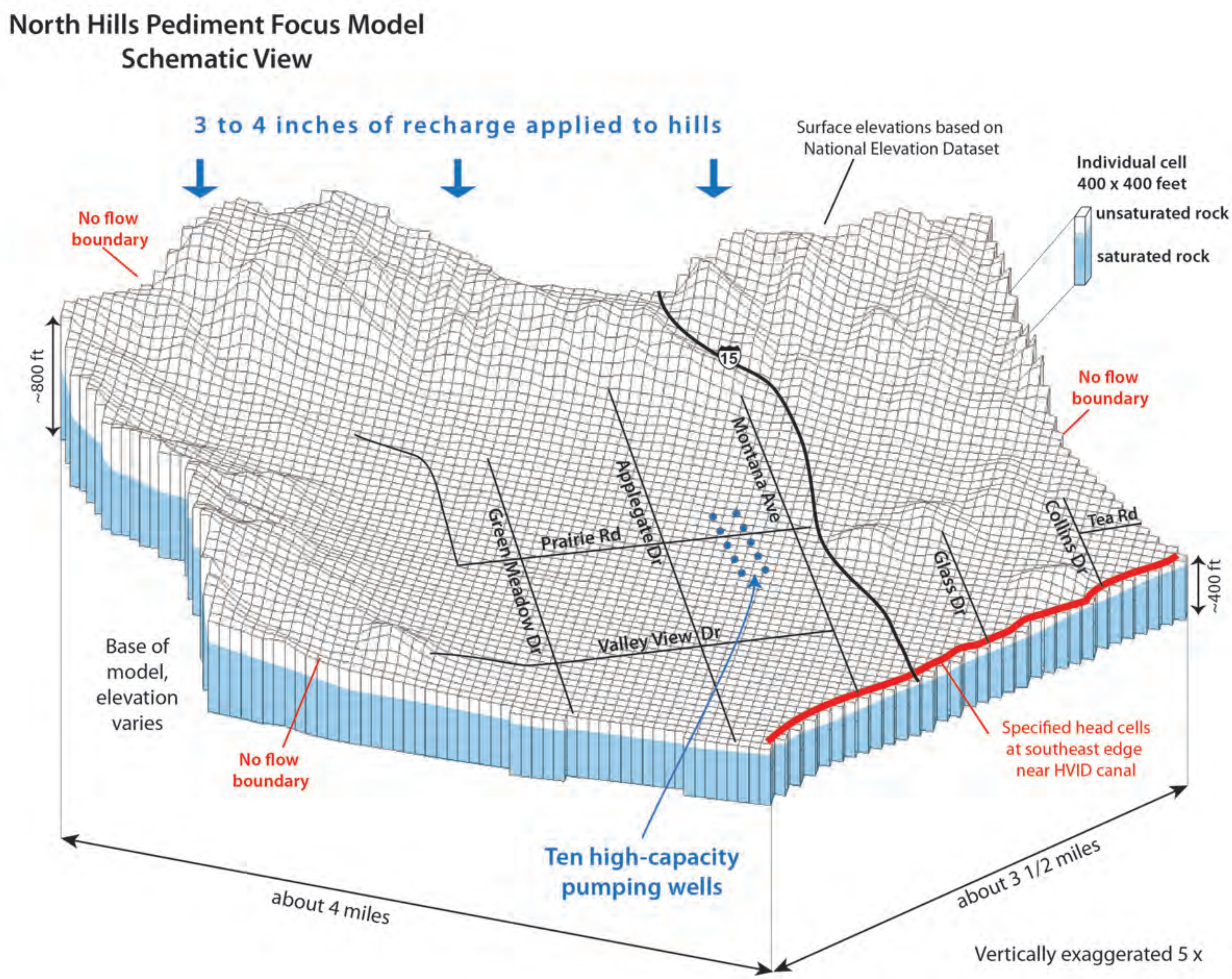
HYDROLOGIC INVESTIGATION OF THE NORTH HILLS STUDY AREA LEWIS AND CLARK COUNTY, MONTANA GROUNDWATER MODELING REPORT



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Montana Bureau of Mines and Geology
Ground Water Investigation Program

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Montana Bureau of Mines and Geology Open-File Report 628

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GENERAL SETTING

The North Hills study area is located at the north end of the Helena Valley north of Helena, Montana (figs. 1, 2). The North Hills, moderate hills with summits at elevations of about 4,400 to 5,300 ft above mean sea level, extend along the western and northern boundaries of the study area (fig. 3). A pediment extending from the base of the North Hills to the Helena Valley is the primary area of interest for this study area. The elevation of the pediment ranges from about 3,780 ft near the Helena Valley Irrigation District's (HVID) canal to about 4,000 to 4,300 ft where the pediment reaches the base of the steeper North Hills. The northern edge of the pediment is controlled by a major west–northwest-trending fault, the Helena Valley Fault (fig. 4). The southern portion of the study area extends into the northern end of the Helena Valley. The HVID main canal is located approximately where the pediment meets the Helena Valley in the central and eastern part of the study area. Bedrock is found at or near the surface in the upper portion of the pediment. Surficial, Tertiary, and Quaternary sediments bury the bedrock to increasing thicknesses toward the Helena Valley, where the Quaternary and Tertiary materials are hundreds to thousands of feet thick.

Residential development in the North Hills study area has progressed over many decades. Local groundwater supplies homes in the area through either individual wells or public water supply systems (fig. 5). Bedrock and surficial aquifers beneath the pediment vary, with well log lithologies ranging from gravel and clay to bedrock and well yields ranging from a few gallons per minute (gpm) to several hundred gpm. Groundwater levels are declining in the vicinity of some of the densest areas of development, raising concerns about whether the North Hills aquifer can sustain current and future water demands. Pumping Centers A, B, and C denote three areas of dense housing development (fig. 5). Pumping Centers B and C are located near the HVID canal, where groundwater levels are generally stable due to the productive nature of the aquifer and recharge from irrigation activities. Pumping Center A, which has been experiencing declining groundwater levels, is located in an area of less productive aquifer materials more than a mile north of the HVID canal and associated irrigation.

MODEL OBJECTIVES

The primary objective of groundwater modeling in the North Hills study area was to create a model that can be used to evaluate what will likely happen in the future with current pumping rates at Pumping Center A, and be able to calculate drawdowns for more or less pumping there or at other areas on the North Hills pediment. A second objective was to estimate the magnitude and timing of impacts of groundwater withdrawals to the closed Missouri River surface waters, which in this case is Lake Helena, since it is essentially backed up from Hauser Lake, formed by a dam on the Missouri River.

Two groundwater models were developed to address project objectives. A smaller area model, called the Pediment Focus model, was developed for evaluating aquifer drawdown associated with groundwater withdrawals on the pediment. This model took advantage of the simpler water budget above the canal and the densest distribution of observation well data for the study area. A larger area model, called the North Hills Area model, was used to address issues related to the magnitude and timing of impacts of groundwater extractions on the Helena Valley aquifer and Lake Helena (fig. 6).

CONCEPTUAL MODEL

Geologic Framework

Reynolds provided a detailed discussion of the geologic setting and a geologic map of the bedrock (fig. 4, from Thamke, 2000). Reynolds and Brandt (2005) provided detailed descriptions of rock formations in the east part of the study area. Schmidt and others (1994) provided detailed descriptions of rock formations in the southwest part of the study area.

Previous workers (Noble and others, 1982; Briar and Madison, 1992, Madison, 2006) recognized three principal aquifers in the North Hills Study Area: the bedrock aquifer, the Tertiary aquifer, and the Helena Valley aquifer (figs. 7, 8).

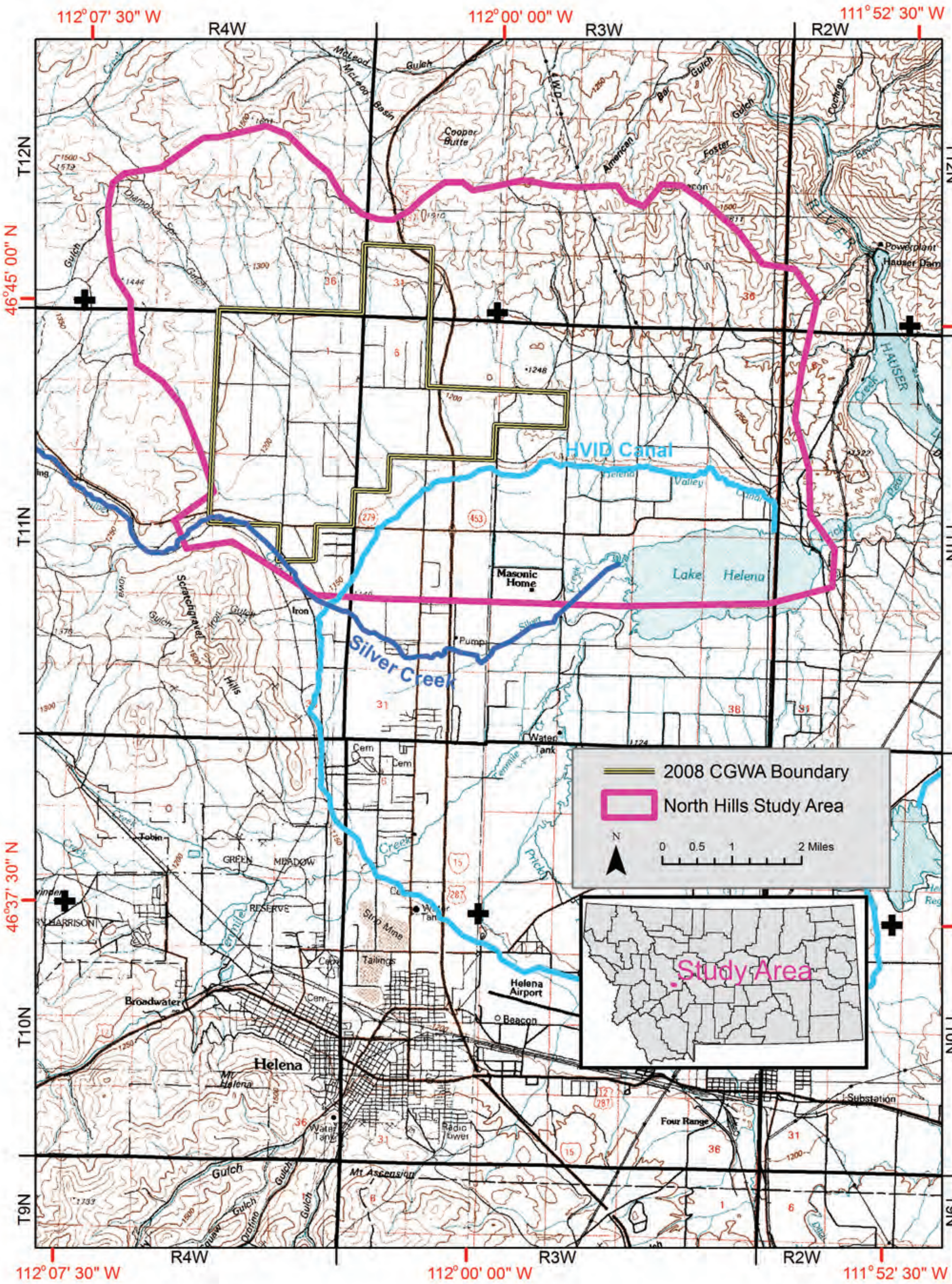

Figure 1. The North Hills Study Area is about 8 miles north of Helena, on the northern edge of the Helena Valley.

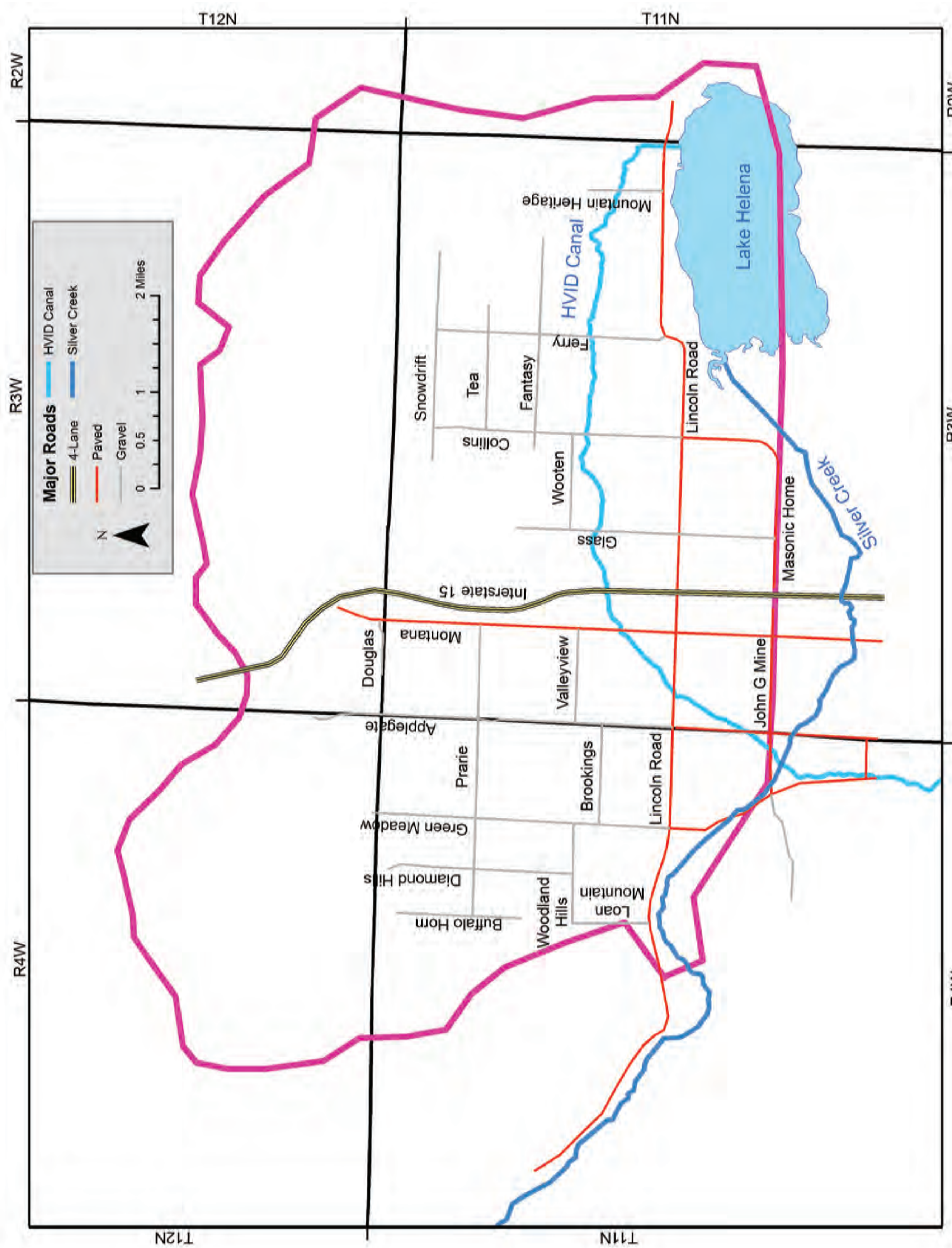

Figure 2. Major roads in and near the North Hills Study Area. Road names are sometimes used to identify locations.

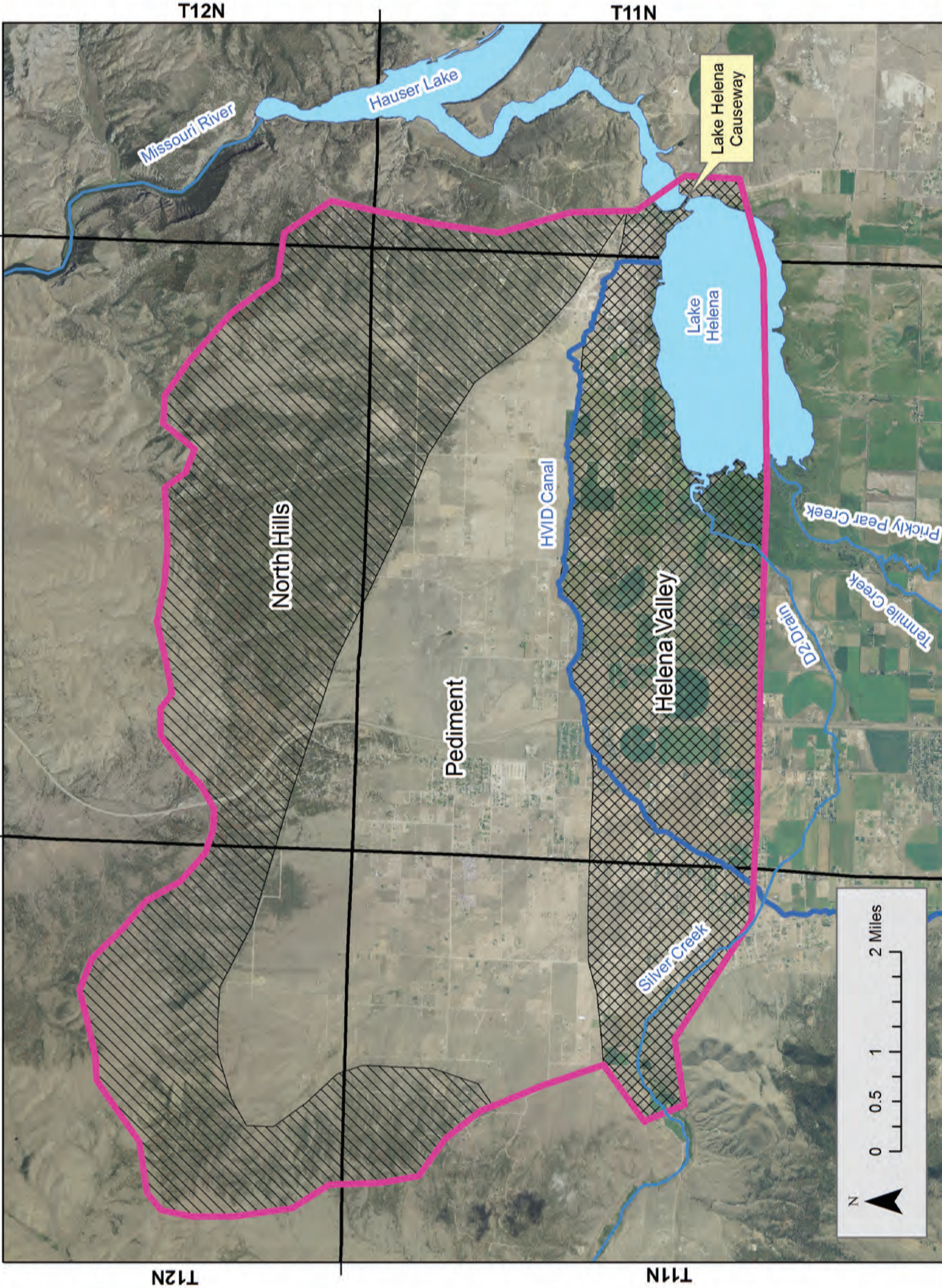

Figure 3. The North Hills Study Area drains to the Missouri River via Lake Helena. The Continental Divide is located approximately 10 miles west of the study area. The study area is split between hills to the west, north and east, a gently sloping pediment in the middle and the relatively flat Helena Valley in the south.

• Bedrock Aquifer: Bedrock outcrops or is very near the surface in hilly parts of the study area, and it is also at or near the surface in the upper portion of the pediment. Where sufficiently saturated, the bedrock is a fractured-rock aquifer. The bedrock aquifer is composed predominately of Precambrian siltite and argillite of the Greyson and Spokane Formations of the Belt Supergroup. Other bedrock formations of lesser areal extent include the Precambrian Helena Formation and several Paleozoic and Mesozoic formations in the northeast corner of the study area. At several locations within the study area granite sills have been reported from drill cuttings within argillite bedrock. Granite is also present in the southwest part of the study area, near the Scratchgravel Hills. The bedrock generally has little primary porosity. The porosity and permeability of the bedrock are typically secondary in nature, a result of fractures in the rock.

• Tertiary Aquifer: This unit is unconsolidated and is dominated by fine-grained materials; however, some sand and gravel is present. This unit overlies bedrock and thickens southward on the pediment toward the Helena Valley. Sand and gravel units are of variable thickness and are discontinuous in places. In many areas, coarser gravel deposits are reported in the lower portion of the Tertiary aquifer. The gravels are typically thicker in the western part of the pediment, west of Interstate 15. Conversely, the clay-rich layer thickens to the east, and may be absent in some areas to the west. The Tertiary materials are typically covered by younger colluvium and alluvium; however, they are exposed at the surface at a few isolated locations within the study area.

• Helena Valley Aquifer: The Helena Valley aquifer is a combination of unconsolidated Tertiary and Quaternary clastic materials that are generally coarser in the western part of the study area and finer toward Lake Helena. The unit is dominated by sand and gravel, and is the most productive aquifer in the study area.

In the bedrock, groundwater moves through and is extracted from fractures. These units have little primary porosity, but they are variably fractured and may have significant secondary porosity and secondary permeability (Thamke, 2000). Within the North Hills Study Area there are several mapped bedrock faults (Schmidt and others, 1994; Thamke, 2000; Reynolds and Brandt, 2005). The most significant of these is the Helena Valley Fault, which runs from the northwest corner to the southeast corner of the study area (fig. 4). Several faults have been mapped subparallel to the Helena Valley Fault, and conjugate faults splay off of these. There are likely additional unmapped faults in the area covered by younger sediments.

Madison (2006) noted that the bedrock, Tertiary, and Helena Valley aquifers are connected and that groundwater flows from one aquifer to the other. They are named and described according to differences in the rock materials, but together form the variable medium through which groundwater flows.

Regional Bouguer gravity anomalies (Kucks, 1999) indicate the presence of a major low-gravity area in the central part of the Helena valley south of Lake Helena. Noble and others (1982) estimated that this gravity anomaly represents a thickness of Tertiary and Quaternary unconsolidated sediments in the valley approaching 6,000 ft.

Water Well Logs

Water well logs were used to further analyze the subsurface conditions in the North Hills study area. There are several thousand well logs in the area available in the Ground Water Information Center (GWIC) database. It was impractical to analyze all available well logs, so well logs for wells drilled to at least 200 ft were extracted from the GWIC database. The locations and elevations for these well logs were checked and adjusted as needed as part of the analysis. Additional logs for wells of shallower depths were later added in selected areas where there were conflicting logs or no logs meeting the initial criteria. Data from over 250 well logs were entered into the Groundwater Modeling System (GMS) software (Aquaveo, Provo, UT) to develop the models for this project.

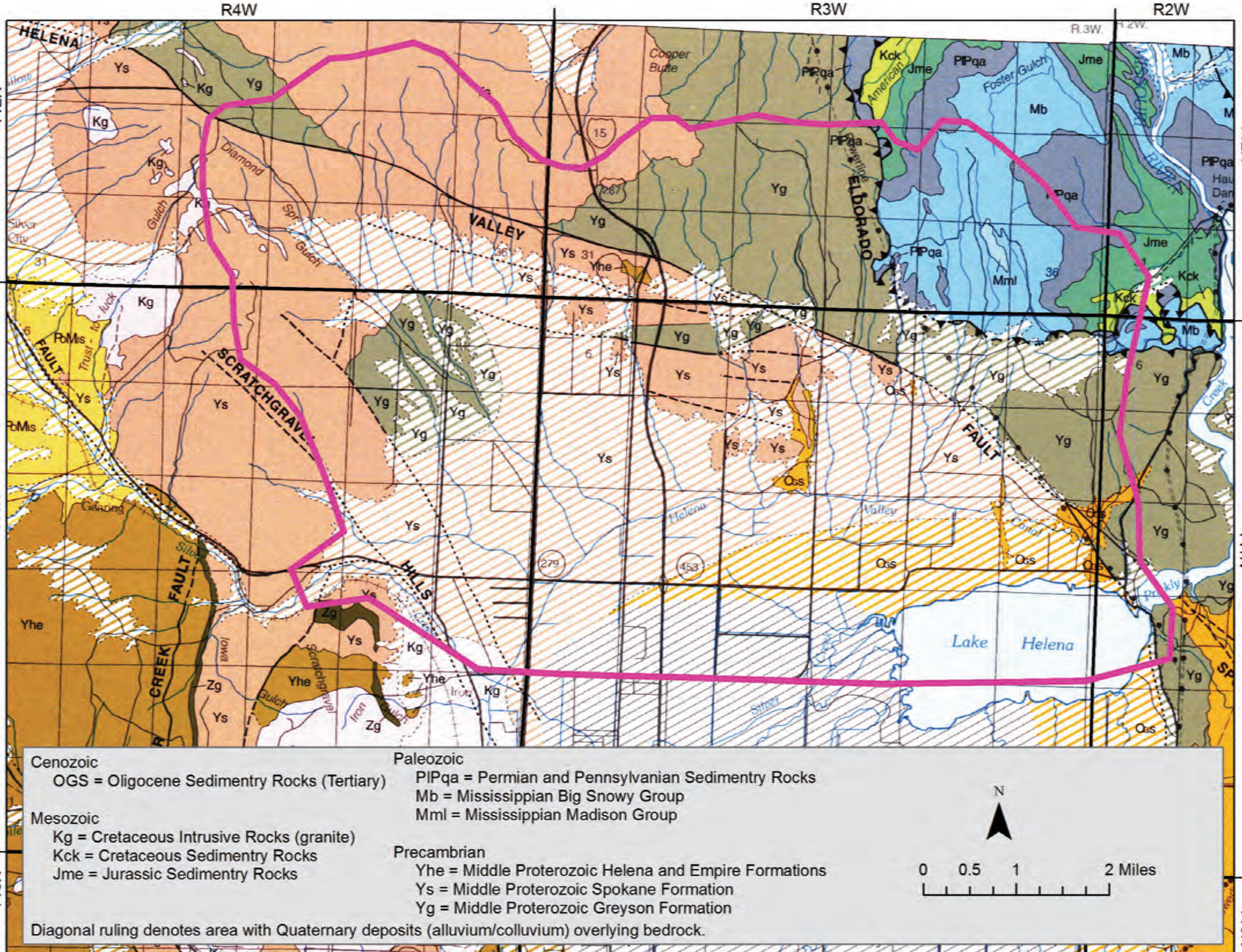

Figure 4. As shown by this Bedrock Geologic Map (Reynolds, from Thamke, 2000) the upper portion of the study area has argillite bedrock at the surface. This bedrock underlies unconsolidated clay-rich Tertiary materials and course-grained Quaternary materials towards the center of the Helena Valley. Several bedrock faults are also present in the area.

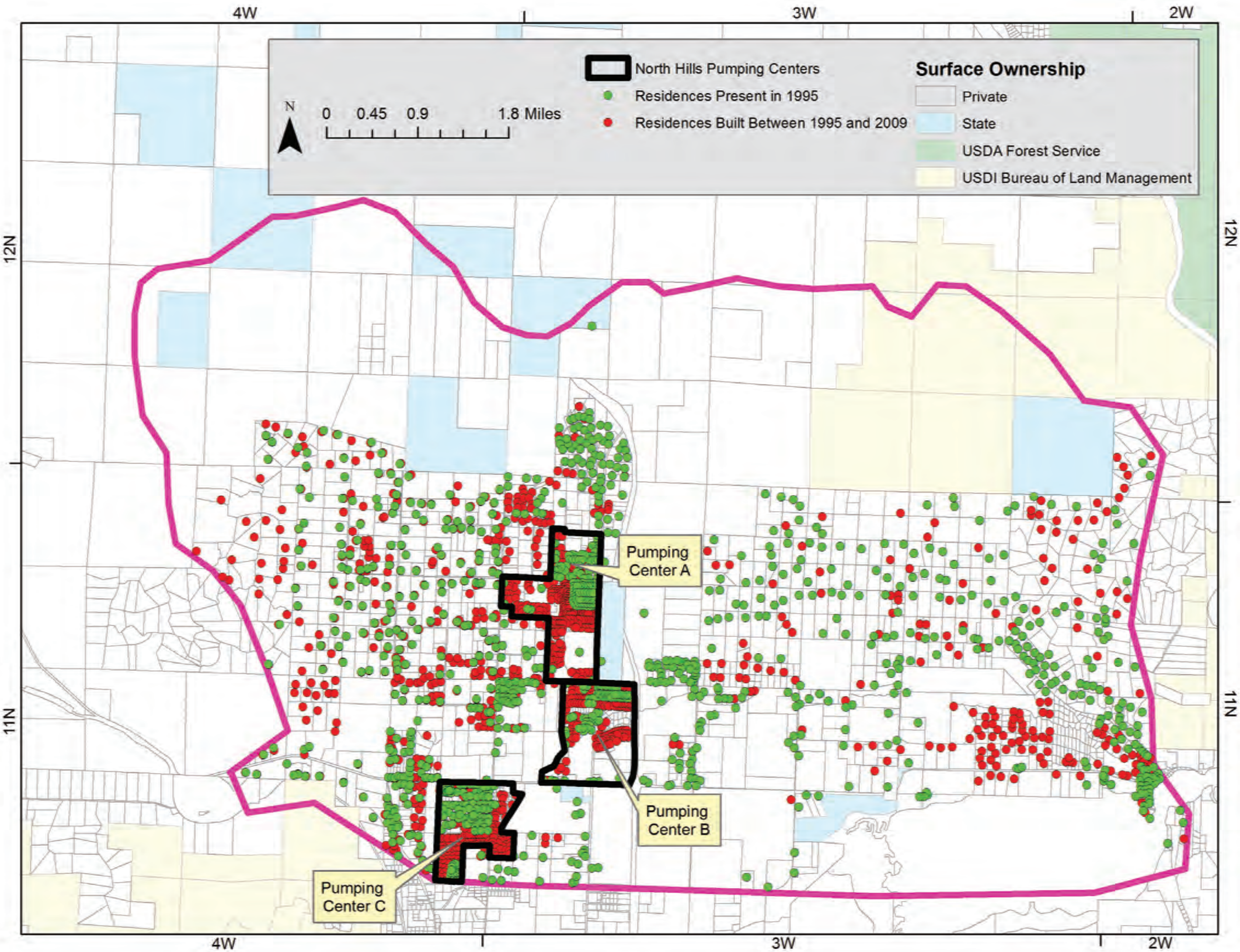

Figure 5. The number of homes in the North Hills Study Area increased from 1,077 to 2,150 between 1995 and 2009. Pumping Centers are designated for the densest residential areas.

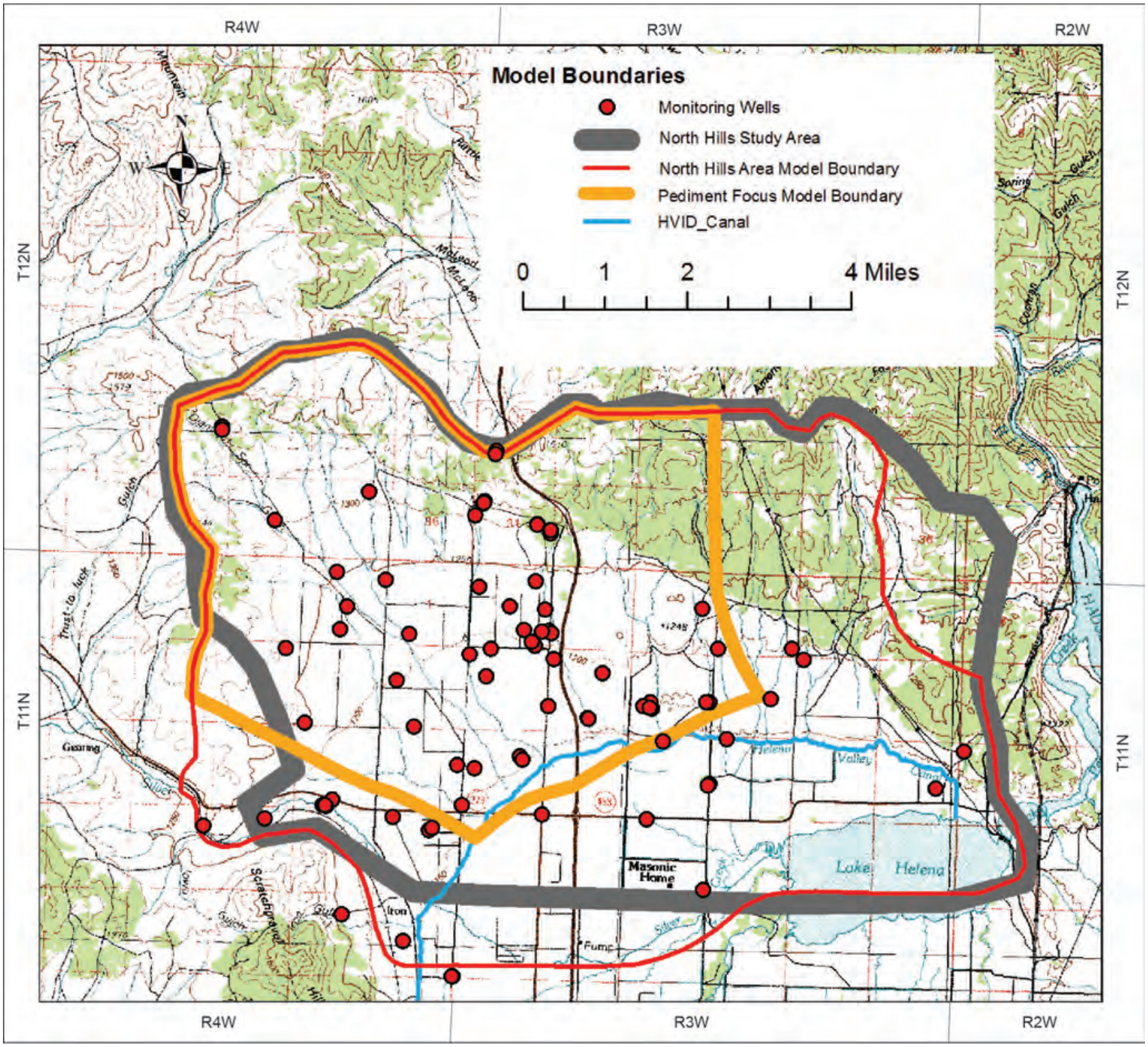

Figure 6. Groundwater model boundaries compared to the study area boundary.

Because drillers use a vast array of terminology to describe the materials encountered while drilling, their descriptions were grouped into the 33 material categories listed in Appendix A. The material category names are used in GMS software to identify different materials. The GMS software also allows the creation of hydrostratigraphic units (HGUs) to further group materials into broader categories that may be used to construct or assign properties to the groundwater flow model. The use of HGUs involves a simple numeric-coding scheme whereby layered HGUs are numbered as horizons from the bottom up. These numbers, shown in the horizons column (fig. 9), must be consistently numbered and aligned with the HGUs shown in the HGU ID column in order to develop cross sections and computer-generated three-dimensional HGU representations. In GMS, these three-dimensional HGU representations are termed solids.

A numbering scheme was selected after reviewing well logs in the area. It was determined that based on the available driller descriptions, it would be useful to limit the analysis by categorizing materials into five broad HGUs. These HGUs, and their horizon numbers from the bottom up, are: (1) granite; (2) shale (representing the shale bedrock); (3) gravel (representing deeper gravels reported beneath clays; (4) clay; and (5) gravel (representing surficial gravels).

An example using the log for GWIC well 64737 (owned by the State of Montana) illustrates how data are processed for the GMS analysis (fig. 9).

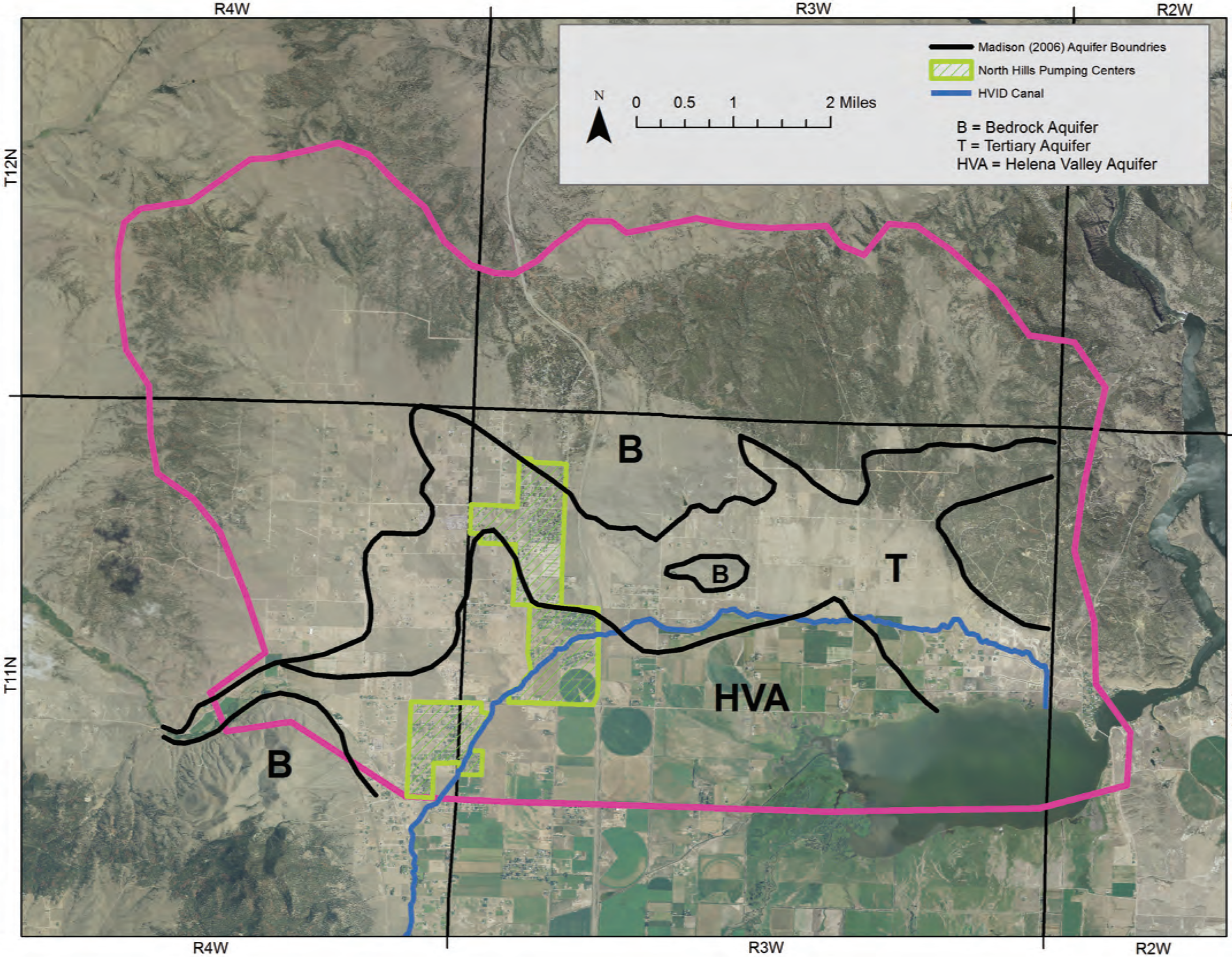

Figure 7. In the northern part of the study area wells depend on the bedrock aquifer. In the central part of the study area wells are completed in sand or gravel lenses within clay-rich Tertiary deposits. In the valley wells are completed in the sand and gravel deposits of the Helena Valley Aquifer (after Madison, 2006).

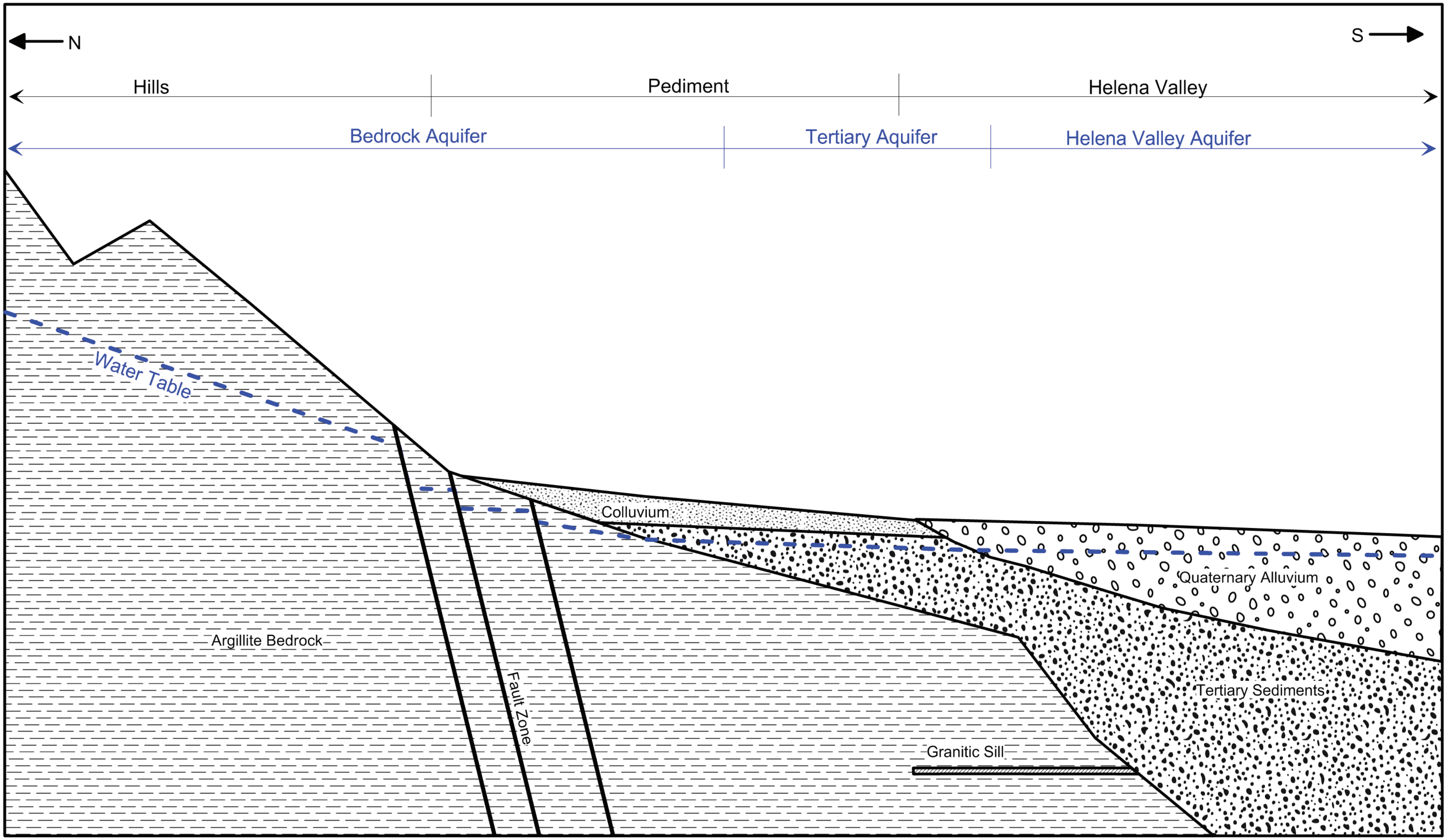

Figure 8. This schematic north–south geologic cross section in the vicinity of Interstate 15 illustrates the basic conceptual model for the North Hills Study Area. Physiographic areas are delineated in black, and principal aquifers are delineated in blue. The clay-rich Tertiary materials include discontinuous sand and gravel lenses.

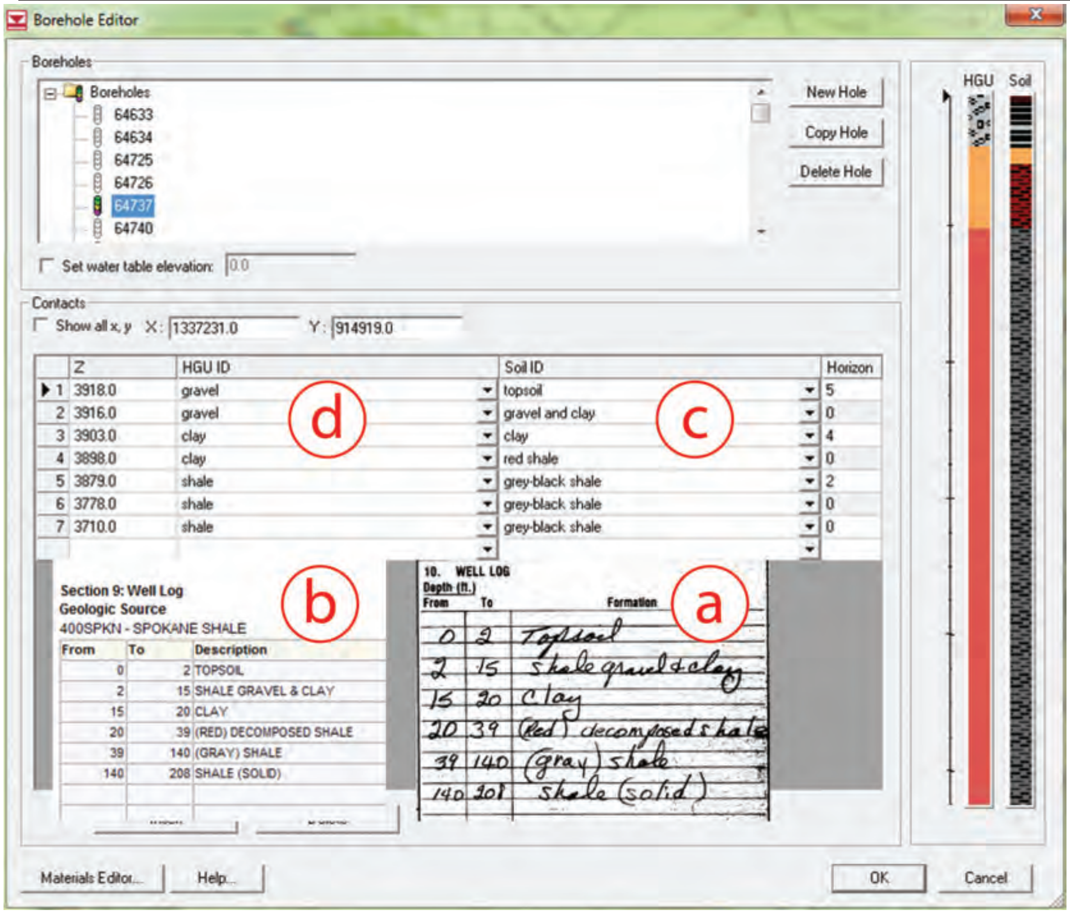

Figure 9. Well log data entry and HGU coding. Ground Water Information Center (GWIC) well log identification numbers are used in GMS to identify each well log. Using this method, the user can access the driller's original well log descriptions (a). Those descriptions are routinely typed verbatim into the Montana Well Log Report in the GWIC database by GWIC staff (b). We categorized the driller's descriptions into one of our 33 materials categories for the GMS analysis (c). Finally the categorized data is assigned into one of our five general hydrostratigraphic units (HGUs) (d).

This well is located near the east edge of Pumping Center A. In step c in the diagram, red shale is described in the Soil ID column. To the left, it is evident that this soil or material was coded as clay to reserve the "shale" HGU code for competent bedrock. During the HGU coding, the driller's original well logs were also reviewed, and since that material was originally described as "(red) decomposed shale," it was considered likely to be more clay-rich than bedrock, and so was coded as clay. The columns in GMS repeat the last material line at the bottom of the HGU ID and Soil ID columns, the convention used in GMS to define the bottom elevation of the lowest unit (shown in the adjacent Z column).

During the HGU coding process, lithologic descriptions of each well log were compared with those of surrounding well logs, providing additional information for assigning the most appropriate coding. Cross sections were created between data entered for the wells included in the analyses (fig. 10). Solids and cross sections through solids can be readily created in GMS using the well log data (fig. 11). The cross sections through solids are located approximately along section lines.

The water well log data generally support the conceptual model as developed from Madison (2006), as described above. The reported lithologies in what has been considered the Tertiary aquifer west of Interstate 15 are particularly variable as reported by well drillers. Materials described range from thick gravel or broken shale and clay to thick clay and soft shale. Yields vary from hundreds of gallons per minute to none. These areas with varied conditions may include a variety of Tertiary materials and faulted or weathered bedrock. The few deep well logs available in the Helena Valley aquifer support the interpretation that the valley sediments get finer from west to east toward Lake Helena.

While the well log analysis with GMS was informative, the solids developed from the well log data were ultimately not used directly in the groundwater model. The uncertainty level of the solids developed was deemed too high to justify creating a layered model with properties assigned by material types. A single-layer approach was selected instead, with variable hydraulic conductivities assigned throughout the model area. The assignment of hydraulic conductivities was done using automated parameter estimation techniques, as described in the Steady-State Calibration section of this report. The resulting distribution of hydraulic conductivities compares well with the approximate distribution of rock types as displayed by the solids generated from well log data.

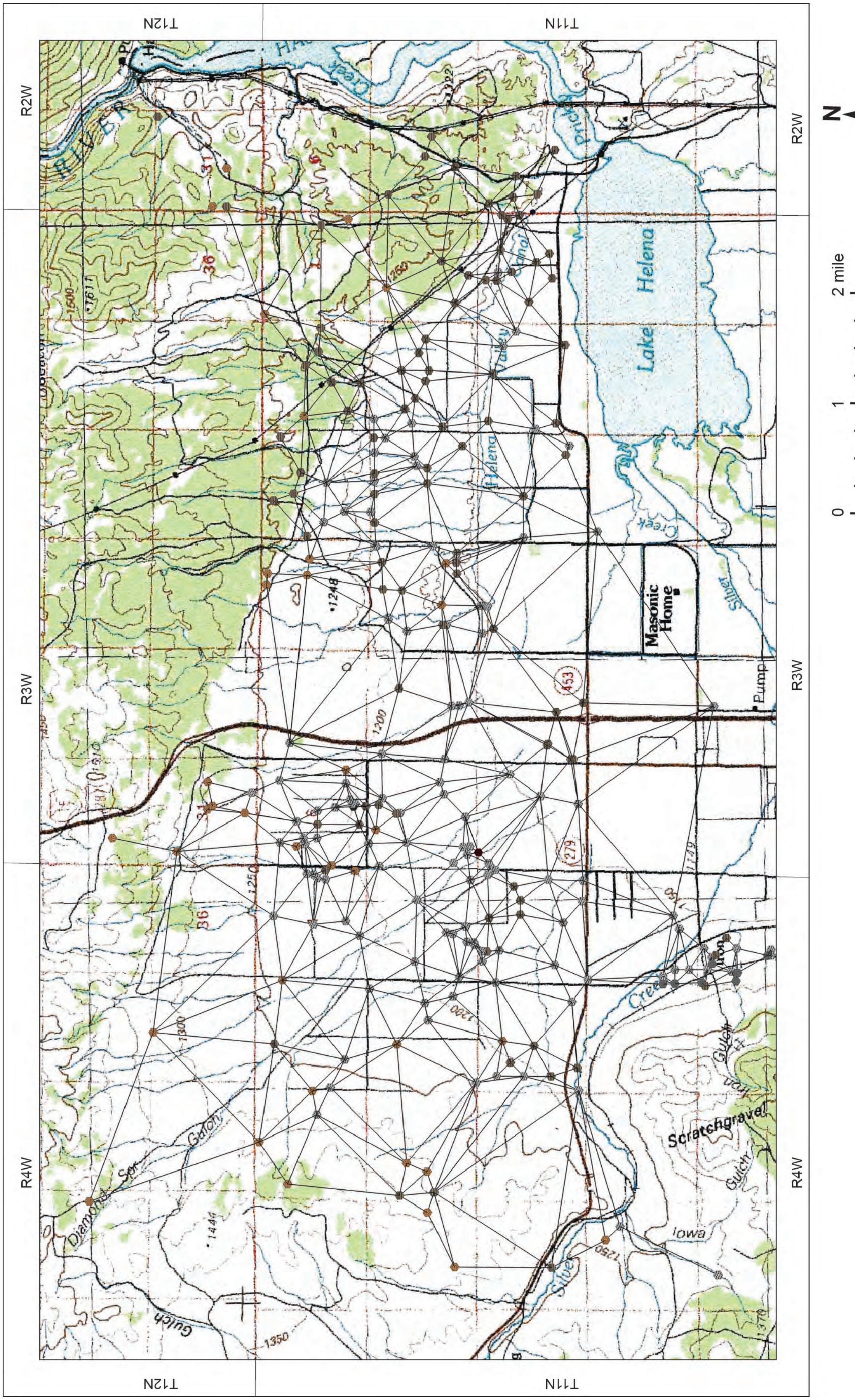

Figure 10. Locations of well log data and cross sections generated for the North Hills study area in GMS.

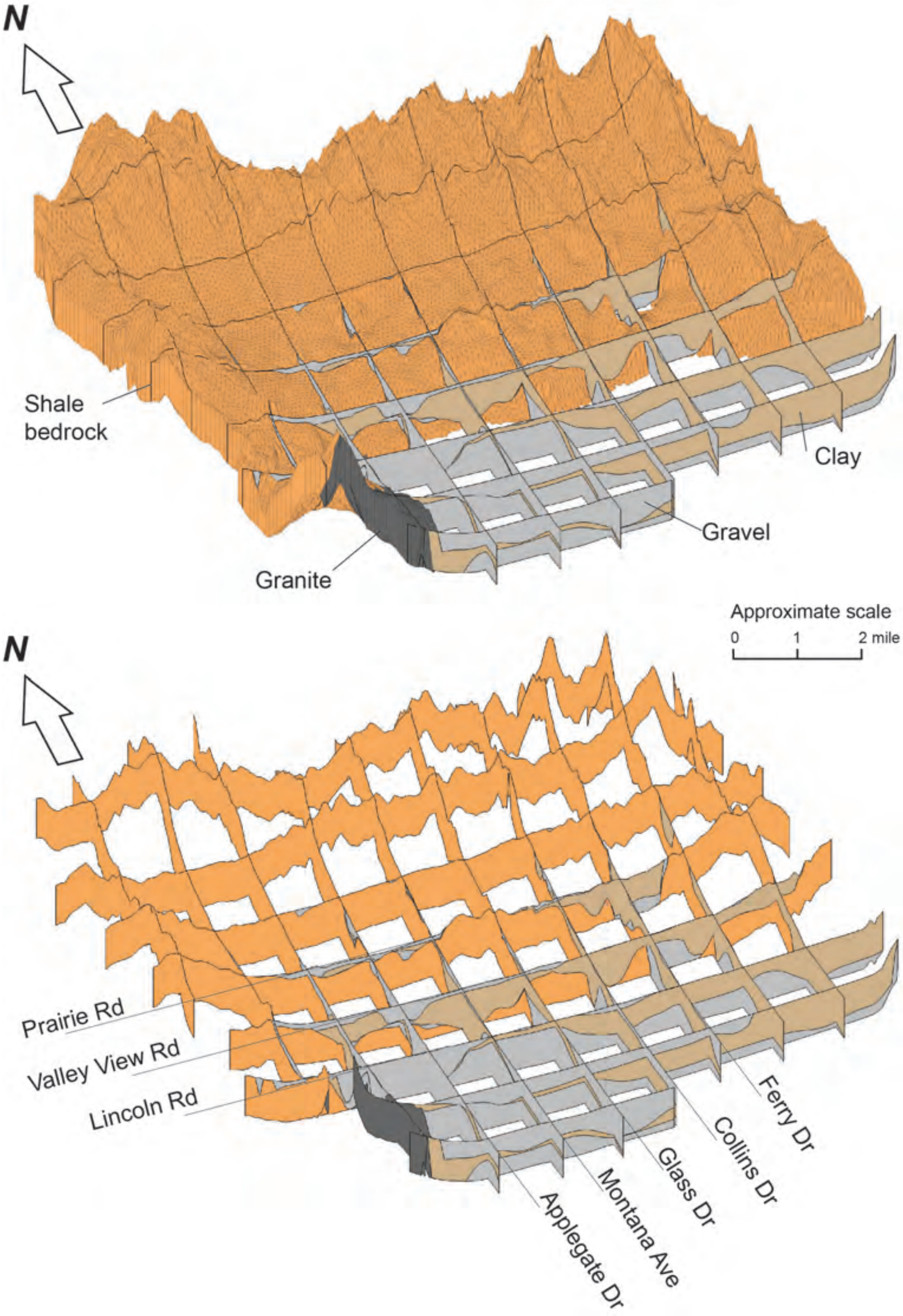

Figure 11. These images are examples of the type of three-dimensional solids that are generated using GMS software. The lines of cross section are along section lines. A few roads are named for reference.

Groundwater Flow System

The groundwater flow system is a localized flow system, with recharge to most of the pediment coming primarily from local precipitation in the North Hills and discharge occurring to the Helena Valley aquifer. The North Hills have very little surface-water runoff, so some portion of precipitation recharges the bedrock aquifer. Mapped potentiometric surfaces (fig. 12) suggest that water originating from the hills moves downslope through the bedrock and Tertiary aquifer materials within the pediment, and then to the Helena Valley aquifer. The Helena Valley aquifer discharges water directly or via agricultural drains to Lake Helena. Lake Helena water flows to Hauser Lake through the Lake Helena Causeway.

The only stream flowing into the study area is Silver Creek. Silver Creek is an intermittent stream, and ceases to flow occasionally because of irrigation withdrawals and bed seepage. When it is flowing, it provides recharge to the west end of the Helena Valley aquifer in the study area through infiltration of stream flow and excess irrigation water.

The HVID canal services a large area in the Helena Valley. Infiltration of water from the canal and associated irrigation activities to the shallow groundwater system are sources of groundwater recharge. Within the North Hills study area, the HVID canal extends some 8.2 miles between the study area boundary and the end of the canal at Lake Helena. There are about 12.4 miles of lateral canals within the study area, servicing an estimated 3,065 acres of irrigated land.

This irrigated part of the Helena Valley within the study area has abundant, relatively shallow groundwater and a network of irrigation drains. Estimates of water amounts moving through the system are provided in the Groundwater Budget section.

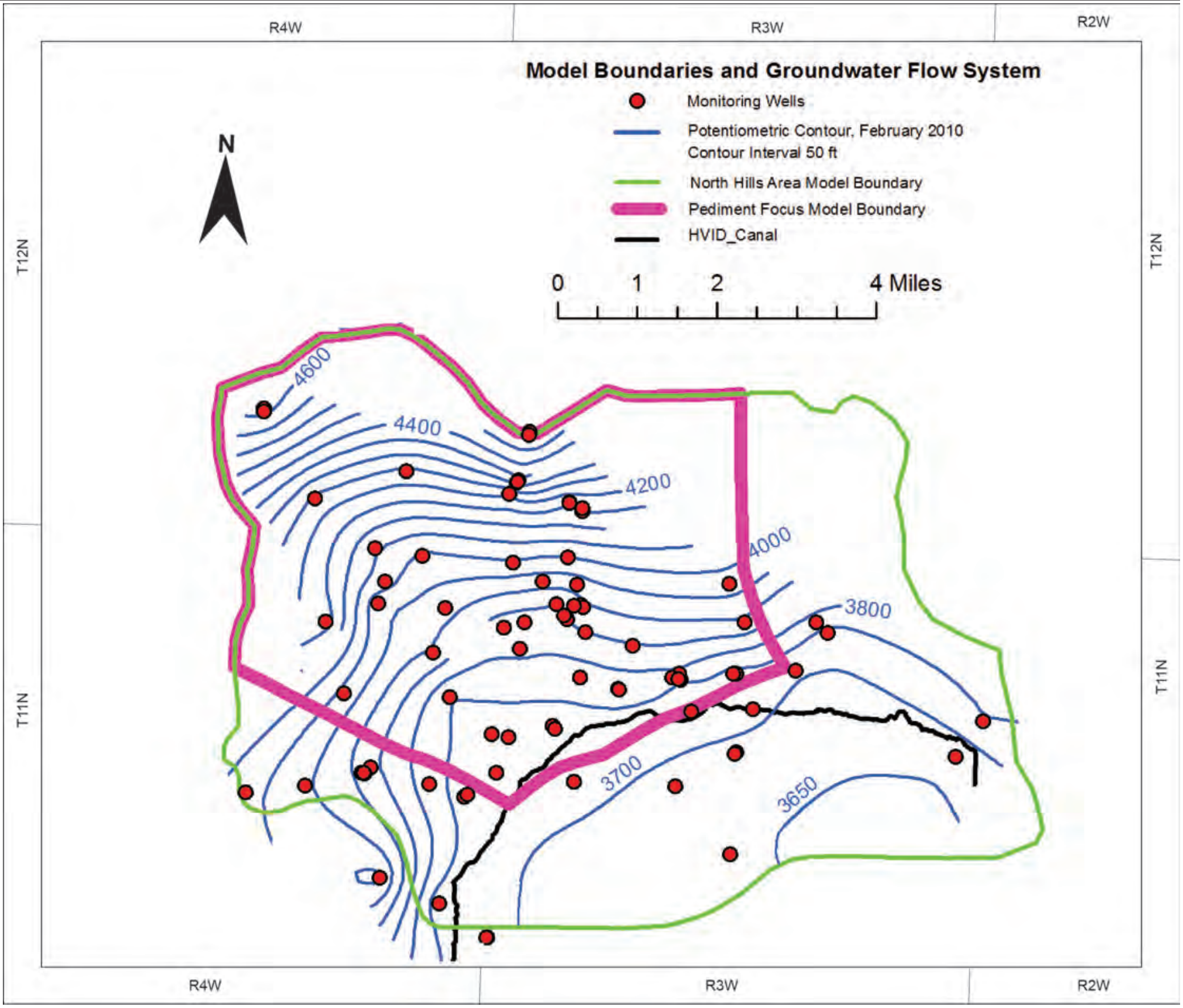

Figure 12. Model boundaries and the groundwater flow system.

HYDROLOGIC BOUNDARIES

The study-area boundaries on much of the west, north, and east edges were located at or near surface-water divides. It is assumed that groundwater recharge from precipitation in the North Hills will cause a groundwater divide to form in about the same location as the surface-water divide. Wells drilled near the divide for this project (State Lands East and West sites, fig. 13) verified that groundwater is at significantly higher elevations near the divide relative to other area wells.

Groundwater flows in approximately a west-to-east direction near the southern study area boundary based on the potentiometric flow of the Helena Valley aquifer as mapped by Briar and Madison (1992). The southern edge of the study area crosses the Helena Valley aquifer nearly coincident with a groundwater flow line.

Some groundwater is expected to flow into the area from the Scratchgravel Hills granitic bedrock in the southwest corner of the study area. The estimated influx of groundwater is provided in the Groundwater Budget section.

The southeast corner of the study area includes Lake Helena, the elevation of which is controlled by the Hauser dam and typically fluctuates less than a foot. It is the ultimate discharge area for virtually all groundwater within the study area. Agricultural drains that intercept groundwater in the Helena Valley discharge to Lake Helena.

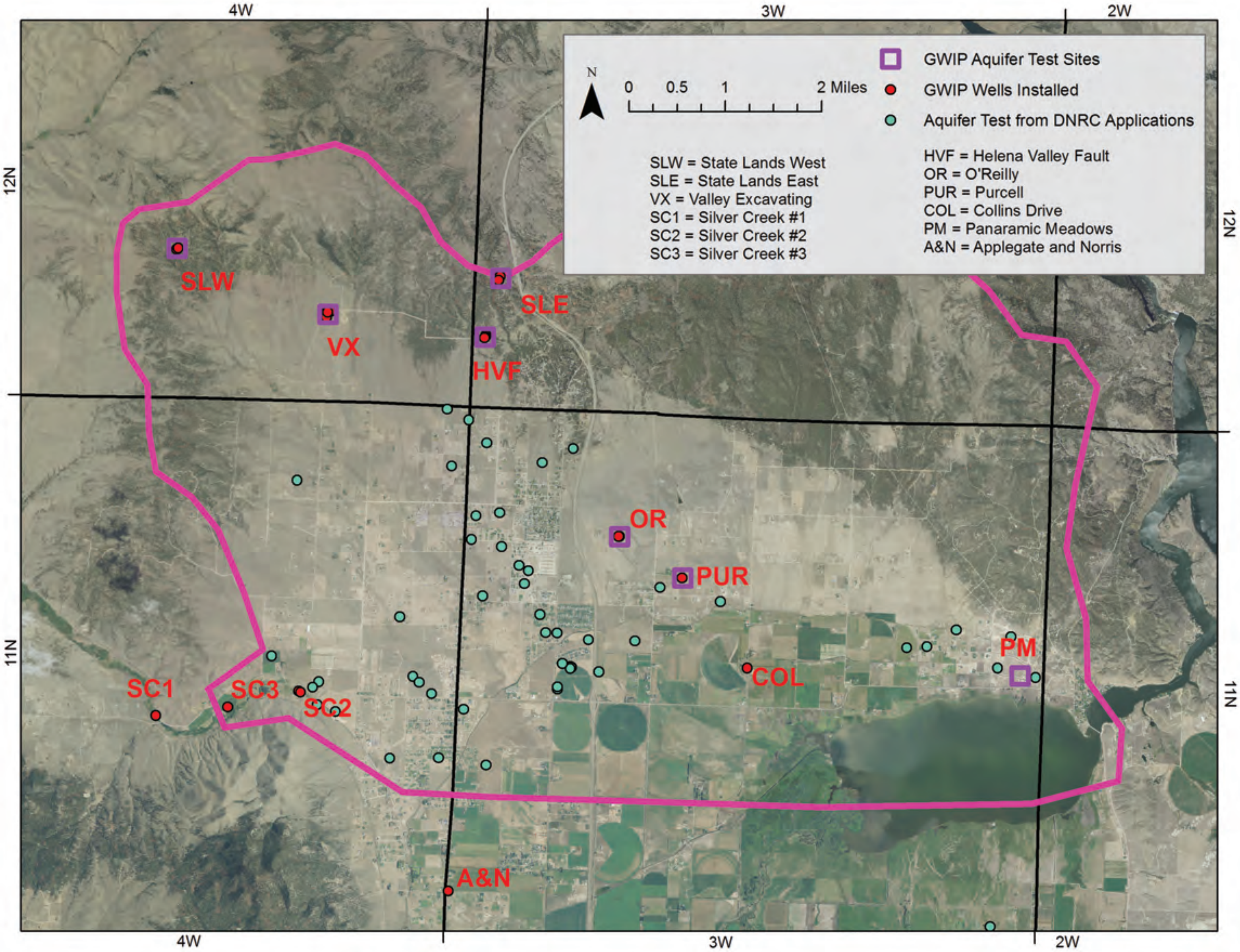

Figure 13. Wells were installed and aquifer tests were conducted at various locations within the North Hills Study Area to acquire water-level information and to evaluate aquifer properties. Aquifer test data from DNRC applications (P. Faber, written commun., 2010) also provided significant additional information on aquifer properties.

HYDRAULIC PROPERTIES

Aquifer properties in the vicinity of the study area were evaluated by compiling existing aquifer test data from a variety of sources and reviewing values used in groundwater studies and flow models in similar areas of western Montana. Aquifer test data sources include reports obtained from the Montana Department of Natural Resources and Conservation (DNRC) and previous hydrogeologic reports for the Helena vicinity. A compilation of aquifer test data for the North Hills and Scratchgravel Groundwater Investigation Program study areas was assembled by area hydrogeologist Patrick Faber (Aqua Bona Consulting) as part of this study. Aquifer properties typically generated by aquifer tests are transmissivity, hydraulic conductivity, and storage coefficient. The range of parameter values exhibited in the three principal aquifers were evaluated using available data, with the bedrock aquifer being further subdivided into two categories: shale bedrock and granite bedrock.

Aquifer Test Reports

Table 1 is a compilation of the aquifer test data compiled by Patrick Faber (Aqua Bona Consulting) for the North Hills study area, including results from aquifer test reports he wrote for DNRC about the area. The following descriptions use only the data that are listed as single aquifers. Those aquifer test data listed for more than one aquifer were not considered. Notes for Table 1: TD, total depth; SWL, static water level; T, transmissivity; ST Coeff, storage coefficient; K, hydraulic conductivity; Sat Z, thickness of saturated zone based on TD and SWL; Aquifer B, shale bedrock aquifer; Aquifer HV, Hel-

Table 1. Aquifer test data compiled by Patrick Faber.

GWIC ID	Site	Well No.	Legal	Sec	Tract	Easting	Northing	Test Date	DNRC ID	DEQ ID	TD (ft)	SWL (ft)	Rate (gpm)	Duration (hrs)	Max DD (ft)	T (ft^2/d)	ST Coeff	Method*	Sat Z	K (ft/d)**
Aquifer HV																				
208453	Frontier	1	T11NR4W	13	DC	405333	275957	10/31/2003	30008141		200	86	175	24	25.18	1630	0.0105	CJTD	114	14.3
209187	Frontier	1	T11NR4W	13	DC	405021	276246	5/19/2004			200	92	211	72	34.17	228		Neuman	108	2.11
—	Frontier	2	T11NR4W	13	DC	405121	276150	1/12/2004			200	92	40	24	53.02	108		CJTD	108	1
228861	Lincoln Heights	2	T11NR4W	14	DC	403448	276162	8/4/2006		EQ072805	80	35	11	24	21.77	2580		TJR	45	57.33
180981	Fieldstone	0	T11NR3W	17	AD	408726	276837	11/15/2002			200	24	894	72	16.2	15100	0.008	TJR	176	85.8
64824	Ranch View III	0	T11NR3W	17	BC	407429	276974	5/13/1997		EQ972693	114	38	600	4	7	52300	0.00082	CJDD	76	688.16
207597	Bridge Cr	0	T11NR3W	17	BD	407956	276856	10/21/2003		EQ032467	58	41	50	24	4.55	4240		TJR	17	249.41
207596	Bridge Cr	0	T11NR3W	17	BD	407956	276856	10/8/2003		EQ032467	68	41	38	24	8.65	3990		TJR	27	147.78
211564	Bridge Cr	0	T11NR3W	17	CA	407518	276462	10/2/2003		EQ032467	59	35	33	24	4.17	1600		TJR	24	66.67
204558	Bridge Cr	0	T11NR3W	17	CB	407648	276383	3/21/2003	30004735	EQ032467	300	39	608	78	20.42	7870		TJR	261	30.15
204557	Bridge Cr	0	T11NR3W	17	CB	407672	276404	4/10/2003	30004735	EQ032467	240	40	560	24	39.06	7950	0.00165	TJR	200	39.75
204558	Bridge Cr	0	T11NR3W	17	CB	407648	276383	7/26/2004	30004735	EQ032467	300	39	505	72	25	10900		HJ	261	41.76
204554	VF	0	T11NR3W	17	CB	407649	276416	4/14/2003	30004749	EQ032467	240	40	565	24	14.88	8590		CJTD	200	42.95
204563	Silver Cr Commer	0	T11NR3W	17	CC	407432	276068	4/5/2003			200	37	470	24	89.29	5790		CJTD	163	35.52
204564	Silver Cr Commer	0	T11NR3W	17	CC	407430	276034	4/8/2003	30004748		200	36	540	24	75.22	6030		CJ/TJ	164	36.77
180982	Fieldstone	0	T11NR3W	17	DB	408128	276323	3/8/2000	30018527		200	24	900	24	21	15855		TJR	176	90.09
64846	Lone Wolf	1	T11NR3W	18	AA	407144	277286	2/7/2000			111	71	75	8	0.68	26700		TJR	40	667.5
216639	Polaris	0	T11NR3W	18	AD	407234	276977	12/8/2004	30012839		120	57	108	24	4.5	33100		TJR	63	525.4
248761	Laibation Station	1	T11NR3W	19	BB	405864	275698	1/13/2009			110	72	86	24	3.23	34800		TJR	38	915.79
237114	Frontier Village	3	T11NR3W	19	CA	406238	274761	3/23/2007	30041569	EQ081420	170	45	953	24	13.91	19500	0.046	CJTD	125	156
—	Rosemary Acres	1	T11NR4W	24	CD	404630	274879	5/11/2002			120	20	20	24	13.1	3710		TJR	100	37.1
156462	Applegate	1	T11NR4W	24	DA	405443	274882	4/16/1997			161	67	175	9	4.18	75500		TJR	94	803.19
Aquifer T or HV																				
223771	North 40	1	T11NR3W	7	BD	406498	278422	6/8/2006			120	56	20	24	4.98	2420		CJTD	64	37.81
206648	Big Valley Lot 17	1	T11NR3W	7	CC	406181	277597	8/8/2003	30006229		320	118	12	24	110	25.5		CJTD	202	0.13
163866	Big Valley 11B2A	0	T11NR3W	7	DB	406791	278105	8/29/2005			160	70	29	72	64.94	1890		TJR	90	21
65293	Lincoln Heights	0	T11NR4W	14	DC	403344	276065	8/18/2006	30027014	EQ072805	113	60	17	24	61.15	1630		TJR	53	30.75
Aquifer T																				
—	North Star	0	T11NR3W	7	BC	405998	278541	8/26/2008	30001684	EQ022105	300	60	30	24	174.32	34		TJR	240	0.14
176013	Foothills	2	T11NR3W	9	CC	409147	277735	5/21/2005			120	70	30	24	44	413		CJTD	50	8.26
154877	Foothills	1	T11NR3W	9	DC	410156	277499	5/19/2005	96189		100	50	27	24	38.95	477		TJR	50	9.54
252835	Panoramic Meadows	1	T11NR3W	13	AB	415016	276907	5/26/2006			260	87	12	24	165.68	17		TJR	173	0.1
202172	Gable Est	2	T11NR3W	13	BB	414099	277024	3/13/2003	30005203		108	65	20	24	2.49	4890		TJR	43	113.72
254311	Panoramic Meadows	2	T11NR3W	13	DA	415426	276229	5/23/2006			141	79	43	24	12.85	1410		TJR	62	22.74
254327	Panoramic Meadows	3	T11NR3W	13	DB	414791	276388	5/30/2006			200	38	37	24	66.25	497		TJR	162	3.07
187343	Gable Est	0	T11NR3W	14	AC	413274	276728	2/13/2001	30002871	EQ012576	98	45	20	4	1.56	6920		TJR	53	130.57
—	Gable Est	3	T11NR3W	14	AD	339006	221025	3/14/2003			118	55	17	24	1.5	7190		TJR	63	114.13

Aquifer T or B																	
—	Hillview	1	T11NR3W	6	BC	406253	280156	5/17/2006			200	40	20	24	2.12	2780		TJR	160	17.38
193701	Northern Lights	2	T11NR3W	7	BA	406467	278986	10/9/2001	30003961	EQ021016	240	105	51	24	13.71	885		Theis	135	6.56
—	Northern Lights	2	T11NR3W	7	BB	406076	278932	6/14/2004			240	105	56	72	12.3	2370	0.000476	Theis	135	17.56
150328	Bandy	1	T11NR4W	13	BA	404799	277248	12/3/1999			203	50	33	24	45.6	119		CJTD	153	0.78
Aquifer B																				
65152	Welsh Estates	0	T11NR4W	1	AA	405956	280539	4/4/2006	9002		110	7	12	24	2.07	875		CJTD	103	8.5
227178	Welsh Estates	1	T11NR4W	1	AA	405592	280722	7/3/2006			120	60	27	24	7.4	1120		CJTD	60	18.67
199996	MJM	1	T11NR4W	1	DA	405667	279767	9/19/2002			300	130	18	24	16.14	165		CJTD	170	0.97
228176	Dee Minor	1	T11NR4W	2	CD	403086	279534	8/17/2006	30023567		245	115	30	24	36.01	823		TJR	130	6.33
64642	Southern View	0	T11NR3W	5	BC	407698	280061	9/30/2005			90	30	13	24	78.8	416		TJR	60	6.93
222881	Overlook	1	T11NR3W	6	DA	407177	279823	11/25/2005	30016480		160	92	30	24	1.9	11100		TJR	68	163.24
—	North Star	0	T11NR3W	7	BC	405998	278541	12/4/2009	30001685	EQ022105	540	70	84	24	235.28	43	0.000204	Theis	470	0.09
194427	North Star	2	T11NR3W	7	DA	406949	278013	2/19/2002	30001682	EQ022105	120	19	65	24	5.75	1110		Theis	101	10.99
—	North Star	1	T11NR3W	7	DB	406882	277795	2/26/2004		EQ022105	120	18	98	72	15.42	1650		CJTD	102	16.18
252485	North Star	8	T11NR3W	7	DB	405998	278541	9/17/2009	30001686	EQ022105	538	68	91	24	226.02	52		TJR	470	0.11
254487	North Star	3	T11NR3W	7	DB	406949	278013	1/11/2008	30001683	EQ022105	475	44	56	72	10.86	1600	0.000623	CJTD	431	3.71
193704	North Star	1	T11NR3W	7	DC	406882	277795	9/25/2001	30001682	EQ022105	120	18	110	25	20.04	1010		CJTD	102	9.9
166421	Hoovestal	1	T11NR4W	14	CB	402656	276591	4/21/1999			420	34	65	6	2.71	6410		TJR	386	16.61
Aquifer GR																				
127089	Maykuth	1	T11NR4W	23	AA	403722	275659	6/7/2000	82942		121	23	15	2	64.22	13.6		CJTD	98	0.14
230903	LincolnH	4	T11NR4W	23	AB	403423	275773	10/4/2006		EQ072805	160	70	17	25	51.48	66.6		TJR	90	0.74

*Method reportedly used to calculate transmissivity.

**Hydraulic conductivity (K) estimated by dividing the transmissivity by the saturated thickness (TD minus SWL).

ena Valley aquifer; Aquifer T, Tertiary aquifer; CJTD, Cooper-Jacob time drawdown; CJDD, Cooper-Jacob distance drawdown; TJR, Theis-Jacob recovery; HJ, Hantush-Jacob; Theis, Theis drawdown.

The reported Helena Valley aquifer transmissivity values ranged from 108 to 52,300 ft^2/d. The estimated hydraulic conductivities ranged from 1 to 803 ft/d, with a geometric mean and average of 73 and 215 ft/d, respectively. Storage coefficients for four tests with observation wells are shown in table 1, and ranged from 0.0008 to 0.046.

Reported transmissivities for the Tertiary aquifer ranged from 17 to 6,920 ft^2/d, yielding hydraulic conductivities in the range of 0.1 to 131 ft/d. The geometric mean and average of the hydraulic conductivity values for Tertiary aquifers were 8.0 and 45 ft/d, respectively.

Transmissivities reported for shale bedrock aquifer wells generally ranged from 43 to 6,410 ft^2/d, resulting in hydraulic conductivities of about 1 to 19 ft/d. There was one unusually high transmissivity of 11,100 ft^2/d for one well, GWIC ID 222881. This well may be completed in gravels derived of shale fragments, or may be in a zone of brecciated bedrock. The hydraulic conductivity for that test was 163 ft/d, which is considered an outlying value. The geometric mean and average of the hydraulic conductivity values for shale bedrock aquifers, not including the value for well 222881, were 3.7 and 8.2 ft/d, respectively. Storage coefficients available for the bedrock aquifer are 0.000204 and 0.000623.

The results from two granite bedrock aquifer test reports indicated transmissivity values of 14 and 67 ft^2/d. Based on the saturated thickness penetrated (total depth less static water level), calculated hydraulic conductivity values were 0.14 and 0.74 ft/d.

Aquifer Tests Conducted

Seven aquifer tests were conducted in the study area. The details of these aquifer tests are presented in the North Hills Technical Report (Bobst and others, in preparation a). The Valley Excavating site (fig. 13) was deemed most representative of shale bedrock away from major fault zones. The hydraulic conductivity determined at that site was 2.9 ft/d, and 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. The Panoramic Meadows site tested unconsolidated Tertiary sediments composed of silt, sand, and gravel. This test yielded a hydraulic conductivity of 150 ft/d and a storage coefficient of 0.006. Test wells were drilled at the Helena Valley Fault site, a known fault zone. The hydraulic properties from that test are probably not representative of bedrock beyond the fault zone. The values derived from the earliest test data, before encountering boundary effects, included a hydraulic conductivity of 3.6 ft/d, and a storage coefficient of 1.38×10^{-7}. The Purcell site did not yield accurate hydraulic properties due to the presence of a fault.

Aquifer tests conducted in the granite aquifer of the nearby Scratchgravel Hills (southwest of the study area) by the MBMG (Bobst and others, in preparation b) were also considered. Transmissivity values from these tests ranged from 0.15 to 225 ft^2/d, and hydraulic conductivity values ranged from 0.001 to 1.5 ft/d. PBS&J (2008) conducted an aquifer test in the Scratchgravel Hills granite, which resulted in a calculated transmissivity of 253 ft^2/d and a hydraulic conductivity value of 0.8 ft/d. PBS&J also conducted rough calculations of transmissivity in the granite based on specific capacity (Driscoll, 1986), which resulted in estimated transmissivities from 11.3 to 27.3 ft^2/d and estimated hydraulic conductivities from 0.04 to 0.38 ft/d (PBS&J, 2008).

Previous Investigations

In a report from the U.S. Geological Survey (Briar and Madison, 1992), estimates of hydraulic conductivity of the upper part of the Helena Valley aquifer are discussed in some detail. From aquifer test data, they estimated that the effective hydraulic conductivity of the Helena Valley aquifer is about 200 ft/d. Hydraulic conductivity values used for various aquifer types in additional groundwater modeling efforts in Montana are shown in table 2.

Summary of Hydraulic Properties

Table 3 is a summary of the hydraulic conduc-

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

Upper Beaverhead - Uthman & Beck (1998), DNRC transient simulation	
Layer 1 (Quaternary alluvium) 25 to 170 ft thick	10–1800 ft/d
Layer 2 (Tertiary basin-fill)	5–10 ft/d
Hayes Creek–Waren (1998), DNRC Limited Transient	
Belt Argillite–Missoula Group, Mount Shields Fm., Member 3	0.1–0.75 ft/d
Helena Valley Aquifer–Briar and Madison (1992), USGS steady-state simulation	
Layer 1 Upper 35 ft thickness of aquifer	80 ft/d
Layer 2 Next 75 ft thickness	40 ft/d
Layer 3 170 to 1000 ft thickness beneath layers 1 and 2	40 ft/d
Lower Beaverhead – MBMG (2007), transient simulation	
Alluvium	75 ft/d
Tertiary basin-fill	4 ft/d
Mesozoic bedrock	1–2 ft/d
Clay	0.01 ft/d
Gallatin Valley and Madison Plateau–MBMG (2007), transient simulation	
Alluvium	82–131 ft/d
Tertiary basin-fill and alluvial fans	3–7 ft/d
Drummond Valley–Kauffman (1999), Montana State University Graduate Thesis, transient simulation	
Alluvium	26–45 ft/d
Tertiary basin-fill	0.05–0.5 ft/d

Table 3. Hydraulic conductivity summary. All values are in units of ft/d.

Aquifer	Approximate Range of values from aquifer tests	Geometric mean	Average	Range of values used in previous groundwater flow models shown in table 2	Expected range (ft/d)
Quaternary	1–920	73	215	10–1800	50–200
Tertiary	0.1–160	11	56	1–40	1–50
Bedrock					
Shale Bedrock	1–20	4	7	0.1-2	0.1–20
Granite	0.001–20	0.13	0.63	n/a	0.01–5

tivity ranges, geometric mean values, and average values for each aquifer. Values were derived from reported data and the aquifer tests conducted during this study. The last column indicates the estimated range of aquifer properties used in groundwater flow calculations and for groundwater modeling based on the reported values while considering the ranges of hydraulic conductivities in other groundwater modeling efforts. The ranges were all within the broad ranges of expected values as described in numerous groundwater textbooks for similar materials. The groundwater model will further refine these estimates.

Storage coefficient values for all aquifers were quite scarce, as shown in table 1. The storage coefficients ranged from about 1 x 10^{-7} to 0.1. The majority of the values were in the range of 0.0001 to 0.01, so this range is considered appropriate for a starting value in the transient modeling simulations.

SOURCES AND SINKS

The sources of groundwater recharge within the North Hills study area included areal recharge in the North Hills, inflow from Silver Creek infiltration, groundwater inflow from the Scratchgravel Hills, water leaking from the HVID canal and laterals, and excess water from HVID irrigation. The sinks for the North Hills Area study area included Lake Helena, drains, and wells. The next section provides estimates of groundwater flux for these sources and sinks.

GROUNDWATER BUDGET

A groundwater budget helps to quantify groundwater recharge and discharge components of the study area. While there is inherent uncertainty associated with the calculations, a groundwater budget is useful for determining the relative importance of different processes. 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 a mass balance: matter cannot disappear or be created spontaneously. Thus, the amount of water that enters a system 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 the system 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 North Hills Groundwater Budget is included in the North Hills Technical Report (Bobst and others, in preparation a). A brief summary of the major components is discussed below. The mass balance equation can be expanded for the North Hills Study Area to:

$$SCal + SG + SC + DI + CL + IR = WL + DR + LH \pm \Delta S,$$

where:

SCal is groundwater inflow from Silver Creek alluvium at the west boundary;
SG is groundwater inflow from the Scratchgravel Hills;
SC is infiltration of water from Silver Creek;
DI is diffuse infiltration;
CL is canal leakage;
IR is irrigation recharge;
WL is withdrawals by wells;
DR is flow to drains;
LH is flow to Lake Helena; and
ΔS is changes in storage.

North Hills groundwater inflow originates from the alluvium of Silver Creek (SCal; ~20 acre-ft per year) and from the bedrock of the Scratchgravel Hills in the southwest (SG; ~1,252 acre-ft per year). Measurements of surface-water flow at the edge of the study area indicated that Silver Creek (SC) inflow averages about 959 acre-ft per year (1.3 cfs). Much of the inflow infiltrates to the alluvium. All of these sources flow into the Helena Valley aquifer.

Diffuse infiltration (DI) occurs when the amount of precipitation exceeds runoff, evaporation, or that used by plants (Lerner and others, 1990; de Vries and Simmers, 2002; Ng and others, 2009). DI was evaluated for the non-irrigated portion of the study area. Irrigation recharge accounted for DI in irrigated areas (see below). DI was calculated only for the forested hills, since evapotranspiration (ET) and precipitation are approximately equal on the pediment (see the Estimation of Evapotranspiration section in the North Hills Interpretive Report, Waren and others, 2012). Average annual precipitation in the study area ranges from about 9 to 17 in/yr (fig. 14). University of Idaho researchers (Trezza and others, written commun., 2011) estimated evapotranspiration rates for the study area (fig. 15). Those results were considered reasonable for the valley and pediment areas, but the evapotranspiration estimates for the North Hills exceeded annual precipitation, so were considered erroneous. Therefore, the recharge for the North Hills was estimated separately. The estimated recharge rate for the forested hills is 25 percent of average annual precipitation, or about 3.75 inches per year. Given that the total forested hill area is about 14,000 acres, the DI rate is approximately 4,380 acre-ft per year.

The HVID canal runs through the study area for about 8.2 miles, and there are about 12.4 miles of laterals. This canal obtains its water from the Missouri River. Because this canal is unlined and it was constructed well above natural groundwater levels, it leaks to the underlying groundwater (CL). Briar and Madison (1992) estimated that the HVID canal infiltrates at a rate of about 0.63 cubic ft per second (cfs) per mile of canal, and smaller canals infiltrate at about 0.21 cfs/mile. Thus, a total of about 2,559 acre-ft per year is estimated to infiltrate from canals during the irrigation season. This water recharges the Helena Valley aquifer.

There are approximately 3,000 acres of irrigated land in the North Hills Study Area (MT-DOR, 2010). The irrigated land is located almost exclusively downgradient from the HVID canal. 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. The result was an estimated irrigation recharge of 1.5 ft per year. Thus, irrigation recharge

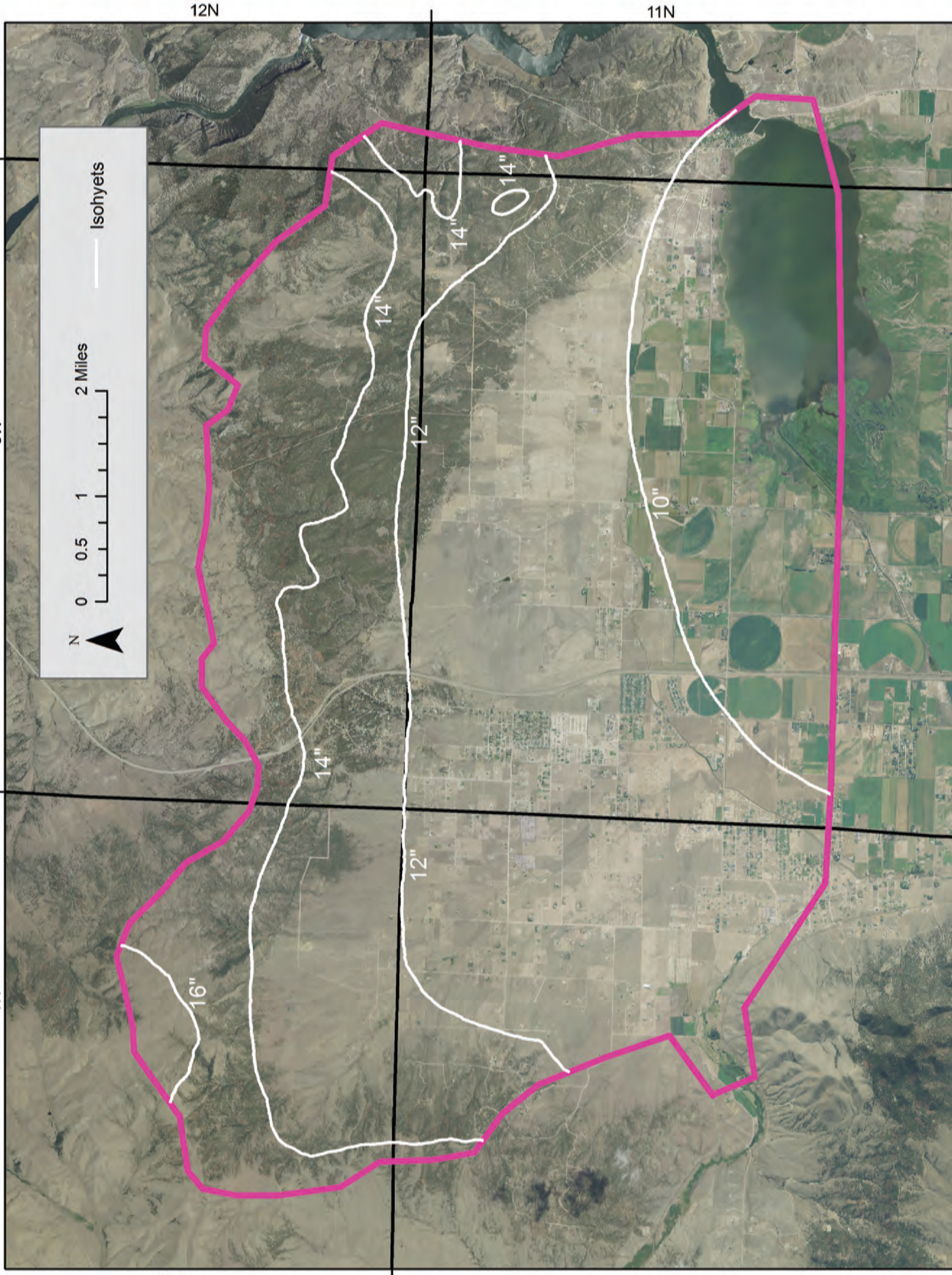

Figure 14. Average annual precipitation isohyets in the North Hills Study Area (1970–2000; P. Farnes, written commun., 2010) show that precipitation ranges from less than 10 in. in the Helena Valley to over 16 in. in the hills.

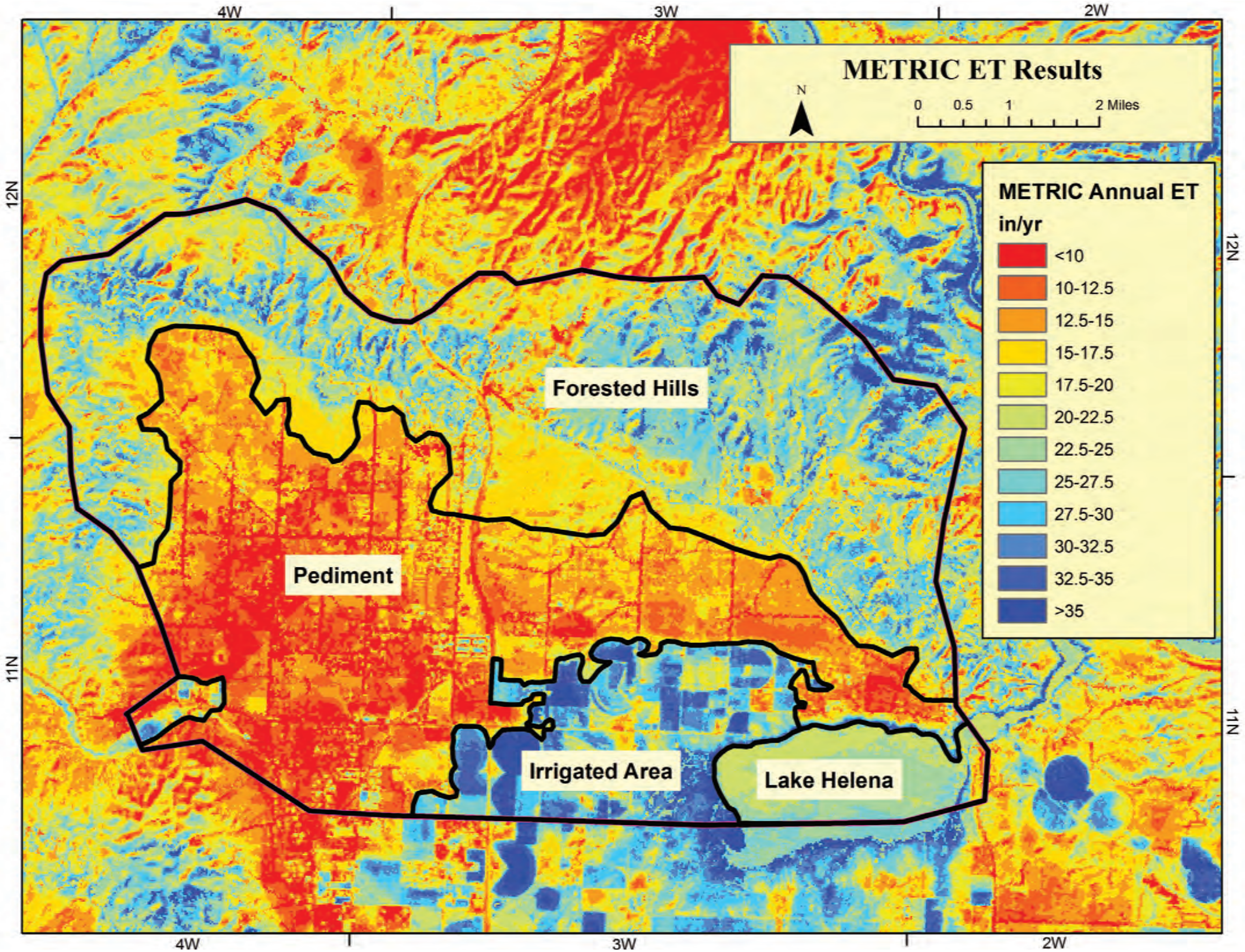

Figure 15. The METRIC ET analysis indicates that ET is approximately 28 in per year in the irrigated area, 13 in per year on the pediment, and 22 in per year in the forested area. Note that precipitation in the forested area averages 15 in per year (fig. 14). The method is considered useful for the pediment and irrigated area, but results for the forested hills are problematic.

accounted for water input of about 4,529 acre-ft per year. This water recharges the Helena Valley aquifer.

Table 4. Estimates of consumptive use in the pumping centers over time (acre-ft/yr).

	Year	Homes	Consumptive Use (Based on an estimated average use of 435 gpd/res)
Pumping Center A	1995	130	63
	2005	312	152
	2009	441	215
Pumping Center B	1995	78	38
	2005	189	92
	2009	250	122
Pumping Center C	1995	120	59
	2005	241	118
	2009	274	134

An analysis of detailed water use data in the area of Pumping Center A (W. Thompson, Hydrometrics, Inc., written commun., 2010) indicated that an average home with a septic system near Helena consumes about 435 gallons of water per day, including irrigation of lawns and gardens. The average amount of septic return is estimated to be about 168 gallons per day. Additional details and comparisons to other estimates are provided in Bobst and others (in preparation a). Aerial photography showed 2,150 homes in the North Hills Study Area in 2009. Therefore, it is estimated that a total of about 1,055 acre-ft per year (1.5 cfs) of water is consumptively used for domestic purposes. Note that the total includes withdrawals from Public Water Supply (PWS) wells and exempt wells. Since PWS wells are located adjacent to homes in the North Hills, the effects of these different well types are negligible. Approximately 98 percent of the water that is consumptively used for domestic purposes (~1,027 acre-ft/yr) is used for the irrigation of yards and gardens.

Estimates of consumptive use were generated for Pumping Centers A, B, and C (table 4). The consumptive use per household is based on water use records. Further details about how these estimates were made are provided in the North Hills Technical Report Water Budget section (Bobst and others, in preparation a). The monthly estimates in table 5 show the seasonal nature of consumptive use for Pumping Center A.

A 41-mile network of open and buried drains has been installed in the downgradient areas of the Helena Valley to drain areas that became boggy (waterlogged) due to irrigation in the valley. These drains collect shallow groundwater and direct it to Lake Helena (Briar and Madison, 1992). Measurements made during this study indicate that flow to surface drains is approximately 1 acre-ft per year per acre drained. Approximately 3,065 acres are drained in the North Hills Study Area. An estimated 3,040 acre-ft/yr of groundwater leaves the study area by drains.

Groundwater flows from the North Hills and discharges to Lake Helena. Briar and Madison (1992) estimated that total groundwater flow to Lake Helena is approximately 50,000 acre-ft/yr. Most of the water is derived from irrigation canal leakage and irrigation recharge; as such, the area topographically

Table 5. Estimated consumptive use in Pumping Center A by month (acre-ft) using 435 gpd/residence.

	% by month	1995	2005	2009
Jan	0.3%	0.2	0.5	0.6
Feb	0.3%	0.2	0.5	0.6
Mar	0.4%	0.3	0.6	0.9
Apr	0.6%	0.4	0.9	1.3
May	10.2%	6.4	15.5	21.9
Jun	18.2%	11.5	27.7	39.1
Jul	26.2%	16.5	39.8	56.3
Aug	26.4%	16.6	40.1	56.8
Sep	14.2%	8.9	21.6	30.5
Oct	2.4%	1.5	3.6	5.2
Nov	0.5%	0.3	0.8	1.1
Dec	0.2%	0.1	0.3	0.4
Total		63	152	215

below the HVID canal can be used to estimate the amount of water coming from the North Hills relative to the rest of the Helena Valley. Approximately 20 percent of the total area below the canal is located in the North Hills Study Area. Therefore an estimated 10,155 acre-ft of groundwater flows from the North Hills to Lake Helena per year.

Table 6 shows the estimated water budget, along with a probable range of values, which takes into account the estimated uncertainty with each calculation. Based on this budget, wells remove about 7.4 percent of the water from the overall groundwater system; however, in localized areas, such as Pumping Center A, the percentage will be significantly greater under current groundwater-pumping conditions.

The results of the calculated water budget and the North Hills Area model budget (operated in steady-state mode) are compared in table 6. The values are generally similar; variations are due to minor differences in the model area and the modeling method used for different components. The differences are further discussed in the Steady-State Calibration section of the North Hills Area model description in this report.

Table 6. North Hills water budget calculated values in acre-ft per year. Modeled values are generally of the same magnitude as estimated values. Significant differences between estimated and modeled values are discussed in North Hills Area Model Steady-State Calibration section of this report.

		Probable Range		
	Best Estimate	Minimum Acre-ft/yr	Maximum Acre-ft/yr	Modeled Values
INPUTS				
Silver Creek Alluvium Inflow	20	14	28	n/a
Bedrock Inflow	1,252	834	1,669	797
Diffuse Infiltration	4,380	3,942	4,818	3,824
Silver Creek Infiltration	959	876	1,071	268
Irrigation Canal Leakage	2,559	2,339	2,858	1,650
Irrigation Recharge	4,529	4,138	5,057	8,712
TOTAL INPUTS	13,699	12,143	15,501	15,251
OUTPUTS				
Drains	3,040	2,704	3,304	3,039
Lake Helena	10,155	9,000	11,000	12,060
Wells	1,055	949	1,160	152
TOTAL OUTPUTS	14,250	12,653	15,465	15,251

COMPUTER CODE

GMS software was used to develop a MODFLOW 2000 groundwater flow model. MODFLOW 2000 is a widely accepted groundwater flow program developed by the U.S. Geological Survey (Harbaugh and others, 2000). It numerically simulates groundwater flow through a porous medium using a finite-difference method. MODFLOW 2000 is an update of the core program MODFLOW (McDonald and Harbaugh, 1988). 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 Watermark Numerical Computing (Doherty, 2010). PEST is used for automated parameter estimation in certain model runs. The version of PEST operated in GMS 7.1.2 is Pest Version 12.0.

Two basic methods of calibrating a groundwater flow model using PEST are available in GMS. The polygonal zone method allows hydraulic conductivities to be applied to polygons within the model. In a simple model, one polygon may suffice for the entire model. Larger area models with more complex geologic conditions may be assigned more polygons. For example, 24 polygons were created for the North Hills Pediment Focus model, and polygon placement was guided by the locations of faults and geologic contacts. The second calibration method is the pilot-point method. The pilot-point method assigns hydraulic conductivities to an array of designated points throughout the model. Individual hydraulic conductivities are assigned to each cell in the model, based on the values determined for the designated points. This method eliminates the potentially sharp contrasts in hydraulic conductivities in the model that can occur at polygon boundaries.

GROUNDWATER FLOW MODEL CONSTRUCTION

Model Grid

The GMS project was conducted using the North American Datum (NAD) 1983 Montana State Plane coordinates, in units of International Feet. The model grid was created in GMS using a grid frame with an X origin of 1301000.0 ft, a Y origin of 907000.0 ft, and a Z origin of 3250.0 ft (table 7). Grid lengths in the X, Y, and Z dimensions were 63,600, 47,600, and 2,000 ft, respectively. A rotation angle of -25 degrees was specified to align the grid approximately with the orientation of the Helena Valley Fault within the active model domain. This grid frame was sufficient for both the North Hills Area model and the Pediment Focus model, as cells within a grid frame can simply be inactivated to change the active model domain. Active cell coverage for the Pediment Focus model extended from the surface water divides in the North Hills to the vicinity of the HVID canal (fig. 16). Cells measured 400 ft x 400 ft. The model had 1 layer, 119 rows, and 159 columns.

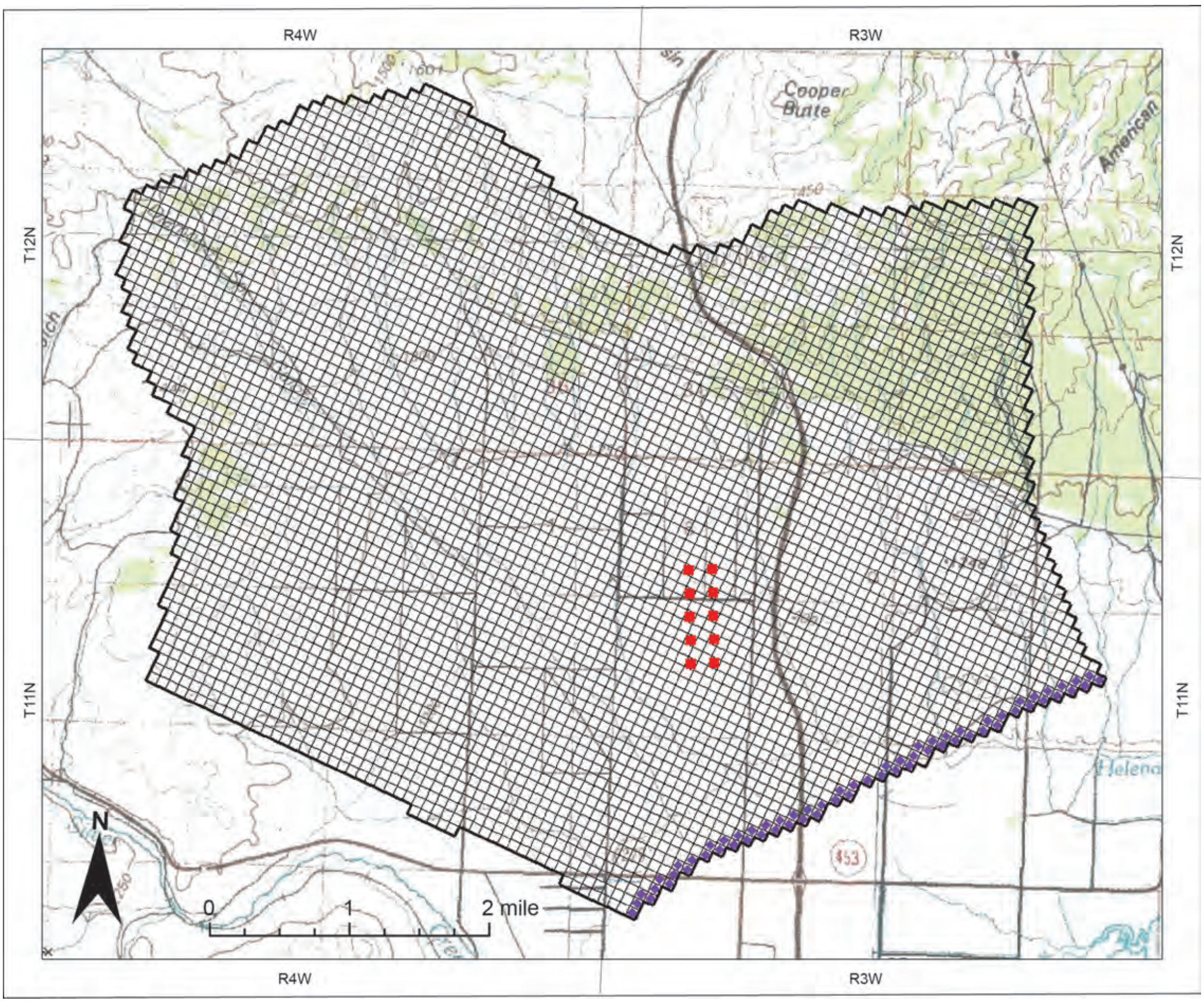

Figure 16. Active model grid cells for the Pediment Focus Model. Constant head cells for steady-state runs and variable head cells for transient runs are shown in purple. Locations of modeled wells used to simulate Pumping Center A groundwater withdrawals are shown in red.

Table 7. Details of the model grid as listed in GMS. This same grid is used in both the Pediment Focus model and the North Hills Area model.

Grid type:	Cell Centered
X origin:	1301000.0 (ft)
Y origin:	907000.0 (ft)
Z origin:	3250.0 (ft)
Length in X:	63600.0 (ft)
Length in Y:	47600.0 (ft)
Length in Z:	2000.0 (ft)
Rotation angle:	-25.0
AHGW X origin:	1321116.6292589 (ft)
AHGW Y origin:	950140.25066294 (ft)
AHGW Z origin:	5250.0 (ft)
AHGW Rotation angle:	115.0
Minimum scalar:	0.005446
Maximum scalar:	68.99177
Num cells i:	119
Num cells j:	159
Num cells k:	1
Number of nodes:	38400
Number of cells:	18921
No. Active cells:	5044
No. Inactive cells:	13877

Table 7 provides additional numeric details about the model grid. The model thickness varied between about 400 to 1100 ft; however, the saturated thickness was typically in the range of about 400 to 800 ft.

The upper surface of the one-layer model was defined using data derived from the U.S. Geological Survey's 1/3-Arc Second National Elevation Dataset (U.S. Geological Survey, 2009). The data were converted into a scatter point dataset and imported into GMS as a text file. The 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, compared to the cell size of 400 ft. In GMS, scatter point data may be mapped to various MODFLOW layer property arrays, and basic math formulas can be applied to a scatter point data set to develop additional scatter point data. The bottom of layer one was defined by a surface derived from two elements. The first element was a surface defined by subtracting 400 ft from the elevation of the DEM scatter point set. This set is referred to as the DEM minus 400 scatter point set. The second element was a flat surface defined at an elevation of 3,250 ft, which is about 400 ft below the mapped elevation of Lake Helena.

A flat-bottom model was tested and found undesirable because the resulting saturated zone under the North Hills was more than twice as thick as the saturated cells in the vicinity of Lake Helena. A model with a layer created using the DEM minus 400 ft scatter point set was tested, but the resulting calculated saturated zone beneath the North Hills became too thin, resulting in some dry cells. A satisfactory surface was created by splitting the difference in elevations between the DEM minus 400 scatter point dataset and the flat surface at elevation 3,250 ft. This created a moderated surface (fig. 17)

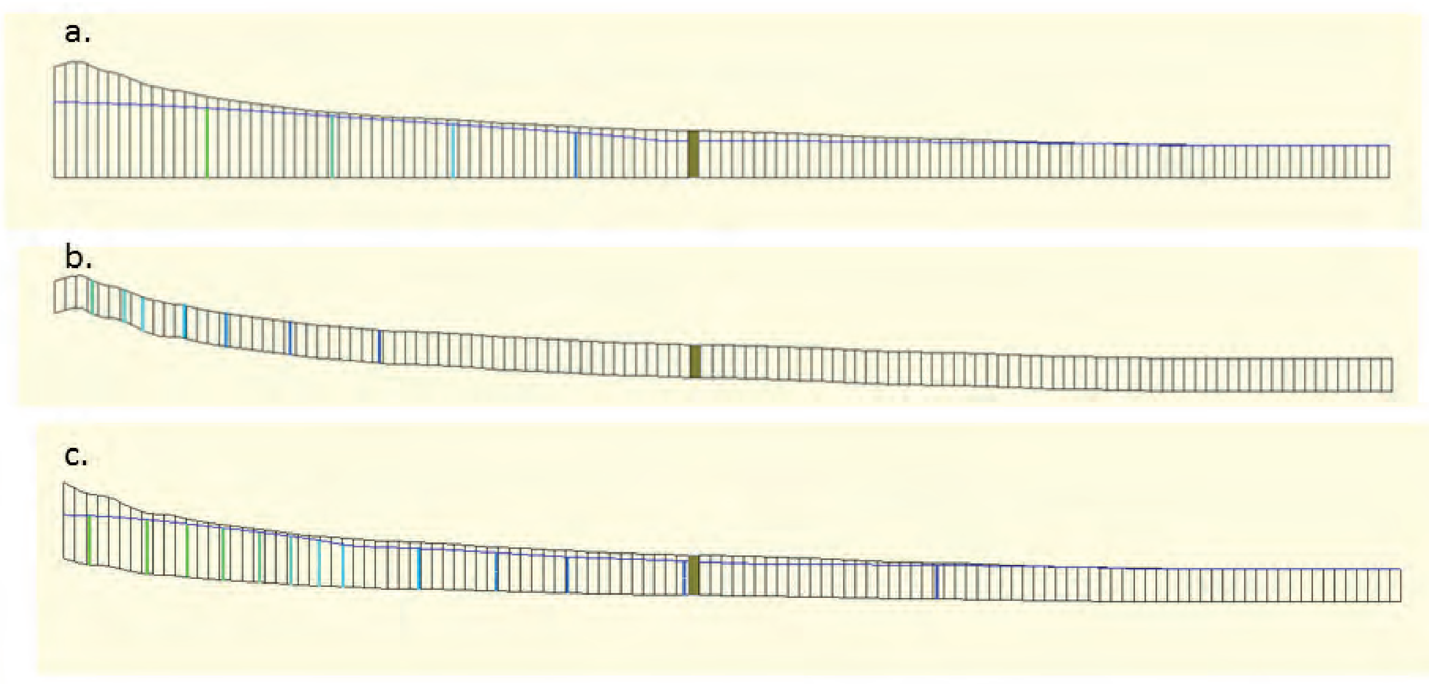

Figure 17. The bottom of layer 1 was defined by splitting the difference between elevations defined by (a) the flat surface elevation 3,250 ft defined bottom and (b) the DEM minus 400 defined bottom to create (c) the moderate bottom surface.

and produced a more uniform calculated saturated thickness in the active model domains.

Additional details about the model products developed are provided in Appendix B. These details include descriptions of the various model products available and informative details for potential model users.

Hydraulic Parameters

To create steady-state simulations of both the Pediment Focus model and the North Hills Area model, initial values of hydraulic conductivity were assigned to polygons based on the results of preliminary runs of the North Hills Area model. The preliminary runs operated on the basic premises of the conceptual model and the water budget for the study area. Of particular importance for the groundwater model simulation for the area above the HVID canal, the limited estimated recharge (3 to 4 in/yr) in the North Hills resulted in hydraulic conductivity (K) values that were at the lower end of the expected values for the bedrock and Tertiary aquifers as listed in table 3.

PEDIMENT FOCUS MODEL

The Pediment Focus model was designed to model the groundwater system above the HVID canal. This model took advantage of the simpler water budget above the canal and the densest distribution of observation-well data for the study area. The active cells of the model grid used in the Pediment Focus model are illustrated in the Model Grid section (fig. 16). A schematic illustration (fig. 18) shows the grid in a three-dimensional view, with some of the key concepts applied in the model annotated.

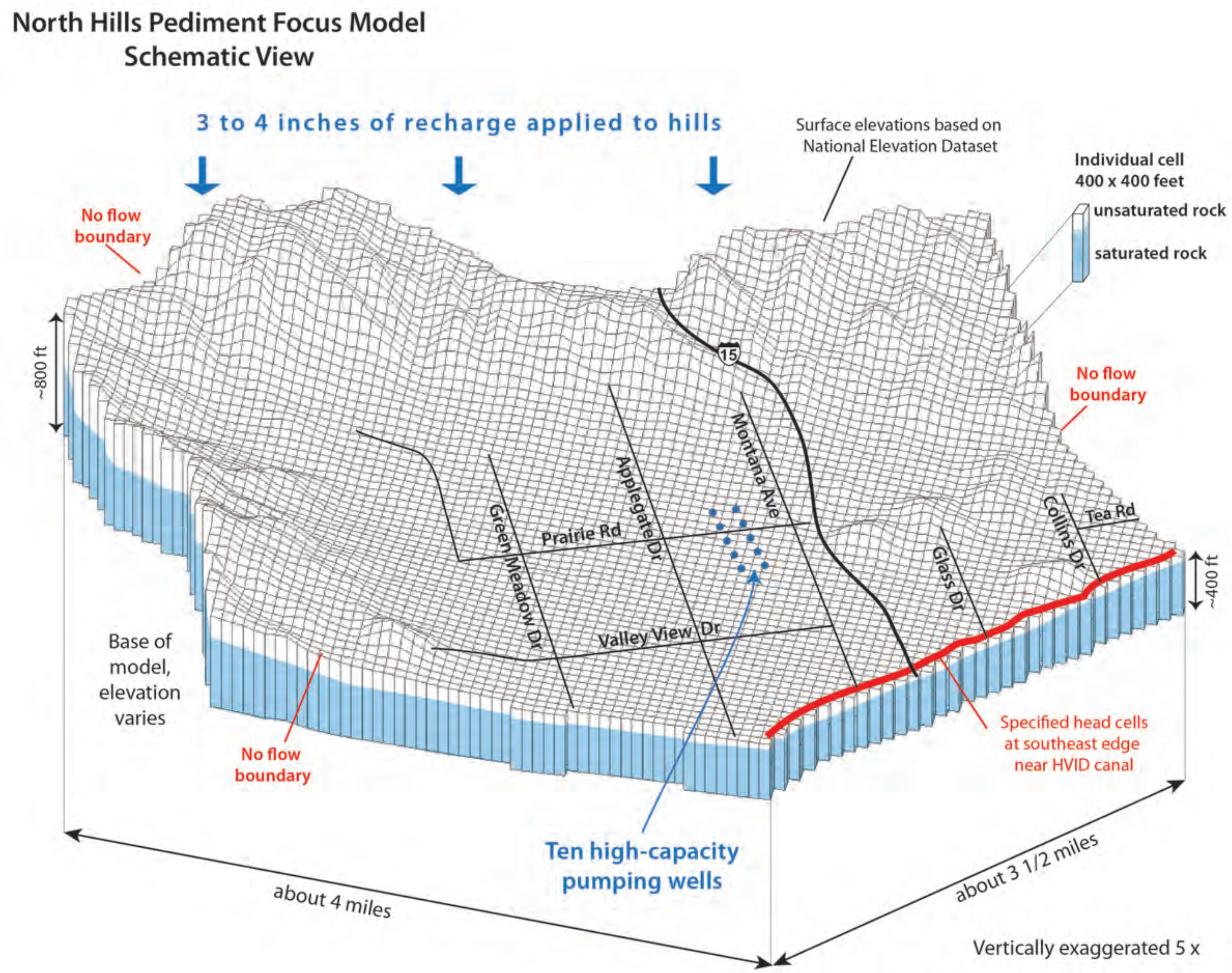

Figure 18. Schematic illustration of the Pediment Focus Model grid.

Boundary Conditions

The boundary conditions for the Pediment Focus model were no-flow boundaries along all sides except the southeast edge of the model. The no-flow boundaries were placed at the locations of the surface-water divides between the Helena Valley and the Silver City area to the west, and the Gates of the Mountains area to the north. The lateral edges of the model were placed along flow lines based on the potentiometric surface map, extending from the divide to the vicinity of the HVID canal and the 3,725-ft potentiometric contour. The southeast edge of the model is a specified head boundary along the approximate location of the 3,725-ft potentiometric contour. This specified head was constant during steady-state simulations, but varied seasonally in transient simulations. The boundary replicated the stable groundwater setting associated with the HVID canal.

Sources and Sinks

The source of water for the Pediment Focus model was recharge applied using the recharge package. Recharge polygons were used in the steady-state calibration run (fig. 19). These polygons limit recharge as shown to the North Hills and a small portion of the model near the southeast edge that extends below the HVID canal. There was no recharge applied to the pediment surface. Recharge was held constant at the indicated values during steady-state calibration.

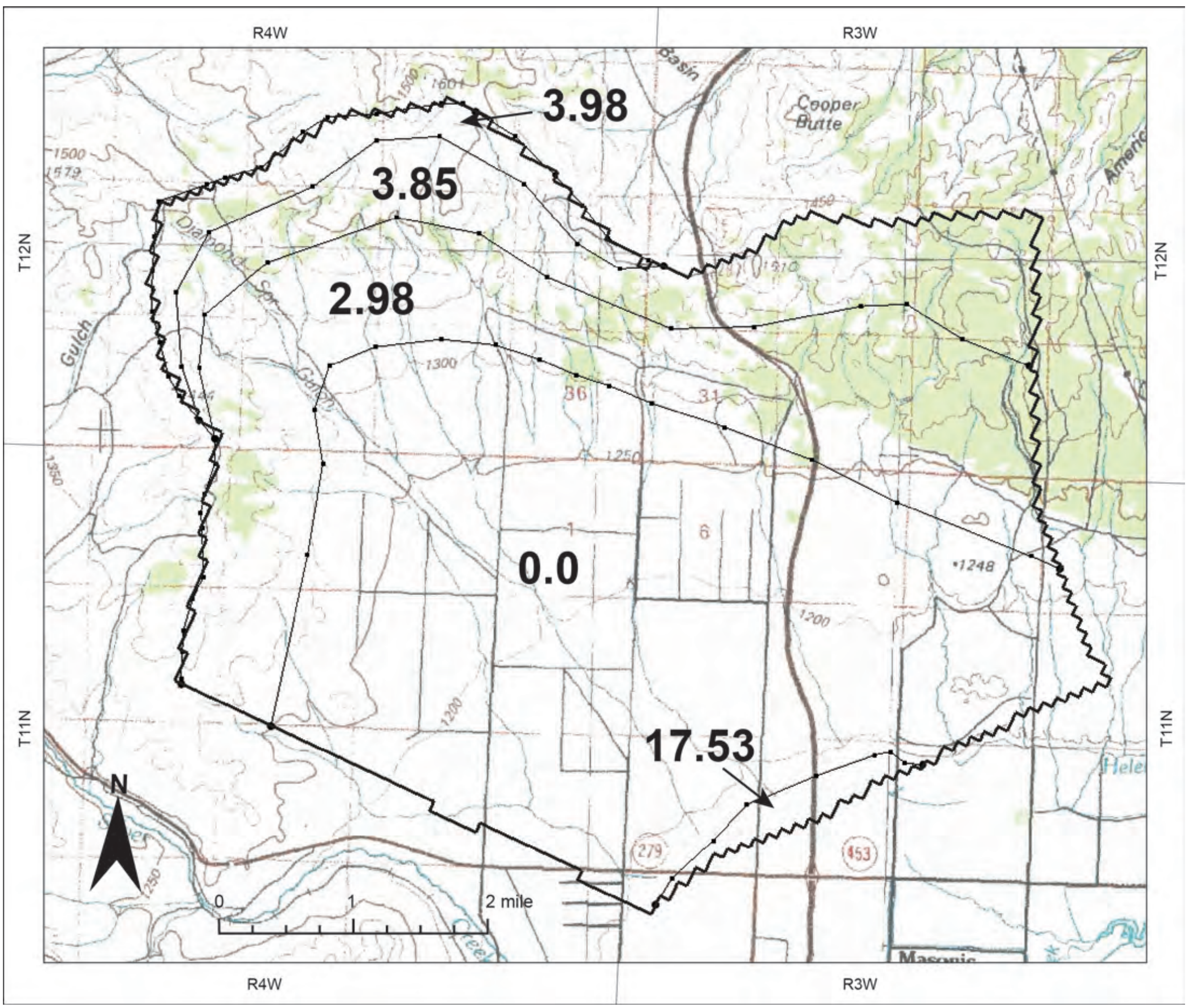

Figure 19. Recharge polygons used in the Pediment Focus model steady-state calibration and recharge values applied (in per year).

The sinks in the model included the specified head cells at the southeast edge of the model and assigned well discharge (fig.16). In steady-state model runs, the specified head cells along the southeast edge of the model were set at a constant head of 3,725 ft. In transient model runs, specified heads were adjusted to mimic the seasonal rise and fall of the groundwater surface near the HVID canal. These values ranged from a high of 3,730 ft in August and September to a low of 3,718 ft in March of each year.

Estimated discharge from wells within Pumping Center A was modeled as a sink by simulating pumping from 10 wells located in the vicinity of Pumping Center A. For the 2006 dataset, the well package was used to simulate 10 wells extracting approximately 152 acre-ft/yr (see tables 4 and 5). In transient mode, these wells simulated the estimated pumping withdrawals for Pumping Center A as detailed in table 8. The specified head boundary described may act as a source of water if sinks added within the model domain caused the calculated groundwater elevations to fall below about 3,725 ft near the boundary.

Selection of Calibration Targets

Groundwater-level data were collected at selected area wells monthly during the project, beginning in fall 2009 and winter 2010, and continuing until June 2011. About 72 well sites provided reasonably complete monthly records of static water levels. Data collected in 2006 for the Madison (2006) study yielded about 181 sites where groundwater levels were measured in the fall and winter of 2005–2006. Without modification, the 2006 and 2010 data sets yielded quite similar potentiometric surfaces when contoured using the default kriging method in Surfer Version 9 (Golden Software, Inc., Golden, CO). Because of the data set differences, there were places within the model area where data were available for wells for 2006, but not for 2010. A few wells were removed from the 2006 data set to create a modified 2006 data set and potentiometric map that compared favorably to the contoured 2010 data.

Table 8. Groundwater usage applied in transient modeling at Pumping Center A for stress periods from 2005 through 2011.

	2005		2006		2007		2008		2009		2010		2011	
Month	Acre-Ft	Q per well	Acre-Ft	Q per well	Acre-Ft	Q per well	Acre-Ft	Q per well	Acre-Ft	Q per well	Acre-Ft	Q per well	Acre-Ft	Q per well
January	0.5	72	0.525	75	0.55	79	0.575	82	0.6	86	0.6	86	0.6	86
February	0.5	72	0.525	75	0.55	79	0.575	82	0.6	86	0.6	86	0.6	86
March	0.6	86	0.675	97	0.75	107	0.825	118	0.9	129	0.9	129	0.9	129
April	0.9	129	1	143	1.1	158	1.2	172	1.3	186	1.3	186	1.3	186
May	15.5	2221	17.1	2450	18.7	2680	20.3	2909	21.9	3138	21.9	3138	21.9	3138
June	27.7	3969	30.55	4377	33.4	4786	36.25	5194	39.1	5603	39.1	5603	39.1	5603
July	39.8	5703	43.925	6294	48.05	6885	52.175	7476	56.3	8067	56.3	8067	56.3	8067
August	40.1	5746	44.275	6344	48.45	6942	52.625	7541	56.8	8139	56.8	8139	56.8	8139
September	21.6	3095	23.825	3414	26.05	3733	28.275	4052	30.5	4370	30.5	4370	30.5	4370
October	3.6	516	4	573	4.4	630	4.8	688	5.2	745	5.2	745	5.2	745
November	0.8	115	0.875	125	0.95	136	1.025	147	1.1	158	1.1	158	1.1	158
December	0.3	43	0.325	47	0.35	50	0.375	54	0.4	57	0.4	57	0.4	57
Total Annual	152		168		183		199		215		215		215	

Note. Pumping schedule is the same each year 2009–2011 and is based on the 2009 water use estimates. 2006–2008 estimates based on a linear relationship between the 2005 and 2009 estimates. Q, pumping rate, in cubic ft per day; values shown are applied for each of 10 wells modeled in Pumping Center A.

The initial steady-state simulation was calibrated to 2006 data. The calibration targets were selected from the 2006 and 2010 data sets. The study area identified 35 wells having data from both 2006 and 2010. Ten of the wells were located outside of the Pediment Focus model area, so were removed from the data set. Water levels from 15 wells measured at distal locations in 2006 (but not measured in 2010) as well as water levels from six new sites from the 2010 data, also in distal locations, were added to expand the potentiometric surface of the calibration target data set and fill as much of the pediment model area as possible. The additional water levels created 46 points for the initial calibration runs. The calibration data for 2006 were derived from observed values or estimated for March 2006. The 2010 calibration data set was derived from observed values or estimated for February 2010.

During initial calibration tests that used the polygonal zone method, three wells were deleted from the data set due to the inability of the model to calibrate the data successfully based on the polygon array. These wells included well 196245, which was shallow relative to surrounding wells, and well 202177, which was deeper than surrounding wells. The third well removed was well 258597, one of the current project-drilled wells at the Helena Valley Fault. Because the fault backs up groundwater, the difference in water-level elevations in wells upgradient and downgradient of the fault are large. Well 253818, located only about ¼ mile south, was selected as a more desirable target in this vicinity because the model effort is focused on conditions in the pediment. The model successfully calibrated to the conditions at both wells by the insertion of a narrow polygon in the vicinity of the fault. However, this method was rejected since information was only available for one point in the model (the Helena Valley Fault aquifer test site) and adding this complexity away from the site created numerous assumptions. Calibration data files are provided with each set of groundwater model files.

Steady-State Calibration

Steady-state model calibration was performed by holding recharge and pumping well rates constant at the designated values and operating PEST automated parameter optimization. The polygonal zone method was performed first and provided reasonable results. The root mean square error using this calibration method was 11.7 ft, which is reasonable for this scale of groundwater model.

The pilot point method was used to further adjust the hydraulic conductivity assignments in the model. In this method, recharge and the pumping stress for Pumping Center A were held constant as in the polygonal zone method. Surveyed well data were available for both the pilot point method and the resulting model, as opposed to the map locations used for the polygonal method. Surveys of well locations were completed and applied to the GWIC database in early May 2011.

Because hydraulic conductivities are generated based on the calibration targets and modeled stresses, such as recharge and wells, control points needed to be added to the calibration target file to constrain the calculated heads in areas where there were no actual observations. For example, data are not available in the uplands in the northeast corner of the model. Therefore, estimates of the approximate position of the potentiometric surface were made and entered as control points to guide the model calculations toward a realistic result. For PEST pilot point model runs, two calibration files, one with control points and one without control points, were used. The file without control points was read back into the model after the PEST run. The model was then run in forward mode to determine the resulting model statistics based on observations measured or estimated data from actual wells (as opposed to control points).

Hydraulic conductivity ranges resulting from the pilot point method can be shown on a map (fig. 20). The colorations are based on ranges of values. Each individual cell in the model is assigned a separate hydraulic conductivity. The potentiometric surface generated by the calibrated model and calibration targets resulted in a mapped surface (fig. 21). The calibration target interval was set at

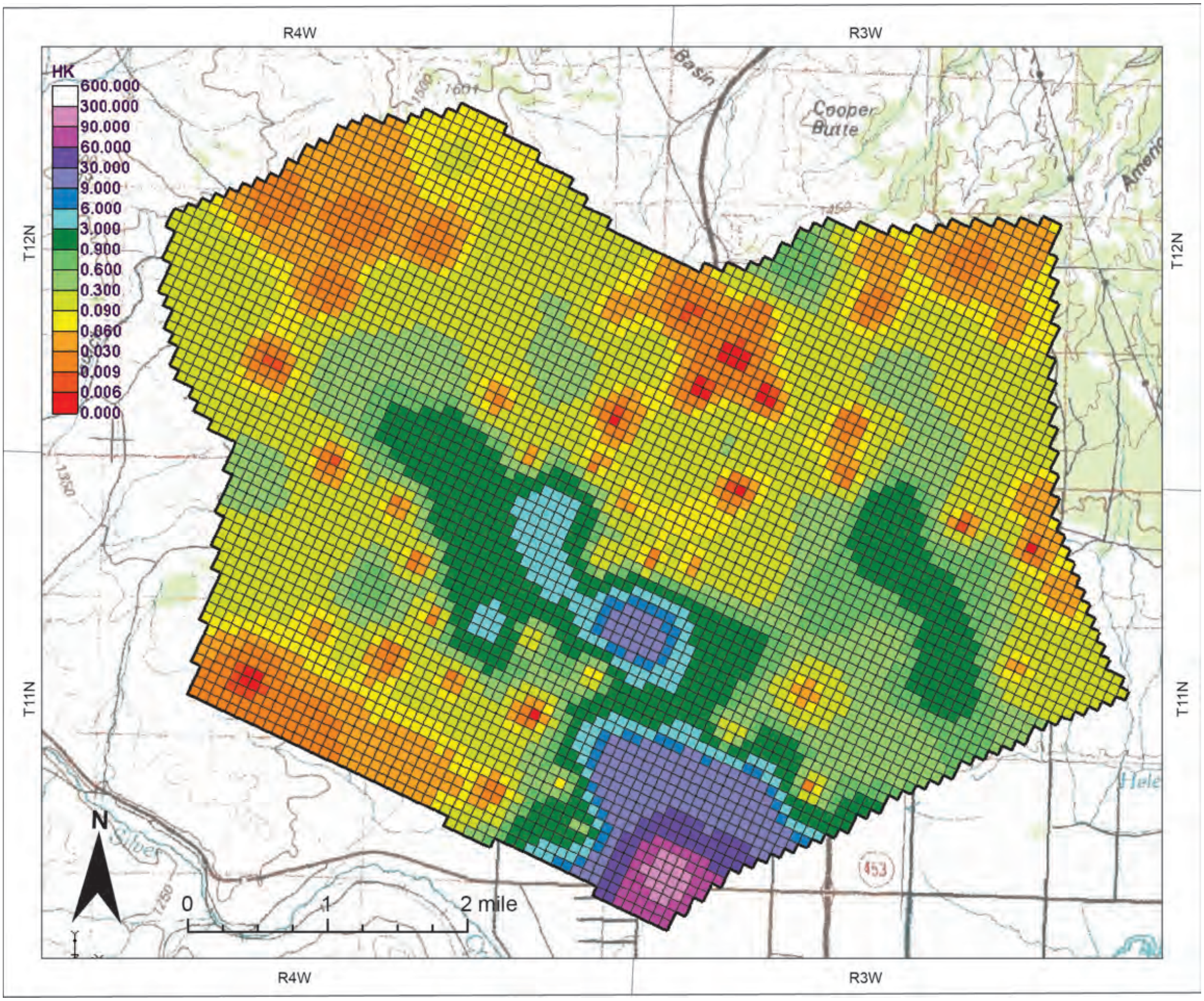

Figure 20. Hydraulic conductivity ranges for the Pediment Focus model shown by colored zones labeled HK in the legend. Individual cells have independent values within the specified range. Values are in ft/d.

10 ft. A graph (fig. 22) shows the computed versus observed head values in the model domain for the model generated using the pilot point method. The root mean square error was about 4.4 ft, a significant improvement over the polygonal zone method result.

The resulting model had an inflow of 299,649 ft^3/d (3.48 cfs, 2,513 acre-ft/yr) derived from recharge. A total of 25,600 ft^3/d of the recharge resulted from the polygon that defined recharge in the area below the canal. Therefore, 274,049 ft^3/d (3.17 cfs, 2,298 acre-ft/yr) of recharge calibrated by the model was generated in the North Hills portion of the model domain. The outflow included 281,509 ft^3/d (3.26 cfs, 2360 acre-ft/yr) discharging at constant head cells (southeast boundary), and 18,140 ft^3/d discharging from wells (0.21 cfs, 152 acre-ft/yr). In this model, the wells discharged about 6.4% of the groundwater generated by the recharge in the North Hills within the model domain.

As was the result with the polygon zone method, hydraulic conductivity values were on the low end of the estimated range of properties. Decreasing recharge would further lower those values, pushing them farther from the estimated range. Therefore, the applied recharge rate was considered reasonable and was perhaps even a conservative estimate

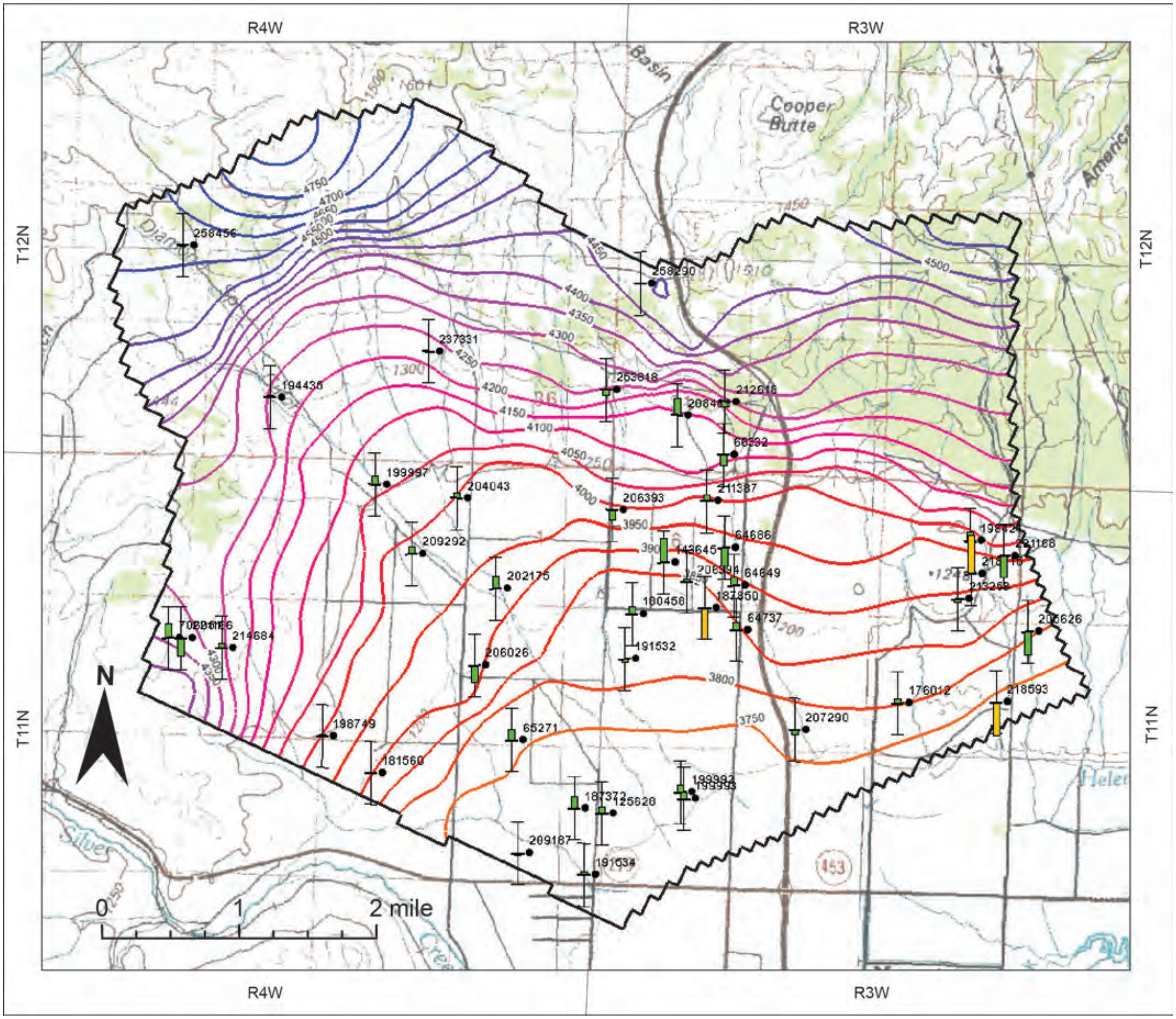

Figure 21. Computed potentiometric surface of the calibrated steady-state Pediment Focus model using the pilot point method. Calibration targets are shown by the dots. The dots are labeled with the GWIC well identification number for the site. The vertical scales show the target elevation (middle hatchure), with colored bars showing the vertical difference between the target elevation and the calculated potentiometric surface. Green indicates the target is within the set calibration criteria; yellow indicates the value is within twice the calibration criteria interval. The calibration interval for this run was set to 10 ft.

of areal recharge from precipitation in the North Hills. Furthermore, the amount of water generated by the model was low in comparison with previous estimates and at the low end of estimates made in the water budget. This further supports the notion that precipitation recharge cannot be much lower than the values selected. Recharge may likely be higher based on the model results.

Model Verification

Data sets for validating the steady-state model were limited; however, a couple of tests indicated that the model generated reasonable drawdown estimates for Pumping Center A. The first test used the estimated annual extraction of 152 acre-ft per year used for 2006. The model was run without pumping center well data to approximate the amount of drawdown calculated by the steady-state model. The results of this test are shown in figure 23. The calculated steady-state drawdown was about 24 to 26 ft at the northern end of Pumping Center A, as defined by the 10 modeled wells used. The drawdown calculated by the model at the location of GWIC well 64737 was about 11 ft. As of 2006, an observed drawdown of about 10 ft had accumulated at well 67737, as evident in the hydrograph (fig. 24).

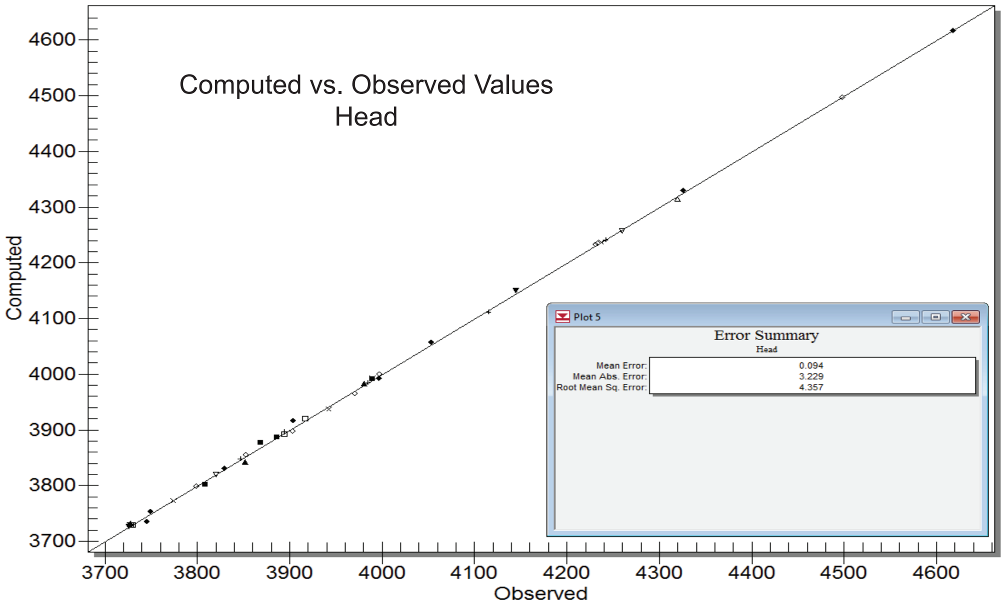

Figure 22. Graph showing computed vs. observed head values at calibration targets in the Pediment Focus model domain resulting from the steady-state pilot point approach, and statistics.

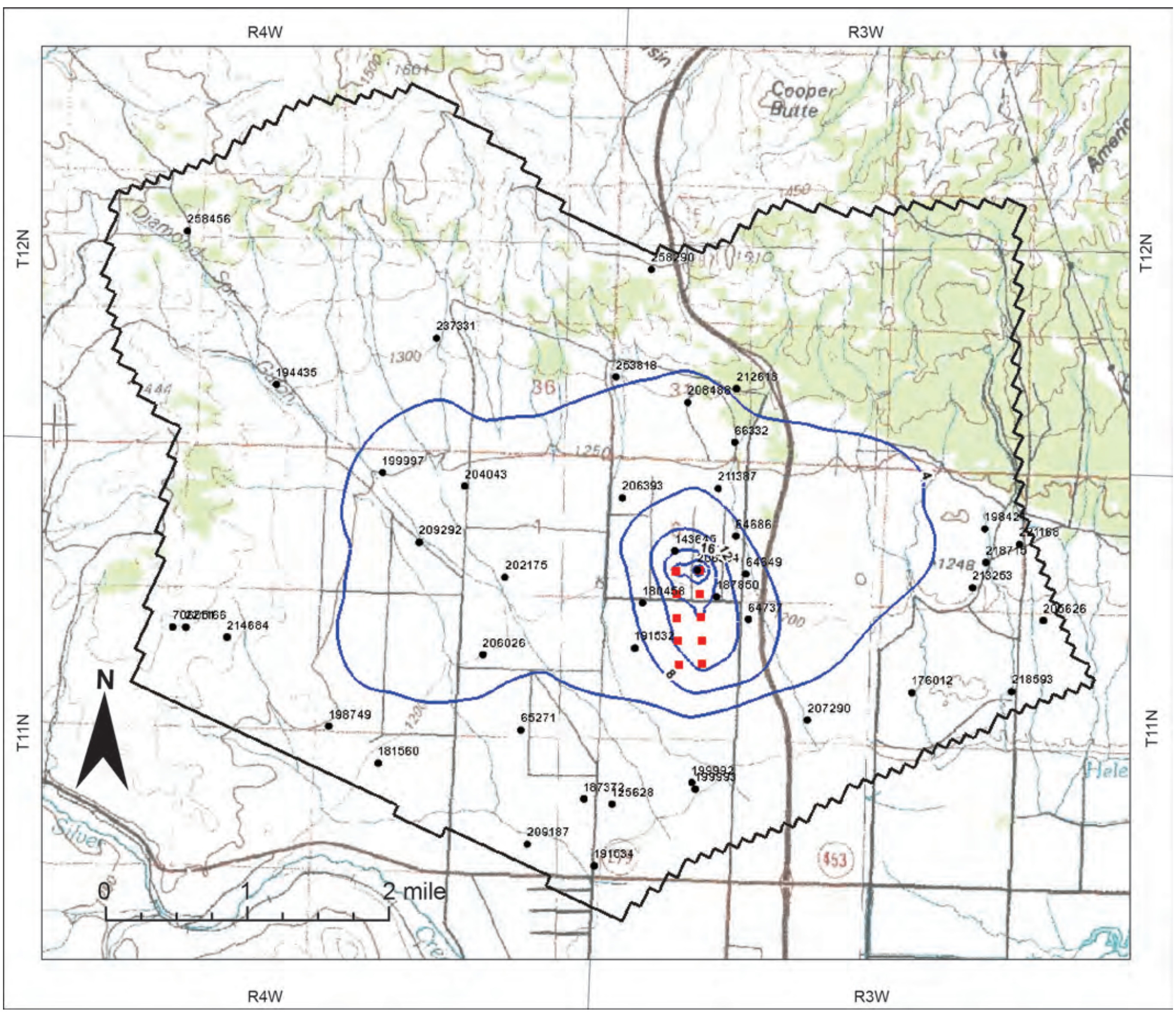

Figure 23. Steady-state drawdown in the Pediment Focus model calculated based on estimated 2006 pumping rates, contour interval, 4 ft. Red squares represent modeled wells.

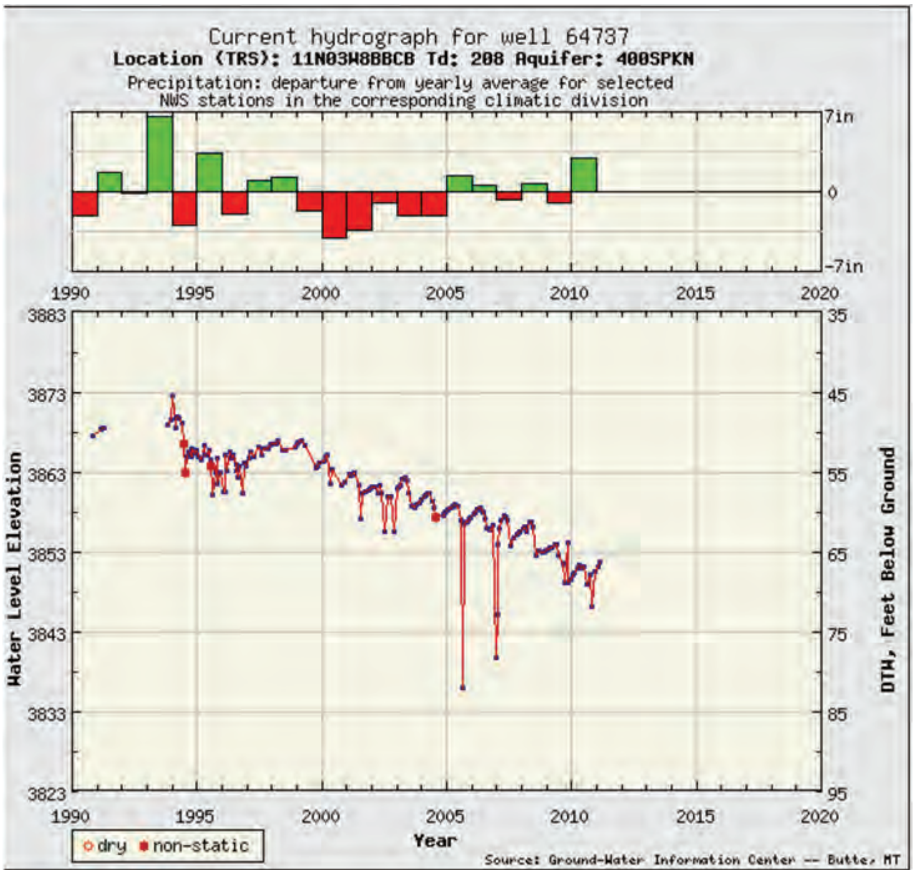

Figure 24. Hydrograph for well 64737, located in the NW¼, NW¼ of Section 8 just east of Pumping Center A.

In the second test, the pumping rate of Pumping Center A wells was increased from the 2005 estimate of 152 acre-ft per year to the 2009 estimate of 215 acre-ft/yr (0.30 cfs, 25640 ft^3/d), and the increase in drawdown was calculated. The test resulted in additional drawdowns as shown in figure 25. The calculated drawdown agrees reasonably well with the observed drawdown in area wells. The hydrograph for well 64737 (fig. 24) shows that about 7 ft of additional drawdown occurred between 2005 and 2010. The model calculated about 6.5 ft of additional drawdown, resulting from the increased estimated pumping rate for 2010. The model run resulted in several additional wells being out of calibration range in the vicinity of Pumping Center A. However, once the calibration targets were updated to reflect 2010 observed values, all three of these wells fell back into calibrated range.

Transient Calibration

Transient model calibration of the Pediment Focus model was performed by varying the pumping rates from Pumping Center A based on available pumping estimates, and replacing the constant head boundary in the vicinity of the HVID canal with a specified head boundary that mimicked the observed seasonal rise and fall of water levels in the Helena Valley aquifer. Varying the recharge seasonally in the North Hills was tested, but resulted in significant seasonal differences of calculated, modeled head in wells at the upper edges of the pediment that were not observed in the actual data collected. Therefore, that effort was eliminated. The recharge rates were the same as those used in the steady-state model runs, except no water was applied at the lower end of the model near the canal because the specified head boundary simulated conditions there. The reasons that groundwater flow appeared as a fairly constant flux out of the hills probably included the fact that water must percolate through a thick unsaturated zone before reaching the water table and that faults and other features may impede the direct movement of groundwater by varying degrees. All of the transient model runs used the hydraulic conductivity array created by the steady-state pilot point parameter estimation technique and the steady-state calculated heads as initial head conditions.

Monthly net extraction estimates of groundwater from Pumping Center A are shown in table 8 and were derived from the estimates made for 2005 and 2009 (table 5). Estimates for intervening years were linearly interpolated. Pumping rates after 2009 were the same rates used for 2009. Initial heads for the 2010 transient run were derived from the steady-state solution that utilized the 2010 observation well data and 2010 pumping estimates for Pumping Center A.

A transient run was conducted for 2010 data using a target calibration file with 30 targets; this is referred to as the 2010 transient model run. The reduced number of targets was due to the removal of targets that had no 2010 data. The initial transient run compared the 2010 monthly pumping rate estimates against the actual observed water levels

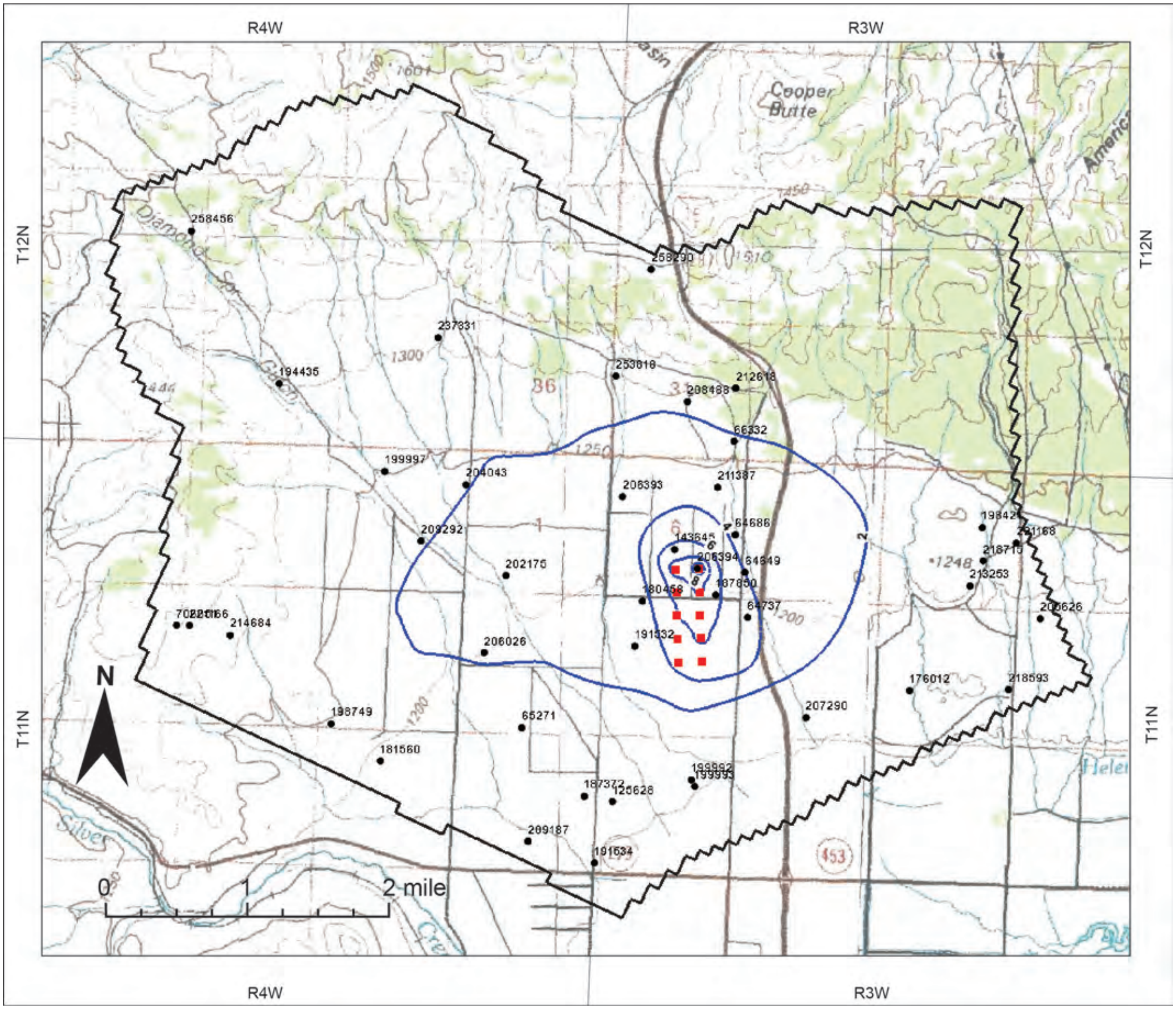

Figure 25. Additional steady-state drawdown calculated in the Pediment Focus model by comparing calculated steady-state drawdown from 2006 estimated pumping rates with calculated steady-state drawdown resulting from increased 2010 estimated pumping rates, contour interval 2 ft. Red squares represent modeled wells.

collected from February 2010 through February 2011. The model had 13 time steps, each starting at midnight on the first day of the month and running through midnight at the end of the last day of the month. The stress period set-up is shown in table 9. This 13-month model was developed first to verify that the model would function in transient mode before attempting to model multiple years.

The results of the 13-month transient run were evaluated, and the specific yield was adjusted until calculated heads reasonably replicated the observed data. The resulting single specific yield value used was 0.02. This agrees reasonably with the range of porosity expected for fractured rock of about 0 to 5 percent (Freeze and Cherry, 1979).

A map of the computed potentiometric surface of the calibrated 2010 transient model run by the Pediment Focus model (fig. 26) shows the solution for March 1, 2010. A plot of the computed and observed heads (fig. 27) includes the error statistics for the model. The root mean square error for all wells in all stress periods was 5.8 ft. Hydrographs from selected wells within the model domain showing the observed and computed heads were generated with GMS (fig. 28).

The water budget for the end of time step 12, representing 1 year, was viewed to determine some annual water budget numbers. The recharge on the North Hills area of the model was producing 2,296 acre-ft/yr. A net 81 acre-ft/yr from storage was

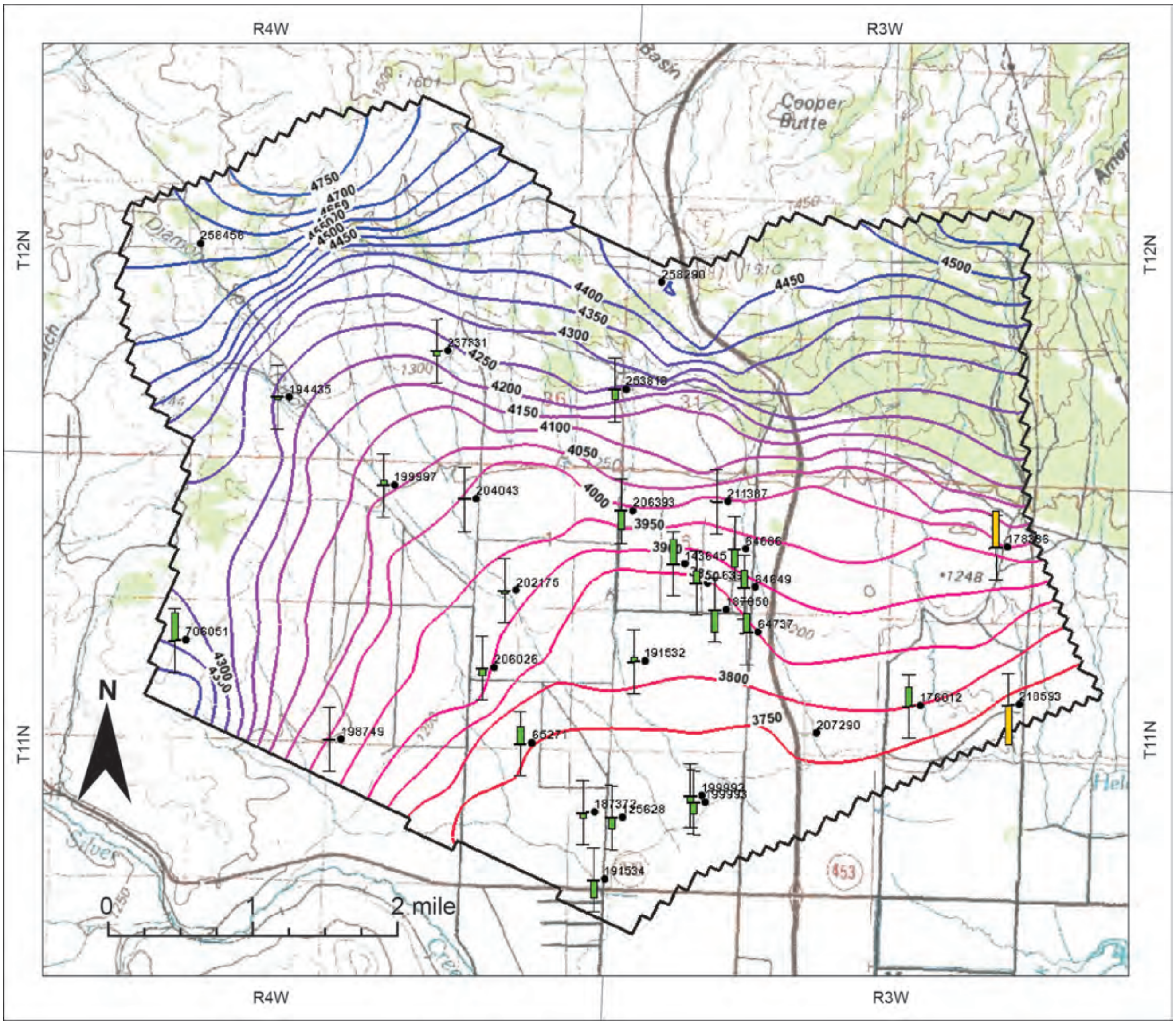

Figure 26. Computed potentiometric surface of the calibrated 2010 transient run by the Pediment Focus model. This image is based on the observed and calculated groundwater data at about the beginning of stress period two, around March 1, 2010. Calibration targets are shown by the dots. The dots are labeled with the GWIC well identification number for the site. The vertical scales illustrate the target elevation (middle hatchure), with colored bars showing the vertical difference between the target elevation and the calculated potentiometric surface. Green indicates the target is within the set calibration criteria; yellow indicates the value is within twice the calibration criteria interval. The calibration interval for this run was set to 10 ft.

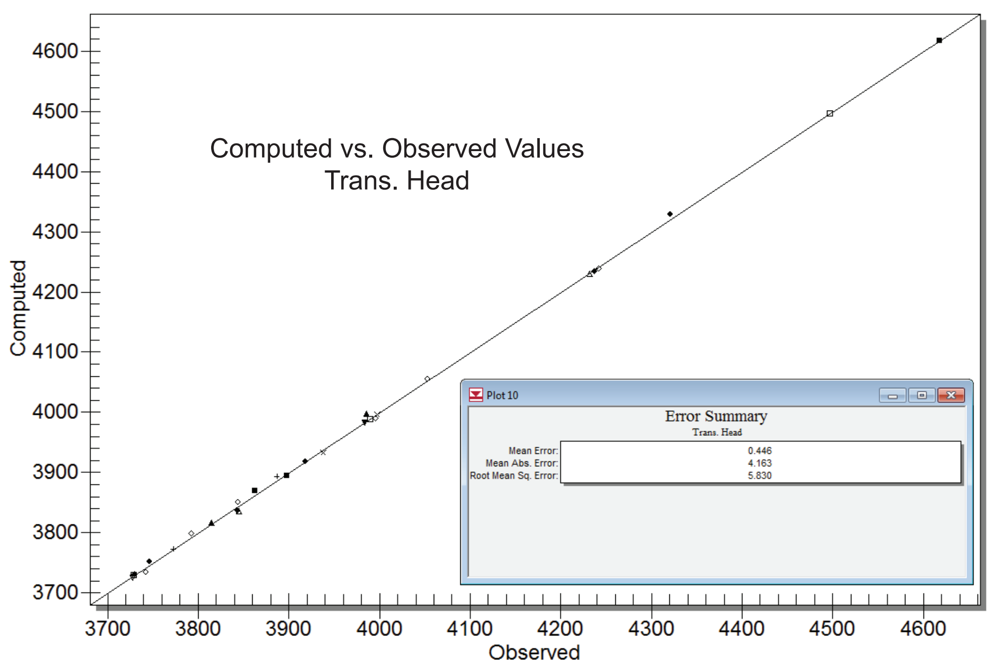

Figure 27. Graph showing computed vs. observed head values at calibration targets in the model domain resulting from the 2010 transient Pediment Focus model run, and statistics. The graph shows the results of the first time step in the model run. The table shows statistics for all calibration targets and all time steps.

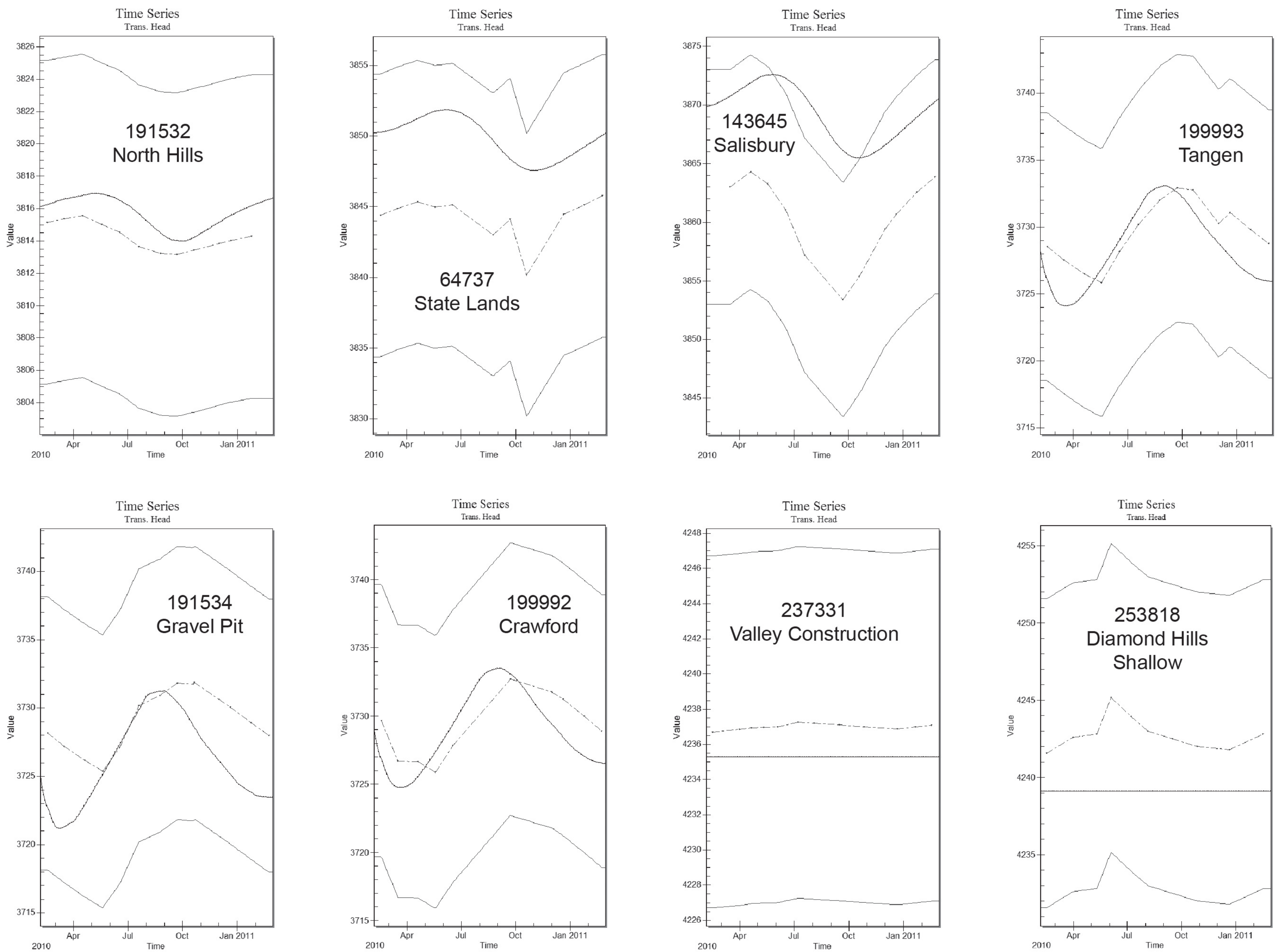

Figure 28. Selected hydrographs showing observed water-level data (center), the 10 ft calibration zone above and below the observed water-level data, and the model-calculated head (darker smooth line) for the 2010 model run of the Pediment Focus model.

Table 9. Stress period start dates, times, length in days, and number of time steps for the 2010 transient model run.

Date Time	Stress period length	No. of time steps
2/1/2010 12:00:00 AM	28.0	10
3/1/2010 12:00:00 AM	31.0	10
4/1/2010 12:00:00 AM	30.0	10
5/1/2010 12:00:00 AM	31.0	10
6/1/2010 12:00:00 AM	30.0	10
7/1/2010 12:00:00 AM	31.0	10
8/1/2010 12:00:00 AM	31.0	10
9/1/2010 12:00:00 AM	30.0	10
10/1/2010 12:00:00 AM	31.0	10
11/1/2010 12:00:00 AM	30.0	10
12/1/2010 12:00:00 AM	31.0	10
1/1/2011 12:00:00 AM	31.0	10
2/1/2011 12:00:00 AM	28	10
2/28/2011 11:59:00 PM		

entered into the model calculations. Of the 2,377 acre-ft/yr of water entering the model calculations, 2,161 acre-ft/yr was calculated to discharge out the specified head boundary and 216 acre-ft/yr was calculated to discharge out of the modeled wells. This compared reasonably to the 3,352 acre-ft/yr used by Madison (1993) as flux into the Helena Valley aquifer from the North Hills, since the Pediment Focus model covers about 2/3 of the North Hills flux boundary used in that study. This will be evaluated further with the North Hills Area model.

A transient run was developed for the period September 2005 through February 2011, referred to as the 2005–2011 transient model run. As in the 2010 transient run, the time steps each start at midnight on the first day of the month and run through midnight at the end of the last day of the month. The stress period set-up is shown in table 10.

The well pumping scheme for the 2005–2011 transient model run was derived from the estimates shown in table 8. The calibration target set included all 43 calibration targets used for the steady-state calibration with pilot points. The computed versus observed heads at selected wells in the model domain over time were determined to be reasonable (fig. 29).

A graph shows the computed and observed heads and the error summary for the 2005–2011 transient model run (fig. 30). The model error was reasonable for the scale of the model. The root mean square error for all calibration targets for all stress periods was 5.3 ft.

Table 10. Stress period start dates, times, length in days, and number of time steps for the 2005–2011 transient model run.

Date Time	Stress period length	No. of time steps
9/1/2005 12:00:00 AM	30.0	10
10/1/2005 12:00:00 AM	31.0	10
11/1/2005 12:00:00 AM	30.0	10
12/1/2005 12:00:00 AM	31.0	10
1/1/2006 12:00:00 AM	31.0	10
2/1/2006 12:00:00 AM	28.0	10
3/1/2006 12:00:00 AM	31.0	10
4/1/2006 12:00:00 AM	30.0	10
5/1/2006 12:00:00 AM	31.0	10
6/1/2006 12:00:00 AM	30.0	10
7/1/2006 12:00:00 AM	31.0	10
8/1/2006 12:00:00 AM	31.0	10
9/1/2006 12:00:00 AM	30.0	10
10/1/2006 12:00:00 AM	31.0	10
11/1/2006 12:00:00 AM	30.0	10
12/1/2006 12:00:00 AM	31.0	10
1/1/2007 12:00:00 AM	31.0	10
2/1/2007 12:00:00 AM	28.0	10
3/1/2007 12:00:00 AM	31.0	10
4/1/2007 12:00:00 AM	31.0	10
6/1/2007 12:00:00 AM	30.0	10
7/1/2007 12:00:00 AM	31.0	10
8/1/2007 12:00:00 AM	31.0	10
9/1/2007 12:00:00 AM	30.0	10
10/1/2007 12:00:00 AM	31.0	10
11/1/2007 12:00:00 AM	30.0	10
12/1/2007 12:00:00 AM	31.0	10
1/1/2008 12:00:00 AM	31.0	10
2/1/2008 12:00:00 AM	29.0	10
3/1/2008 12:00:00 AM	31.0	10
4/1/2008 12:00:00 AM	30.0	10
5/1/2008 12:00:00 AM	31.0	10
6/1/2008 12:00:00 AM	30.0	10
7/1/2008 12:00:00 AM	31.0	10
8/1/2008 12:00:00 AM	31.0	10
9/1/2008 12:00:00 AM	30.0	10
10/1/2008 12:00:00 AM	31.0	10
11/1/2008 12:00:00 AM	30.0	10
12/1/2008 12:00:00 AM	31.0	10
1/1/2009 12:00:00 AM	31.0	10
2/1/2009 12:00:00 AM	28.0	10
3/1/2009 12:00:00 AM	31.0	10
4/1/2009 12:00:00 AM	30.0	10
5/1/2009 12:00:00 AM	31.0	10
6/1/2009 12:00:00 AM	30.0	10
7/1/2009 12:00:00 AM	31.0	10
8/1/2009 12:00:00 AM	31.0	10
9/1/2009 12:00:00 AM	30.0	10
10/1/2009 12:00:00 AM	31.0	10
11/1/2009 12:00:00 AM	30.0	10
12/1/2009 12:00:00 AM	31.0	10
1/1/2010 12:00:00 AM	31.0	10
2/1/2010 12:00:00 AM	28.0	10
3/1/2010 12:00:00 AM	31.0	10
4/1/2010 12:00:00 AM	30.0	10
5/1/2010 12:00:00 AM	31.0	10
6/1/2010 12:00:00 AM	30.0	10
7/1/2010 12:00:00 AM	31.0	10
8/1/2010 12:00:00 AM	31.0	10
9/1/2010 12:00:00 AM	30.0	10
10/1/2010 12:00:00 AM	31.0	10
11/1/2010 12:00:00 AM	30.0	10
12/1/2010 12:00:00 AM	31.0	10
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2/1/2011 12:00:00 AM	28.0	10
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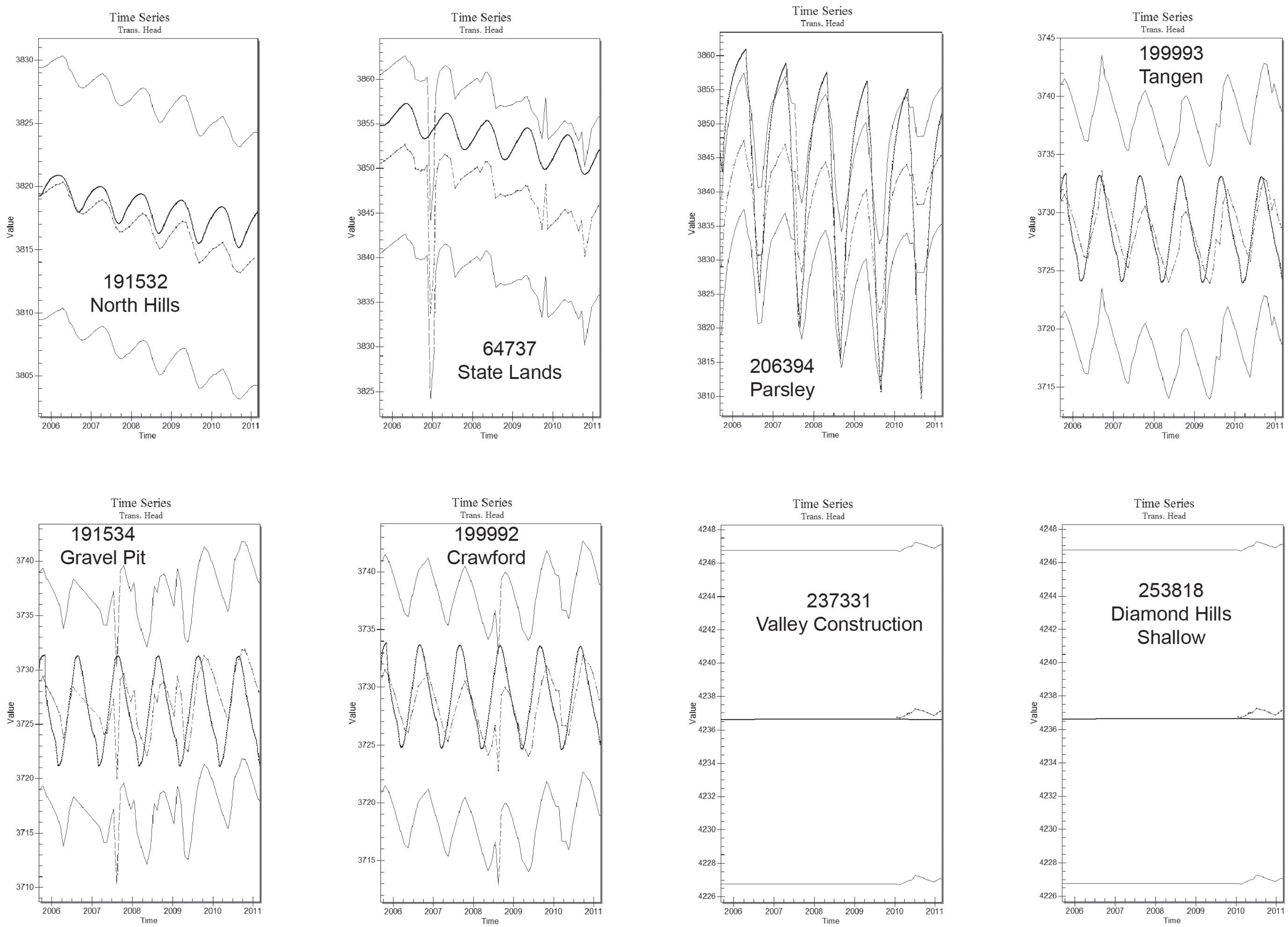


Figure 29. Selected hydrographs showing observed water-level data (center), the 10 ft calibration zone above and below the observed water-level data, and the model-calculated head (darker smooth line) for the September 2005 through February 2010 Pediment Focus model run for selected wells.

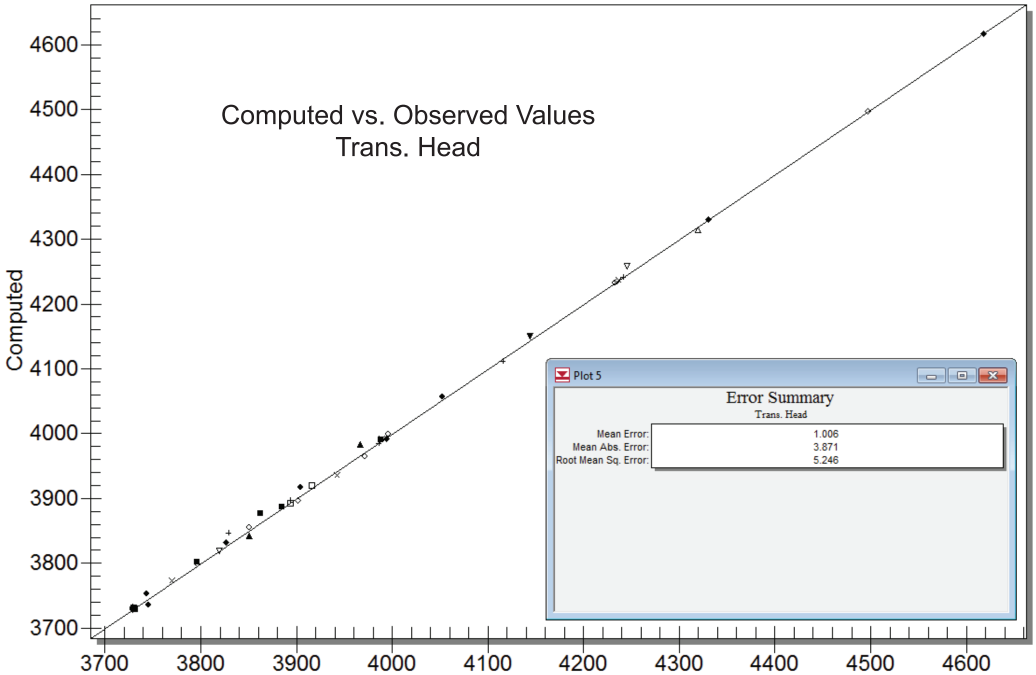


Figure 30. Graph showing computed vs. observed head values at calibration targets in the model domain resulting from the September 2005 through February 2011 transient Pediment Focus model run, and statistics. The graph shows the results of the first time step in the model run. The table shows statistics for all calibration targets and all time steps.

The water budget was similar to that for the 2010 transient model, with the same amount of calculated recharge. The first year of the 2005–2011 transient model run was shifted to start in September instead of February, and consequently there were some minor differences in the amount of water calculated to leave the model at the specified head boundary at the lower end of the model (2,090 acre-ft). Some 35 acre-ft of water (net) exited the model calculations as storage; hence the model calculated a net increase of water in storage.

Sensitivity Analysis

A sensitivity analysis was conducted on the September 2005 through February 2011 transient Pediment Focus model to determine relative sensitivities of the model to assigned values of recharge (R), hydraulic conductivity (K), and specific yield (Sy). For the analysis, all parameters were held constant except for the one being evaluated. The root mean square (RMS) error in feet was evaluated for changes of 25 and 50 percent in the parameter values (figs. 31, 32, and 33). From this analysis, it is evident that the model was most sensitive to changes in the values of recharge, and least sensitive to values of specific yield.

NORTH HILLS AREA MODEL

The intent of the North Hills Area model was to create a groundwater model that reasonably simulated the water budget of the greater North Hills Study Area, including the irrigated lands below the HVID canal. The seasonal rise and fall of the groundwater surface due to irrigation activities is modeled by applying recharge to the irrigated part of the Helena Valley. A schematic illustration shows the model grid in a three-dimensional view with some of the key concepts applied in the model annotated (fig. 34).

The North Hills Area model extends into areas with considerably less control in terms of observation well data. Therefore, it is not as well constrained as the Pediment Focus model. Its purpose was to test the approximate timing of impacts of seasonal groundwater withdrawals or other changes to the internal water budget to Lake Helena and to further evaluate the study area water budget. The timing and magnitude of changes in groundwater flux to Lake Helena has certain legal implications that are of interest to the Montana DNRC, because Lake Helena is essentially part of the Missouri River and therefore subject to the Upper Missouri Basin closure.

Figure 35 shows the location of the North Hills Area model active cell coverage using the same model grid as described for the Pediment Focus model, but with the active cell coverage expanded to the area model extent.

Boundary Conditions

The North Hills Area model encompasses almost the entire study area, extending west to the surface-water divide between the North Hills pedi-

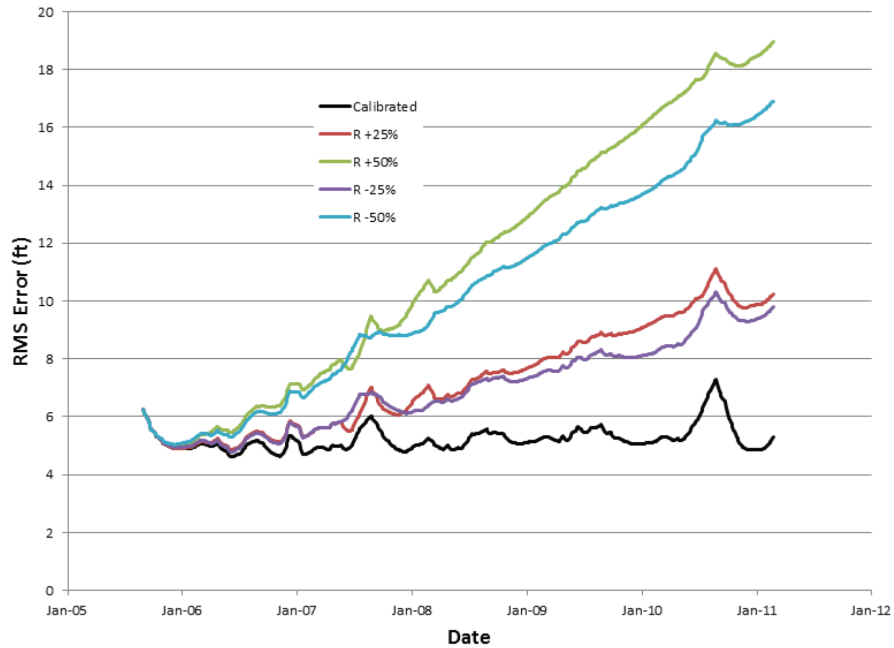
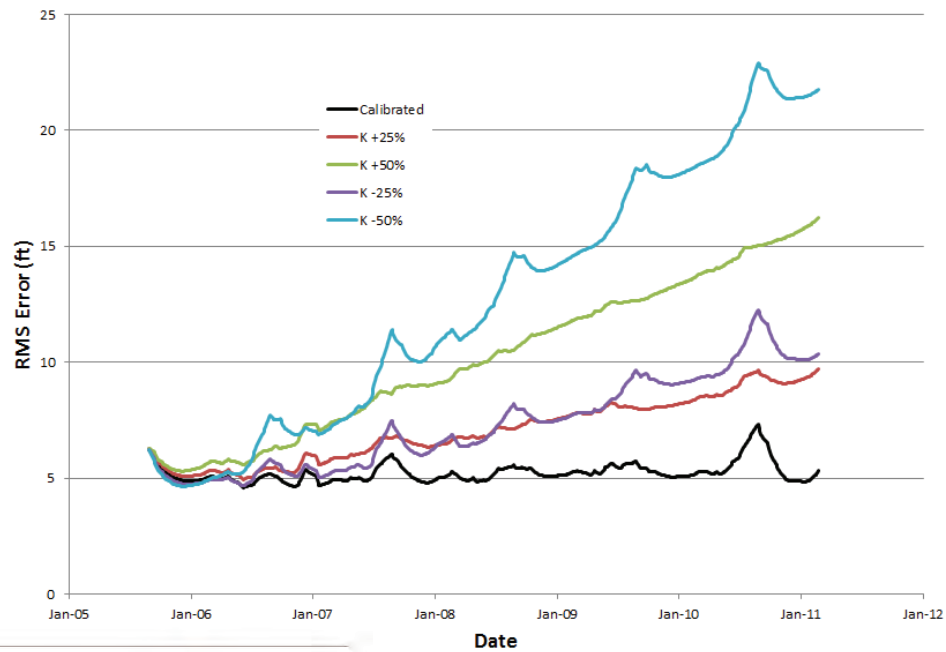


Figure 31. Sensitivity analysis for recharge (R) in the transient September 2005 to February 2011 Pediment Focus model.

Figure 32. Sensitivity analysis for hydraulic conductivity (K) in the transient September 2005 to February 2011 Pediment Focus model.



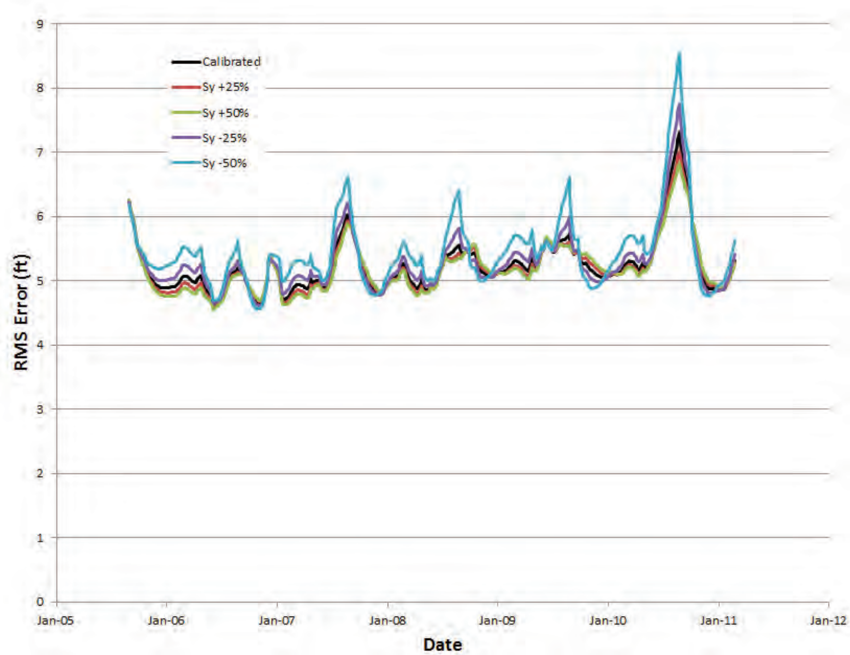


Figure 33. Sensitivity analysis for specific yield (Sy) in the transient September 2005 to February 2011 Pediment Focus model.

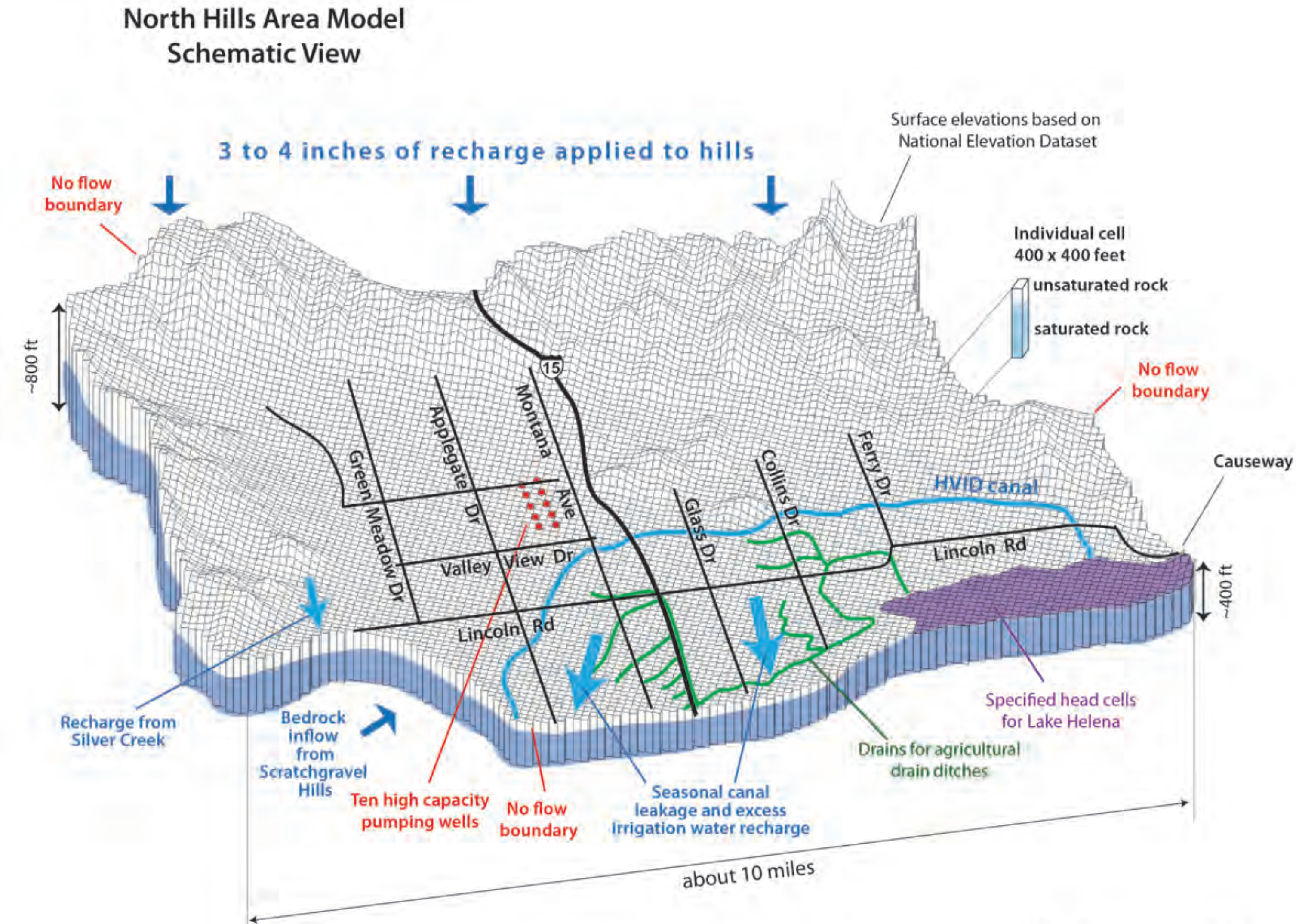


Figure 34. Schematic illustration of the North Hills Area model grid.

ment in the study area and the valley where Silver City is located to the west. The northern boundary is the surface-water divide between the Helena Valley and the Seiben Ranch valley to the north. The eastern boundary is along the surface-water divide between the Helena Valley and the Missouri River at and below Holter Lake. All boundaries along surface-water divides are treated as no-flow boundaries in the groundwater model. The southern boundary approximately follows a groundwater flow line in the Helena Valley aquifer as mapped by Briar and Madison (1992) and is also treated as a no-flow boundary. The southwest corner of the North Hills Area model includes a constant-flux boundary to represent groundwater inflow from the granite of the Scratchgravel Hills. The southeast corner of the model includes constant head cells representing Lake Helena, the elevation of which is controlled by the Hauser dam and typically fluctuates less than a foot.

Sources and Sinks

The North Hills Area model used the same recharge and pumping rates as the Pediment Focus model for recharge from precipitation in the hills and for pumping from Pumping Center A. Recharge from infiltration of water from Silver Creek and the HVID canal, and from irrigation water derived from these sources, were added to this larger area model. Constant head cells at the location of Lake Helena were used as the dominant sink in the model. Agricultural drains were modeled in the irrigated area between the HVID canal and Lake Helena, which also act as sinks. The drain elevations were set based on surveyed elevations of the zero mark on staff gauges at five sites where drain stage and flow were monitored during the study, and the approximate elevation of the western shore of Lake Helena (3,654 ft).

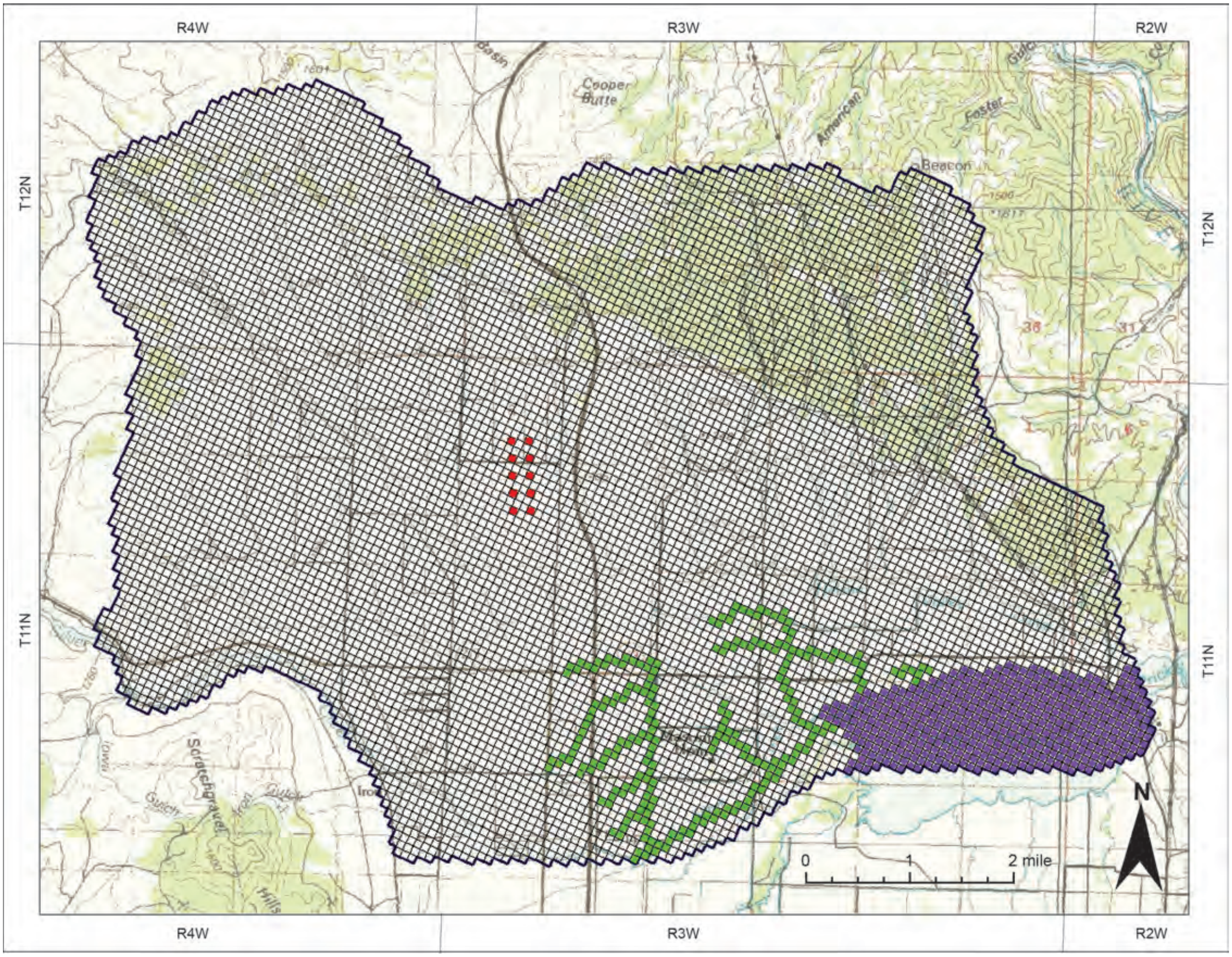


Figure 35. Active cells for the North Hills Area model grid. Green cells are drain cells and purple symbols indicate constant head cells. Red cells represent the modeled wells in Pumping Center A.

Polygons were used to assign recharge in the North Hills Area model (fig. 36). The nearly 18 in per year of recharge being applied in the irrigated portion of the valley was based on the approximate area of irrigated land within the study area. The 18-in recharge rate was derived from the recharge estimates from infiltration of excess applied irrigation water as calculated and reported in Briar and Madison (1992) (27,000 acre-ft of estimated recharge for an irrigated area of 17,600 acres in the Helena Valley). They also estimated that the HVID canal loses about 0.63 cfs per mile. This value was applied to model cells along the simulated location of the canal, resulting in a steady-state recharge rate of about 47 in per year for those cells. Recharge was added to cells along the southwest boundary of the model to simulate water entering the model domain from Scratchgravel Hills bedrock.

Simulated recharge from infiltration and irrigation activities associated with Silver Creek were entered as average annual rates in steady-state model runs. The water was distributed over a 5-month period in the transient model runs, from the start of May through the end of September of each modeled year. The steady-state model value of about 9 in per year was derived taking into account the sporadic availability of both flow in the creek and water available for irrigation relative to the irrigated acreage serviced by the canal. Because of the sporadic availability of Silver Creek water, the value used for HVID irrigation was simply halved, resulting in the value of about 9 in. The result was a modeled application of about 340 acre-ft per year in the polygon representing Silver Creek recharge. The value was markedly less than the estimated recharge from Silver Creek presented in the water budget section above (about 960 acre-ft per year). Because of the

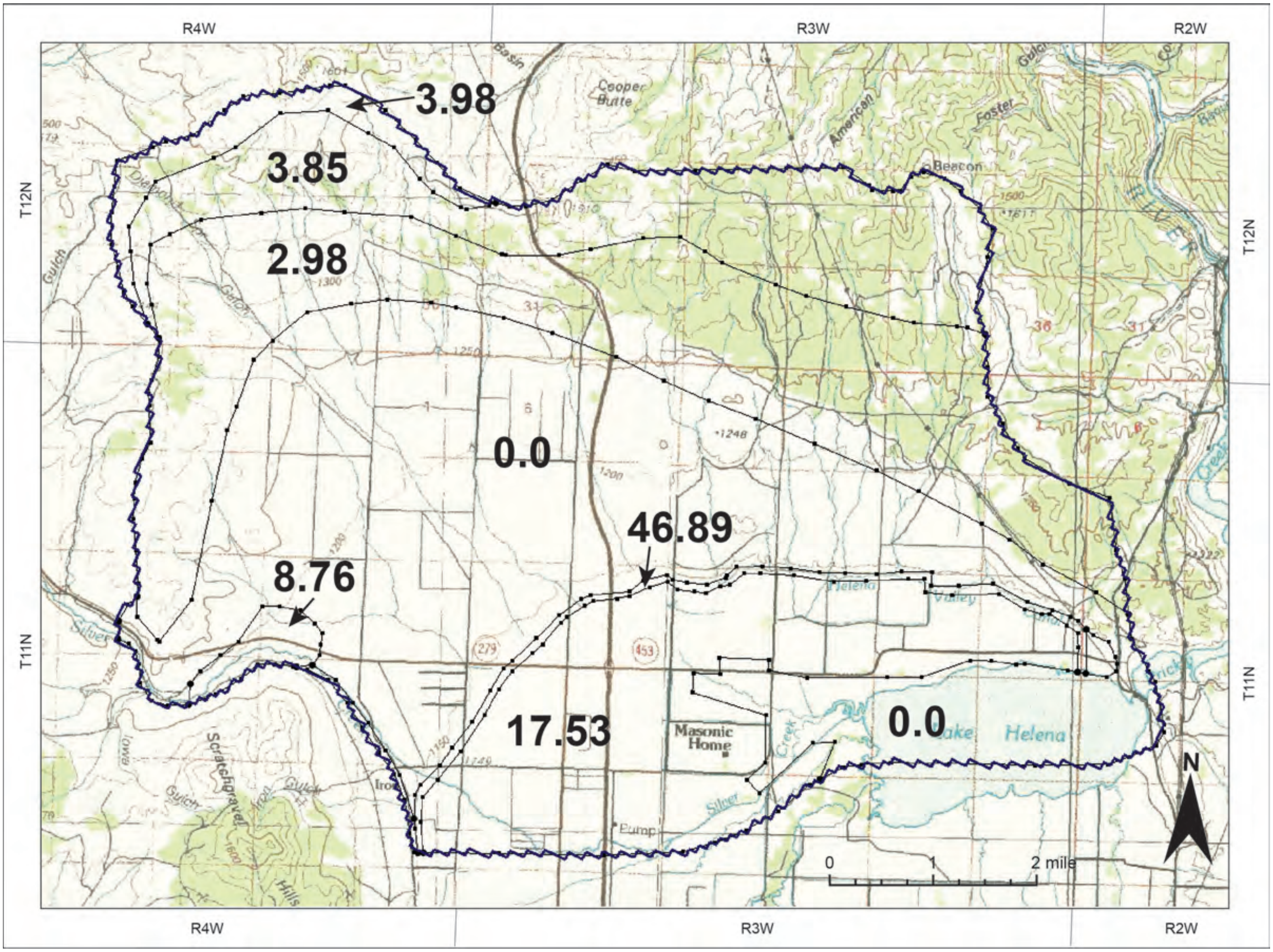


Figure 36. Recharge polygons used in the North Hills Area model steady-state calibration and recharge values applied (inches per year).

intermittent availability of water both in the creek and for irrigation, and because some water flowing down Silver Creek during a wet year like 2010 is probably intercepted by agricultural drains, the modeled value was considered viable. The model should prove useful in testing the impacts of more or less recharge from Silver Creek and its associated irrigation.

Lake Helena was assigned a constant head of 3,654 ft, based on the surveyed elevation of the top of the staff gauge at the causeway projected to the 0.0 mark on the gauge. The 0.0 mark is at an altitude of 3,651.84 ft, and the lake was typically observed on the staff gauge during 2009 and 2010 to be at levels between 1.8 and 2.3 ft. Based on this information, 3,654 ft was used for the modeled elevation of the lake.

Selection of Calibration Targets

The Pediment Focus model calibration target set was used as a starting point. Nine wells that had matching 2006 and 2010 data within the study area, but were located outside the Pediment Focus model area, were added to the dataset. One older, unused well (GWIC 65422) located on the same property as well 189417 was not included in the target set. Five additional wells with water-level measurements available for varying periods of record were added to the calibration target set. These were GWIC wells 202174, 5854, 194432, 246101, and 254242. The result was a calibration target set of 57 wells with water-level measurements. For calibration purposes, the same control points used for areas with little or no data in the Pediment

Focus model were used again in the North Hills Area model, and new control points were added for similar situations encountered in new portions of the larger area model.

Steady-State Calibration

Steady-state calibration was conducted using the PEST pilot point method in the same manner as described for the Pediment Focus model. Steady-state recharge conditions were held constant, and multiple pilot point runs were made to evaluate the amount of water flowing out of the modeled drain cells that represented agricultural drains. The calibration target data were from the denser data set of 2006, and thus the pumping rate used in the initial calibration runs is the 2006 pumping rate for Pumping Center A (152 acre-ft/yr). The conductance of the drains was adjusted until the calculated flow out of the drains was in agreement with the estimated water budget. The resulting distribution of hydraulic conductivity calculated by PEST and the steady-state calculated potentiometric surface was mapped (figs. 37, 38). The root mean square error for the steady-state, pilot point calibrated model was 6.5 ft (fig. 39).

The North Hills Area model steady-state water budget was reasonably similar to water budget estimates described in the Water Budget section of this report. Table 6 shows the calculated groundwater budget from the model compared to the water budget values described in the Water Budget section of this report.

The DI water, representing recharge from precipitation in the North Hills as modeled, generated 3,824 acre-ft of water. This was slightly less than the estimated range of 3,941–4,818 acre-ft per year. Madison (written commun., 2011) used a value of 3,352 acre-ft/yr for groundwater flux from the North Hills area in his groundwater model of the Helena Valley aquifer. The model is documented in Madison (1993), and a steady-state version of the model is described in Briar and Madison (1992).

There were some notable differences in the water budget estimates and modeled values. In the model effort, infiltration from Silver Creek and its associated irrigation was estimated to be half of that for areas serviced by the Helena Valley Canal. This was based on the fact that in many years before 2009, the creek was dry almost year-round, and the density of irrigation within the polygon modeled was considerably less than in similar areas serviced by the Helena Valley Canal. Using this approach, a total of 268 acre-ft/yr was modeled for Silver Creek infiltration. Approximately 797 acre-ft/yr was modeled as groundwater entering the system from the Scratchgravel Hills bedrock along the southwest edge of the model.

The Irrigation Canal Leakage estimate shown in table 6 reflects water leaking from both the Helena Valley Canal and laterals. In the model, leakage was distributed differently. In the model, the 1,650 acre-ft/yr Irrigation Canal Leakage only reflected modeled leaking of water from the Helena Valley Canal, not its laterals. The laterals' infiltration as calculated per cell was not much different from the rate used for irrigation recharge, so it was considered a sufficient value of recharge to apply to the broader irrigated area. The contrast between crop leaching fraction estimates and modeled values was partly due to (1) the increased acreage created by applying the model's 1.5 ft/yr recharge rate to a bulk area polygon, rather than using exact irrigated acreages, and (2) the fact that the model encompassed several square miles of additional irrigated lands south of John G. Mine Road and Masonic Home Road relative to the study area estimates.

The principal difference between the numerical (modeled) water budget outputs and the conceptual budget outputs (table 6) was that only Pumping Center A was modeled. The estimated water budget included the two pumping centers near the HVID canal and the diffuse withdrawals of individual wells throughout the study area. These features were not modeled during this effort. Pumping Centers B and C can readily be added to the model, but this may best be accomplished by re-running the steady-state pilot point automated parameter estimate with the added stresses and then re-converting the results to a transient model. Because these pumping centers are located near the canal, and groundwater-level declines have not been observed, the expected result will be a rather direct decrease in discharge from the modeled area to the agricultural drains and Lake Helena.

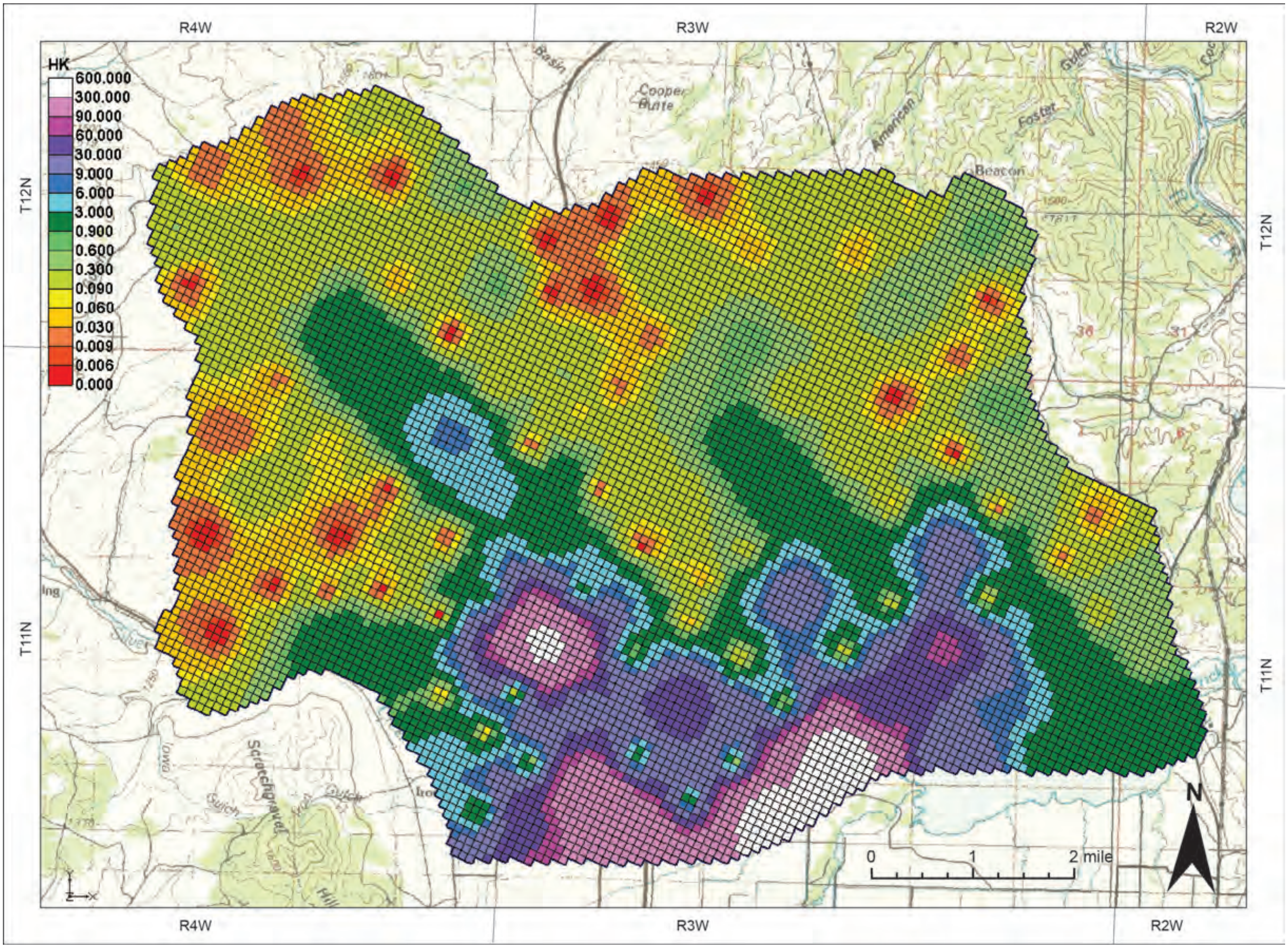


Figure 37. Hydraulic conductivity ranges for the North Hills Area model shown by colored zones labeled HK in the legend. Individual cells have independent values within the specified range. Values are in ft/day.

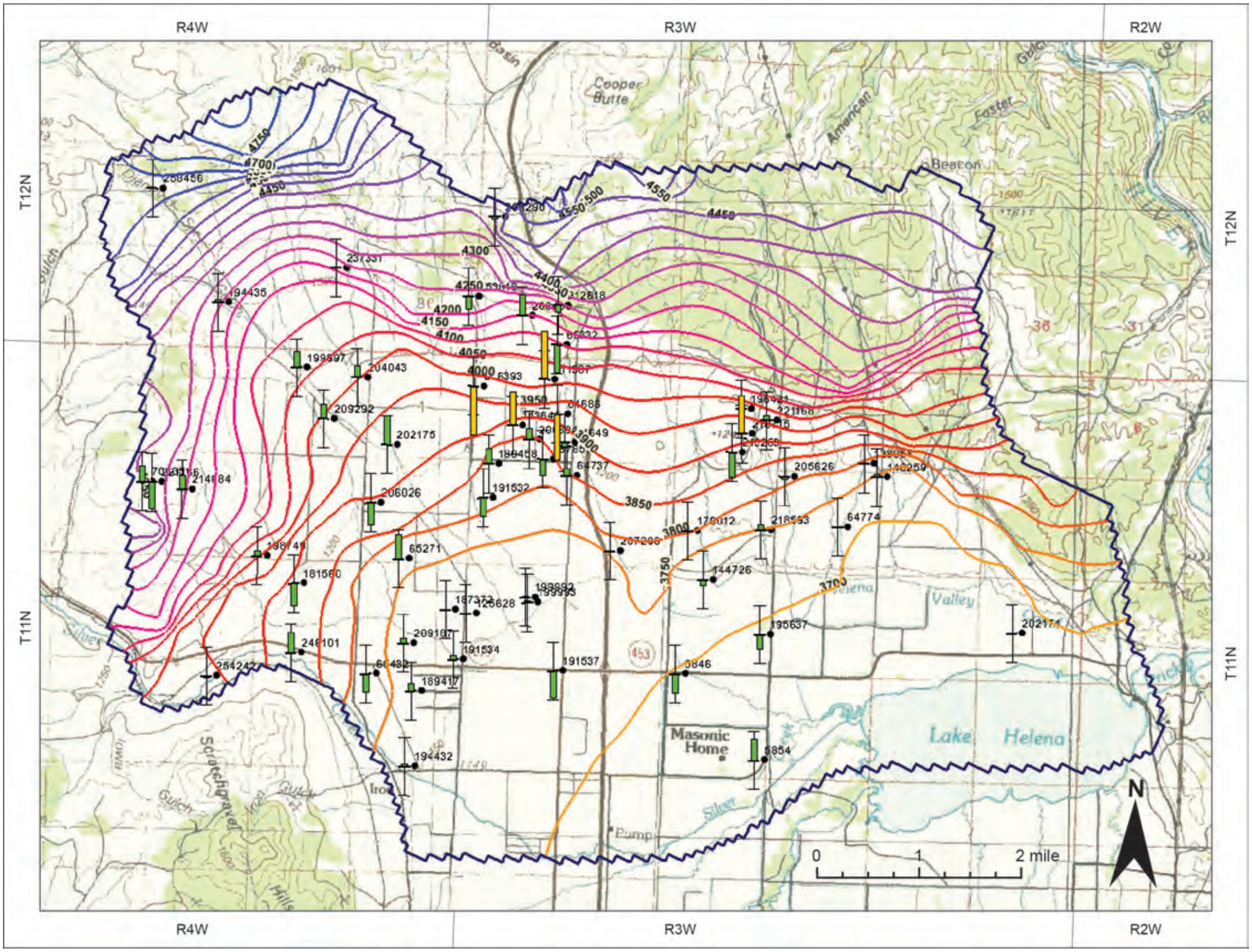


Figure 38. Computed potentiometric surface of the calibrated steady-state North Hills Area model using the pilot point method. Calibration targets are shown by the dots. The dots are labeled with the GWIC well identification number for the site. The vertical scales illustrate the target elevation (middle hatchure), with colored bars showing the vertical difference between the target elevation and the calculated potentiometric surface. Green indicates the target is within the set calibration criteria; yellow indicates the value is within twice the calibration criteria interval. The calibration interval for this run was set to 10 ft.

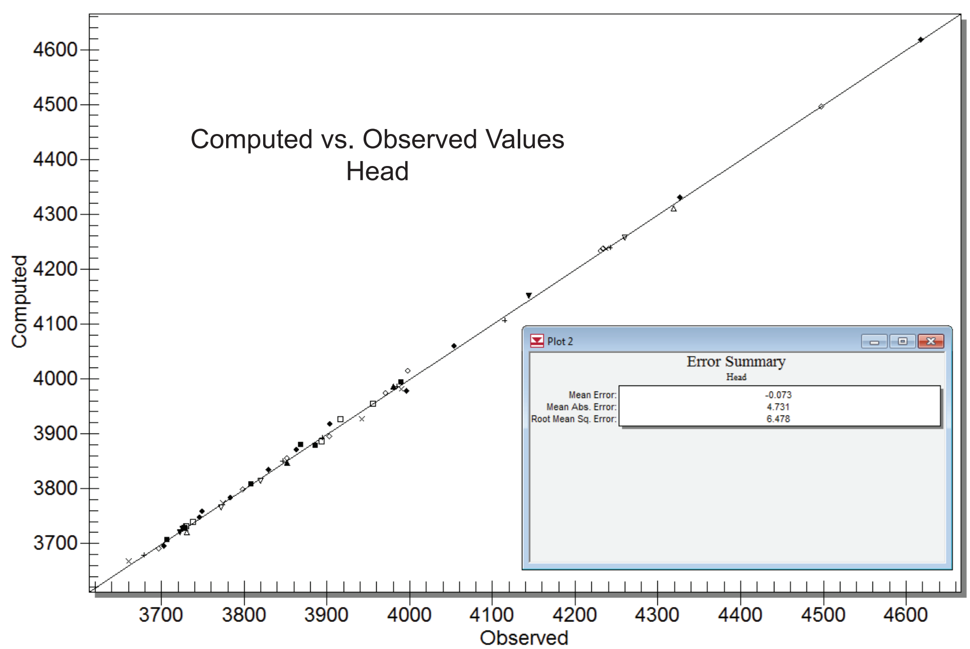


Figure 39. Graph showing computed vs. observed head values at calibration targets in the North Hills Area model domain resulting from the steady-state pilot point approach, and statistics.

Additional manipulation of water budget elements such as the irregular influence of Silver Creek water, changes in bedrock inflow from Scratchgravel Hills, or any other element of the budget can be readily incorporated into the model to test its effect on the water budget.

Transient Model Calibration

The steady-state model was converted to a transient model. The transient model was developed to approximate conditions for the period September 2005 through February 2011. The North Hills Area transient model calibration was conducted using the same stress period set-up and the same pumping rate estimates from Pumping Center A as were used in the Pediment Focus model. As noted above, the recharge rate occurring as a result of irrigation activities was applied during the 5-month period from May through September, and was zero during the other 7 months of each simulated year. All of the transient model runs used the hydraulic conductivity array generated by the steady-state pilot point parameter estimation technique and the steady-state calculated (modeled) heads as initial head conditions.

Specific yield values in portions of the model were adjusted so that the magnitudes of modeled seasonal water-level changes reasonably approximated observed data. Figure 40 shows the resulting distribution of specific yield values. Higher specific yield values in the Helena Valley aquifer are justified since the Helena Valley aquifer is an alluvial aquifer likely to have significant primary porosity.

Figure 41 shows the North Hills Area transient model potentiometric surface for March 1, 2006.

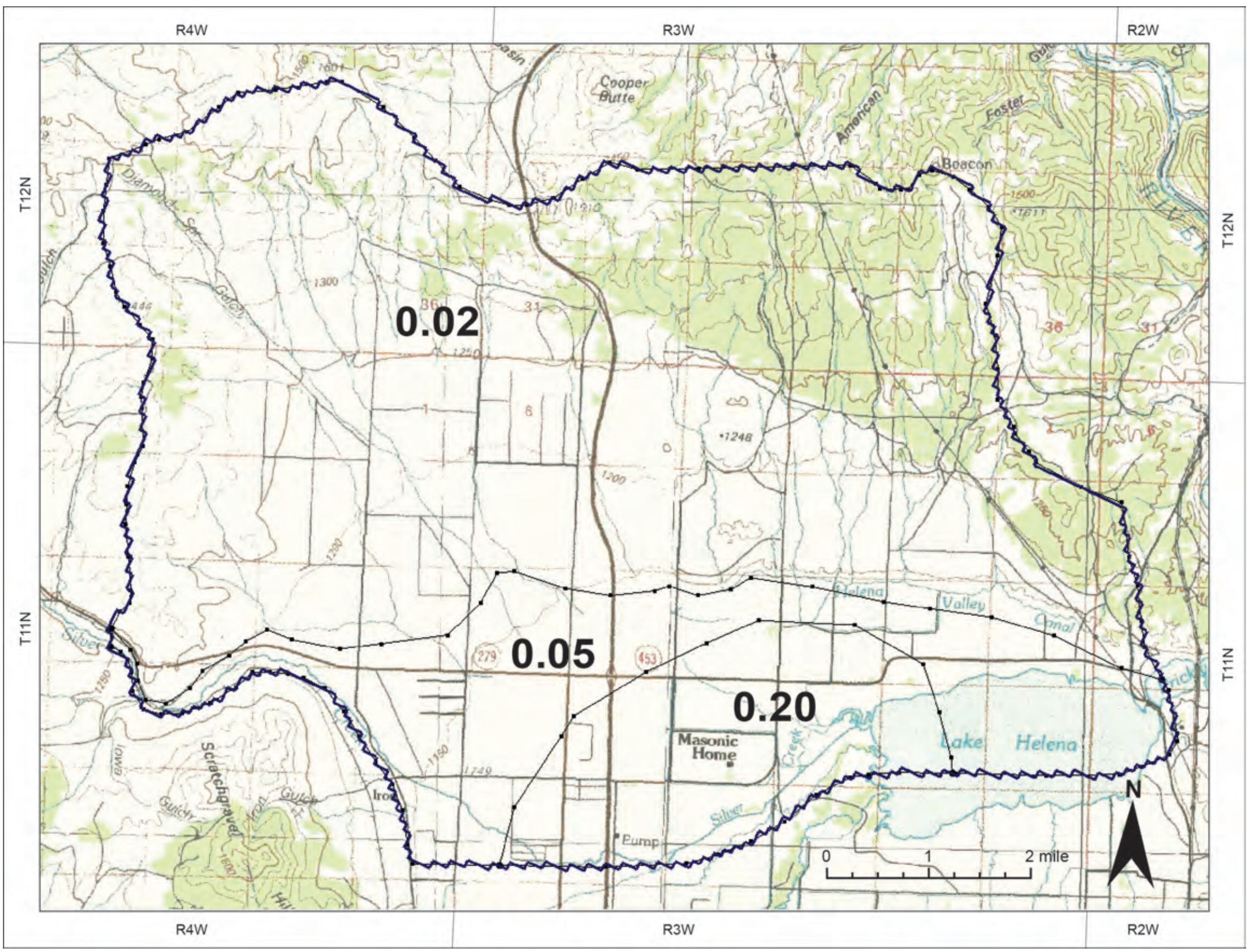


Figure 40. Specific yield polygons used in the North Hills Area model steady-state calibration and values applied (dimensionless).

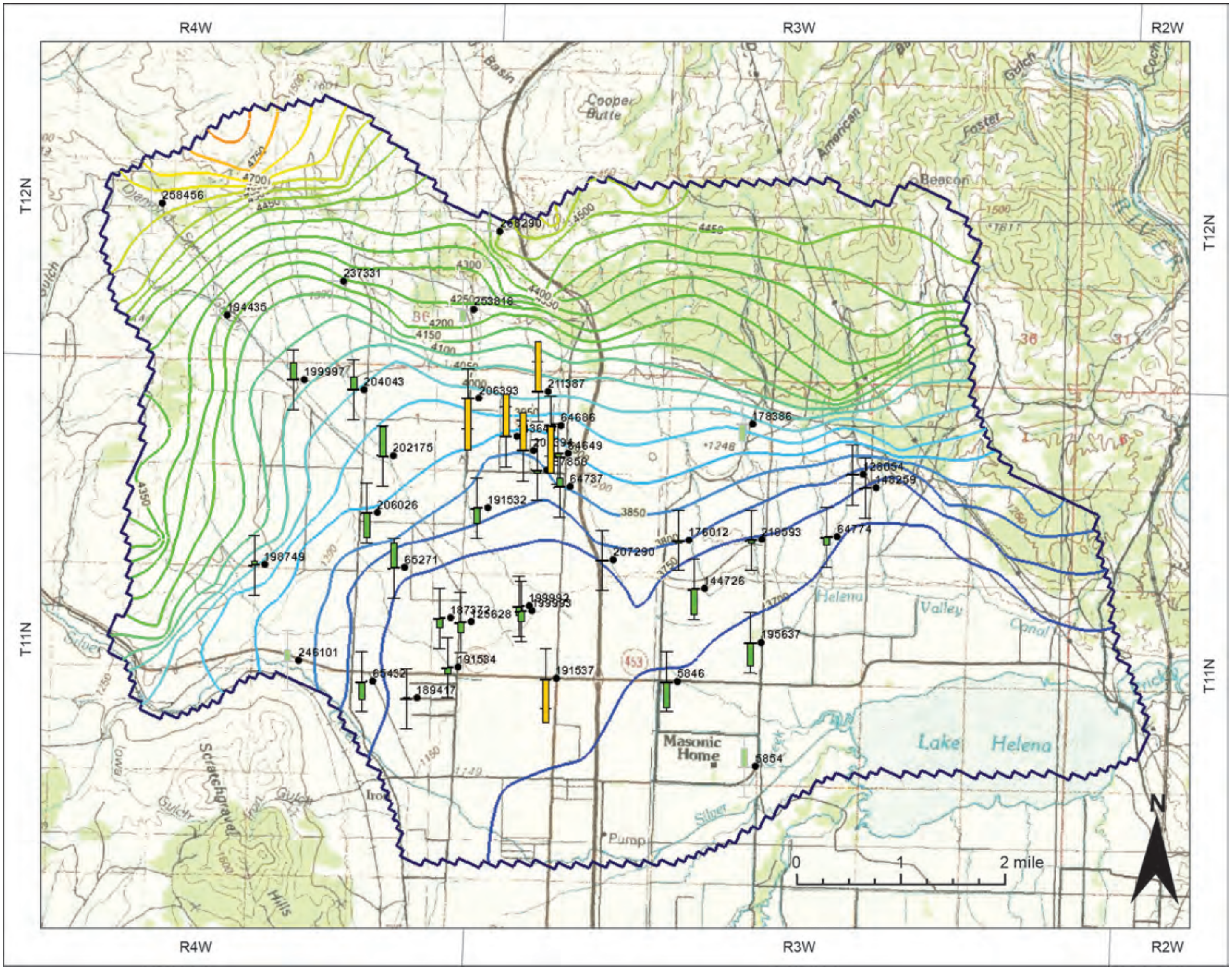


Figure 41. Computed potentiometric surface of the calibrated September 2005 through February 2011 transient run by the North Hills Area model. This image is based on the observed and calculated groundwater data at about the beginning of stress period two, around March 1, 2006. Calibration targets are shown by the dots. The dots are labeled with the GWIC well identification number for the site. The vertical scales illustrate the target elevation (middle hatchure), with colored bars showing the vertical difference between the target elevation and the calculated potentiometric surface. Green indicates the target is within the set calibration criteria; yellow indicates the value is within twice the calibration criteria interval. The calibration interval for this run was set to 10 ft.

Statistics for the transient run (fig. 42) indicated that the root mean square error for all observation wells and all time steps was about 7.5 ft. Representative hydrographs comparing the groundwater model calculated water levels over time with actual observed measurements demonstrated the model functionality (fig. 43).

Sensitivity Analysis

An analysis was conducted on the September 2005 through February 2011 North Hills Area model to determine relative sensitivities of the model to assigned values of recharge (R), hydraulic conductivity (K), and specific yield (Sy). For the analysis, all parameters were held constant except for the one being evaluated. Figures 44, 45, and 46 show the RMS error in feet for changes of 25 and 50 percent for each of the parameter values evaluated. From this analysis, it is evident that the model is most sensitive to changes in the values of recharge, and least sensitive to values of specific yield.

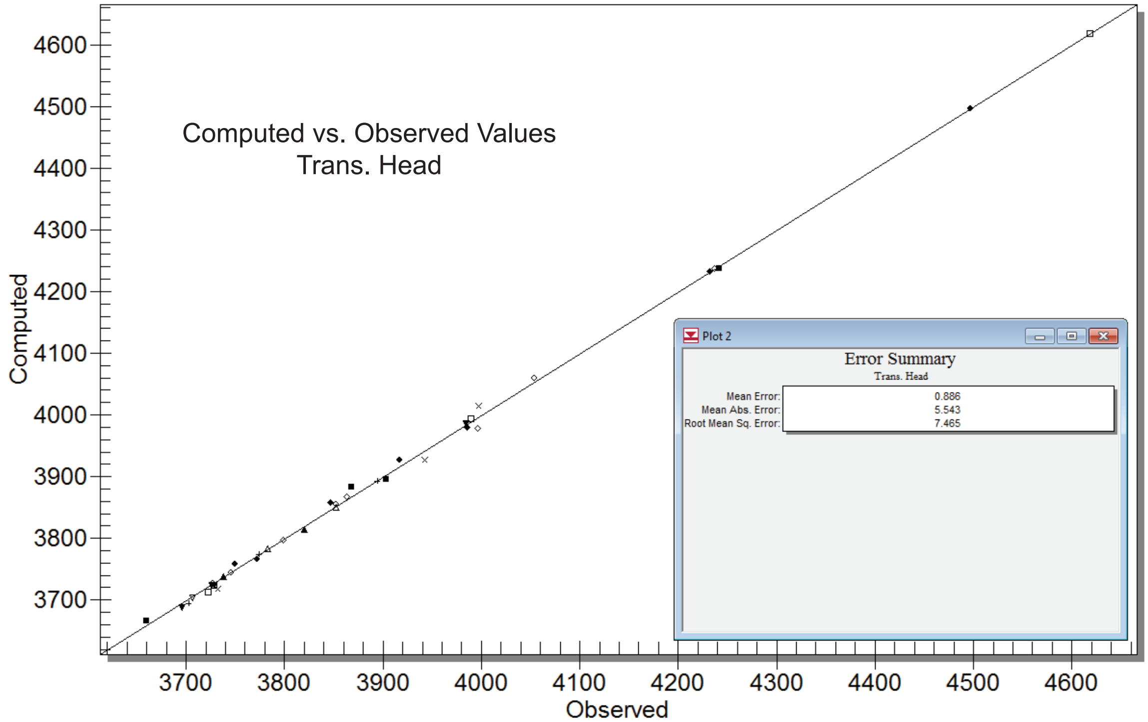


Figure 42. Graph showing computed vs. observed head values at calibration targets in the model domain resulting from the September 2005 through February 2011 transient North Hills Area model run, and statistics. The graph shows the results of the first time step in the model run. The table shows statistics for all calibration targets and all time steps. The root mean square error for this model, for all calibration targets and all stress periods, is 7.6 ft.

EXAMPLE SIMULATIONS

A variety of scenarios were analyzed to determine the ability of the models to calculate changes in groundwater elevations and the groundwater budget from varying stresses. Scenarios included investigating the effects of various pumping rates in the vicinity of Pumping Center A, evaluating the effects of pumping groundwater from new wells in an undeveloped quarter section, evaluating the effect of a 5-year drought, and, finally, evaluating the effect of removing the HVID canal and irrigation from the Helena Valley.

Simulations to test the effects of new stresses on the groundwater system can be made with the model, by extending the model stress periods into the future and specifying the stresses to be tested. Steady-state simulation can be used to evaluate the average annual effects of a particular stress. Transient simulations are useful to estimate the timing and seasonal magnitudes of a particular stress, such as seasonal pumping.

Future drawdown expected as a result of pumping the wells in Pumping Center A at 2009 levels was evaluated using the Pediment Focus model in transient mode. To operate the model for 20 simulated years (September 2005 through August 2025), 240 1-month stress periods were set up. The model revealed that if groundwater extractions in Pumping Center A (subdivisions north of Valley View Road and west of Montana Avenue) remain at 2009 levels, the groundwater levels would be expected to stabilize (less than 0.25 ft of drawdown per year) in 2017, at a level approximately 3 ft below modeled January 2011 water levels. This calculation is based on an assumption that other stresses and components of the water budget are unchanged.

An increase in future pumping at Pumping Center A was also evaluated. Estimated pumping rates for the 5-yr period 2005 through 2009 at Pumping Center A indicate that pumping increased from about 152 acre-ft/yr to 215 acre-ft/yr. Based on these numbers, an increase of 63 acre-ft/yr (7,500 ft^3/d) was applied to the model to simulate projected future increases in pumping for the 5-year period 2010 through 2014 For simplicity, and to better illustrate the impact of increased pumping, the increase in average annual pumping projected for

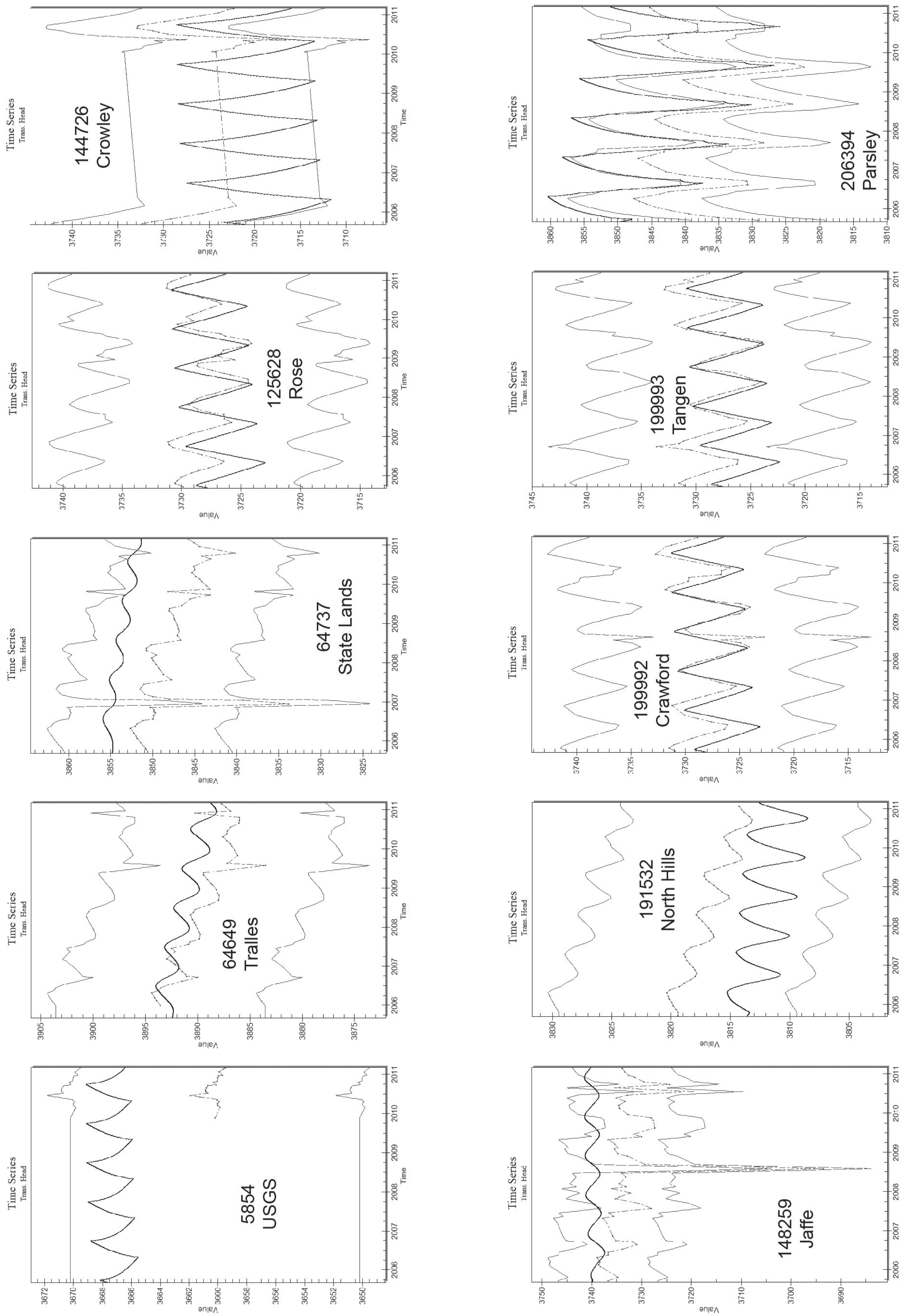


Figure 43. Hydrographs for selected wells showing observed water-level data (center), the 10 ft calibration zone above and below the observed water-level data, and the model-calculated head (darker smooth line) for the 2010 model run of the Pediment Focus model.

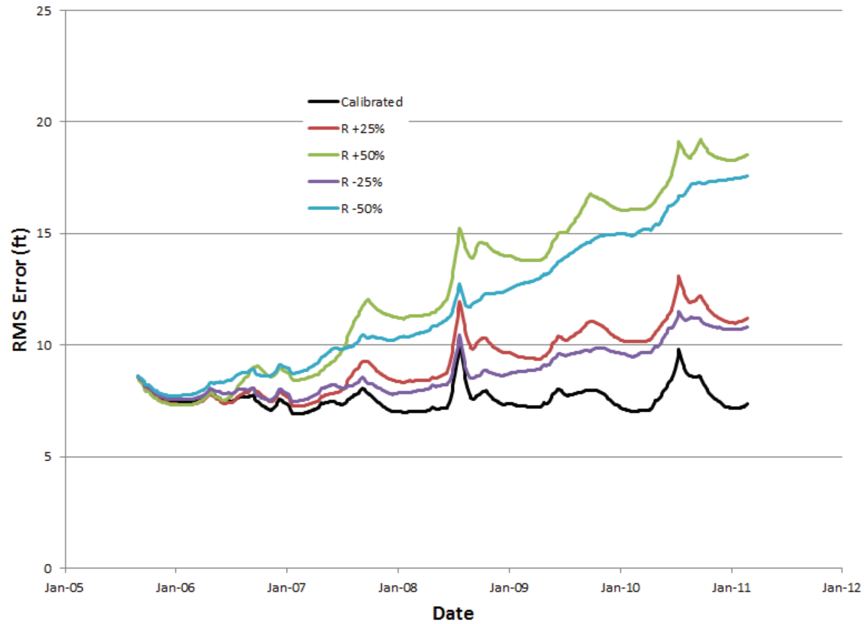


Figure 44. Sensitivity analysis for recharge (R) in the transient September 2005 to February 2011 North Hills Area model.

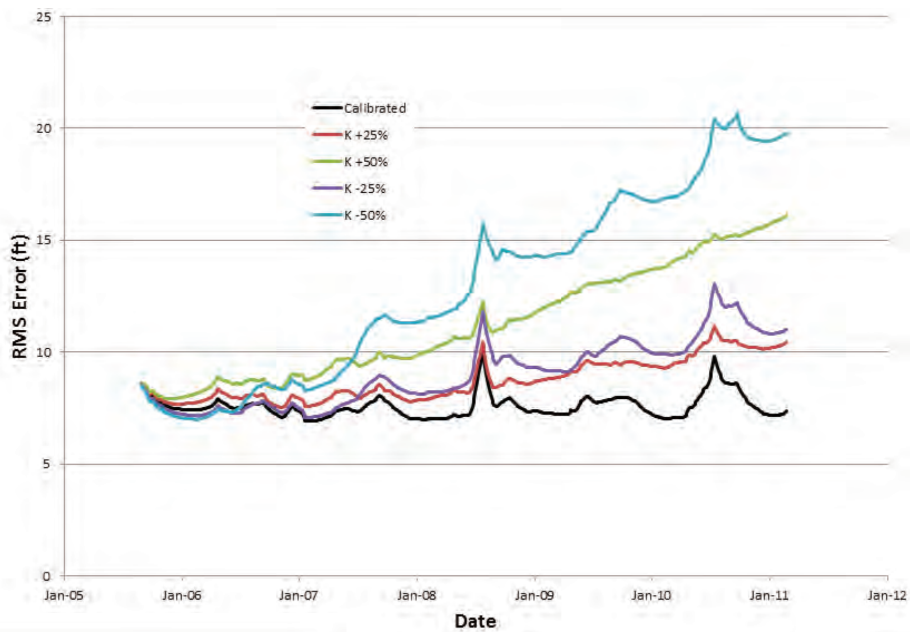


Figure 45. Sensitivity analysis for hydraulic conductivity (K) in the transient September 2005 to February 2011 North Hills Area model.

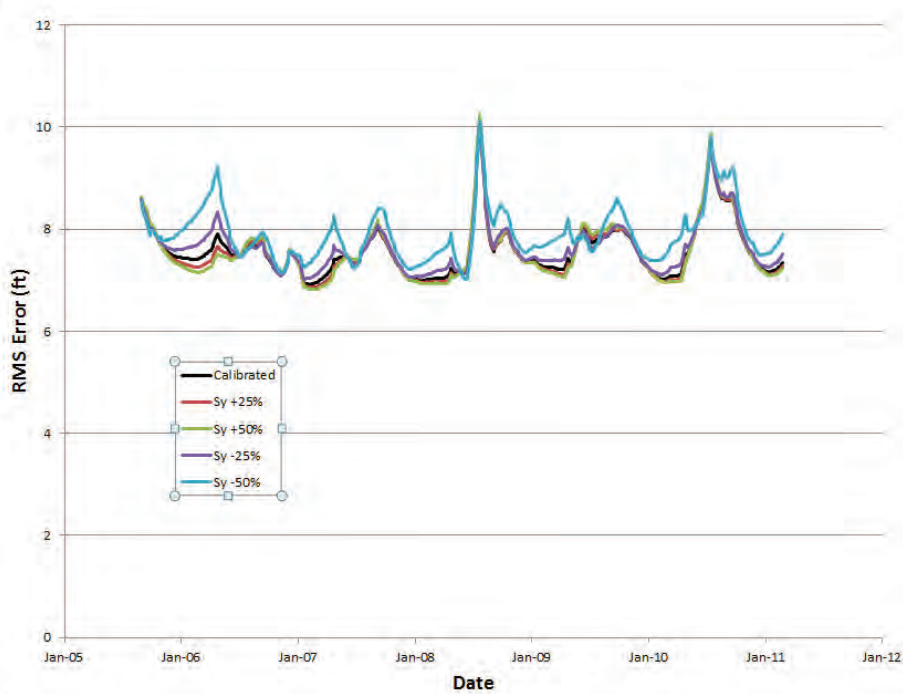


Figure 46. Sensitivity analysis for specific yield (Sy) in the transient September 2005 to February 2011 North Hills Area model.

the 5-year period 2010 through 2014 was applied in the model entirely at the end of 2014. The increased average annual pumping rate was then sustained throughout the modeled time period that ended at the end of August 2025.

The additional drawdown calculated to occur by 2025 from the increased pumping rate applied in the model in 2014 was about 10 to 14 ft in the vicinity of the well field (fig. 47). Other stresses and components of the water budget were assumed unchanged. As illustrated, the amount of drawdown occurred generally in the vicinity of the pumping wells. Less drawdown occurred at greater distances away from the pumping center.

The potential for increased pumping from wells in Pumping Center A was further evaluated with the steady-state North Hills Area model by drastically increasing pumping rates of the 10 wells modeled in Pumping Center A. Pumping rates of 10 times the 2009 estimated average annual pumping rates were assigned to the 10 wells. This resulted in dry cells at six of the wells in the model, which caused them to stop functioning. Four wells continued to operate. Based on the result, the modeled pumping rates were reduced to four times the 2009 estimated average annual pumping rates. The 2009 estimated

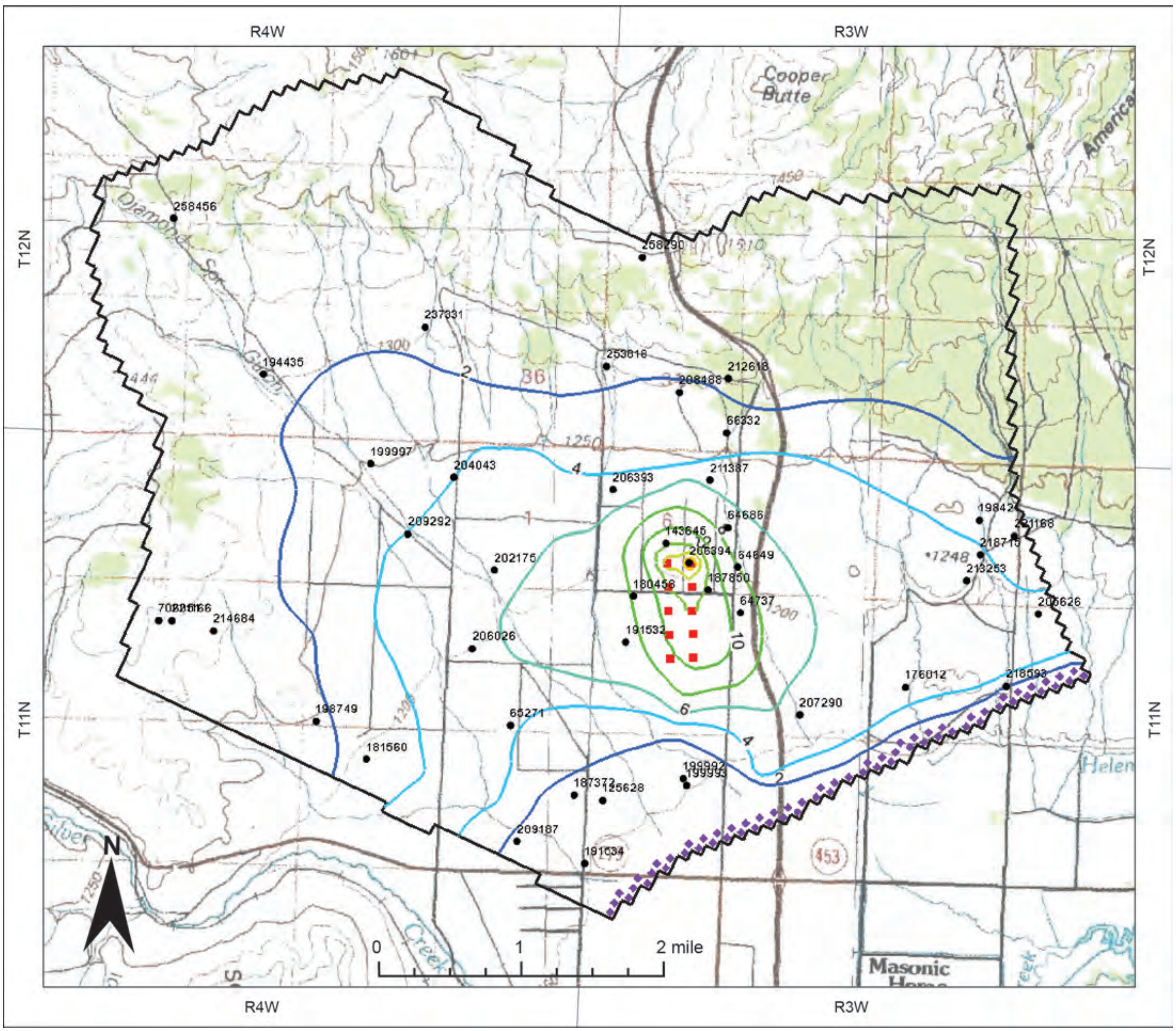


Figure 47. Additional drawdown (ft) calculated for a 5-year increase in the average annual groundwater pumping rates in Pumping Center A of the same amount as that estimated to have occurred from 2005 through 2009. An increase in the pumping rate from the Pumping Center of 7,500 ft^3/d is applied at the end of model year 2014 and continued until the end of the modeled time period, the end of August 2025. This map shows calculated additional drawdown as of March 1, 2025.

pumping rates for all wells in Pumping Center A was 215 acre-ft/yr (0.30 cfs, 25,640 ft^3/d). Therefore, the pumping rate was increased to 860 acre-ft/yr (1.19 cfs, 102,560 ft^3/d), resulting in a maximum modeled additional drawdown in the well field of 123 ft. The configuration of the potentiometric surface created by this extreme pumping scenario was calculated by the model (fig. 48). Note that the groundwater levels in the pumping center were drawn down to about the level of groundwater previously mapped near the edge of the Helena valley in the vicinity of the HVID canal (3,725 ft).

The approximately 0.89 cfs of added pumping in the steady-state simulation reduced groundwater outflow to the drains (0.48 cfs) and constant head cells representing Lake Helena (0.41 cfs). This suggested that if pumping in Pumping Center A is quadrupled relative to 2009 pumping rates, the impact to Lake Helena outflow and the Missouri River would ultimately be a flow reduction of 0.89 cfs. The U.S. Geological Survey (Briar and Madison, 1992) estimated that the total flow out of Lake Helena averages about 148 cfs.

The timing of the effects on surface waters by increasing pumping rates at Pumping Center A four times was tested using the North Hills Area model in transient mode. In this simulation, 2009 estimated monthly pumping rates were multiplied by four and applied to the matching months of modeled years 2010 to 2025. The model ran for 240 months, or

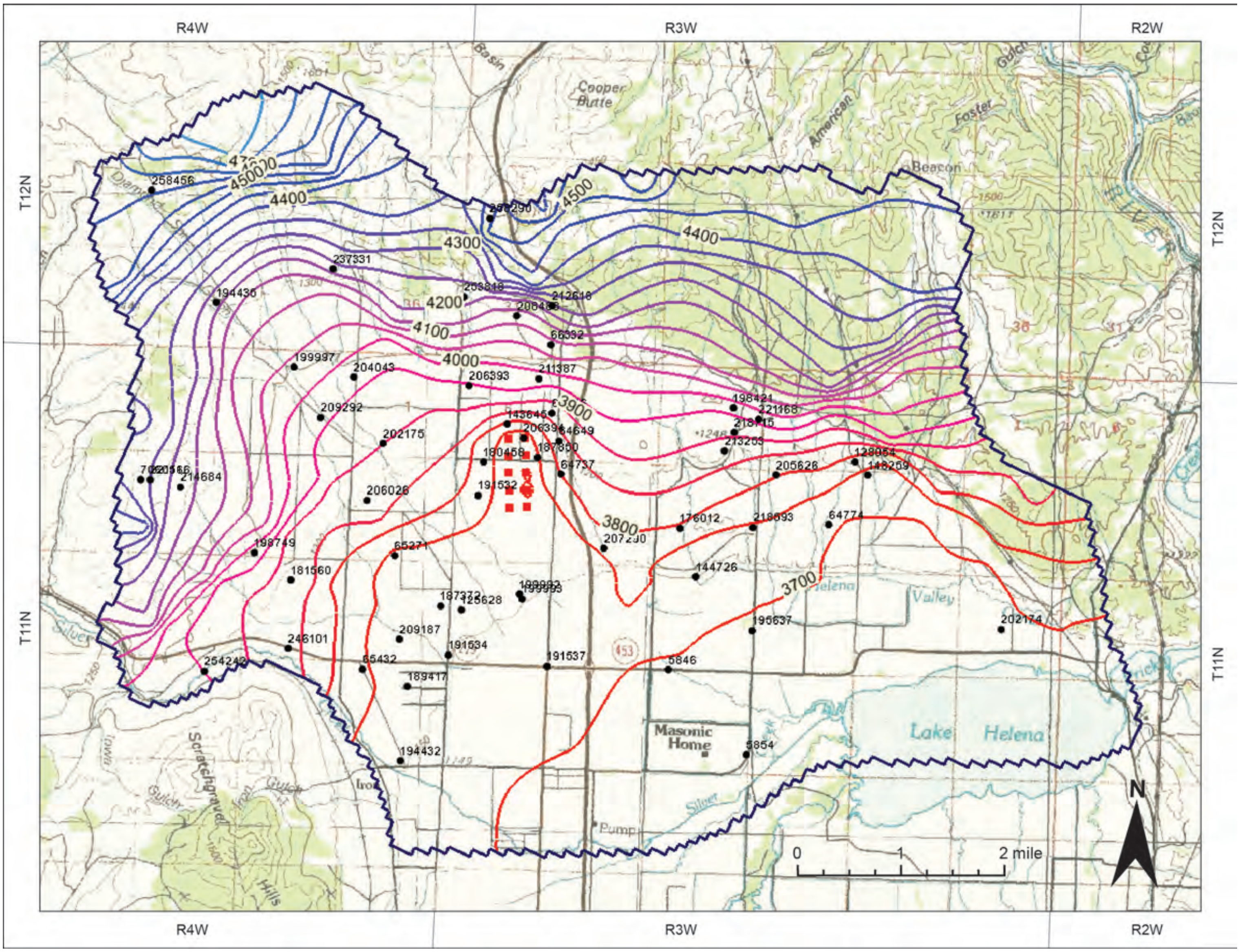


Figure 48. Potentiometric surface predicted by the North Hills Area model if the pumping rates at Pumping Center A were increased to four times the 2009 estimated pumping rates. The model suggests about 120 ft of additional drawdown would occur at the pumping center, drawing water down to about the elevation of groundwater beneath the HVID canal.

20 years, from September 1, 2005 through August 31, 2025.

The effects of the increased pumping on modeled or calculated outflow rates to storage, wells, and surface-water sources were calculated for four points in time during the last modeled year (fig. 49). The model calculated amounts of water flowing to constant head cells (representing Lake Helena) and to drain cells (representing the agricultural drains in the Helena Valley). The water flow calculated to these sinks was added to represent the calculated outflow to surface-water sources. Water calculated as "out" to storage represented water entering aquifer storage. Negative storage values indicated water derived from storage. Note that the outflow to wells in the model with four times the 2009 pumping rate was noticeably greater on the first and last dates, reflecting the much higher summer pumping rates, approaching about 4 cfs. The overall seasonal changes in rates to the various components of outflow were largely driven by the huge amounts of irrigation recharge from applied water that represented the HVID canal and associated irrigation activities. The extreme pumping modeled at Pumping Center A had only modest effects on the overall water budget.

The differences between calculated outflow rates at the selected dates between the model operating with four times the 2009 pumping rates versus the 2009 pumping rate were compared (fig. 50). The high rates of pumping from wells on the first and last dates shown on the graph were buffered by groundwater derived from storage. This model scenario calculated that if summer pumping at Pumping Center A approached 4 cfs, the effect on surface water was buffered by the aquifer, with calculated surface-water outflow decreases of less than 1 cfs. Ultimately, the calculated transient average annual depletions will be equal to the steady-state value of 0.89 cfs.

A simulation of a possible future development in the southwest quarter of Section 31, T. 12 N., R. 03 W., was developed using the North Hills Pediment Focus model in steady-state and transient modes. This work was done with the permission and assistance of the landowner, who generously allowed us to develop an aquifer test site along the Helena Valley Fault, an important hydrogeologic feature in the North Hills study area, and allowed the Montana Tech Geophysics Department access to the same site for their 2011 Geophysical Summer Program to test various geophysical methods to investigate subsurface materials.

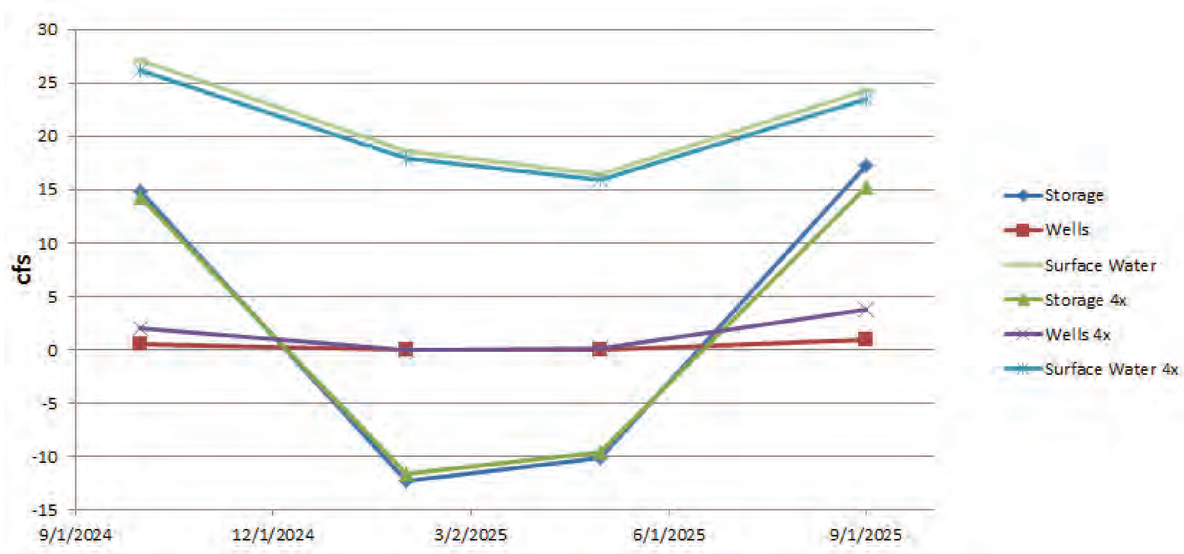


Figure 49. Model-calculated effect of increasing 2009 estimated monthly pumping rates in Pumping Center A four times beginning in 2010 to the calculated outflow rates for four dates about 15 years later. The data are plotted for the dates of Oct 1, 2024, Feb 1, 2025, May 1, 2025, and Sep 1, 2025. The first three outflow values shown in the legend are based on the model pumping 2009 estimated pumping rates, and the second three values (labeled "4x") are based on the model pumping four times the 2009 rates. The extreme pumping modeled at Pumping Center A has modest effects on the overall water budget.

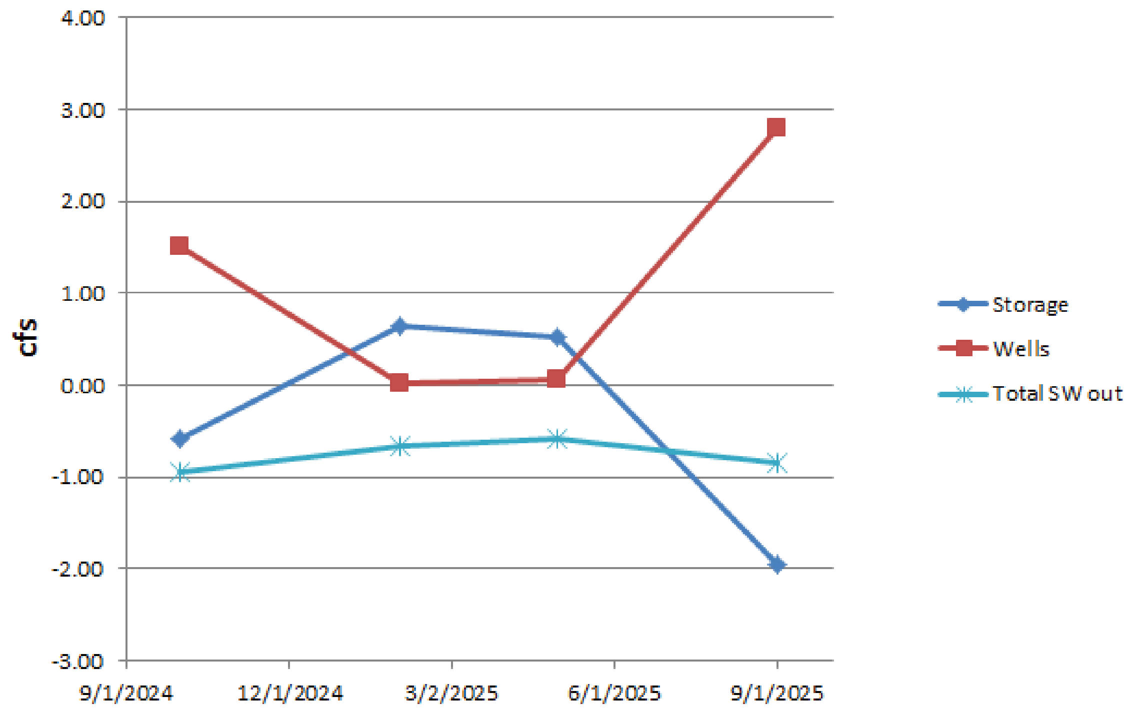


Figure 50. Model-calculated effect of increasing 2009 estimated monthly pumping rates in Pumping Center A four times beginning in 2010 to the calculated outflow rates for four dates about 15 years later. The data are plotted for the dates of Oct 1, 2024, Feb 1, 2025, May 1, 2025, and Sep 1, 2025.This graph shows the difference in calculated outflows in cfs. The immediate effects of seasonal summer groundwater withdrawals, best illustrated by the Sep 1, 2025 data, are reflected in the water that gets delivered by aquifer storage (negative aquifer storage flow rates). The “Total SW out” is the sum of water calculated to flow out of drains and to constant head cells, which both represent water flowing to Lake Helena. Thus, the increased seasonal groundwater pumping rates approaching 3 cfs are buffered and result in monthly surface-water depletions of about 0.7 to 1 cfs. Ultimately, they will average 0.89 cfs, which is the steady-state calculated depletion rate for the increased pumping.

The scenario included 47 wells serving homes spread about the southwest quarter of Section 31. The pumping rates of the 47 wells were modeled at the same rates as those estimated for wells in Pumping Center A, with an average use of 435 gallons per day. Table 11 shows the pumping values used in the scenario. The wells are fairly evenly spaced, and not based on any actual plats. There is one well in each groundwater model cell within the quarter section. Figure 51 is based on a steady-state model, and thus represents the ultimate (steady-state) total drawdown calculated by the model for sustained withdrawals of 435 gallons per day by 47 wells at the locations modeled. The red symbols show the modeled well locations. Figures 52 through 55 show how drawdown was calculated to propagate over time if all pumping were in place and operating at expected

Table 11. Modeled pumping scheme for each simulated household—typical seasonal rates derived from the North Hills water budget report (Bobst and others, in preparation a)—were applied to this scenario.

Month	Pumping rate, gal/d	Days	Gal/mo.
January	14.57645	31	451.87
February	14.57645	28	408.1406
March	21.86468	31	677.805
April	31.52581	30	945.7744
May	531.871	31	16488
June	949.6727	30	28490.18
July	1367.305	31	42386.46
August	1379.509	31	42764.77
September	740.6871	30	22220.61
October	126.2727	31	3914.455
November	26.77999	30	803.3997
December	9.661136	31	299.4952

Additional descriptions:

159851	gallons per year per household (0.49 acre-ft)
21370.45	cu. ft/yr per household
1004411	cu. ft/yr (47 houses)
23.05811	acre-ft/yr (47 houses)

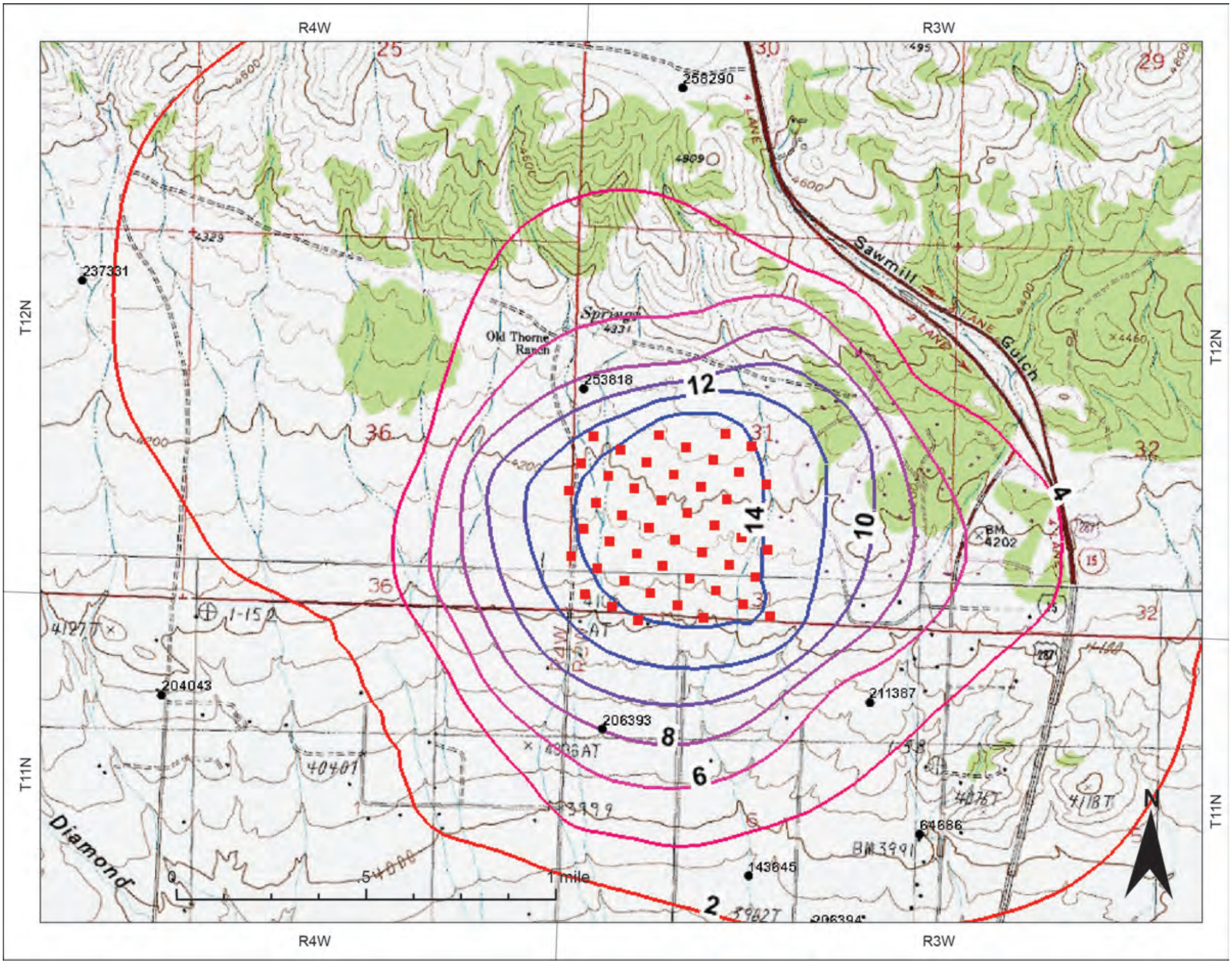


Figure 51. Steady-state drawdown (ft) calculated for 47 wells each pumping 435 gallon per day at the locations shown on the map. This represents the calculated long-term impact of the modeled stress of 47 households pumping an average of about 435 gallons per day (3.67 acre-ft/yr) per household. The red symbols are modeled well locations.

seasonal pumping rates as of May 1, 2012. The seasonal pumping rates are based on the estimated pumping ratios in the North Hills Technical Report, Water Budget section (Bobst and others, in preparation a) and shown in table 5.

Figure 56 shows the modeled drawdown for a hypothetical situation in which lot sizes were reduced to about 0.35 acres in size, and some 470 wells placed in the same quarter section instead of 47 wells. To run this simulation, pumping rates for the 47 modeled wells were simply increased tenfold, since there was room for only one well in a MODFLOW model cell. Interestingly, the model predicted the aquifer might sustain such a denser development, but with proportionally more drawdown at the sites and surrounding areas.

The hypothetical dense lots scenario was further explored by withdrawing all the water from a single well. The scenario required a constant pumping rate of 27,260 ft^3/d, or 141 gpm. If such a well could be constructed, the model predicts a drawdown of 316 ft at the pumping well (fig. 57). Notice that the 160-ft contour and contours of lesser drawdown outside of it are in about the same place as the steady-state simulation with individual wells.

A drawdown for such a development might be deemed problematic by regulatory agencies. A pos-

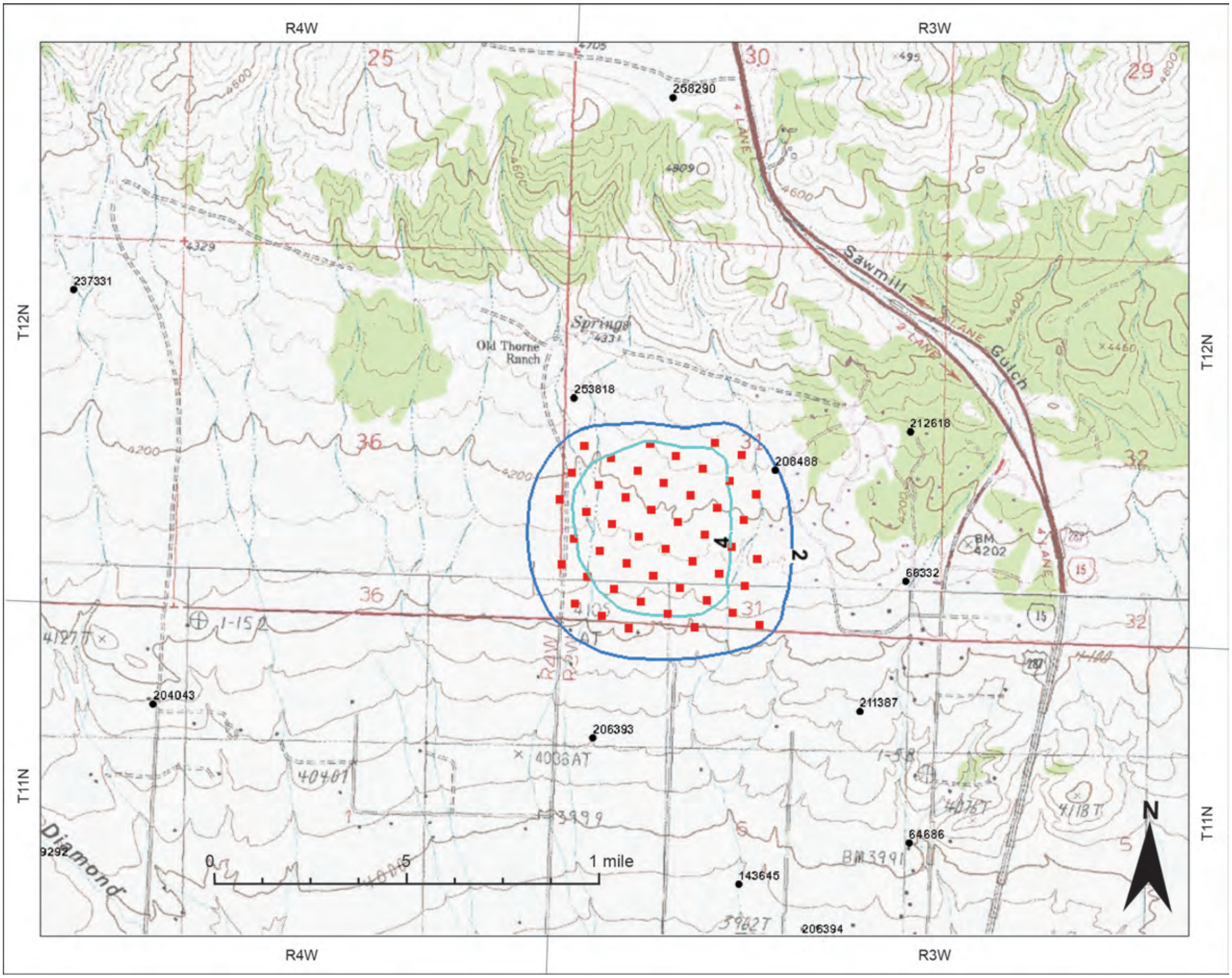


Figure 52. Drawdown (ft) calculated by a transient groundwater model for 47 wells pumping at typical seasonal rates from May 1, 2012 to October 1, 2012. The red symbols are modeled well locations.

sible solution would be to locate the project production well (or wells) to a more productive part of the aquifer system. This concept was tested by moving the pumping well to a location about 1/3 mile north of the HVID canal. Here, the hydraulic conductivity of the aquifer is around 30 to 40 ft/d, as compared to values of about 0.2 ft/d at the actual location of the development. The resulting maximum model-predicted drawdown from a well producing 141 gpm near the canal, at the well, was 1.3 ft. Drawdown of up to 0.25 ft extended over a large area. In this simulation, less water was discharged to the specified head boundary located near the canal, but the gradient was not reversed. Because the well was placed relatively close to the specified-head model boundary, the scenario was also tested with the North Hills Area model. That simulation resulted in a model-predicted drawdown of about 2.5 ft, an increased drawdown of about 1 foot. In both cases, model-predicted drawdown was modest and would not be expected to cause problems for existing neighboring wells.

The North Hills Area model was used to test the effect of reduced recharge in the North Hills and no recharge from Silver Creek and its associated irrigation. The idea was to simulate 5 years of reduced recharge in the hills and the loss of recharge from Silver Creek due to a five-year drought. The recharge from precipitation in the North Hills was reduced from the constant rates estimated for the groundwater modeling effort by 25% for the 5-year

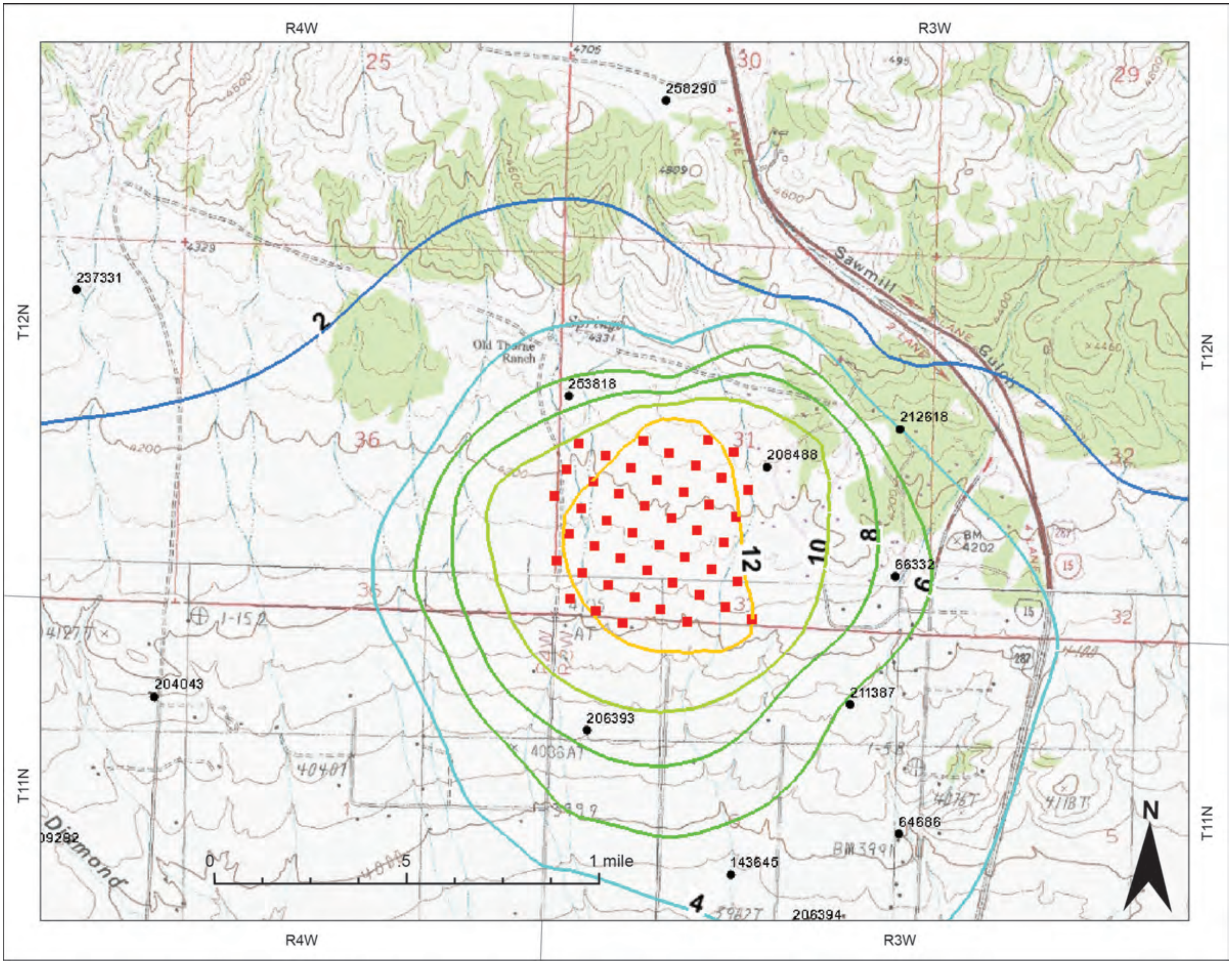


Figure 53. Drawdown (ft) calculated by a transient groundwater model for 47 wells pumping at typical seasonal rates from May 1, 2012 to October 1, 2025. The red symbols are modeled well locations.

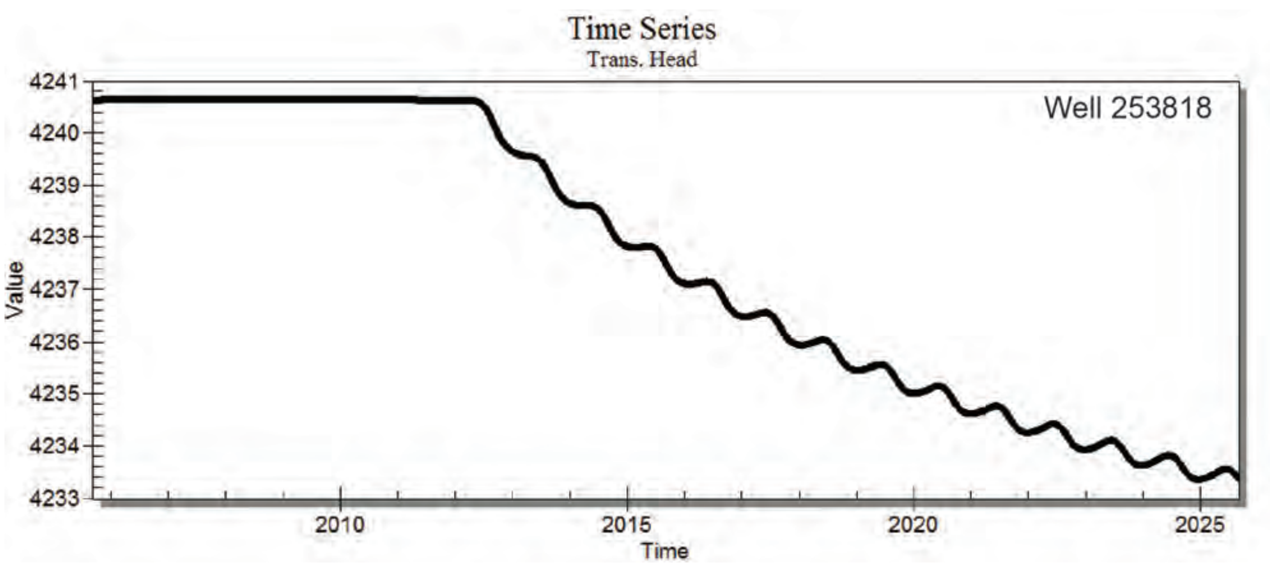


Figure 54. Groundwater elevations calculated at GWIC well 253818 from the transient scenario shown in figs. 52 and 53. The vertical axis represents groundwater elevations in feet. This well is about 1000 ft north of the north edge of the southwest quarter of Section 31.

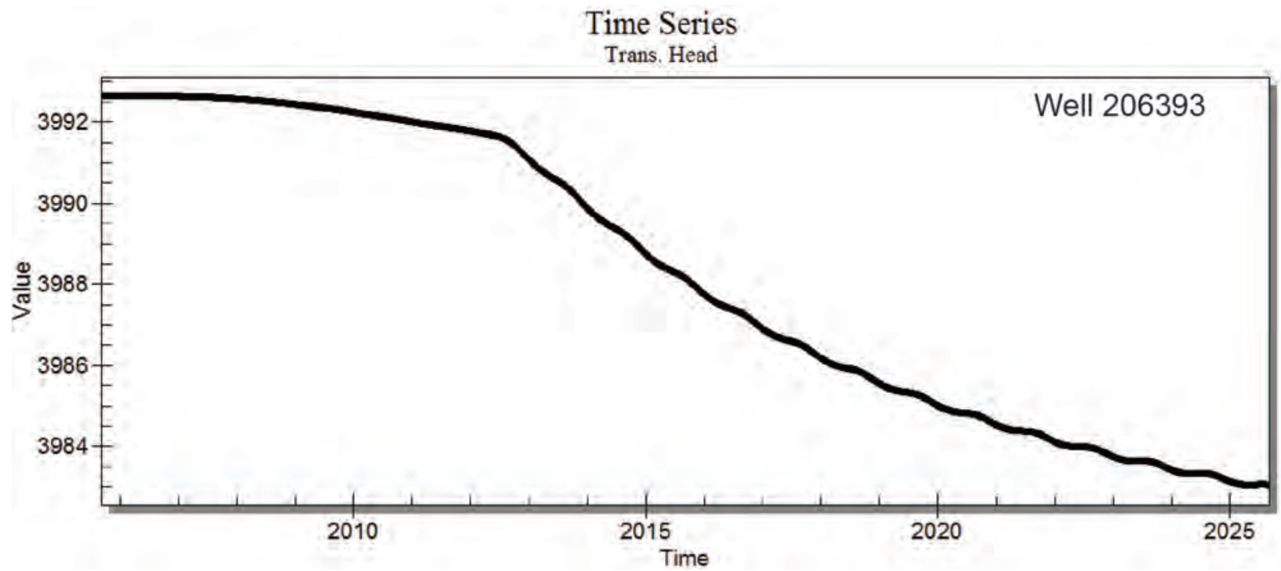


Figure 55. Groundwater elevations calculated at GWIC well 206393 from the transient scenario shown in figs. 52 and 53. The vertical axis represents groundwater elevations in feet. This well is about 1/4 mile south of the southern boundary of Section 31, and about 500 ft east of Applegate Drive.

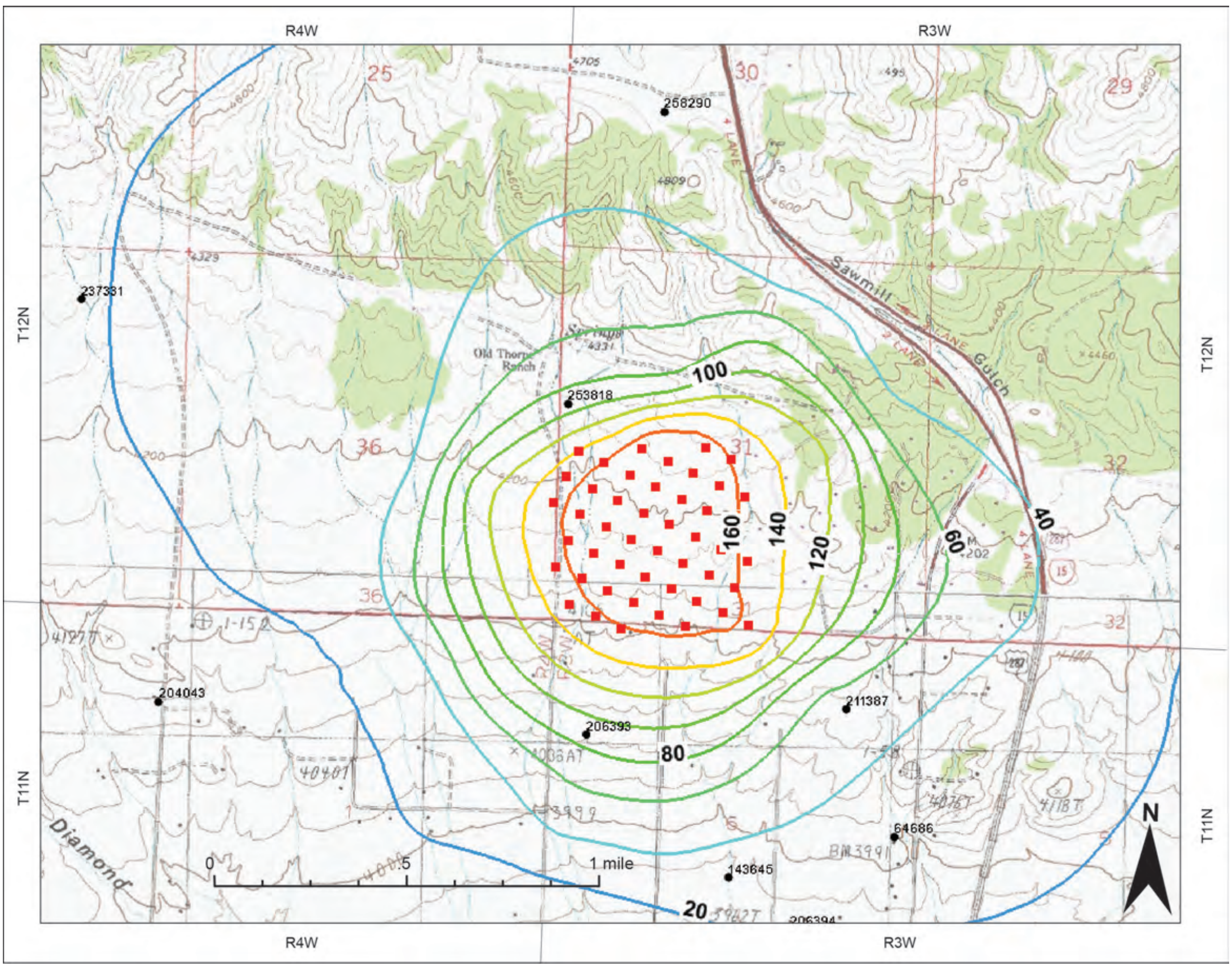


Figure 56. Calculated drawdown (ft) for ten times the amount of steady-state pumping shown in Figure 51.This shows the approximate impact resulting if lots were reduced to about 0.35 acres in size, and groundwater withdrawals for 470 homes averaging 435 gallons per day each for a total annual extraction of about 230 acre-ft per year for the hypothetical subdivision.

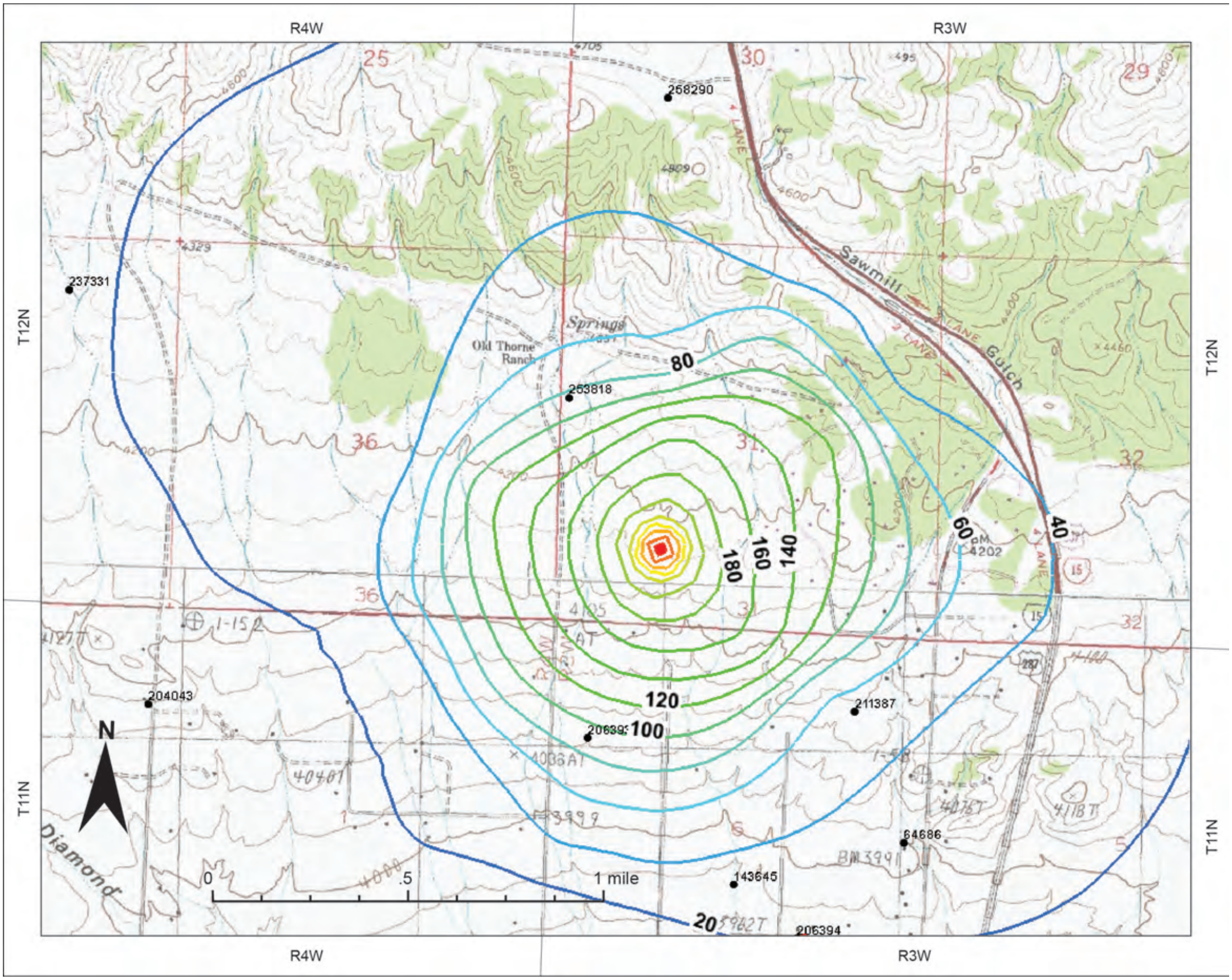


Figure 57. Calculated drawdown (ft) for a single public water-supply well for 470 homes instead of individual wells. Note that the 160-ft contour, and those outside of it, are not changed much from the locations calculated for individual wells. The main difference is the drastic drawdown within the vicinity of the subdivision.

period from January 1, 2012 to January 1, 2017. Also, recharge representing water from Silver Creek and its associated irrigation was set to zero during the same time period. How realistic this scheme might be was uncertain, but it served as a useful tool to evaluate what areas are most susceptible to water-level changes related to drought or loss of water from Silver Creek. At the end of the modeled drought, recharge in the hills and recharge for Silver Creek and associated irrigation were resumed at pre-drought rates in this scenario.

Figure 58 is a map of drawdown that occurred at the end of the modeled 5-year drought (model time January 1, 2017). There were two areas of rather extreme water-level declines. One, in the vicinity of Silver Creek, was due to the modeled total loss of recharge coming from Silver Creek and its associated irrigation. The second occurred along the western boundary just north of Silver Creek. This area of drawdown should be ignored, as the drawdown was merely due to some flooded model cells in that particular area of the model. It is an area of the model for which data are sparse and might be improved in the future if more data become available. Other than Silver Creek, predicted drawdown due to drought was most severe beneath the recharge areas of the North Hills. Since the HVID canal and associated irrigation were modeled to be unaffected by the drought, the result represents a vast area of little change in the south and east parts of the model.

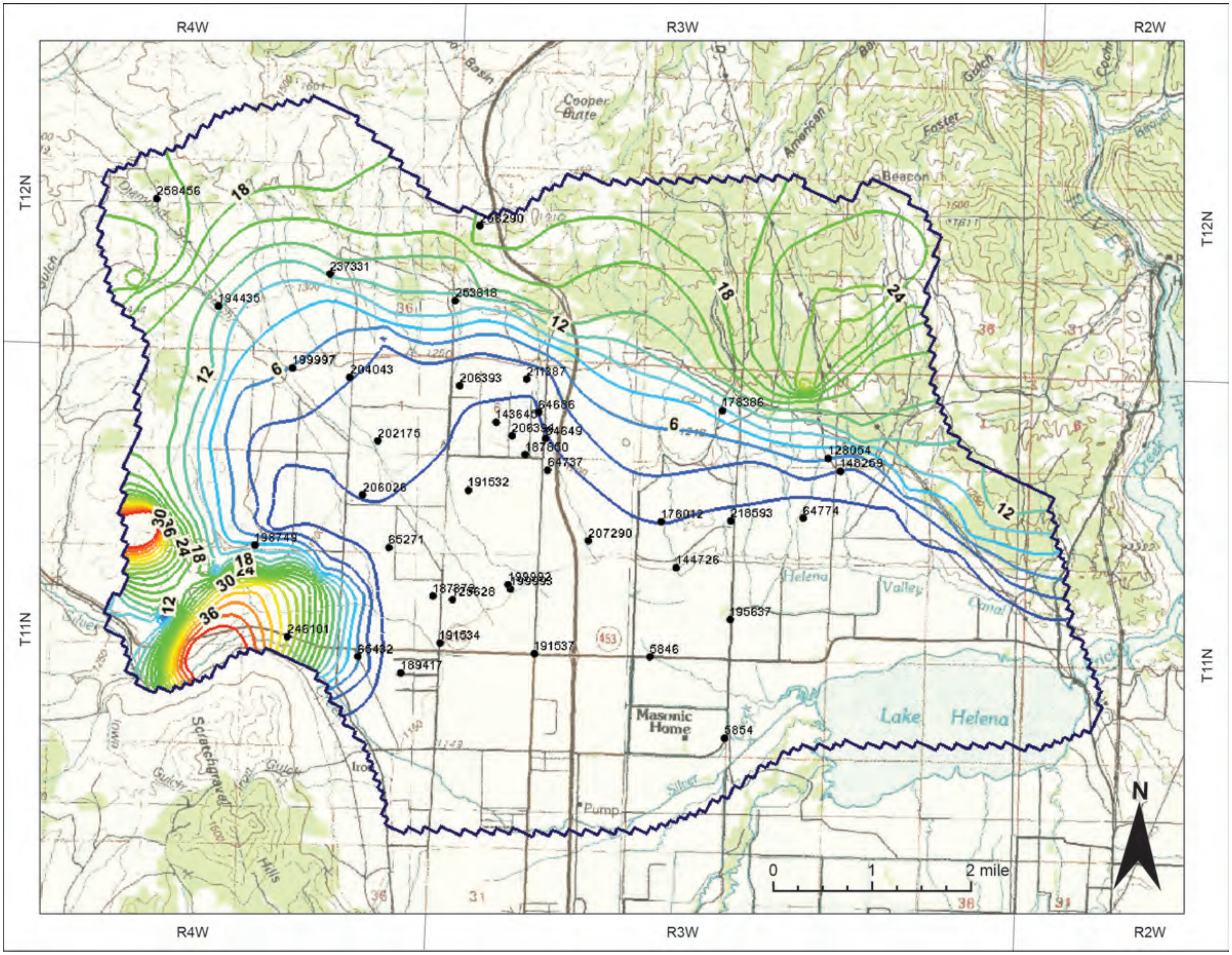


Figure 58. Calculated drawdown (ft) for a 5-year drought scenario at the end of 5 years with 75% of the modeled recharge occurring in the hills, and no recharge applied from Silver Creek and its associated irrigation. Model time: January 1, 2017. The results suggest the west end of the Helena Valley aquifer is particularly sensitive to changes in recharge from Silver Creek.

Figure 59 shows residual drawdown 5 years after the modeled 5-year drought at January 1, 2022. Here, the model predicted (after conditions return to average recharge rates) that the system was rather slow to fully return to its steady-state condition, as drawdown lingers in upgradient areas and near the Silver Creek recharge area. Drawdown also increased or propagated outward onto the pediment in the area west of Interstate 15. Figure 60 shows residual drawdown resulting from the 5-year drought near the end of the model run, in January 2025. Conditions were slow to change out on the pediment, as contours were in almost the same locations as in January 1, 2022 modeled time. The model predicted continued modest water-level rises in the upgradient areas in the time between January 1, 2022 and January 1, 2025. There were no wetter years simulated in this scenario. Obviously, one modeled wet year, or a series of such modeled wet years, could cause water-level rises of similar magnitude.

Figure 61 shows hydrographs generated for three modeled observation well sites. The top graph depicts well 191532, located just west of Pumping Center A. Here, the impacts of the modeled 5-year drought were somewhat subtle (just a few feet of drawdown), but slow to recover. The middle graph depicts well 237331, located high on the pediment in an undeveloped area in the northwest area of the model. The simulated water levels in this well were more drastically affected by the drought, with mod-

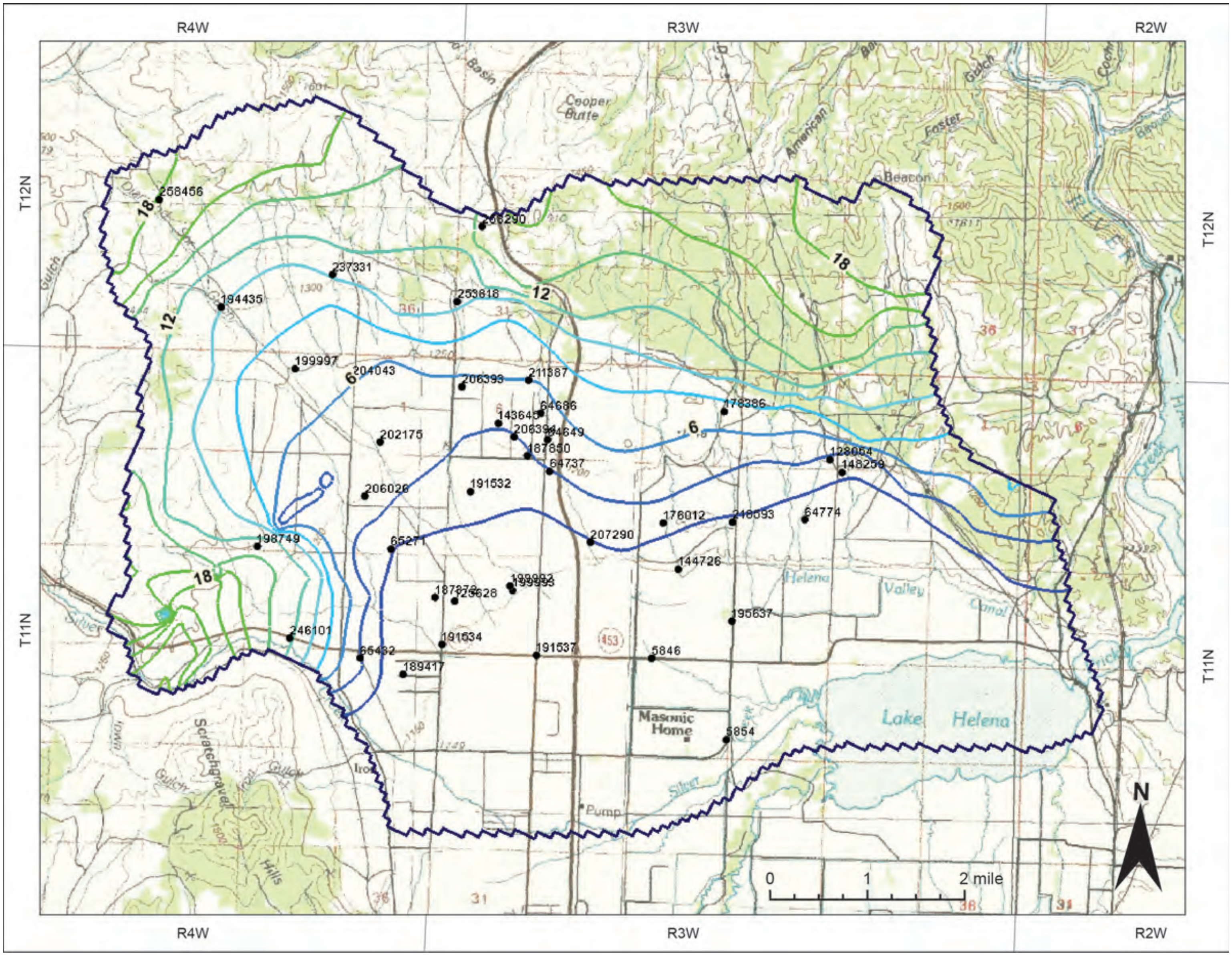


Figure 59. Calculated residual drawdown (ft) 5 years after the end of the 5-year drought. Model time: January 1, 2022. Notice that groundwater levels in the hills area are slow to recover at normal recharge rates, and the calculated drawdown is propagating southward on the pediment.

eled drawdown of about 12 ft; these water levels were slow to recover upon returning to the modeled average recharge rates. The bottom graph depicts well 246101, located near Silver Creek and its associated irrigated areas. Here, the modeled water-level elevations dropped about 40 ft due to the loss of recharge from Silver Creek. However, when the modeled conditions returned to average rates after 2016, the modeled water levels in this well responded markedly faster than in the other two sites.

Another scenario of interest was to estimate the effect of removing the HVID canal and its associated irrigation from the Helena Valley. The scenario was modeled by operating the North Hills Area model in steady-state mode without any recharge from the HVID canal or its associated irrigated areas. Figure 62 shows the change in groundwater levels predicted by the model as a result of removing all HVID-related recharge.

These few scenarios provide examples of how the groundwater models can be used to evaluate changes in stresses or other conditions such as recharge on water levels and the water budget of the aquifer. The groundwater models address the area aquifers at a system level. Site-specific conditions such as the presence of faults or unmapped subsurface geologic units may influence conditions locally.

In the area east of Collins Drive and north of Lake Helena, the aquifer is typically composed of

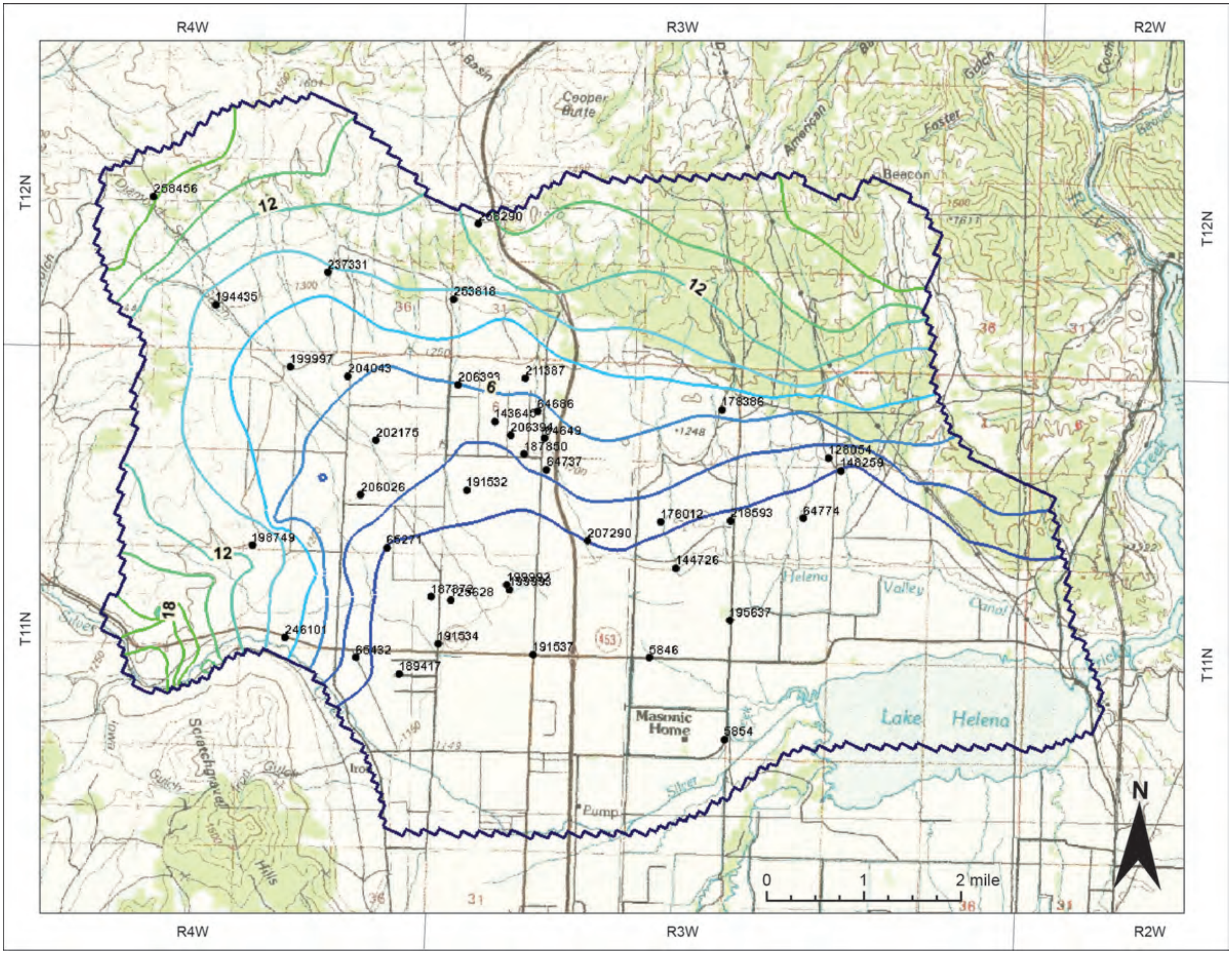


Figure 60. Calculated residual drawdown (ft) in the last year modeled. Model time: January 1, 2025.

gravels beneath thick clays. Here, the aquifer is likely highly confined, and the current groundwater models may underestimate drawdown associated with local groundwater withdrawals. The development of a focus model or modification of the current models may be useful for this part of the aquifer if this area becomes subject to increasing development.

MODEL SUMMARY AND CONCLUSIONS

Two groundwater models were developed for the North Hills Study Area. The North Hills Area model is a larger area groundwater model that utilized water budget information from this and previous studies to develop a reasonable approximation of the water budget in the study area. It included modeling of the north end of the Helena Valley's irrigated areas serviced by the Helena Valley Canal and Silver Creek. The model was developed to provide a tool for evaluating the overall water budget of the groundwater system, and for determining the approximate timing of impacts of various water resource activities to Lake Helena and the Missouri River. Examples include groundwater drawdown estimates and water budget impacts (groundwater and surface water) associated with specific groundwater pumping scenarios, artificial recharge schemes, location changes of groundwater pumping, effects of wet or dry years, etc. The model was used to evaluate the effects of a 5-year drought on the groundwater system. The basic water budget was replicated in sufficient detail for these purposes, and further improvements can be made if needed.

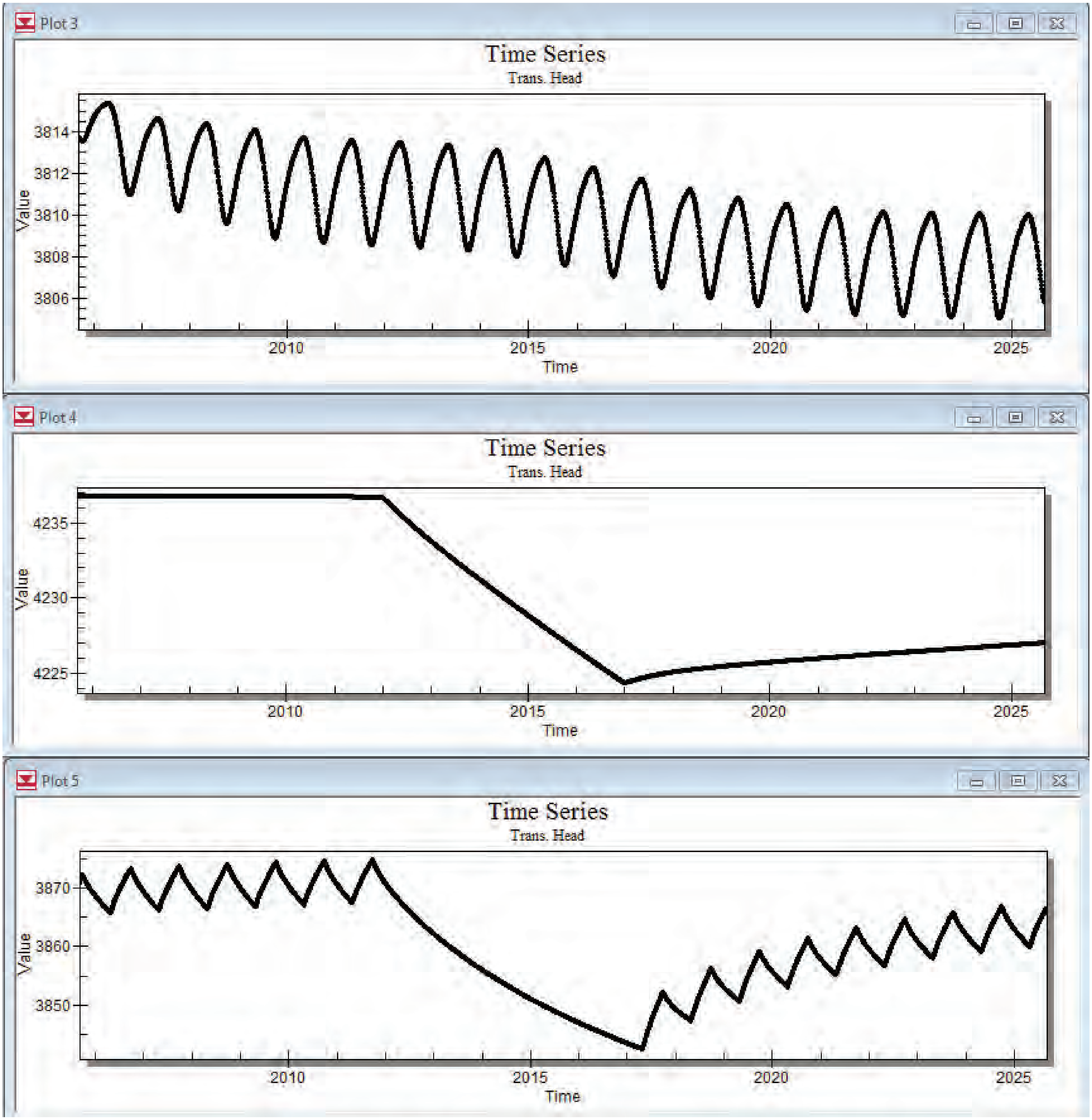


Figure 61. Model-generated hydrographs for wells 191532 (top), 237331 (middle), and 246101 (bottom). The y-axis labeled “value” is elevation in feet.

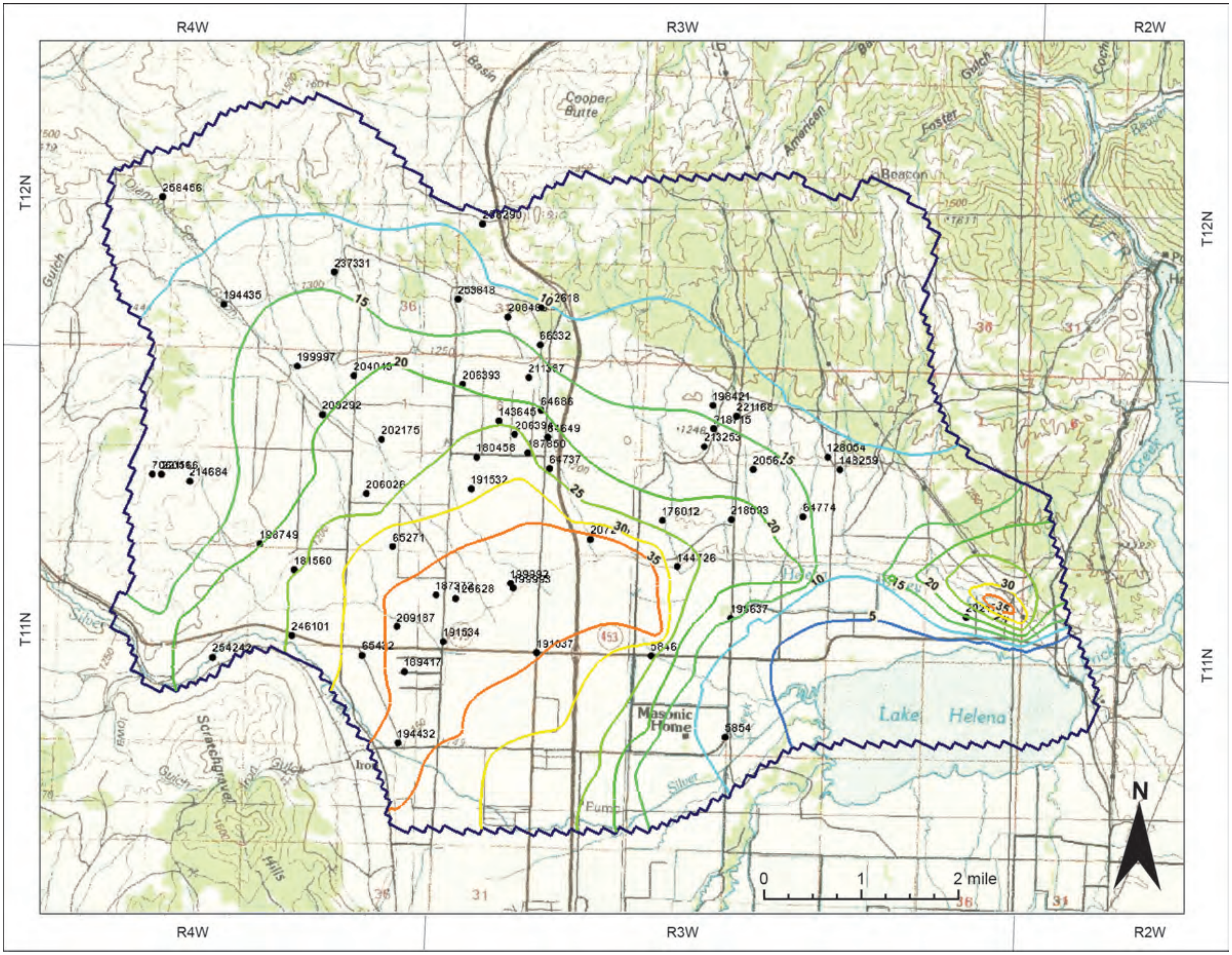


Figure 62. The model-estimated steady-state drawdown (relative to current conditions) that would occur if the HVID irrigation project were to be shut off entirely.

The Pediment Focus model was designed specifically to address the issues in the core area of interest in the study area, that area most recently designated by the Montana DNRC as a Controlled Groundwater Area. This model was designed to evaluate the water budget of the North Hills and the pediment above the Helena Valley Canal. The model successfully replicated the observed drawdown over the period from September 2005 through February 2011. This model was operated through February 2025, and the model calculated that if groundwater extractions in Pumping Center A (subdivisions north of Valley View Road and west of Montana Avenue) remain at 2009 levels, the groundwater levels would be expected to stabilize (less than 0.25 ft of drawdown per year) in 2017, at a level approximately 3 ft below modeled January 2011 water levels. The Pediment Focus model was used to evaluate the impacts of pumping rates increasing incrementally at the same rate as was estimated during the period from 2005 to 2009. It was also applied to estimate drawdown of the potentiometric surface as a result of a possible future development in an undeveloped area.

Scenarios operated using these groundwater models represented system-scale estimates of effects of applied stresses, based on the available data at the time of their construction. There will undoubtedly be new information to incorporate into future groundwater model versions such as modifications made by the Montana Bureau of Mines and Geology or other users for their own purposes. Local groundwater models for smaller areas within the model domain may be appropriate for a variety of problems addressing specific issues as needed. For example, the general aquifer characteristics and groundwater flux from the present models can be used as a starting point for the development of a local model, one that could have multiple layers defining known local conditions where data are sufficient to do that.

Additional details about the model products developed are provided in Appendix B. These details include descriptions of the various model products available and informative details for potential model users.

ACKNOWLEDGMENTS

We thank the many landowners and residents of the North Hills study area for their interest in the study, and for their permission to conduct various aspects of the investigation on their properties. Lewis and Clark County Local Water Quality Protection District provided significant assistance by allowing us to contract the services of Gary Burton for monthly measuring of water levels in about 50 wells, and for hydrogeologist James Swierc to work on and contribute to this project. Joe Michaletz of GeoLux, Inc. kindly provided some shallow magnetic geophysical results from a property in the northwest part of the study area. Russell Levens and James Beck of the Montana DNRC contributed substantially to this project by providing us with comments and direction regarding water-rights issues, groundwater-modeling efforts, and surface-water monitoring.

Richard Berg, Jeff Lonn, Tom Patton, James Madison, and Gary Icopini from the MBMG provided technical assistance for various aspects of this study. Allison Brown, a Montana Tech student, provided assistance in both field and office aspects of this project. The Montana Tech Geophysics Department conducted a number of geophysical projects that provided students an opportunity to test geophysical techniques and provided us with information on subsurface conditions at the sites. Editing and layout by Susan Barth, MBMG.

The Tenmile Creek and Lake Helena watershed groups provided opportunities for us to discuss the study, increasing our public presence in the Helena area and allowing us to better understand the issues. The Montana Watershed Coordinating Council Groundwater Work Group provided a format to share our plans and activities with hydrologists and geologists from other agencies and vice versa. The Lewis and Clark County Conservation District provided permission for stream access for instrumentation used in the study. The Helena Valley Irrigation District (HVID) provided permission for access to the HVID canal and agricultural drains to measure flows and to instrument drains as needed.

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APPENDIX A. MATERIALS KEY FOR WELL LOG DATA

This appendix lists first the 33 material codes used in the Groundwater Modeling System software to identify geologic materials, followed by lists that show the driller's descriptions found in the GWIC database that were categorized in each material type.

MATERIAL CODES

1) Topsoil
2) Gravel and Sand
3) Sandstone
4) Clay and Sand
5) Gravel and Clay
6) Granite
7) Rhyolite
8) Gravel/Shale/Sand
9) Clay and Shale
10) Fill
11) Limestone
12) Brown Clay
13) Gravel
14) Clay
15) Shale
16) Red-Green Shale
17) Tan/Brown Shale
18) Yellow Shale
19) Gray/Black Shale
20) Red Shale
21) Water
22) Sand
23) Rock
24) Bedrock
25) Blank/Unknown/No File/No Data
26) Reddish Brown Argillite
27) Greenish Gray Argillite
28) Mixed Argillites
29) Green Shale
30) Red Clay
31) Yellow Clay
32) White Clay
33) Multicolored/Mixed Shales

DRILLERS DESCRIPTIONS THAT WERE CATEGORIZED INTO EACH MATERIAL CODE:

Topsoil

-topsoil
-sand/silt
-topsoil and clay
-silty sand
-sandy topsoil and gravels
-topsoil/clay sand mix
-overburden

Gravel and Sand

-sandstone/red/gravel/gravel and sand intermingled
-brown/sand/stone/gravel intermingled
-brown/sandstone/sand/gravel
-med. big gravel and sand
-small med. gravel and sand
-gravel and sand
-sand and gravel
-sand gravel mix
-sand gravel intermingled
-sandstone/gravel(mix)
-clay/sand and fine gravel
-brown sandstone/fractured granite/gravel
-red sandstone/gravel/fractured granite
-sand gravel and clay
-sand gravel and clay w/ gravel layers
-sand gravel rocks
-unconsolidated
-dirt and rock
-comp. sand and gravel

Sandstone

-sandstone
-broken tan sandstone
-red brown sandstone

Clay and Sand

-sand and clay
-sandy clay
-silty clay
-silty clay w/ small layers sand and gravel

-brown clay and sand
-hard brown clay w/ small coarse sand lense
-clay sand and silt
-tan clay and sand

Gravel and Clay
-gravel and clay
-med. gravel and clay
-light brown clay and gravel
-clay and gravel
-clay and rocks
-hard clay w/ fine gravel
-gravelly clay
-clay w/ fine gravel
-brown clay and fine gravel
-shaley gravel and pink clay
-red angular gravels and clay
-clay cobbles and gravel
-clay sand and gravel
-brown clay w/ gravel lense
-clay/boulders
-clay/gravel seams
-silty clay and gravel
-brown sandy clay and decomposed granite
-clay and broken rock

Granite
-fractured granite
-decomposed granite
-granite
-faulted green granite
-gray granite
-soft granite
-weathered granite
-brown decomposed granite
-brown granite
-broken granite and sand
-black granite
-hard dark granite
-soft dark granite
-granite bedrock

Gravel/shale/sand/clay
-shaley gravel
-cemented shale and gravel
-sand gravel w/shale lens
-gravelly shale and clay
-shale gravel and hard clay
-shale/gravel and clay
-shaley gravel and clay
-brown clay, some shaley gravel
-shaley gravel and brown clay
-red/green gravelly shale and clay
-sand and gravelly shale
-sands gravel H2O red fractured shale
-shale w/sand lense
-shale and gravel
-red shale, gravel and h2O
-shale and gravel clay seams
-shale granite gravel and clay

Clay and Shale
-clay and fine shale
-hard brown clay and shale
-brown clay, some shale
-brown clay and shale
-shale clay
-clay and broken shale
-fractured shale w/clay
-hard clay and broken shale
-weathered shale and clay
-brown clay and small shale
-brown clay and tan shale
-tan shale w/ brown clay
-fractured red shale and clay
-broken shale and clay
-tan clay and shale
-red clay and shale
-clay/decomposed shale
-gray shale and clay
-tan shale and clay
-black clay and shale
-clay with red shale lense
-claystone and mudstone
-gray clay and shale
-fractured yellow shale and clay

Bentonite

Fill
-fill
-fill/shale
-topsoil fill

Limestone
-limestone
-fractured limestone
-lime
-tan/gray limestone

Brown Clay
- -Brown Clay
- -Hard Brown Clay
- -tan clay

Gravel
- -cemented gravel
- -gravel
- -gravels
- -gravel/minor water
- -gravels and water

Clay
- -clay
- -hard clay
- -clay layers
- -broken clay w/clay seams
- -clay w/ H_2O
- -clay ash

Shale
- -decomposed shale
- -soft shale
- -fractured shale
- -shale
- -broken shale
- -dark shale w/fractures
- -shale/broken shale
- -hard shale
- -blue shale
- -shale/frac. throughout
- -shale rock/sand
- -shale bedrock
- -shale and bedrock
- -faulted shale bedrock

Red-Green Shale
- -red/green shale
- -firm red/green shale
- -red/green gravelly shale
- -fractured red and green shale w/ small clay seams
- -multicolored red-green shale
- -green and red shale
- -broken red green shale

Tan Shale
- -brown shale
- -tan shale
- -broken tan shale
- -light brown shale w/bentonite
- -soft brown shale
- -brown fractured shale
- -light brown shale

Yellow Shale
- -fractured yellow shale
- -yellow shale
- -fractured yellow shale w/ clay seams
- -soft yellow shale
- -dark yellow shale
- -fractured dark yellow shale

Green Shale
- -light green shale
- -fractured green shale
- -green shale

Gray/Black Shale
- -broken black shale
- -gray black shale
- -gray shale
- -dark gray shale
- -fractured gray shale
- -black shale
- -light gray shale

Red Shale
- -red shale
- -purple shale
- -red brown shale
- -fractured red shale
- -fractured red shale/water
- -red shale water
- -fractured purple shale

Water
- -water

Sand
- -water sand
- -gravel/sand water
- -sand lense

Rock
- -red rock
- -yellow rock
- -rock
- -broken rock

Bedrock
- fault bedrock
- fractured
- broken bedrock
- decomposed bedrock

Blank/unknown/no file/no data
- existing well
- old well

Rhyolite
- decomposed rhyolite
- rhyolite bedrock

Reddish Brown Argillite
- reddish brown argillite
- reddish brown argillite with trace yellow/orange fracture fill

Greenish Gray Argillite
- greenish gray argillite
- greenish gray argillite with trace yellow/orange fracture fill

Mixed Argillites
- reddish brown silt with clasts of reddish brown and greenish gray argillite
- reddish brown argillite with greenish gray argillite
- reddish brown and greenish gray argillite and trace yellow/orange fracture fill

Red Clay
- red clay
- pink clay

Yellow Clay
- yellow clay

White Clay
- white clay
- gray clay

Multicolored/Mixed Shales
- multicolored shale
- tan and red shale
- purple and green shale
- blue and green shale
- yellow and brown shale
- brown and gray shale
- orange and brown shale
- green and brown shale
- gray and tan shale
- red/green/brown/tan shale
- yellow and green shale
- red and brown shale
- red and gray shale
- red and purple shale

APPENDIX B. MODEL DETAILS

North Hills Ground Water Investigation Program Groundwater Models

North Hills Borehole Analysis

This analysis uses GMS to assemble well log data for wells more than 200 ft deep, and with selected shallower well logs added where well records were sparse. Cross sections and solids were developed from the well log data using material codes and hydrostratigraphic units (HGUs).

The HGU and material coding scheme used to develop cross sections and solids is as follows:

HGU 5 (top)	Material 13	Gravel (upper)
HGU 4	Material 14	Clay
HGU 3	Material 13	Gravel (lower)
HGU 2	Material 15	Shale (bedrock)
HGU 1	Material 6	Granite (bedrock)

North Hills Preliminary Area Model

Attempts were made to build a multiple-layer groundwater model from solids generated with the North Hill Borehole Analysis. This effort was deemed unsuitable for the purposes of modeling the North Hills aquifer system. A one-layer model was developed for the study area and, the basic premises of a one-layer groundwater flow model were tested, including a suitable geometry for a larger-area North Hills water budget model. The model grid developed is used for both the North Hills Pediment Focus Model and the North Hills Area Model.

North Hills Pediment Focus Model

This model focuses on the pediment between the North Hills and the Helena Valley. This model takes advantage of the simpler water budget above the Helena Valley Irrigation District (HVID) canal and the densest distribution of observation well data for the study area. It is the best model for evaluating impacts of pumping above the canal and west of Interstate 15. It receives recharge from precipitation in the North Hills, and groundwater discharges to wells in Pumping Center A and to specified head cells that represent the aquifer in the vicinity of the HVID canal, where water levels area stable from year to year. This boundary was drawn at the approximate location of the 3725-ft contour of the potentiometric surface in the vicinity of the canal. Steady state runs a constant head of 3725 ft for the specified head cells. Transient runs specify monthly heads for the specified head cells based on observed data.

In the distributed transient groundwater model, the pumping rates for Pumping Center A remain at 2009 estimated monthly rates for all years after 2009. The transient model is calibrated to observation well data for the first 66 stress periods, September 2005 through February, 2011. The distributed model is set up to run for 240 months, or 20 years from September 2005 through September 2025.

North Hills Area Model

This larger-area model is used to address issues related to how groundwater extractions impact the Helena Valley Quaternary aquifer and Lake Helena. The intent of the North Hills Area Model is to create a groundwater model that reasonably simulates the water budget of the greater North Hills study area, including the irrigated lands below the HVID canal.

In the steady state model, average annual recharge is applied to the irrigated areas in the model. In the transient model, the seasonal rise and fall of the groundwater surface due to irrigation activities is modeled by applying recharge to the irrigated part of the Helena Valley only during the modeled five-month irrigation season, May through September. Discharge is to wells, drains, and specified-head cells representing Lake Helena.

In the distributed transient groundwater model, the pumping rates for Pumping Center A remain at 2009 estimated monthly rates for all years after 2009. The transient model is calibrated to observation well data for the first 66 stress periods, September 2005 through February, 2011. The distributed model is set up to run for 240 months, or 20 years from September 2005 through September 2025.

Groundwater Modeling Software

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

The MODFLOW 2000 files were tested using MODFLOW downloaded from the US Geological Survey website: http://water.usgs.gov/nrp/gwsoftware/modflow2000/modflow2000.html. The downloaded US Geological Survey version of MODFLOW is 1.19.01, compiled on March 25, 2010.

Groundwater Vistas files were created by importing the MODFLOW 2000 text files using Groundwater Vistas Version 5.51, build 18b. This version of Groundwater Vistas runs MODFLOW 2000 Version 1.18.00, compiled August 23, 2007.

PEST is a general purpose parameter estimation utility developed by John Doherty of Watermark Numerical Computing (Doherty, 2010). PEST was used for automated parameter estimation is certain GMS model runs. The version of PEST operated in GMS 7.1.2 is 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 International Ft. The model grid was created in GMS using a grid frame with an X origin of 1301000.0 ft, Y origin of 907000.0 ft, and Z origin of 3250.0 ft. Lengths of the grid in the X, Y, and Z dimensions respectively are 63600, 47600, and 2000 ft. A rotation angle of -25 degrees is specified to align the grid approximately with the orientation of the Helena Valley Fault within the active model domain. This grid frame is sufficient for both the North Hills Area Model and the Pediment Focus model, as cells within grid frame can simply be inactivated to change the active model domain. Figure 14 shows the active cell coverage for the Pediment Focus Model. Cells are 400 ft X 400 ft, and the model has 1 layer, 119 rows, and 159 columns. Table B1 provides additional numeric details about the model grid. The model thickness is between about 400 to 1100 ft thick, with saturated thicknesses generally in the range of about 400 to 650 ft in the pediment areas of the model, and some saturated thicknesses extending to about 850 feet in the hills areas.

Table B1. Details of the model grid as listed in GMS. This same grid is used in both the Pediment Focus model and the North Hills Area model.

Grid type:	Cell Centered
X origin:	1301000.0 (ft)
Y origin:	907000.0 (ft)
Z origin:	3250.0 (ft)
Length in X:	63600.0 (ft)
Length in Y:	47600.0 (ft)
Length in Z:	2000.0 (ft)
Rotation angle:	-25.0
AHGW X origin:	1321116.6292589 (ft)
AHGW Y origin:	950140.25066294 (ft)
AHGW Z origin:	5250.0 (ft)
AHGW Rotation angle:	115.0
Minimum scalar:	0.005446
Maximum scalar:	68.99177
Num cells i:	119
Num cells j:	159
Num cells k:	1
Number of nodes:	38400
Number of cells:	18921
No. Active cells:	5044
No. Inactive cells:	13877

Recharge Values

The recharge assigned to polygons representing recharge from precipitation and snowmelt in the hills, and that used to simulate bedrock groundwater inflow from the Scratchgravel Hills was applied in both steady-state and transient model versions at constant, steady-state rates.

Recharge for Silver Creek and its associated irrigation, HVID canal leakage, and HVID irrigation were assigned steady-state values in steady-state runs, but the same amounts of water were applied over a period of five months (May through September) in transient runs. The values were applied as listed in Table B2.

Table B2. Transient recharge values used for the North Hills groundwater models.

	Steady-State Recharge	Transient Recharge
Silver Creek	0.002 ft/d (8.77 in/yr)	0.00494 ft/d
HVID canal	0.0107 ft/d (46.90 in/yr)	0.0258 ft/d
HVID irrigation	0.004 ft.d (17.53 in/yr)	0.00987 ft/d

File Management

The original groundwater model files were developed on a local hard drive, and these are backed up in directory M:\Gwip\Projects\North Hills\GMS_Backups. The subdirectory names within this backup folder are the dates of the file backup. Within each subdirectory are subdirectories organized by model type. For each model type, one or more model series are present, along with numbered versions within each series. The GMS file names are structured like this: NorthHills_5pt25.gpr indictates the model series is 5 and the version is 25. The .gpr extension is the GMS version 7 file format. All associated files for this particular GMS version are in subdirectory with a similar name, followed by the word MODFLOW (Example: NorthHills_5pt25_MODFLOW). Table B3 shows the organization of folders in the model files directory, and the model series and versions within each folder.

Final Products

Listed below are the source series and versions used to create the indicated products provided on the CD and website for downloads. MODFLOW files were generated using the "Export Native MF2K text" function in GMS. These files were then converted to GW Vistas formats by importing the native MODFLOW MF2K files into GW Vistas with the Import-MODFLOW data set function, and saving the resulting *.gwv file.

Upon opening the main folder for any of the model files distributed, the GMS project file (filename.gpr) is provided, along with its same-name GMS MODFLOW folder (folder: filename_MODFLOW). Two other folders will are named MODFLOW_4GWV and MODFLOW_V_1_19_01. Folder MODFLOW_4GWV contains the Groundwater Vistas (filename.gwv) file with associated input and output files, and the MODFLOW_V_1_19_01 contains the operational MODFLOW name file (filename.nam) with associated input and output files. Large cell-by-cell flow and head-and- flow files generated in the output were removed from the dataset due to their large size. They will be regenerated when the model is run. These files were of the types *.ccf, cbb, and hff.

Table B3. North Hills groundwater model file organization.

Model	Directory	Series	Versions	Products
North Hills Borehole Analysis	\GMS_2	1	1pt1 through 1pt14	NorthHills_1pt14
North Hills Preliminary Area Model Concepts	\GMS_2	2, 3	2pt1 through 2pt11 3pt1 through 3pt13	N/A
North Hills Preliminary Area Model	\GMS_SS_1	4	4pt1 through 4pt6, 4pt11	NorthHills_4pt11_rev
North Hills Pediment Focus Model - SS	\GMS_SS_1	4,5,10	4pt7 through 4pt10 4pt12 through 4pt36 5pt1 through 5pt32 10pt4, 10pt7 through 10pt10	NorthHills_5pt32 (SS)
North Hills Pediment Focus Model TR	\GMS_TR_1	6,10	6pt1 through 6pt28 10pt1 through 10pt3, 10pt5,10pt6	NorthHills_6pt24 (TR_) (Sept 2005–Feb 2011) NorthHills_6pt30 (TR) (Sept 2005–Sept 2025)
North Hills Area Model	\GMS_SS_NHA	7,9	7pt1 through 7pt15 9pt5, 9pt7, 9pt8	NorthHills_7pt15 (SS)
North Hills Area Model	\GMS_TR_NHA	8,9	8pt1 through 8pt42 9pt1 through 9pt4, 9pt6	North Hills_8pt42 (TR) (Sept 2005–Feb 2011) NorthHills_9pt4 (TR) (Sept 2005–Sept 2025)

Note. SS, steady-state model; TR, transient model.

North Hills Pediment Focus Model—Steady-State Version

Generated from steady-state file NorthHills_5pt32.gpr
One stress period

NHPFMSS.gpr	GMS project file
NHPFMSS.nam	MODFLOW 2000 name file
NHPFMSS.gwv	Groundwater Vistas project file

Supporting files:
NHPFMSS_2006_PEST_calibr.csv calibration file used to run PEST
NHPFMSS_2006_obs_well_data.csv 2006 observation well data
NHPFMSS_2010_obs_well_data.csv 2010 observation well data

North Hills Pediment Focus Model—Transient Version

Generated from transient file NorthHills_6pt30.gpr
240 stress periods, representing calendar months from Sept. 2005 through Sept. 2025

NHPFMTR.gpr	GMS project file
NHPFMTR.nam	MODFLOW 2000 name file
NHPFMTR.gwv	Groundwater Vistas project file

Supporting files:
NHPFMTR_2006_2010_Obs_Wells.csv Sept. 2005–Feb. 2011 observation well sites
NHPFMTR_ Transient_swl_data Sept. 2005–Feb. 2011 observation well data

North Hills Area Model—Steady State Version

Generated from steady-state file NorthHills_7pt15.gpr
One stress period

NHAMSS.gpr	GMS project file
NHAMSS.nam	MODFLOW 2000 name file
NHAMSS.gwv	Groundwater Vistas project file

Supporting files:
NHAMSS_2006_PEST_Calibr.csv calibration file used to run PEST
NHAMSS_2006_obs_well_data 2006 observation well data
NHAMSS_2010_obs_well_data 2010 observation well data

North Hills Area Model—Transient Version

Generated from transient file NorthHills_9pt4.gpr
240 stress periods, representing calendar months from Sept. 2005 through Sept. 2025

NHAMTR.gpr	GMS project file
NHAMTR.nam	MODFLOW 2000 name file
NHAMTR.gwv	Groundwater Vistas project file

Supporting files:
NHAMTR_2006_2010_Obs_Wells Sept. 2005–Feb. 2011 observation well sites
NHAMTR_Transient_swl_data Sept. 2005–Feb. 2011 observation well data

Map Files—Projected in Montana NAD 1983 State Plane Coordinates:

24K_SP_NAD83_FT.sid: 1:24,000 scale USGS topographic map
100K_SP_NAD83_FT.sid: 1:100,000 scale USGS topographic map
NAIP_2009.tif: 2009 NAIP* color aerial imagery
NAIP2009CIR.tif: 2009 NAIP* color infrared aerial imagery

* NAIP—National Agricultural Imagery Program