

Prepared in cooperation with the U.S. Air Force Civil Engineer Center

# Potentiometric Surface Map of the Southern High Plains Aquifer in the Cannon Air Force Base Area, Curry County, New Mexico, 2020

By A. Blake Goodwin and Meghan T. Bell



*Pamphlet to accompany*  
Scientific Investigations Map 3504

**Cover.**

**Left:** U.S. Geological Survey (USGS) employee Nathan Myers standing next to caliche layer in Curry County, New Mexico. Photograph by Fred Gebhardt, USGS.

**Right:** Ogallala Formation near Ragland, New Mexico. Photograph by Rebecca Lambert, USGS.

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## Sheet

[Available at <https://doi.org/10.3133/sim3504>]

Potentiometric surface of winter 2020 groundwater conditions and groundwater-level change between winter 2015 and winter 2020 in the Cannon Air Force Base area, Curry County, New Mexico (figs. 6–8 on sheet)

## Conversion Factors

U.S. customary units to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft <sup>2</sup> )	0.09290	square meter (m <sup>2</sup> )
	Rate	
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)

International System of Units to U.S. customary units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
meter (m)	3.281	foot (ft)

## Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

## Abbreviations

AFB	Air Force Base
LOOCV	leave-one-out cross validation
NWIS	National Water Information System
RMSE	root mean square error
USGS	U.S. Geological Survey

# Potentiometric Surface Map of the Southern High Plains Aquifer in the Cannon Air Force Base Area, Curry County, New Mexico, 2020

By A. Blake Goodwin and Meghan T. Bell

## Abstract

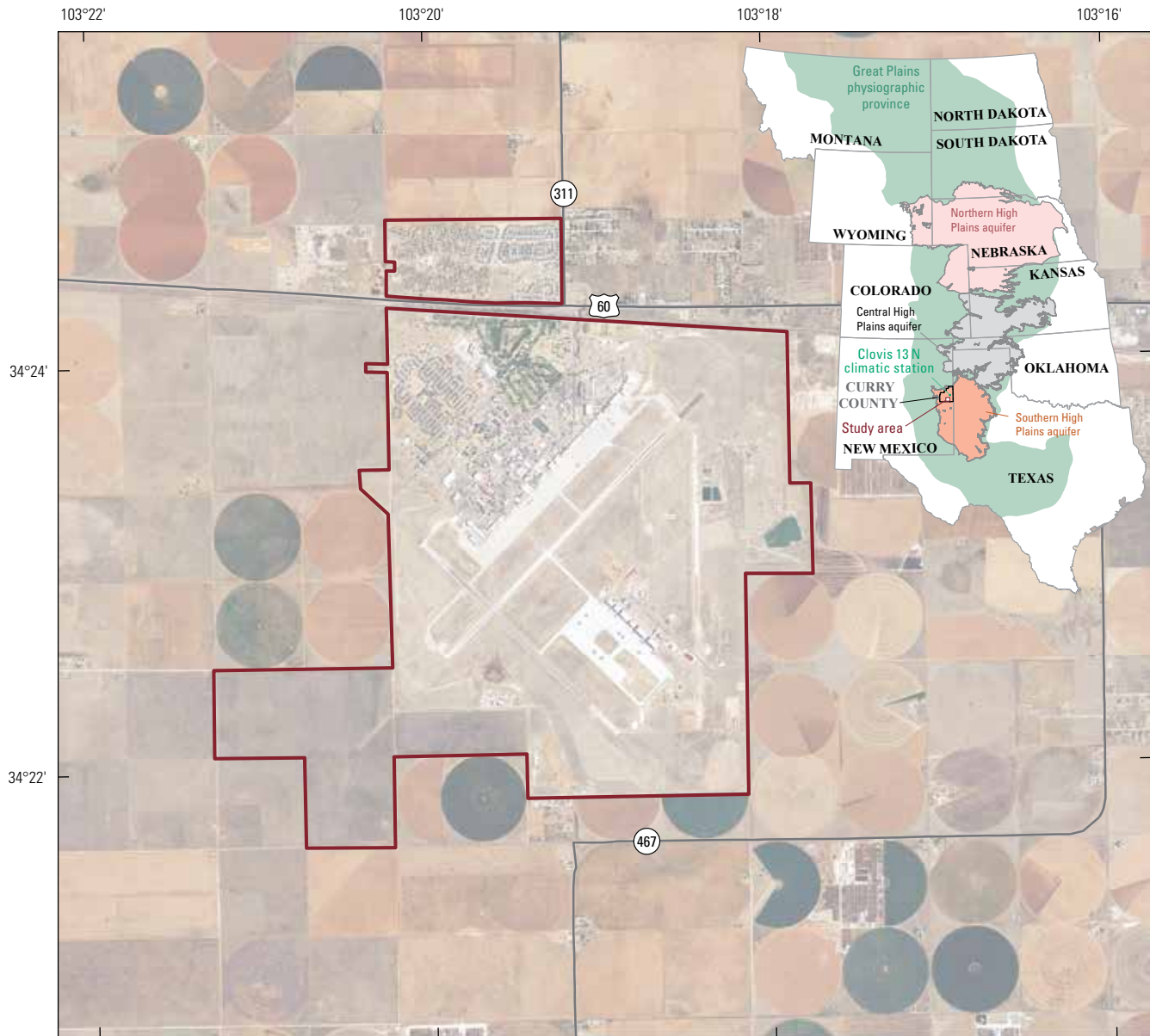
Declining water levels and the potential impact on water resources on and around Cannon Air Force Base (AFB), New Mexico, has necessitated an up-to-date review of the potentiometric surface to evaluate the availability of water resources for future use. Analysis of groundwater-flow directions and hydraulic gradients can provide an understanding of depletion by heavy groundwater pumping and recharge through playa lakes, as well as the relationship between the groundwater levels and underlying geology. The objectives of this study, conducted by the U.S. Geological Survey in cooperation with the U.S. Air Force Civil Engineer Center, are to assist Cannon AFB in understanding and interpreting current and local hydrologic conditions and to evaluate groundwater-level change from 2015 to 2020 using new and historical data. A groundwater potentiometric surface contour map was constructed to better understand the Southern High Plains aquifer around Cannon AFB and to show the altitude of the water-table surface and groundwater-flow patterns. Four hydrographs were created from periodic measurements of groundwater levels in wells on and around Cannon AFB to provide information about historical groundwater-level changes and visualize trends from the water-level records. The long-term trend present in all four hydrographs is a steady decline in groundwater levels, with some areas declining faster than others. The groundwater-level change map presented in this study provides a visual representation of the change in groundwater level from the winter 2015 to winter 2020 measuring events. Results show that among corresponding wells measured in 2015 and 2020, 50.7 percent indicated a decline in water levels, 29.9 percent indicated neutral water levels, and 19.4 percent indicated a rise in water levels. The region to the north of the groundwater trough on Cannon AFB contained most of the groundwater-level rises, whereas the regions located near the trough and just west of Clovis, N. Mex., contained most of the declines. These results suggest that continued monitoring of declining groundwater levels in the area would provide valuable decision-support information for assessing the sustainability of this water resource.

## Introduction

Cannon Air Force Base (Cannon AFB) is in the Great Plains physiographic province of east-central New Mexico, in Curry County about 8 miles west of Clovis ([fig. 1](#)) (Miller, 2000). The area surrounding the base is primarily used for agriculture that includes irrigated croplands and dairies. The Southern High Plains aquifer is the principal source of water for Cannon AFB, the nearby town of Clovis, and for the local agriculture and dairies. Within this area, the unconfined Southern High Plains aquifer consists of three subsurface geologic formations: the top of the Triassic Dockum Group (Chinle Formation), the Tertiary Ogallala Formation, and the Quaternary Blackwater Draw Formation (Langman and others, 2006). Declining groundwater levels and the potential impact on water resources has necessitated an up-to-date review of the potentiometric surface to evaluate the availability of water resources for future use (Langman and others, 2006). A groundwater-level survey with associated hydrographs and maps of the potentiometric surface (the surface representing the hydraulic head, the altitude to which groundwater will rise in a tightly cased well) was completed in 2013 and 2015 (Collison, 2016) to investigate the possible effects of seasonal differences in groundwater use (summer and winter) on groundwater-flow directions in the vicinity of Cannon AFB.

In 2020, the U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force Civil Engineer Center, developed a potentiometric surface contour map of winter 2020 groundwater levels documenting the altitude of the water table and groundwater-flow patterns of the Southern High Plains aquifer on and around Cannon AFB. The objectives of the current study are to assist Cannon AFB in understanding and interpreting current and local hydrologic conditions and to evaluate groundwater-level change from 2015 to 2020 using new and historical data. The potentiometric surface can be used to better understand the hydrologic conditions of the Southern High Plains aquifer within the study area. Analysis of groundwater-flow directions and hydraulic gradients can provide an understanding of depletion by heavy groundwater pumping and recharge through playa lakes, as well as the relationship between the groundwater levels and underlying geology.

## 2 Potentiometric Surface Map of the Southern High Plains Aquifer in the Cannon Air Force Base Area, Curry County, N. Mex.



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Roads from Earth Data Analysis Center, University of New Mexico  
Universal Transverse Mercator, zone 13 north  
North American Datum of 1983

0 0.5 1 MILE  
0 0.5 1 KILOMETER

### EXPLANATION

— Cannon Air Force Base boundary  
(U.S. Census Bureau, Department  
of Commerce)

**Figure 1.** Aerial imagery of the general study area, Cannon Air Force Base, and surrounding lands within Curry County, New Mexico.



## Purpose and Scope

The purpose of this report is to present the results of a groundwater-level survey completed in winter 2020 by means of potentiometric surface contour maps of winter 2020 groundwater levels and present an analysis of the potentiometric surface. Recent (2015–20) groundwater-level change was also evaluated by constructing a map showing the change in groundwater level between the winter 2015 and winter 2020 measuring events. Four hydrographs presented herein, created from periodic measurements of groundwater levels in wells on and around Cannon AFB, were developed to provide information about historical groundwater-level changes and provide localized data to assist in understanding regional trends.

## Hydrogeology

The groundwater hydrology of the Southern High Plains aquifer in the Cannon AFB area is primarily controlled by recharge characteristics, groundwater withdrawals, and the contact between the saturated Ogallala Formation and the underlying Dockum Group (Chinle Formation). The Dockum Group and Chinle Formation have been used interchangeably in the past to refer to the uppermost rocks underlying the Ogallala Formation; the Chinle Formation is the uppermost unit of the Dockum Group. Although most recent literature has transitioned to using the more general term “Dockum Group,” some references cited in this report include the use of the term “Chinle Formation” (Collison, 2016; McGowen and others, 1977). For continuity and to reduce confusion, this report uses the term “Dockum Group” throughout. Groundwater levels have substantially declined throughout the Southern High Plains aquifer since the mid-1940s, when groundwater was first used for irrigated agriculture (McGuire and others, 2003; Tillery, 2008). Groundwater used for drinking water and irrigation in this region occurs in the Ogallala Formation that is part of the Southern High Plains aquifer. The contact between the Ogallala Formation and the Dockum Group contact provides the main control for regional aquifer conditions in the aquifer, and pumping likely has a strong effect on local conditions. The Ogallala Formation was deposited on top of an eastward-dipping erosional surface containing paleochannels that cut into the Dockum Group (Dutton and others, 2001). These paleochannels contain coarser, more hydraulically conductive sediment than the sediment found in the underlying Dockum Group and can act as preferential pathways for groundwater movement. The paleochannels generally coincide with troughs in the water-table surface.

The Dockum Group consists mostly of clay with some intermixed sand and silt and ranges in thickness from 0 to 400 feet (ft) in eastern New Mexico (McGowen and others, 1977). The Ogallala Formation consists of aeolian sand and silt and fluvial and lacustrine sand, silt, clay, and gravel (McLemore, 2001) and ranges in thickness from 30 to 600 ft in eastern New Mexico and west Texas (Gustavson, 1996).

The Blackwater Draw Formation overlies the Ogallala Formation at Cannon AFB, is composed mostly of eolian sand deposits, and ranges in thickness from 0 to 80 ft in eastern New Mexico (McLemore, 2001). A laterally discontinuous caliche layer is typically present in the unsaturated zone of the Blackwater Draw or Ogallala Formations (Hart and McAda, 1985). Drilling at Cannon AFB has indicated the caliche layer is discontinuous but typically found within 30 ft of the surface and of variable thickness when present (Langman and others, 2006).

Recharge to the Southern High Plains aquifer has previously been estimated to range from 0.01 inch per year (in/yr) (Stone and McGurk, 1985) to 1.71 in/yr (Mantei and others, 1966–67); but most estimates are less than 1 in/yr (Musharrafiéh and Logan, 1999). It has long been debated how the aquifer is recharged, but the current conceptual model indicates that most recharge occurs through playa areas and that interplaya areas contribute very little to aquifer recharge (Scanlon and others, 2003). Potential evapotranspiration in excess of precipitation likely limits diffused areal recharge (Langman and others, 2006). Groundwater pumping in the area has occurred since the early 1900s, but large-scale agriculture did not develop near the study area until the 1950s (Musharrafiéh and Logan, 1999). Groundwater in the Southern High Plains aquifer generally flows eastward or southeastward, which is consistent with the overall direction of regional flow in the unconfined aquifer surrounding Cannon AFB. Groundwater pumping has created numerous cones of depression that have locally reversed groundwater-flow gradients around heavily irrigated areas.

## Methods

### Hydrographs

Four hydrographs were created from periodic measurements of groundwater levels in wells on and around Cannon AFB (USGS, 2020) and were developed to provide information about historical groundwater-level changes. The hydrographs of well IDs 4, 76, 81, and 108 were created using R programming language, version 4.0.2 (R Core Team, 2020). The hydrographs were created for four wells with the most complete and longest running groundwater-level records and were selected to represent areas on and around Cannon AFB. The wells used to create the hydrographs are similar to those in Collison (2016), except for well 26, which was inaccessible in winter 2020. Groundwater levels at these four wells are measured up to twice a year by the USGS in cooperation with the New Mexico Office of State Engineer. Data from AFSOC (2013) were used to fill in a gap from 2005 to 2013 at Cannon AFB well 81.

## Potentiometric Surface Contour Map

The potentiometric surface contour map of the study area was constructed using the groundwater-level altitudes presented in table 1. Groundwater-level measurements were attempted at 155 sites during a nonirrigation season (winter of 2020; January 13–31, 2020). Irrigation, domestic, and monitoring wells within approximately 6 miles of the Cannon AFB boundary were selected for measurement. Although we tried to measure groundwater levels in all wells that were measured in the 2015 survey, some wells were not accessible in 2020. The wells measured in this study were assumed to be screened in the Ogallala Formation, with the total depth of the wells generally coinciding with the top of the Dockum Group. This assumption is based on drilling logs, a previous USGS report (Collison, 2016), and discussions with local farmers and drillers. Well identifiers (IDs) 2 through 129 are numbered in accordance with wells that were accessible and in Collison (2016), whereas well IDs 200 through 232 are new locations that were added to fill in data gaps and improve the accuracy of the potentiometric surface. Some measurements may have been affected by recent pumping before they were made, although groundwater levels were not measured in wells that were pumping. The presence of nearby pumping was noted on field forms, and those wells were not used in the development of the potentiometric surface. Additionally, for wells encountered that were pumping, notes were taken on field forms and the wells were revisited on a separate date when the well wasn't pumping. In total, 112 wells measured during the 2020 survey were used to construct the potentiometric surface: 75 irrigation wells, 15 domestic wells, and 22 monitoring wells; of these, 3 irrigation wells and 1 monitoring well have associated hydrographs presented later herein.

An additional groundwater-level survey was conducted in March 2021 and used as a testing mechanism to validate previously collected data and to provide additional support for determining flow directions through Cannon AFB. Groundwater levels were measured during a nonirrigation season at 31 wells, 10 of which produced a valid measurement; the rest were either pumping, obstructed, or dry. These wells were not used in the creation of the potentiometric surface but as a secondary validation in areas of high concern.

Groundwater-level measurement and quality-control procedures set forth by Cunningham and Schalk (2011) were followed; specifically, a minimum of two groundwater-level measurements that were within 0.02 ft of each other were required at each well measured. Data collected for this study are available from the USGS National Water Information System (NWIS) database (<https://nwis.waterdata.usgs.gov/usa/nwis/gwlevels>) (USGS, 2020).

Land surface datums were updated for the 2020 groundwater-level measurements in conjunction with a separate geophysical logging project by the USGS at Cannon AFB (Payne and others, 2022). This will allow future work in the area to assume a uniform digital elevation model for collaborative work and create the framework for future products and

ArcGIS surfaces within Cannon AFB. Land surface datum measurement corrections were retroactively applied to well locations measured during the 2015 event that overlapped with locations of wells used in this report. The new 1-meter (m) resolution digital elevation model altitudes were obtained from The National Map and are referenced to the North American Vertical Datum of 1988 (USGS, 2019).

The potentiometric surface contour map was constructed by interpolating between measurement locations using universal kriging (Fisher, 2013). This approach estimates the values at unmeasured locations as a weighted average of measured values. The weights are derived from the spatial correlation of measurements, as indicated by an empirical semivariogram (Fisher, 2013). Kriging assumes stationarity, where the mean value of the data being contoured and the empirical semivariogram are roughly constant throughout the area of interest. A first-order polynomial trend function representative of the regional groundwater-level altitude trend was subtracted from the measured values during semivariogram modeling and kriging to favor stationarity. The removed trend was formulated as

$$z(s) = \beta_0 + \beta_1 x(s) + \beta_2 y(s) \quad (1)$$

where

- $z(s)$  is groundwater-level altitude at point  $s$ , in feet above the North American Vertical Datum of 1988;
- $\beta_0$  is deterministic unknown trend coefficient, in feet above the North American Vertical Datum of 1988;
- $\beta_i$  is deterministic unknown trend coefficient, in dimensionless units ( $i = 1$  through 5);
- $x(s)$  is easterly coordinate at point  $s$ , in feet; and
- $y(s)$  is northerly coordinate at point  $s$ , in feet.

The trend was added back to the kriged surface to arrive at the potentiometric surface. The kriging analysis was performed by using the R programming language, version 4.0.2 (R Core Team, 2020). Points of equal hydraulic head in the potentiometric surface were connected to form contour lines used for visualization of the surface. The Pearson correlation coefficient of the trend predictions to measurements is 0.91, indicating large-scale regional trends were reasonably represented. Normally distributed residuals (measured minus predicted) had a mean of 0 ft and median of 0.12 ft, thereby suggesting an acceptable level of spatial stationarity to validate the application of kriging. The final contoured area was restricted to the perimeter of groundwater-level measurements to avoid universal kriging estimation errors introduced by low data density on the margins of the study area.

The empirical semivariogram is a graphical representation of how variances in measured values (in terms of semivariance) change as a function of distance between the measurement locations (separation distance). A continuous semivariogram model was fit to the curvature of the empirical semivariogram to provide a data-driven method for kriging

**Table 1.** Inventory of sites and associated groundwater data used to construct winter 2015 and winter 2020 potentiometric surface contour maps and water-level change maps for the Cannon Air Force Base (AFB) area, Curry County, New Mexico.

[Map identification number corresponds to those shown on figures in this report. Well type: D, domestic, I, irrigation, MW, monitoring well (followed, if applicable, by name of well on Cannon AFB); Map identification numbers shown in bold indicate an associated hydrograph is provided for these wells. USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988. Land surface datum for 2020 and 2015 have been updated and this table reflects new groundwater-level altitudes]

Map identification number	Well type	USGS site ID	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)	January 13–20, 2020, groundwater-level altitude (feet above NAVD 88)	January 20–30, 2015, groundwater-level altitude (feet above NAVD 88)	Groundwater-level change from winter 2015 to winter 2020 (feet)
2	D	342743103221901	34.462181	-103.37202	4,080.48	4,082.21	-1.73
3	I	342747103211301	34.463783	-103.35465	4,075.02	4,077.03	-2.01
<b>4</b>	I	342736103203701	34.464319	-103.34574	4,071.06	4,074.76	-3.70
6	D	342743103161301	34.463781	-103.27175	4,042.56	--	--
8	D	342750103155101	34.464058	-103.26419	4,035.75	--	--
9	D	342739103154201	34.460975	-103.26167	4,030.94	4,031.41	-0.47
11	D	342725103151901	34.457003	-103.25536	4,021.36	4,021.67	-0.31
12	I	342654103163101	34.448394	-103.27552	4,023.37	4,021.15	2.22
13	I	342658103144101	34.449447	-103.24484	4,007.24	4,009.75	-2.51
14	I	342655103135201	34.448642	-103.23111	3,992.10	3,994.23	-2.13
16	I	342624103173501	34.440350	-103.29324	4,018.30	4,016.71	1.59
17	I	342604103183801	34.434475	-103.31078	4,026.81	4,023.16	3.65
18	I	342604103173601	34.434611	-103.29360	4,012.11	4,008.58	3.53
19	I	342602103172201	34.434086	-103.28972	4,004.99	4,002.29	2.70
20	D	342606103151001	34.435197	-103.25289	3,996.77	4,000.57	-3.80
21	I	342551103232201	34.4307	-103.39009	4,005.32	4,003.60	1.72
24	I	342520103165601	34.426836	-103.28431	3,994.02	3,992.74	1.28
25	I	342537103164101	34.427203	-103.2782	3,990.87	3,989.08	1.79
28	I	342455103183301	34.419531	-103.31142	4,017.60	--	--
29	I	342509103180801	34.419419	-103.30248	4,006.50	4,000.99	5.51
30	I	342506103164701	34.419447	-103.28	3,986.56	3,986.36	0.20
34	I	342444103163201	34.412311	-103.27556	3,985.05	3,986.94	-1.89
35	I	342419103232301	34.408669	-103.39189	4,067.87	4,068.92	-1.05
37	D	342421103211801	34.405864	-103.35525	3,990.92	3,994.10	-3.18
38	MW	342418103201201	34.404994	-103.33683	3,980.13	3,980.04	0.09
43	D	342429103170201	34.408253	-103.28395	3,988.09	--	--
46	I	342404103161901	34.401281	-103.272	3,983.11	3,986.37	-3.26

**Table 1.** Inventory of sites and associated groundwater data used to construct winter 2015 and winter 2020 potentiometric surface contour maps and water-level change maps for the Cannon Air Force Base (AFB) area, Curry County, New Mexico.—Continued

[Map identification number corresponds to those shown on figures in this report. Well type: D, domestic, I, irrigation, MW, monitoring well (followed, if applicable, by name of well on Cannon AFB); Map identification numbers shown in bold indicate an associated hydrograph is provided for these wells. USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988. Land surface datum for 2020 and 2015 have been updated and this table reflects new groundwater-level altitudes]

Map identifica- tion number	Well type	USGS site ID	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)	January 13–20, 2020, groundwater-level altitude (feet above NAVD 88)	January 20–30, 2015, groundwater-level altitude (feet above NAVD 88)	Groundwater- level change from winter 2015 to winter 2020 (feet)
47	D	342408103155201	34.402394	-103.26453	3,987.07	3,984.37	2.70
48	D	342415103153501	34.404281	-103.25978	3,982.54	3,982.44	0.10
49	I	342358103151601	34.400197	-103.25453	3,974.79	3,978.29	-3.50
50	I	342327103232401	34.390922	-103.39014	4,060.64	4,062.47	-1.83
52	D	342343103222201	34.395289	-103.37283	4,032.14	4,033.42	-1.28
53	D	342328103221701	34.391272	-103.3716	4,030.33	4,032.34	-2.01
54	D	342328103212501	34.391144	-103.35713	4,004.60	4,007.70	-3.10
55	MW-W	342348103175801	34.396844	-103.29935	3,962.43	3,965.63	-3.20
57	MW-Fa	342321103181401	34.389222	-103.30402	3,957.23	--	--
58	MW-Ga	342313103181201	34.386831	-103.30333	3,957.29	--	--
61	MW-Na	342318103174601	34.388397	-103.29629	3,956.27	3,958.70	-2.43
68	MW-X	342222103194301	34.372817	-103.32866	3,978.96	3,982.41	-3.45
74	I	342139103211801	34.361050	-103.35509	4,035.51	4,036.35	-0.84
75	I	342206103192501	34.368675	-103.32411	3,969.33	3,972.01	-2.68
<b>76</b>	I	342140103190501	34.361361	-103.31989	3,966.24	3,967.73	-1.49
78	MW-D	342157103181701	34.365869	-103.30679	3,936.23	3,939.39	-3.16
79	MW-Ca	342157103181601	34.365728	-103.30458	3,932.78	--	--
80	MW-Ua	342205103181002	34.367967	-103.30278	3,934.50	--	--
<b>81</b>	MW-B	342203103181001	34.367408	-103.30288	3,933.92	3,936.26	-2.34
82	MW-Ta	342200103180902	34.366617	-103.30264	3,932.44	--	--
83	I	342225103173401	34.374242	-103.29326	3,936.75	3,937.39	-0.64
84	I	342209103173901	34.369325	-103.29423	3,931.02	3,931.70	-0.68
85	I	342203103174001	34.367633	-103.29466	3,926.25	3,928.33	-2.08
86	I	342155103171801	34.365128	-103.28904	3,917.79	3,927.85	-10.06
87	I	342212103170401	34.370575	-103.28505	3,932.67	3,934.64	-1.97
90	I	342126103164501	34.361239	-103.28001	3,900.24	3,900.61	-0.37
92	I	342145103160501	34.362669	-103.26833	3,899.27	3,899.86	-0.59

**Table 1.** Inventory of sites and associated groundwater data used to construct winter 2015 and winter 2020 potentiometric surface contour maps and water-level change maps for the Cannon Air Force Base (AFB) area, Curry County, New Mexico.—Continued

[Map identification number corresponds to those shown on figures in this report. Well type: D, domestic, I, irrigation, MW, monitoring well (followed, if applicable, by name of well on Cannon AFB); Map identification numbers shown in bold indicate an associated hydrograph is provided for these wells. USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988. Land surface datum for 2020 and 2015 have been updated and this table reflects new groundwater-level altitudes]

Map identifica- tion number	Well type	USGS site ID	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)	January 13–20, 2020, groundwater-level altitude (feet above NAVD 88)	January 20–30, 2015, groundwater-level altitude (feet above NAVD 88)	Groundwater- level change from winter 2015 to winter 2020 (feet)
96	I	342140103154401	34.3617	-103.2625	3,891.51	3,890.86	0.65
97	I	342157103152901	34.365931	-103.2583	3,929.69	--	--
98	I	342142103152901	34.361889	-103.25815	3,887.80	3,890.77	-2.97
101	I	342048103183401	34.346789	-103.30953	3,953.37	3,957.49	-4.12
103	I	342048103180901	34.346811	-103.30268	3,932.07	3,932.95	-0.88
104	I	342104103173501	34.351150	-103.2933	3,906.22	--	--
105	I	342113103173101	34.353869	-103.2920	3,904.53	3,905.71	-1.18
106	I	342048103164301	34.346789	-103.27863	3,896.15	3,894.34	1.81
107	I	342047103145801	34.3464	-103.24957	3,858.14	3,863.29	-5.15
<b>108</b>	I	342121103142301	34.360489	-103.24043	3,916.72	3,917.91	-1.19
109	I	342115103141501	34.3543	-103.23782	3,886.71	3,886.98	-0.27
110	I	342049103141601	34.347131	-103.23779	3,858.60	3,855.92	2.68
114	MW	342032103204501	34.342267	-103.34610	4,017.39	4,018.52	-1.13
116	MW	342003103194401	34.334203	-103.32899	3,993.88	3,995.55	-1.67
117	MW	342000103192501	34.333406	-103.32379	3,993.00	3,994.13	-1.13
118	I	342033103184001	34.342531	-103.31133	3,958.77	--	--
119	I	342036103182301	34.343369	-103.30651	3,949.24	3,950.22	-0.98
120	MW	342015103163201	34.3375	-103.27561	3,899.33	--	--
121	MW	342004103160101	34.3347	-103.26718	3,895.17	3,895.19	-0.02
122	I	342022103143001	34.339539	-103.24191	3,853.66	3,855.90	-2.24
123	I	34200010341801	34.333211	-103.23946	3,867.52	3,860.78	6.74
124	I	342022103141001	34.339589	-103.23623	3,849.75	3,850.26	-0.51
126	I	341943103151601	34.328881	-103.25446	3,870.59	3,888.23	-17.64
127	I	341921103142701	34.322669	-103.24091	3,874.96	3,875.10	-0.14
128	I	341917103141101	34.321619	-103.23662	3,871.82	3,871.50	0.32
129	I	341928103140001	34.324711	-103.23341	3,866.28	3,865.74	0.54
200	I	342814103252801	34.470481	-103.42455	4,074.19	--	--

**Table 1.** Inventory of sites and associated groundwater data used to construct winter 2015 and winter 2020 potentiometric surface contour maps and water-level change maps for the Cannon Air Force Base (AFB) area, Curry County, New Mexico.—Continued

[Map identification number corresponds to those shown on figures in this report. Well type: D, domestic, I, irrigation, MW, monitoring well (followed, if applicable, by name of well on Cannon AFB); Map identification numbers shown in bold indicate an associated hydrograph is provided for these wells. USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988. Land surface datum for 2020 and 2015 have been updated and this table reflects new groundwater-level altitudes]

Map identification number	Well type	USGS site ID	Latitude (decimal degrees, NAD 83)	Longitude (decimal degrees, NAD 83)	January 13–20, 2020, groundwater-level altitude (feet above NAVD 88)	January 20–30, 2015, groundwater-level altitude (feet above NAVD 88)	Groundwater-level change from winter 2015 to winter 2020 (feet)
201	I	342649103221601	34.446883	-103.37121	4,066.29	--	--
202	I	342603103194301	34.434136	-103.32865	4,032.54	--	--
203	I	342641103191101	34.444750	-103.31979	4,040.67	--	--
204	I	342537103184001	34.4269	-103.31105	4,019.90	--	--
205	I	342618103170401	34.438450	-103.28445	4,007.51	--	--
206	I	342632103163301	34.442247	-103.27574	4,007.96	--	--
207	I	342321103142601	34.389289	-103.24052	3,961.75	--	--
208	I	342323103145601	34.390069	-103.24894	3,965.00	--	--
209	I	342312103151401	34.386781	-103.25377	3,964.37	--	--
210	I	341950103160001	34.330550	-103.2668	3,902.34	--	--
211	I	341950103162101	34.330639	-103.2726	3,907.56	--	--
212	I	342009103180901	34.335761	-103.30257	3,951.48	--	--
213	I	342034103175101	34.346889	-103.29822	3,920.86	--	--
214	I	342031103191201	34.341931	-103.31993	3,988.22	--	--
215	I	342115103194901	34.354069	-103.3304	4,004.74	--	--
216	I	342142103220401	34.361739	-103.36781	4,046.92	--	--
217	D	342156103232901	34.365631	-103.39142	4,053.22	--	--
218	I	342221103233901	34.372539	-103.39419	4,063.20	--	--
219	D	342236103220501	34.376772	-103.36807	4,046.03	--	--
220	I	342302103201501	34.3839	-103.33745	3,983.58	--	--
221	I	342425103214901	34.407011	-103.36363	3,996.78	--	--
222	I	342155103181701	34.365231	-103.30483	3,932.74	--	--
223	I	342154103184601	34.365131	-103.31273	3,947.97	--	--
224	I	342207103193701	34.3687	-103.32689	3,975.17	--	--
225	MW-Sa	342158103181001	34.366111	-103.30280	3,931.34	--	--
227	MW-A	342218103182601	34.371897	-103.30876	3,949.28	--	--
228	I	342240103175001	34.381786	-103.29861	3,949.07	--	--

**Table 1.** Inventory of sites and associated groundwater data used to construct winter 2015 and winter 2020 potentiometric surface contour maps and water-level change maps for the Cannon Air Force Base (AFB) area, Curry County, New Mexico.—Continued

[Map identification number corresponds to those shown on figures in this report. Well type: D, domestic, I, irrigation, MW, monitoring well (followed, if applicable, by name of well on Cannon AFB); Map identification numbers shown in bold indicate an associated hydrograph is provided for these wells. USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988. Land surface datum for 2020 and 2015 have been updated and this table reflects new groundwater-level altitudes]

<b>Map identifica- tion number</b>	<b>Well type</b>	<b>USGS site ID</b>	<b>Latitude (decimal degrees, NAD 83)</b>	<b>Longitude (decimal degrees, NAD 83)</b>	<b>January 13–20, 2020, groundwater-level altitude (feet above NAVD 88)</b>	<b>January 20–30, 2015, groundwater-level altitude (feet above NAVD 88)</b>	<b>Groundwater- level change from winter 2015 to winter 2020 (feet)</b>
229	MW-Oa	342300103175001	34.383450	−103.29737	3,949.57	--	--
230	MW-Y	342301103180501	34.383581	−103.30141	3,952.85	--	--
231	MW-Pa	342310103180801	34.386267	−103.30231	3,955.80	--	--
232	MW-Rb	342321103180801	34.389222	−103.30230	3,958.72	--	--

to estimate spatial correlation at all separation distances. The semivariogram model has four primary attributes: model type, sill, range, and nugget. The model type defines the overall shape of the semivariogram model and will change depending on how rapidly measured values change as a function of separation distance. Semivariance in semivariograms typically levels off at a certain separation distance, beyond which there is minimal spatial correlation between measured and unmeasured locations. This distance is called the range, and the semivariance value that the semivariogram levels off at is called the sill. The nugget is the semivariance at a separation distance of zero, or y-intercept of the semivariogram model, and is therefore typically related to measurement error.

The empirical semivariogram in this study was calculated by using the variogram function within the gstat R package, version 2.0-0 (Pebesma and Graeler, 2019). The maximum distance considered in the empirical semivariogram was 10,000 m, or approximately half the maximum distance between

observation locations (24,140.2 m; Fisher, 2013), which is greater than both the mean (7,203.3 m) and median (6,790.3 m) distance between all observation pairs. A bin width of 500 m was used in the empirical semivariogram calculation, since it yielded the most readily identifiable semivariogram curvature (20 bins of maximum separation distance). The fit. variogram function of the gstat R package was then used to fit a continuous semivariogram model to the empirical semivariogram. The resulting semivariogram model was of spherical type, with a range of 7,444.8 m, a sill of 640.2 square feet, and a nugget of 0 square feet (fig. 2). The modeled semivariogram well-represents the general curvature of the empirical semivariogram, as evidenced by their Pearson correlation coefficient of 0.84.

Kriging was then performed by using the krige function within the gstat R package to estimate the potentiometric surface on a uniform raster grid. Interpolated root-mean-square error (RMSE) at measured locations decreased as a function

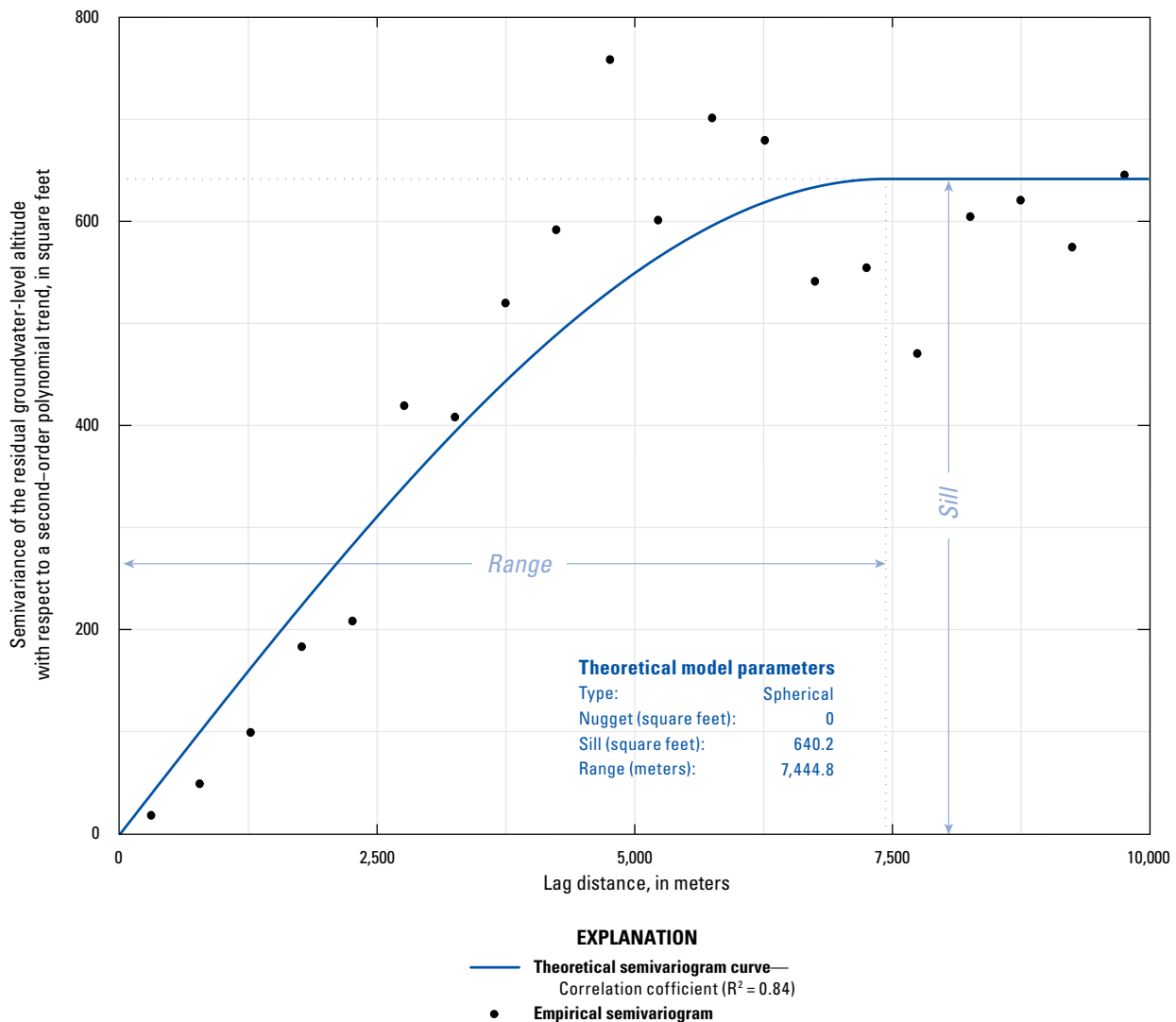


Figure 2. Empirical semivariogram fit with continuous spherical variogram model.



of raster grid cell size. A uniform grid cell size of 15 ft was selected as a tradeoff between raster file size and RMSE. Measured values were very well represented by kriged raster predictions, with an RMSE of 0.029 ft, a Pearson correlation coefficient of 1.00, a mean residual of 0.001 ft, and a median residual of 0.0019 ft. The resulting potentiometric surface contour map will be discussed and presented in the results section of this report.

Leave-one-out cross validation (LOOCV) was performed to further evaluate the predictive capabilities of the kriging approach. LOOCV provides insight into predictive capability by removing one data point, kriging the remaining data, and computing kriged prediction error at the removed location. This process is repeated for all measurement locations. LOOCV was performed by using the RunCrossValidation function within the ObsNetwork R package, version 1.0.1.9000 (Fisher, 2013). Mean LOOCV error (measurements minus LOOCV predictions) would ideally be zero and was  $-0.145$  ft in the analysis, indicating the kriging approach had a high-level of predictive ability with a small bias toward over-predicting groundwater-level altitudes. The high level of predictive ability of the kriging approach is further emphasized by the low negative correlation of  $-0.0903$  between LOOCV predictions and prediction error, as well as the high correlation of  $0.986$  between measured groundwater-level altitudes and LOOCV predictions (fig. 3). Sites with more than 25 ft of LOOCV error included site 21 ( $-59.63$  ft), site 200 ( $-41.99$  ft), site 97 ( $27.60$  ft), and site 55 ( $37.24$  ft). Most of these sites are located within a short distance of the paleochannels where groundwater-level altitudes spatially vary more across a given distance than elsewhere in the area. This indicates a greater sensitivity to data density and elevated prediction

uncertainty in this area. Overall, the kriged solution performed well and is thought to reasonably estimate the potentiometric surface throughout the area of interest; however, by using a new geophysical surface created by the USGS that represents the top of the Dockum Group and bottom of the Ogallala Formation, we were able to modify the 3,980-, 3,990-, 4,000-, and 4,010-ft potentiometric contour lines just north of Cannon AFB in areas where groundwater-level data were sparse. This surface along with the March 2021 groundwater-level survey allowed us to predict groundwater flow with greater accuracy than possible by using kriging alone.

## Groundwater-Level Change Map

Of the 112 wells measured in this report, 67 were also measured in 2015. Groundwater-level change values (winter 2020 minus winter 2015 groundwater-level altitude) were computed at 67 well sites having groundwater-level measurements in 2015 and 2020. ArcGIS 10.7.1 was used to interpolate a groundwater-level change surface from the well points using the natural-neighbor method with an output cell size of  $5.7078 \times 10^{-4}$  (Childs, 2004). The groundwater-level change surface was divided into six groups (1) greater than or equal to a 1.1-ft increase to indicate a rise in groundwater level, (2) between 1.0 to  $-1.0$  ft to indicate a neutral change in groundwater level, and (3–6) between  $-1.1$  to  $-5.0$  ft,  $-5.1$  to  $-10.0$  ft,  $-10.1$  to  $15.0$  ft, and  $-15.1$  to  $-17.6$  ft to indicate a decline in groundwater level. The six groups were visually inspected for reasonability and corrected as necessary.

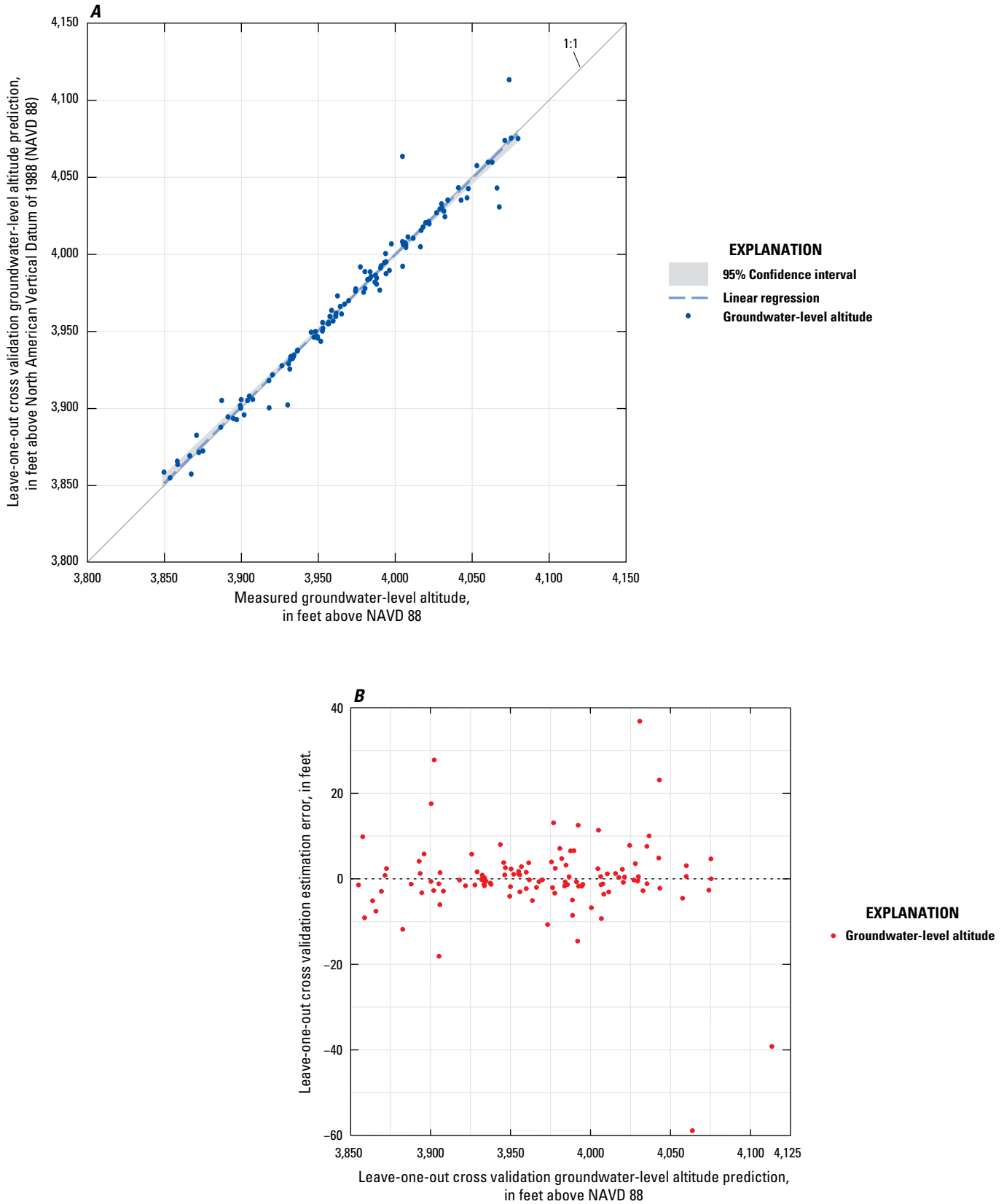


Figure 3. A, Leave-one-out cross validation (LOOCV) predictions verses measurements and, B, LOOCV estimation errors verses LOOCV predictions (bottom).

## Results and Discussion

### Hydrographs

The period of record for the four hydrographs ranges from 27 years (well 81) to 66 years (wells 4 and 76; [fig. 4](#)). The long-term trend present in all four hydrographs is a steady decline in groundwater levels, with water levels in some wells declining faster than others. The decadal differences in rates of decline mentioned in Collison (2016) are still apparent at wells 4, 76, and 108, which indicates less groundwater decline or static groundwater-level conditions during the mid- to late 1980s, possibly related to an above average period of precipitation from 1984 to 1988 ([fig. 5](#)). The hydrographs also appear to show less groundwater decline or static groundwater-level conditions from 2013 through 2020 at wells 4, 76, 81, and 108 ([fig. 4](#)).

Well 4 data indicate water levels have declined since the mid-1960s, including a sharp 3.7-ft decline between 2017 and 2020 ([fig. 4](#)); however, remarks made in NWIS indicate that the technicians may have obtained a poor water-level measurement that may account for the steep drop. Well 76 data show an overall decline since 1954 with a brief rebound in 2018 ([fig. 4](#)), but remarks on the 2019 water-level measurement show difficulties associated with collecting the measurement. Future water-level recordings may confirm that the above average precipitation in Clovis from 2015 to 2019, excluding 2016, and conscious water conservation practices, may be responsible for a less pronounced groundwater decline, compared to prior years, or near-static groundwater-level conditions.

Well 81, in the southeastern corner of Cannon AFB, had the largest average annual groundwater-level decline of approximately 2.36 feet per year (ft/yr) ([fig. 4](#)). Well 108, east-southeast of Cannon AFB, had the second largest decline in average annual groundwater levels of 1.87 ft/yr. Well 76, directly south of Cannon AFB, had the third largest average annual groundwater-level decline of 1.28 ft/yr ([fig. 4](#)). Lastly, well 4, north-northwest of Cannon AFB, had the smallest average annual groundwater-level decline of approximately 0.44 ft/yr ([fig. 4](#)). Overall, the southern part of the study area exhibited the greatest average annual groundwater-level decline, with decline also occurring in the northwest portion of the study area. Collison (2016) showed the northwestern part of the study area having the smallest average annual decline, with the northeastern part having similar declining values.

### Potentiometric Surface Contour Map

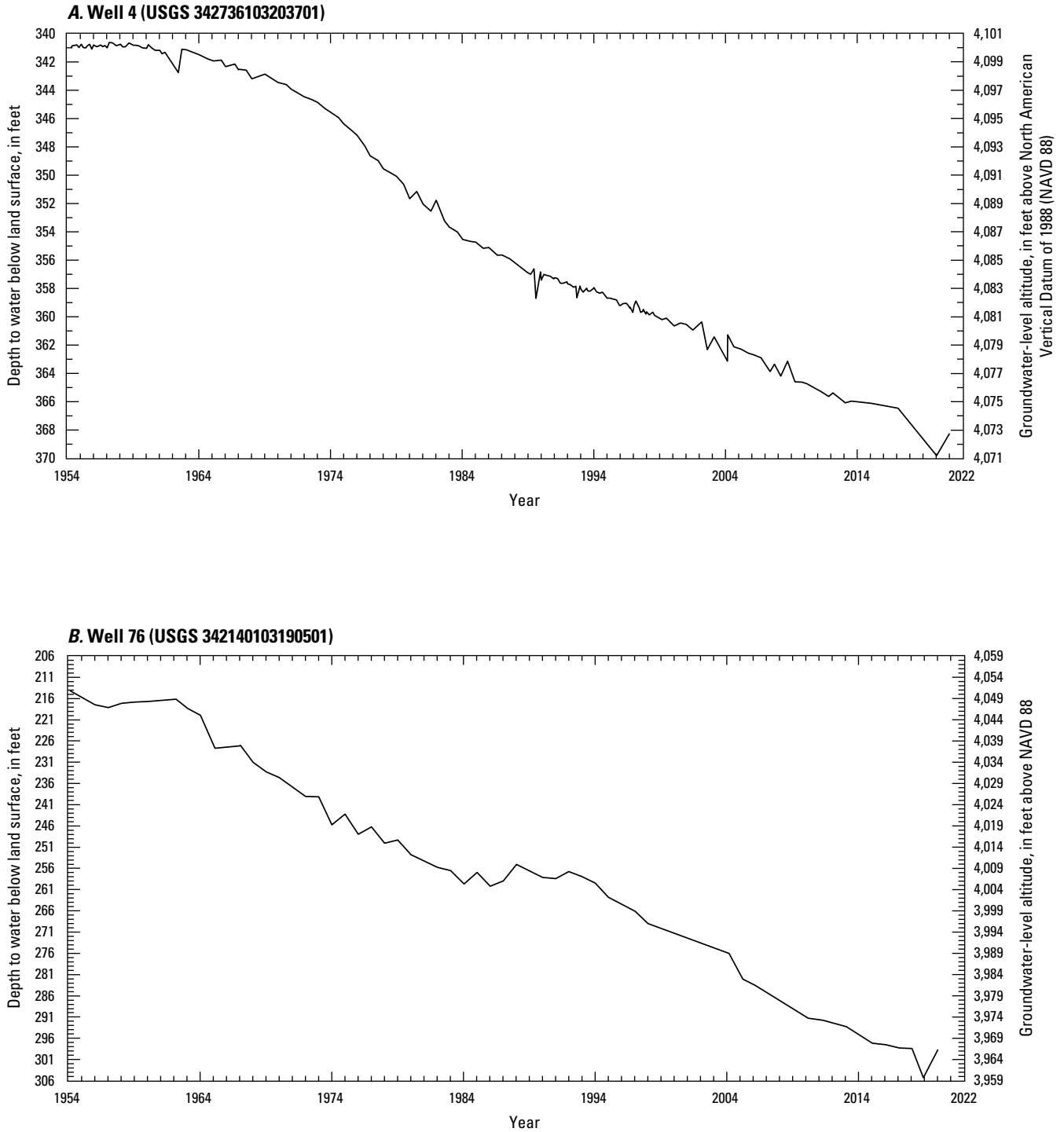
The January 13–31, 2020, potentiometric surface representing winter groundwater conditions, as well as interpreted groundwater-flow directions, are both illustrated in figures 6 and 7 (on sheet). The groundwater-flow directions were derived by using the hydrologic principle that groundwater flows in the direction of the steepest hydraulic gradient (from high to low hydraulic head), perpendicular to contour lines of equal hydraulic head (Ingebritsen and others, 2006). The

potentiometric surface indicates that groundwater flows from the northwest toward the southeast, following a mesoscopic regional trend pattern indicated by Langman and others (2006). The potentiometric surface also shows groundwater flow from the north and west converging on a trough in the potentiometric surface. This groundwater trough is thought to be the hydraulic expression of a Tertiary paleochannel, commonly found in the Southern High Plains aquifer (Gustavson, 1996), which contains coarser, more hydraulically conductive material than the underlying formation (Fahlquist, 2003).

Although regional groundwater-flow directions are similar for winter 2020 and winter 2015 (Collison, 2016), there are local differences between the maps. The potentiometric contours along the west and north borders of Cannon AFB shifted with the addition of the top of the Dockum Group surface as a reference. The addition of a groundwater measurement in the northwest corner (well 200) provides a more complete picture of the water table, which now shows a cone of depression around well 21 and an increase in the distances between potentiometric surface contours in the northwest part of the study area ([fig. 6](#), on sheet). Slight differences between the winter 2020 and winter 2015 potentiometric contours may be, in part, due to different interpolation methods that were used for the two studies as well as small deviations in the surface contours, because it was not possible to measure the exact same wells in 2020 as in 2015, owing to access and pumping issues. The kriging interpolation used in this study, supported by the statistical analysis, provides a more representative potentiometric surface than the standard natural neighbor interpolation method used in the previous study (Collison, 2016).

### Groundwater-Level Change Map

The groundwater-level change map ([fig. 8](#), on sheet) shows a visual representation of the change in groundwater level from winter of 2015 to winter of 2020 measuring events and includes 67 wells whose data were used to construct the map. The periods between both groundwater-level measurement events contained several cycles of increased irrigation pumping and winter dormancy. The largest groundwater-level rise occurred in the southeastern section of the study area (6.74 ft) and the second largest rise occurred just north of the base (5.51 ft). The mean groundwater-level change for the 67 wells measured is approximately  $-1.12$  ft. Much of the area measured, covering 34 out of 67 wells, shows declining water levels ranging from  $-1.1$  to  $-17.6$  ft. The 20 groundwater-level changes that range from  $-1.0$  to  $1.0$  ft are considered neutral, with levels neither declining nor rising, and only 13 out of 67 wells measured show rising water levels ranging from 1.28 to 6.74 ft. Of the wells that were included in both the 2015 and 2020 winter surveys, 50.7 percent show a decline, 29.9 percent are neutral, and 19.4 percent show a rise. Most of the wells showing a groundwater-level rise were in the region to the north of U.S. Highway 60, whereas most of the wells showing groundwater-level declines were in the regions south of the highway and just west of Clovis.



**Figure 4.** Groundwater-level altitude hydrographs from selected wells on and around Cannon Air Force Base, Curry County, New Mexico, 1954–2020.

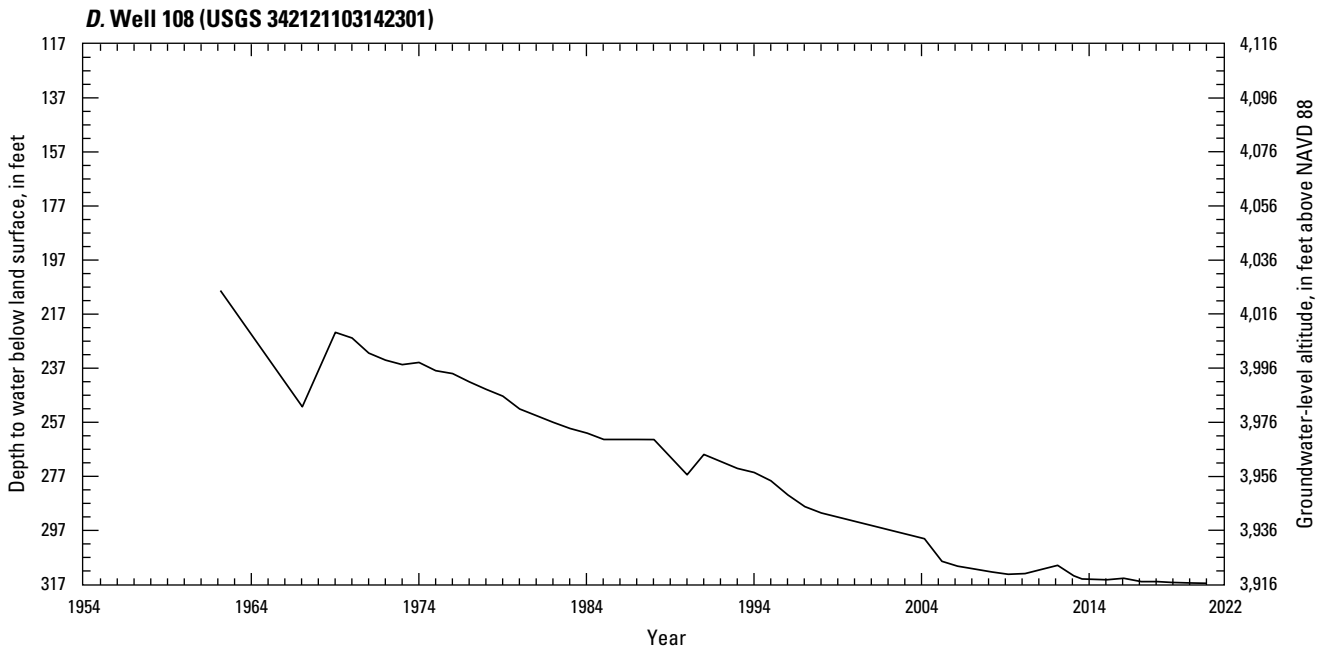
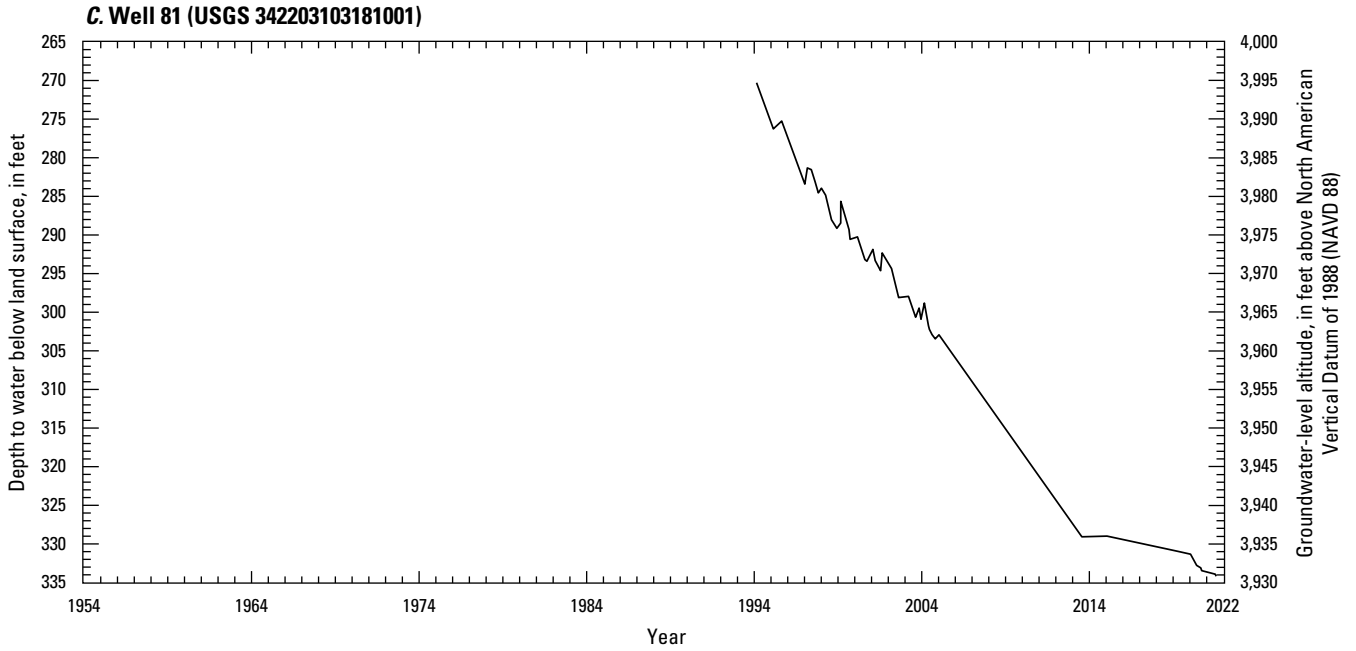
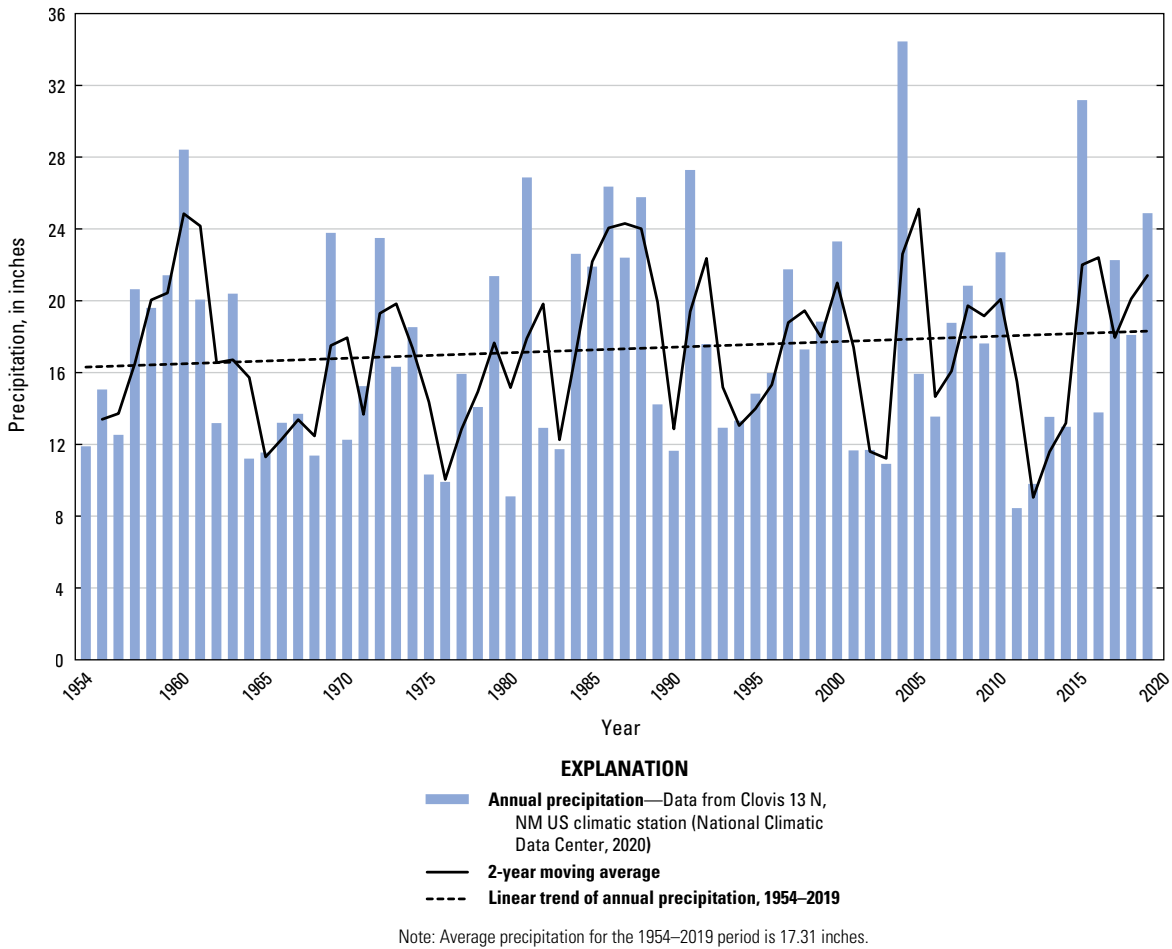


Figure 4.—Continued



**Figure 5.** Annual average precipitation in Clovis, New Mexico, 1954–2020. Data from National Climatic Data Center (2020), Clovis 13N climatic station.

## Summary

This study was conducted by the U.S. Geological Survey, in cooperation with the U.S. Air Force Civil Engineer Center, to assist Cannon Air Force Base in understanding and interpreting current and local hydrologic conditions and to evaluate groundwater-level change from 2015 to 2020 using new and historical data. Groundwater-level data collected in 2015 and 2020 indicate that water levels have declined over much of the study area during this 5-year period. The long-term trend in all four hydrographs was a steady decline in groundwater levels, with some areas declining faster than others. Overall, the southern part of the study area exhibited the greatest average annual groundwater-level decline, with declining levels also present in the northwestern and northeastern portions of the study area. However, decadal differences in rates of decline that show less groundwater decline or static groundwater-level conditions during the mid- to late 1980s at wells 4, 76, and 108 were also present from 2013 through 2019 at wells 4, 76, 81, and 108. Future water-level data may confirm that the above average precipitation in Clovis, New Mexico, from

2015 to 2019, excluding 2016, and conscious water conservation practices, may be responsible for less dramatic groundwater decline or near static groundwater-level conditions, when compared to prior years.

The potentiometric surface map indicates that groundwater flows from the northwest toward the southeast, following a megascopic regional pattern as indicated by an earlier study. The map also shows groundwater flow from the north and west converging on a trough in the potentiometric surface. The slight differences between the winter 2020 and winter 2015 potentiometric contours may be, in part, due to a different interpolation method used in the current study relative to the preceding study. The kriging interpolation used in this study, however, supported by the statistical analysis, provided a more representative potentiometric surface than other interpolation methods.

The 67 corresponding wells measured in 2015 and 2020 were used to create the groundwater-level change map. Of these wells, 50.7 percent showed a water-level decline, 29.8 percent indicated neutral water levels, and 19.4 percent indicated a rise in water levels. The region north of U.S. Highway 60 contained most of the groundwater-level rise,

whereas the regions located south of the highway and just west of Clovis, N. Mex., contained most of the groundwater-level decline.

Long-term water-level monitoring during periods of substantial land-use change is helpful to assess changes in aquifers. Monitoring the effects of climate variability, regional effects of groundwater development, changes in flow direction, groundwater and surface-water interactions, as well as future groundwater-level surveys and potentiometric surface maps, would provide resource managers with important information to aid in the decision process.

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