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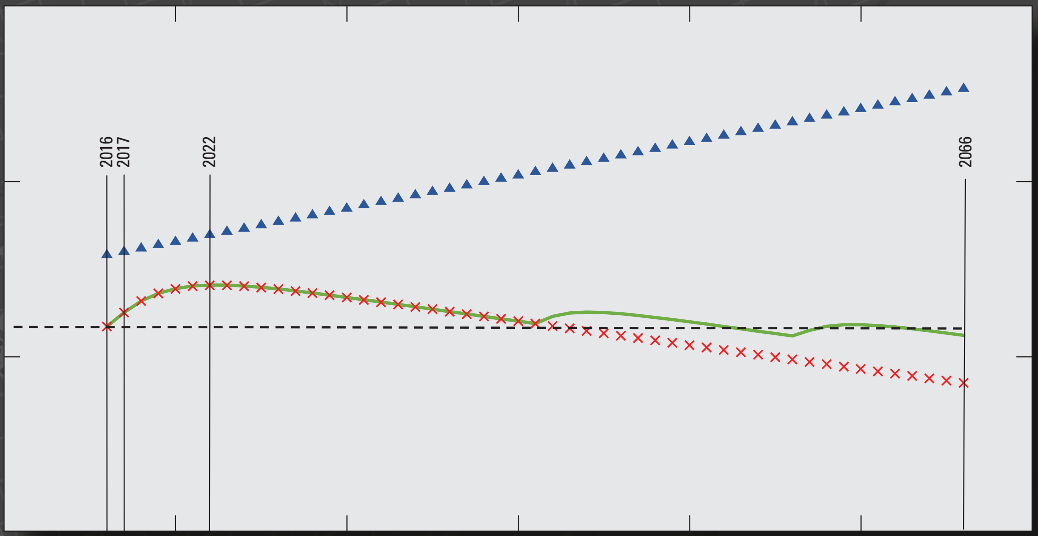
Groundwater Management Process Simulations Using an Updated Version of the Three-Dimensional Numerical Model of Groundwater Flow in Northern Utah Valley, Utah County, Utah



Scientific Investigations Report 2021–5010

U.S. Department of the Interior
U.S. Geological Survey

Cover: Sample graph showing potential impacts to groundwater discharge along Utah Lake.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
acre-foot per year (acre-ft/yr)	3.3794	cubic meter per day (m^3/d)

Datum

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

BCM	Basin Characterization Model
CUWCD	Central Utah Water Conservancy District
GWM	Groundwater Management
MAR	managed aquifer recharge
NUCAC	North Utah County Aquifer Council
USGS	U.S. Geological Survey

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Abstract

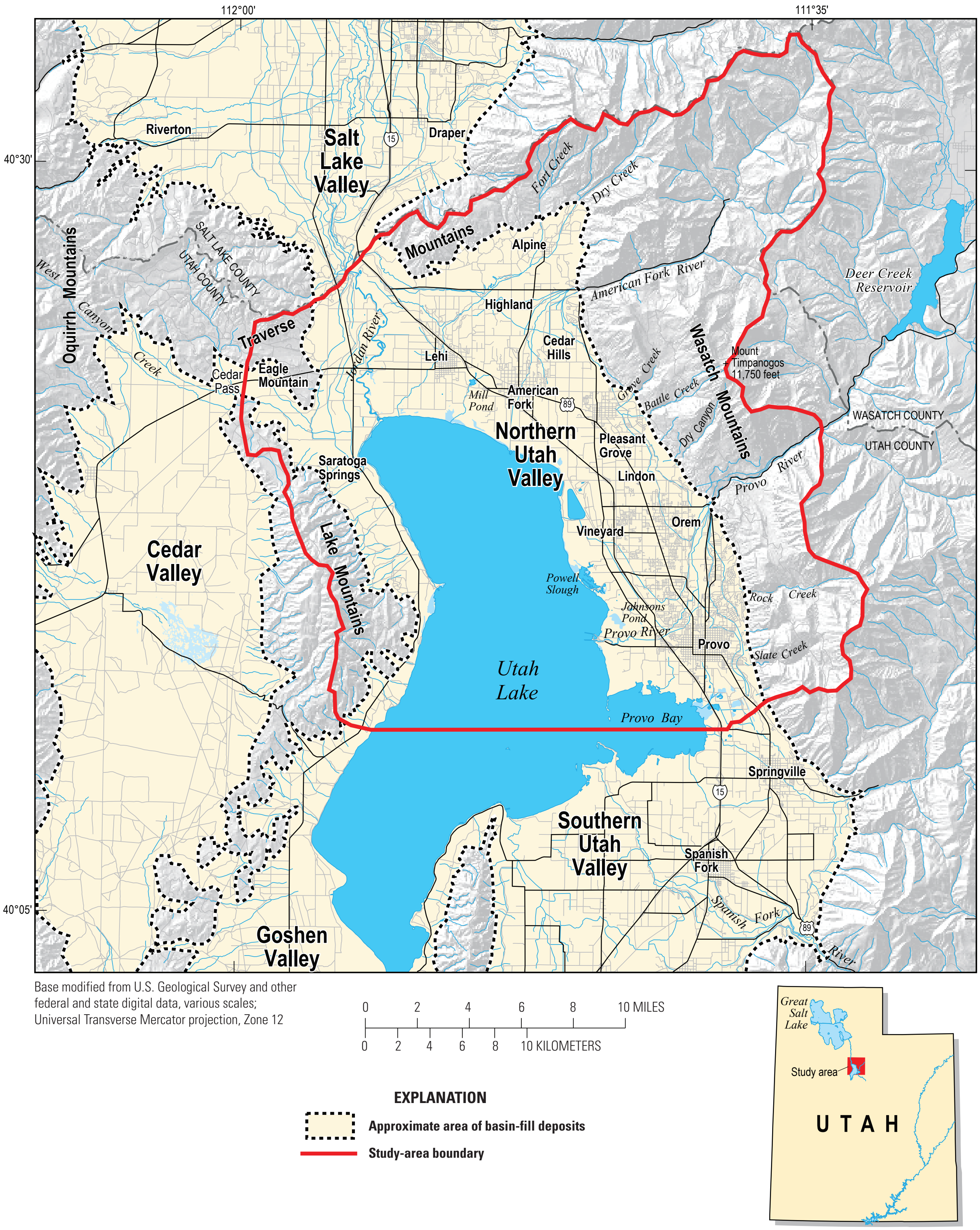
Groundwater is a primary source of drinking water in northern Utah County. The groundwater system is recharged mainly from precipitation in the adjacent Wasatch Mountains and infiltration of streamflow. In 2004, groundwater withdrawals were estimated to be roughly 44,500 acre-feet per year. In 2016, groundwater withdrawals were estimated to be greater than 63,400 acre-feet per year. To prepare for anticipated future increases in groundwater withdrawals, local cities identified 16 locations as feasible for managed aquifer recharge. Using an updated version of an existing U.S. Geological Survey groundwater flow model of northern Utah County, the Groundwater-Management Process for MODFLOW-2005 was used to investigate optimal managed aquifer recharge scenarios with the objective of maintaining acceptable reductions in simulated discharge at 12 groundwater discharge areas and flowing wells along Utah Lake.

The Groundwater-Management Process is applied to a 50-year (2017–66) projection of groundwater conditions using average recharge conditions and a linear increase of approximately 750 acre-feet per year of municipal groundwater withdrawals. Two sets of discharge constraints were applied. The first scenario constrains discharge to greater than or equal to 80 percent of the 2016 simulated groundwater discharge along Utah Lake. The constraint was met with a total managed aquifer recharge rate of roughly 7,300 acre-feet per year during 2042–56, and 15,600 acre-feet per year during 2057–66. A second scenario constrains discharge to greater than or equal to 90 percent of the 2016 simulated discharge. This constraint can only be met at 8 of the 12 discharge areas along Utah Lake. This required a managed aquifer recharge rate of roughly 10,000 acre-feet per year during 2042–56 and 15,400 acre-feet per year during 2057–66. For both scenarios, the Groundwater-Management Process indicated that all managed aquifer recharge sites need to be used to meet discharges constraints. The discharge constraints were informally defined on the basis of the water rights hierarchy associated with Utah Lake.

Introduction

Groundwater is a primary source of drinking water in the northern Utah County study area (fig. 1). Monitoring, sensible management, and informed decisions are required to ensure the ongoing viability of the groundwater system. Cederberg and others (2009) describe the hydrogeology of northern Utah Valley, which includes interpretations of aquifer properties and geometry, groundwater recharge and discharge, and groundwater flowpaths. These attributes are combined in a three-dimensional numerical groundwater flow model constructed by Gardner (2009). The numerical model represents conditions from 1947 to 2004. Groundwater withdrawals in 1947 were approximately 1,300 acre-feet per year (acre-ft/yr). By 2004, groundwater withdrawals had increased to roughly 44,500 acre-ft/yr. In 2016, the estimated groundwater withdrawals for northern Utah County was more than 63,400 acre-ft/yr. The average annual simulated groundwater recharge from precipitation and stream loss for 1947–2016 is 167,000 acre-ft/yr. Increased withdrawals are reflected in groundwater levels. At most of the wells monitored by the U.S. Geological Survey (USGS) in northern Utah County (Burden and others, 2016, fig. 13), groundwater levels were the lowest on record in 2016. Measured water-levels date back to the mid-1940s. Water-level declines after the highest recorded levels in 1984–85 ranged from 5 feet (ft) to more than 60 ft.

To prepare for anticipated future increases in groundwater withdrawals, the municipalities of Alpine, American Fork, Highland, Lehi, Pleasant Grove, and the Central Utah Water Conservancy District (jointly referred to as the North Utah County Aquifer Council [NUCAC]) are considering diverting surface water to 16 managed aquifer recharge (MAR) sites. The proposed MAR sites are spreading basins



Base modified from U.S. Geological Survey and other federal and state digital data, various scales; Universal Transverse Mercator projection, Zone 12

Figure 1. Location of the study area, northern Utah County, Utah.

and injection wells that were identified by the engineering firm of Hansen, Allen and Luce, Inc. Engineers (2012). The USGS, in cooperation with the NUCAC, used an update of the groundwater flow model of northern Utah County by Gardner (2009) and the Groundwater-Management (GWM) Process for MODFLOW-2005 (Ahlfeld and others, 2005, 2009) to project groundwater conditions for 50 years (2017–66). The projection uses average recharge conditions and a linear increase of roughly 38,000 acre-ft/yr of groundwater withdrawals. The benefits of MAR are measured in terms of maintaining acceptable reductions in simulated discharge at 12 groundwater discharge areas and flowing wells along Utah Lake. Discharge along Utah Lake is considered a robust descriptor of overall groundwater conditions because it summarizes the terminal end of the active groundwater flow system.

The GWM Process is an optimization process that adjusts decision variables (recharge at 16 MAR sites) to maintain a user-defined amount of discharge at state variables (discharge at 12 locations along Utah Lake). The optimization process is constrained by the maximum amount of MAR, as defined in Hansen, Allen and Luce, Inc. Engineers (2012), and reductions in discharge along Utah Lake. Two sets of constraints (scenarios) were tested. Constraint values are loosely based on water rights associated with Utah Lake and qualitatively acceptable impacts on the 12 discharge areas along Utah Lake.

Purpose and Scope

This report describes modifications made to the numerical model of groundwater flow in northern Utah County by Gardner (2009) and implementation of the GWM optimization process (Ahlfeld and others, 2009). The model by Gardner (2009) is updated by adding 12 annual stress periods that incorporate observed groundwater conditions for 2005–16, revised estimates of recharge from mountain and valley precipitation, changes in land use, piping of the Murdock Canal, and simulation of 29 additional groundwater withdrawal wells. Simulated well withdrawals increased by 18,900 acre-ft/yr during 2005–16. A projection model is used to simulate average conditions, and a 50-year linear increase of roughly 38,000 acre-ft/yr in groundwater withdrawals (starting in 2017 and ending in 2066). All other specified boundaries in the model simulate 1947–2016 average flux rates. New and existing well locations, and projections of increased groundwater withdrawals were made in concurrence with the NUCAC.

To better understand how MAR can be optimized to mitigate the impacts of increased groundwater withdrawals, the GWM Process (Ahlfeld and others, 2009) was applied to the 50-year (2017–66) period of linearly increasing groundwater withdrawals. The objective of the GWM Process is to minimize the amount of surface water (Hansen, Allen and Luce, Inc. Engineers, 2012) diverted to the 16 MAR sites while maintaining a predefined amount of groundwater discharge along the shoreline of Utah Lake.

Using the linear increase in groundwater withdrawal rates (of approximately 750 acre-ft/yr), the first projection simulates future groundwater conditions without the use of MAR. The second projection optimizes MAR with the constraint of maintaining 80 percent of the 2016 simulated groundwater discharge along Utah Lake. The third projection optimizes MAR with the constraint of maintaining 90 percent of the 2016 simulated discharge along Utah Lake. The 80-percent constraint represents a value that can be sustained without a large disruption to the current water rights hierarchy. The 90-percent constraint was simulated to test the limits of MAR to offset impacts of increase in groundwater withdrawals.

Description of Study Area

The study area covers approximately 430 square miles (mi^2) and includes the northern half of Utah Valley and adjacent mountain areas (fig. 1). The center of Utah Valley is covered by Utah Lake, a natural and shallow (about 10 ft deep) fresh waterbody. Both surface water and groundwater within the study area reach their terminus at Utah Lake. The valley area consists of unconsolidated basin-fill; the surrounding mountains are made of Paleozoic carbonates, quartzites, and shales. Relief between Utah Lake and the crest of the Wasatch Mountains is nearly 7,000 ft.

Land use in the 1960s was mainly irrigated and non-irrigated agriculture. By the 2000s, land use had become predominately residential/commercial as a result of the population more than doubling between 1990 and 2010. A large source of drinking water in the study area is groundwater, which is provided by local municipalities and the Central Utah Water Conservancy District.

Groundwater Hydrology

Groundwater recharge is from precipitation and irrigation, seepage from rivers and canals, and subsurface inflow from Cedar Valley (fig. 1). Groundwater discharge occurs to municipal and irrigation wells, flowing wells, drains, and springs along Utah Lake, springs and diffuse seepage beneath Utah Lake, rivers, evapotranspiration, and subsurface outflow to Salt Lake Valley (Cederberg and others, 2009, table 4). The general direction of groundwater flow is from the Wasatch Mountains to Utah Lake (Cederberg and others, 2009, figs. 26–28). Groundwater from the Wasatch Mountains (mountain block) is a subsurface source of recharge to the adjacent unconsolidated basin-fill of northern Utah Valley. The unconsolidated basin-fill is separated into 11 hydrogeologic units (Cederberg and others, 2009, figs. 11–16) that are simulated as 4 model layers using the Hydrogeologic-Unit Flow (HUF) package (Gardner, 2009, p. 7; Anderman and Hill, 2000).

Updated Model

The numerical model of groundwater flow in Northern Utah County by Gardner (2009) simulates groundwater conditions in the consolidated-rock mountains and adjacent unconsolidated basin-fill deposits from 1947 through 2004. The updated model described in this report extends the model by Gardner (2009) by 12 annual stress periods to describe groundwater conditions from 1947 through 2016. The updated model incorporates the same boundaries and geometry as the Gardner (2009) model, with modifications to (1) the amounts and timing of areal recharge in the mountain and valley areas, (2) geometry of the stream and canal network that includes cessation of recharge from the Murdock Canal due to piping in 2012, (3) adjustments to drain elevations that simulate discharge along Utah Lake to equate to land-surface elevation, (4) minor modifications to selected model cell-bottom elevations and thicknesses to avoid dry cells, (5) the addition of 29 groundwater withdrawal wells that were brought into production during 2005–16, (6) observations of groundwater and surface-water conditions during 2005–16, (7) annual average water elevation of Utah Lake, and (8) water-level observations for 2005–16.

Recharge from Precipitation

Groundwater recharge from precipitation in the mountain and valley areas are incorporated in the 12 additional stress periods of the updated model, using the same procedures as described by Gardner (2009, p. 22). The distribution of groundwater recharge in the mountain areas in the model by Gardner (2009, figs. 3 and 12) is scaled from the Basin Characterization Model (BCM) estimates of annual average recharge for 1970–2004 (Flint and others, 2004). The BCM combines monthly spatial estimates of precipitation, air temperature, potential plant evapotranspiration, soil characteristics, topography, and bedrock permeability to determine spatially distributed estimates of recharge (Hevesi and others, 2003). In the groundwater model, recharge scalers are used to input the annual variations in recharge as multiples of the BCM annual average estimate of recharge. Scaling is justified on an analysis of the annual BCM estimates of recharge, which showed minimal variation in the spatial distributions of annual recharge and considerable variation in the amounts of annual recharge (Gardner, 2009, p. 22). For the updated model, an extended BCM dataset that defines 1940–2014 recharge amounts is used. Recharge scalers for 1947–2014 are calculated as a ratio of the BCM annual recharge for the specific year to the BCM 1940–2014 average annual recharge. Additional information describing BCM inputs, uncertainty, and limitations are described in Flint and others (2011, appendix 3).

For 2015 and 2016, scaling was based on a regression equation that relates the average annual gaged streamflow in the American Fork River above the upper power plant for 1947–2005 to the annual BCM recharge values for 1947–2005 (fig. 2).

Groundwater recharge also is simulated from valley precipitation on coarse-grained basin-fill, which is delineated as the primary recharge area of northern Utah Valley (Gardner, 2009, figs. 3 and 14; Anderson and others, 1994). The average areal recharge from direct infiltration of valley precipitation is estimated to be 3,200 acre-ft/yr for 1975–2000 (Cederberg and others, 2009, p. 31) and is distributed across the primary recharge area (fig. 3) using the 1971–2000 average precipitation contours derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) average precipitation raster datasets. The average recharge amount is varied for each stress period by dividing the annual precipitation at Pleasant Grove by the 1971–2000 average precipitation at Pleasant Grove (Gardner, 2009, fig. 14). For the updated model, recharge from valley precipitation is based on precipitation at Pleasant Grove for a period of complete records (2001–09) and a 5-year regression of monthly precipitation between the Pleasant Grove and Alpine meteorological stations for a period when both stations recorded conditions without missing data. The regression was used to fill in missing data at Pleasant Grove. The hybrid meteorological dataset was used to scale the 1971–2000 average precipitation at Pleasant Grove for 2005–16 in the updated model.

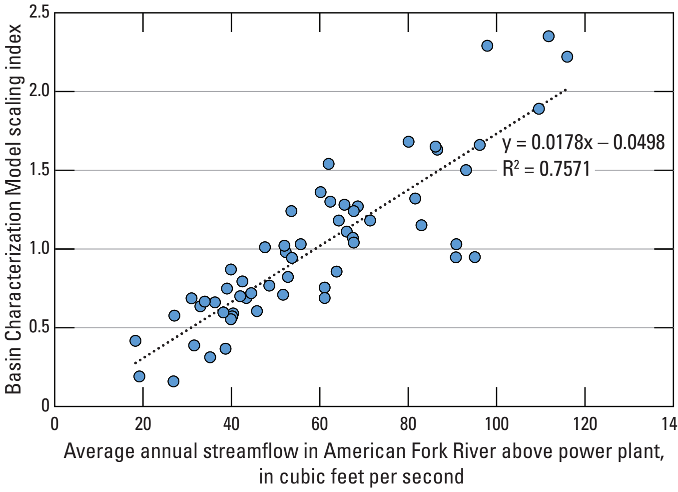
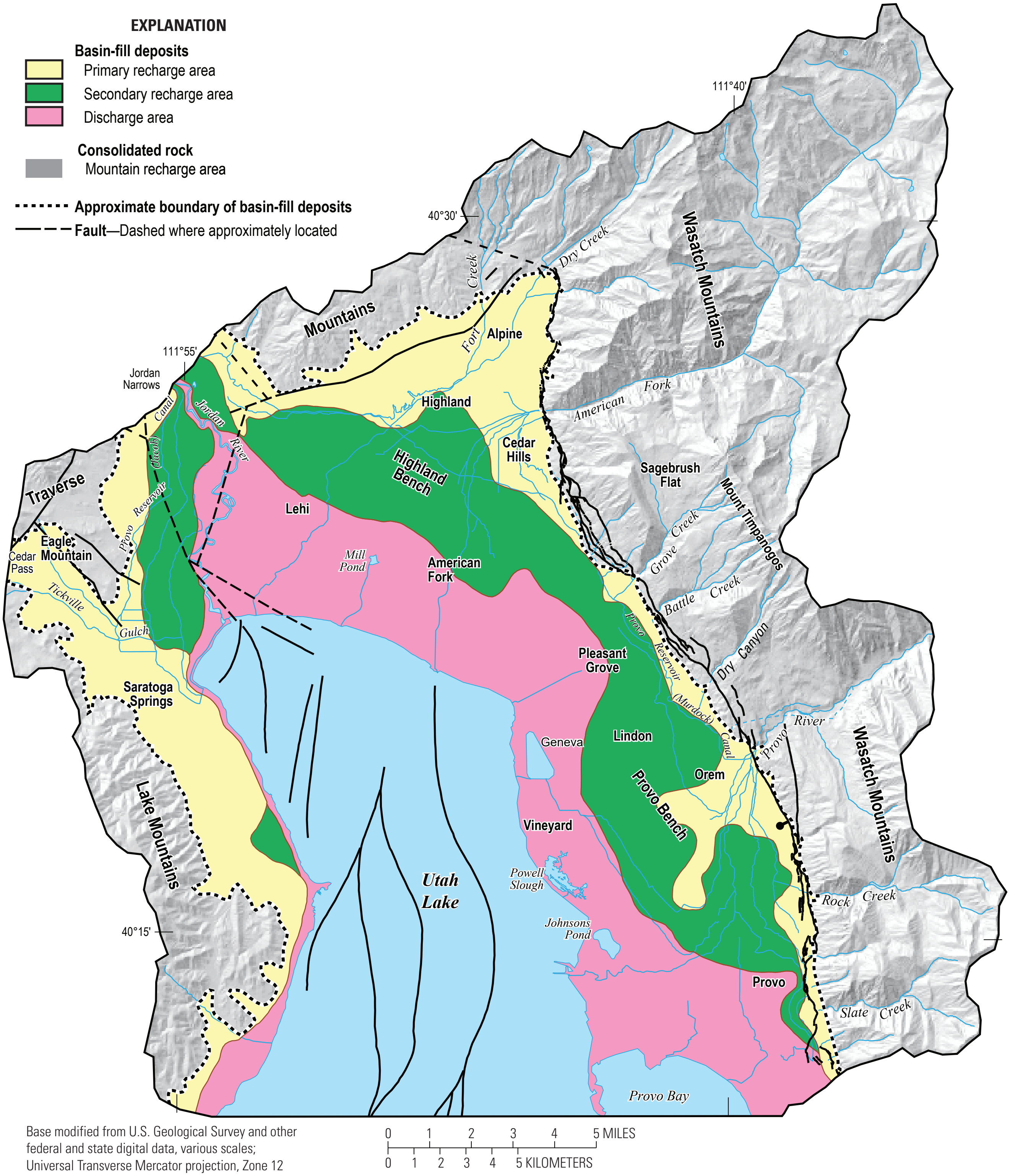


Figure 2. Basin Characterization Model scaling index as a function of average annual streamflow in the American Fork River above upper power plant near American Fork (U.S. Geological Survey streamflow-gaging station 10164500), northern Utah County, Utah.



Base modified from U.S. Geological Survey and other federal and state digital data, various scales; Universal Transverse Mercator projection, Zone 12

Figure 3. Location of recharge and discharge areas, northern Utah County, Utah (modified from Gardner, 2009, fig. 2).

Recharge from water applied to agriculture fields and residential lawns within the primary recharge area (Gardner, 2009, fig. 15) also is modified to describe conditions in 2005–16. The spatial distribution within the primary recharge area is based on water-related land-use surveys made in 1966, 1980, 1988, 1995, and 2002 (Utah Department of Natural Resources, https://drive.google.com/drive/folders/0B8agagPrSa5xanpqWlBnd2xlakU) for the previous model. For the update period, the spatial distribution is based on the 2012 water-related land use (Utah Department of Natural Resources, https://drive.google.com/drive/folders/0B8agagPrSa5xanpqWlBnd2xlakU).

Well Withdrawals

The first stress period of both the model by Gardner (2009) and the updated model simulate conditions for 1947, during which groundwater withdrawals at four wells totaled 1,282 acre-feet (acre-ft; fig. 4). Simulated withdrawals in 2004, the final stress period of the model by Gardner (2009), is 44,500 acre-ft (rounded). Simulated withdrawals in 2016, the final stress period of the updated model, is 63,400 acre-ft (rounded). The updated model simulates an additional 29 wells (table 1) that were identified as being constructed between 2004 and 2016. The horizontal and vertical locations of wells simulated in the updated model were modified if more recent information, provided by cooperators or revised by USGS, improved accuracy. Model layer bottoms and thicknesses were adjusted slightly in one area where the original model was dry in layer 1, and in two areas where new withdrawals caused numerical instability because of thin saturated thicknesses in layer 1. The Eagle Mountain Well #5 is simulated in two adjacent cells to prevent drying model cells in layer 1 during the projection run.

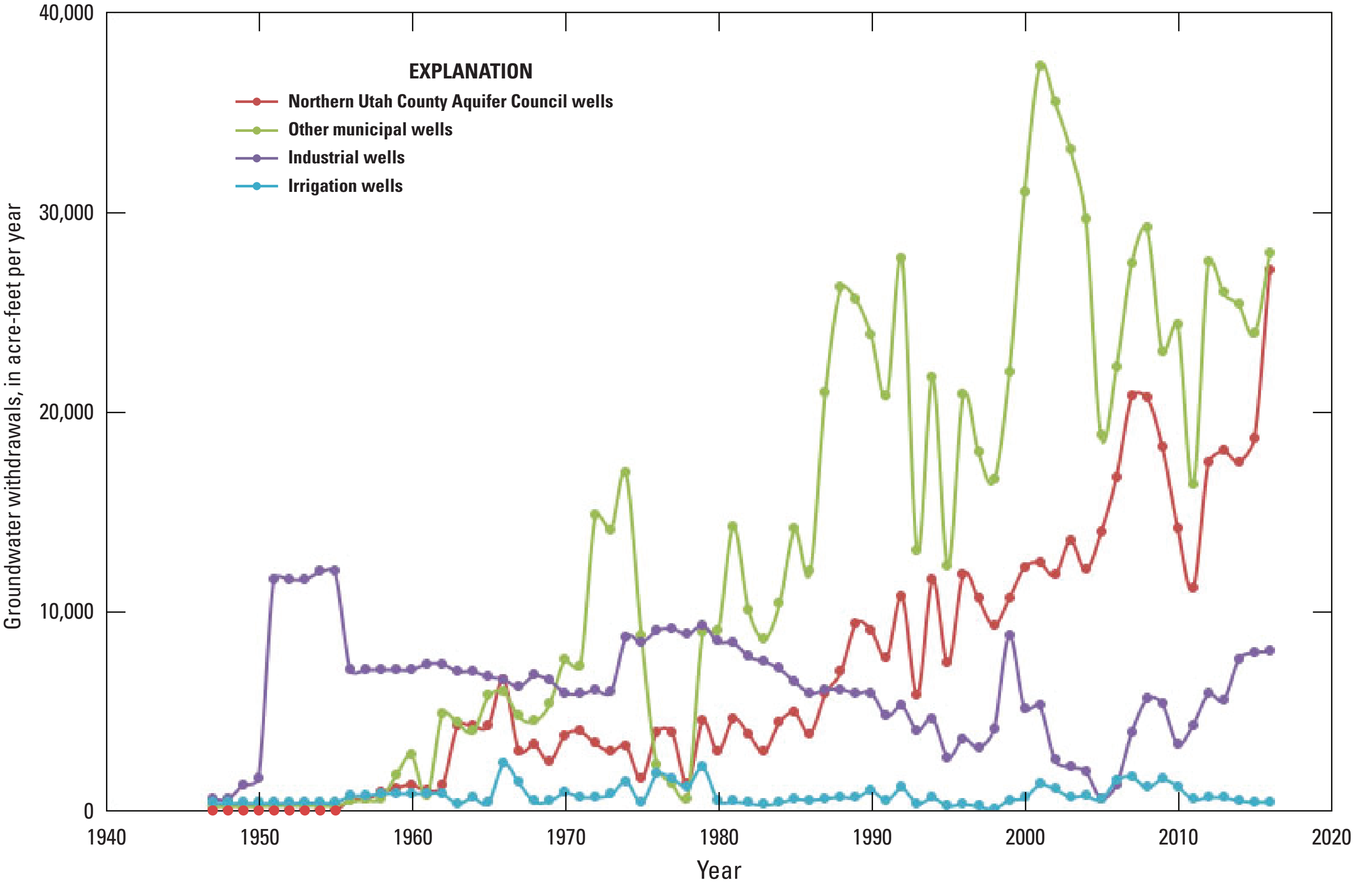


Figure 4. Annual groundwater withdrawals from wells for 1947–2016 simulated in the updated groundwater flow model, northern Utah County, Utah.

Table 1. Additional groundwater withdrawal wells simulated in the updated groundwater flow model, northern Utah County, Utah.

[NWIS, Natonal Water Information System; —, information is not available or unknown; NUCAC, North Utah County Aquifer Council; CUWCD, Central Utah Water Conservancy District]

Well name	Operating entity	Local site identifier	NWIS identifier	Use	Classification	Year drilled	Diameter (inches)
Ranch Well	Alpine City	(D- 4- 1)25bca- 1	402642111471801	—	NUCAC	—	—
Cottonwood Well	Cedar Hills	(D- 4- 2)31dda	—	Public supply	NUCAC	2008	20
Well #12	CUWCD	(D- 6- 2) 8aaa	—	Public supply	NUCAC	2011	24
Well #11	CUWCD	(D- 6- 2) 8add	—	Public supply	NUCAC	2011	24
Site B: Main Well (8”)	Dyno Nobel	(D- 6- 1)30baa	—	—	Industrial	—	—
Golf Course Well #6	Eagle Mountain	(C- 5- 1)20ada	—	Irrigation	Public supply	—	—
Well #5	Eagle Mountain	(C- 5-1)30cbb	—	—	Public supply	2007	20
Pelican Point	Geneva Rock Orem	(D- 6- 1)31add	—	Industrial	Industrial	2009	10.75
Well #6 (11800 North)	Highland City	(D- 4- 1)26abc- 1	402648111480701	Irrigation	NUCAC	2004	—
Well #2	IM Flash	(D- 4- 1)33bbb	—	Industrial	Industrial	2008	16
Jordan Narrow Well	Lehi City	(C- 4- 1)26dac- 1	402621111543801	Irrigation	NUCAC	—	—
Airport Well	Lehi City	(D- 5- 1) 4dcb- 1	402432111502301	Public supply	NUCAC	—	—
Sand Pit Well	Lehi City	(D- 5- 1) 5aab	—	Public supply	NUCAC	—	—
Mitchell Well	Lehi City	(D- 5- 1)10acc	—	Public supply	NUCAC	—	—
Minnie Creek Well	Lehi City	(D- 5- 1)21caa	—	Irrigation	NUCAC	2011	16
Pilgrim Well	Lehi City	(C- 4- 1)25abb- 1	402652111540301	—	NUCAC	—	—
Well no. 8	Orem City	(D- 6- 2)23bda	—	Public supply	Municipal	—	—
Well no. 9	Orem City	(D- 6- 2)24bcd	—	Public supply	Municipal	—	—
Well #2	Pacificorp	(D- 6- 2) 6aac	—	Industrial	Industrial	2006	—
Well #4	Pacificorp	(D- 6- 2) 6aac	—	Industrial	Industrial	—	—
Well #3	Pacificorp	(D- 6- 2) 6aad	—	Industrial	Industrial	2006	—
Well #1	Pacificorp	(D- 6- 2) 6ada	—	Industrial	Industrial	2005	—
Gibson Well	Pleasant Grove City	(D- 5- 2)28aac	—	Public supply	NUCAC	—	—
West Union Canal Well	Provo City	(D- 6- 2)26ddd- 1	401612111403501	—	Municipal	—	—
Riverwoods	Provo City	(D- 6- 3)18cbb- 1	401745111392501	—	Municipal	—	—
Timpview Well	Provo City	(D- 6- 3)19dcc- 1	401638111384701	—	Municipal	—	—
Canyon Road Well	Provo City	(D- 6- 3)30bca	—	—	Municipal	—	—
Well #6	Saratoga Springs	(C- 5- 1)24adc- 1	402214111532901	Public supply	Municipal	2001	12
Well	TalonCove Golf	(D- 6- 1)31add	—	Industrial	Industrial	2009	10.75

Groundwater Discharge

Drain boundaries are used to simulate diffuse groundwater discharge, springs, and flowing wells next to the eastern side of Utah Lake (fig. 5; Gardner, 2009, fig. 19). Drain boundaries representing diffuse groundwater discharge (seepage) and springs are assigned to model layer 1. Drain boundaries that represent flowing wells are assigned to model layers 2 and 3. Gardner (2009, p. 33) stated that all drain elevations are set equal to land surface; however, examination of model files showed some discrepancies with that definition. The discrepancies are likely due to differences in methods used to determine the altitude of drains and altitude at the center of a cell. The top of model layer 1 is defined for the center point of the cell; drain altitude is defined for the location of the spring or flowing well. When cell center and spring locations do not align, the altitudes may not equate. For the updated model, drain altitude in layer 1 was not adjusted if it was within 20 ft of the top of model layer 1. Drains that were more than 20 ft below the top of model layer 1 were adjusted to be 20 ft below the top of model layer 1. Drain altitudes in layers 2 and 3 were often much higher than drain altitude in layer 1 or top of model layer 1. Drain altitude for all drains in model layers 2 and 3 are changed to be equal to the top elevation of model layer 1. These adjustments created more discharge to flowing wells and less discharge to springs. The parameters listed in table 2 were adjusted in the updated model to maintain approximately the same distribution and total amount of discharge as in the model by Gardner (2009; table 7).

General-head boundaries are used to simulate subsurface inflow of groundwater from Cedar Valley through the Cedar Pass area (Cederberg and others, 2009, fig. 5), and also for subsurface outflow to Salt Lake Valley. Outflow to Salt Lake Valley is simulated at the Jordan Narrows (fig. 5). The water levels (heads) and conductance values assigned to the general-head boundaries are the same as those used by Gardner (2009, p. 28).

Surface Water

Surface water is simulated in terms of recharge to the groundwater system (loss of surface water to the underlying aquifer) and discharge from the groundwater system (discharge out of the aquifer that creates and sustains stream baseflow). Surface water is not considered in terms of runoff from precipitation or tracking total water mass-balance along streams reaches and inflow to Utah Lake. Head-dependent boundaries used to simulate streams and canals (Prudic, 1989) incorporate the hydraulic gradient between simulated groundwater levels and elevations for streams and canals. The boundaries are shown on figure 6 and are limited to the mountains and primary recharge area. Additional groundwater interaction that occurs where streams cross the secondary recharge area is estimated to be minimal. Streamflow that enters the discharge areas becomes mixed with diffuse groundwater discharge and is accounted for in discharge area flow observations. Outflow from Utah Lake is to the Jordan River, which is simulated as a head-dependent boundary. The Jordan River is located in the lowest elevation parts of the study area and is the only stream simulated in the valley discharge area (fig. 6).

Canals and diversions also are simulated as head-dependent boundaries (Gardner, 2009). The updated model incorporates some modifications to the simulated canal network. These modifications include points of diversion from streams, splits to smaller distribution canals, some changes to streambed elevation, and tributary inflows. The level of detail incorporated in the simulation of groundwater and surface-water interaction required additional information about streamflows, canal diversions from streams, canal routing connections, and irrigation practices. This was provided by members of the NUCAC, Provo River Water Users Association, PacificCorp, and local water managers. In 2012, the Murdock Canal was replaced with a 10.5-ft-diameter pipeline and is no longer simulated. Utah Lake is simulated as a constant-head boundary (Harbaugh, 2005, p. 8–21), and lake levels for each year were assigned to the boundary.

Table 2. Modified MODFLOW parameter values in the updated groundwater flow model, northern Utah County, Utah.

Parameter	Model by Gardner (2009)	Updated model
DRN_SARTGA	0.01	0.05
DRN_DRYCRK	0.01	0.0002
DRN_BYU_G1	0.0005	0.05
DRN_MILPND	0.05	0.05
DRN_BYU_G2	0.0005	0.0003
DRN_BYU_G3	0.0005	0.01
DRN_GENEVA	0.001	0.005
DRN_BYU_G4	0.0005	0.005
DRN_POWELL	0.005	0.01
DRN_JOHNSN	0.0005	0.0002
DRN_SSPRGS	0.05	0.05
DRN_BGDRCK	0.0002	0.0002
FLOWEL	0.00009	0.000057

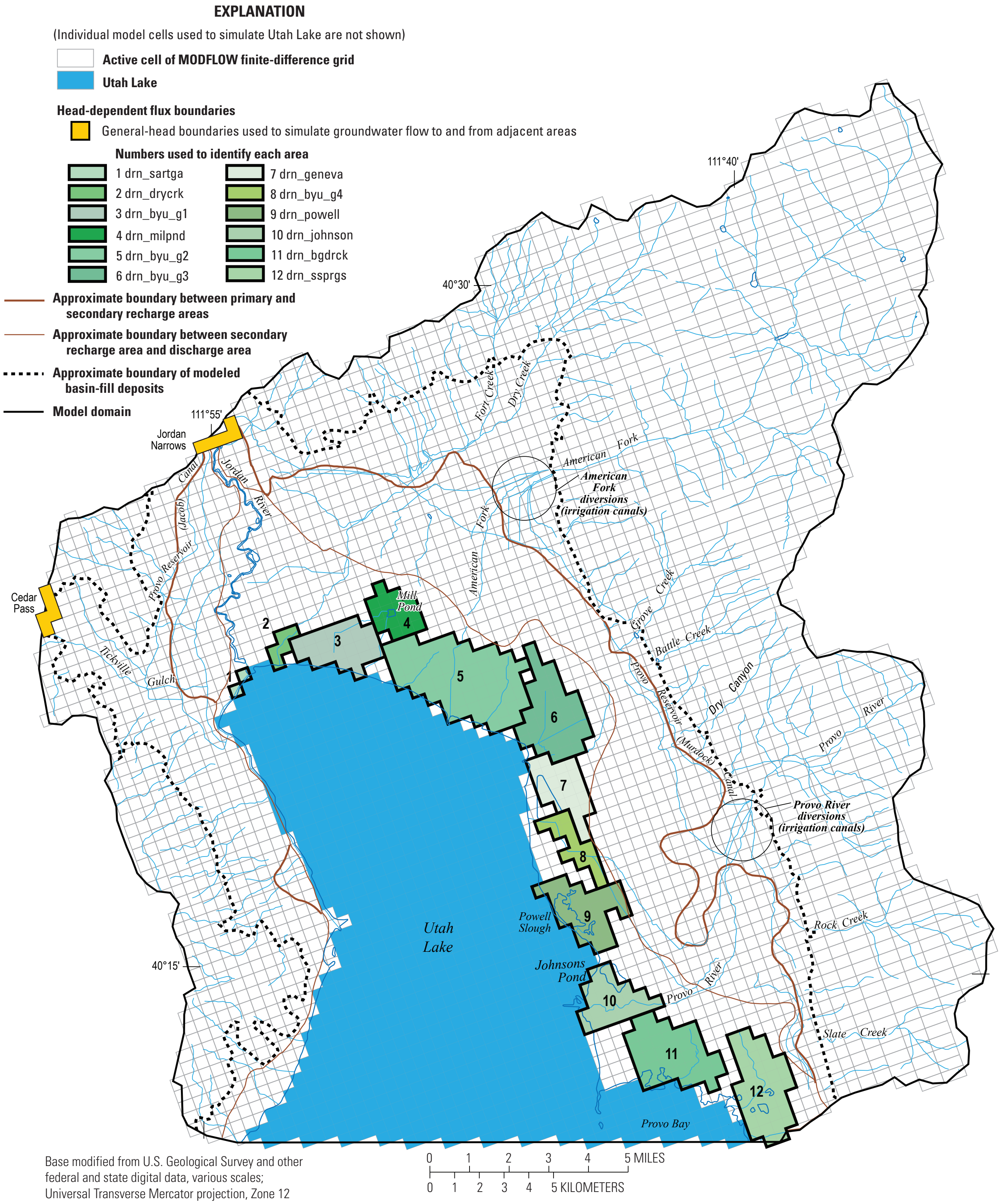
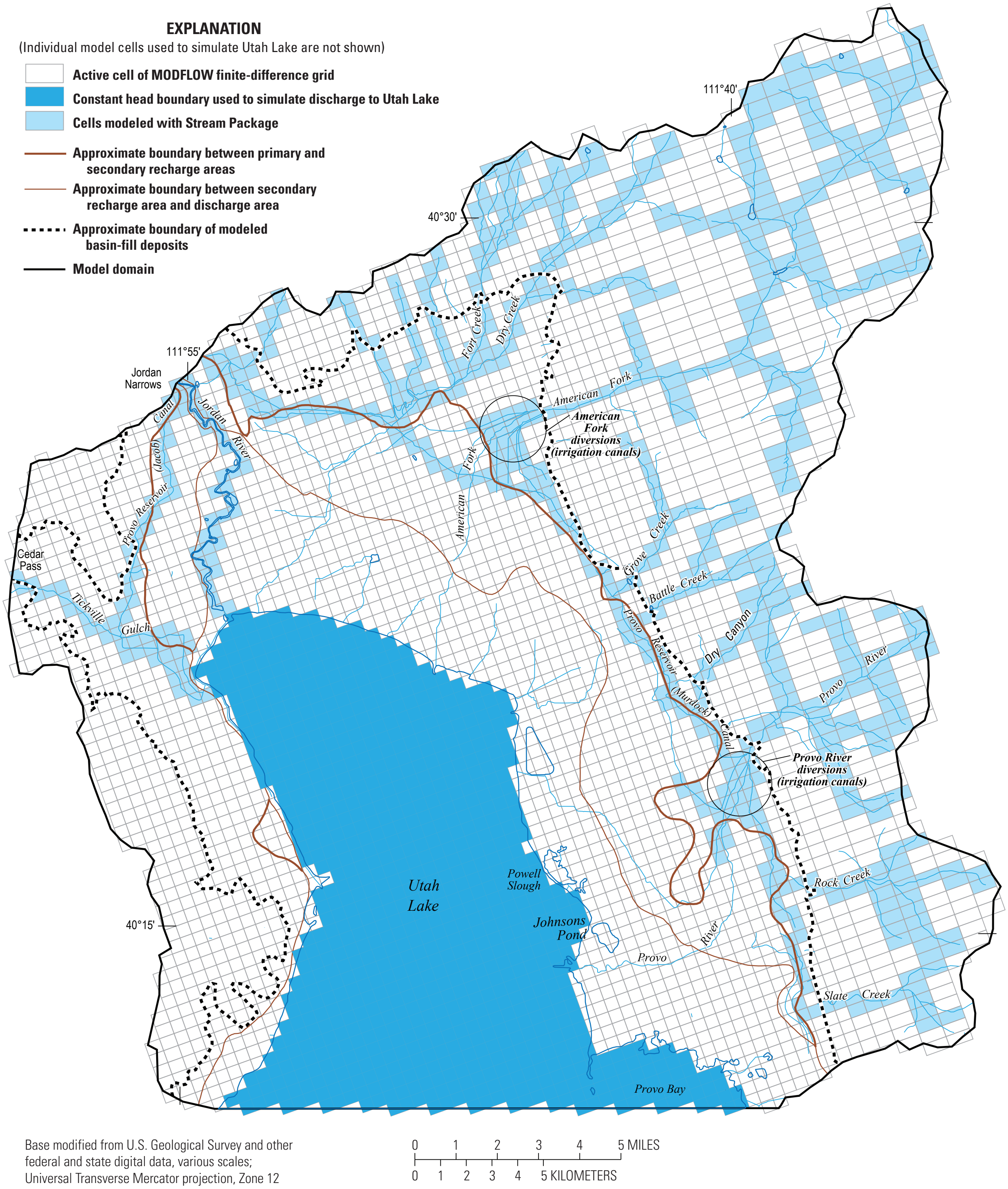


Figure 5. Location of model cells containing head-dependent flux boundaries that simulate groundwater inflow and outflow from adjacent areas and diffuse groundwater seepage and spring discharge on the eastern side of Utah Lake, in the updated groundwater flow model, northern Utah County, Utah.



Base modified from U.S. Geological Survey and other
federal and state digital data, various scales;
Universal Transverse Mercator projection, Zone 12

Figure 6. Location of model cells containing head-dependent flux boundaries that simulate groundwater interaction with mountain streams, valley stream reaches and canals, and the constant-head boundary that simulates Utah Lake in the updated groundwater flow model, northern Utah County, Utah.

Stream boundaries in the mountain areas were used during calibration of the model by Gardner (2009) to evaluate the simulated hydraulic conductivities assigned to consolidated rock. Parameters that determine the hydraulic conductivity values were adjusted by Gardner (2009) to obtain reasonable matches between observed and estimated baseflows in mountain streams. To prevent differences between simulated and observed streamflow in the mountain areas from carrying over to routing surface water in the valley areas, surface-water boundaries are not continuous across the mountain front (Gardner, 2009, p. 32). Streamflow assigned to stream segments closest to the mountain front are reset to gaged or best-estimate values for those locations (Cederberg and others, 2009). This reset guarantees that surface water crossing the primary recharge area, where high infiltration rates are conceptualized to occur (Cederberg and others, 2009, p. 25), are a reasonable facsimile of observed streamflow. Parameters used to calculate mountain and valley streambed conductance were not adjusted in the updated model.

Additional information about canal diversions from streams, canal routing connections, and irrigation practices were provided by members of the NUCAC, Provo River Water Users Association, and PacifiCorp. Utah Lake levels are monitored and recorded by the Central Utah Water Conservancy District (CUWCD) and Utah Division of Water Rights. Utah Lake levels for the 2005–16 update period were provided by CUWCD (Caitlyn Erickson, written commun., July 21, 2017). The longest record of gaged streamflow in the study area is the American Fork River above upper power plant near American Fork (USGS streamflow-gaging station 10164500). Continuous discharge has been recorded at the site since 1927 and the station is currently (2019) still in operation. However, from July 2006 to June 2011, the gage was not operated, and streamflow for the interval was estimated using a statistical regression between BCM estimated recharge and annual average gaged streamflow (fig. 7).

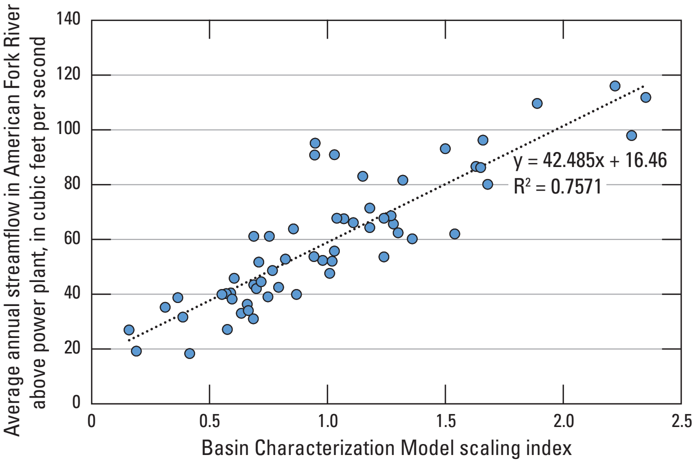


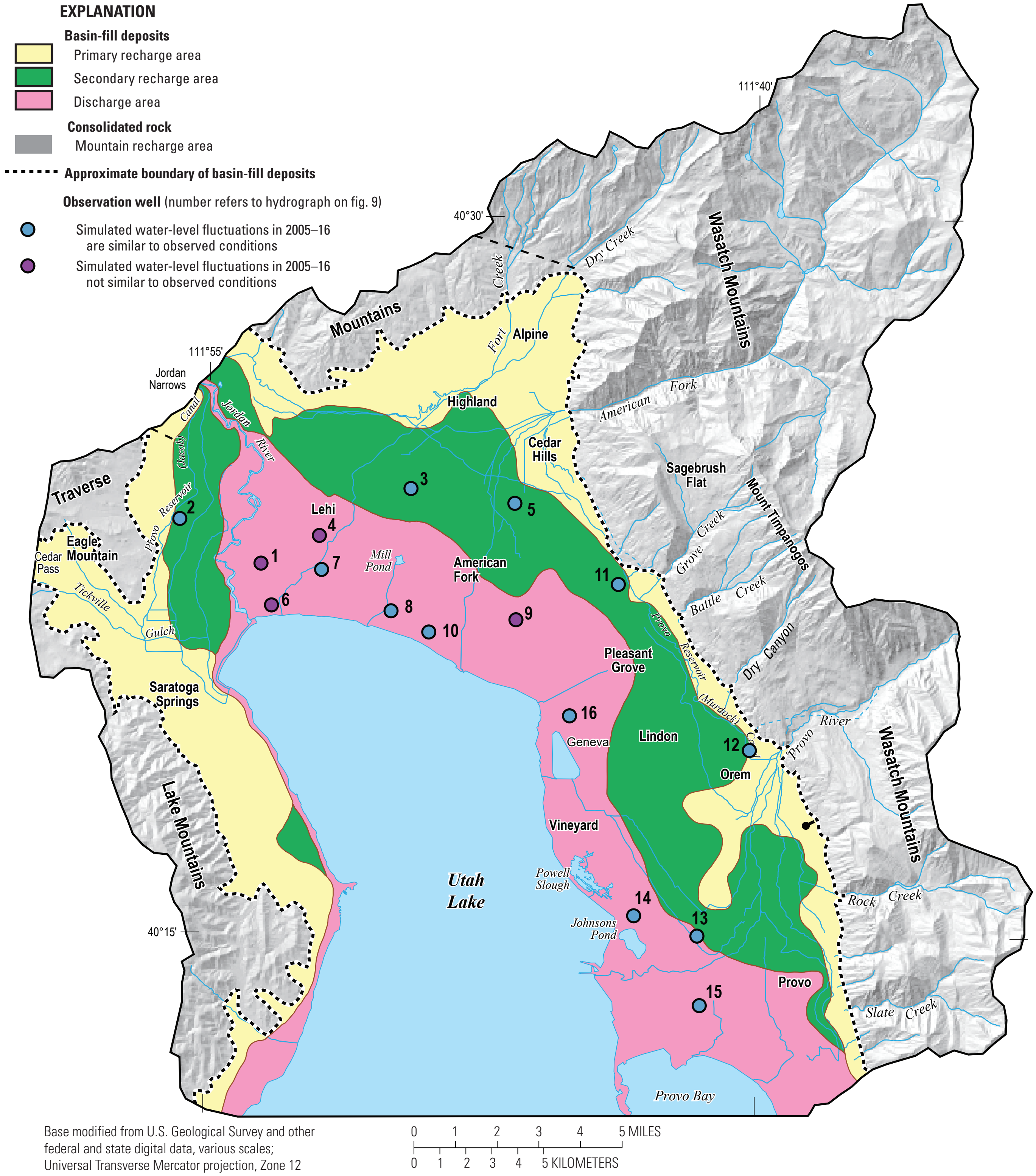
Figure 7. Annual average streamflow in the American Fork River above upper power plant near American Fork (U.S. Geological Survey streamflow-gaging station 10164500) as a function of the Basin Characterization Model scaling index, northern Utah County, Utah.

Assessment of the Updated Model

The ability of the updated model, without further calibration, to replicate the model by Gardner (2009) for 1947–2004 is appraised by comparison of water levels and water budgets. The average simulated water level in layer 1 of the updated model, for 2004, is about 1.0 ft higher then simulated by Gardner (2009). At limited areas near Utah Lake, simulated water levels in the updated model differ from Gardner (2009) by ±20 ft. This is likely related to adjustments in drain elevations and parameters. In general, water levels simulated by the updated model trend slightly higher than in the model by Gardner (2009). For the 16 observation wells shown on figures 8 and 9, the average difference between simulated water levels for 1947–2004 (no shading) was 2.6 ft higher in the updated model. The updated model simulates a budget for 2004 that is almost identical to the budget simulated by Gardner (2009). Therefore, the formal model sensitivity and parameter correlation analyzed by Gardner (2009, p. 37 and 50) are considered valid for the updated model.

Water Levels

Observed water levels (fig. 8) during 2005–16 (fig. 9, shaded areas) include two distinct periods of rising water levels. These are in response to increased precipitation during 2005–06 and 2008–11. The measured water-level declines after 2011 are nearly 40 ft at some wells and are caused by below normal precipitation, increased groundwater withdrawals (fig. 4), and the cessation of recharge from Murdock Canal in 2012. Simulated water-level declines in 2016, related specifically to piping of the Murdock Canal, ranged from 0 to 20 ft in model layer 1 and from 0 to 14 ft in model layer 4. Water level declines greater that 8 ft are limited to small areas directly adjacent to the canal. At 12 of the 16 observation wells (fig. 9, blue shading), simulated water-level fluctuations are considered similar in trend to the observed fluctuations during 2005–16. At a subset of those wells (2, 7, 8, 10, 11, 12, 13, 14, and 15), the difference between simulated and observed water levels was approximately the same for the entire observational period (1947–2016). The best match between observed and simulated water levels was for wells 2, 3, 7, 8, 10, 14, 15, and 16.



Base modified from U.S. Geological Survey and other federal and state digital data, various scales;
Universal Transverse Mercator projection, Zone 12

Figure 8. Location of selected wells used for the comparison of simulated and observed water levels for 2005–16 in the updated groundwater flow model, northern Utah Valley, Utah.

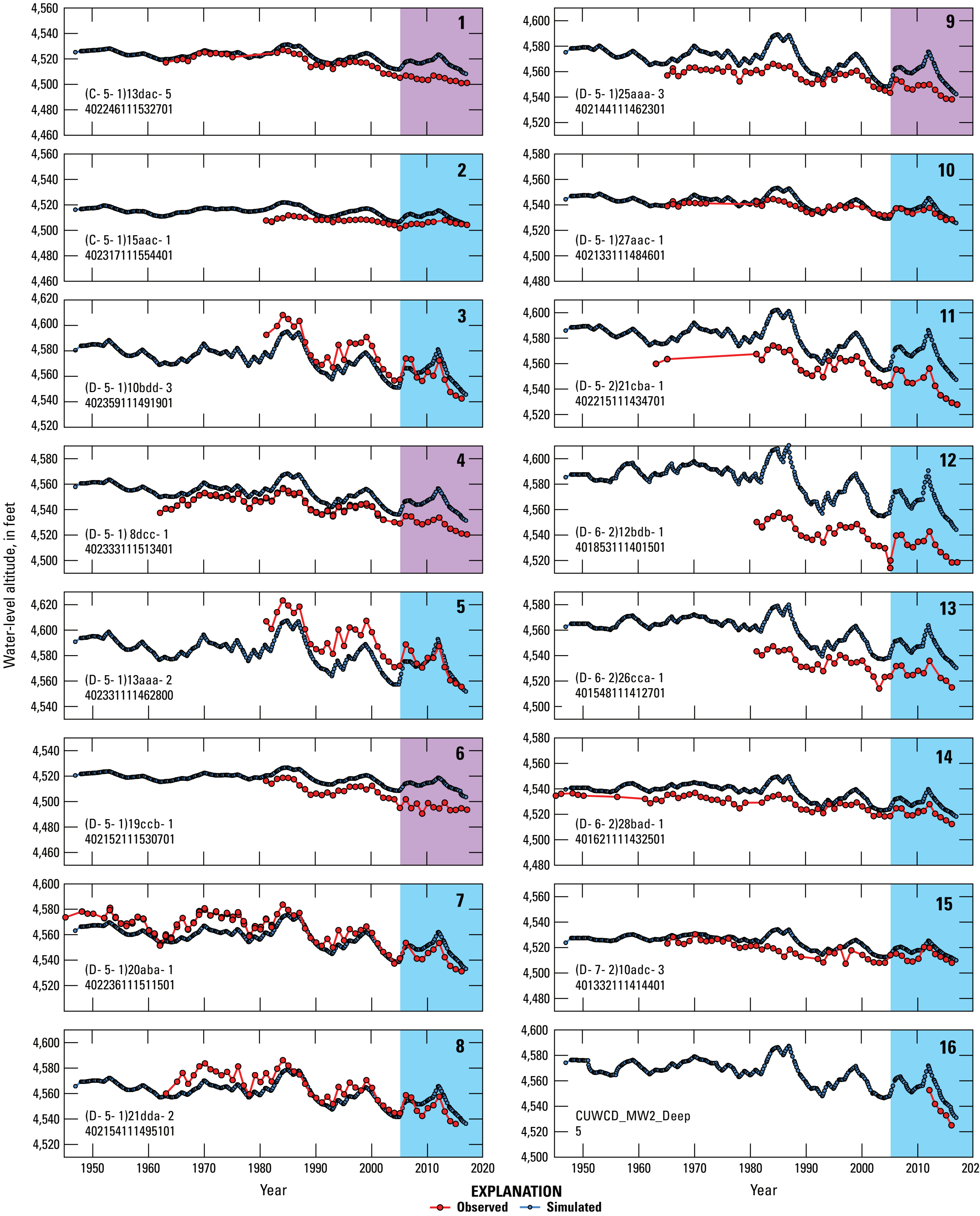


Figure 9. Water levels simulated by the updated groundwater flow model and observed water levels from March 1947 to March 2016 at 16 wells, northern Utah County, Utah. (Blue shading indicates simulated water-level fluctuations are similar to observed conditions for 2005–16. Purple indicates simulated water-level fluctuations are different from observed conditions. Number in upper righthand corner refers to figure 8.)

Simulated water levels have greater variability than observed values at wells 1, 4, 6, and 9 (fig. 9, purple shading) during 2005–16. This is likely due to underestimating nearby groundwater withdrawals or overestimating a localized component of recharge during the update period. Because characteristics of the misfit were different during 1947–2004 (Gardner, 2009) and 2005–16 (updated model), variability in simulated water-level difference was not likely caused by simulated aquifer characteristics (for example, thickness, hydraulic conductivity, and storage). Any misfit related to aquifer properties would affect water levels during the entire simulation period and not just during the update period (2005–16).

The overestimation of water levels at wells 11, 12, and 13 during the entire simulation period indicated that model parameters that define hydraulic conductivity and storage coefficients for the southern half of the primary discharge area (fig. 8) could be underestimated. The hydrostratigraphic framework of Cederberg and others (2009, fig. 12) identifies four confining units within the basin fill that consist of clay and silt (Cederberg, 2009, p. 18, fig. 11). As per Gardner (2009, p. 47), "*model cells may include thick sections of low-permeability deposits that effectively lower the overall model cell horizontal and vertical conductance.*"

Water Budgets

Water budgets from Gardner (2009, table 7) and the updated model are listed in table 3. The largest sources of recharge are precipitation and irrigation and stream/canal seepage. The largest discharges from the system were well withdrawals and groundwater discharge along and beneath Utah Lake. Comparison of model budgets for 2004 confirm that modifications in the updated model created groundwater fluxes that are similar to those simulated in the model by Gardner (2009) for 2004. Minor inequalities between total simulated recharge and discharge are caused by rounding individual budget components to the nearest 100 acre-ft/yr.

Precipitation in 2005 and 2009–11 was nearly 140-percent above the long-term average. Simulated groundwater budgets for 2005 and 2011 reflect the increase in precipitation. Increased precipitation is simulated at stream boundaries by increasing specified flows at upstream segments, which in turn increases stream depth and steepens the hydraulic gradient between surface water and groundwater. In response, head-dependent recharge fluxes from surface-water to groundwater increase. An ancillary effect of increased precipitation is the reduction in well withdrawals. Discharge to pumping wells in 2005 and 2011 was about 70 percent of the 2004 conceptual budget. Discharge to pumping wells increased in 2016 in response to below-normal precipitation during 2012–16 (80 percent of normal). The changes in simulated water budgets created by fluctuations in annual precipitation illustrate the importance of high-precipitation years to the groundwater resources overall (Masbruch and others, 2016).

Prediction of Future Conditions

The model by Gardner (2009) incorporates spatially and temporally referenced hydrologic boundaries that address hydrogeology, recharge, well withdrawals, streams, diffuse groundwater discharge, and evapotranspiration. The updated model maintains characteristics similar to Gardner (2009) at 12 of the 16 wells for 2005–16, a period that included two significant wet/dry cycles. This demonstrates that the hydrostratigraphic framework constructed by Cederberg and others (2009, p. 17) and the parameter values assigned by Gardner (2009, p. 37) are robust, and that the model can simulate circumstances that differ from calibration conditions.

All groundwater flow models represent a significant simplification of the existing hydrologic system. This simplification creates model uncertainty and uncertainty of model-derived predictions of future hydrologic conditions (Hill and Tiedeman, 2007, p. 340). Common sense usually can predict a simple description of future conditions. Predicting decreases in groundwater discharge to Utah Lake in response to increasing groundwater withdrawals is simple causality and carries a high degree of certainty. A more detailed description of future outcomes, such as timing, location, and amounts of decreased groundwater discharge to Utah Lake requires a more sophisticated approach. Although a groundwater flow model gives a more comprehensive description of future hydrologic conditions, the results should not be considered as the only and definitive prediction of future outcomes. Considering these limitations, a projection of future hydrologic conditions was made by extending the updated model of northern Utah County by 50 years (2017–66).

Table 3. Conceptual groundwater budget for 2004 and simulated groundwater budgets for 2004, 2005, 2011, and 2016, in the updated groundwater flow model, northern Utah County, Utah.

[Units in acre-feet per year. Imbalances in the 2004 conceptual budget are because groundwater exchange from and to storage is not estimated.]

Budget component	Conceptual budget for 2004 (Gardner, 2009, table 7)	Simulated budget for 2004 (Gardner, 2009, table 7)	Updated model budget for 2004 (Stress period 58)	Updated model budget for 2005 (Stress period 59)	Updated model budget for 2011 (Stress period 65)	Updated model budget for 2016 (Stress period 70)
Recharge (rounded)						
Areal recharge of precipitation and irrigation	77,300	83,200	83,200	174,400	185,500	55,400
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	63,700	63,200	66,600	104,000	122,000	60,200
Subsurface inflow from Cedar Valley	7,500	9,800	9,800	9,200	9,000	9,800
Groundwater inflow from storage (into model domain from storage)	Not estimated	1,400	1,400	200	0	23,500
Managed aquifer recharge	0	0	0	0	0	0
Total recharge	**148,500**	**157,600**	**161,000**	**287,800**	**316,500**	**148,900**
Discharge (rounded)						
Pumping wells (municipal and irrigation)	46,900	44,500	44,500	34,000	32,400	63,400
Flowing wells, drains, and springs along Utah Lake	66,600	58,800	57,600	77,500	99,400	46,800
Springs and diffuse seepage beneath Utah Lake	20,400	24,000	24,600	25,000	29,000	23,900
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	14,000	10,400	12,200	35,800	45,100	6,400
Evapotranspiration	4,400	7,200	7,400	8,100	8,600	6,900
Subsurface outflow to Salt Lake Valley	2,600	1,800	1,900	2,000	2,200	1,500
Groundwater outflow to storage (out of model domain into storage)	Not estimated	12,700	12,700	105,600	99,600	0
Total discharge	**154,900**	**159,400**	**160,900**	**288,000**	**316,300**	**148,900**

[1] The Provo River (Murdock) Canal was enclosed in a pipe in 2012 and is not simulated in stress periods 66–120.

Projection to 2066 Without Groundwater Management

The projection model estimates groundwater conditions for 2017–66 without managed aquifer recharge and defines a baseline of future hydrologic conditions. The projection model simulates recharge from precipitation at the 1947–2014 average conditions, recharge from irrigation at the amount estimated for 2014, and stream/canal flows are specified equal to the 1947–2016 average. The combination of long-term average recharge and streamflows, and most recent (2014) land use is considered an acceptable estimate of future conditions. The potential effects of climate trends and increased air temperatures on groundwater recharge and surface-water flows are not simulated.

To predict well withdrawals for 2017–66, the wells are split into four categories: industrial, irrigation, municipalities that are members of NUCAC, and other cities within the study area. These cities include Eagle Mountain, Lindon, Orem, Provo, and Saratoga Springs (fig. 1). The wells operated by NUCAC and other cities in 2016 are projected using linear regressions based on historical pumping records from 1947 to 2016 (fig. 10). The intercept of the regressions are adjusted to create a smooth transition from the recorded-to-projected withdrawals. Based on current water-use changes (agriculture to residential and heavy industry to information technology) the amount of pumping from irrigation and industrial wells were held constant at the 2016 withdrawal rates. This approach results in a simulated increase from 64,200 acre-ft/yr in 2017 to 101,400 acre-ft/yr in 2066. Utah Lake levels are held constant, at 4,487 ft, for the 50-year projection. The level is an average determined from January 1, 2001, to June 17, 2017, daily levels (provided by Caitlyn Erickson, Central Utah Water Conservancy District, July 2017). During that time, lake levels varied between 4,481 and 4,491 ft.

Total recharge simulated by the projection model in 2017 is about 1.2 times more than simulated for the last year of the updated model (tables 3 and 4). The increase causes a turn-around from depletion to replenishment of groundwater storage (23,500 acre-ft/yr of depletion in 2016 to 21,600 acre-ft/yr of replenishment in 2017). As a result, water levels and discharge along Utah Lake generally exceed 2016 values during the first 25 years (2017–41) of the projection period (fig. 11). During the remaining 25 years of the projection simulation (2042–66), discharge along Utah Lake decreases as the projected withdrawals at pumping wells increase.

Groundwater Management Scenario 1

The projection model is used in conjunction with the Groundwater-Management Process (Ahlfeld and others, 2009) to evaluate the effects of managed aquifer recharge (MAR) at 16 potential sites (fig. 12) as it affects diffuse groundwater discharge, spring flows, and discharge from flowing wells along Utah Lake (fig. 5). Historically, the discharge was quantified by Cordova and Subitzky (1965), Clark and Appel (1985), and Cederberg and others (2009, p. 36). The quantifications are based on field measurements of (1) flowing well discharge, (2) seepage to ditches and waterways, and (3) outlets from lowlands along Utah Lake. The observations of discharge were aggregated to describe total flows from the 12 discharge areas (fig. 5). Flowing well discharge is based on individual well measurements. When possible, surface-water flows entering the discharge areas from the east were subtracted from the aggregated outflow. The state variables in the GWM Process are the aggregated outflows from each of the 12 discharge areas, and the aggregated discharge from flowing wells. These discharges define the ‘condition’ or state of the groundwater system and were an important component of the model calibration by Gardner (2009, table 4).

The objective of the scenario_1 model is to minimize MAR at the 16 sites, while maintaining total simulated outflow at each of the 12 discharge areas and flowing wells along Utah Lake (fig. 5) at greater than or equal to 80 percent of the simulated values in the last stress period of the updated model (table 3, 46,800 acre-ft/yr). Identification of MAR locations, hydraulic properties, and sources of surface water for the MAR sites was done by the engineering firm of Hansen, Allen and Luce, Inc. Engineers (2012, table E-2). Because no direct measurements of groundwater discharge beneath Utah Lake exist, that component is not constrained.

The amount of recharge at each of the MAR sites (decision variables) is adjusted by the GWM Process to attain the objective. Adjustment of decision variables (the amount and location of MAR) was allowed at the 1st, 26th, and 41st stress periods. This creates reasonable simulation times and allows the simulated system to equilibrate from the stepwise increase of recharge (the long-term average) during the first 25 years. In addition to constraining the total decrease in discharge along Utah Lake, the total recharge applied at the 12 MAR sites is constrained at no more than 16,500 acre-ft/yr.

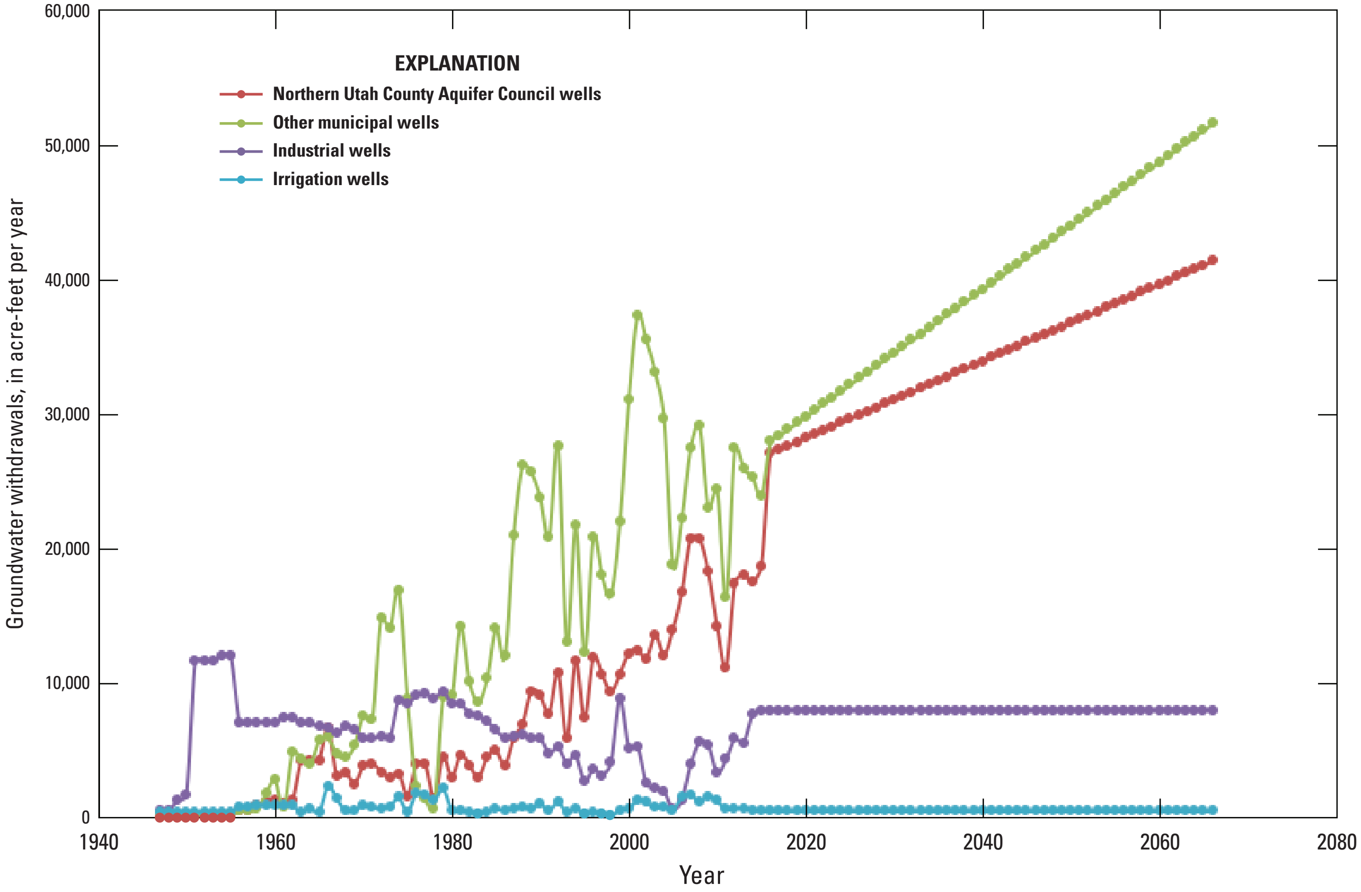


Figure 10. Annual groundwater withdrawals from wells for 1947–2016 simulated in the updated groundwater flow model and simulated annual groundwater withdrawals for the 2017–66 projection period, northern Utah County, Utah.

Table 4. Conceptual groundwater budget for 2004 and simulated groundwater budgets for 2017 and 2066, in the projection groundwater flow model, northern Utah County, Utah.

[Units in acre-feet per year. Imbalances in the 2004 conceptual budget are because groundwater exchange from and to storage is not estimated.]

Budget component	Conceptual budget for 2004 (Gardner, 2009, table 7)	Projection model budget for 2017 (stress period 71)	Projection model budget for 2066 (stress period 120)
Recharge (rounded)			
Areal recharge of precipitation and irrigation	77,300	84,800	84,800
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	63,700	79,400	79,400
Subsurface inflow from Cedar Valley	7,500	9,500	10,200
Groundwater inflow from storage (into model domain from storage)	Not estimated	800	1,300
Managed aquifer recharge	0	0	0
Total recharge	**148,500**	**174,500**	**175,700**
Discharge (rounded)			
Pumping wells (municipal and irrigation)	46,900	64,200	101,400
Flowing wells, drains, and springs along Utah Lake	66,600	50,000	33,900
Springs and diffuse seepage beneath Utah Lake	20,400	21,100	17,100
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	14,000	9,100	16,000
Evapotranspiration	4,400	7,100	6,100
Subsurface outflow to Salt Lake Valley	2,600	1,500	1,100
Groundwater outfow to storage (out of model domain into storage)	Not estimated	21,600	0
Total discharge	**154,900**	**174,600**	**175,600**

[1] The Provo River (Murdock) Canal was enclosed in a pipe in 2012 and is not simulated in stress periods 66–120.

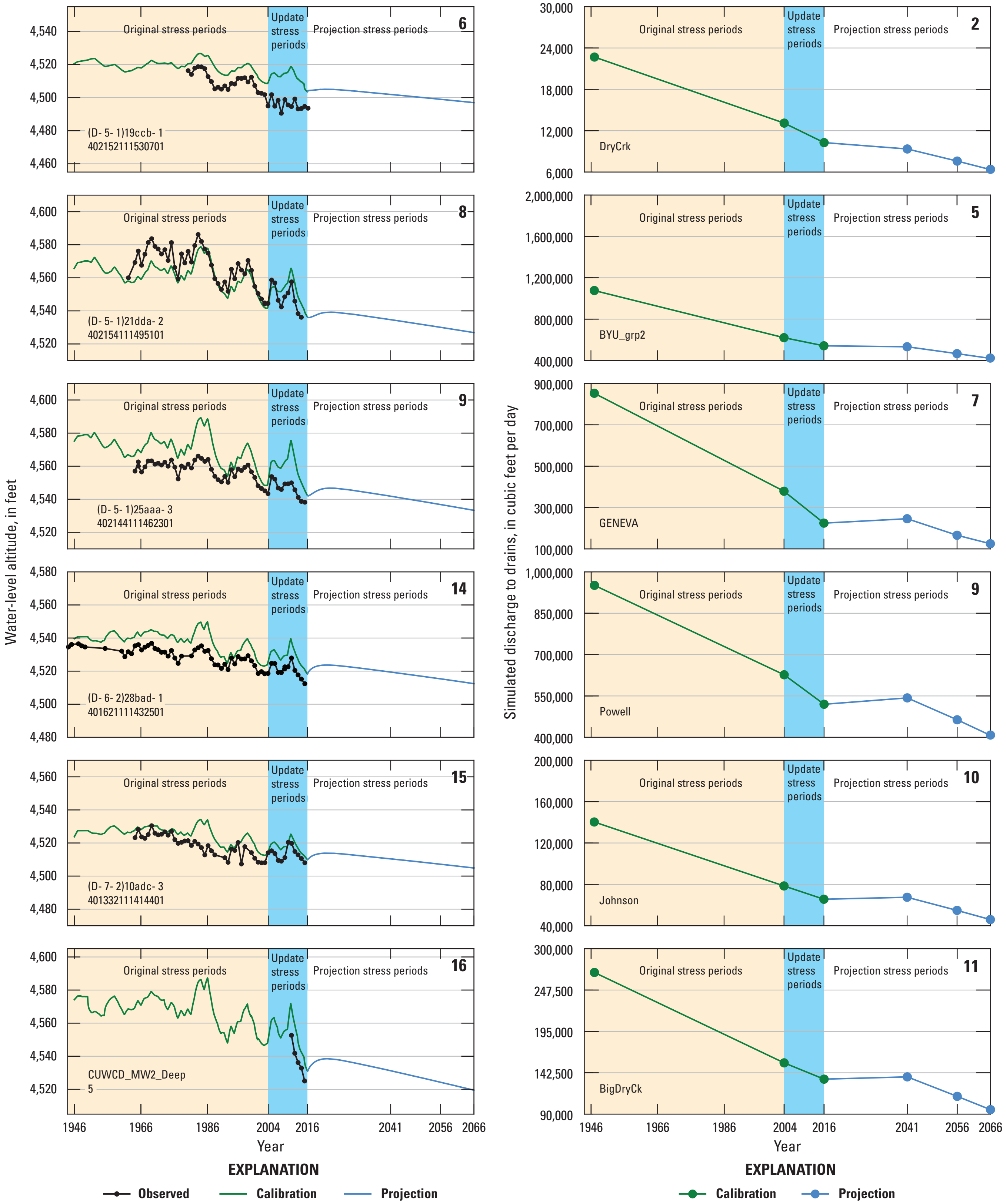


Figure 11. Simulated and observed water levels at six wells and simulated flow at six discharge areas along Utah Lake for the 1947–2066 projection period, northern Utah County, Utah. (Number in righthand corner of well hydrographs corresponds to figure 8; number in righthand corner of discharge hydrographs corresponds to figure 5.)

As the result of using a long-term average recharge and streamflow (see “Projection to 2066 Without Groundwater Management” section), simulated discharge along Utah Lake did not decrease below the scenario_1 threshold (80 percent), and no MAR was initiated during the initial 25-year period (2017–41). During the next 15 years, a total of about 7,300 acre-ft/yr of MAR was initiated at 14 sites (tables 5 and 6). For the last 10 years, MAR is increased to about 15,600 acre-ft/yr at 14 MAR sites. Simulated discharge at the 12 groundwater discharge areas and flowing wells along Utah Lake, with and without MAR, are shown on figure 13. Without MAR, discharge at 11 of the 12 discharge areas falls below the 80-percent threshold during the last 10 years of the projection period (as shown by the blue line on fig. 13 hydrographs). With the addition of MAR, discharge at all sites are at or above the 80-percent constraint (red line on fig. 13 hydrographs). These GWM results only are valid if the 1940–2014 average recharge rate persists through 2066. If predicted recharge is overestimated, additional MAR will be needed to meet the 80-percent constraint.

For the 2057–66 period, the groundwater budget indicates near steady-state conditions (table 6). Changes are limited to groundwater into and out of storage and well withdrawals, and on the order of 5,000 acre-ft/yr. This suggests that the simulated system could reach a steady-state condition with (1) 1947–2014 average recharge, (2) MAR of approximately 16,000 acre-ft/yr, and (3) well withdrawals that do not exceed the 2057–66 average.

Figure 14 graphically shows the increase in total well withdrawals and the corresponding decrease in total discharge along Utah Lake. During 2017–22, the increase in discharge is caused by applying the long-term average recharge to the 2017–66 projection period. Increased recharge offsets the effects of increased well withdrawals until 2043, when without MAR the simulated discharge along Utah Lake declines below the 2016 amount (fig. 14). For 2043–66, the reduction of discharge along Utah Lake, without MAR, was about 70 percent of the increased well withdrawals for the same time period. This is not a one-to-one relationship because well withdrawals are simultaneously causing reductions in groundwater storage and other discharge processes. Initiation of MAR in 2042 and 2057 has the clear effect of maintaining discharge along Utah Lake (fig. 14). With the application of MAR, total discharge along Utah Lake in 2066 is close to the discharge in 2016 , assuming that average areal recharge during 2017–66 remains similar to the 1947–2016 average. This result aligns with the GWM objective.

Groundwater Management Scenario 2

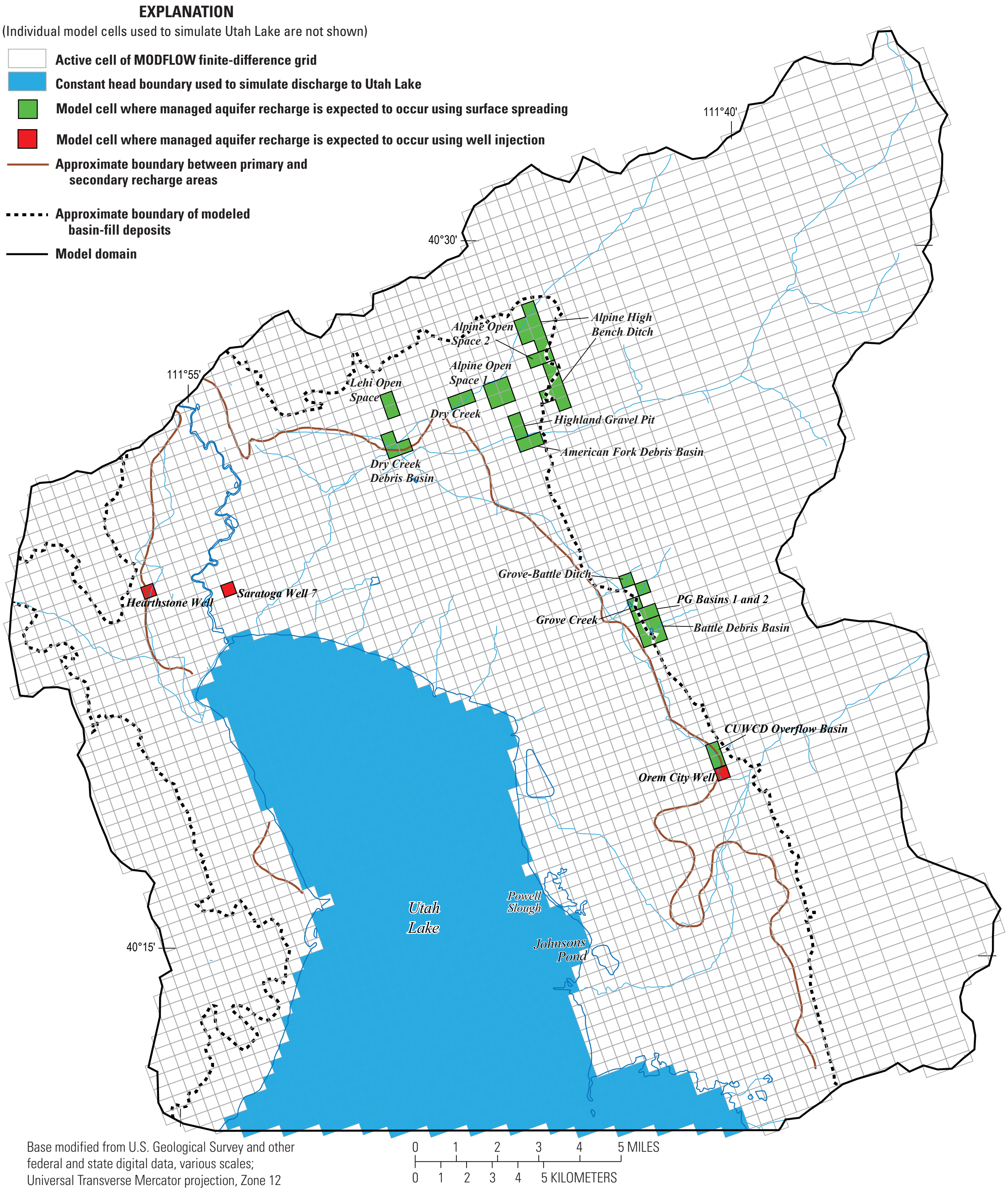
A second groundwater management scenario was simulated to better understand the limitations of MAR. The objective of scenario_2 model is to minimize MAR at the 16 sites, while maintaining total simulated outflow at each of the 12 discharge areas and flowing wells along Utah Lake (fig. 5) at greater than or equal to 90 percent of the simulated values in the last stress period of the updated model (table 3, 46,800 acre-ft/yr). The GWM Process was not able to achieve a feasible solution when this constraint was applied. Even with the maximum infiltration rates simulated at all but one of the MAR sites, groundwater discharge along Utah Lake could not be maintained at the 90-percent constraint. Simulated discharge is reduced by more than 10 percent at discharge areas 2, 8, 10, 11, and 12 (fig. 5) during 2057–66. With that in mind, discharge constraints at those sites were assigned the 80-percent constraint value for 2057–66. The GWM Process was able to derive a feasible solution at that point, which is shown in table 7. Placing the 90-percent constraint on discharge creates a solution where the amount of MAR is increased for the 2042–56 period. The cumulative amount of MAR required to meet the adjusted constraints for scenario 2 is about 312,000 acre-ft. This is 17,000 acre-ft more MAR than calculated for scenario 1.

Future Monitoring

The projection model, used in conjunction with the GWM Process (Ahlfeld and others, 2009), is used to frame scenarios of future groundwater conditions. However, model predictions of future conditions include a high level of uncertainty. To identify how and when model prediction deviates from actual conditions, initiation of an internally consistent data collection program is recommended. All data must be recorded in a manner that the information can be retrieved and used in perpetuity.

Useful data includes well withdrawals, water levels in wells, and groundwater flow from the discharge areas. Well withdrawals should be monitored so that comparisons can be made to the estimated increases in withdrawals shown on figure 10. Withdrawals need to be recorded on a well-to-well basis and not as an aggregated total.

Water levels should be collected on an annual basis and represent annual average conditions. In most circumstances, water levels in March are a reasonable representation of hydrologic conditions for the previous 12 months. By March, water levels usually have recovered from the previous summer’s groundwater withdrawals and are not yet affected by current year surface-water runoff, canal diversions, and groundwater withdrawals. If there are isolated cases where there is active groundwater pumping nearby (within a half mile), that should be noted. Water levels need to be measured from a consistent measurement point so that they are comparable from year to year. Check measurements greatly improve data quality. To avoid redundancies, any water-level monitoring program would benefit by noting existing and historic monitoring in northern Utah County.



Base modified from U.S. Geological Survey and other federal and state digital data, various scales; Universal Transverse Mercator projection, Zone 12

Figure 12. Location of 16 potential managed aquifer recharge sites that are simulated in the 2017–66 groundwater management simulations, northern Utah County, Utah (from Hansen, Allen and Luce, Inc. Engineers, 2012).

Measurement of total groundwater discharge from the individual areas shown on figure 5 is deemed a robust gage of study-area scale hydrologic conditions. However, such observations are difficult and time consuming to make. A reasonable approach is to identify one or two locations in each of the discharge areas where discrete points of discharge exist (for example, spring, drain, or pond outlet) and a control structure (weir or flume) can be installed. A control structure ensures consistency between measurements and can be checked at prescribed time intervals (annually or quarterly) to record discharge.

Table 5. Description of managed aquifer recharge decision variables in the groundwater management scenario 1 flow model, northern Utah County, Utah.

[Units in acre-feet per year. **Abbreviations**: ID, identification; acre-ft/yr, acre-feet per year; CUWCD, Central Utah Water Conservancy District; —, information is not available or unknown]

Name/site description[1]	Map ID (see fig. 13)	Decision variable name	Ranking[1]	Maximum managed aquifer recharge rate[1]	Managed aquifer recharge rate during 2017–41	Managed aquifer recharge rate during 2042–56	Managed aquifer recharge rate during 2057–66	Period of operation
American Fork Debris Basin	American Fork Debris Basin	SURF#7	1	5,472	0	0	5,472	2057–66
Battle Creek Debris Basin[2]	Battle Debris Basin	SURF#3b	2	1,224	0	1,224	1,224	2042–66
Dry Creek	Dry Creek	SURF#12	3	778	0	713	713	2057–66
Highland Gravel Pit	Highland Gravel Pit	SURF#8	4	2,880	0	0	2,880	2042–66
CUWCD Sludge Beds	CUWCD Overflow Basin	SURF#1	5	605	0	605	605	2042–66
Battle Creek Debris Basin using Salt Lake Aqueduct	Battle Debris Basin	Simulated as SURF#3b	6	—	—	—	—	—
Battle Creek Debris Basin with ditch	Battle Debris Basin	Simulated as SURF#3b	7	—	—	—	—	—
Alpine Open Space 1	Alpine Open Space 1	SURF#10	8	355	0	355	355	2042–66
Alpine High Bench Ditch	Alpine High Bench Ditch	SURF#13	9	317	0	317	317	2042–66
Orem City Well	Orem City Well	WELL#2	10	557	0	557	557	2042–66
Pleasant Grove Basins 1 and 2	PG Basins 1 and 2	SURF#4	11	461	0	461	461	2042–66
Lehi Open Space	Lehi Open Space	SURF#14	12	1,152	0	1,152	1,152	2042–66
Grove Creek - Battle Creek Ditch	Grove-Battle Ditch	SURF#6	13	288	0	288	288	2042–66
Dry Creek Debris Basin	Dry Creek Debris Basin	SURF#9	14	216	0	216	216	2042–66
Alpine High Bench Ditch and Alpine Open Space 2	Alpine High Bench Ditch and Alpine Open Space 2	SURF#11	15	240	0	240	240	2042–66
Saratoga Springs Well 7	Saratoga Well 7	WELL#15	16	557	—	—	—	Not used
Grove Creek Recharge Basin without and with Salt Lake Aqueduct	Grove Creek	SURF#5a	[3]17 or 19	1,152	0	1,152	1,152	2042–66
Heathstone Well	Heathstone Well	WELL#16	18	278	—	—	—	Not used
Total					**0**	**7,280**	**15,632**	

[1] Hansen, Allen and Luce, Inc. Engineers (2012, table 3-4).

[2] Maximum managed aquifer recharge for Battle Creek Debris Basin is the rate listed in Hansen, Allen and Luce, Inc. Engineers (2012, table 3-4), for Battle Creek Debris Basin using Salt Lake Aqueduct.

[3] Rank dependents on water source.

Table 6. Conceptual groundwater budget for 2004 and simulated groundwater budgets for 2017, 2042, 2057, and 2066 in the groundwater management scenario 1 flow model, northern Utah County, Utah.

[Units in acre-feet per year. Imbalances in the 2004 conceptual budget are because groundwater exchange from and to storage is not estimated.]

Budget component	Conceptual budget for 2004 (Gardner, 2009, table 7)	Groundwater management scenario 1 budget for 2017 (stress period 71)	Groundwater management scenario 1 budget for 2042 (stress period 96)	Groundwater management scenario 1 budget for 2057 (stress period 111)	Groundwater management scenario 1 budget for 2066 (stress period 120)
Recharge (rounded)					
Areal recharge of precipitation and irrigation	77,300	84,800	84,800	84,800	84,800
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	63,700	79,400	79,300	79,300	79,400
Subsurface inflow from Cedar Valley	7,500	9,500	9,800	10,000	10,000
Groundwater inflow from storage (into model domain from storage)	Not estimated	800	100	100	1,000
Managed aquifer recharge	0	0	7,300	15,600	15,600
Total recharge	**148,500**	**174,500**	**181,300**	**189,800**	**190,800**
Discharge (rounded)					
Pumping wells (municipal and irrigation)	46,900	64,200	83,200	94,600	101,400
Flowing wells, drains, and springs along Utah Lake	66,600	50,000	49,100	45,900	44,800
Springs and diffuse seepage beneath Utah Lake	20,400	21,100	20,200	19,600	19,700
American Fork, Provo, and Jordan Rivers, creeks, and canals[1]	14,000	9,100	16,900	16,800	16,900
Evapotranspiration	4,400	7,100	7,000	6,800	6,700
Subsurface outflow to Salt Lake Valley	2,600	1,500	1,400	1,300	1,300
Groundwater outflow to storage (out of model domain into storage)	Not estimated	21,600	3,500	4,900	0
Total discharge	**154,900**	**174,600**	**181,300**	**189,900**	**190,800**

[1] The Provo River (Murdock) Canal was enclosed in a pipe in 2012 and is not simulated in stress periods 66–120.

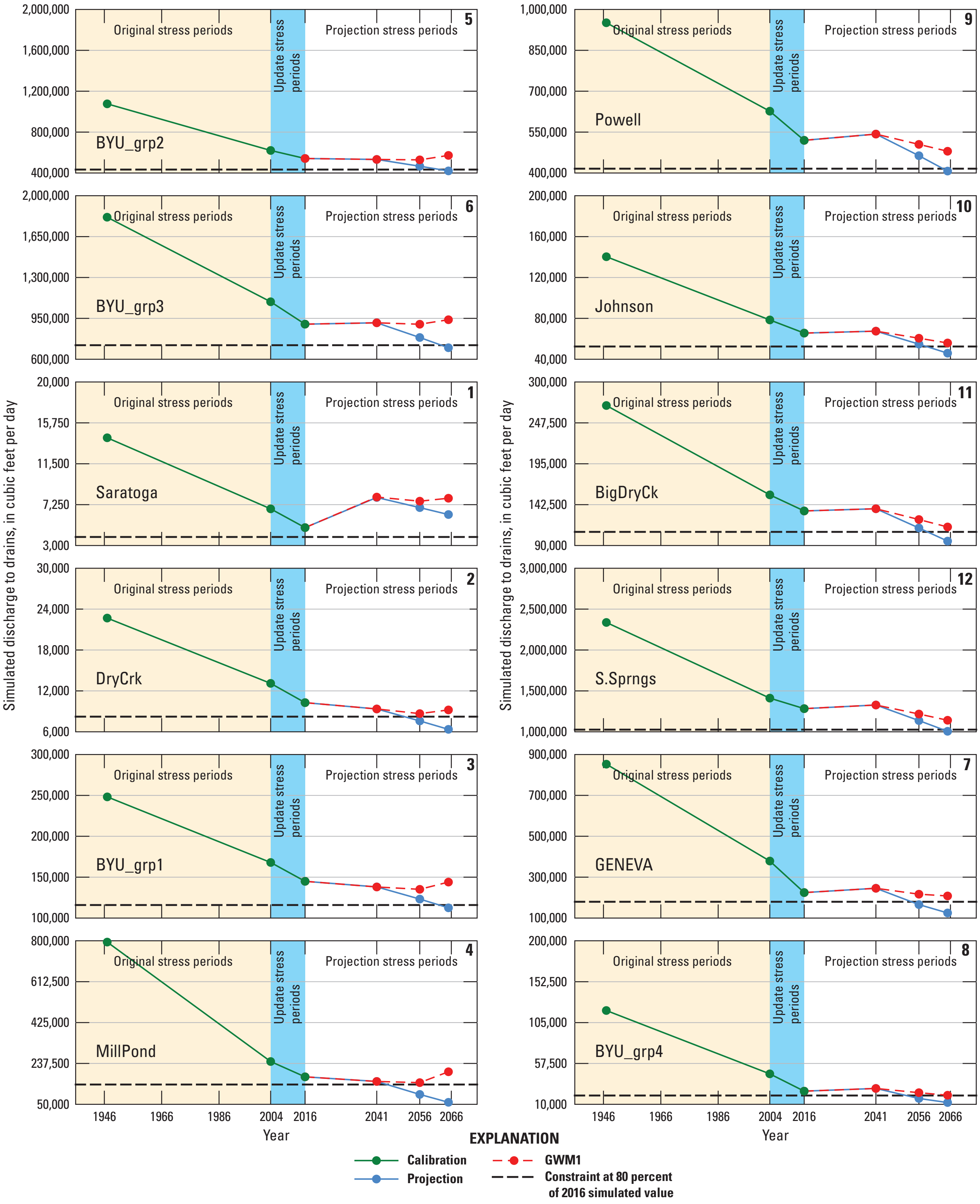


Figure 13. Simulated flow at 12 discharge areas along Utah Lake for 1947–2066, with and without management scenario 1 aquifer recharge, northern Utah County, Utah. (Number in upper righthand corner refers to fig. 5)

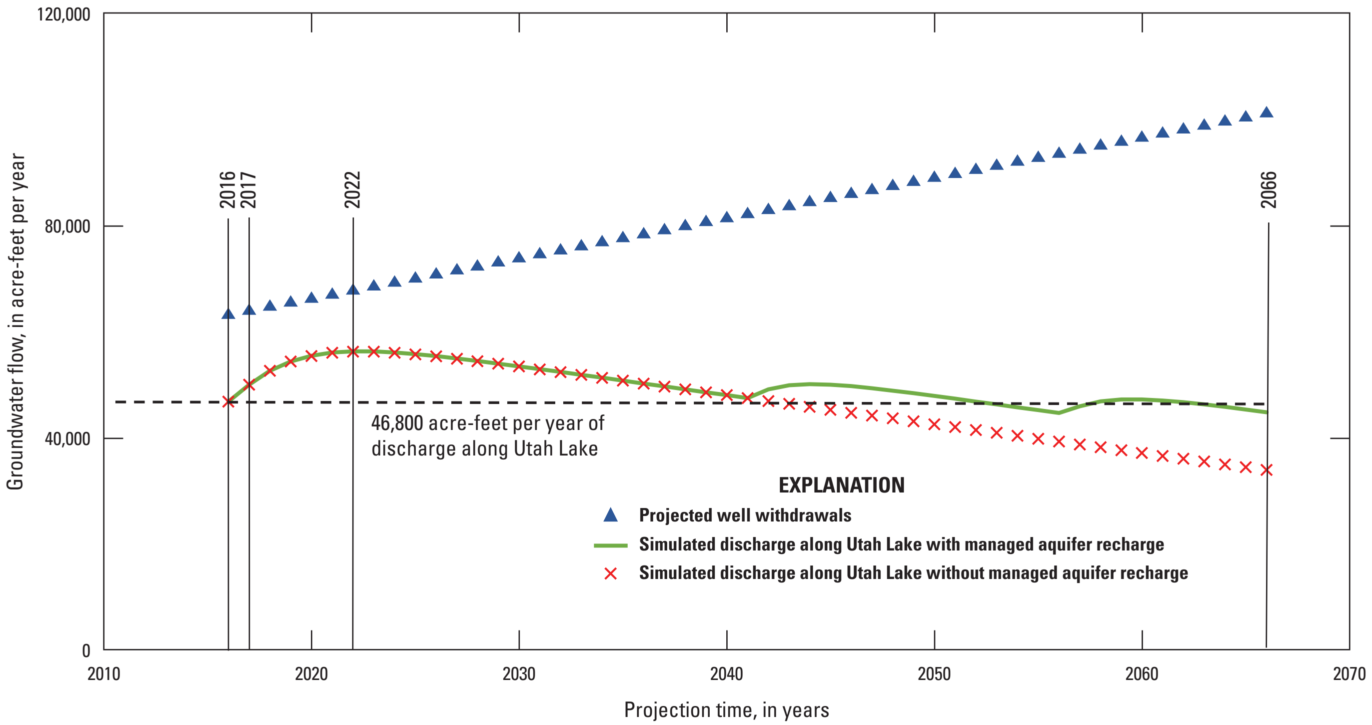


Figure 14. Comparison of annual total simulated well withdrawals and annual total simulated discharge along Utah Lake, with and without management scenario 1 aquifer recharge, northern Utah County, Utah.

Table 7. Description of managed aquifer recharge decision variables in the groundwater management scenario 2 flow model, northern Utah County, Utah.

[Units in acre-feet per year. **Abbreviations**: ID, identification; acre-ft/yr, acre-feet per year; —, information is not available or unknown; CUWCD, Central Utah Water Conservancy District]

Name/site description[1]	Map ID (see fig. 13)	Decision variable name	Ranking[1]	Maximum managed aquifer recharge rate[1]	Managed aquifer recharge rate during 2017–41	Managed aquifer recharge rate during 2042–56	Managed aquifer recharge rate during 2057–66	Period of operation
American Fork Debris Basin	American Fork Debris Basin	SURF#7	1	5,472	0	74	5,472	2042–66
Battle Creek Debris Basin[2]	Battle Debris Basin	SURF#3b	2	1,224	0	1,224	1,224	2042–66
Dry Creek	Dry Creek	SURF#12	3	778	0	778	778	2042–66
Highland Gravel Pit	Highland Gravel Pit	SURF#8	4	2,880	0	2,880	2,880	2042–66
CUWCD Sludge Beds	CUWCD Overflow Basin	SURF#1	5	605	0	605	605	2042–66
Battle Creek Debris Basin using Salt Lake Aqueduct	Battle Creek Debris Basin	Simulated as SURF#3b	6	—	—	—	—	—
Battle Creek Debris Basin with ditch	Battle Creek Debris Basin	Simulated as SURF#3b	7	—	—	—	—	—
Alpine Open Space 1	Alpine Open Space 1	SURF#10	8	355	0	355	355	2042–66
Alpine High Bench Ditch	Alpine High Bench Ditch	SURF#13	9	317	0	317	317	2042–66
Orem City Well	Orem City Well	WELL#2	10	557	0	557	557	2042–66
Pleasant Grove Basins 1 and 2	PG Basins 1 and 2	SURF#4	11	461	0	461	461	2042–66
Lehi Open Space	Lehi Open Space	SURF#14	12	1,152	324	1,152	1,152	2017–66
Grove Creek - Battle Creek Ditch	Grove-Battle Ditch	SURF#6	13	288	0	31	31	2042–66
Dry Creek Debris Basin	Dry Creek Debris Basin	SURF#9	14	216	0	216	216	2042–66
Alpine High Bench Ditch and Alpine Open Space 2	Alpine High Bench Ditch and Alpine Open Space 2	SURF#11	15	240	0	240	240	2042–66
Saratoga Springs Well 7	Saratoga Well 7	WELL#15	16	557	—	—	—	Not used
Grove Creek Recharge Basin without and with Salt Lake Aqueduct	Grove Creek	SURF#5a	[3]17 or 19	1,152	0	1,152	1,152	2042–66
Heathstone Well	Heathstone Well	WELL#16	18	278	—	—	—	Not used
Total					**324**	**10,042**	**15,440**	

[1] Hansen, Allen and Luce, Inc. Engineers (2012, table 3-4).

[2] Maximum managed aquifer recharge for Battle Creek Debris Basin is the rate listed in Hansen, Allen and Luce, Inc. Engineers (2012, table 3-4), for Battle Creek Debris Basin using Salt Lake Aqueduct.

[3] Rank dependents on water source.

Summary

Groundwater is a primary source of drinking water in northern Utah County. By 2066, total annual withdrawals from wells are estimated to be roughly 60 percent of simulated areal recharge from precipitation, irrigation, rivers, creeks, and canals. To plan for anticipated future increases in groundwater withdrawals, the Northern Utah County Aquifer Council, along with the engineering firm of Hansen, Allen and Luce, Inc. Engineers (2012) identified 16 sites where managed aquifer recharge is feasible. This report describes the use of an updated groundwater flow model to evaluate the ability of these managed aquifer recharge sites to maintain a defined groundwater discharge along Utah Lake, using the Groundwater-Management (GWM) Process.

The groundwater model by Gardner (2009), which represents conditions from 1947 to 2004, was updated with 12 additional stress periods representing 2005–16. The additional stress periods simulate annual estimates of mountain and valley recharge, an increase in groundwater withdrawals, and the effects of lining the Murdock Canal. Based on the updated model, a projection model was constructed to simulate an estimated increase of 38,000 acre-feet per year (acre-ft/yr) in well withdrawals over a 50-year period (2017–66). The projection model predicts potential declines in water levels and groundwater discharge along Utah Lake.

To better manage and understand projected changes in the groundwater system, the Groundwater-Management (GWM) Process (Ahlfeld and others, 2009), was implemented. The GWM Process uses optimization to determine the best combination of timing, location, and amounts of managed aquifer recharge that is required to achieve stated goals of minimizing the decline in groundwater discharge along Utah Lake.

The GWM Process identified that a managed aquifer recharge (MAR) rate of about 7,300 acre-ft/year in 2042–56 and 15,600 acre-ft/yr in 2057–66 will maintain 80 percent of the groundwater discharge along Utah Lake. The GWM Process also was used to optimize a second scenario. Recharging a total of about 300 acre-ft/yr in 2017–41, 10,000 acre-ft/yr in 2041–56 and 15,400 acre-ft/yr of MAR in 2057–66, would allow 90 percent of discharge to be maintained at 7 of the 12 groundwater discharge areas along Utah Lake. For both scenarios, the GWM process indicated that all potential MAR sites would need to be used to maintain observed discharge.

Results of GWM modeling is one part of an integrated approach based on continued long-term monitoring of surface-water and groundwater resources. Additional data can become part of a continuing process of updating estimates of natural recharge, tracking water use, and implementing model improvements. The modeling and the GWM Process described in this report is a simplification of the existing hydrologic system. This creates model uncertainty in terms of correctly predicting future hydrologic conditions. Model predictions need to be verified with continued monitoring of water levels, streamflow, and groundwater discharge along Utah Lake.

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