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Montana Bureau of Mines and Geology Open-File Report 742

GROUNDWATER MODEL OF THE MEADOW VILLAGE AQUIFER AT BIG SKY, MONTANA

Kirk Waren, James Rose, and Ronald Breitmeyer

Ground Water Investigation Program

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ABSTRACT

Big Sky is a mountain resort community located in southwest Montana. Big Sky is currently undergoing a period of rapid population growth, leading to expected increase in demand on water resources. An area within Big Sky of particular concern is Meadow Village, which hosts mixed commercial and residential developments, open space, and a golf course. Meadow Village sources water from a productive, but aerially limited, unconsolidated and unconfined aquifer.

The Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP) developed calibrated numerical groundwater models of the Meadow Village aquifer (MVA) as part of a broader study of water resources of the Big Sky area. The models include a steady-state model representative of typical baseflow conditions expected in the aquifer and a transient model that reflects seasonal changes in pumping, recharge, and interactions between the groundwater system and the Middle Fork of the West Fork of the Gallatin River (referred to as Middle Fork). The transient model can be used to test various management and water-use scenarios.

The MVA groundwater model is an analysis tool that can be used for evaluating changes in the aquifer system in response to ongoing development and water resource stress changes in the area. Simulations of water use and growth scenarios specific to the GWIP study were conducted with the key objectives of assessing aquifer productivity with respect to the existing well field and potential changes to baseflow in the Middle Fork. Simulations indicated that high-intensity pumping of the MVA over short periods of time result in reductions in groundwater discharge to the Middle Fork and drawdown of groundwater levels below current public water supply well depths; these wells fully penetrate the alluvial aquifer. A second scenario included sustained increases of 25%, 50%, and 75% over current pumping rates. This resulted in a near 1:1 change in simulated groundwater discharge to the Middle Fork. The maximum simulated groundwater discharge to the Middle Fork accounted for approximately 20% of Middle Fork baseflow. Thus, our models show that increased utilization of the MVA should be expected to affect baseflow in the Middle Fork.

INTRODUCTION

Background

Big Sky is a ski resort community in the Madison Mountain Range of southwest Montana, about 40 mi south of Bozeman. Established in 1971, the resort now includes more than 78 mi^2 with 5,800 acres of skiable terrain. During the resort's first 25 yr, development was sporadic; however, since 2013 Big Sky experienced a 21 percent growth in full-time residents, the largest population growth rate in the State (Big Sky Chamber of Commerce, 2019). As of 2019, the resort has 3,000 full-time residents and a growing seasonal visitor population. During the 2017–2018 ski season the resort hosted more than 500,000 skiers, with capacity for many more. According to the 2019 Big Sky, Montana Economic Profile, summer visitations are also increasing (Big Sky Chamber of Commerce, 2019). With growth expected to continue, the community is searching for additional sources of groundwater to satisfy the anticipated demand.

The Meadow Village area of Big Sky hosts commercial development that includes boutique shops, restaurants, grocery stores, office space, lodging facilities, water and sewer treatment and distribution facilities, and medical and other first responder services. These commercial spaces provide the support infrastructure for the broader Big Sky resort. Additionally, the Meadow Village area hosts residences and the Meadow Village Golf Course.

Water demand fluctuates with the seasonal nature of resort activities and population. Monitoring records at the Big Sky Water and Sewer District (BSWSD), which operates the Meadow Village and Mountain Village water systems, show water consumption more than doubles between off seasons (March–May and September–October), and peaks in winter (November–April) and summer (June–August) seasons (Rose and Waren, in review). Summer irrigation of lawns and four golf courses adds to water demand. Irrigation water for the golf courses comes from a combination of groundwater and treated wastewater reuse. Irrigation of residential lawns is sourced from groundwater.

Big Sky relies solely on groundwater for its water supply. In 1993, the Upper Missouri River Basin Closure declared all surface water allocated in the watersheds of the Missouri River, which includes the West Fork of the Gallatin River at Big Sky. Surface-water development is limited, and public water supply (PWS) system growth must come from groundwater. The Meadow Village area relies on an aquifer hosted in unconsolidated alluvial and glacial outwash deposits for their water supply. For the purposes of this report, the aquifer is referred to as the Meadow Village aquifer (MVA).

Objectives

The Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP) developed a numerical groundwater model of the MVA as part of a broader study of water resources at the Big Sky, Montana Resort Area. Details of the project can be accessed through the GWIP portion of the MBMG website (mbmg.mtech.edu). The MVA groundwater model is an analysis tool that community stakeholders and water planners can use for evaluating changes in the aquifer system in response to ongoing development and water resource stress in the area. Results are presented from hypothetical simulations of the timing of water use and growth in water use specific to the study.

This report documents the MVA groundwater models that include the MODFLOW simulation input and output files. Details on model construction, operation, calibration, and analysis of sensitivity are provided for groundwater modelers who may utilize and/or modify the MODFLOW models to meet their needs. In the context of the GWIP study, the numerical model is used as a tool to refine the conceptual water budget for the Meadow Village area and evaluate the capacity of the MVA in response to current and hypothetical future uses.

AREA DESCRIPTION

Meadow Village is an approximately 1.7 mi^2, relatively flat-lying area at the lower elevations of the Middle Fork of the West Fork Gallatin River Basin (referred to as Middle Fork in this report; fig. 1). Meadow Village includes the Big Sky Golf Course, Town Center, businesses, residences, recreational features (e.g., hiking and biking trails), and supporting infrastructure (e.g., water/sewer treatment). Prior to development, the Meadow Village area was largely grassland, as evident in aerial photos from 1970 (fig. 2). The Big Sky Golf Course currently occupies much of the northern and central parts of the Meadow Village area (fig. 3).

The MVA lies largely beneath the Big Sky Golf Course and extends into adjacent areas. It is an unconfined aquifer composed of Quaternary-aged unconsolidated glacial outwash and modern alluvium. The MVA provides some of the best quality groundwater in the area and is a productive water supply source (Rose and Waren, in review).

BSWSD operates five municipal wells that draw water from the MVA. These wells are connected to a system that delivers water to all residences and businesses within the district, the extent of which is shown in figure 3. BSWSD has issued a moratorium on the drilling and use of privately owned domestic wells within the water and sewer district boundaries, with limited exceptions applying to older wells. The moratorium was established in 1971 within covenants that established the Meadow Village subdivision (Meabon, 1994). Thus, the presumption is that wells established prior to 1971 would be grandfathered in. However, no pre-1971 pumping wells are completed in the MVA, and since the MVA is wholly within the BSWSD, all pumping of the groundwater in the MVA is managed by the BSWSD. Most of the Meadow Village area is within the BSWSD, except for a small developed area along the southwest border of the BSWSD boundary shown in figure 3. Since this area is outside the BSWSD, any developments are not connected to community water supply or sewer systems and rely upon individual wells and septic tank systems for wastewater handling.

All residences and businesses within the BSWSD are connected to BSWSD’s sewer system. Wastewater conveyed by the sewer system is highly treated and stored in lined lagoons at the BSWSD sewer treatment plant to the east of the Big Sky Golf Course (fig. 3). During the growing season (typically when snow is clear from the ground in the period between March and September), the treated effluent is used to irrigate the Meadow Village, Spanish Peaks, and Yellowstone Club golf courses. Two pasture areas north of the Middle Fork are also periodically irrigated with the treated effluent. Additional detail on irrigation is provided below.

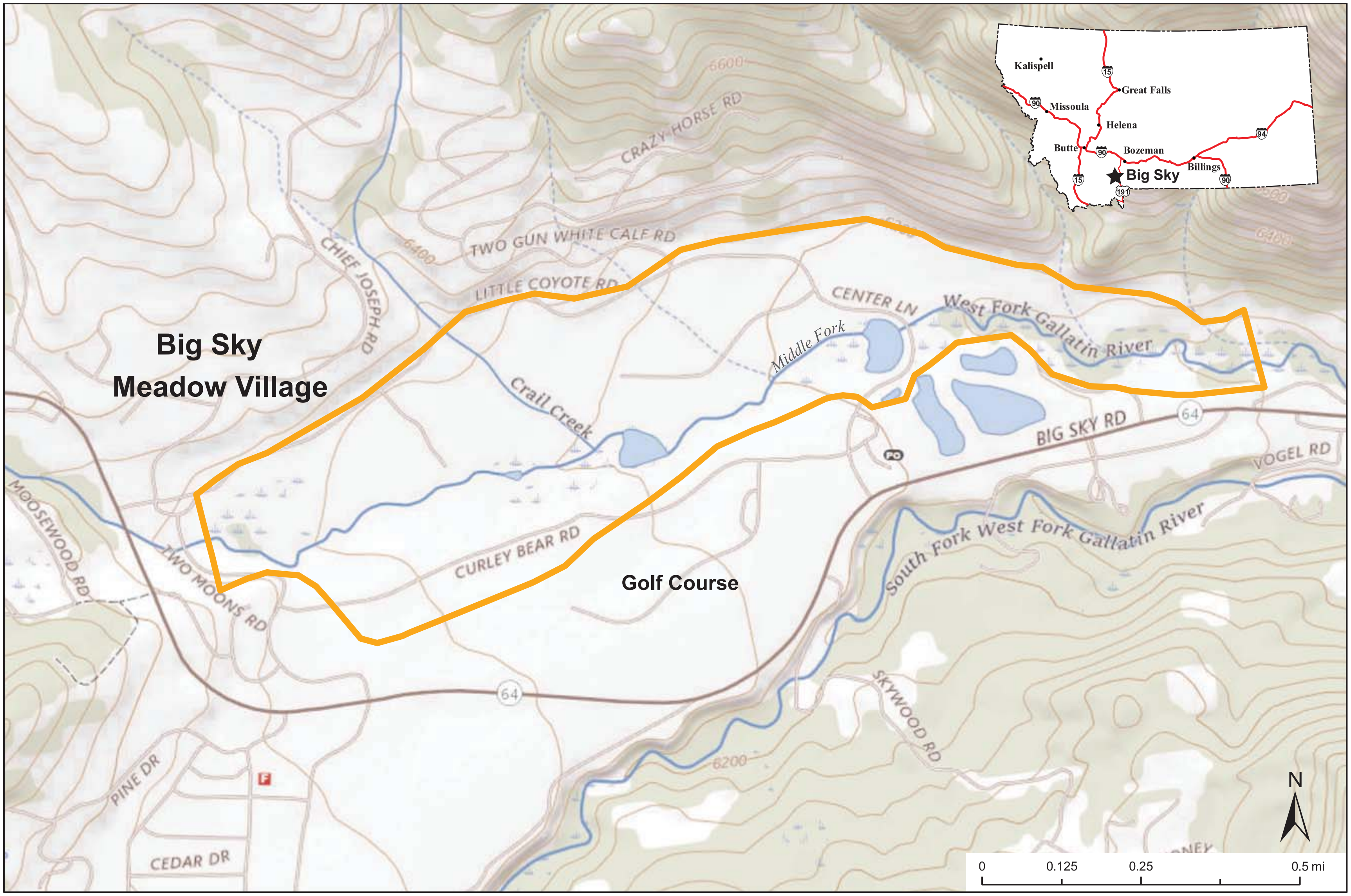


Figure 1. Topographic map of the Meadow Village area of Big Sky, Montana area with Meadow Village groundwater model domain boundary. Shown on the map are key tributaries (Crail Creek) to the Middle Fork of the West Fork of the Gallatin River (Middle Fork), location of the Meadow Village Golf course, and river crossings at Center Lane and State Highway 64.

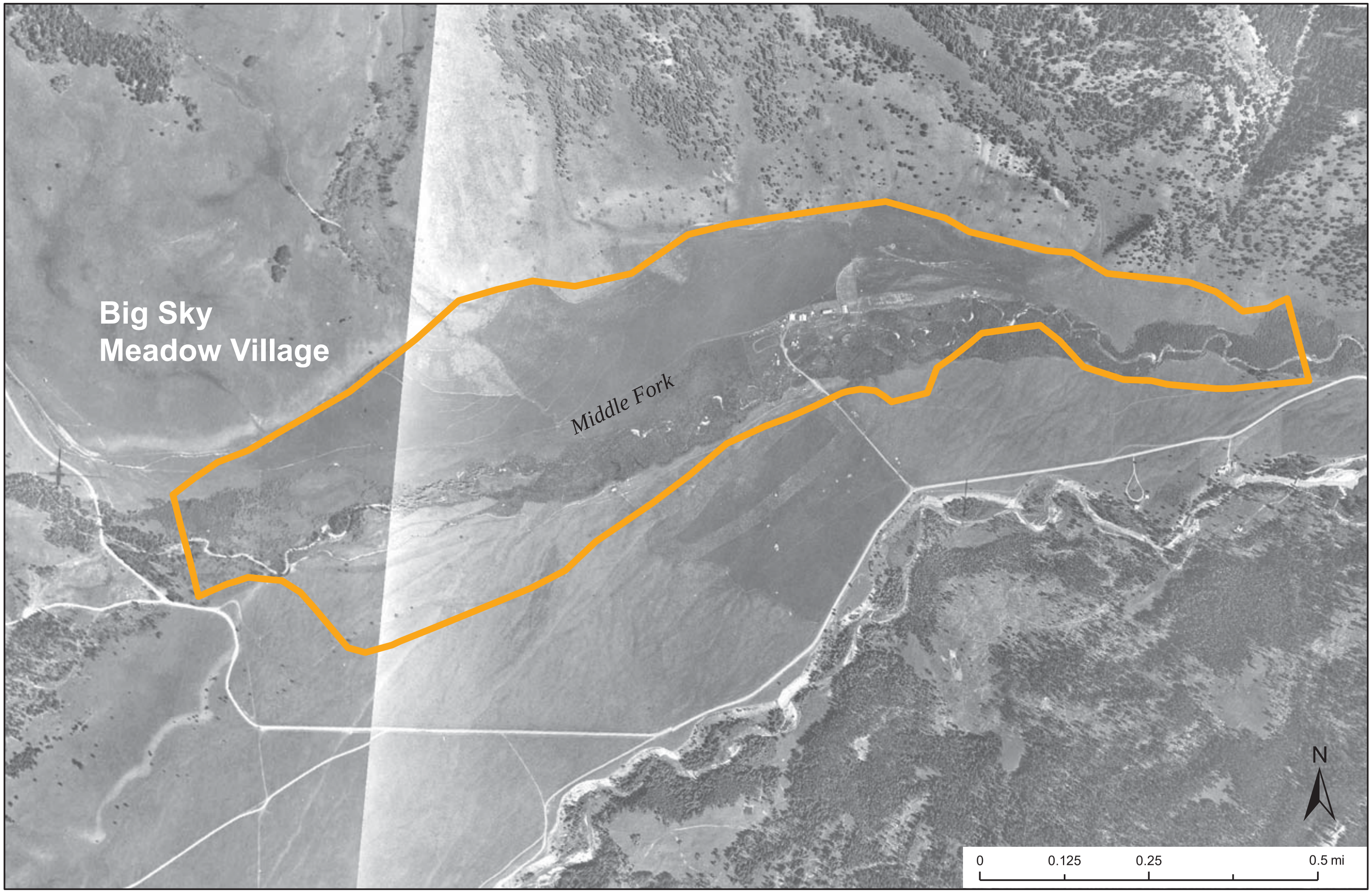


Figure 2. Aerial photograph of the Meadow Village Area circa 1970. Prior to development, the Meadow Village area was primarily characterized by meadow grasses and a riparian environment adjacent to the Middle Fork.

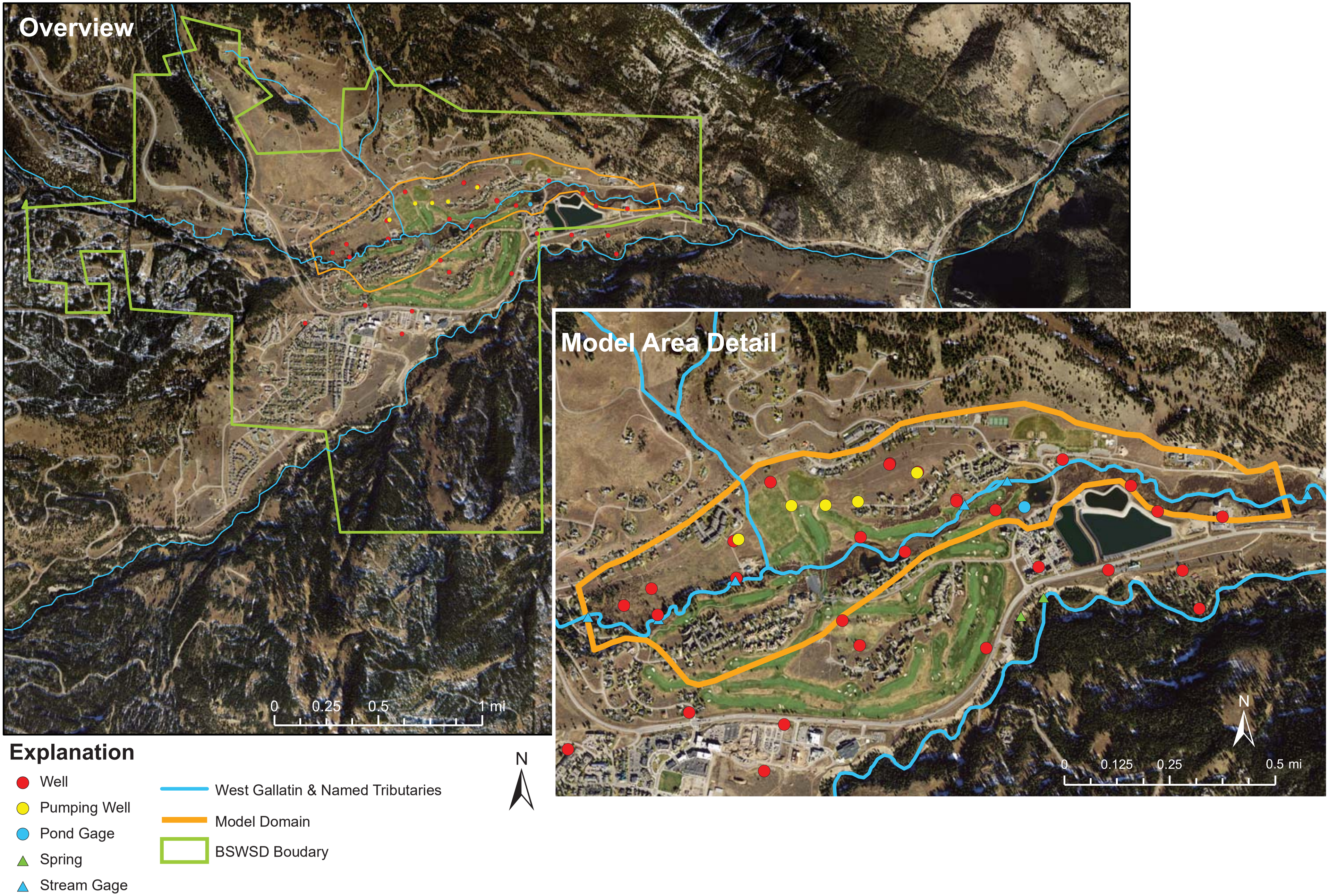


Figure 3. Modern aerial photograph of the Meadow Village area showing current state of development. Overview shows the BSWSD area (green outline). Model Area Detail shows Big Sky Golf Course and the BSWSD treatment ponds.

DATA COLLECTION METHODS

GWIP hydrogeologists collected data to support model development and calibration. These data included stream discharge in the Middle Fork, groundwater levels, pumping rates from water supply wells, irrigation rates from the Big Sky Golf Course, aquifer characteristics from aquifer tests, and meteorological parameters such as precipitation. These data are incorporated into the numerical model as calibration objectives (water levels), boundary conditions (irrigation, pumping, and meteorological inputs), and calibration constraints (aquifer characteristics from aquifer tests). Monitoring took place during 2014–2016. Additionally, GWIP installed 15 wells in the Meadow Village area to refine definition of the base of the Meadow Village aquifer. Included in the drilling were three pairs of nested wells for monitoring vertical hydraulic gradients.

Data Management

Data collected for the Big Sky area investigation and the Meadow Village groundwater model are stored in the MBMG's Ground Water Information Center (GWIC) database (mbmggwic.mtech.edu). GWIC contains information on well completions, groundwater levels, water chemistry, aquifer tests, surface water, and other information. GWIC identification numbers (GWIC IDs) reference locations and sites where data were collected for this report (i.e., referred to as well 275232 or for surface water as site 274333). The data for this study can also be accessed through the relevant project page within the GWIP section of the MBMG website (mbmg.mtech.edu).

Stream Discharge and Stage

Streamflow measurements were made at defined stations using the velocity-area method (Turnipseed and Sauer, 2010), with a Flowtracker™ current meter. Flows were gaged periodically (about monthly when the river was not frozen) during the study period at six locations along the Middle Fork (fig. 4) in the vicinity of Meadow Village (sites 275228, 282927, 275230, 282928, 275231, and 274333). Data logging pressure transducers were installed at each staff gage (discharge measurement point) to track stream stage every hour.

Groundwater Levels

Groundwater levels were monitored in the well network shown in figure 4. Unvented *in situ* RuggedTroll 100s or LevelTroll 300s and two Solinst transducers with specific conductivity (SC) sensors recorded hourly water levels. Two transducers recorded SC and were located in a shallow and a deep well over the duration of the study. SC values were comparable in shallow and deep groundwater. Barometric pressure transducers collected data used for correction of the unvented transducer measurements. Instrument readings were corrected for offset by adjusting transducer-measured levels to monthly hand measurements. Offsets may have occurred when pulling and replacing the transducers. Monthly surface-water-level measurements were collected and transducers were downloaded during each monthly measurement run. Drift of the loggers was not found to be a problem and therefore did not require correction. Water-level data were converted into elevations for preparation of potentiometric maps and utilization in the numerical model. Water-level elevations were calculated by differencing the water-level depth measurements from ground-level elevations obtained via LiDAR data (Gardner, 2012).

BSWSD Well Pumping Rates

Pumping data from public water supply (PWS) wells were obtained from BSWSD (Ron Edwards, General Manager, BSWSD, written commun., 2018). BSWSD monitors pumping rates from their supply wells using flowmeters. Hourly pumping data were compiled and totaled into daily and monthly summaries as necessary for the numerical simulations. The BSWSD PWS wells account for all pumping wells completed in the MVA.

Irrigation Rates

Irrigation in the Meadow Village area includes residential and commercial lawn and garden watering using groundwater supplied by BSWSD. Treated effluent from the BSWSD sewage treatment plant is used to irrigate the golf course and the two pasture areas north of the Middle Fork. Irrigation of the Big Sky Golf Course is not expected to significantly affect groundwater recharge since the irrigation rates (obtained from BSWSD) are carefully controlled to match evapotranspiration on the golf course such that there is a net zero water balance between irrigation and evapotranspiration. This has been verified by BSWSD, which uses lysimeters located on the golf course to track water-level changes during irrigation season.

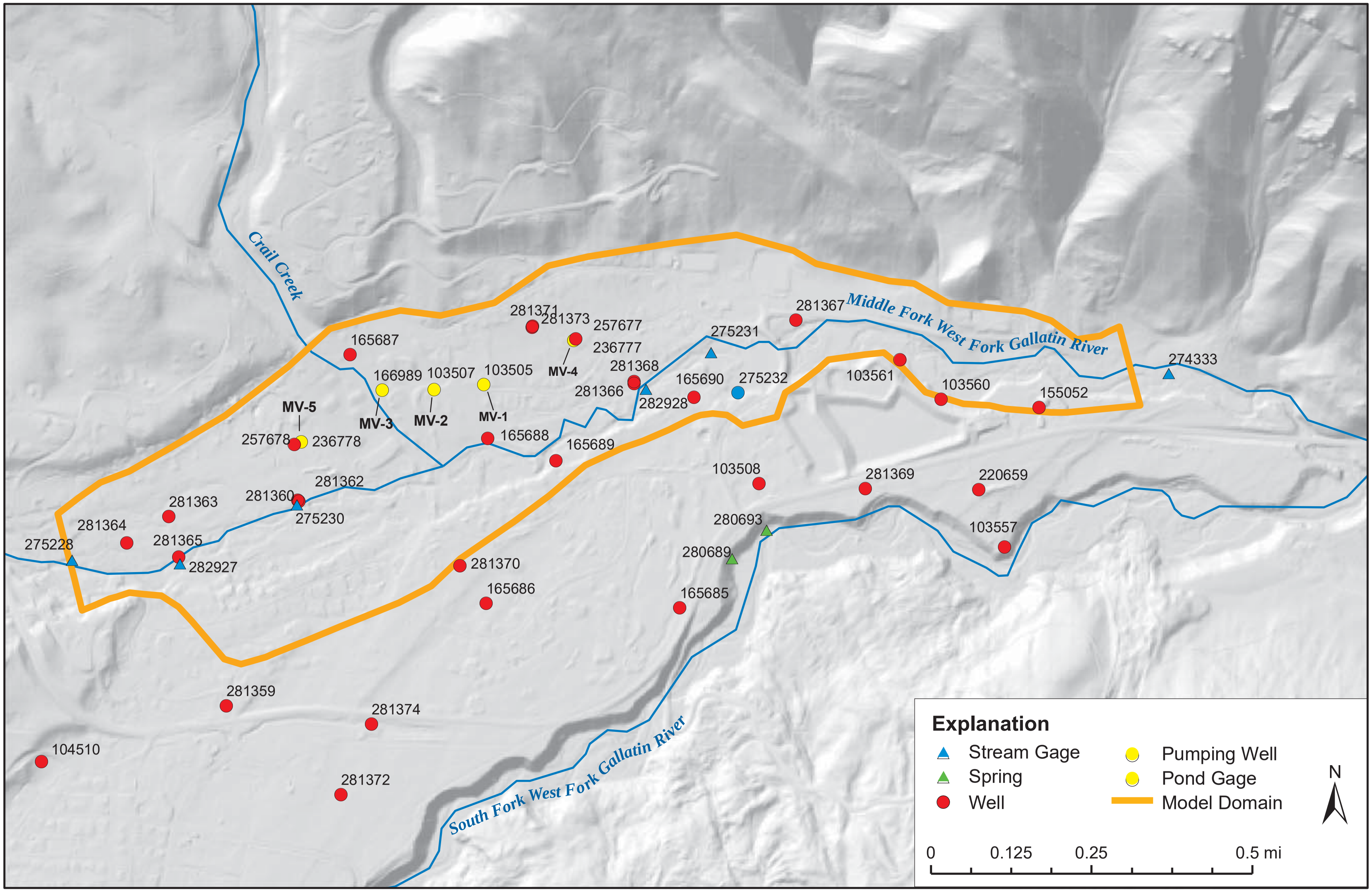


Figure 4. Map of monitoring sites in the Meadow Village area with GWIC identifiers.

Aquifer Characteristics

Aquifer test data for wells in Big Sky compiled from consultant's reports, literature, and DNRC records were matched to the appropriate GWIC numbers (table 1). A summary table of aquifer test analyses from Western Groundwater Services d.b.a. (WGS, 2002, 2008, 2015) provided transmissivity (T) and specific yield (S_y) values for the five BSWSD municipal pumping wells in the Meadow Village aquifer. GWIP personnel calculated hydraulic conductivity (K) using transmissivity and estimated saturated thickness from well logs available from GWIC.

Meteorological Inputs

Precipitation measurements for the lower elevations are recorded at the BSWSD weather station BS-STA01 (Ron Edwards, written commun., General Manager, BSWSD, 2014), located in Meadow Village at about 6,100 ft elevation. Big Sky 2WNW, located just west of Meadow Village, records weather data at 6,600 ft elevation (WRCC, 2016). Low-elevation (6,700 ft amsl) snowfall and snowmelt records were obtained from SNOTEL 924 in the Madison Mountain Range at West Yellowstone, 43 mi south of the study area (not shown on maps; SNOTEL 924, 2018). SNOTEL 924 is in the Madison Range. SNOTEL Site 590 at Lone Mountain, elevation 8,880 ft amsl, provided data for higher elevations (SNOTEL 590, 2018). Data from a Gallatin River Task Force (GRTF) sonic depth sensor also allowed for tracking of snow depth on the Middle Fork river ice near Meadow Village (Kristen Gardner, GRTF, written commun., 2018). For steady-state simulations, average daily precipitation was estimated from the meteorological records to apply to the single, daily stress period. For the transient simulations, daily summaries from the period of interest, 2014 to 2016, were used directly.

CONCEPTUAL MODEL

A conceptual model is a site-specific interpretation of the characteristics and dynamics of the physical system of interest. It includes descriptions of the geology and hydrology of the aquifer system, hydrologic boundaries, hydraulic properties, sources and sinks, and a water budget. The level of detail is driven by the available data (ASTM, 1995). The conceptual model for the MVA is developed by interpreting monitoring well data and surface-water gaging stations, and reviewing historical documents. Monitoring sites are shown in figure 4.

Geologic Framework

Figure 5 is a geologic map (after Vuke, 2013) of the Meadow Village area. Well logs available from the PWS wells, existing monitoring wells, and additional monitoring wells drilled for this study showed that the MVA consists of unconsolidated Quaternary glacial outwash and modern alluvial deposits that extend from the ground surface to a depth of up to 100 ft. Surface geological observations and interpretation of the PWS and monitoring well logs do not show occurrence of continuous deposits of glacial till or other potentially low-conductivity material in the Meadow Village area. The underlying Cretaceous age bedrock is dominated by shale of the Frontier Formation (fig. 5), which crops out along the South Fork south of the Big Sky Golf Course (see fig. 5). The unconsolidated glacial outwash and alluvial deposits form an asymmetrical system that is thicker on the north side of the valley and thins to the south.

Table 1. Aquifer characteristics obtained from aquifer tests at the Meadow Village public water supply wells.

GWIC ID	Sitename	Date of Test	Saturated Thickness (ft)[a]	T (ft^2/d)	Specfic Yield	K (ft/d)[b]
103505	Meadow Village #1	September 1999	39	5,903	0.037	151
103507	Meadow Village #2	September 1999	45	5,000	0.25	111
166989	Meadow Village #3	August 1999	34	5,000	0.25	147
236777	Meadow Village #4	December 2006	45.5	3,057	0.036	67
236778	Meadow Village #5	November 2006	40.7	4,124	0.028	101

[a] Obtained from well logs in GWIC database (total well depth minus static water level). Wells are assumed to be fully penetrating based on well log interpretation.

[b] Calculated as T divided by saturated thickness.

Note. Transmissivity (T), storativity, and specific yield taken directly from WGS (2008).

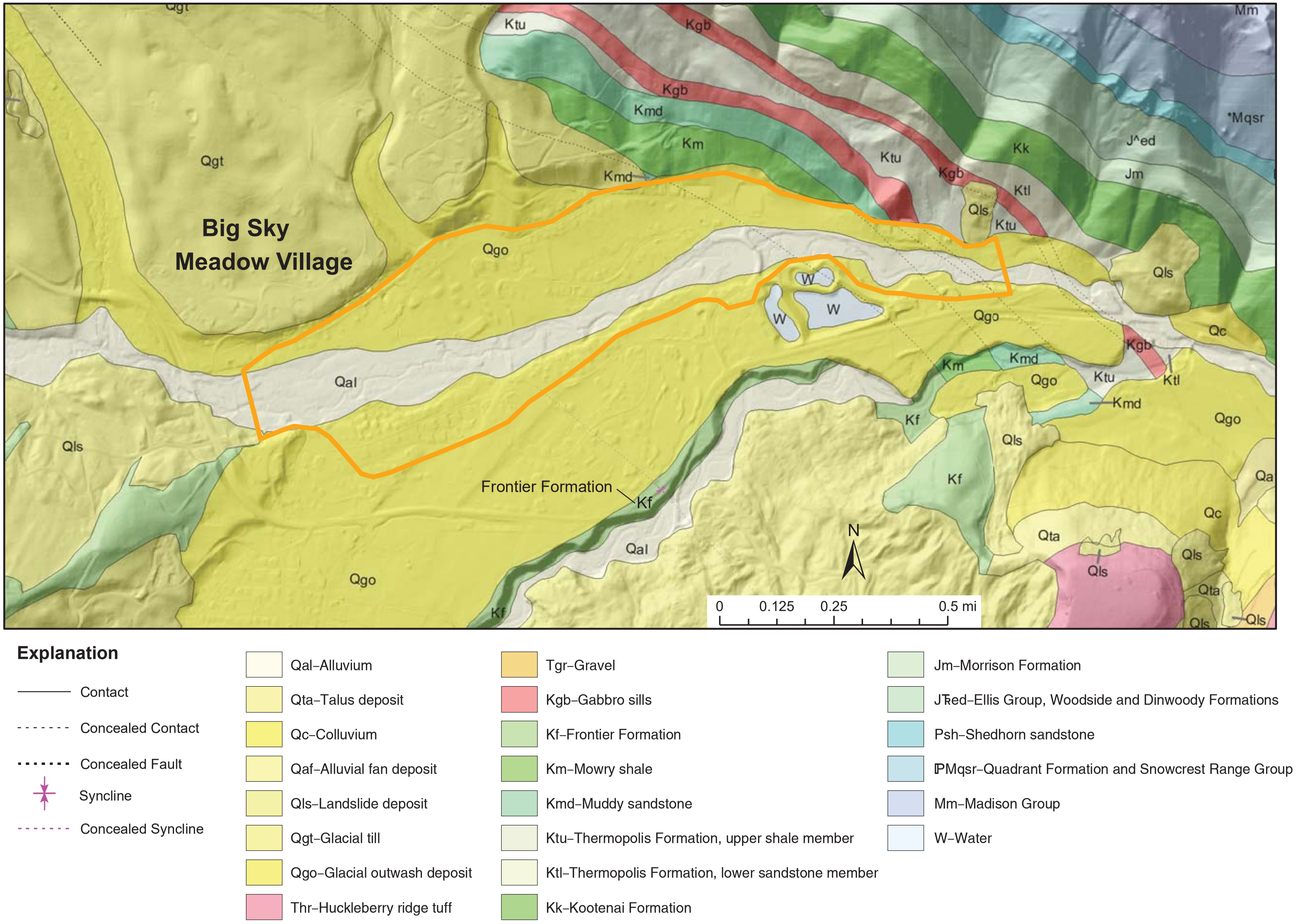


Figure 5. The surficial geology in the model area consists of alluvium along the Middle Fork (Qal) and glacial outwash (Qgo; from Vuke, 2013). Note the outcropping of the Frontier Formation south of the model domain.

Hydrogeological Setting

Climate

Big Sky is located in mountainous terrain where climate varies from continental-type climate areas at around 6,000 ft elevation to alpine-type climate above 11,000 ft. Meadow Village is located in the lower elevation, continental-type climate area that receives a 30-yr average of 20.5 in/yr precipitation (1967–2016; WRCC, 2016). Rainfall typically occurs in the spring and throughout the summer; snow is common from late fall through early spring. In 2013, precipitation was 20.4 in; in 2014, the site received 26.7 in, an annual high for the period of record (WRCC, 2016). Records for 2015 and 2016 are incomplete. SNOTEL 924 in West Yellowstone, at 6,700 ft, received 19.2 in of precipitation in 2013, 30.4 in. in 2014, 24.0 in. in 2015, and 26.2 in. in 2016. The 30-yr mean annual precipitation at West Yellowstone is 23.8 in (WRCC, 2016). Three of the four monitored years received above-average precipitation.

Meadow Village Aquifer

The MVA occurs in the Quaternary glacial outwash and modern alluvial deposits. This is an aerially limited, productive, unconfined aquifer. The MVA is considered unconfined and hydraulically connected across its entire thickness based on data from three pairs of nested monitoring wells that were installed for monitoring vertical hydraulic gradients as part of this study (Rose and Waren, in review). For all three pairs of nested wells, static water levels responded similarly to seasonal fluctuations and were comparable regardless of screen depth. The geological setting and observed water levels in local monitoring and PWS wells indicate the MVA is hydrologically interconnected with the Middle Fork. Therefore, for purposes of this study, we assume the aquifer and Middle Fork are hydrologically connected.

The underlying shale bedrock serves as a hydrologic boundary that isolates the alluvial aquifer from the deeper, confined, bedrock groundwater system. Glacial till and shale bedrock occur along the northern boundary of the aquifer. Based on observed lithology, these units are not expected to contribute much flow to the aquifer. At the southern edge of the aquifer, the underlying shale slopes upward toward the surface, such that the saturated zone thins and steepens to the south. The southernmost monitoring wells (e.g., wells 281359, 281374, and 281372 in fig. 4), drilled as part of this study, were completed at the bottom of the MVA at the bedrock contact. These wells showed seasonal saturation after recharge events, but generally dry conditions during other times. The maximum saturated thickness of the aquifer is between 40 and 50 ft depending on location (fig. 6).

Surface Waters

The Middle Fork enters the model domain boundary at the west end of the Meadow Village area (fig. 1). From there it flows eastward through the Big Sky Golf Course area. Portions of the stream appear to have been reconfigured in the golf course area. Below the bridge on Center Lane, the river flows in an apparently undisturbed, natural channel for about a mile before exiting the model boundary, turning south, and passing beneath State Route (SR) 64 (Big Sky Road; fig. 1). The confluence between the South Fork of the West Fork (South Fork) and the Middle Fork is a few hundred yards below the SR 64 bridge. Below this confluence, the river is referred to as the West Fork. Immediately below the SR 64 bridge, the Middle Fork flows on bedrock, and the alluvium is limited to bouldery areas adjacent to the channel. The West Fork flows into the Gallatin River about a mile east of the Middle Fork–South Fork confluence.

The Meadow Village Aquifer and the Middle Fork are interdependent according to Van Voast (1972). This is expected in this geologic setting, where there is no evidence of till or other low-conductivity material within the alluvial and outwash material lining the Middle Fork valley (fig. 5). Because of their interconnection, the stream and aquifer constitute a single water resource and withdrawals from one source affect water availability in the other. Based on the small size of the system, only 254 acres aerially and less than 50 ft of saturated thickness, pumping from the aquifer is expected to affect streamflows with only modest buffering by storage in the aquifer.

Streamflows in the Middle Fork across the MVA are available in the GWIC database for sites 274333, 275228, and 275230 (see fig. 4). Flow measurements ranged between 8 and 35 cfs with an average flow of 13 cfs for all measurements between 2013 and 2017. Excluding peak flow measurements (30 and 35 cfs in June 2016 for sites 275228 and 274333, respectively), the average flow in the Middle Fork is approximately

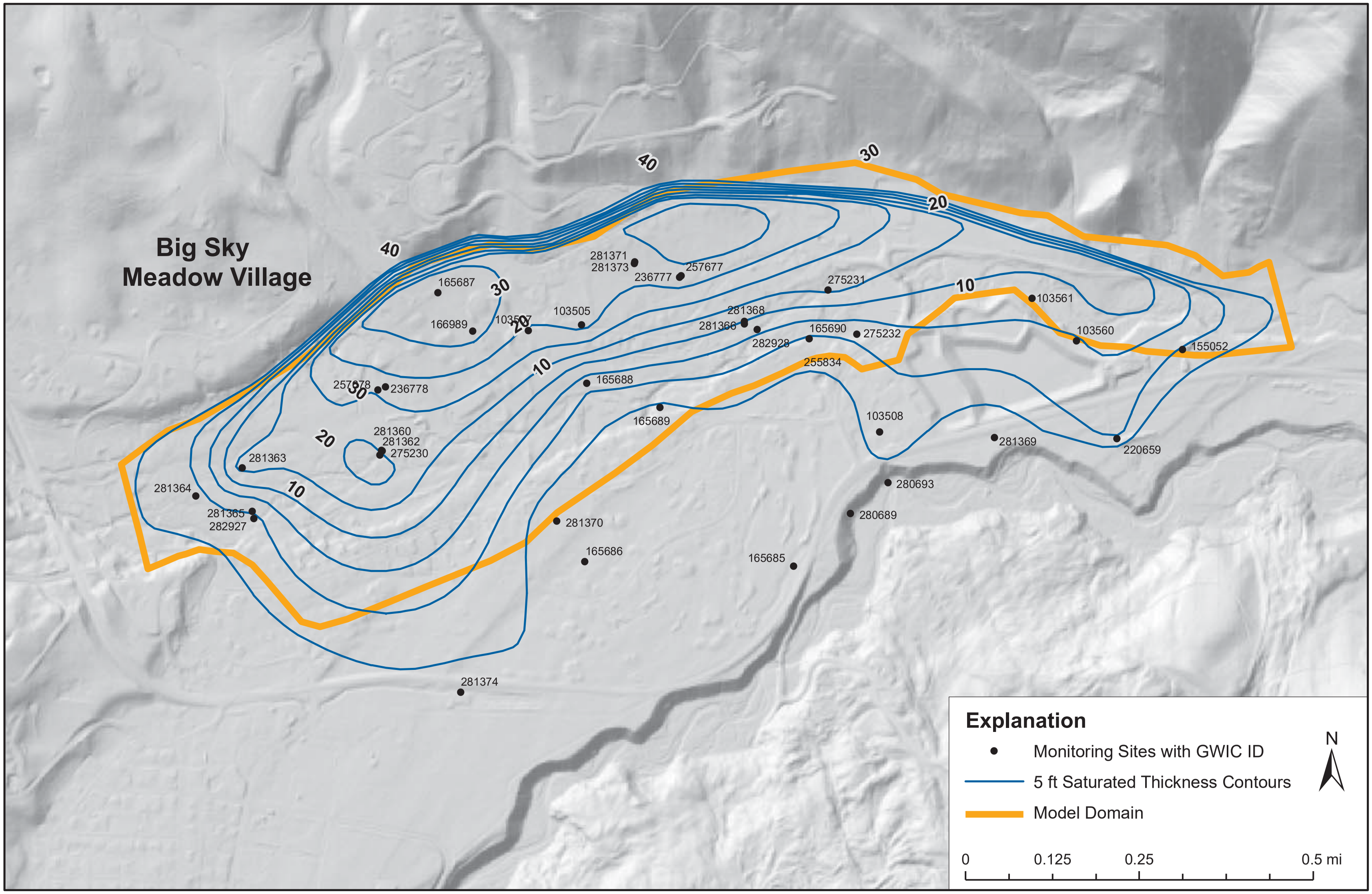


Figure 6. The saturated thicknesses contour map of the Meadow Village aquifer is based on interpolation of measured thickness of alluvium reduced by depth to water. The saturated thickness is greatest in the northern section of the model area near the mountains and thins in the upstream and downstream direction along the Middle Fork and toward the Southfork. The model domain includes aquifer where the thickness is at least 10 ft.

12 cfs. Peak flows generally occur over a brief period each year associated with runoff from snowmelt (Rose and Waren, in review). Therefore, the typical flow in the Middle Fork is better represented by the lower average of 12 cfs.

Groundwater Flow System

Potentiometric Surface

A water table elevation map (fig. 7) developed for the MVA based on February 12, 2016 groundwater elevations represents near base-level conditions. The map includes surface-water elevations at the west and east ends of the aquifer based on staff gage readings at sites 275228 and 271433 (see fig. 4). These sites are both in locations of relatively undisturbed alluvium, where groundwater is expected to be at about the same elevation as surface water. Water elevations at two wells near the southern edge of the area, 281372 and 281374, dropped below the level of the pressure transducers during annual low water periods. Water elevations in these wells were thus based on seasonal low levels measured with a sounder instead of transducer data.

The water table surface is generally similar to the ground surface topography sloping eastward along the course of the Middle Fork. The shale bedrock underlying the aquifer acts as a floor, restricting groundwater from downward or upward flow from the deeper bedrock aquifer system. Groundwater in the aquifer flows generally eastward, perpendicular to the contours (fig. 7).

Aquifer Properties

Transmissivities, hydraulic conductivities, and storage coefficients are available from aquifer test analysis for the five BSWSD municipal pumping wells (WGS, 2008). The BSWSD municipal wells in Meadow Village, MV-1 through MV-5 (fig. 4), have pumping rates between 100 and 250 gpm (table 2). The calculated K for the five wells (summarized in table 1) are consistent with K reported in the literature for glacial outwash aquifers (Fetter, 2010). Specific yield (S_y) values of 0.036 and 0.028 were calculated for the two aquifer tests with observation wells (MV-4 and MV-5, respectively).

As an independent check on S_y, we analyzed the response of wells to three recharge events: snowmelt in years 2015 and 2016, and one large rain event. The groundwater response was based on the relationship between the amount of recharge and the change in the volume of aquifer saturated:

$$S_y = V_d/V_t,$$

where S_y is specific yield, V_d is volume drained, and V_t is total volume of a soil or rock sample (Heath, 1983). This formula was applied using an estimated recharge (tables 3, 4) and the corresponding response in each well by considering the estimated recharge the "volume drained," even though it is actually a volume saturated, and considering the response representative of the total volume affected. Using well 281363 as an example:

Snow (2015): S_y = 0.23 ft (estimated recharge)/4.01 ft (response) = 0.057

Rain: S_y = 0.0275 ft (estimated recharge)/0.81 ft (response) = 0.034

The S_y calculated by these means were about the same order of magnitude as those derived from the aquifer test data. The snowmelt-based S_y ranged from 0.028 to 0.26 (median of 0.059), and the rain-event-based S_y ranged from 0.015 to 0.12 (median of 0.059). These values are consistent with reported S_y for a silty or fine-sand unconsolidated aquifer (Dingman, 2002; Fetter, 2010).

Table 2. Meadow Village municipal wells depth and pumping rate information.

BSWSD Well Name	GWIC ID	Depth (ft)	Pumping Rate (gpm)[a]
MV-1	103505	50	250
MV-2	103507	59	200
MV-3	166989	67	100
MV-4	236777	56	220
MV-5	236778	57	220

[a] Pumping rates obtained via personal communication between Kirk Waren and Ron Edwards (2018—specific date unknown).

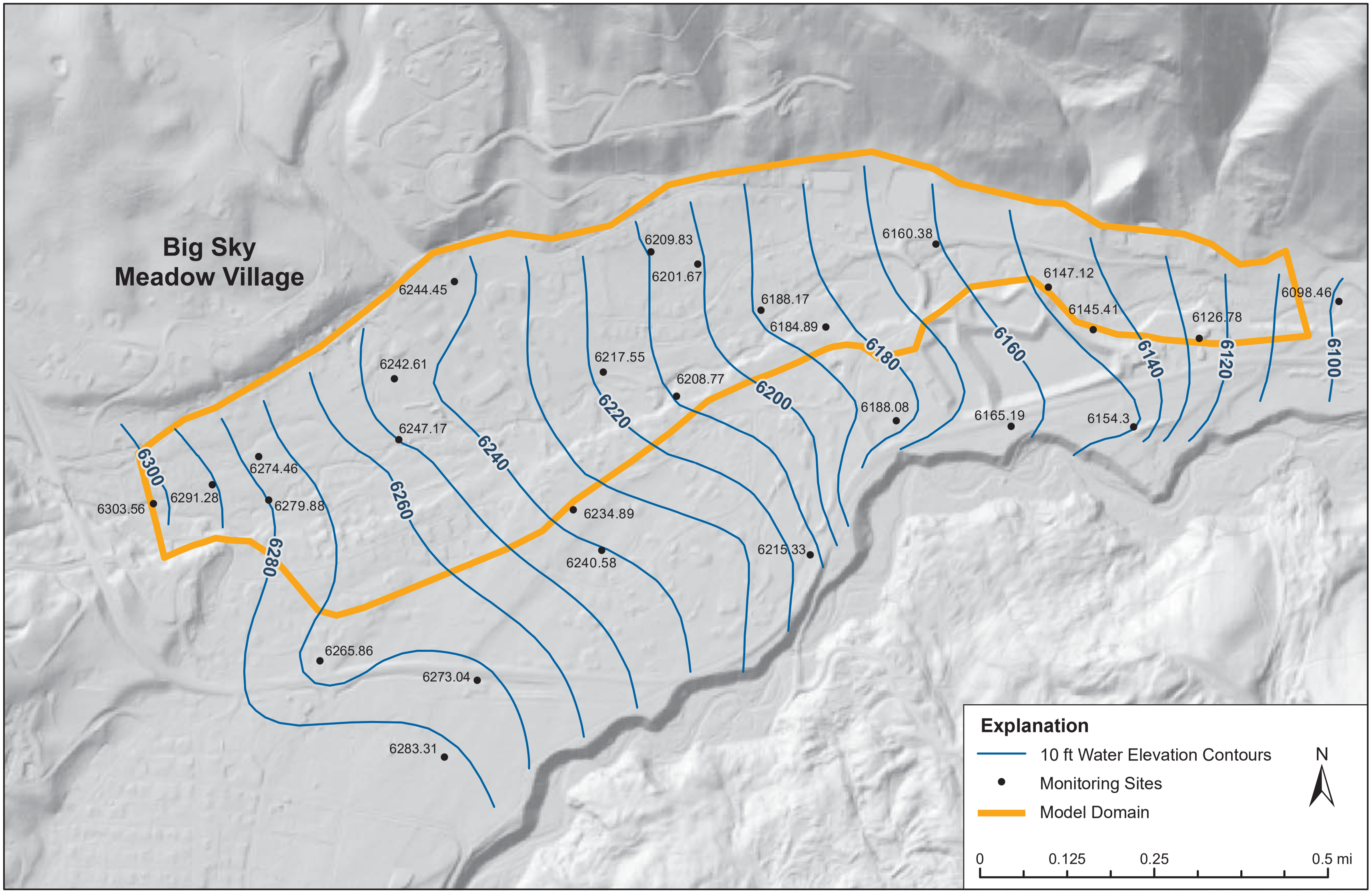


Figure 7. Contour map of the Meadow Village aquifer potentiometric surface based on water levels form February 12, 2016. Contour interval is 10 ft. Water flows perpendicular to potentiometric contours (generally west to east) consistent with flow direction of the Middle Fork.

Table 3. Recharge estimates for rain events from March 2015–September 2016.

Date	Recharge (in)	Recharge (ft)
03/25/15	0.06	0.01
04/25/15	0.04	0.00
04/30/15	0.00	0.00
05/05/15	0.02	0.00
05/07/15	0.04	0.00
05/12/15	0.13	0.01
05/15/15	0.02	0.00
05/16/15	0.58	0.05
05/25/15	0.06	0.01
05/30/15	0.00	0.00
06/10/15	0.00	0.00
07/05/15	0.00	0.00
07/23/15	0.27	0.02
07/27/15	0.61	0.05
08/08/15	0.34	0.03
08/12/15	0.04	0.00
09/15/15	0.10	0.01
09/16/15	0.81	0.07
10/20/15	0.01	0.00
10/26/15	0.01	0.00
2015 total	**3.14**	**0.26**
04/14/16	0.03	0.00
04/23/16	0.01	0.00
05/09/16	0.05	0.00
05/15/16	0.08	0.01
05/19/16	0.01	0.00
05/20/16	0.10	0.01
05/27/16	0.07	0.01
06/15/16	0.10	0.01
06/16/16	0.02	0.00
07/10/16	0.24	0.02
09/04/16	0.06	0.00
09/21/16	0.17	0.01
09/22/16	0.11	0.01
2016 total	**1.04**	**0.09**

GROUNDWATER BUDGET

A groundwater budget based on field measurements collected by GWIP personnel between 2014 and 2016 and/or published and proprietary data (WGS, 2008; WRCC, 2016; Ron Edwards, General Manager, BSWSD, written commun., 2018; Kristen Gardner, GRTF, written commun., 2018; Rose and Waren, in review) was developed for the MVA. The groundwater budget establishes an initial, quantitative estimate of water fluxes in the groundwater system being modeled. The water budget serves as a tool to evaluate the numerical groundwater model. Since the MVA serves as the control volume for the water budget, inflows refer to flow into the aquifer, and outflows refer to flow out of the aquifer.

For the purposes of groundwater modeling and water budgeting, hydrologic boundaries where water flows into the modeled groundwater system are considered sources and boundaries that represent flow out of the groundwater system are considered sinks. The Middle Fork acts as a source or sink depending on relative elevations of the groundwater surface and river stage; the gaining or losing nature of the river can vary over space and time. These fluctuations cannot typically be captured in a monthly water budget but can be captured in the models. Other hydrologic boundaries include the five BSWSD municipal wells (sinks), groundwater inflow from upgradient areas of the aquifer (source), and groundwater outflow to downgradient alluvium (sink). There is also some groundwater discharge (sink) to small springs in the area.

An atmospheric boundary exists at the ground surface and includes sources and sinks. At the atmospheric boundary, precipitation (snowmelt and large rainfall events) serves as a source of aquifer recharge. Evapotranspiration by riparian vegetation and from ponds is a sink. Irrigation of the golf course occurs at the atmospheric boundary. However, golf course irrigation should normally not be recharging the MVA due to the deliberate efforts to not overirrigate; therefore, golf course irrigation is not considered as a hydrologic boundary in this conceptual model.

Groundwater Budget Components

The groundwater budget for the MVA can be represented as a mass balance equation where inflows (sources) = outflows (sinks) ± changes in storage. Broken down into components relevant to the Meadow

Table 4. Precipitation recharge fractions.

Precipitation (in)	Precipitation Exceeding 0.5 in	Precipitation between 0.2 and 0.5 in (within the Range of Threshold Values)	Half of the Precipitation between 0.2 and 0.5 in	Calculated Recharge: Sum of Exceeding 0.5 in, and Half of that in the Threshold Range (0.2 to 0.5 in)	Fraction of Precipitation Allocated to Recharge
0.1	0	0	0	0	0.00
0.2	0	0	0	0	0.00
0.3	0	0.1	0.05	0.05	0.17
0.4	0	0.2	0.1	0.1	0.25
0.5	0	0.3	0.15	0.15	0.30
0.6	0.1	0.3	0.15	0.25	0.42
0.7	0.2	0.3	0.15	0.35	0.50
0.8	0.3	0.3	0.15	0.45	0.56
0.9	0.4	0.3	0.15	0.55	0.61
1.0	0.5	0.3	0.15	0.65	0.65
1.1	0.6	0.3	0.15	0.75	0.68
1.2	0.7	0.3	0.15	0.85	0.71

Note. Only five precipitation events in 2015 and 2016 exceeded a calculated recharge of 0.25 in. All but nine calculated recharge values were less than 0.10 in (table 2).

Village aquifer, the resulting mass balance equation is:

$$SW_{in} + GW_{al\text{-}in} + R + GW_{lat\text{-}in} = SW_{out} + GW_{al\text{-}out} + PW + ET + SPR \pm \Delta S,$$

where SW_{in} is surface-water inflow to the aquifer; $GW_{al\text{-}in}$ is groundwater inflow through the aquifer at the upgradient end of the model area; R is recharge from snowmelt and precipitation; $GW_{lat\text{-}in}$ is lateral groundwater inflow from south and north of the model area; SW_{out} is groundwater outflow to the Middle Fork; $GW_{al\text{-}out}$ is groundwater outflow through the aquifer at the downgradient end of the model area; PW is pumping wells; ET is riparian evapotranspiration; SPR is discharge to springs; and ΔS is changes in storage.

The rates and volumes for this groundwater budget are based on the 254-acre groundwater model domain (fig. 1). Estimates for each component in the water budget are described below, and are summarized in table 5. Daily flows in and out of the aquifer were calculated by distributing average annual conditions over the appropriate number of days in the study period (2014–2016).

Surface-Water Inflow (SW_{in})

Surface-water inflow describes inflow to the aquifer from the Middle Fork and is based on field measurements. Increases in streamflow between sites 275228 and 274333 (measurements available in the GWIC database) show that the MVA typically discharges water to the Middle Fork at a flow rate of between 1 and 5 cfs. This is a net streamflow increase from the upstream end to the downstream end of the model area (see fig. 4). Within the model area, flow measurements at individual sites between sites 275228 and 2743333 (see fig. 4) indicate that modest net streamflow gains or losses occur along individual, shorter reaches of the Middle Fork within the model area. However, the overall measured streamflow gains (i.e., outflow from the MVA) exceeded measured losses, indicating that over the entire study area, the stream was gaining groundwater from the MVA. The net gains and losses calculated between stations during baseflow conditions were near or below the measurement error for surface-water measurements, suggesting that these gains and losses are likely small enough to be negligible to the overall water budget. Therefore we estimated river loss to the aquifer, or SW_{in}, as zero in the analytical groundwater budget calculation. The numerical MODFLOW model calculates this component of the water budget as a model output.

Alluvial Groundwater Inflow ($GW_{al\text{-}in}$)

Groundwater inflow from the upstream alluvium was estimated using Darcy's Law (Fetter, 2010):

$$Q = -KA(dh/dl),$$

where: Q is total flow (ft^3/d); K is hydraulic conductivity (ft/d); A is cross-sectional area perpendicular to flow (ft^2); and dh/dl is groundwater gradient (dimensionless, or ft/ft).

Table 5. Conceptual model average annual groundwater budget.

Sources	ft^3/d	acre-ft/yr
Surface-water inflow (net)	0	0
Alluvial aquifer inflow[a]	38,556	323
Recharge from snowmelt and precipitation	13,459	113
Lateral groundwater inflow[b]	22,999	193
Total (sources)	**75,014**	**629**
Sinks		
Surface-water outflow	26,447	222
Alluvial aquifer outflow[a]	7,854	66
Pumping wells	31,738	266
Riparian evapotranspiration	8,975[c]	75
Discharge to springs	(unquantified)	
Changes in storage	(assumed to be zero)	
Total (sinks)	**75,014**	**629**

[a] Alluvial aquifer inflow/outflow are flow into and out of the MVA at west and eastern model boundaries.

[b] Lateral groundwater inflow is flow into the MVA along the southern model boundary and the narrow area adjacent to Crail Creek along the northern boundary.

[c] Since this is an annualized budget, daily ET rate is calculated as the annual total divided over 365 days. Several months of the year likely have little to no ET and the annual total of 75 acre-ft would be concentrated over a shorter period of time. The daily ET rate would therefore be higher during this period of time.

Note. Surface-water outflow is calculated to balance the outflows with inflows.

Using high (151 ft/d) and low (67 ft/d) bounds on K established from aquifer tests for the five BSWSD municipal wells (see table 1), an estimated saturated alluvial thickness of 10 ft (estimated from the average distance between the water table and underlying shale contact at the western edge of the model domain), and a hydraulic gradient of 0.0238 (calculated from the potentiometric surface, e.g., fig. 7), the groundwater inflow across the 1,620 ft upgradient end of the model area is estimated to be between 25,832 and 58,220 ft^3/d (0.30 to 0.67 cfs). For modeling purposes, an initial, uniform K was applied across the model domain. This initial K was then adjusted during automated calibration. A K of 100 ft/d was used for model initialization. This is consistent with calculated K values for the MVA (table 1) and literature values for a sandy aquifer composed of glacial outwash (Fetter, 2010). Using an initial K = 100 ft/d results in a flow of 38,556 ft^3/d (0.4 cfs) across this boundary.

Recharge (R)

Recharge estimates applied a simple mathematic treatment to meteorological data based on how water levels in instrumented wells responded to snowmelt and precipitation events (tables 3, 4). Threshold values of daily precipitation were defined for the MVA by identifying the minimum amount of daily precipitation necessary to generate a water-level signal change in groundwater. The threshold values for different sites generally ranged from 0.2 to 0.5 in of daily precipitation. Based on this analysis, any precipitation less than 0.2 in/d is assumed to result in zero recharge, since water levels in wells typically showed no response to events this size or smaller. Precipitation from these small events is likely confined to vadose zone storage or consumed by evapotranspiration prior to reaching groundwater. Half of precipitation between 0.2 and 0.5 in was estimated to contribute to recharge, since some wells responded to rainfall events in this range while others did not. Water levels in all wells responded to rain events over 0.5 in, which indicates that all events of this size contribute to recharge. The simplifying assumption is made that all precipitation above 0.5 in was considered recharge.

For rain amounts between 0.2 and 0.5 in, non-zero recharge estimates using this method fall within 5% and 30%, consistent with typical percentages found in literature (Healy, 2010). This suggests that for at least the smaller rainfall events in the study area, this recharge estimation method is comparable to that presented in the literature. The largest rain event observed during this study was 1.16 in, on September 16, 2015. The calculated recharge from that event (0.81 in) was nearly 70 percent of precipitation, which is higher than typical percentages found in the literature. Thus, for the highest rainfall events, this method likely overpredicts recharge from rainfall. The total calculated recharge from rain events in 2015 was 3.14 in and 1.04 in. in 2016 (table 3), which is approximately 18% and 9%, respectively, of total precipitation for those years. The average total annual recharge over the 2 yr was 0.17 ft (2.1 in). The model area is 254 acres, so the average annual recharge from rain was calculated to be approximately 1,881,000 ft^3. Although this method is an approximation, the estimated recharge rates resulted in reasonable model calibration (i.e., the calibrated K obtained with the resulting recharge is within expected ranges for this aquifer).

Major snowmelt events also supply recharge. Snow accumulation and melt were quantified for 2015 and 2016 using weather station data and the GRTF sonic data. Eighty percent of the melted snow water equivalent was estimated to be recharge. This high proportion of snowmelt to recharge was based on observation of well hydrographs that showed a large-magnitude response during snowmelt period. The amount of recharge applied from snowmelt resulted in satisfactory calibration of the model and therefore is assumed to be a reasonable estimate. Periods of snow accumulation were 11/10/2014–3/17/2015, and 11/6/2015–4/9/2016. Periods of snowmelt were short, on the order of several days during each year: 3/10/2015–3/17/2015 and 4/2/2016–4/9/2016. The estimated recharge amounts from the two major snowmelt events over the model area were 0.23 ft in 2015 and 0.31 ft in 2016. The average annual value was 0.27 ft/yr, which generates approximately 2,987,000 ft^3/yr (on average about 8,000 ft^3/d) over the 254-acre model area. Snow and rain together generate about 4,868,000 ft^3 of recharge annually (on average about 13,000 ft^3/d).

Lateral Groundwater Inflow ($GW_{lat\text{-}in}$)

About 436 acres of land south of the model area has the potential to transmit groundwater northward toward the model area. The estimated inflow was calculated by applying an estimated annual recharge of 0.00111 ft/d over the 436 acres. This recharge was then assumed to flow across the southern model boundary, resulting in an annual inflow of 7,695,000 ft^3 or approximately 21,000 ft^3/d.

Groundwater was present periodically in shallow well 165687 at the north edge of the model where the Crail Creek enters the area. This suggested that some water enters from Crail Creek or alluvium in the Crail Creek drainage. Therefore, a modest flux of 10 gpm (1,925 ft^3/d) was assumed to flow into the model along a short arc spanning the width of the Crail Creek alluvium. This flow was assumed because flows in Crail Creek were too small to be practically measured.

Surface-Water Outflow (SW_{out})

Stream discharge measurements indicated that stream losses or gains in the model area are expected to be in the range of single digits of flow (between 0 and 5 cfs; see section “Surface-Water Inflow”) and are often within expected measurement error of the discharge measurement methods. Flow from the MVA to the Middle Fork was not measurable at the accuracy of the measurement methods and therefore was estimated using a water balance calculation. Net stream gains are estimated for a monthly groundwater budget discussed at the end of this section.

Alluvial Groundwater Outflow ($GW_{al\text{-}out}$)

Darcy’s Law was used to estimate alluvial groundwater outflow. Using high and low K (151 ft/d and 67 ft/d, respectively; see table 1) from the five BSWSD municipal wells aquifer tests, an estimated saturated alluvial thickness of 5 ft, and a hydraulic gradient of 0.0238, the groundwater outflow across the 660-ft-long downgradient model boundary was estimated to be between 5,262 and 11,860 ft^3/d (0.06 to 0.14 cfs). Using an initial K of 100 ft/d, flow was calculated at 7,854 ft^3/d (0.09 cfs). The alluvial thickness of 5 ft is based on aquifer thickness and water levels at the east (downgradient) end of the MVA.

Pumping Wells (PW)

BSWSD provided pumping records for their municipal wells. Pumping rates reported for these wells are summarized in table 2. The pumping data were provided in 6-min increments, for years 2015 and 2016. From this information, daily and monthly pumping volumes were extracted (fig. 8). According to the data provided, the wells pumped a total of 77,360,640 gallons in 2015, and 95,941,860 gallons in 2016. The average annual pumping was 86,651,250 gallons (11,584,392 ft^3/yr; 31,738 ft^3/d).

Riparian Evapotranspiration (ET)

A variety of phreatic trees and bushes grow in the vicinity of Middle Fork and its floodplain, covering an estimated 47 acres. Butler and Bobst (2017), using cited literature sources, estimate a riparian vegetation evapotranspiration (ET) rate of 28 in per year in the Boulder Valley, about 60 mi from the MVA. This ET rate is based on areas at lower elevations and with longer growing seasons than the Meadow Village area. Therefore, we assumed 2/3 of the 28 in per year (~19 in) to calculate an annual ET of 3,276,000 ft^3 (on average 8,975 ft^3/d). Over a 100-d growing season this equates to 32,276 ft^3/d.

Discharge to Springs (SPR)

There are some small springs and drains in the golf course area that deliver nominal amounts of water to the Middle Fork. These flows were less than 5 gpm and too small to measure. These were treated as a component of surface-water outflow.

Changes in Storage (ΔS)

Changes in the amount of groundwater storage occurred due to large recharge events (annual snowmelt and heavy rain events), but typically groundwater levels returned to baseline conditions within a week or two. Higher summer pumping rates cause localized drawdown in the aquifer, which also recovered rapidly once pumping returned to lower rates. Thus, in terms of an overall annual water budget, changes in storage are assumed to be zero.

Transient Groundwater Budget

Daily and monthly water budget datasets were developed for input into daily and monthly versions of the transient model. A monthly transient water budget was constructed where the net streamflow gains (or losses, where negative) were calculated as the differ-

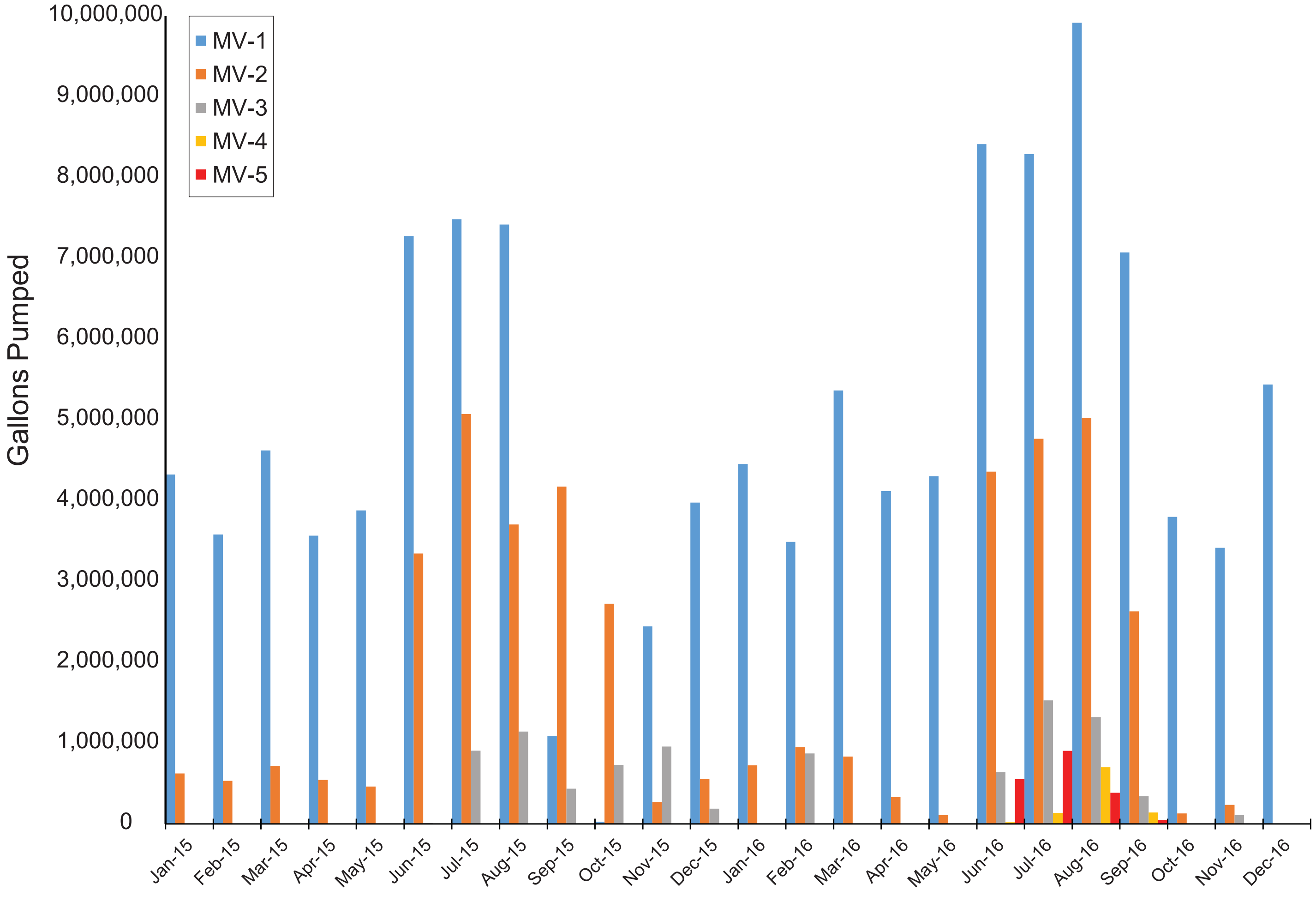


Figure 8. Graph of daily volume (gallons) compiled from pumping data from BSWSD water supply wells. The highest pumping occurred in well MV-1.

ence between the other inflows and outflows (fig. 9, table 6) to and from the MVA. This calculation assumes that aquifer storage plays no significant role in the monthly groundwater budget.

NUMERICAL MODEL CONSTRUCTION

Development of the Meadow Village groundwater model included preparation of both steady-state and transient groundwater models. The steady-state model was based on late winter conditions (February 2016) when the area was approaching a quasi-steady-state. The transient model is based on calendar years 2015 and 2016, corresponding to when most wells and stream sites were instrumented with pressure transducers (fig. 4). The steady-state model can be used to test the effect of a new or ongoing stress to the overall system. The transient models were used to evaluate how the pumping of municipal wells influences net stream gains and losses.

Software Description

We used the U.S. Geological Survey (USGS) MODFLOW code, version 1.19.01 (Harbaugh and others, 2000) with Groundwater Modeling System software (GMS version 14.01; Aquaveo, 2014) as a graphical user interface. GMS facilitates the use of maps, images, and geographical information systems (GIS) products for groundwater modeling. Parameter Estimation software (PEST) was used for automated model calibration in certain model runs. PEST is a general-purpose parameter estimation program (Doherty and others, 2010; version 14.01).

Model Domain

The lateral extent of the model domain was defined by tracing the portion of the Meadow Village alluvium with a minimum saturated thickness between 5 ft and 10 ft (fig. 6). The majority of areas with a saturated thickness less than 5 ft were excluded from the model domain because these areas represent a

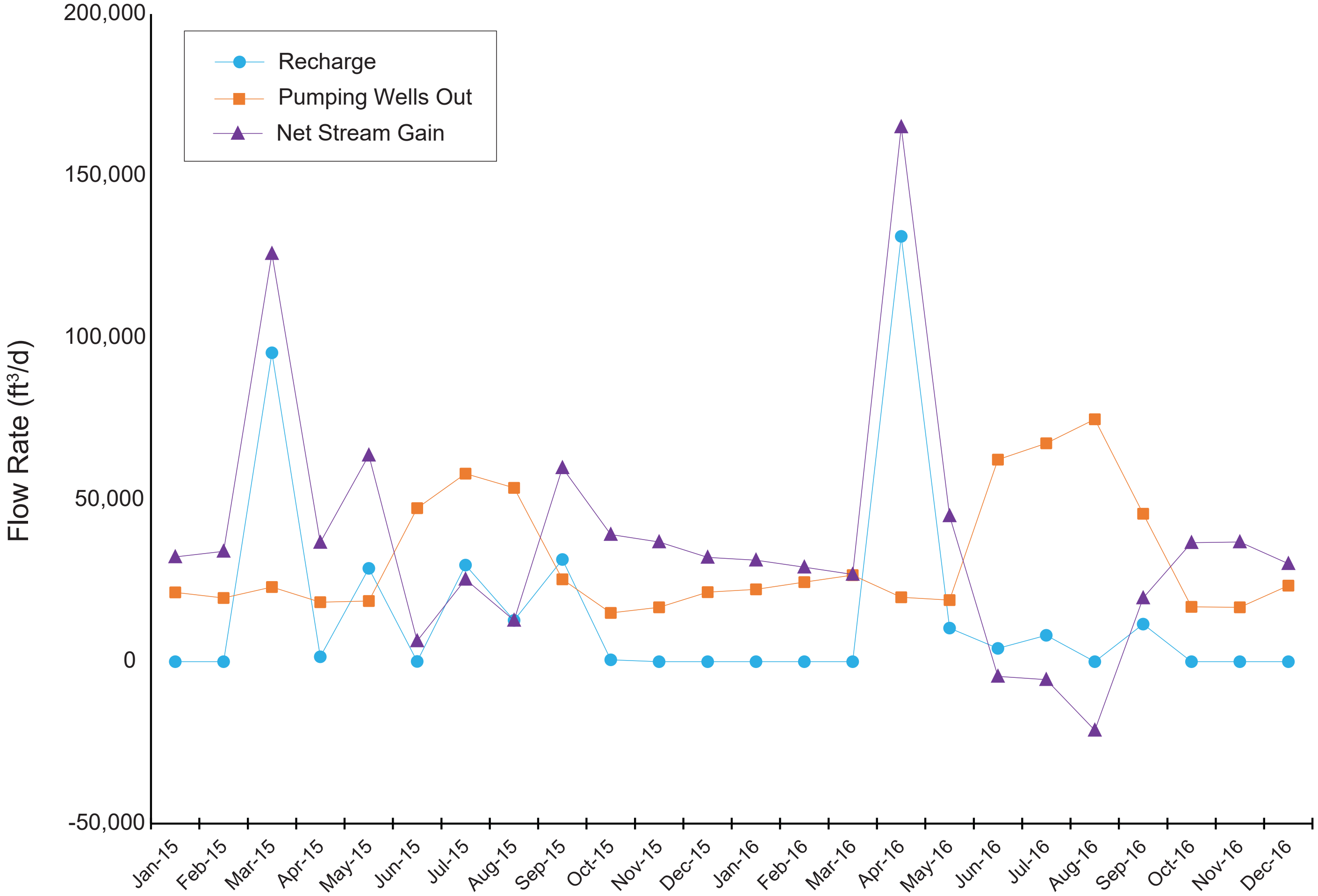


Figure 9. Graph of monthly water budget components. Negative flows indicate flow out of the Meadow Village aquifer. The drop in calculated net stream gain associated with increases in pumping and direct relationship between recharge and rise in stream gain suggests strong groundwater to surface-water interaction.

Table 6. Monthly groundwater budget for the 2015–2016 study period.

Month-Year	Recharge	Net Lateral Groundwater Flow in[a]	Net Alluvial Groundwater Flow in[b]	Pumping Wells	Net Stream Gain from Water Balance Calculation
Jan-15	0	22,999	30,700	21,357	32,342
Feb-15	1	22,999	30,700	19,658	34,042
Mar-15	95,342	22,999	30,700	23,047	125,994
Apr-15	1,478	22,999	30,700	18,334	36,842
May-15	28,808	22,999	30,700	18,738	63,770
Jun-15	86	22,999	30,700	47,390	6,395
Jul-15	29,816	22,999	30,700	58,072	25,443
Aug-15	12,753	22,999	30,700	53,693	12,759
Sep-15	31,539	22,999	30,700	25,395	59,842
Oct-15	564	22,999	30,700	15,031	39,232
Nov-15	0	22,999	30,700	16,780	36,919
Dec-15	0	22,999	30,700	21,488	32,211
Jan-16	0	22,999	30,700	22,337	31,362
Feb-16	0	22,999	30,700	24,529	29,170
Mar-16	1	22,999	30,700	26,746	26,955
Apr-16	131,300	22,999	30,700	19,861	165,138
May-16	10,397	22,999	30,700	19,042	45,055
Jun-16	4,091	22,999	30,700	62,349	-4,559
Jul-16	8,144	22,999	30,700	67,413	-5,570
Aug-16	0	22,999	30,700	74,859	-21,160
Sep-16	11,612	22,999	30,700	45,654	19,657
Oct-16	0	22,999	30,700	16,950	36,749
Nov-16	0	22,999	30,700	16,784	36,915
Dec-16	0	22,999	30,700	23,454	30,245

[a] Net lateral flow into the MVA model domain from the north and south boundaries.

[b] Net alluvial flow into the MVA model domain (difference between inflow at the west end of the model domain and outflow at the east end of the model domain) based on the daily flow rates calculated in annual water budget (table 5). These inflows and outflows are assumed to be constant for the purposes of this calculation.

Note. Flows expressed in ft^3/d. Positive flows indicate flow into the Meadow Village aquifer. Net stream gains calculated to balance other source and sink components assuming no change in storage.

small portion of the aquifer, do not store a substantial amount of groundwater, and in preliminary model design, caused numerical instability in the model. These areas lie on the periphery of the Meadow Village area where the unconsolidated alluvial and glacial deposits thin and underlying bedrock crops out along topographic breaks in slope. In general, the model domain is a basin shape with a relatively thick middle region that thins toward the edges. The model domain has an area of 254 acres. The top surface of the model was defined using LiDAR elevation data (Gardner, 2012). The bottom of the model was defined using the top-of-shale contoured surface (fig. 10). This surface was based on well logs in the GWIC database for wells shown in figure 6.

Spatial Discretization

Table 7 includes the details of the one-layer model. The grid has 86 rows and 296 columns, with a uniform horizontal grid spacing of 30 ft. The single layer has a variable cell thickness reflective of unconsolidated deposits that constitute the Meadow Village aquifer. The projection was set to Montana State Plane coordinates, North American Datum 1983, with units of international feet. The vertical datum is NAVD88. The grid has a counterclockwise rotation angle of 15º to orient it approximately parallel to the overall flow direction as recommended by Anderson and others (2015).

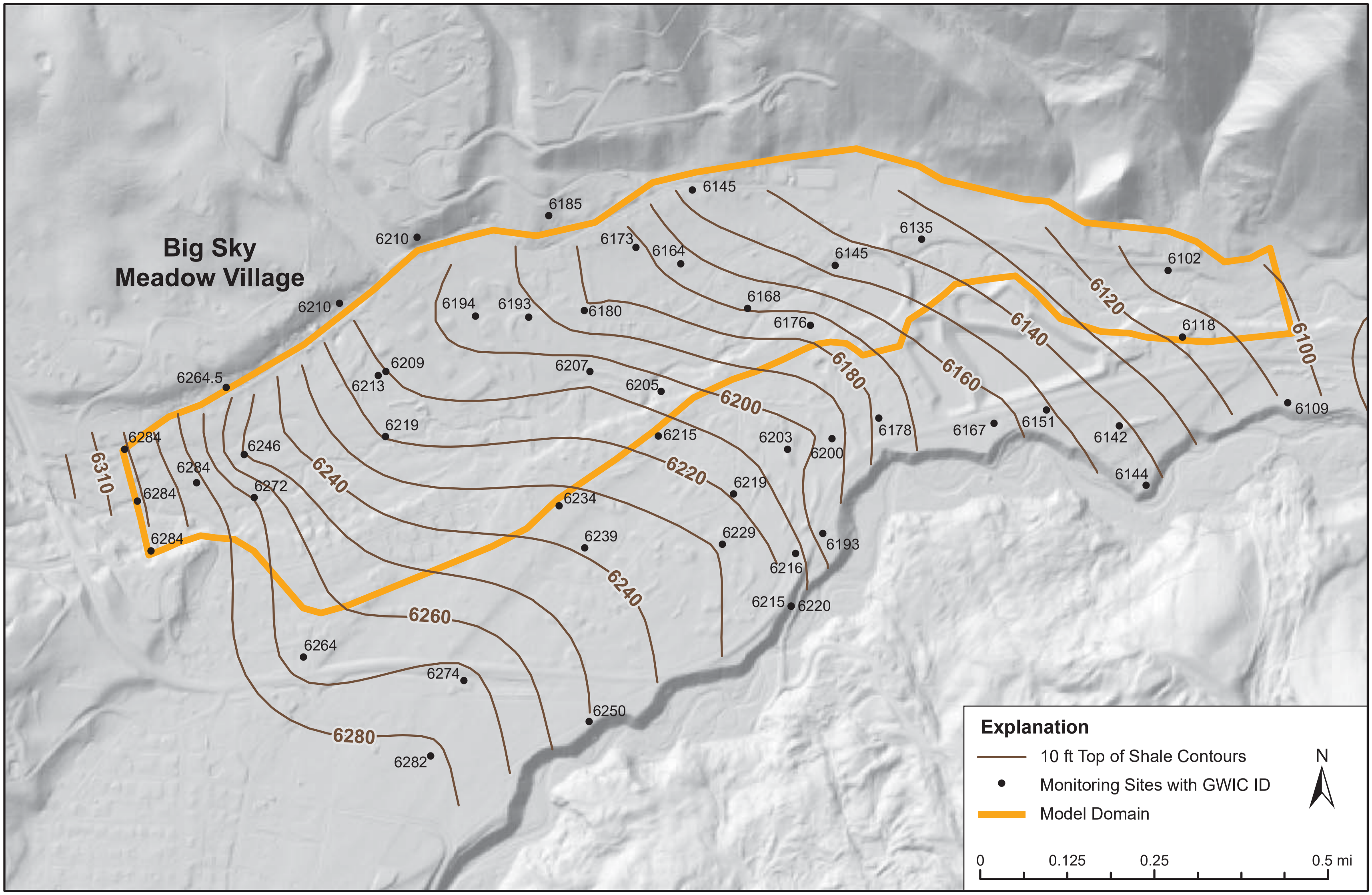


Figure 10. Contour map of the elevation of the surface of the Frontier Shale underlying the Meadow Village aquifer. Contours show the shale sloping downward from west to east.

Temporal Discretization

Steady-State Model

The steady-state model represents a single unit–time stress period, which is represented as a day for this simulation. This is strictly a presentation of typical, long-term aquifer baseflow conditions per unit day and not any specific day of the year. For steady-state simulations, we utilized average annual boundary conditions, calculated as daily rates. The model was subsequently calibrated to groundwater head data typical of the January/February 2016 time period. We selected these data because they represent a relatively static, quasi-steady condition for the MVA, consistent with literature guidance for calibration of a steady-state model (Anderson and others, 2015).

Transient Model

Time intervals for transient data ranged from 6 min (pumping well data) to hourly (stream stage and groundwater-level data). These data were assembled for the transient model using two schemes: (1) a 2-yr (2015–2016) model with 731 daily stress periods (2016 was a leap year) and (2) the same 2-yr period with 24 monthly stress periods. All models used days as the time units (i.e., all appropriate parameters and boundary flux rates were cast in units of days).

Hydraulic Parameters

An initial hydraulic conductivity of 100 ft/d was applied to the entire model grid. For the transient model, a specific yield of 0.032 was used, which is the average of the values from the two aquifer tests with observation wells. These initial parameters were adjusted during model calibration.

Internal Boundary Conditions—Sources and Sinks

"Internal boundary conditions" refers to sources and sinks within a model domain, as opposed to those boundaries that lie along the edges of the domain. In the MVA model, sources within the domain include recharge from snowmelt and precipitation events, and streamflow losses to the aquifer from the Middle Fork. These features were modeled using the MODFLOW recharge and river packages. Pumping wells and streamflow gains from groundwater to the Middle Fork are the primary sinks in the models. These features were modeled using the wells and river packages. Evapotranspiration from riparian vegetation is also a likely sink in the system but was not explicitly simulated in MODFLOW, as discussed in the section focusing on riparian evapotranspiration.

Table 7. Details of the MODFLOW model grid as constructed in GMS.

Grid type:	Cell Centered
X origin:	1501845
Y origin:	374225
Z origin:	6020
Length in X:	8880
Length in Y:	2580
Length in Z:	410
Rotation angle (degrees):	15
AHGW X origin:	1501177.25[a]
AHGW Y origin:	376717.09[a]
AHGW Z origin:	6430
AHGW rotation angle (degrees):	75
Minimum scalar:	6104
Maximum scalar:	6303
Num cells i:	86
Num cells j:	296
Num cells k:	1
Number of nodes:	51678
Number of cells:	25456
No. active cells:	14016
No. inactive cells:	11440

[a] Projection: State Plane Coordinate System, NAD83, international feet, Zone 2500.

Recharge

Recharge from precipitation was applied to the entire model area. For the steady-state model the recharge rate was 0.00122 ft/d. This value was derived from the combined average annual recharge from both snow (0.27 ft/yr) and rain (0.174 ft/yr) of 0.444 ft/yr. Snowmelt was applied to the transient models based on the GRTF sonic data and responses in instrumented monitoring wells. In both years, snowmelt occurred over 8 days: 3/10/2015–3/17/2015 and 4/2/2016–4/9/2016. The calculated, cumulative snowmelt recharge values (0.23 ft in 2015 and 0.31 ft in 2016) were divided by eight and applied in the daily transient models at the appropriate times. In the monthly version of the transient model the snowmelt recharge was included in the month in which it occurred, along with any recharge from rain events in the same month. Rain events were entered into the transient models using the calculated daily and monthly values (tables

3, 4). Monthly values were the sum of the daily values for each month.

River

Recent aerial photographs (e.g., fig. 3) were used to define the location of the Middle Fork. Model cells intersecting the river were assigned as river cells. Initial river package nodes with streambed and stream stage elevations were positioned at the locations of the surveyed staff gage sites (fig. 4, table 8). Auxiliary nodes were added to the river package at points between the staff gages on the Middle Fork, and stage elevations were assigned using LiDAR. The streambed elevation was assigned 0.5 ft below the stage elevations, consistent with field observations. The purpose of these auxiliary points was to add elevation detail at locations where the slope of the stream is likely to be affected by the presence of ponds and structures, such as where Center Lane crosses the Middle Fork.

The river package nodes in cells with gaged sites were populated with stage data recorded during intervals of operation. Daily stage data from all staff gages (sites 165688, 281371, and 281366) were similar, with modest changes in magnitude at each site showing typical water depths of approximately 0.5 ft. MBMG gage sites were started in 2015 and 2016 after the initiation of the springtime rise in stage, and due to ice, winter season data were not recorded. We relied on GRTF data (Kristen Gardner, GRTF, written commun., 2018) to fill in gaps in each staff gage record by adjusting the GRTF data elevations to match that of the gage with the missing record. The steady-state models used a winter, low-stage value for each site.

Table 8. River node information.

Modeled Nodes:	Position in Montana State-Plane Coordinates NAD83 Datum			
Node ID	X	Y	Bottom Elevation (ft amsl)	Gage Used to Generate Transient Data
Two Moon Bridge staff gage	1501581.78	375425.29	6302.9	Two Moon Bridge staff gauge 282927
Golf Course staff gage	1503425.38	375859.17	6256.4	Golf Course staff gage 275230
Crail Ranch Staff site	1506298.67	376809.45	6186.4	Crail Ranch staff 275231
GRTF gage site	1510564.30	376940.58	6097.8	GRTF stage site 274333 (sensor)
Auxiliary node 1	1504426.06	376041.06	6232.4	Golf Course Shop
Auxiliary node 2	1505232.27	376249.93	6219.3	Crail Ranch staff
Auxiliary node 3	1505411.31	376132.20	6216.4	Crail Ranch staff
Auxiliary node 4	1505758.53	376438.74	6200.2	Crail Ranch staff
Auxiliary node 5	1507009.61	377107.68	6174.7	Crail Ranch staff
Auxiliary node 6	1507234.22	377118.53	6174.4	Crail Ranch staff
Auxiliary node 7	1507337.30	377173.87	6174.4	Crail Ranch staff
Auxiliary node 8	1507438.22	377244.40	6165.6	GRTF site
Auxiliary node 9	1507560.83	377321.44	6160.5	GRTF site
Auxiliary node 10	1508387.65	377223.78	6148.8	GRTF site
Auxiliary node 11	1508734.87	376928.64	6136.8	GRTF site
Auxiliary node 12	1509757.01	376866.80	6114.3	GRTF site
Auxiliary node 13	1510264.25	376903.72	6103.7	GRTF site
Auxiliary node 14	1512086.65	376170.72	6051.3	GRTF site
Auxiliary node 15	1500366.25	375922.34	6347.1	GRTF site
Auxiliary node 16	1502469.77	375374.73	6279.7	GMS[a]
Auxiliary node 17	1502896.64	375700.34	6266.8	GMS (steady-state version only)

[a] These nodes transient data were generated by GMS automatically using data from the Two Moon Bridge (upstream) and Golf Course Shop staff gages.

Wells

Pumping wells are the primary internal sinks in the model. Pumping data were provided for each of the five municipal wells in 6-min increments. The data were flagged with an indicator variable specifying whether the well was on or off at the time of measurement. These data were combined with pumping rates for each well (table 2) to develop daily and monthly pumping schedules for the transient models. The steady-state models used a winter pumping rate of 21,351 ft^3/d from wells 1 and 2 (18,360 and 2,991 ft^3/d, respectively).

Riparian Evapotranspiration

Riparian evapotranspiration was not explicitly included in the models. As discussed above (Water Budget section), the monthly water budget incorporates riparian ET by applying an evapotranspiration rate of 32,276 ft^3/d for the 100-d growing season, between June and August. The monthly water budget graph (fig. 11) shows that the addition of ET would result in lower stream gains during the summer, since ET would remove water that otherwise would flow to the stream. Since the ET would occur near the stream there would be little buffering of this effect by storage in the aquifer.

External Boundary Conditions

Figure 12 is a map view of the model boundary conditions. The northern border of the model consists primarily of no-flow boundaries. Along the western portion of this boundary, a thin veneer of glacial till overlies the shale bedrock. The shale bedrock tilts upward in the eastern part of the model area, and is exposed at the surface to the south of the model area (fig. 5). The shale bedrock and glacial till are much less permeable than the sand and gravels of the Meadow Village aquifer, and so they are treated as no-flow. Near the center of the northern border Crail Creek enters the valley, and some thin alluvium may be present. A modest groundwater inflow of 1,925 ft^3/d (10 gpm)

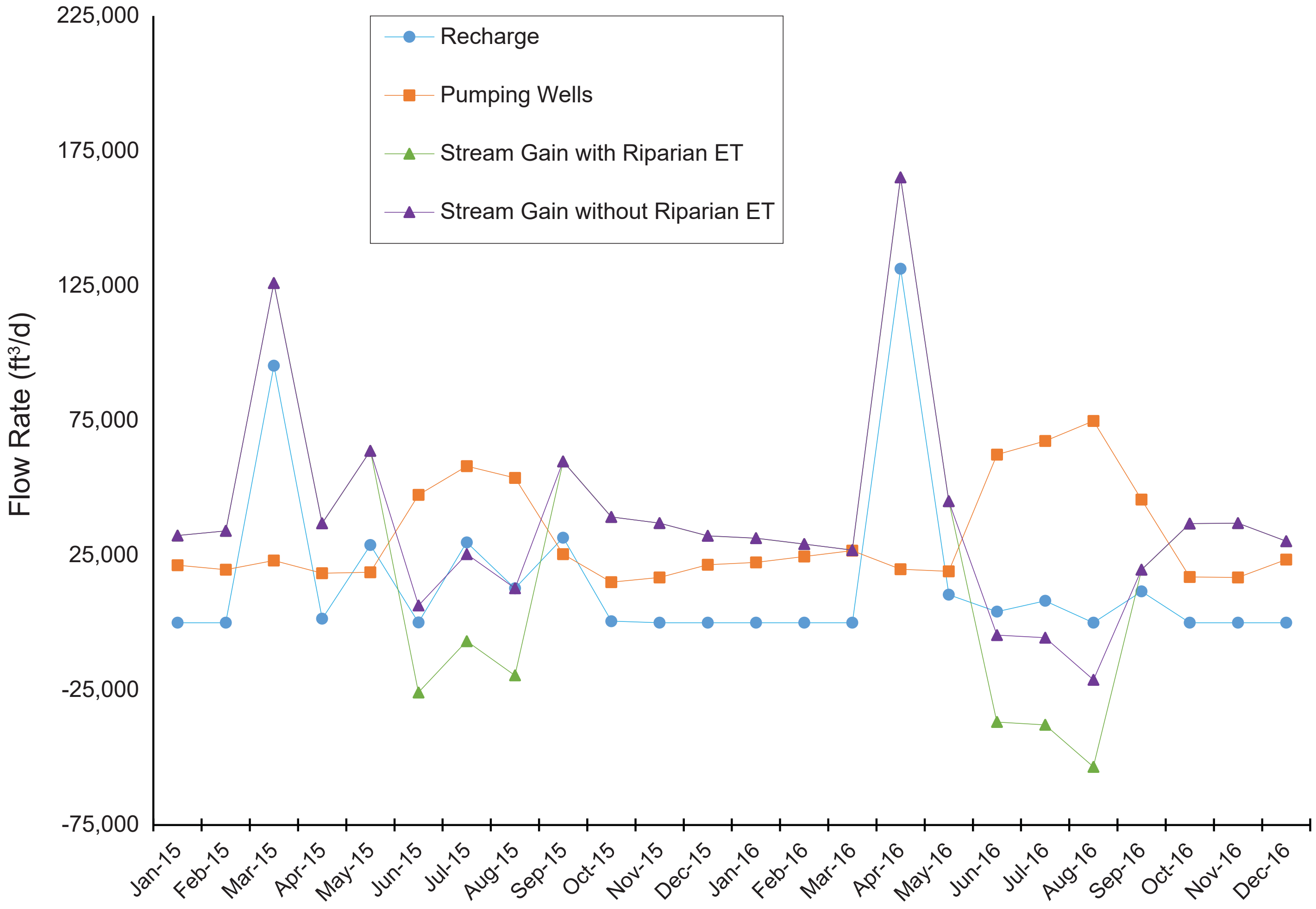


Figure 11. Monthly transient water budget incorporating riparian evapotranspiration component indicates that stream gain is decreased (green line below zero cfs) relative to calculated stream gain when riparian evapotranspiration is not included in the water budget.

was delivered by specified-flow cells along the model edge where it intersects the Crail Creek valley.

The southern edge of the model includes a specified flow boundary over about half its length, and no-flow boundaries at the western and eastern ends (fig. 12). The specified flow boundary accounted for the 436 acres of thin unconsolidated materials that respond to rain and snowmelt events, and delivered the recharge to the Meadow Village aquifer to the north. Although the flow is generally unknown at this area, applying a constant flow reflects our assumption that the seasonal variation in heads, with some periods of drying out of aquifer sediments, indicates some recharge to aquifer. A constant 21,074 ft^3/d was applied as a specified flow in all steady-state and transient models.

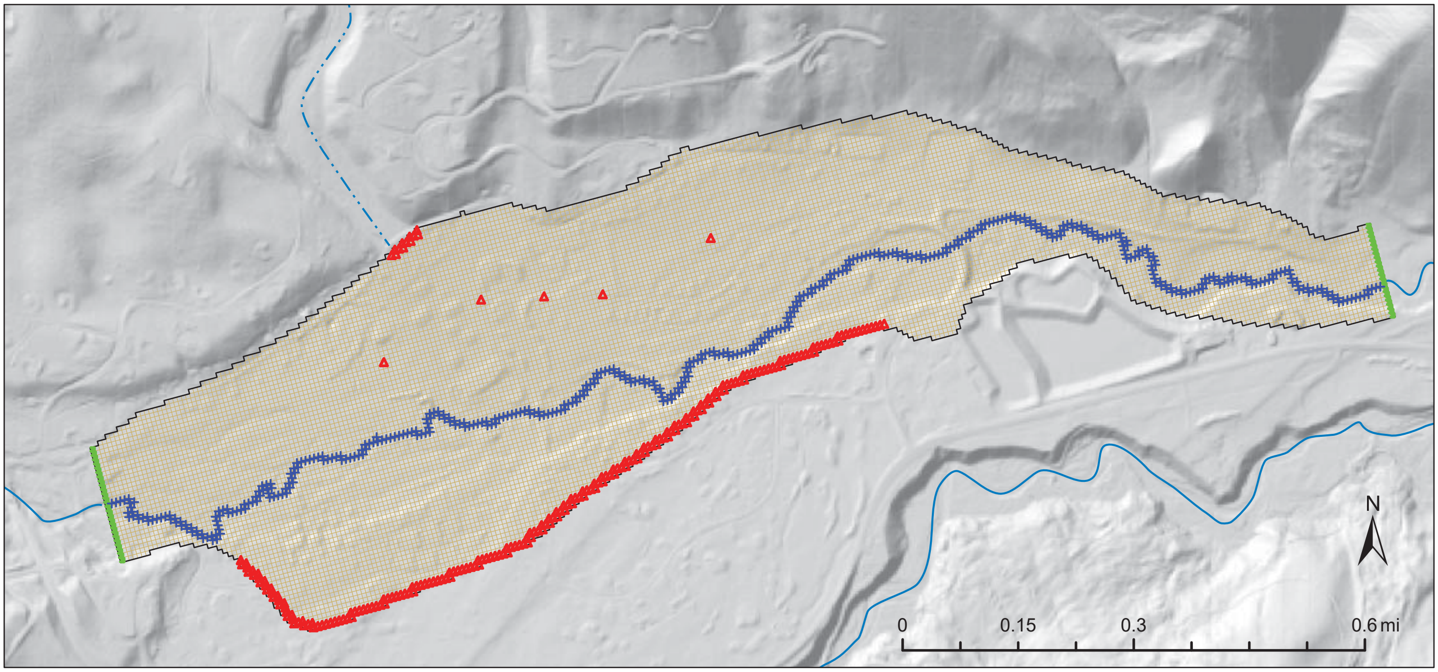
General-head cells were used at the western (upstream) and eastern (downstream) ends of the model area (fig. 12). These cells simulate alluvial groundwater inflow (at the upstream end) and outflow (at the downstream end). All model versions have constant specified heads of 6,303 ft at the upstream end, and 6,104 ft at the downstream end. The flows in and out at these boundaries vary by stress period, depending on the head in nearby cells.

CALIBRATION

The model calibration was performed using PEST, an "inverse modeling" or "parameter estimation" tool. PEST systematically varies user-specified parameters (e.g., hydraulic conductivity and storage coefficient) until the model replicates a set of measurements or calibration targets (e.g., well water levels) within an acceptable error (i.e., goals). These optimized parameters are then used as input to help achieve a calibrated model.

Selection of Calibration Targets and Goals

Groundwater and selected stream-stage elevations (in the West Fork) were the calibration targets. Since the Middle Fork is interconnected with the MVA, the stream elevations have continuity with the groundwater elevations and therefore can be utilized as calibration targets for the groundwater model. For the steady-state model, late winter groundwater elevations recorded or estimated for February 12, 2016 were used to calibrate the model (table 9). These are



Explanation

- ◪ Variable Head Boundary
- + River
- △ Well/Specified Flow

Figure 12. Map of MODFLOW grid and boundary conditions overlain on DEM hillshade image. Specified flow boundaries along the north and south edges of the model are implemented as injection wells. Wells in the middle of the model domain are implemented as pumping wells.

the same data used to create the water table elevation map (fig. 7), excluding data falling outside the model domain. The goal of steady-state calibration was to get the majority of modeled elevations to agree with measurements within a calibration interval of 3 ft. For the daily and monthly transient model calibration, observed water elevations were used for each calibration point to compare with transient model results. The goal of the transient calibration was to reasonably replicate observations.

Steady-State Calibration

Steady-state calibration was achieved by adjusting the K of the aquifer within a narrow range using PEST. Using PEST's pilot point method, K was estimated at various points in the model domain; interpolation between those points creates a calibrated K "field" across the model domain. A field of spatially variable K represents a heterogeneous distribution of materials within the alluvial/glacial deposits of the MVA, as opposed to application of a uniform K throughout the aquifer. Sixty-nine pilot points were used within the model domain for calibration. Implemented in this fashion, the distribution of K reflects the best match of simulated to measured heads at calibration targets.

Hydraulic conductivity estimates were restricted during the PEST runs to range from 50 ft/d (one-half the initial value) to 200 ft/d (twice the initial value). This range is slightly wider than the range from aquifer tests at the five BSWSD municipal wells (67 ft/d to 151 ft/d). The K field yielded all but one calibration target within the 3-ft calibration interval (figs. 13, 14). The K values at pilot points nearest to wells MV-1 and MV-4 (fig. 4), which are the farthest west and east of the pumping wells, were fixed at 100 ft/d or the geometric mean of the K from the aquifer tests in these two wells (table 1). This constrained K estimates in the vicinity of the pumping wells to the range of values observed during aquifer tests. The K field resulting from the calibration is shown in figure 14.

The water budget was also used to assess the steady-state calibration. The model-calculated ground-

Table 9. Steady-state calibration targets for the Meadow Village groundwater model.

GWIC ID	Other Id[a]	Name	Calibration Point Coordinates Easting (ft)	Calibration Point Coordinates Northing (ft)	Water Table Elevation (ft)
103561		RID 305 Well 1 past shed	1508374.75	377055.62	6147.12[b]
165688	DH-4	DH-4 End Spotted Elk	1504994.96	376410.88	6217.55
165689	DH-5	DH-5 Silverbow #12	1505551.06	376227.48	6208.77
257677	TW-3	BSWSD Test Well 3	1505712.27	377228.62	6201.67
257678	TW-2	BSWSD Test Well 2	1503407.27	376360.09	6242.61
275228		West Fork below Two Moon bridge	1501581.22	375409.20	6303.56[b]
275232		Lower Pond staff gage	1507045.76	376785.52	6175.13[b]
281360	MV14-2	MV14-2	1503435.71	375900.93	6245.40
281362	MV14-3	MV14-3	1503443.97	375896.06	6247.17
281363	MV14-4	MV14-4	1502376.62	375767.61	6274.46
281364	MV14-5	MV14-5	1502030.00	375553.95	6291.28
281365	MV14-6	MV14-6	1502454.53	375437.38	6279.88
281366	MV14-7	MV14-7	1506194.30	376862.39	6188.13
281367	MV14-9	MV14-9	1507520.42	377380.63	6160.38
281368	MV14-8	MV14-8	1506192.86	376879.64	6188.17
281371	MV14-14	MV14-14	1505361.51	377333.00	6208.06
281373	MV14-15	MV14-15	1505357.16	377321.70	6209.83

[a]Other IDs are identification numbers assigned by various engineering companies and sometimes adapted by Big Sky Water and Sewer District or MBMG for various purposes.
[b]Elevations estimated from similar time-of-year measurements from previous years due to low water levels stranding pressure transducers on February 12, 2016.
Note. Groundwater elevations relative to mean sea level based on data from February 12, 2016. Well coordinates are in Montana State Plane NAD83.

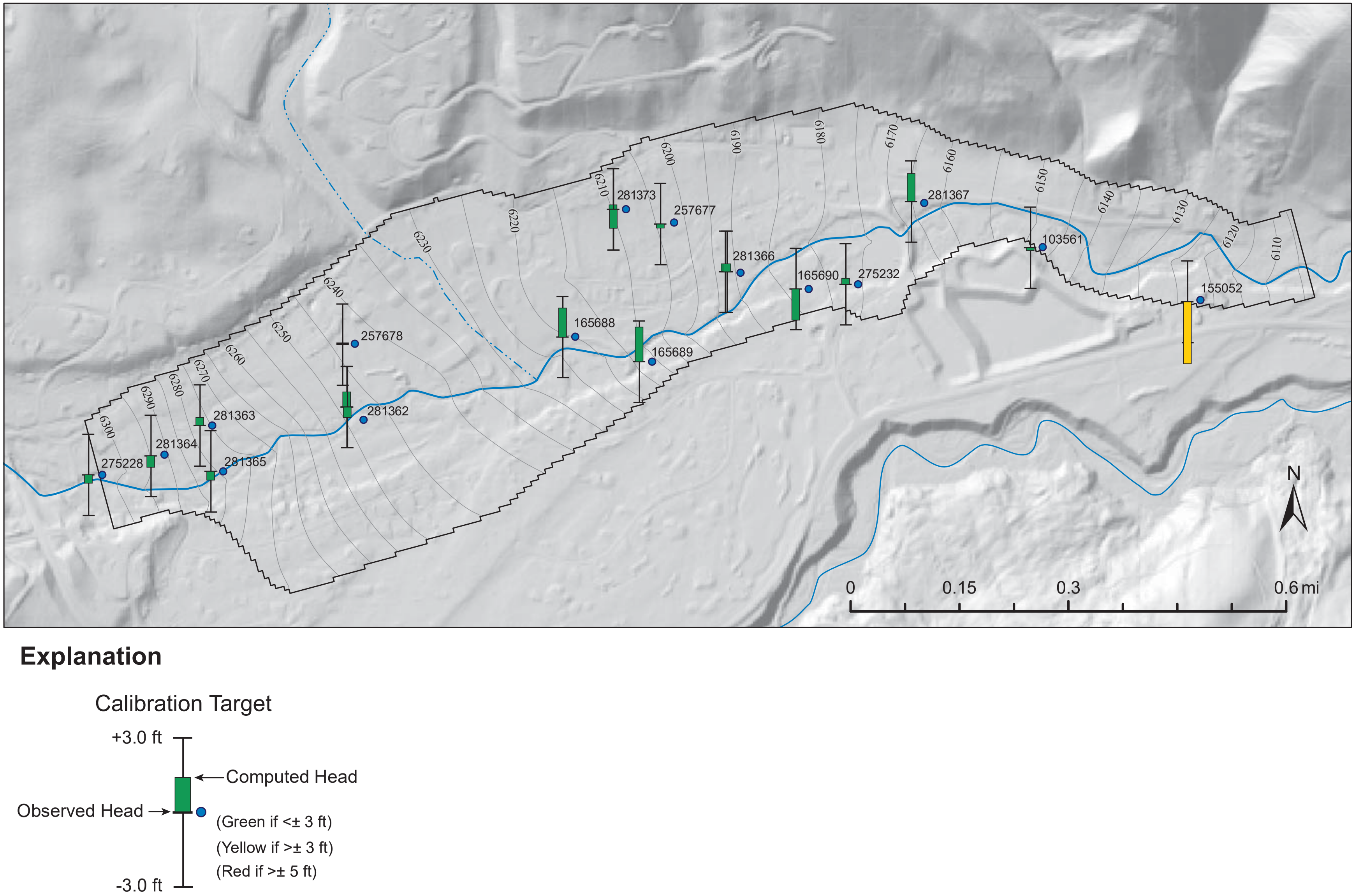


Figure 13. Map of heads and associated calibration target errors after steady-state calibration. Green error bars are within the 3-ft calibration goal.

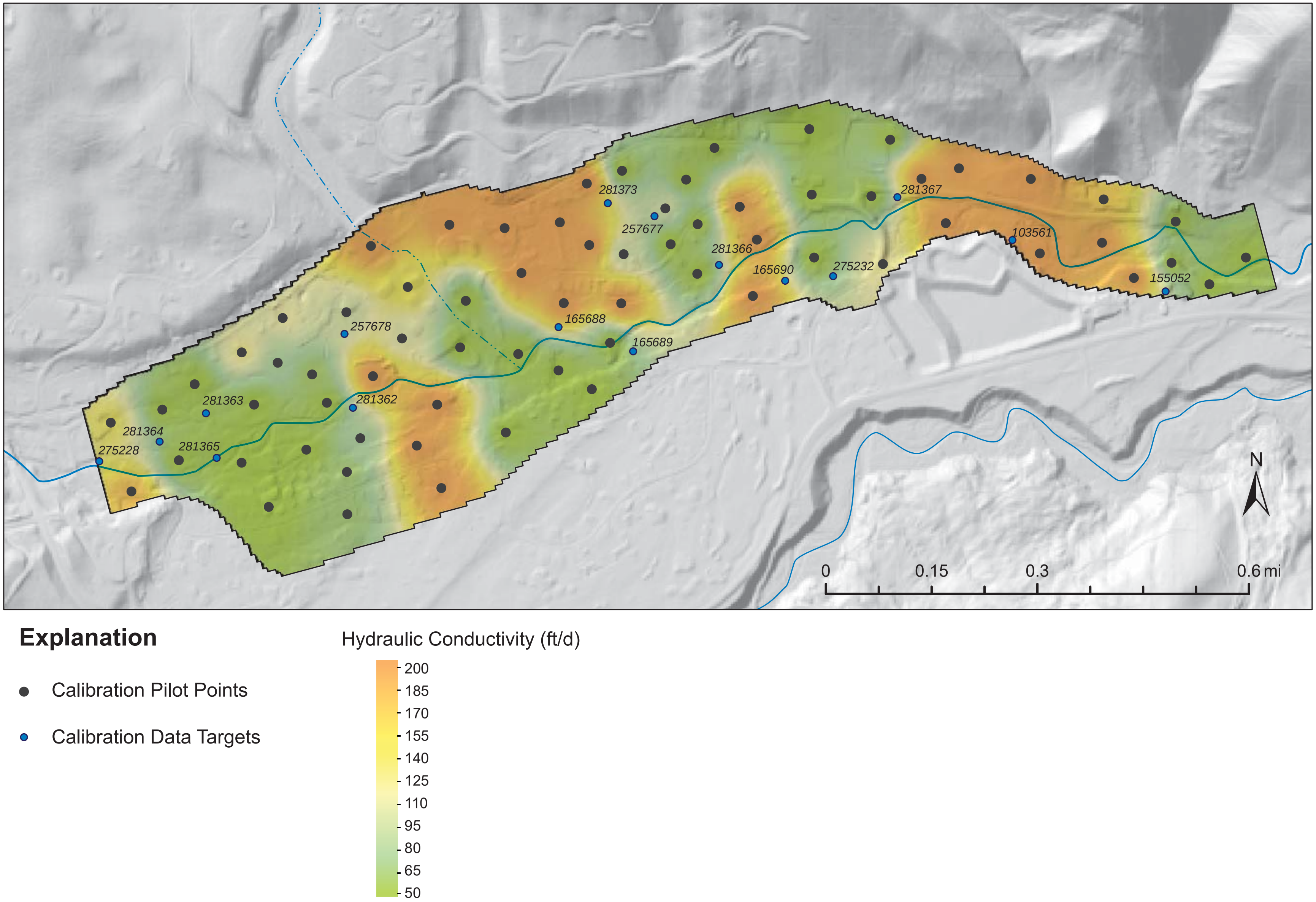


Figure 14. Hydraulic conductivity field obtained from steady-state calibration. Pilot points and calibration target locations are shown.

water flow through column 86 (about the middle of the model) was compared to a simple Darcy's Law calculation of flux at the same location. The model-calculated flow was 111,047 ft^3/d (1.29 cfs), while the Darcy flux was 138,240 ft^3/d (1.60 cfs). The model produced a flow approximately 24% smaller than those estimated using a simple Darcy calculation. Since uncertainty in the magnitude and distribution of hydraulic conductivity can result in order-of-magnitude errors in heterogeneous aquifers, these flows indicate a "good" model calibration allowing procession to transient calibration.

Transient Calibration

The transient model used an initial specific yield of 0.032, which was estimated based on the aquifer tests and well hydrograph data discussed previously. The K field from the steady-state calibration was applied directly to the transient model. When the model was run, the modeled versus observed water levels for wells in key locations was within about 5 ft, which was considered an acceptable error for this model (fig. 15). Although the transient model error exceeds the 3 ft errors achieved for the steady-state model, 5 ft represents only about 3% of the total head drop across the model domain. Therefore, the transient model is considered adequately calibrated with the K field shown in figure 14. PEST was not implemented for the transient model because of these results. The out-of-calibration bars (generally illustrating water-level errors exceeding 5 ft) shown in red for well 281363 (fig. 15C) correlate to time periods when a leak in the irrigation system affected groundwater levels (the leak was corrected by BSWSD shortly after it was discovered in 2015). The model deviates from the observed data at well 165688 (fig. 15B). The cause for this is uncertain, but may result from localized aquifer variability (e.g., in hydraulic conductivity or aquifer thickness) not captured in the model or due to proximity to the Middle Fork. However, excluding those two locations, the model reasonably reproduced observations at most of the calibration targets.

Note the March 2015 and April 2016 snowmelt events and other precipitation events are reflected in water-level increases in both observations and model results at wells shown in figure 15. The magnitude of the simulated change in the wells is consistent with field observations, which suggest that recharge estimates from these events are reasonable. Four wells, 257677, 165688, 281371, and 281366 (figs. 15E, 15B, 15D, and 15F, respectively) are located near pumping wells. Drawdown related to summer pumping in both the observations and the modeled results were evident during 2015 and 2016. Thus, the model is capturing the effects of observed transient stresses.

The transient calibration was also evaluated for the monthly stress period model. The modeled versus measured observation well data for wells in key locations is reasonable, again, with most modeled water levels predicted within 5 ft of measurements (fig. 16). This is expected because the same data drive the daily and monthly models, just input and output with different stress period lengths.

SENSITIVITY ANALYSIS AND MODEL VERIFICATION

The calibrated groundwater model contains the best estimates of the hydrogeological system parameters, producing results that are in good agreement with target values (steady-state and transient model calibration sections). A sensitivity analysis quantifies uncertainty of the calibrated model caused by uncertainty of aquifer parameter measurements, applied stresses, and boundary conditions (Anderson and others, 2015). A limited sensitivity analysis was conducted on the steady-state model to test how the model solution is affected by changes in K, R, $GW_{lat\text{-}in}$, and river conductance (RC), which represents how easily water moves between the streambed and the aquifer.

The sensitivity analysis was conducted by applying multipliers (first column of table 10) to each of the calibrated parameters and variables tested (top row of table 10). The optimized parameters and applied variables from the calibrated model are represented in the row for multiplier of one. For instance, for the calibrated, base-case model, the net gain to the Middle Fork would be 0.69 cfs. The K multipliers were applied to the 2D scatter point data set used in GMS to define K at the 69 PEST pilot points and the K field was reinterpolated. Sensitivity of the model was considered using two criteria: changes in aquifer flow to the Middle Fork and changes in the model calibration error.

The results (table 10) show that the modeled stream gain in the Middle Fork and model calibration error are sensitive to higher or lower K, higher

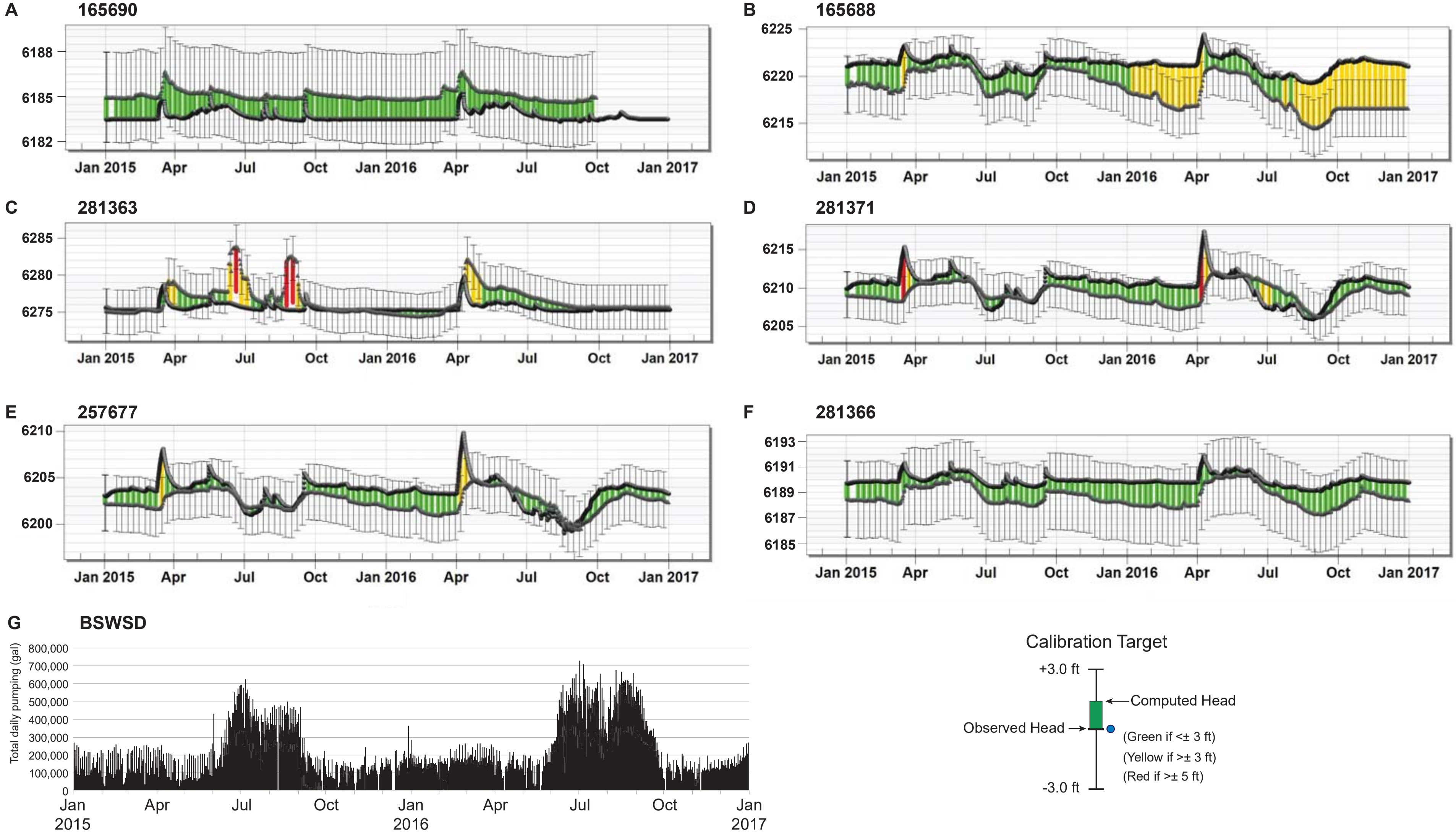


Figure 15. Graphs of daily transient calibration results for key wells (GWIC IDs shown in each graph). Pumping records for BSWSD shown for reference (G). Red bars indicate more than 5 ft of error between measured and modeled heads. Limited high errors indicate successful calibration of the transient model.

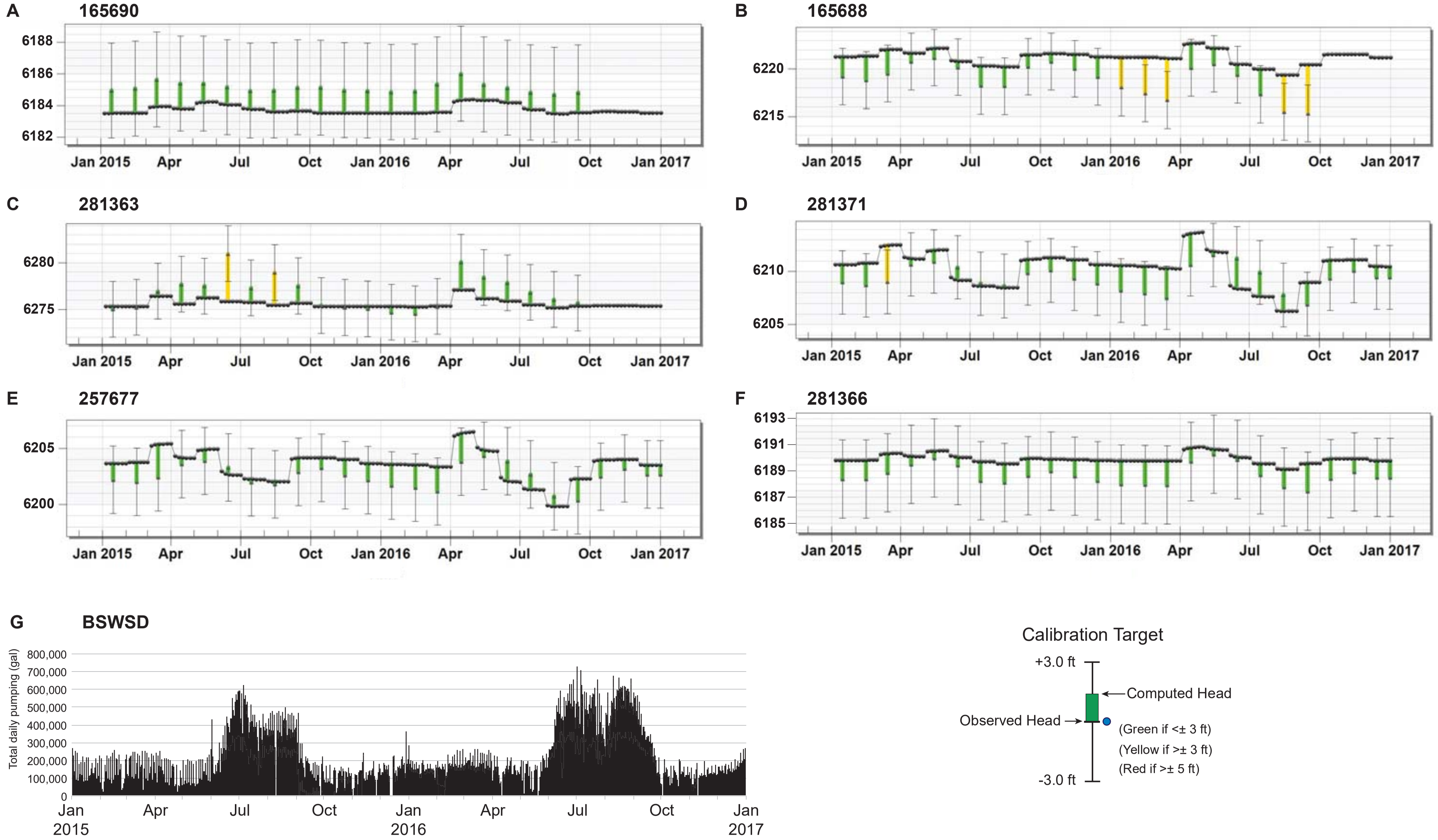


Figure 16. Graphs of monthly transient calibration results for key wells (GWIC IDs shown in each graph). Pumping records for BSWSD shown for reference.

Table 10. Sensitivity analysis for the steady-state model.

Multipliers	K	R	SF_{in}	RC
Net gain to West Fork, cfs:				
0.05	0.43	0.53	0.43	*
0.1	0.45	0.53	0.44	*
0.25	0.31	0.56	0.47	0.67
0.5	0.44	0.60	0.54	0.69
1	***0.69***	***0.69***	***0.69***	***0.69***
2	1.53	0.86	0.95	0.69
4	2.08	1.20	1.48	0.68
10	5.01	2.26	3.08	0.68
20	9.74	3.97	5.74	0.68
Mean absolute error (heads at calibration targets)				
0.05	4.36	1.12	1.13	*
0.1	3.18	1.12	1.13	2.76
0.25	1.84	1.12	1.13	1.1
0.5	1.26	1.12	1.13	1.62
1	***1.13***	***1.13***	***1.13***	***1.13***
2	1.2	1.19	1.17	2.26
4	1.33	1.32	1.31	2.29
10	1.64	2.05	1.95	2.31
20	2.19	3.19	3.12	2.32
Root mean squared error (heads at calibration targets)				
0.05	5.19	1.59	1.59	*
0.1	3.92	1.59	1.59	3.46
0.25	2.42	1.59	1.59	1.43
0.5	1.68	1.59	1.59	2.11
1	***1.59***	***1.59***	***1.59***	***1.59***
2	1.63	1.61	1.62	3.3
4	1.73	1.72	1.75	3.37
10	2.1	2.36	2.48	3.43
20	3.01	3.76	3.95	3.45

*Model would not converge with these parameter modifications. Bold italicized runs represent unmodified, calibrated, steady-state model

Note. K, Hydraulic conductivity; R, Recharge; SF_{in}, Specified flow in; RC, River conductance.

R, higher $GW_{lat\text{-}in}$, and higher or lower RC values. For lower values of R or $GW_{lat\text{-}in}$ the model does not go much out of calibration (i.e., calibration errors do not change much if at all).

In terms of net gain to the Middle Fork, the model is most sensitive to K and $GW_{lat\text{-}in}$. For instance, a 10-fold increase in K (one order of magnitude) resulted in a little over 7-fold increase in gain to the West Fork. The sensitivity is lower for an equivalent decrease in K. This suggests that there is sufficient water within the MVA to supply additional discharge to the river but it is limited by K. The increase in net gain to the Middle Fork also increases with increased $GW_{lat\text{-}in}$. This is likely associated with increased gradients associated with more water flowing in along these boundaries. This sensitivity is lower than for K (roughly a 4-fold increase in net gain for a 10-fold increase in $GW_{lat\text{-}in}$). Notably, the modeled stream gain is insensitive to RC. This suggest that RC is high enough in the model to not be the inhibitor of flow to the river channel, and thus flow to the Middle Fork from the MVA is governed by the K of the aquifer. This is true even for decreasing RC by up to a factor of four. However, decreasing the RC by a factor of 10 or greater resulted in non-convergence problems in the model and couldn’t be tested. Because the model is sensitive to the parameters tested, any parameter or variable uncertainties are expected to result in model uncertainties. Therefore, any modification of the parameters and variables by model users should be carefully considered as they will likely change the model result.

Calibration errors generally increased for any change of parameter or variable value. This is expected if an optimal parameter set is identified by PEST. The only exceptions are small decreases in the errors in head at the calibration targets observed when R was decreased; RC was decreased by a multiple of 0.25. However, the error reductions are small (0.01 and 0.03 ft in terms of mean absolute error). The calibration error appears to be insensitive to decreases in R and $GW_{lat\text{-}in}$ and only increases by 3 to 4 ft for a 20-fold increase of either variable. For reference, a 4-ft increase in error represents about 2% of the total head drop across the model domain. These results suggest that the calibrated model is relatively robust with respect to uncertainties in these two variables. This means that the model would retain low error in predicted head at the calibration targets even with reasonably large changes to R and $GW_{lat\text{-}in}$.

No independent dataset was available for model verification as all available data were used for model calibration. However, the response of the model to two separate years of snowmelt, recharge, river stage, and pumping data indicates that the model does respond to these specific stresses consistent with observations (figs. 15, 16).

EVALUATION OF THE MODELS

The steady-state model serves mainly as a model calibration tool, and it provides the necessary initial conditions for transient simulations. Since it is based on quasi-steady-state conditions that occur in late winter, the model fails to capture the dynamic, seasonal nature of this system that is observed throughout the year. The steady-state simulation cannot reflect transient changes in water management (e.g., changing pumping schedule or irrigation practices over short time-scales). Therefore, the steady-state model is of limited utility to simulate varying management scenarios or projected pumping changes. The steady-state model may be useful to evaluate the effects of long-term changes in annual recharge due to climate variability, improve understanding of recharge dynamics, or develop zones of contribution for wellhead protection efforts. The steady-state model can also be used to perform additional sensitivity analysis not considered in this report.

The daily and monthly transient model versions are more robust tools (relative to the steady-state model) that reasonably simulate observations from 2015 and 2016, and can be used to test changing water-use scenarios. The results comparing daily and monthly pumping rates to model-calculated heads provide an interesting demonstration of the similarities and differences with the two different stress-period lengths (figs. 15, 16). Notice that overall results are similar, but the daily details are not exhibited in the monthly version. The daily model shows varying cones of depression, reflecting groundwater into and out of storage on a daily basis. These details cannot be seen in the monthly models because of the longer stress periods.

The monthly model results for stream gain from the aquifer are similar to the calculated net stream gains presented in the monthly groundwater budget section (fig. 17). This demonstrates that at a monthly stress period, a simple water budget calculation to estimate effects to streamflow from increased pumping provides a result similar to that of the numerical model. The modeled stream gains from groundwater discharge are generally less than 1 cfs (86,400 ft^3/d), compared to an average flow rate of 12 cfs. The simulated groundwater contribution to streamflow in the Middle Fork are reduced when increased pumping is applied in the groundwater model. The maximum simulated discharges to the Middle Fork were around 2 cfs (150,000 ft^3/d), which corresponds to approximately 20% of baseflow (September–November flows at site 274333) and around 6% of peak flow.

The numerical groundwater model results suggest gaining and losing reaches alternate due to the geometry of the stream (i.e., temporal variation in stage, presence of ponds and structures) relative to water levels in the underlying aquifer. Variations in subsurface geology, such as changes in aquifer thickness or the spatial distribution of hydraulic conductivity, may also affect interactions between the stream and the aquifer. Although both gaining and losing reaches may occur between any two measuring stations, overall the Middle Fork gains streamflow from groundwater discharge through the model domain.

Scenarios

Two transient model simulations evaluated changes in the current pumping regime. The first scenario considers a simulation where all BSWSD production wells are pumped at their maximum rate for a short time (one day). The objective of this simulation was to estimate if the aquifer could sustain daily maximum rates to the wells and evaluate the related effects of this pumping on the Middle Fork. This scenario might represent unusually high, short-term water demand conditions such as wildland fires. The second scenario tested effects on the aquifer and Middle Fork flows associated with longer duration but smaller magnitude increases in pumping rates. This scenario might represent additional water demand from residential and commercial growth.

Scenario 1: Short-Duration, High-Intensity Pumping

This scenario was modeled using the daily stress period model. The date selected for this test was January 1, 2016, the middle of the 2-yr model run and during a time of year when pumping is generally low. The model results did not indicate excessive drawdown, demonstrating the aquifer's capacity to supply this pumping rate for short periods of time. The higher

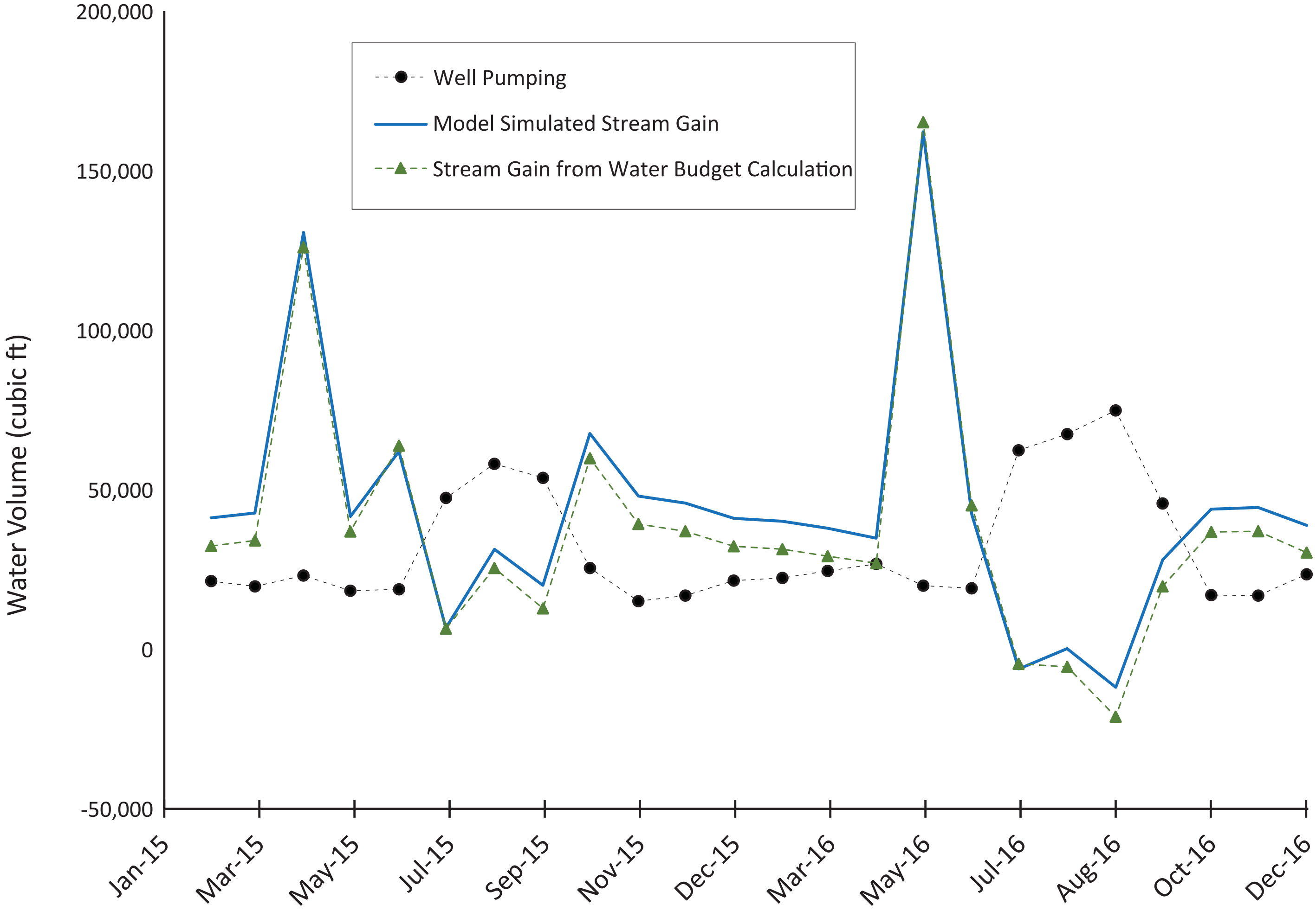


Figure 17. Graph of groundwater pumping and simulated discharge from the aquifer to the Middle Fork, compared to water budget estimated discharge to the Middle Fork. Negative stream gain indicates periods during which there is a net loss from the Middle Fork to the aquifer. Stream gains correspond to total gain across the model domain.

pumping rates withdrew the equivalent of 152,195 ft^3/d, or 791 gpm, from the aquifer and resulted in a decrease of about 0.2 cfs in groundwater discharge to the Middle Fork (fig. 18). Fourteen days after the additional pumping ended, groundwater discharge to the river recovered by about 89%. In figure 18, reduction of discharge from the aquifer to the river (reduction in river gain) occurs rapidly after the start of pumping. This simulation illustrates that the short-duration, high-intensity pumping would likely cause temporary stream depletion due to the limited aerial extent of the MVA and the wells' proximity to the Middle Fork, which reduces any buffering effect between the river and the aquifer. For reference, the reduction in stream gain of approximately 0.2 cfs is about 2% of the lowest discharge measured on the Middle Fork at site 274333 (per information available in the GWIC database).

Scenario 2: Long-Duration, Increased Pumping

The monthly transient model was used to simulate increasing pumping rates at all wells by 25, 50, and 75 percent (fig. 19) according to the schedule applied by BSWSD in 2015 and 2016 (fig. 8). The results show that on a monthly basis there is essentially a 1:1 relationship between increased pumping and decreased groundwater discharge to the Middle Fork. The daily model was also run with 50 and 75 percent pumping increases and, although not presented in this report, showed similar results.

Simulations with 100% increases in pumping with the daily and monthly models resulted in dry cells in both cases. Thus, because the model is based on an assumption of fully penetrating wells that draw water from the entire saturated thickness of the aquifer, the model simulated the aquifer going dry in these locations. Development of dry cells in the model limits interpretation of those model results because pumping

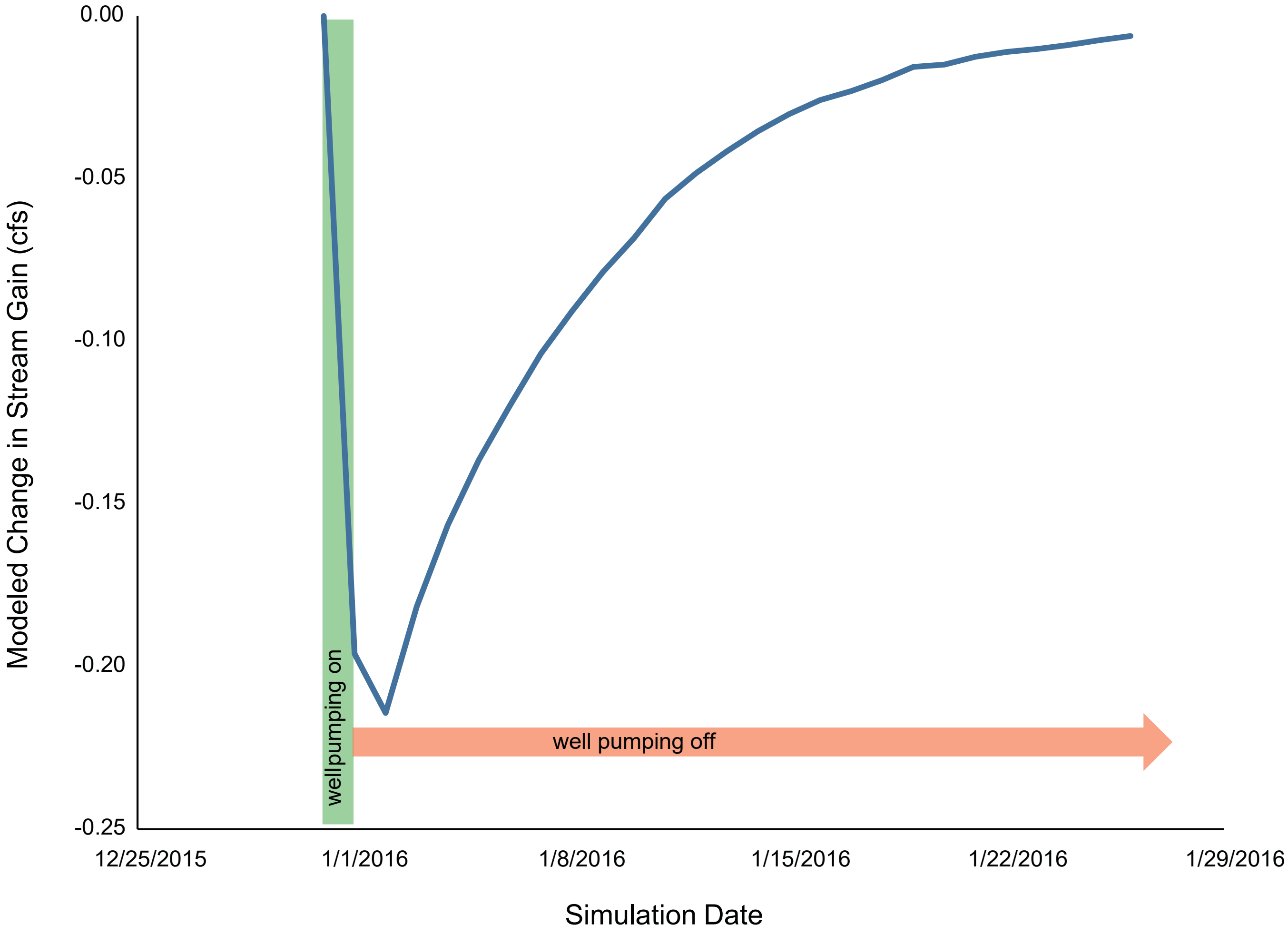


Figure 18. Modeled change in groundwater discharge to the Middle Fork associated with short-duration, high-intensity pumping. Stream gains are reduced rapidly in response to pumping, demonstrating the interconnection between the aquifer and the Middle Fork. Reductions in groundwater discharge to the stream in response to short-duration, high-intensity pumping require nearly 1 month to fully recover, although most recovery occurred within 2 weeks.

ceases once the aquifer dries out at the pumping well. Under real-world conditions, a well field can be managed to limit pumping rates or pumping duration at specific wells. The model result suggests that doubling the pumping rates at all wells would result in problematic drawdown in the aquifer. A practical solution would be to redistribute pumping to the other wells.

MODEL LIMITATIONS

The groundwater model described in this report is a tool to evaluate the hydrologic response to different stressors to the Meadow Village aquifer. Care should be taken by groundwater modelers if incorporating changes to model input variables and parameters, as sensitivity analysis indicated that the model results can be affected by model inputs such as hydraulic conductivity. The model calibrations and results presented are based upon the best available information as of 2016. Modelers should consider recalibrating the model if any substantial changes in data or understanding of the hydrologic system becomes available.

As currently structured, the model does not explicitly simulate ET. Incorporating such a change within the MODFLOW model, by applying the evapotranspiration package, would allow for more sophisticated simulations of various management strategies, such as irrigation with, or infiltration of, treated wastewater effluent.

The Middle Fork was assumed to have a constant conductance along its length across the surface of the MVA. This assumption allowed simplification of the model calibration process (i.e., fewer estimated parameters). If a more detailed investigation of the interaction between the Middle Fork and the MVA is required, further investigation of the variability of the river conductance could be considered.

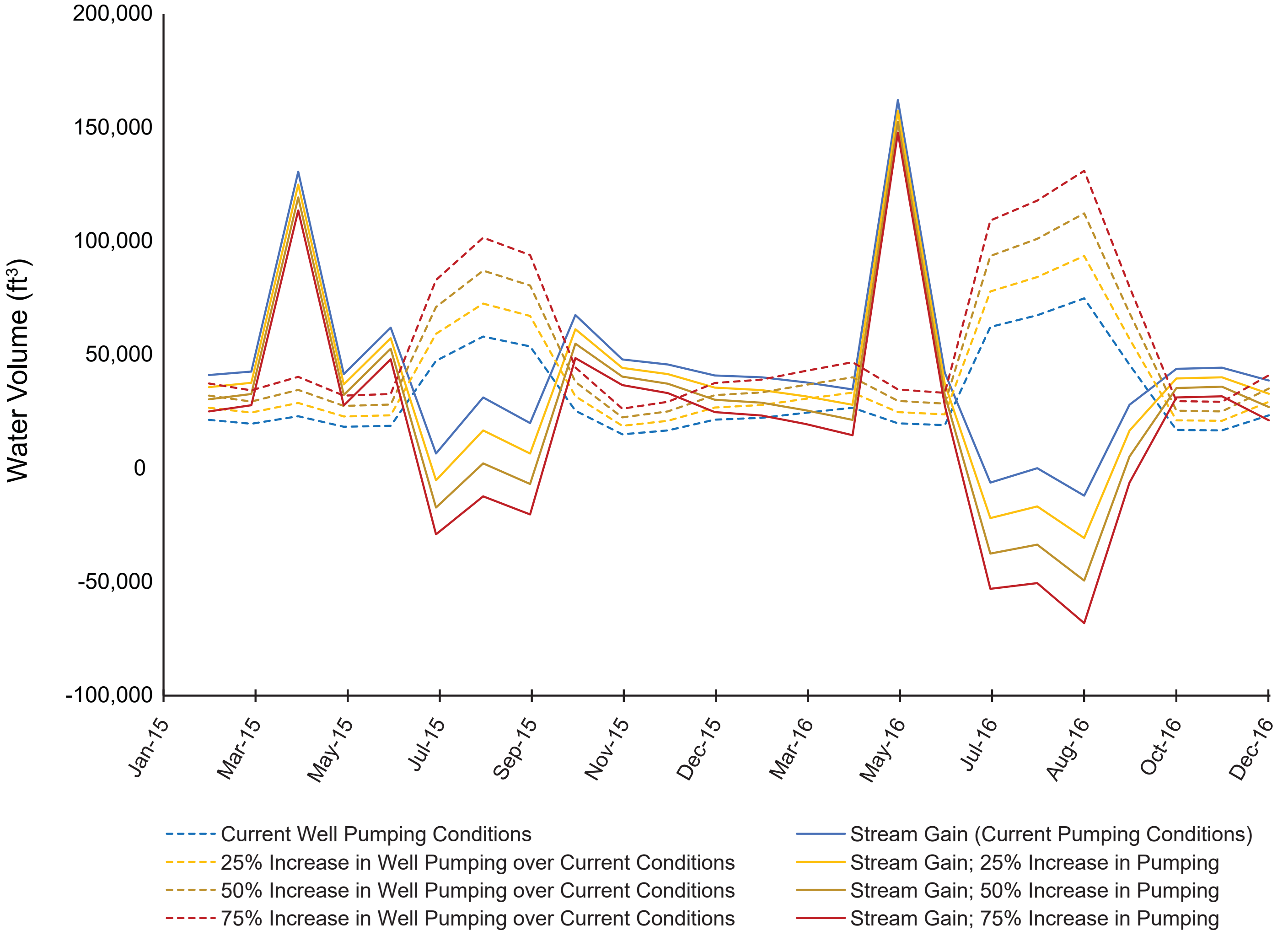


Figure 19. Modeled stream depletion associated with long-duration increases in pumping (scenario 2). Dashed lines are volumetric withdrawals from pumping wells; solid lines are stream gain from aquifer. Negative volumes indicate periods of stream loss to the aquifer. Note the correlation between change in stream gain and pumping indicate connection between the aquifer and stream.

Groundwater–surface-water interactions in this model were simulated using the MODFLOW river package. MODFLOW’s river package simulates and tracks the exchange of water between the river and the aquifer, which was sufficient for the objectives of this study and model preparation. However, if a more sophisticated representation of flow in the Middle Fork was desired, application of MODFLOW’s stream and streamflow routing packages might be appropriate. The stream and streamflow routing packages simulate and track groundwater–surface-water exchange, but also simulate the head in the stream and the volume of flow within it.

Additional limitations include the simplifying assumptions regarding interaction between the MVA and Crail Creek and exclusion of areas with less than 5–10 ft of saturated thickness. Interactions between Crail Creek and the MVA were not directly simulated. The flows in Crail Creek were too small to be practically measured and therefore contribution to the MVA was estimated and implemented as a specified flow boundary. For low-saturated thickness areas, model boundaries were set to account for estimated flow from these portions of the MVA while excluding them from the numerical calculation. This was done to avoid numerical instability and dry cell problems in the model. Additionally, monitoring wells in this portion of the MVA occasionally did not contain water, suggesting transitory saturation of this portion of the MVA. MODFLOW 2005, which was used for this study, does not allow for simulation of this transitory saturation. MODFLOW-NWT, MODFLOW-USG, and MODFLOW 6 are more recent iterations of MODFLOW that include the ability to treat this problem. Thus, modelers may consider utilizing one of these versions of MODFLOW if simulation of the low saturated thickness portions of the system are required.

CONCLUSIONS

This project yielded an unusually detailed set of model input information, presented either here or in the companion report (Rose and Waren, in review). The model input included the geometry of the aquifer and its connection to the Middle Fork, detailed groundwater levels in wells, recorded stream stages, snowmelt and precipitation recharge events, and volume pumped from the five municipal wells.

The steady-state and transient versions of the model are well calibrated and suggest each version reasonably represents the long-term, monthly, and daily response of the system in terms of water in and water out of the domain. There is good agreement between calculated and simulated monthly groundwater discharge to the Middle Fork. The power of the model is its capacity to simulate the complex interactions that arise from pumping multiple wells located at various distances from each other and from the Middle Fork. The numerical model can simulate a wide range of pumping rates and schedules, useful to fine-tune well field operations and to adequately plan for seasonal growth in water use. The transient models in particular are exceptional tools for evaluating operational issues, such as including well interference and excessive drawdown.

Specific pumping scenarios indicated a direct influence on discharge from the MVA to the Middle Fork. This is most strongly shown in the long-duration, increased pumping scenarios (described above as scenario 2), which show an approximately 1:1 relationship between changes in pumping rate and losses/gains to and from the Middle Fork. Groundwater from the MVA was simulated to be as much as 20% of baseflow to the Middle Fork. Thus, reductions in groundwater discharge associated with increased pumping from the MVA may lead to significant depletion in the Middle Fork's baseflow.

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