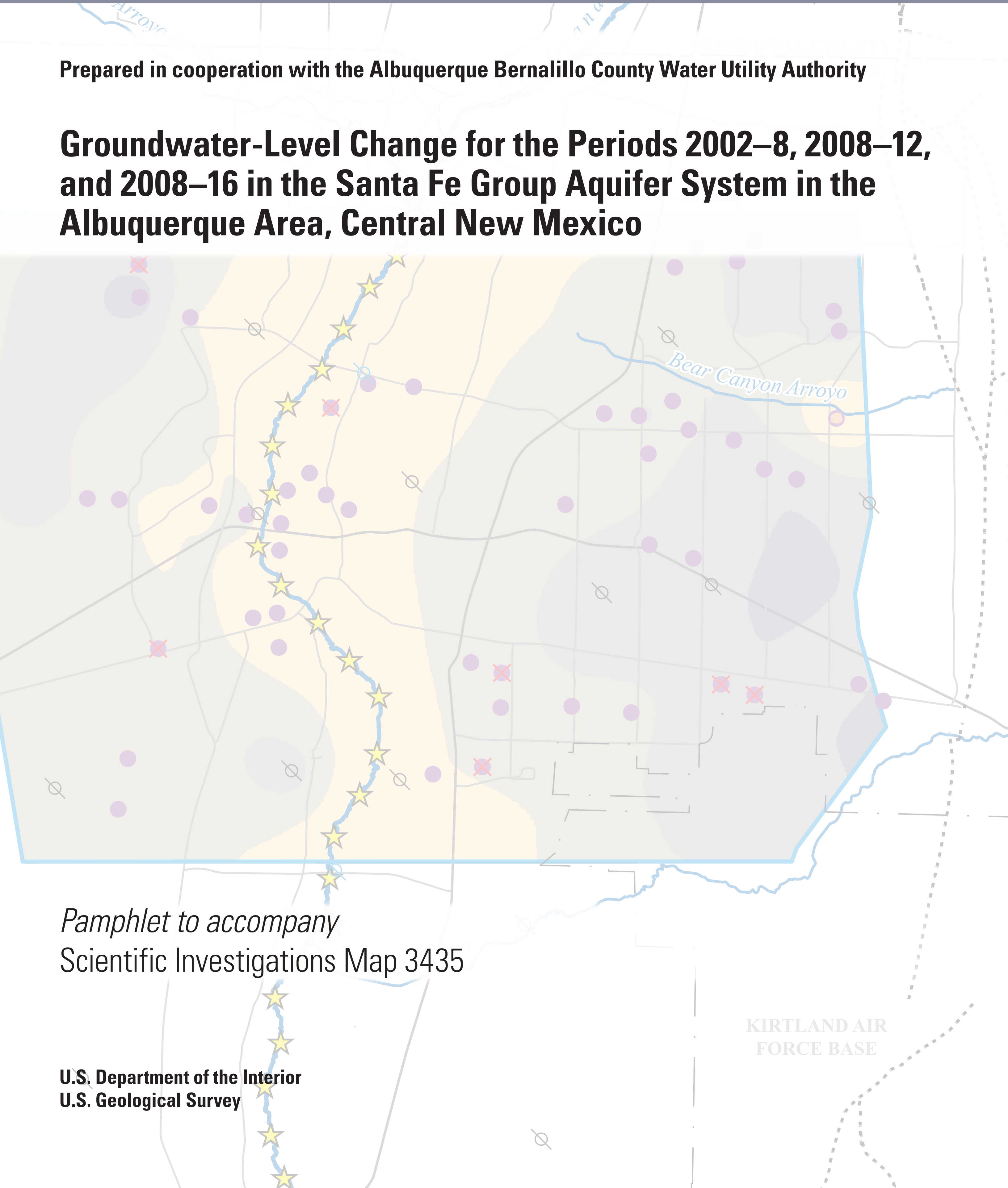
Prepared in cooperation with the Albuquerque Bernalillo County Water Utility Authority

Groundwater-Level Change for the Periods 2002–8, 2008–12, and 2008–16 in the Santa Fe Group Aquifer System in the Albuquerque Area, Central New Mexico



Pamphlet to accompany

Scientific Investigations Map 3435

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

Groundwater-Level Change for the Periods 2002–8, 2008–12, and 2008–16 in the Santa Fe Group Aquifer System in the Albuquerque Area, Central New Mexico

By Andre B. Ritchie, Amy E. Galanter, and Lucas T.S. Curry

Prepared in cooperation with the Albuquerque Bernalillo County
Water Utility Authority

Pamphlet to accompany
Scientific Investigations Map 3435

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
Ritchie, A.B., Galanter, A.E., and Curry, L.T.S., Groundwater-level change for the periods 2002–8, 2008–12, and 2008–16 in the Santa Fe Group aquifer system in the Albuquerque area, central New Mexico: U.S. Geological Survey Scientific Investigations Map 3435, 1 sheet, pamphlet, https://doi.org/10.3133/sim3435.

ISSN 2329-1311 (print)
ISSN 2329-132X (online)

ISBN 978-1-4113-4323-8

Acknowledgments

This report would not be possible without the efforts of the many U.S. Geological Survey colleagues who maintained and collected data at the groundwater-level monitoring network over the years. The authors would also like to thank the many U.S. Geological Survey colleagues who have contributed to this report, notably the efforts of Nathan C. Myers, Rachel I. Powell, Jacob Wikle, Joseph E. Beman, and Christina F. Bryant.

Contents

Sheet

Figures

Tables

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	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)

Datum

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Abbreviations

ABCWUA	Albuquerque Bernalillo County Water Utility Authority
NWIS	National Water Information System
SJCDWP	San Juan-Chama Drinking Water Project
USGS	U.S. Geological Survey

Groundwater-Level Change for the Periods 2002–8, 2008–12, and 2008–16 in the Santa Fe Group Aquifer System in the Albuquerque Area, Central New Mexico

By Andre B. Ritchie, Amy E. Galanter, and Lucas T.S. Curry

Abstract

The U.S. Geological Survey, in cooperation with the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), has developed a series of maps and associated reports, beginning in 2002, that document groundwater levels in the production zone of the Santa Fe Group aquifer system beneath a large area of the City of Albuquerque, New Mexico (hereafter called the study area). Herein, we document the construction of groundwater-level change maps for representative conditions during three periods: 2002–8, 2008–12, and 2008–16.

Groundwater-elevation changes correspond to water use by the ABCWUA, with declines occurring prior to 2008 and accelerating recovery after 2008. Prior to 2008, the ABCWUA relied exclusively on groundwater from the Santa Fe Group aquifer system for municipal water supply. For the period 2002–8, near the end of the period of exclusive groundwater use, groundwater elevations in the production zone of the Santa Fe Group aquifer system declined as much as 20 to 30 feet. The largest 2002–8 groundwater-elevation declines were observed near the southeast corner of the study area and to the west of the Rio Grande. Since the ABCWUA implemented the San Juan-Chama Drinking Water Project in 2008, the proportion of municipal water supply sourced directly from surface water has increased to approximately two-thirds of the total water supply in 2016. Following initiation of this change in supply in 2008, groundwater elevations in the production zone of the Santa Fe Group aquifer system cumulatively rose as much as 20 to 30 feet by 2012 and 30 to 40 feet by 2016. The largest groundwater-elevation rises were observed near the northeast and southeast corners of the study area and to the west of the Rio Grande, whereas groundwater-elevation declines since 2008 were restricted to a localized area on the eastern margin of the study area. The area beneath the pre-flood-control-era (1971) flood plain of the Rio Grande underwent the least amount of groundwater-level change during any period, with minimal change prior to 2008 and small groundwater-elevation rises of less than 10 feet since 2008.

Introduction

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA) provides water and wastewater services to the greater Albuquerque, New Mexico, area (City of Albuquerque and surrounding areas of Bernalillo County) within the Middle Rio Grande Basin (fig. 1, on sheet), serving over 600,000 water users with a combination of surface water (through the San Juan-Chama Drinking Water Project [SJCDWP]) and groundwater (ABCWUA, 2016). The ABCWUA is the largest single municipal-supply water user within the Middle Rio Grande Basin (Longworth and others, 2013), and because of limited water resources and competing demands, there is a critical need for long-term datasets to understand the Santa Fe Group aquifer system beneath a large area of the City of Albuquerque. Prior to 2008, the ABCWUA relied exclusively on groundwater for municipal water supply, but conservation programs and the addition of surface water as a source of supply have resulted in rising groundwater levels since 2008 (ABCWUA, 2016).

The Middle Rio Grande Basin in central New Mexico is defined as the extent of sediments of Cenozoic age (less than 66 million years ago), encompassing about 3,060 square miles within the structural Rio Grande Rift (fig. 1) (Thorn and others, 1993; McAda and Barroll, 2002; Hudson and Grauch, 2013). ABCWUA production wells are typically screened (open to the aquifer) over a part of the Cenozoic-age Santa Fe Group aquifer system, hereafter called the production zone, which consists of the interval from within about 200 feet of the water table to 900 feet or more below the water table (Bexfield and Anderholm, 2002; Powell and McKean, 2014).

Purpose and Scope

This report describes the change in groundwater level in the production zone resulting from reducing production zone pumping and increasing SJCDWP surface-water diversion to supply ABCWUA needs. Groundwater-level change maps were constructed for three periods (2002–8, 2008–12, and 2008–16), and changes were analyzed to identify timing and magnitude of groundwater-elevation rises or declines before and after 2008, when SJCDWP diversions began.

Background

As part of the cooperative Middle Rio Grande Basin monitoring program between the ABCWUA and the U.S. Geological Survey (USGS), groundwater levels are periodically measured (Beman and others, 2019), and a series of maps and associated reports documenting groundwater levels in the production zone were constructed for water years 2002, 2008, 2012, and 2016 (Bexfield and Anderholm, 2002; Falk and others, 2011; Powell and McKean, 2014; Galanter and Curry, 2019). A water year is the 12-month period October 1 through September 30 designated by the calendar year in which it ends. Maps and reports in this series also document net groundwater-elevation declines (called drawdown) since widespread groundwater pumping began in the early 1960s (designated as marking the end of predevelopment conditions).

An initial network of wells was established by the USGS in cooperation with the City of Albuquerque from April 1982 through September 1983 to monitor changes in groundwater levels throughout the Middle Rio Grande Basin. In 1983, this network consisted of 6 wells with analog-to-digital recorders and 27 wells where groundwater levels were measured monthly. Since the initial installation, additional wells and piezometers have been added to the network. The current (2019) groundwater-level monitoring network consists of 120 monitoring wells and piezometers; 66 are equipped with pressure transducers and data loggers recording at an hourly interval, and 54 are monitored semiannually, quarterly, or irregularly with a steel or electric tape (Beman and others, 2019). A piezometer is a specialized well open to a specific depth in the aquifer and is often of small diameter. In the basin, three piezometers typically are constructed in proximity (together called a nest), with one piezometer near the water table, one near the middle of the production zone, and one near the bottom of or below the production zone (Bexfield and Anderholm, 2002). The USGS also monitors approximately 40 to 50 ABCWUA production wells annually with a steel tape during a period of decreased seasonal water use (winter). The number of production wells that are monitored annually varies depending on access constraints.

The Santa Fe Group aquifer within the Middle Rio Grande Basin consists of unconsolidated to moderately consolidated Cenozoic basin-fill deposits of the Santa Fe Group. The Rio Grande alluvial aquifer overlies the Santa Fe Group, consisting of younger unconsolidated to poorly consolidated Quaternary deposits associated with the pre-flood-control-era (1971) flood plain of the Rio Grande (called the inner valley, fig. 1; McAda and Barroll, 2002) (Bartolino and Cole, 2002; Plummer and others, 2012; Rankin and others, 2013). The Santa Fe Group and Rio Grande alluvial aquifers are variably hydraulically connected to each other and to the Rio Grande and are collectively called the Santa Fe Group aquifer system (Bartolino and Cole, 2002; Plummer and others, 2012; Rankin and others, 2013). The Rio Grande alluvial aquifer consists of channel, flood plain, terrace, and tributary deposits that form a thin but extensive aquifer that is as much as 120 feet thick beneath the Rio Grande inner valley (Rankin and others, 2013). The Santa Fe Group sediments range in thickness from about 3,000 to more than 14,000 feet and have been divided informally into upper, middle, and lower units based on depositional environment and age (Hawley and Haase, 1992). Despite the large thickness of Santa Fe Group sediments, only about the upper 2,000 feet of the aquifer system is used for groundwater withdrawals, and much of the lower part of the Santa Fe Group may make a poor aquifer (Bartolino and Cole, 2002).

Historically, the ABCWUA relied exclusively on groundwater from the Santa Fe Group aquifer system for municipal water supply, with groundwater withdrawals peaking in 1989 (fig. 2, on sheet) (Bexfield and Anderholm, 2002; ABCWUA, 2016; Galanter and Curry, 2019). Groundwater withdrawals began generally declining in 1990, despite continued population increases, because of conservation programs initiated by the ABCWUA and implemented by the citizens of Albuquerque (ABCWUA, 2016). In December 2008, the ABCWUA began diverting surface water from the Rio Grande as part of the SJCDWP to supplement municipal water supply, allowing for additional reductions in groundwater withdrawals (Powell and McKean, 2014; ABCWUA, 2016; Driscoll and Brandt, 2017; Galanter and Curry, 2019).

Methods

Change maps were constructed to document the change in groundwater levels that occurred during three periods: 2002–8, 2008–12, and 2008–16. Maps were generated using all sites where groundwater levels were measured at the start and end of each period. The spatial distribution of groundwater-level change throughout the study area was estimated by interpolating between measurement locations using ordinary kriging. Uncertainty associated with the change maps was assessed using visual analysis; the standard error, or square root of the variance, for kriging; and leave-one-out cross-validation.

Data Sources

Groundwater-level measurements, in feet below land surface (called depth to water), used for change map construction were collected at monitoring wells, piezometers, and ABCWUA production wells that are monitored by the USGS as part of the Middle Rio Grande Basin monitoring program (fig. 1). All quality-assured groundwater-level measurements are publicly available from the USGS National Water Information System (NWIS; USGS, 2019). Groundwater-level measurements from the winter (November to March) of each water year were used because winter groundwater levels are less affected by pumping because of decreased seasonal water use (ABCWUA, 2016) and are therefore more representative of static conditions in the aquifer. Some areas lacked data for winter groundwater levels for each water year, so sparsely covered regions were supplemented with winter groundwater levels for a 1- to 2-year period before or after each water year. Groundwater levels were chosen from wells and piezometers screened in the middle of the production zone as they were considered to best represent the groundwater level in the production zone. The few exceptions are discussed below.

For areas near the Rio Grande, few groundwater-level measurements from the production zone were available, but typical measured vertical gradients between the Rio Grande alluvial aquifer and the production zone within about 1 mile of the Rio Grande were used to estimate the change in groundwater elevation in the production zone under the river (fig. 1). A similar approach was previously successfully employed for construction of the 2016 groundwater-levels map (Galanter and Curry, 2019). In this approach, four nested piezometers in which groundwater levels are measured in the Rio Grande alluvial aquifer and the production zone were selected (sites 4, 9, 18, and 23, fig. 1). All piezometers were within about 1 mile of the Rio Grande, and winter (November to March) groundwater elevations for each water year in each pair of piezometers were subtracted to calculate the vertical groundwater-elevation difference between the Rio Grande alluvial aquifer and the production zone. These differences were then linearly interpolated to the Rio Grande by using points at 1-mile intervals along the river (Rio Grande difference points; fig. 3, on sheet, and fig. 4).

The dates of the groundwater-level measurements at each site that were used to calculate the changes from 2002 to 2008, 2008 to 2012, and 2008 to 2016 are presented in table 1. Table 1 also presents the groundwater-level changes at each site from 2002 to 2008, 2008 to 2012, and 2008 to 2016 that were used to construct the change maps. Vertical groundwater-elevation differences and the dates of the groundwater-level measurements used to calculate the differences at the four nested piezometers along the Rio Grande (sites 4, 9, 18, and 23, fig. 1) for water years 2002, 2008, 2012, and 2016 are presented in table 2. Table 2 also presents the changes in groundwater elevation beneath the Rio Grande at the four nested piezometers from 2002 to 2008, 2008 to 2012, and 2008 to 2016 that were used to construct the change maps. The accuracy of groundwater-level measurements used to calculate change ranged from the nearest foot to the nearest hundredth of a foot. The groundwater-level change calculated at each site and beneath the Rio Grande was rounded to the accuracy of the least accurate groundwater-level measurement used to calculate the change.

Calculation of Change in Groundwater Level

Groundwater-level change at each site was calculated as the difference between the measured depth to water for the earlier water year minus depth to water for the later water year. Groundwater-level change beneath the Rio Grande was calculated at the Rio Grande difference points as the difference between the estimated vertical groundwater-elevation difference for the earlier water year minus the estimated vertical groundwater-elevation difference for the later water year. Positive differences correspond to groundwater-elevation rise, and negative differences correspond to groundwater-elevation decline. Interpolation between measurement points (that is, site or Rio Grande difference point) was done with ordinary kriging. To prevent edge effects associated with interpolation, measurements were included from outside the study area to properly account for spatial trends, and the resulting map was clipped to the study area (fig. 1).

The ordinary kriging interpolation was performed using the R programming language (R Development Core Team, 2011). RStudio, version 1.1.456, was used to run R version 3.5.1. The “krige” function within the R package “gstat,” version 2.0-0 (Pebesma and Graeler, 2019), was used to perform the kriging interpolation onto a uniform grid with a square block side length of 100 feet. The kriging interpolation was chosen because every estimate of groundwater-level change has a measure of the uncertainty associated with the estimate (that is, the standard error, or square root of the estimation variance) and the ability to match the measurements of groundwater-level change at the point locations.

The degree of spatial correlation between measurement points was quantified with an empirical semivariogram developed for each of the three periods (Fisher, 2013). Kriging estimates the spatial distribution of the measured values by using a theoretical semivariogram model that is fitted to the empirical semivariogram and a minimization of the estimation variance at the measurement points (Fisher, 2013). The empirical semivariograms were estimated using the “variogram” function within the R package “gstat,” with a constant bin width (spatial separation distance to which semivariogram values for point pairs are averaged to estimate an empirical semivariogram value) of 4,000 feet and a maximum spatial separation distance to which point pairs are included in the empirical semivariogram estimates of 100,000 feet (about half of the maximum separation distance between point pairs).

Theoretical semivariogram models were fit to the empirical semivariograms by using the “fit.variogram” function within the R package “gstat.” For 2002–8, the theoretical semivariogram was modeled as exponential with no nugget, a sill of 25 feet, and a range of 8,800 feet. For 2008–12, the theoretical semivariogram was modeled as exponential with no nugget, a sill of 41 feet, and a range of 19,000 feet. For 2008–16 the theoretical semivariogram was modeled as circular with no nugget, a sill of 120 feet, and a range of 56,000 feet.

One of the underlying assumptions of kriging is stationarity (that is, the mean of the data being estimated does not change when shifted in space, and the theoretical semivariogram model is the same everywhere) (Fisher, 2013). The validity of this assumption was tested for each period by using leave-one-out cross-validation. The leave-one-out cross-validation was performed in R by using the “RunCrossValidation” function within the R package “ObsNetwork,” version 1.0.0 (Fisher, 2013). The leave-one-out cross-validation removes each measurement point from the dataset one by one and estimates the groundwater-level change at the removed location by using the theoretical semivariogram model developed for the entire dataset to krige with the remaining data. The estimation error from leave-one-out cross-validation was calculated as the difference between the measured and estimated groundwater-level change at the omitted location.

Uncertainty in Groundwater-Level Change

Locations where measurements were made in both the starting and ending year are assumed to be good estimators of groundwater-level change, but computed differences using measurements from other years were visually evaluated to ensure that these data points did not appear to bias the change map compared with surrounding data. Uncertainty in the change maps was also assessed using the standard error for kriging and leave-one-out cross-validation.

Groundwater-Level Change and Discussion

The groundwater-level change maps generally show groundwater-elevation declines until 2008 (fig. 3*A*) followed by recovery after 2008 (figs. 3*B* and 3*C*). Groundwater levels are changing fastest farther away from the Rio Grande. Generally, the west and southeast margins of the grids have the largest uncertainty because of a lack of data points in areas west and east of the grids (fig. 4). Important measurement points derived from the leave-one-out cross-validation for constructing the groundwater-level change maps are generally located west of the Rio Grande and near the eastern margin of the study area (fig. 5).

Change From 2002 To 2008

The 2002–8 change map presented in figure 3*A* indicates widespread groundwater-elevation decline throughout the study area. The largest groundwater-elevation declines (about −30 to about −10 feet) are near the southeast corner of the study area and to the west of the Rio Grande. These regions are generally near the areas of maximum groundwater-elevation declines since predevelopment conditions (hereafter called the maximum declines since predevelopment) that are depicted in the 2008 groundwater-elevation map of the production zone (Falk and others, 2011). Groundwater-elevation declines are generally as much as about 20 to 30 percent of the maximum declines since predevelopment to the west of the Rio Grande (101 to 120 feet maximum decline, Falk and others, 2011) and as much as about 10 to 20 percent of the maximum declines since predevelopment near the eastern margin of the study area (greater than 120 feet maximum decline, Falk and others, 2011). Regions of minimal groundwater-level change (boundary between −10 to 0 feet and 0 to 10 feet shading intervals) occur along the Rio Grande inner valley (fig. 1) and in the southwest and northeast regions of the study area. Localized regions of groundwater-elevation rise occur in the Rio Grande inner valley (fig. 1) and in the southwest and northeast regions of the study area.

Change From 2008 To 2012

The 2008–12 change map presented in figure 3*B* indicates widespread but modest (when compared with the 2008–16 change map, fig. 3*C*) groundwater-elevation rise throughout the study area. The largest groundwater-elevation rises (10 to 30 feet) are near the northeast and southeast corners of the study area and to the west of the Rio Grande, generally corresponding to the regions of largest groundwater-elevation declines in the 2002–8 change map (fig. 3*A*). Groundwater-elevation rises are generally as much as about 10 to 20 percent of the maximum declines since predevelopment to the west of the Rio Grande (101 to 120 feet maximum decline, Falk and others, 2011) and near the eastern margin of the study area (greater than 120 feet maximum decline, Falk and others, 2011). The Rio Grande inner valley has a comparatively small groundwater-elevation rise. A localized region of groundwater-elevation decline persists near an ABCWUA production well on the eastern margin of the study area.

Change From 2008 To 2016

Similar to the 2008–12 change map (fig. 3*B*), the 2008–16 change map presented in figure 3*C* indicates widespread groundwater-elevation rise throughout the study area. The largest groundwater-elevation rises are near the southeast and northeast corners of the study area and to the west of the Rio Grande, generally corresponding to trends in the 2008–12 change map. However, compared with the 2008–12 change map, the 2008–16 change map displays larger groundwater-elevation rises (as much as 30 to 40 feet as compared with as much as 20 to 30 feet) occurring over an increased spatial extent, suggesting continued recovery from previous drawdown. Groundwater-elevation rises are generally as much as about 30 to 40 percent of the maximum declines since predevelopment to the west of the Rio Grande (101 to 120 feet maximum decline, Falk and others, 2011) and as much as about 20 to 30 percent of the maximum declines since predevelopment near the eastern margin of the study area (greater than 120 feet maximum decline, Falk and others, 2011). The Rio Grande inner valley is a region of small groundwater-elevation rise. Also similar to the 2008–12 change map, a localized region of groundwater-elevation decline continues to persist near the ABCWUA production well on the eastern margin of the study area. This decline is small and localized relative to the surrounding rises.

Uncertainty Analysis

Visual analysis of computed differences using measurements from years not in the starting and ending year did not reveal any potential biases for any of the change maps. Local maximums and minimums in the interpolated change surfaces have high uncertainty if there are no measurements nearby. These maximums and minimums are an artifact of trends in the data that may not persist in the natural system. The extent of the groundwater-elevation declines near the ABCWUA production well on the eastern margin of the study area are poorly constrained because of low data density.

Standard error from kriging for 2002–8, 2008–12, and 2008–16 are shown in figures 4*A*, 4*B*, and 4*C*, respectively. Standard error from kriging for 2002–8 ranged from 0.28 to 4.9 feet, for 2008–12 ranged from 0.24 to 5.3 feet, and for 2008–16 ranged from 0.27 to 6.7 feet. The west and east margins of the study area show the largest uncertainty for all periods resulting from the lack of measurement points in these areas.

Estimation error from leave-one-out cross-validation for 2002–8, 2008–12, and 2008–16 are shown in figures 5*A*, 5*B*, and 5*C*, respectively. Estimation error from leave-one-out cross-validation for 2002–8 ranged from −12 to 10 feet with a mean of −0.023 feet, for 2008–12 ranged from −16 to 19 feet with a mean of −0.14 feet, and for 2008–16 ranged from −29 to 28 feet with a mean of −0.43 feet. The mean estimation error, which would ideally be zero, was small (with an absolute value of less than 0.5 foot) for all periods, indicating an absence of systematic errors from kriging (Fisher, 2013). A strong linear correlation between estimation error and the estimated groundwater-level change at the omitted locations was not observed for any period (Pearson correlation coefficient of −0.02, −0.12, and −0.21 for periods 2002–8, 2008–12, and 2008–16, respectively), with estimation error equally scattered around a horizontal line, which indicate that the estimation error is independent of the magnitude of the estimated groundwater-level change from cross-validation and that stationarity may be assumed for the groundwater-level change measurements used for kriging (Fisher, 2013).

Important measurement points for constructing the groundwater-level change maps (points with larger magnitudes of estimation error; Fisher, 2013) are generally located west of the Rio Grande and near the eastern margin of the study area (fig. 5). Large magnitudes of estimation error at measurement points located west of the Rio Grande and in the eastern margins of the study area likely result from the lack of measurement points in these areas. Large magnitudes of estimation error at measurement points within about 1 mile west of the Rio Grande and 1 mile north of Interstate 40 result from the rapid increase in groundwater-level change west of the Rio Grande likely associated with groundwater pumping.

Observations for All Change Maps

For the period 2002–8, near the end of the period of exclusive groundwater use, groundwater elevations in the production zone of the Santa Fe Group aquifer system declined as much as 20 to 30 feet (fig. 3*A*). Following initiation of the change in supply in 2008, groundwater elevations in the production zone of the Santa Fe Group aquifer system cumulatively rose as much as 20 to 30 feet by 2012 (fig. 3*B*) and 30 to 40 feet by 2016 (fig. 3*C*). The largest groundwater-elevation declines and rises were observed near the southeast corner of the study area and to the west of the Rio Grande. All change maps indicate that the Rio Grande inner valley has undergone the least amount of groundwater-level change in the study area from 2002 to 2016. This pattern could be affected by the partial hydraulic connection between the Rio Grande and the production zone, by the locations of ABCWUA production wells where pumping has been reduced over time, and by the locations of other groundwater withdrawals in surrounding areas, such as near the southeast corner of the study area. In addition, this pattern could be affected by the presence of bedrock rather than transmissive aquifer near the eastern margin of the study area, which would contribute to greater groundwater-elevation declines for a given amount of groundwater withdrawal.

Further analysis is needed to explain the localized region of groundwater-elevation decline surrounding the ABCWUA production well on the eastern margin of the study area, despite the large rises nearby that have resulted from reductions in pumping over time.

Table 1. Groundwater-level change at each measured site in the greater Albuquerque, New Mexico, study area for the periods 2002–8, 2008–12, and 2008–16.

[USGS, U.S. Geological Survey; NA, not applicable. Groundwater-level measurements used to calculate change were obtained from the National Water Information System (USGS, 2019)]

USGS site number	Figure 1 number	Date of 2002 groundwater-level measurement	Date of 2008 groundwater-level measurement	Date of 2012 groundwater-level measurement	Date of 2016 groundwater-level measurement	2002 to 2008 change, in feet	2008 to 2012 change, in feet	2008 to 2016 change, in feet
343753106430602	1	2/20/2002	3/3/2008	2/17/2012	3/15/2016	−0.53	0.02	−0.27
344258106460902	2	2/19/2003	2/28/2008	3/2/2012	2/29/2016	−2.13	2.28	2.15
344431106393402	3	2/20/2002	3/3/2008	2/21/2012	3/15/2016	−0.95	−0.06	−0.29
345650106415902	4	1/17/2002	1/3/2008	2/6/2012	2/19/2016	−1.51	0.39	0.76
345758106364002	5	1/17/2002	1/4/2008	2/6/2012	1/5/2016	−1.27	4.56	8.49
345842106443102	6	1/17/2002	1/3/2008	2/2/2012	3/14/2016	−0.08	0.97	1.58
350056106370102	7	2/20/2002	3/10/2008	2/6/2012	1/5/2016	−0.75	4.17	7.82
350100106405701	8	1/17/2002	1/2/2008	12/7/2011	11/2/2015	−0.97	3.25	4.50
350138106401103	9	3/12/2002	2/25/2008	3/5/2012	3/1/2016	0.26	0.63	1.27
350244106450202	10	1/22/2002	1/2/2008	2/3/2012	2/18/2016	4.31	11.35	13.28
350256106390801	11	2/14/2002	2/14/2008	2/2/2012	2/19/2016	4.81	3.17	6.15
350307106410602	12	NA	1/2/2008	2/2/2012	3/14/2016	NA	23.38	25.81
350534106354702	13	2/21/2002	2/8/2008	2/8/2012	3/14/2016	−0.08	12.81	25.21
350545106335902	14	NA	1/9/2008	2/2/2012	3/14/2016	NA	13.17	28.43
350638106413702	15	1/22/2002	1/2/2008	2/1/2012	3/15/2016	−0.25	4.49	5.87
350653106311602	16	2/21/2002	3/10/2008	2/1/2012	3/11/2016	1.1	8.9	26.0
350706106390302	17	1/28/2002	1/8/2008	2/3/2012	3/21/2016	0.82	4.78	9.45
350836106395401	18	1/2/2002	1/8/2008	2/3/2012	1/6/2016	0.71	3.49	7.58
350908106344402	19	1/28/2002	1/25/2008	1/4/2012	3/11/2016	−3.27	7.14	18.63
350910106414802	20	1/22/2002	1/28/2008	1/3/2012	2/19/2016	−4.64	2.10	3.24
351035106364703	21	3/12/2002	2/26/2008	3/6/2012	3/1/2016	−1.45	2.46	7.4
351040106482801	22	1/22/2002	1/9/2008	2/10/2012	3/3/2016	−1.30	−0.30	0.05
351059106385903	23	3/12/2002	2/26/2008	3/7/2012	3/1/2016	−1.49	1.37	4.99
351114106330602	24	1/29/2002	1/25/2008	1/4/2012	1/6/2016	0.46	8.36	15.99
351201106400502	25	1/22/2002	1/28/2008	1/3/2012	2/19/2016	−2.46	−0.82	2.20
351357106323002	26	1/28/2002	1/30/2008	1/5/2012	2/18/2016	−2.92	2.36	6.40
351515106410402	27	1/23/2002	1/28/2008	1/4/2012	3/11/2016	−5.23	−6.33	−3.65
351821106333901	28	1/15/2002	2/22/2007	1/4/2012	3/11/2016	−8.91	−4.16	−5.41
352019106474801	29	2/16/2001	2/26/2008	2/10/2012	12/15/2015	−0.89	−0.43	−2.31
350223106435401	30	1/16/2001	12/20/2007	11/14/2011	11/4/2015	3.13	14.09	16.25
350301106383601	31	2/25/2002	11/29/2007	11/15/2011	11/5/2015	5.92	3.28	9.12
350308106374601	32	2/27/2002	1/8/2007	11/22/2010	NA	1.66	7.6	NA
350309106434501	33	2/25/2002	12/20/2007	11/14/2011	11/4/2015	2.24	13.53	15.87
350355106351501	34	1/28/2002	3/13/2007	1/17/2012	12/8/2015	−0.72	12.33	17.56
350358106372901	35	2/26/2001	12/1/2007	NA	11/5/2015	−1.30	NA	16.44
350359106362401	36	2/26/2002	12/20/2007	11/18/2011	11/5/2015	−1.07	10.25	18.21
350401106331401	37	1/29/2002	12/21/2007	1/21/2011	NA	−4.7	12.5	NA
350408106310101	38	12/18/2001	1/17/2008	12/21/2011	1/25/2016	−20.9	27.43	40.38
350420106334401	39	12/18/2001	3/13/2007	12/23/2011	NA	−1.1	13.50	NA
350422106312401	40	12/18/2001	11/14/2008	11/15/2011	12/8/2015	−10.8	9.6	23.7

Table 1. Groundwater-level change at each measured site in the greater Albuquerque, New Mexico, study area for the periods 2002–8, 2008–12, and 2008–16.—Continued

[USGS, U.S. Geological Survey; NA, not applicable. Groundwater-level measurements used to calculate change were obtained from the National Water Information System (USGS, 2019)]

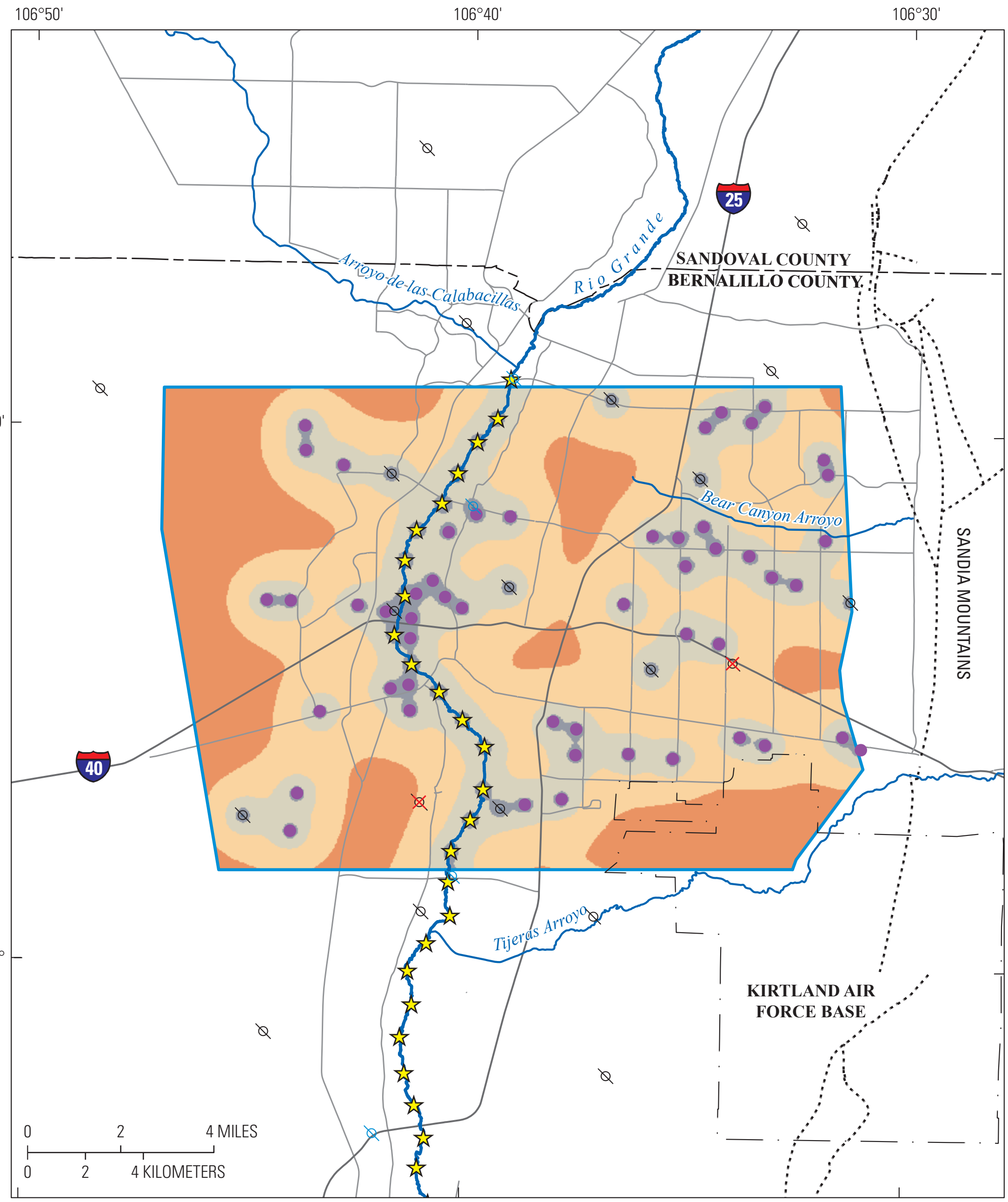
USGS site number	Figure 1 number	Date of 2002 groundwater-level measurement	Date of 2008 groundwater-level measurement	Date of 2012 groundwater-level measurement	Date of 2016 groundwater-level measurement	2002 to 2008 change, in feet	2008 to 2012 change, in feet	2008 to 2016 change, in feet
350426106372601	41	2/26/2001	1/17/2007	1/25/2012	NA	−2.42	3.97	NA
350435106380101	42	2/26/2001	11/29/2007	11/15/2011	11/5/2015	−2.46	5.59	16.03
350442106431801	43	1/12/2000	11/28/2007	12/1/2010	NA	−11.04	22.1	NA
350445106411501	44	1/14/2002	3/1/2007	11/30/2011	11/19/2015	−1.60	5.43	5.58
350508106411901	45	1/28/2002	1/16/2008	12/14/2011	11/19/2015	−1.31	4.17	4.03
350509106414401	46	1/28/2002	1/30/2007	12/23/2011	11/19/2015	−3.40	7.15	6.08
350605106411801	47	1/28/2002	1/16/2008	12/14/2011	11/4/2015	−2.43	2.48	1.97
350606106341101	48	1/14/2002	1/25/2008	12/21/2011	1/25/2016	−1.23	6.57	24.07
350615106345901	49	1/2/2002	3/23/2007	1/17/2012	11/19/2015	−7.23	10.10	21.77
350628106411501	50	1/28/2002	1/17/2008	11/22/2010	12/27/2016	0.30	4.63	3.97
350635106415001	51	2/11/2002	1/30/2007	1/25/2012	11/4/2015	−16.04	17.47	16.93
350642106401101	52	12/17/2001	11/29/2007	11/18/2011	12/8/2015	0.17	3.25	6.33
350642106422801	53	2/11/2002	11/28/2007	1/25/2012	11/4/2015	−17.92	12.50	7.23
350646106443201	54	1/28/2002	12/11/2006	11/14/2011	11/4/2015	−1.88	16.30	19.04
350647106440001	55	1/28/2002	3/13/2007	11/14/2011	11/4/2015	4.09	9.39	11.19
350648106362501	56	2/12/2001	11/29/2007	12/14/2011	11/5/2015	−3.78	7.31	16.68
350653106403001	57	1/28/2002	12/11/2006	12/30/2011	11/4/2015	−0.41	4	6.37
350655106395001	58	1/30/2001	1/8/2007	1/18/2012	11/19/2015	−1.61	1.40	1.24
350708106405801	59	12/17/2001	1/30/2007	11/18/2011	12/8/2015	0.12	2.76	0.82
350711106323101	60	2/13/2001	11/29/2007	1/17/2012	11/20/2015	−1.61	17.91	28.33
350720106330401	61	2/11/2002	1/17/2007	1/3/2012	11/20/2015	−0.7	14.82	26.64
350732106350101	62	2/25/2002	2/6/2008	11/30/2011	12/8/2015	−3.87	4.92	17.87
350744106333501	63	2/11/2002	1/16/2008	11/15/2011	11/5/2015	1.3	10.24	26.37
350752106342101	64	12/4/2001	1/4/2007	11/30/2011	1/25/2016	3.30	1.02	18.41
350800106315001	65	1/29/2002	3/19/2008	11/30/2011	12/8/2015	−5.8	−3.5	−2.1
350802106402901	66	1/14/2002	12/11/2006	2/16/2010	NA	1.24	0.94	NA
350803106351101	67	2/25/2002	2/6/2008	12/14/2011	1/25/2016	−5.10	6.75	20.83
350805106354901	68	1/2/2002	3/5/2008	11/18/2011	12/3/2014	−4.1	5.5	15.0
350819106344001	69	12/4/2001	2/19/2008	12/21/2011	11/20/2015	−2.5	6.6	19.2
350821106390101	70	1/14/2002	11/29/2007	11/16/2012	1/29/2014	−0.28	3.22	5.45
350827106395001	71	1/14/2002	3/19/2008	12/14/2011	11/19/2015	−1.38	3.71	6.02
350918106315401	72	3/7/2000	1/25/2008	11/10/2011	11/6/2015	8.29	9.86	22.43
350918106425401	73	1/14/2002	11/28/2007	11/14/2011	11/19/2015	−12.7	8.48	10.53
350931106315501	74	1/29/2002	12/21/2007	11/10/2011	11/6/2015	−0.3	13.40	27.68
350950106434001	75	1/2/2002	12/20/2007	2/25/2011	11/4/2015	−22.85	13.9	35.43
351007106343801	76	1/14/2002	11/30/2007	12/14/2011	11/5/2015	−0.71	7.64	13.12
351007106434201	77	2/11/2002	12/11/2006	NA	NA	−17.82	NA	NA
351013106333501	78	2/11/2002	11/30/2007	11/10/2011	11/8/2016	−0.4	9.74	21.74
351025106341601	79	2/26/2002	11/30/2007	11/15/2011	11/5/2015	0.69	8.85	17.69
351029106332001	80	12/17/2001	11/30/2007	11/10/2011	11/6/2015	0.2	9.50	20.36

Table 2. Vertical groundwater-elevation difference and groundwater-level change between the Rio Grande alluvial aquifer and the production zone of the Santa Fe Group aquifer system at the four nested piezometers along the Rio Grande in the greater Albuquerque, New Mexico, study area for the periods 2002–8, 2008–12, and 2008–16.

[USGS, U.S. Geological Survey. Groundwater-level measurements used to calculate change were obtained from the National Water Information System (USGS, 2019). The two USGS sites that are listed for each figure 1 number are nested piezometers at the same location. For each figure 1 number, the top USGS piezometer was assumed to measure the Rio Grande alluvial aquifer, and the bottom USGS piezometer was assumed to measure the production zone of the Santa Fe Group aquifer system]

USGS site number	Figure 1 number	Date of 2002 groundwater-level measurement	Date of 2008 groundwater-level measurement	Date of 2012 groundwater-level measurement	Date of 2016 groundwater-level measurement	2002 vertical difference, in feet	2008 vertical difference, in feet	2012 vertical difference, in feet	2016 vertical difference, in feet	2002 to 2008 change, in feet	2008 to 2012 change, in feet	2008 to 2016 change, in feet
351059106385902	23	3/12/2002	2/26/2008	3/7/2012	3/1/2016	37.74	39.87	37.60	34.77	−2.13	2.27	5.10
351059106385903		3/12/2002	2/26/2008	3/7/2012	3/1/2016							
350836106395603	18	1/2/2002	2/25/2008	3/6/2012	2/29/2016	21.67	22.19	17.36	15.12	−0.52	4.83	7.07
350836106395401		1/2/2002	3/7/2008	3/26/2012	1/6/2016							
350138106401102	9	12/19/2001	2/25/2008	3/5/2012	3/1/2016	6.80	6.59	6.06	5.88	0.21	0.53	0.71
350138106401103		12/19/2001	2/25/2008	3/5/2012	3/1/2016							
345650106415904	4	2/20/2002	3/3/2008	2/6/2012	2/19/2016	1.10	2.48	1.17	1.03	−1.38	1.31	1.45
345650106415902		2/20/2002	3/3/2008	2/6/2012	2/19/2016							

A



Base modified from U.S. Geological Survey and other Federal, State, and city digital data, various scales

Site locations and groundwater-level measurements were obtained from the National Water Information System (U.S. Geological Survey, 2019)
Military base from U.S. Department of Commerce and U.S. Census Bureau (Geography Division)
Streams delineated from 2010 lidar (Caerllion Thomas, Middle Rio Grande Council of Governments, written commun., 2017)

EXPLANATION

Study area

Standard error from the application of kriging, in feet

- 0 to 1
- 1.1 to 2
- 2.1 to 3
- 3.1 to 4
- 4.1 to 5
- > 5

Major fault (concealed and exposed) as identified by Connell (2006) and Minor and Hudson (2006)

Rio Grande difference point

Wells

- Primary use of well is for observation
- Primary use of well is for observation; also used to estimate vertical groundwater elevation difference between the Rio Grande alluvial aquifer and the production zone of the Santa Fe Group aquifer system
- Primary use of well is for observation; data not available to calculate change
- Production well
- Production well; data not available to calculate change

Figure 4. Standard error from kriging for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.

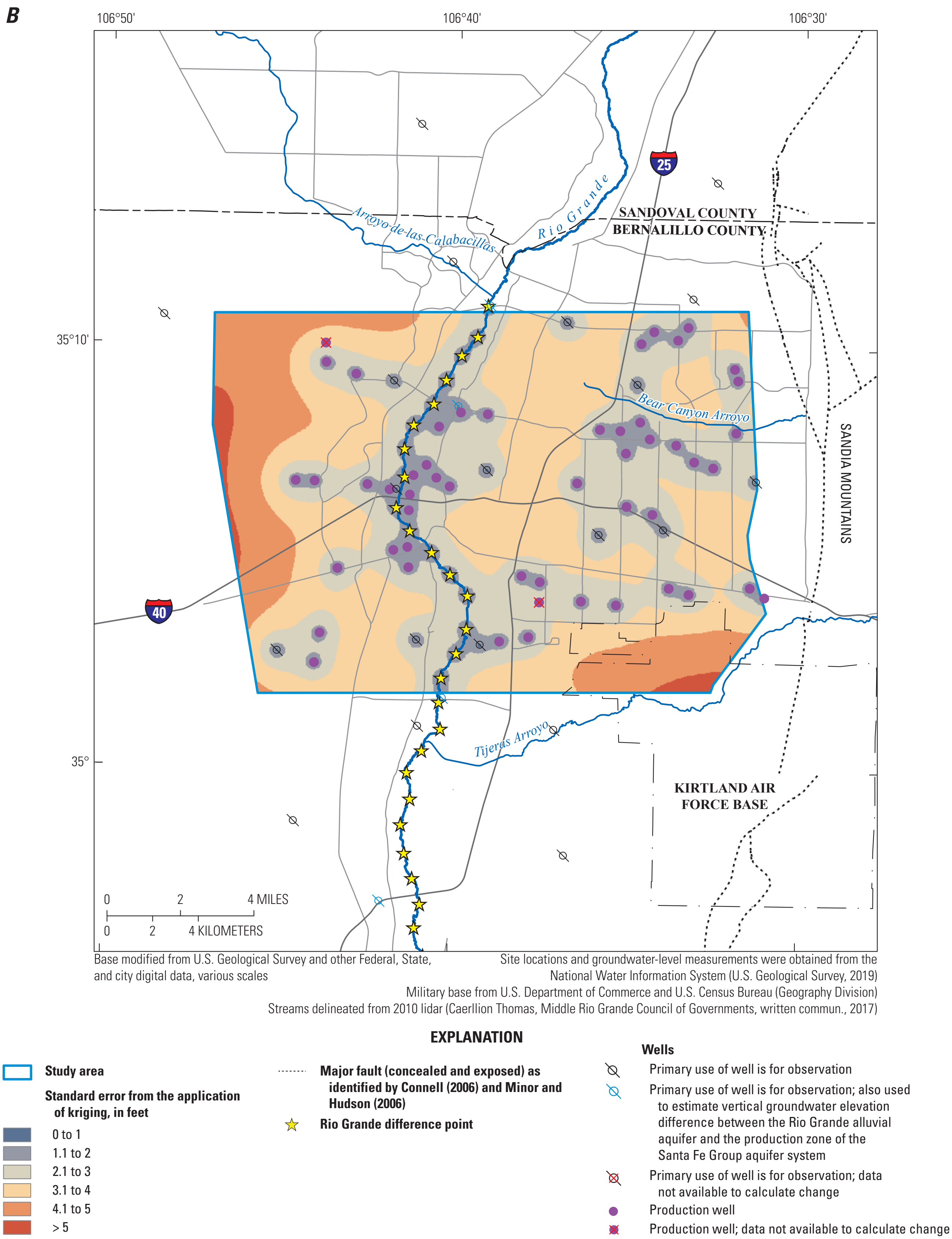
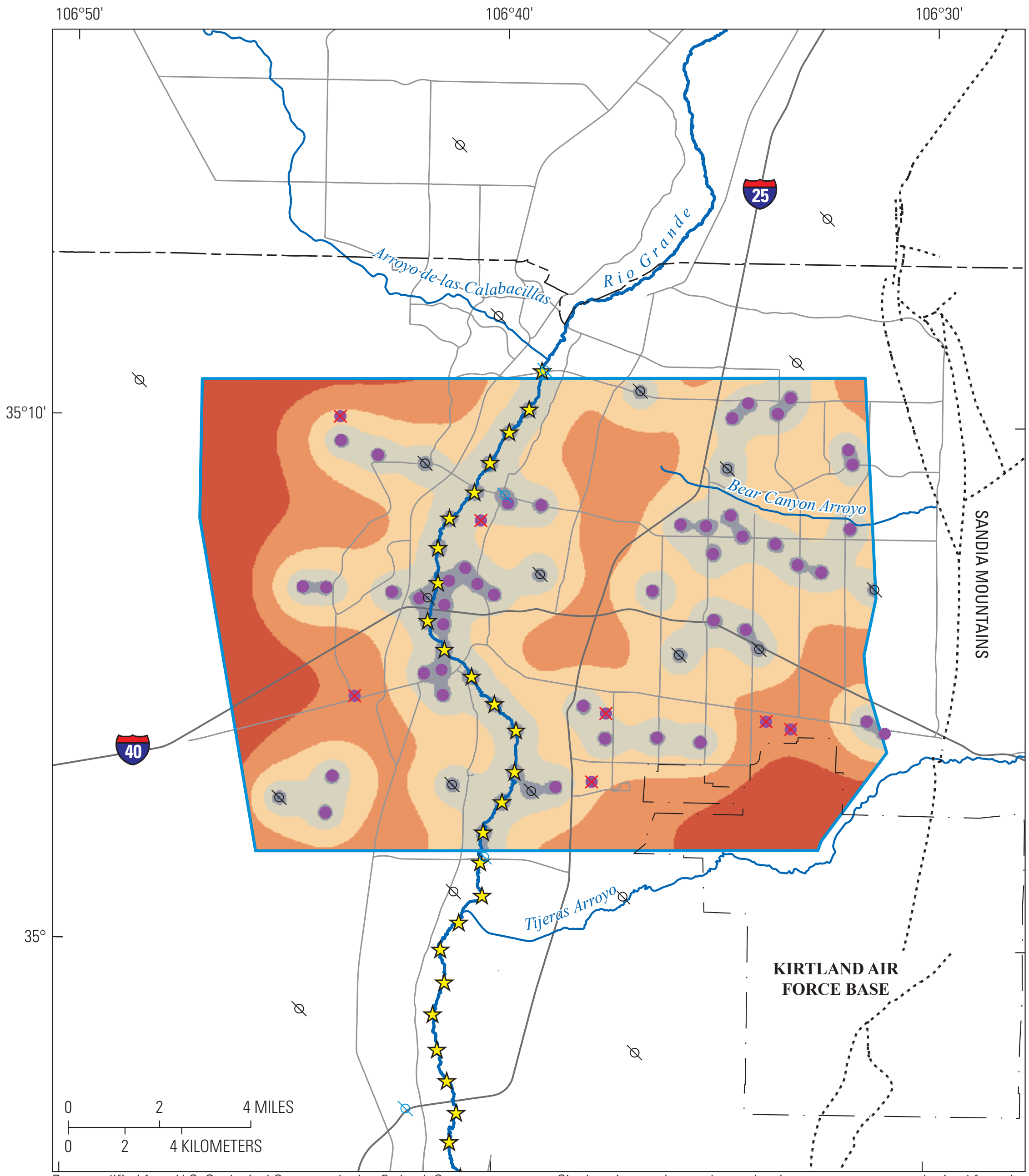


Figure 4. Standard error from kriging for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.—Continued

C



Base modified from U.S. Geological Survey and other Federal, State, and city digital data, various scales

Site locations and groundwater-level measurements were obtained from the National Water Information System (U.S. Geological Survey, 2019)
Military base from U.S. Department of Commerce and U.S. Census Bureau (Geography Division)
Streams delineated from 2010 lidar (Caerllion Thomas, Middle Rio Grande Council of Governments, written commun., 2017)

EXPLANATION

Study area

Standard error from the application of kriging, in feet

- 0 to 1
- 1.1 to 2
- 2.1 to 3
- 3.1 to 4
- 4.1 to 5
- > 5

Major fault (concealed and exposed) as identified by Connell (2006) and Minor and Hudson (2006)

Rio Grande difference point

Wells

- Primary use of well is for observation
- Primary use of well is for observation; also used to estimate vertical groundwater elevation difference between the Rio Grande alluvial aquifer and the production zone of the Santa Fe Group aquifer system
- Primary use of well is for observation; data not available to calculate change
- Production well
- Production well; data not available to calculate change

Figure 4. Standard error from kriging for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.—Continued

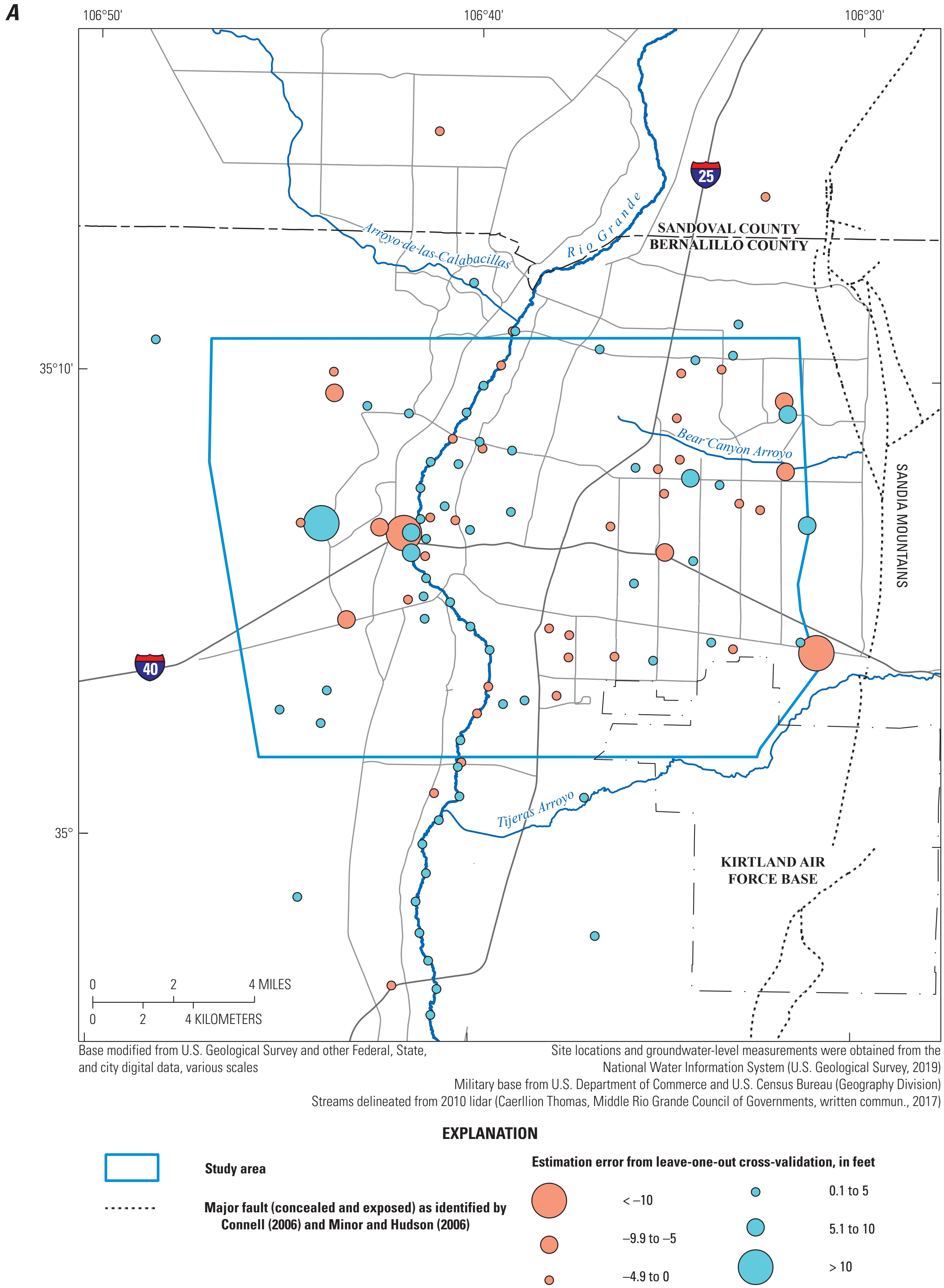
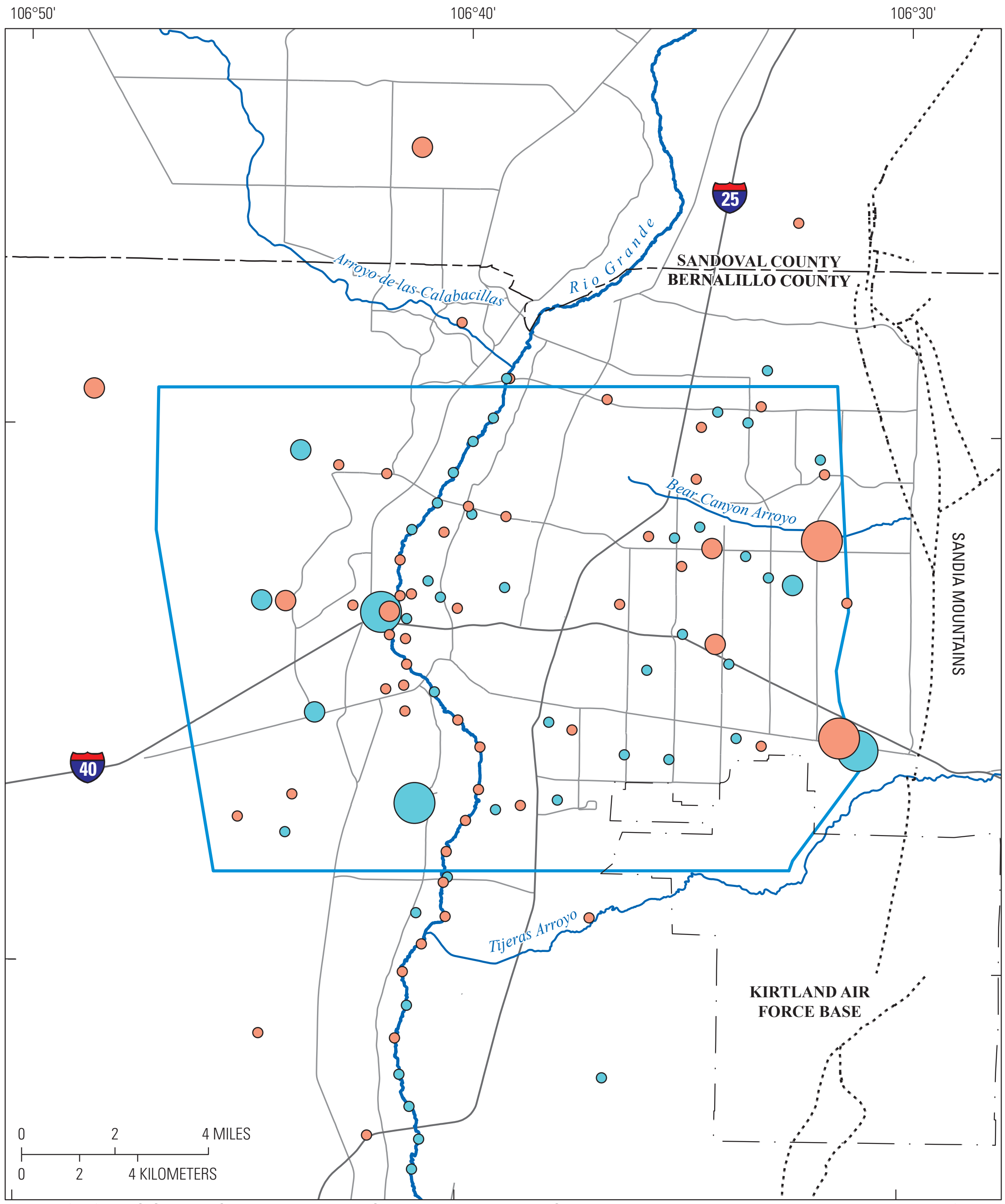


Figure 5. Estimation error from leave-one-out cross-validation for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.

B



Base modified from U.S. Geological Survey and other Federal, State, and city digital data, various scales

Site locations and groundwater-level measurements were obtained from the National Water Information System (U.S. Geological Survey, 2019)
Military base from U.S. Department of Commerce and U.S. Census Bureau (Geography Division)
Streams delineated from 2010 lidar (Caerllion Thomas, Middle Rio Grande Council of Governments, written commun., 2017)

EXPLANATION

Study area

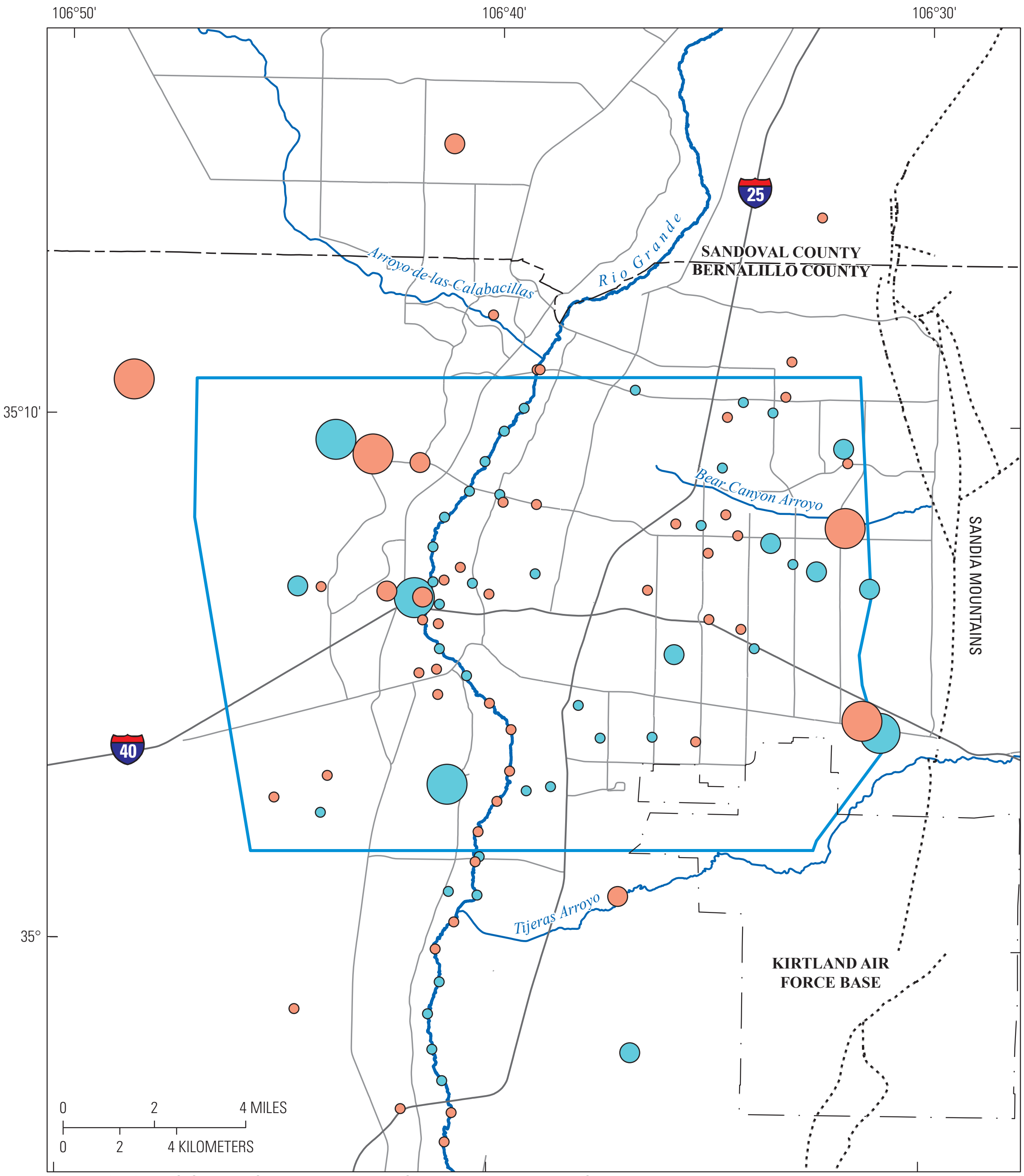
Major fault (concealed and exposed) as identified by Connell (2006) and Minor and Hudson (2006)

Estimation error from leave-one-out cross-validation, in feet

< –10 | 0.1 to 5
–9.9 to –5 | 5.1 to 10
–4.9 to 0 | > 10

Figure 5. Estimation error from leave-one-out cross-validation for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.—Continued

C



Base modified from U.S. Geological Survey and other Federal, State, and city digital data, various scales

Site locations and groundwater-level measurements were obtained from the National Water Information System (U.S. Geological Survey, 2019)
Military base from U.S. Department of Commerce and U.S. Census Bureau (Geography Division)
Streams delineated from 2010 lidar (Caerllion Thomas, Middle Rio Grande Council of Governments, written commun., 2017)

EXPLANATION

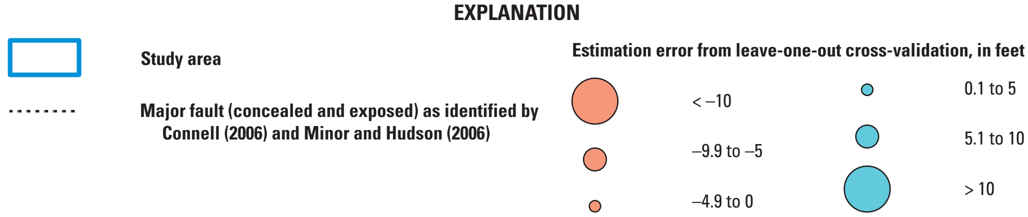


Figure 5. Estimation error from leave-one-out cross-validation for the periods *A*, 2002–8, *B*, 2008–12, and *C*, 2008–16 for the production zone of the Santa Fe Group aquifer system in the greater Albuquerque area, central New Mexico.—Continued

Summary

The U.S. Geological Survey, in cooperation with the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), has developed a series of maps and associated reports, beginning in 2002, that document groundwater levels in the production zone of the Santa Fe Group aquifer system beneath a large area of the City of Albuquerque, New Mexico. Herein, we document the construction of groundwater-level change maps for representative conditions during three periods: 2002–8, 2008–12, and 2008–16.The change maps were analyzed to identify regions recovering after 2008, when the ABCWUA began diverting surface water from the Rio Grande as part of the San Juan-Chama Drinking Water Project to supplement municipal water supply. Prior to 2008, the ABCWUA relied exclusively on groundwater from the Santa Fe Group aquifer system for municipal water supply, and groundwater elevations were declining. Since 2008, the proportion of municipal water supply sourced directly from surface water has increased to approximately two-thirds of the total water supply in 2016.

The 2002–8 change map indicates widespread groundwater-elevation decline throughout the study area, with the largest groundwater-elevation declines (−30 to −10 feet) near the southeast corner of the study area and to the west of the Rio Grande. The 2008–12 and 2008–16 change maps indicate widespread groundwater-elevation rise throughout the study area, with the largest groundwater-elevation rises near the northeast and southeast corners of the study area and to the west of the Rio Grande. Groundwater-elevation declines since 2008 were restricted to a localized area on the eastern margin of the study area. Relative to the 2008–12 change map, the 2008–16 change map displays larger groundwater-elevation rises (as much as 30 to 40 feet as compared with as much as 20 to 30 feet) occurring over an increased spatial extent, suggesting continued recovery from previous drawdown. Groundwater-elevation rises from 2008 to 2016 are generally as much as about 30 to 40 percent of the maximum declines since predevelopment to the west of the Rio Grande (101 to 120 feet maximum decline) and as much as about 20 to 30 percent of the maximum declines since predevelopment near the eastern margin of the study area (greater than 120 feet maximum decline). All change maps indicate that the Rio Grande inner valley has undergone the least amount of groundwater-level change in the study area from 2002 to 2016, with minimal change prior to 2008 and small groundwater-elevation rises of less than 10 feet since 2008.

References Cited

Albuquerque Bernalillo County Water Utility Authority [ABCWUA], 2016, Water 2120: Securing our water future: Volume I: Main text and appendices: Albuquerque Bernalillo County Water Utility Authority, 309 p., accessed December 7, 2017, at https://www.abcwua.org/uploads/files/Water_2120_Volume_I.pdf.

Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the Middle Rio Grande Basin: U.S. Geological Survey Circular 1222, 132 p., accessed October 23, 2018, at https://pubs.usgs.gov/circ/2002/circ1222/.

Beman, J.E., Ritchie, A.B., and Galanter, A.E., 2019, Water-level data for the Albuquerque Basin and adjacent areas, central New Mexico, period of record through September 30, 2017: U.S. Geological Survey Data Series 1113, 39 p., accessed May 24, 2019, at https://doi.org/10.3133/ds1113.

Bexfield, L.M., and Anderholm, S.K., 2002, Estimated water-level declines in the Santa Fe Group aquifer system in the Albuquerque area, central New Mexico, predevelopment to 2002: U.S. Geological Survey Water-Resources Investigations Report 02–4233, 1 sheet, accessed May 5, 2017, at https://pubs.er.usgs.gov/publication/wri024233.

Connell, S.D., 2006, Preliminary geologic map of the Albuquerque-Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: Socorro, New Mexico Bureau of Geology and Mineral Resources, Open-File Report 496, 2 sheets, scale 1:50,000.

Driscoll, J.M., and Brandt, J.T., 2017, Land subsidence and recovery in the Albuquerque Basin, New Mexico, 1993–2014: U.S. Geological Survey Scientific Investigations Report 2017–5057, 31 p., accessed October 23, 2018, at https://doi.org/10.3133/sir20175057.

Falk, S.E., Bexfield, L.M., and Anderholm, S.K., 2011, Estimated 2008 groundwater potentiometric surface and predevelopment to 2008 water-level change in the Santa Fe Group aquifer system in the Albuquerque area, central New Mexico: U.S. Geological Survey Scientific Investigations Map 3162, 1 sheet, accessed October 23, 2018, at https://pubs.usgs.gov/sim/3162/.

Fisher, J.C., 2013, Optimization of water-level monitoring networks in the eastern Snake River Plain aquifer using a kriging-based genetic algorithm method: U.S. Geological Survey Scientific Investigations Report 2013–5120 (DOE/ID-22224), 74 p., accessed May 24, 2019, at http://pubs.usgs.gov/sir/2013/5120/.

Galanter, A.E., and Curry, L.T.S., 2019, Estimated 2016 groundwater level and drawdown from predevelopment to 2016 in the Santa Fe Group aquifer system in the Albuquerque area, central New Mexico: U.S. Geological Survey Scientific Investigations Map 3433, 1 sheet, 13-p. pamphlet, accessed May 24, 2019, at https://doi.org/10.3133/sim3433.

Hawley, J.W., and Haase, C.S., 1992, Hydrogeologic framework of the northern Albuquerque Basin: New Mexico Bureau of Mines and Mineral Resources Open-File Report 387, variously paged, accessed April 23, 2019, at https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=387.

Hudson, M.R., and Grauch, V.J.S., 2013, Introduction, *in* Hudson, M.R., and Grauch, V.J.S., eds., New perspectives on Rio Grande Rift Basins: From tectonics to groundwater: Geological Society of America Special Paper 494, p. v–xii, https://doi.org/10.1130/2013.2494(16).

Longworth, J.W., Valdez, J.M., Magnuson, M.L., and Richard, K., 2013, New Mexico water use by categories 2010: New Mexico Office of the State Engineer Technical Report 54, 128 p., accessed April 23, 2019, at http://www.ose.state.nm.us/Pub/TechnicalReports/TechReport%2054NM%20Water%20Use%20by%20Categories%20.pdf.

McAda, D.P., and Barroll, P., 2002, Simulation of ground-water flow in the Middle Rio Grande Basin between Cochiti and San Acacia, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02–4200, 81 p., accessed October 23, 2018, at https://pubs.usgs.gov/wri/wri02-4200/.

Minor, S.A., and Hudson, M.R., 2006, Regional survey of structural properties and cementation patterns of fault zones in the northern part of the Albuquerque Basin, New Mexico—Implications for ground-water flow: U.S. Geological Survey Professional Paper 1719, 28 p., accessed February 21, 2019, at https://pubs.usgs.gov/pp/1719/.

Pebesma, E., and Graeler, B., 2019, Package 'gstat': Comprehensive R Archive Network (CRAN), accessed May 16, 2019, at https://cran.r-project.org/web/packages/gstat/gstat.pdf.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybiades, 2012, Geochemical characterization of ground-water flow in the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico (ver. 1.2, November 20, 2012): U.S. Geological Survey Water-Resources Investigations Report 03–4131, 395 p., CD-ROM in pocket. [Also available at https://pubs.usgs.gov/wri/wri034131/.]

Powell, R.I., and McKean, S.E., 2014, Estimated 2012 groundwater potentiometric surface and drawdown from predevelopment to 2012 in the Santa Fe Group aquifer system in the Albuquerque metropolitan area, central New Mexico: U.S. Geological Survey Scientific Investigations Map 3301, 1 sheet, accessed April 7, 2017, at https://pubs.er.usgs.gov/publication/sim3301.

R Development Core Team, 2011, R—A language and environment for statistical computing: Vienna, Austria, The R Foundation for Statistical Computing, accessed October 31, 2018, at http://www.R-project.org.

Rankin, D.R., McCoy, K.J., Moret, G.J.M., Worthington, J.A., and Bandy-Baldwin, K.M., 2013, Groundwater hydrology and estimation of horizontal groundwater flux from the Rio Grande at selected locations in Albuquerque, New Mexico, 2003–9: U.S. Geological Survey Scientific Investigations Report 2012–5007, 66 p., accessed October 23, 2018, at https://pubs.er.usgs.gov/publication/sir20125007.

Thorn, C.R., McAda, D.P., and Kernodle, J.M., 1993, Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 93–4149, 106 p., accessed October 23, 2018, at https://pubs.er.usgs.gov/publication/wri934149.

U.S. Census Bureau, 1952, Number of inhabitants, 1950 Census of Population, vol. 1: Washington, D.C., 1,329 p., accessed November 9, 2018, at https://www.census.gov/prod/www/decennial.html.

U.S. Census Bureau, 1973, Characteristics of the population, New Mexico, 1970 Census of Population, vol. 1, part 33: Washington, D.C., 85 p., accessed November 9, 2018, at https://www2.census.gov/prod2/decennial/documents/1970a_nm-01.pdf.

U.S. Census Bureau, 1982, General population characteristics, New Mexico, 1980 Census of Population, vol. 1, chapter B, part 33, PC80-1-B33, 170 p., accessed November 9, 2018, at https://www2.census.gov/prod2/decennial/documents/1980/1980censusofpopu80133unse_bw.pdf.

U.S. Census Bureau, 2012, New Mexico: 2010—Population and housing unit counts, 2010 Census of Population and Housing CPH-2-33: Washington, D.C., 79 p., accessed November 9, 2018, at https://www2.census.gov/library/publications/decennial/2010/cph-2/cph-2-33.pdf.

U.S. Census Bureau, 2019, ACS demographic and housing estimates 2012–2016 American Community Survey 5-year estimates, American Fact Finder, accessed February 2, 2019, at https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF.

U.S. Geological Survey (USGS), 2019, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed February 4, 2019, at https://doi.org/10.5066/F7P55KJN.

For more information about this publication, contact
Director, New Mexico Water Science Center
U.S. Geological Survey
6700 Edith Blvd. NE
Albuquerque, NM 87113

For additional information, visit
https://www.usgs.gov/centers/nm-water

Publishing support provided by
Lafayette Publishing Service Center

USGS

Ritchie and others—**Groundwater-Level Change in the Santa Fe Group Aquifer System in the Albuquerque Area, Central New Mexico**—SIM 3435

ISBN 978-1-4113-4323-8

ISSN 2329-1311 (print)
ISSN 2329-132X (online)
https://doi.org/10.3133/sim3435