were held constant at those used in the steady-state model runs. The groundwater flow appeared as a fairly constant flux out of the hills throughout the year, most likely because water percolates through a thick unsaturated zone before reaching the water table, and faults and other features may impede the direct movement of groundwater to varying degrees.

Table 5. Stress periods and time steps in the 2010 transient model run.

Date	Stress Period Length (days)	No. of Time Steps
2/1/2010	28	1
3/1/2010	31	1
4/1/2010	30	1
5/1/2010	31	1
6/1/2010	30	1
7/1/2010	31	1
8/1/2010	31	1
9/1/2010	30	1
10/1/2010	31	1
11/1/2010	30	1
12/1/2010	31	1
1/1/2011	31	1
2/1/2011	28	1

Sensitivity Analysis

A sensitivity analysis was performed to assess the uncertainty in the model caused by uncertainty in the estimates of aquifer parameters. During the analysis, parameter values were adjusted systematically, such that one parameter was changed per model run while all other parameters remained at their calibrated values. The magnitude of change in heads from the calibrated heads was a measure of the sensitivity of the solution to the given parameter (Anderson and Woessner, 2002).

The sensitivity analysis was conducted on the steady-state model rather than the transient model due the relatively brief data record (1 year), and because little temporal change was observed, especially within the bedrock aquifer system. Tested parameters included recharge and K. In each simulation, a single parameter's values were adjusted. Each of the two parameters was adjusted four times (by +25%, -25%, +50%, and -50%), which resulted in a total of eight simulations. The RMS error was used to evaluate the model's sensitivity to each parameter change.

Decreases in both K and recharge produced larger RMS errors than increases in the parameter values (fig. 23). The model output was most sensitive to decreases in K. In contrast, RMS errors resulting from increases in recharge and K were relatively comparable.

The effect on the spatial distribution of head

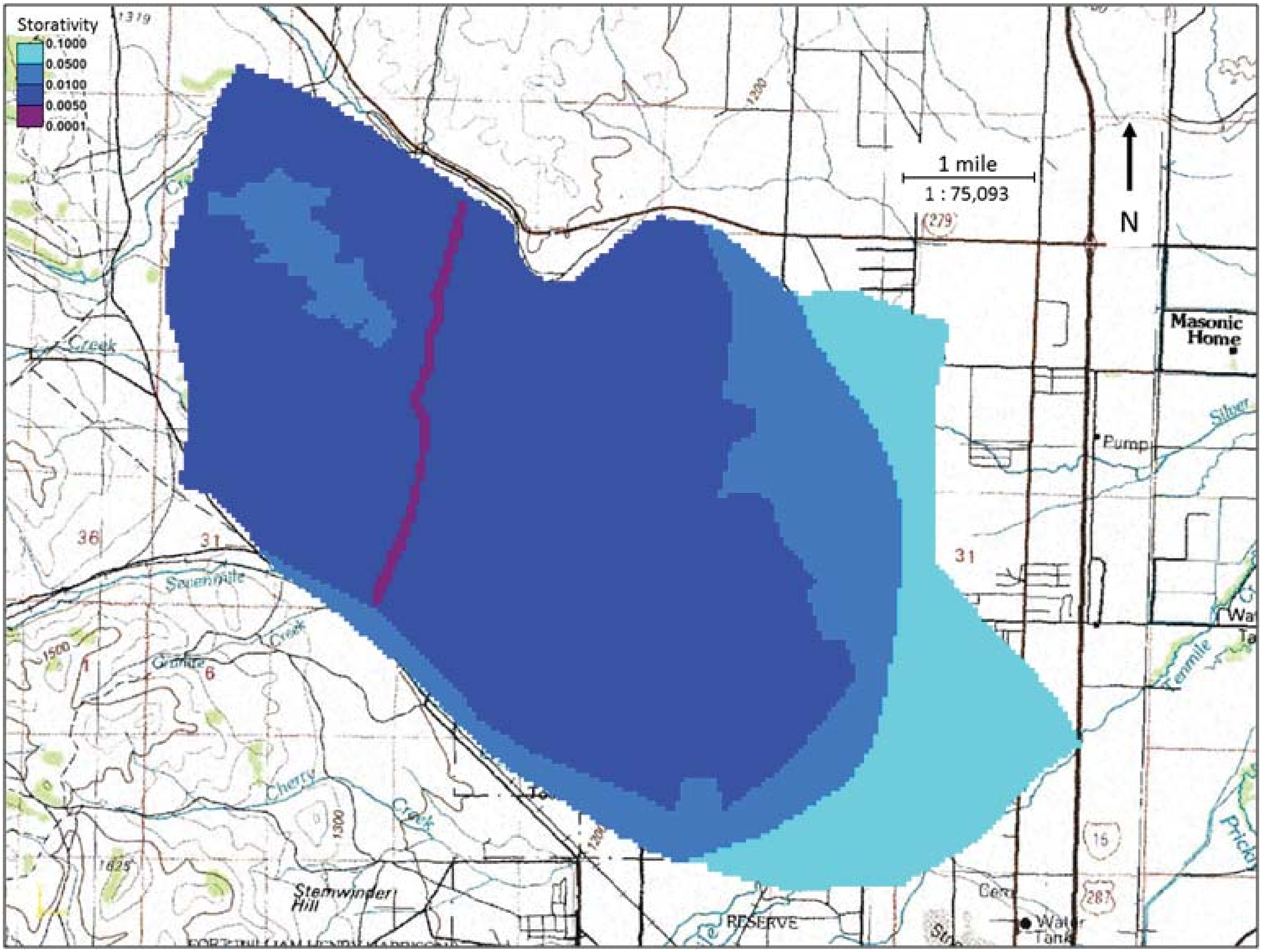


Figure 21. Storativity values were assigned to simulate observed seasonal groundwater-level f uctuations. The alluvium of the Helena Valley was assigned a value of 0.08, alluvium closer to bedrock was assigned a value of 0.05, and fractured bedrock was assigned a value of 0.01.

residuals was also examined. A spatial sensitivity analysis helps to identify areas where confidence in parameter estimates is most important and, conversely, where accurate estimates are less important. Thus, the analysis can identify areas where future data collection efforts should be focused. In the Scratchgravel Hills model, the analysis illustrated large head errors in the bedrock relative to the unconsolidated sediments due to the relatively low K values in the bedrock (figs. 24, 25). These results suggest that efforts to estimate K and recharge values should be more focused on the bedrock aquifers rather than the alluvial aquifer. Such data collection could also help to independently estimate parameters, thus improving the model fit and refining the conceptual understanding of the groundwater system.

The simulation results also revealed lower sensitivity near the eastern and western constant-head boundaries (figs. 24, 25). Due to the nature of a constant-head boundary condition, changes in head near such a boundary are inhibited. The constant-head boundaries would need to be altered to another kind of boundary condition in order to further evaluate parameter sensitivity in these two areas.

Model Verification

Model verification is a process in which calibrated parameters and stresses are used to reproduce a second set of field data; the process is intended to provide greater confidence in the model (Anderson and Woessner, 2002). Field data within the Scratchgravel Hills study area were limited

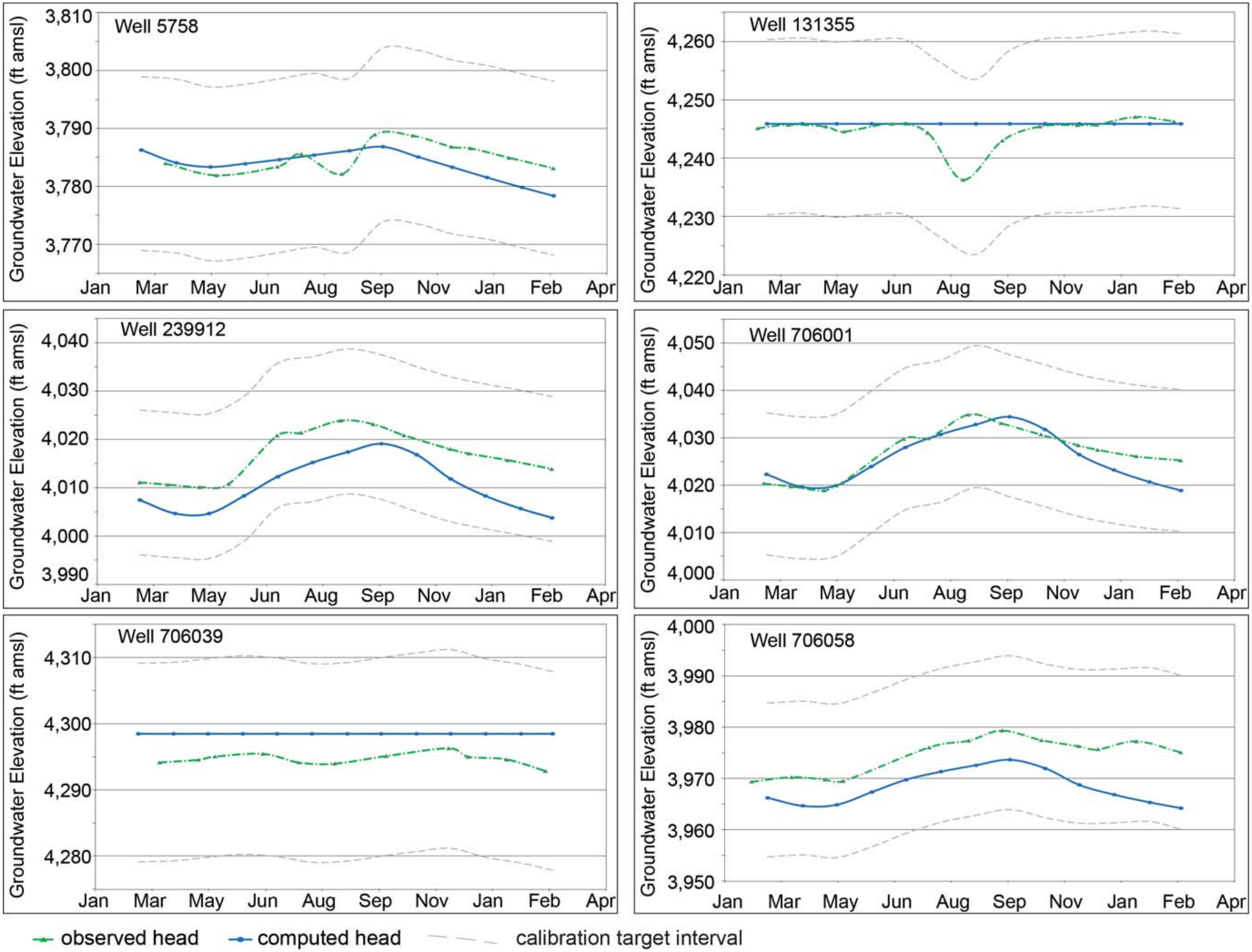


Figure 22. Hydrographs of observed water-level data were used to set storativity values for the model that reproduced observed water-level f uctuations. The upper and lower dashed lines show the range of acceptable calibration (the observed value ±15 ft). The period from February 2010 through February 2011 was used for calibration.

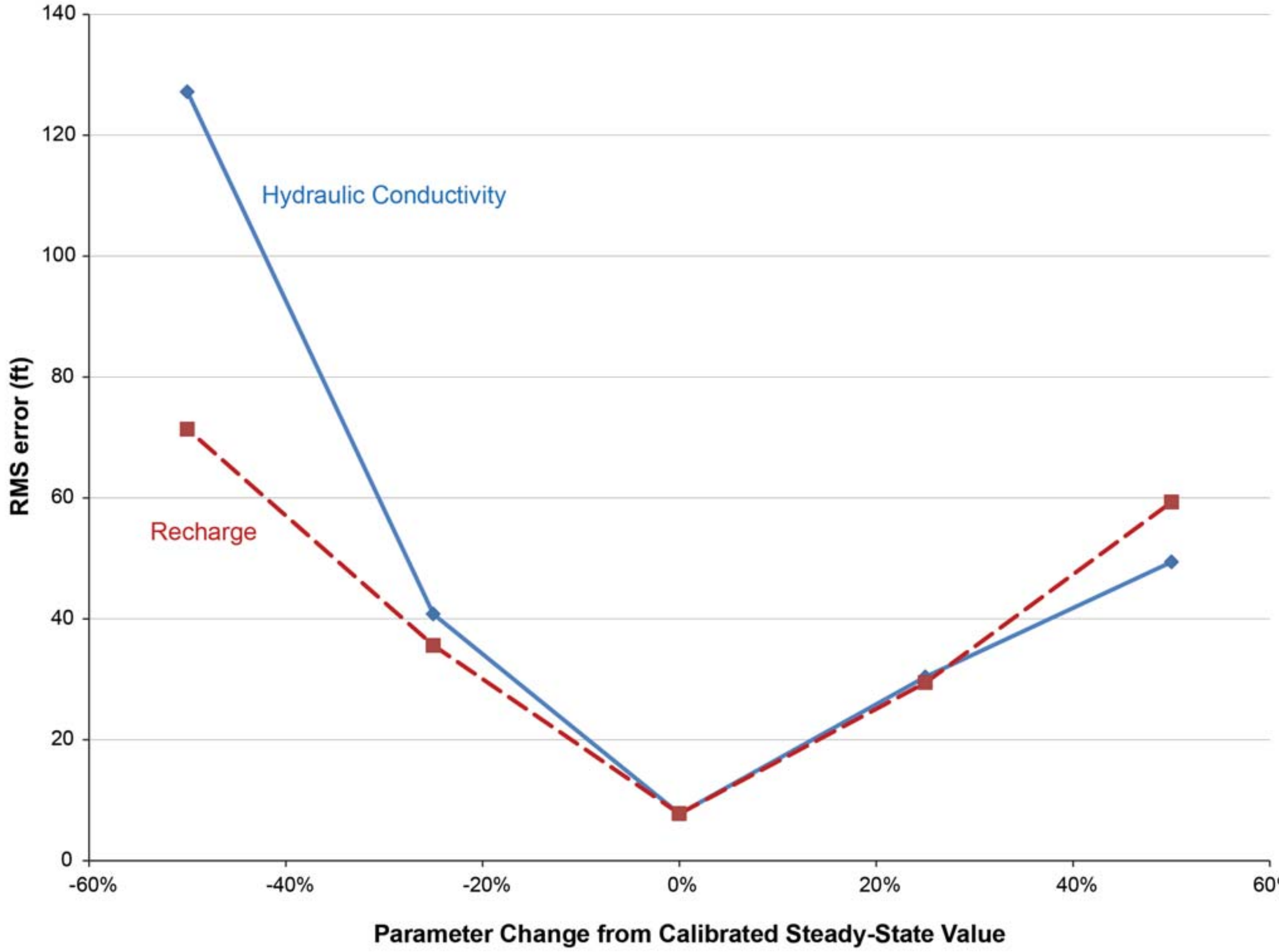


Figure 23. Root mean square (RMS) error caused by changing K and recharge values by various percentages.

outside of the 2010–2011 study period. The available water-level records did not constitute a second set of field data, so model verification was not possible. However, the model could be verified in the future if monitoring continues in the study area. In particular, model verification would be useful if subdivisions are developed; verification would test whether the modeled drawdown agrees well with the observed drawdown in area wells.

PREDICTIVE SIMULATIONS

Prediction is one of the three main applications of modeling (Anderson and Woessner, 2002). In the Scratchgravel Hills groundwater investigation, the modeling purpose was to predict the consequences of a proposed action; namely, the consequences of the proposed Cornerstone Estates development and its associated well withdrawals. However, the predictive modeling scenarios described below were not attempts to predict the real future; in other words, a given 20-year simulation was not intended to represent groundwater levels and groundwater flow that will occur in the next 20 years. Rather, the scenarios were intended to predict groundwater levels and groundwater flow under the hypothetical modeled conditions. In reality, future conditions will inevitably differ from the modeled conditions due to changes in climate, land use, and other factors.

A variety of scenarios were run to predict changes in groundwater elevations and in the groundwater budget. The baseline selected to evaluate impacts from the scenarios were the modeled transient conditions, which featured no development in the Cornerstone Estates area. Subsequent scenarios investigated the effects of various development approaches in Cornerstone Estates, which was the subdivision of greatest concern when the Green Meadow CGWA was established. Specific attention was given to the effects of varying well pumping rates and well locations. The pumping rates ranged from those needed for the subdivision's currently proposed 10-acre lots to those

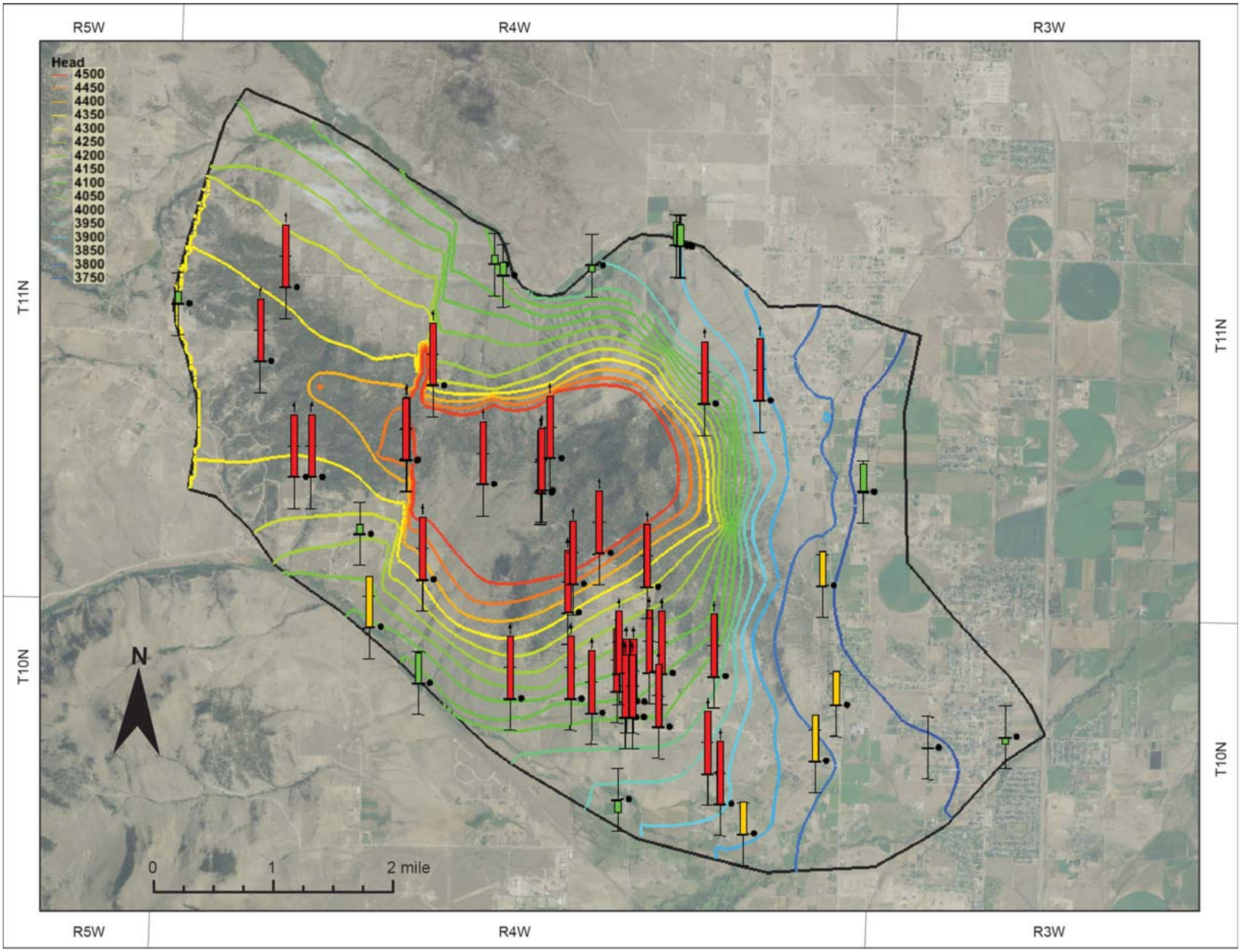


Figure 24. Potentiometric surface and head residuals at calibration targets resulting from a 50% decrease in K values. The vertical scales illustrate the target elevation (middle hachure), with colored bars showing the vertical difference between the target elevation and the computed head value. Green indicates head values within the set calibration criterion (15 ft); yellow indicates values within twice the calibration interval (30 ft); and red indicates head values beyond twice the calibration interval.

needed for the originally proposed 0.4-acre lots. The pumping well locations ranged from a single public water supply (PWS) well in the extreme southeast corner of the Cornerstone property (in the unconsolidated sediments aquifer) to one exempt well per lot (predominantly in the granite bedrock aquifer).

Predictive simulations can be made by extending the model stress periods into the future and specifying the stresses to be tested. In the Scratchgravel Hills predictive simulations, 240 1-month stress periods were set up to operate the model for 20 years. No stress (i.e., pumping) was applied for the first half of each simulation (10 years) in order to establish that water levels were stable. Pumping then commenced for the second half of the simulation (10 years); thus, each scenario simulated 10 years of an applied stress.

Four pumping scenarios were planned for the Scratchgravel Hills model: (1) one PWS well for 33 homes (i.e., 10-acre lots); (2) 33 wells for 33 homes; (3) one PWS well for 800 homes (i.e., 0.4-acre lots); and (4) 338 wells at 200-ft spacing (one per model cell) for 800 homes (table 6). Drawdown was so great in both 0.4-acre-lot scenarios that model cells went dry in the first year of pumping, and the simulations could not be completed. In order to complete the high-density simulations, pumping rates were reduced to one-third the originally modeled value. The reduced rates were suf-

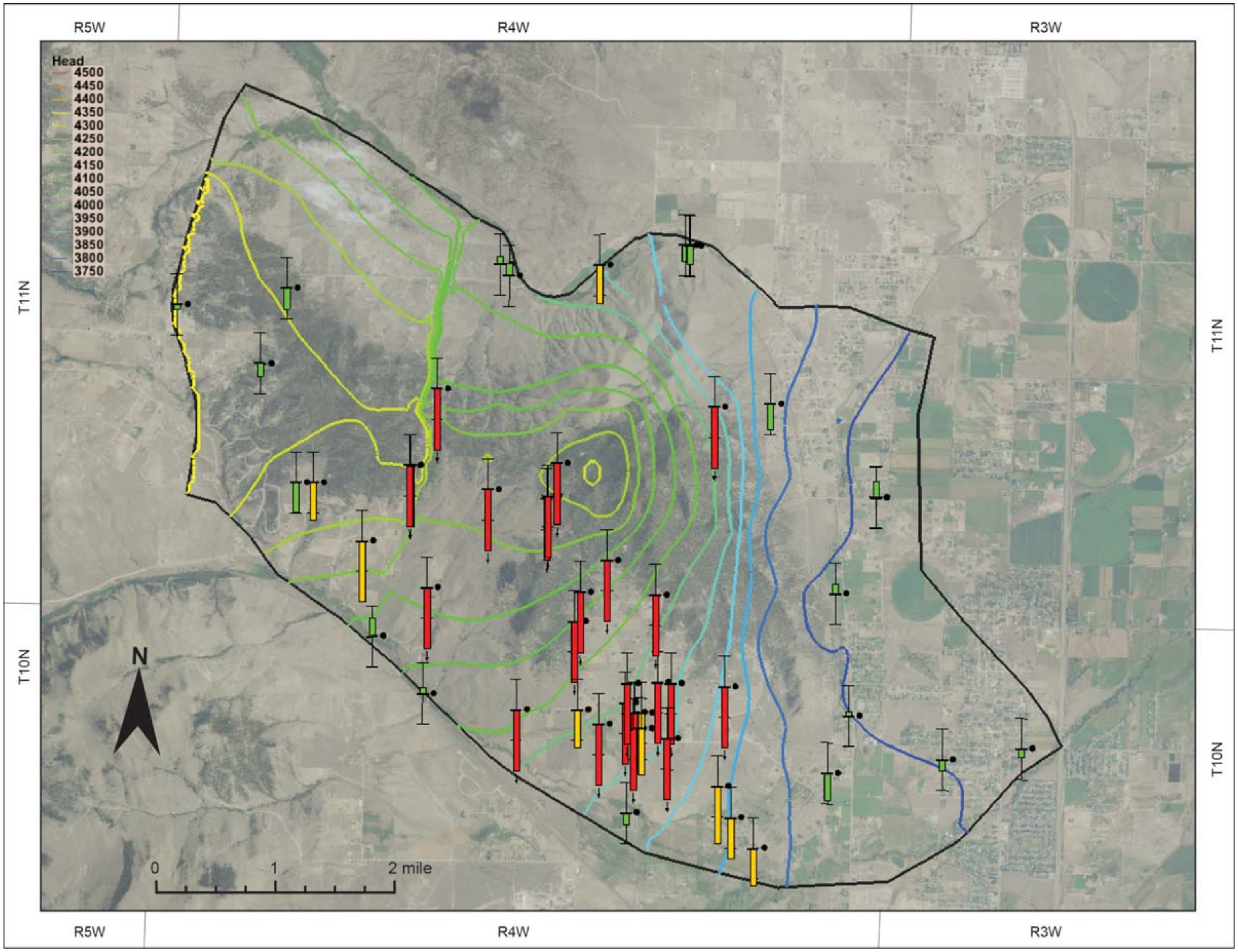


Figure 25. Potentiometric surface and head residuals at calibration targets resulting from a 50% decrease in recharge values.

ficient to supply water to 1.2-acre lots (267 homes) or, interpreted alternatively, the new rates represented water-use restrictions in the 0.4-acre lots that reduced water use by two-thirds. These lower pumping rates were used for Scenarios 3 and 4. As in the groundwater budget analysis (Groundwater Budget section), pumping rates were based on groundwater usage of the Townview Subdivision in the North Hills of Helena (fig. 26 and table 6). Each well was screened throughout layer 1 of the grid. In the PWS-well scenarios (Scenarios 1 and 3), the thickness of the well's cell was 289 ft; in the well-field scenarios (2 and 4), the wells' cells ranged in thickness from 200 to 343 ft.

The results of each scenario are described below. Table 7 compares the quantitative details of the results. For comparison purposes, a drawdown of one ft was set as the threshold for defining the zone of influence of the pumping well(s). The results of each scenario were quantified using the maximum radial distance that the one-ft drawdown contour extended from the point of maximum drawdown. Because the surface-water bodies in the vicinity of the proposed subdivision were modeled as losing streams (i.e., Sevenmile Creek and Sunny Vista Canal), impacts to surface water were not analyzed.

Scenario 1

Scenario 1 featured one PWS well supplying water to homes in 10-acre lots of the proposed subdivision, which amounted to the consumptive use of 33 homes. The PWS well was placed in the southeast corner of the subdivision, where the unconsolidated sediments were the thickest and

Table 6. Pumping well numbers and pumping rates in the predictive scenarios.

			Scenario 1			Scenario 2			Scenario 3			Scenario 4		
			33-Homes - 10 Ac - PWS			33-Homes - 10 Ac			800-homes - PWS			800-homes - 200' well spacing		
		No. of Wells		1			33			1			338	
		gal/year		5243164			5243164			127107000			127107000	
Month	Days	% by Mo	total gal	gal/well	gpm/well	total gal	gal/well	gpm/well	total	gal/well	gpm/well	total	gal/well	gpm/well
Jan	31	0.30%	15729	15729	0.35	15729	477	0.01	381321	381321	8.54	381321	1128	0.03
Feb	28.25	0.30%	15729	15729	0.39	15729	477	0.01	381321	381321	9.37	381321	1128	0.03
Mar	31	0.40%	20973	20973	0.47	20973	636	0.01	508428	508428	11.39	508428	1504	0.03
Apr	30	0.60%	31459	31459	0.73	31459	953	0.02	762642	762642	17.65	762642	2256	0.05
May	31	10.20%	534803	534803	11.98	534803	16206	0.36	12964914	12964914	290.43	12964914	38358	0.86
Jun	30	18.20%	954256	954256	22.09	954256	28917	0.67	23133474	23133474	535.50	23133474	68442	1.58
Jul	31	26.20%	1373709	1373709	30.77	1373709	41628	0.93	33302034	33302034	746.01	33302034	98527	2.21
Aug	31	26.40%	1384195	1384195	31.01	1384195	41945	0.94	33556248	33556248	751.71	33556248	99279	2.22
Sep	30	14.20%	744529	744529	17.23	744529	22561	0.52	18049194	18049194	417.81	18049194	53400	1.24
Oct	31	2.40%	125836	125836	2.82	125836	3813	0.09	3050568	3050568	68.34	3050568	9025	0.20
Nov	30	0.50%	26216	26216	0.61	26216	794	0.02	635535	635535	14.71	635535	1880	0.04
Dec	31	0.20%	10486	10486	0.23	10486	318	0.01	254214	254214	5.69	254214	752	0.02

*The pumping rates in Scenarios 3 and 4 were lowered to 1/3 of the original rates due to drying of model cells.

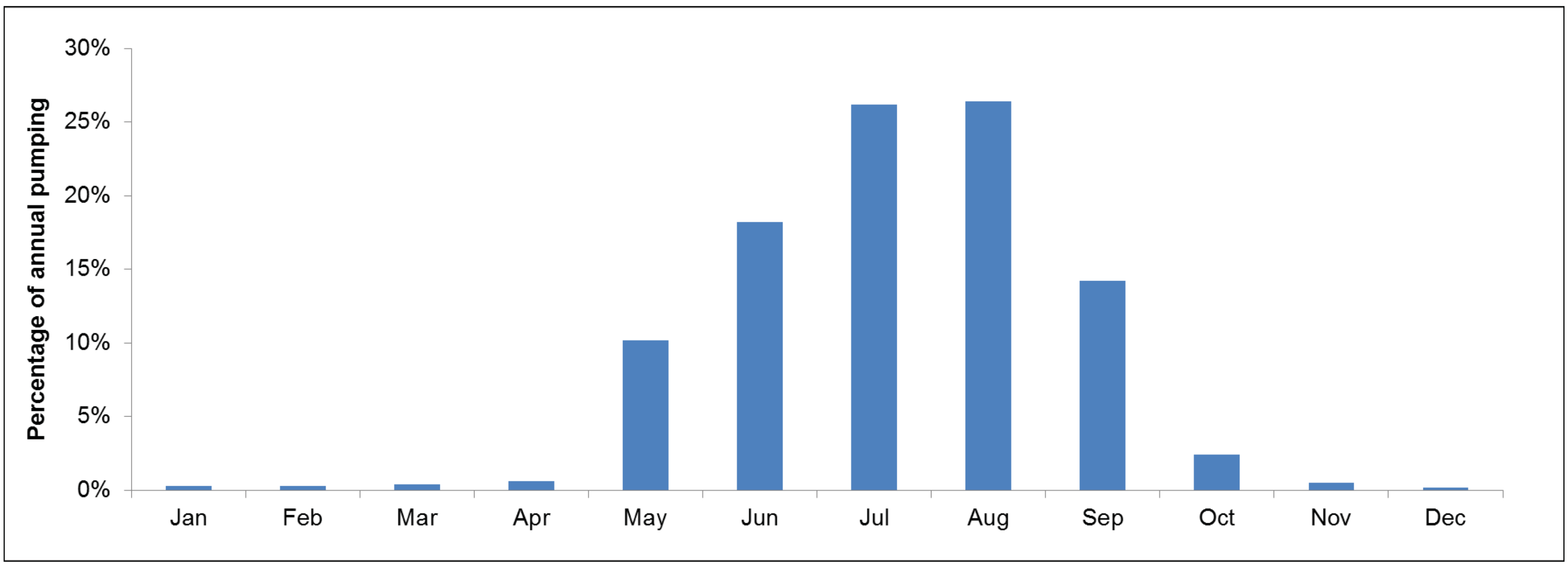


Figure 26. Graphical display of monthly pumping rate variation in predictive model scenarios.

Table 7. Predictive scenario results.

Scenario	Maximum Radius of 1 ft of Drawdown (miles) N	E	S	W	Maximum Drawdown (ft)	Time of Maximum Drawdown*[1]	Maximum Drawdown Location
1	0.47	0.33	0.31	0.36	11.2	August of Year 20	PWS well
2	0.86	0.68	0.52	0.71	7.4	August of Year 20	500 ft N of well field center
3	1.33	0.79	0.54	0.87	112	August of Year 20	PWS well
4	1.92	1.14	0.75	~2.0[2]	52.5	September of Year 20	500 ft NE of well field center

*The timing of maximum drawdown did not coincide with the maximum radius of 1 ft of drawdown. The maximum radius occurred 1 to 2 months after the maximum drawdown in Scenarios 1 and 2, and at the end of the simulation (December of Year 20) in Scenarios 3 and 4.

[1]Pumping began in Year 11 of each simulation, and so Year 20 represents 10 years of pumping.

[2]The western maximum radius of the 1 ft drawdown contour was approximated in Scenario 4 because it hit the grid boundary.

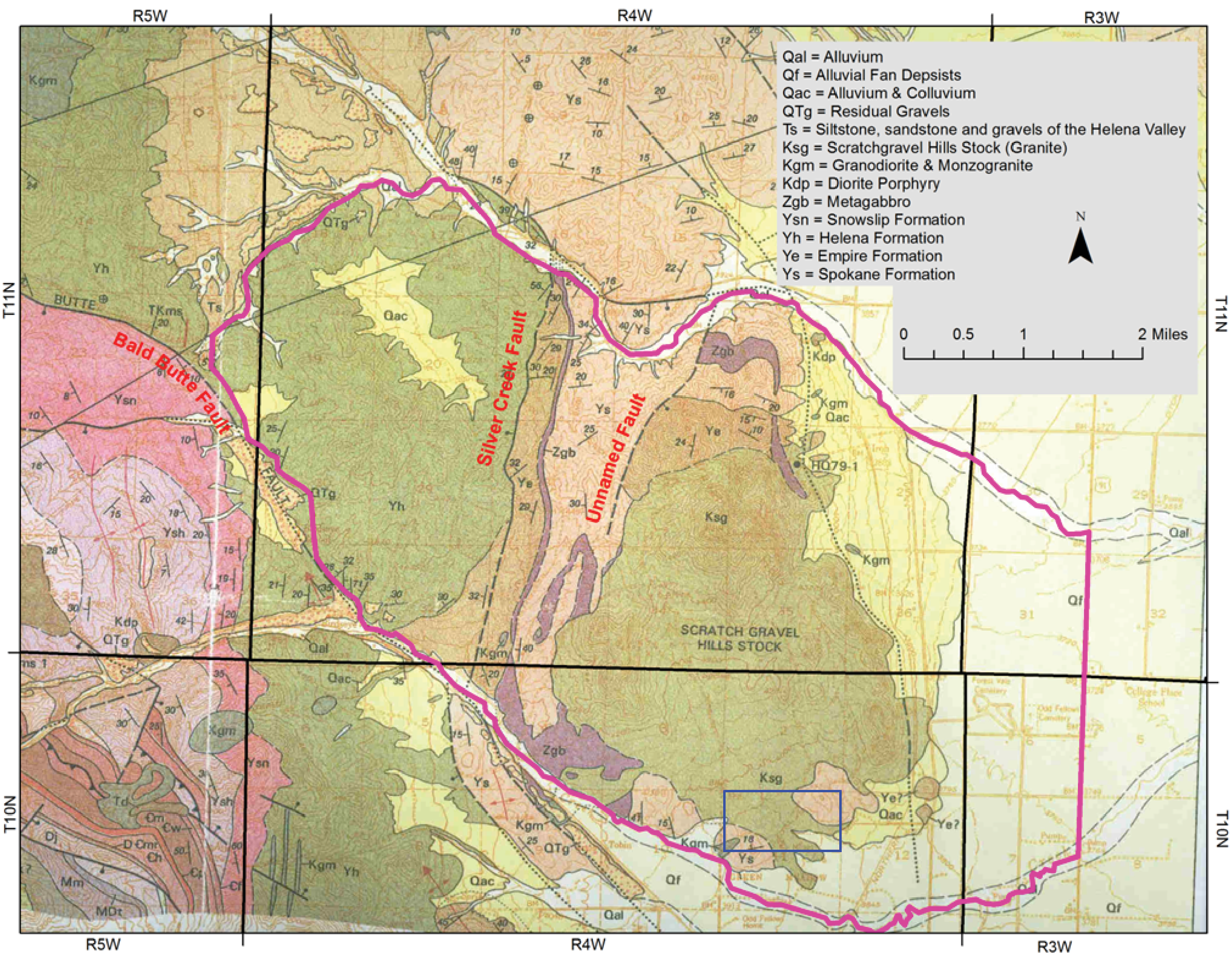


Figure 27. Geologic map of the Scratchgravel Hills study area, showing the location of the proposed Cornerstone Estates (blue rectangle in T. 10 N., R. 4 W.). Note that Quaternary fan deposits(Qf) are present in the southeast corner of the property. The PWS well (featured in Scenarios 1 and 3) was strategically placed in that corner to maximize the well's productivity.

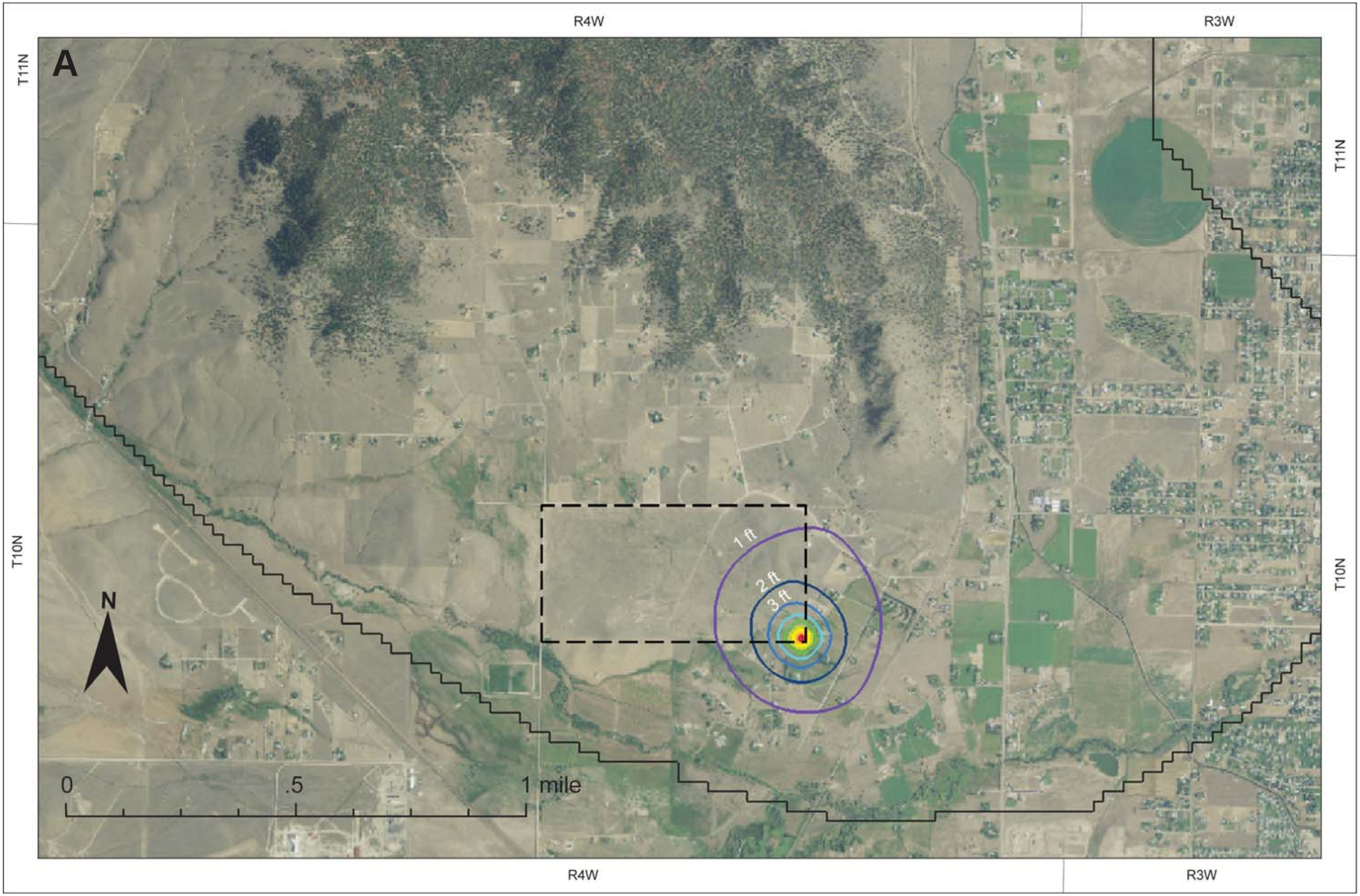
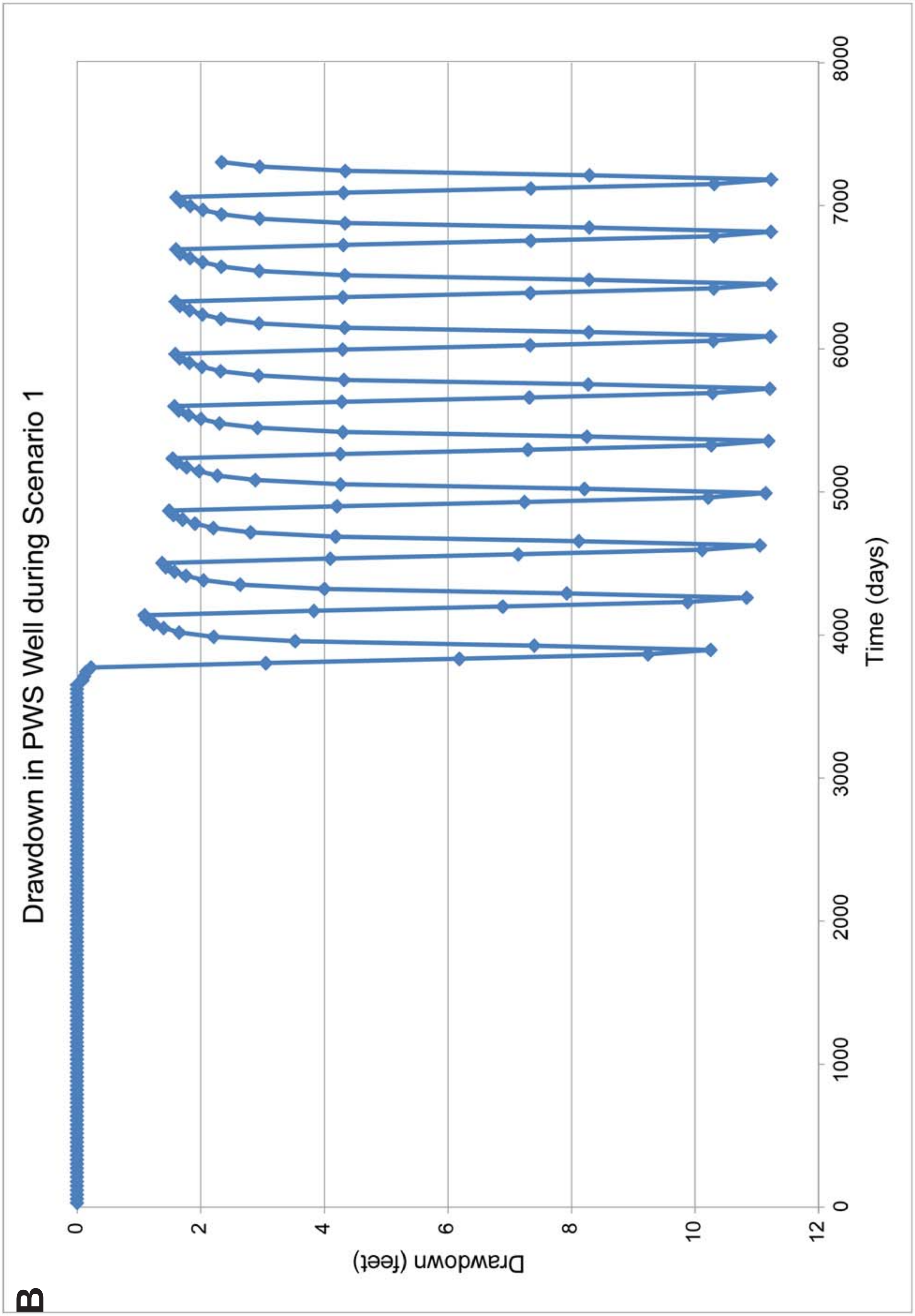


Figure 28. Scenario 1 results showed the projected impact on groundwater levels from development of the Cornerstone Estates area (dashed outline) using one PWS well and 10-acre lots. The maximum radius of inf uence extended 0.47 miles from the PWS well (A). Maximum drawdown was on the order of 11 ft, and water levels had nearly stabilized by the end of the simulation (B).


B
Drawdown in PWS Well during Scenario 1
Drawdown (feet)
0
2
4
6
8
10
12
Time (days)
0
1000
2000
3000
4000
5000
6000
7000
8000

most transmissive (fig. 27). The simulation resulted in a maximum drawdown of 11.2 ft, which occurred at the PWS well in July of the final year of pumping (year 20). The increase in drawdown from year to year decreased over time; the maximum drawdown in year 20 was 0.002 ft greater than in year 19. The maximum radius of influence was 0.47 miles and occurred north of the PWS well (fig. 28).

Scenario 2

Scenario 2 used the same cumulative consumptive use as Scenario 1, but with a different well configuration. Rather than a PWS well, Scenario 2 featured one domestic well per 10-acre lot, for a total of 33 wells. The distribution of these wells was based on the currently proposed development (J. Larson, written commun., 2010). The simulation resulted in a maximum drawdown of 7.4 ft, which occurred in August of the final year of pumping. The increase in drawdown from year to year decreased over time; the maximum drawdown in year 20 was 0.02 ft greater than in year 19. The maximum radius of influence was 0.86 miles and occurred north of the pumping center (fig. 29).

Scenario 3

Like Scenario 1, Scenario 3 featured a single PWS well. However, it was designed to supply water to homes in 0.4-acre lots of the proposed subdivision, which amounted to 800 homes. The PWS well was placed in the same location as in Scenario 1. The simulation could not be completed due to the drying of the cell representing the PWS well. The high rate of pumping caused the water level to drawdown below the bottom of the cell, which was 289 ft thick. This drawdown occurred 6 months into the first year of pumping. Additional simulation changes were attempted, such as varying the pumping rate, and adding PWS wells to distribute drawdown impacts over a larger area (table 8). Results showed that, in a PWS well scenario, the maximum stress the model could sustain involved a single PWS well pumping at 1/3 of the original rate. This result is strictly applicable to the model because it is a function of layer thickness; however, it also implies limits to the aquifer's productivity in this area. For instance, adding two pumping wells across the subdivision did not reduce drawdown because all but the southeastern corner of the property is underlain by the granite bedrock (fig. 27), and pumping from the granite aquifer results in relatively large drawdown levels.

At 1/3 of the originally specified pumping rates (an annual average of 81 gpm rather than 242 gpm), the PWS well produced a maximum drawdown of 112 ft, which occurred in July of the final year of pumping. The rate of drawdown from year to year decreased over time but still continued into the final year of the simulation; the maximum drawdown in year 20 was 0.03 ft greater than in year 19. The maximum radius of influence was 1.33 miles and occurred north of the PWS well; the radius extended beyond the subdivision boundary to the north, east, and south (fig. 30). The southern extent of the model grid was expanded in Scenario 3 to prevent the well's cone of depression from reaching the model boundary, which acts as a flow barrier (fig. 30). This grid expansion was also used in Scenario 4. The results of Scenarios 1 and 2 were unaffected by the expansion.

Table 8. Attempted Scenario 3 simulations.

Scenario	PWS Well Pumping Rates (average annual gpm)			Maximum Drawdown (ft)	Time of Maximum Drawdown[1]
	$PWS_{original}$	PWS-2[2]	PWS-3[2]		
3A	242	—	—	>255	April of Year 11
3B	81	81	81	>255[3]	June of Year 11
3C	121	—	—	>255	August of Year 11
3 (final)	81	—	—	112	September of Year 20

[1]Pumping began in Year 11 of each simulation; thus, Year 20 represents 10 years of pumping.

[2]PWS-2 was located in the northwest corner of the subdivision property; PWS-3 was located in the southwest corner of the property.

[3]In Scenario 3B, drawdown exceeded the bottom of each of the wells' cells; drawdown exceeded 255 ft at $PWS_{original}$, 173 ft at PWS-2, and 188 ft at PWS-3.

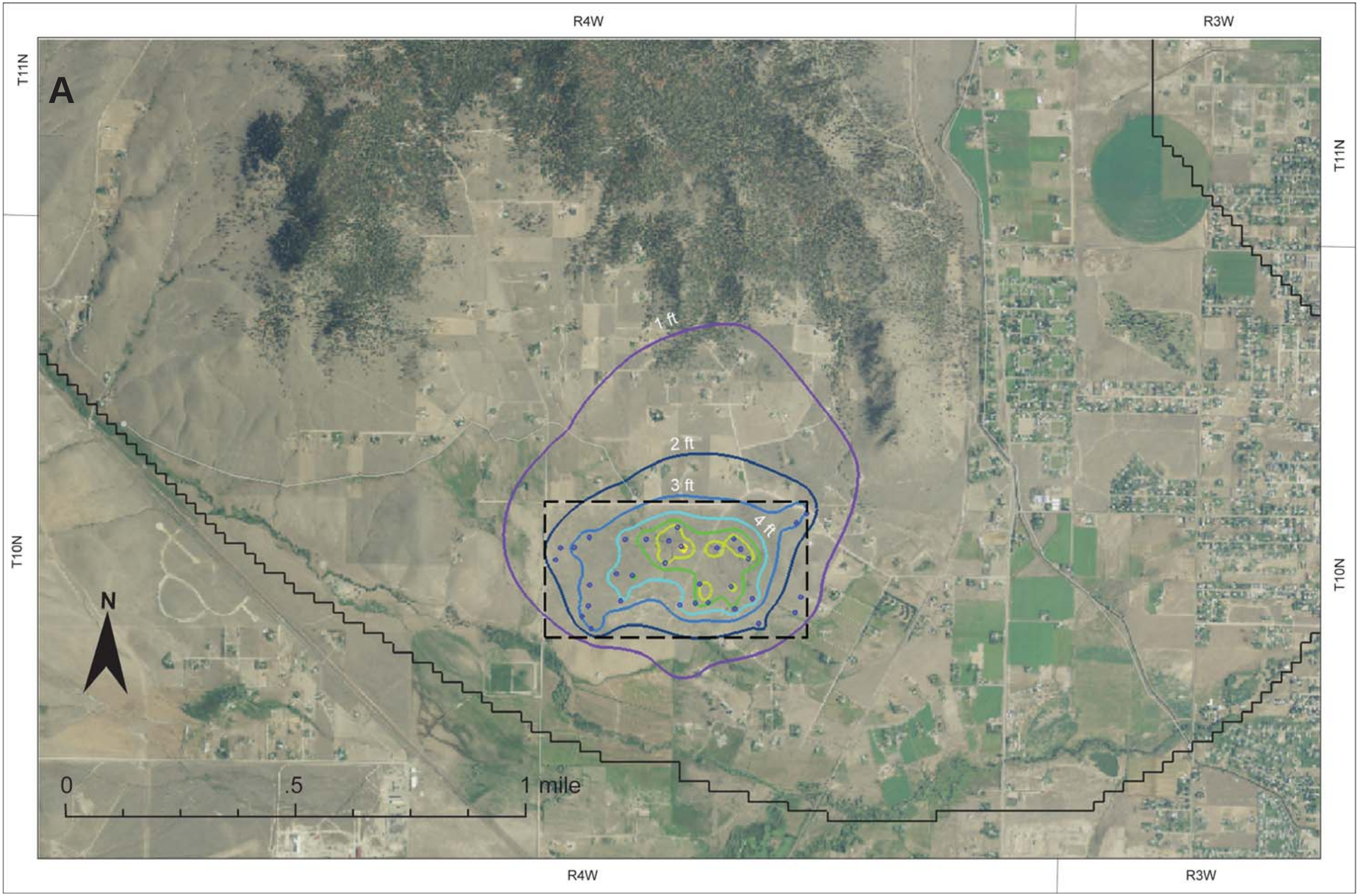


Figure 29. Scenario 2 results showed the projected impacts on groundwater levels from development of the Cornerstone Estates area (dashed outline) using a domestic well (blue dots) for each lot and 10-acre lots. The maximum radius of inf uence extended 0.86 miles beyond the outermost well (A). Maximum drawdown was on the order of 7 ft, and water levels had nearly stabilized by the end of the simulation (B).

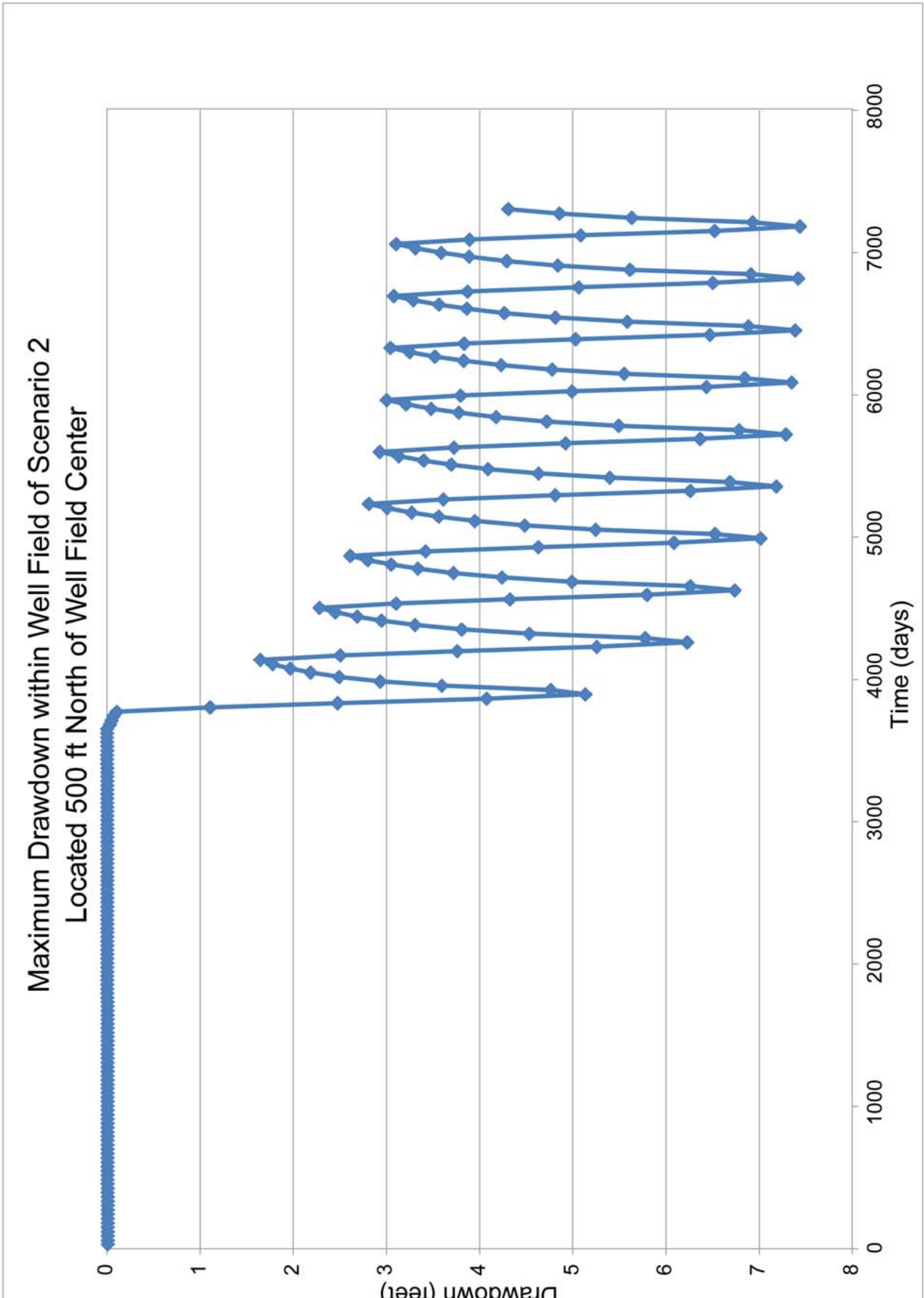

B
Maximum Drawdown within Well Field of Scenario 2
Located 500 ft North of Well Field Center
Drawdown (feet)
0
1
2
3
4
5
6
7
8
Time (days)
0
1000
2000
3000
4000
5000
6000
7000
8000

Figure 29B.

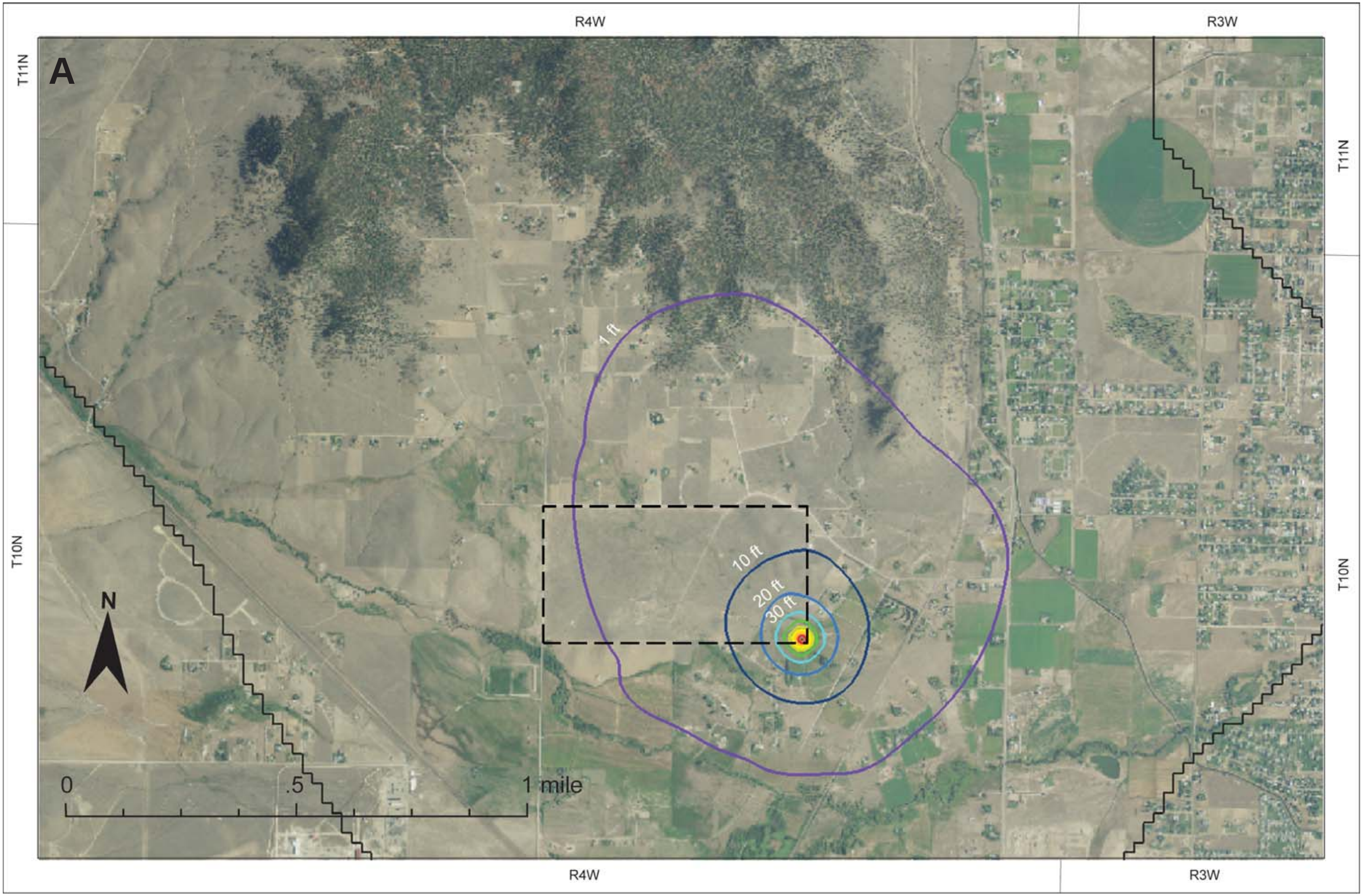


Figure 30. Scenario 3 results showed the projected impacts on groundwater levels from development of the Cornerstone Estates area (dashed outline) using one PWS well and 1.2-acre lots. The maximum radius of inf uence extended 1.33 miles beyond the PWS well (A). Maximum drawdown was on the order of 112 ft, and water levels had nearly stabilized by the end of the simulation (B).

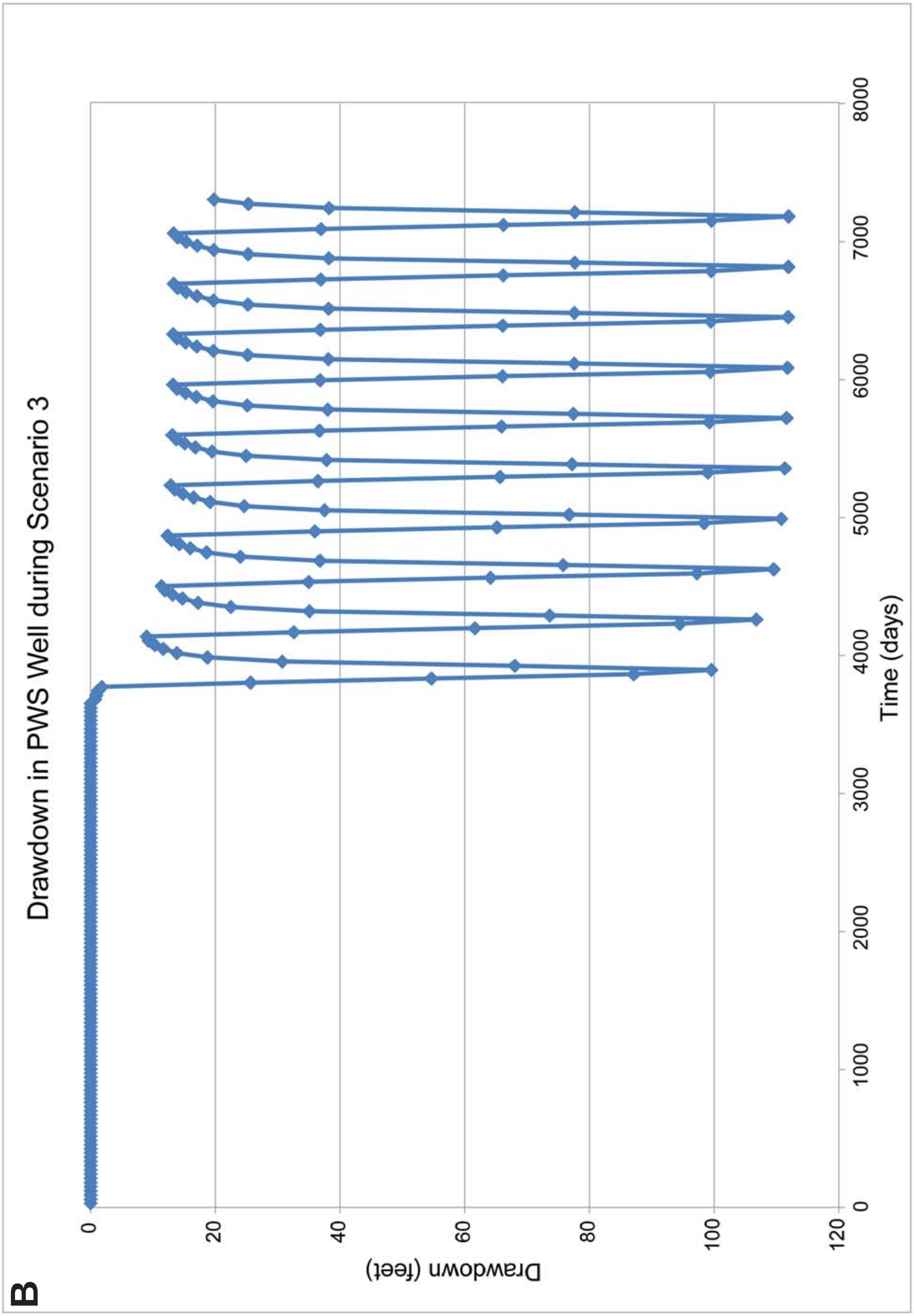

B
Drawdown in PWS Well during Scenario 3
Drawdown (feet)
0
20
40
60
80
100
120
Time (days)
0
1000
2000
3000
4000
5000
6000
7000
8000

Figure 30B.

Scenario 4

Scenario 4 used the same cumulative pumping rates as Scenario 3, but it featured a well field rather than a PWS well. Wells were arranged in a grid with one well per 200 ft by 200 ft cell (fig. 31). The cumulative pumping rate was held at 1/3 of the originally specified rate for comparison to Scenario 3. The simulation resulted in a maximum drawdown of 52.5 ft, which occurred in August of the final year of pumping. Drawdown from year to year decreased over time but still continued until the end of the simulation; the maximum drawdown in year 20 was 0.26 ft greater than in year 19. The maximum radius of influence was roughly 2 miles and occurred west–northwest of the pumping center; the radius extended beyond the subdivision boundary in all directions. This distance was approximate because the cone of depression reached the edge of the model grid. That portion of the model edge was a no-flow boundary. In reality, bedrock lies west of the model grid, which might also act as a barrier to flow, given its low transmissivity relative to the unconsolidated sediments (fig. 31).

Scenario Summary

A few model results were common in all four simulations. For instance, water levels continued to decline throughout each 20-yr simulation, though the rate of drawdown decreased with time. Also, the zone of influence was consistently greatest to the north and west of the pumping center. Because the north and west areas are upgradient of the pumping center and they contain relatively low K values, this larger northwestern influence was expected.

Maximum drawdown occurred at the pumping well for the PWS well scenarios (1 and 3), whereas in the well field scenarios (2 and 4), maximum drawdown occurred about 500 ft northeast of the well field's geographic center. This off-center location was likely caused by the K distribution of the grid cells; the K values were slightly lower in the northeast portion of the well field than in the center, and greater drawdown tended to occur in lower-K areas.

Results showed the maximum vertical drawdown to be smaller for the well field scenarios than the PWS well scenarios. However, the lateral zone of influence was larger in the well field scenarios due to the selective placement of the PWS well in the relatively productive unconsolidated sediments.

Last, results revealed that both the lateral and vertical extent of drawdown increased substantially with denser development. In Scenario 3, the model could not sustain more than 1/3 of the originally specified pumping rate for 0.4-acre lots. Pumping more than 1/3 of the original rate immediately lowered the water level of the well's cell below the cell bottom. This caused the simulated pumping to cease, and the scenario could not be completed. The maximum radius of influence in Scenarios 1 and 2 lagged 1 to 2 months behind the occurrence of maximum drawdown. In the scenarios featuring greater withdrawals (Scenarios 3 and 4), the maximum radius of influence occurred in the final stress period of the simulation (December of Year 20). Both Scenarios 3 and 4 exhibited a pattern in which the radius gradually increased throughout the simulation despite a decrease in withdrawals during the winter months. This gradual expansion would likely continue if the simulation ran longer than 20 years.

SUMMARY AND CONCLUSIONS

Assumptions and Limitations

The groundwater model served as a useful tool in developing the conceptual model and evaluating potential future scenarios; however, the model does have limitations. For example, the model was not intended to accurately simulate phenomena at scales finer than the design scale. In the model, certain parameter values, such as irrigation canal recharge, were assumed uniform. In a smaller area model, such assumptions would not necessarily be appropriate. Likewise, while it was considered valid to treat the fractured and faulted bedrock as porous media from an area-wide perspective, the geometry of fractures and faults at a specific site strongly influence local groundwater conditions.

Model results were also more sensitive to some parameters than others. For example, during the calibration process it was evident that model head results were more sensitive to varying K and recharge in the bedrock aquifers than in the unconsolidated sediments aquifer. Varying K and recharge within the unconsolidated sediments aquifer produced relatively little change in head values; consequently, a given array of heads could

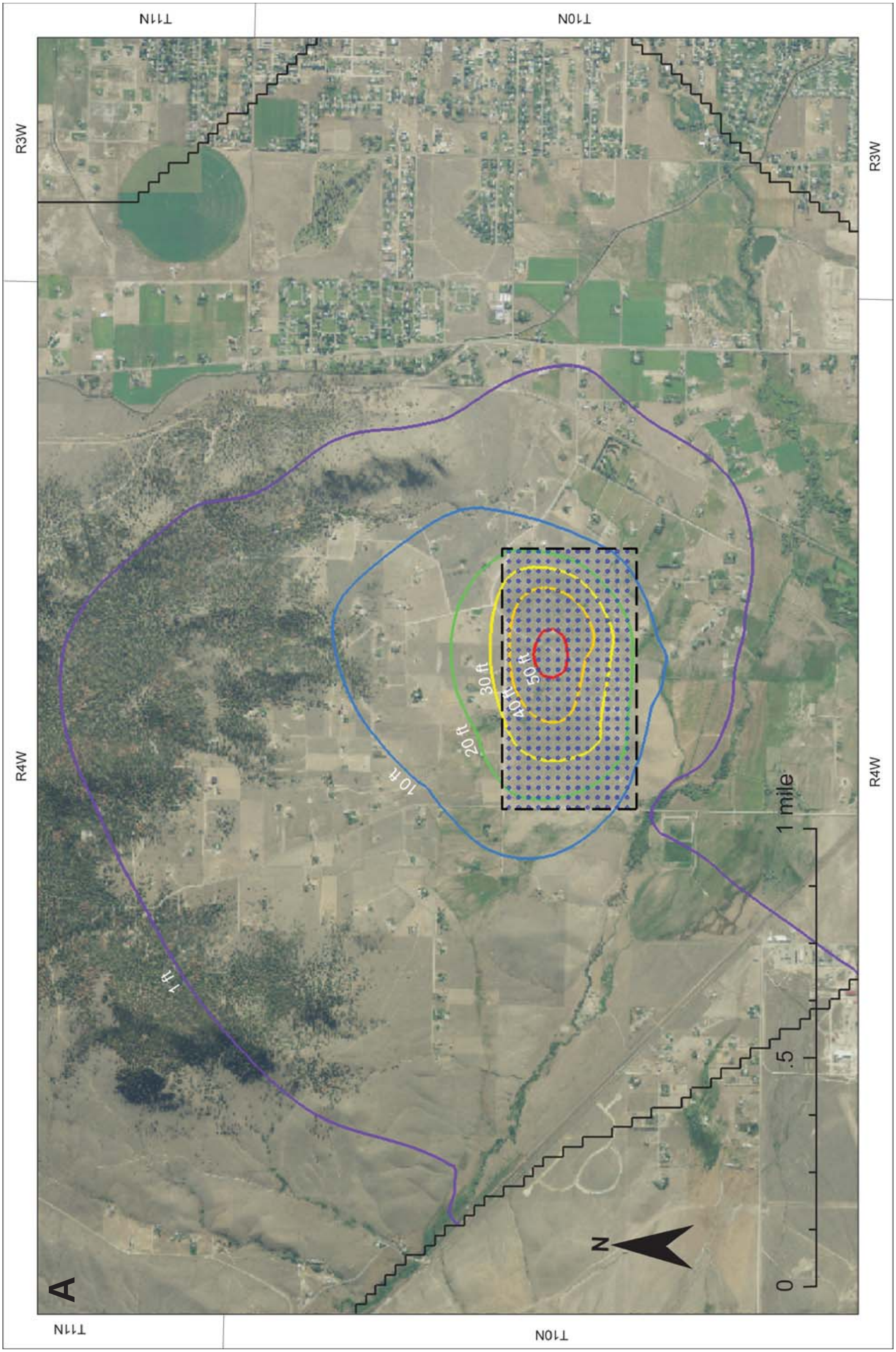


Figure 31. Scenario 4 results showed the projected impacts on groundwater levels from development of the Cornerstone Estates area (dashed outline) using a well in each cell (domestic wells; B) and 1.2-acre lots. The maximum radius of inf uence extended 2 miles beyond the outermost well (A). Maximum drawdown was on the order of 52 ft, and water levels did not stabilize during the model run (B).

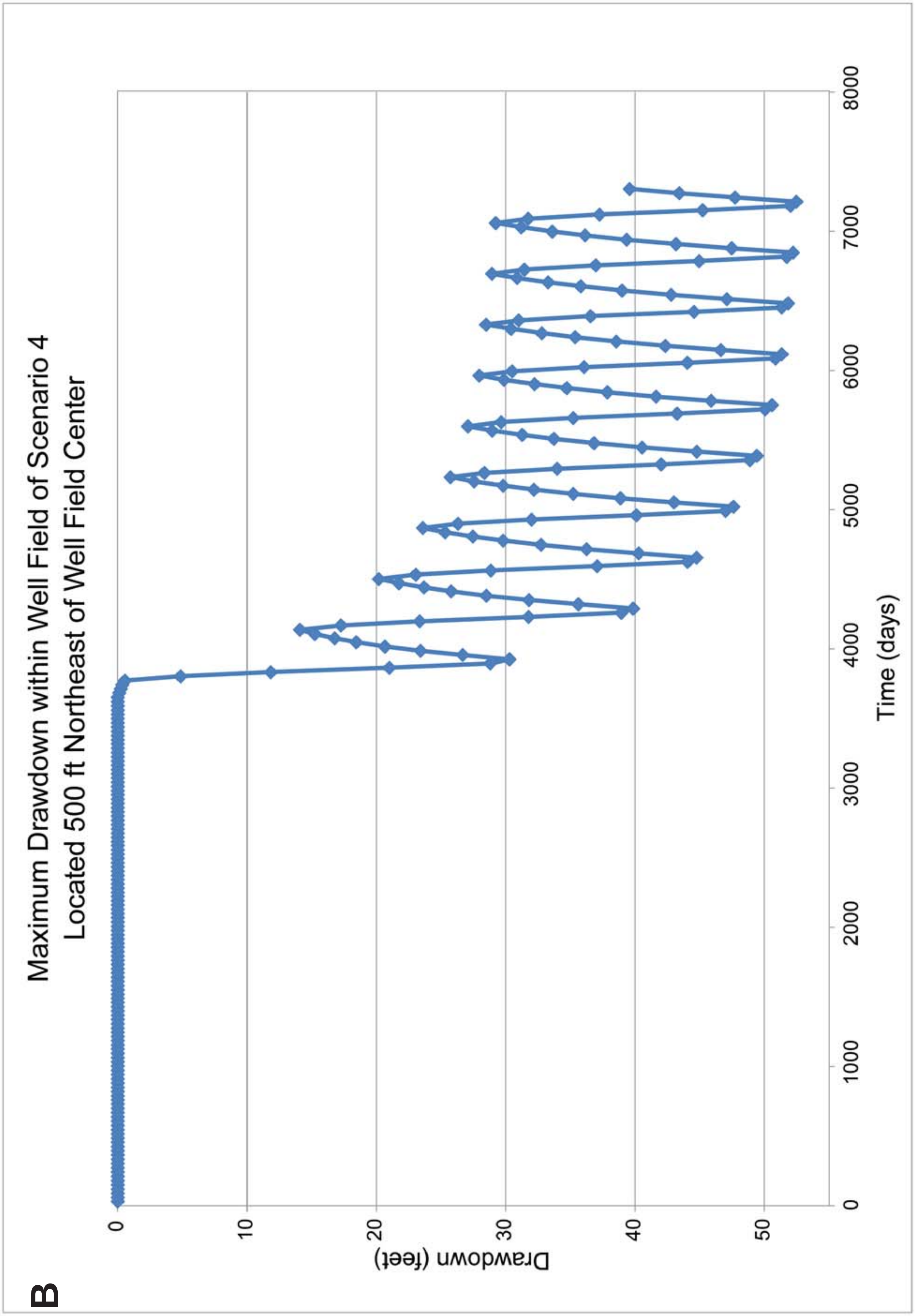

B
Maximum Drawdown within Well Field of Scenario 4
Located 500 ft Northeast of Well Field Center
Drawdown (feet)
0
10
20
30
40
50
Time (days)
0
1000
2000
3000
4000
5000
6000
7000
8000

Figure 31B.

be a non-unique solution. More detailed data for precipitation and aquifer properties would aid in independently estimating these parameters.

A lack of long-term monitoring records also presented modeling limitations. For example, due to the constraints of a 1-year dataset, 2010 conditions were assumed to approximate steady-state conditions during model calibration. Similarly, in the predictive scenarios, climatic conditions were held constant for 20 years. Future climatic conditions cannot be determined now, so this was a necessary and valid approach. However, it did eliminate normal variations, such as high and low recharge years.

The predictive scenarios represented system-scale effects of applied stresses, and they were based on data available at the time of model construction. There will undoubtedly be new information to incorporate into future groundwater model versions. Individuals who plan to operate the model should read this report, review the derivation of model parameters, and use caution in interpreting results, especially if any stress is located near the boundaries of the model. Modeling a subset of the current model domain may be appropriate to address specific issues. In such models, the aquifer characteristics and groundwater fluxes in the present model should serve as a starting point rather than the final analysis; parameters should be modified locally where new data warrant it.

Model Predictions

The groundwater model was used to evaluate several pumping scenarios in the proposed Cornerstone Estates development. The model showed that development of the Cornerstone Estates on 10-acre lots resulted in the 1-ft drawdown contour extending approximately 0.5 mile. If the area was instead developed on 0.4-acre lots with bedrock wells, as originally proposed, a substantial increase in drawdown would occur. This scenario was not fully quantified due to the occurrence of dry cells in the model.

Groundwater modeling was also used to evaluate the difference in impacts from exempt wells relative to PWS wells. If aquifer properties are fairly homogeneous across a development area, and a PWS well is placed in the center of the development, the model results suggest that the drawdown at the edge of the development area and beyond would be virtually the same as would result from a series of exempt wells. However, in terms of water management, there are certain advantages to PWS wells. PWS wells can be preferentially located where aquifers are the most productive (as was the case in the predictive scenarios) or otherwise located to minimize drawdown impacts on neighboring wells. In addition, water conservation strategies may be more easily implemented with a metered PWS system. A PWS system would also be easier to monitor and protect from contamination.

Recommendations

Model results concurred with the Scratchgravel Hills study findings. Namely, the study showed that the granitic core of the Scratchgravel Hills and the Helena Formation are particularly limited in their ability to supply water to wells. Current lot sizes on these units are typically 10 acres or more, and no regional groundwater decline has been observed. Given the low productivity of these units, development at a density greater than one home per 10 acres could have notable impacts on groundwater levels. Defining groundwater-level drawdown targets would aid in identifying appropriate monitoring and follow-up actions. For example, a 20-ft decline in groundwater levels would cause 10 percent of the wells in the Green Meadow CGWA to become unusable. These wells would need to be deepened, or abandoned and replaced. The target groundwater levels would likely be determined by measuring groundwater elevations in dedicated monitoring wells. Once target groundwater levels are defined, groundwater modeling should be conducted to determine what (if any) control measures would be needed to prevent unacceptable groundwater declines. This approach should allow effective but not overly restrictive controls to be adopted. Long-term monitoring would be needed to ensure that target groundwater levels are maintained; modification of the controls could be warranted if the target groundwater levels are not achieved. Long-term monitoring would also increase confidence in the model by providing a longer record of observations to simulate. This would allow for better calibration and enhance the model's predictive capabilities.

Several years after publication of this report, a postaudit of the model would be beneficial. The postaudit would use the long-term monitoring data (recommended above) to test whether the model's predictions were correct (Anderson and Woessner, 2002). It is also recommended that if site-specific decisions are needed, more detailed data from that site be collected and incorporated into the decision-making process. In particular, if geologic conditions are encountered that differ from those assumed in the model (e.g., the presence of a fault), the model must be modified to incorporate such features. Further data collection, especially with regard to precipitation-derived recharge and K in the bedrock aquifer system, would also benefit the existing model by making independent parameter estimation more feasible.

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APPENDIX A

Model File Index

SCRATCHGRAVEL HILLS GROUNDWATER INVESTIGATION—

GROUNDWATER MODEL

This appendix indexes the files of the simulations that served as final modeling products. The files include the GMS project file, MODFLOW input and output files, and background map files. This information is sufficient for a third party to rebuild the model, reproduce 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***
  - Steady-State Calibration: Calibrated heads and water budget in steady-state mode
  - Transient Calibration: Calibrated heads and water budget in transient mode from February 2010 to February 2011

- ***Predictive Scenarios***
  - Scenario 1: Evaluated the impacts of pumping a PWS well for 10-acre lots in the proposed Cornerstone Estates
  - Scenario 2: Evaluated the impacts of pumping individual domestic wells for 10-acre lots in the proposed Cornerstone Estates
  - Scenario 3: Evaluated the impacts of pumping a PWS well for 1.2-acre lots in the proposed Cornerstone Estates
  - Scenario 4: Evaluated the impacts of pumping individual domestic wells for 1.2-acre lots in the proposed Cornerstone Estates

Table A1 provides the filename, date, type, and primary action for the simulations listed above; the required supporting files are also included. Table A2 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-scratchgravel.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 A3 provides the maps used as background images in the model. Future model users may find importing these maps to be useful, though none are required to run the model. Map coordinates are projected in Montana NAD 1983 State Plane Feet or Meters.

Table A1. Scratchgravel Hills Groundwater Model File Organization.

Simulation ID	Simulation Date	Simulation Type	Primary Action	File Name	Supporting Files
Steady-state calibration	6/12/2011	Calibration	Final run of steady-state calibration	SG_2.1_SS	Obs_Wells_Oct-2010.csv
Transient calibration	6/8/2011	Calibration	Final run of transient calibration	SG_1.107_Trans	Compiled_2010-2011_trans_Obs_Wells.csv
Scenario 1	6/12/2011	Predictive scenarios	Simulated Scenario 1	Scenario1	
Scenario 2	6/12/2011	Predictive scenarios	Simulated Scenario 2	Scenario2	
Scenario 3	6/14/2011	Predictive scenarios	Simulated Scenario 3	Scenario3	
Scenario 4	6/14/2011	Predictive scenarios	Simulated Scenario 4	Scenario4	

Table A2. Input and Output Files in the Scratchgravel Hills 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	
Drain Package	DRN	
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
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	

Table A3. Map Files Used as Background Images in the Scratchgravel Hills Model.

Filename	Description	Projection
24k_topo_clip_SP_ft.sid	1:24,000 scale USGS topographic map	Montana NAD 1983 State Plane Feet
100k_topo_New_Bdy_ft.sid	1:100,000 scale USGS topographic map	Montana NAD 1983 State Plane Feet
NAIP_2009.tif	2009 NAIP* color aerial imagery	Montana NAD 1983 State Plane Feet
SG_shaded_relief_map.tif	Shaded relief map	Montana NAD 1983 State Plane Feet
Scratchgravel Geol3_Page_1.jpg	Geologic map (Schmidt and others, 1994)	Montana NAD 1983 State Plane Meters
geomap_SP83_ft.tif	Geologic map (Reynolds, 2000)	Montana NAD 1983 State Plane Feet

*NAIP, National Agricultural Imagery Program.