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Groundwater-Storage Change in the North Phoenix Aquifer, Arizona, 2020–23



Scientific Investigations Report 2024–5120

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

Cover. View to the northeast from Union Hills of the northern part of Paradise Valley and the north Phoenix aquifer. Photograph by Jeffrey Kennedy, U.S. Geological Survey.

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Abbreviations

ADWR	Arizona Department of Water Resources
ASR	artificial storage and recovery
CAP	Central Arizona Project
GNSS	global navigation satellite system
InSAR	interferometric synthetic aperture radar

Groundwater-Storage Change in the North Phoenix Aquifer, Arizona, 2020–23

By Jeffrey R. Kennedy

Abstract

The city of Phoenix, Arizona, relies primarily on surface water for municipal water supply. The city also maintains wells to withdraw groundwater, particularly in times of drought and reduced surface-water supply, and to recharge groundwater when excess surface water is available. As of 2023, withdrawals from the aquifer in the northeastern part of the city are a small volume of water, less than 3,000 acre-feet in most years. Each year a similar volume of water is recharged through injection wells. The withdrawal wells are permitted to produce in total more than 20,000 acre-feet per year; increased pumping could lead to future groundwater-storage declines.

To better understand groundwater-storage change in the north Phoenix aquifer, a repeat microgravity monitoring network was established in 2020. Measurements of changes in Earth's gravity provide a direct, non-invasive measurement of subsurface mass change. Groundwater-storage changes were small during the 2020–23 study period, consistent with the relatively small volumes of pumping and recharge. Groundwater levels measured in monitoring wells were stable or increased slightly during this period, although the number of monitoring wells within the area of the gravity monitoring network is sparse. In total, about 15,000 acre-feet of water were pumped and 31,000 acre-feet recharged through injection in the north Phoenix aquifer during the 2020–22 period. Within the monitored area, groundwater storage increased by a small amount, about 1,000 acre-feet, in 2020, and decreased by a larger amount, about 6,000 acre-feet, each year in 2021 and 2022. Storage decreased at 89 of 102 stations from 2020 to 2023. Groundwater-storage decreases greater than the volume of net pumping indicate down-gradient subflow from the aquifer is greater than recharge plus incoming subflow, drying of the unsaturated zone resulting from decreased land-surface recharge, or both.

At present (2023), the aquifer appears able to store and supply the relatively small amounts of water needed without excessive drawdown or harmful effects, such as land subsidence and surface inundation. If pumping or recharge increases in the future, the established repeat microgravity network is well suited to capture the spatial extent and magnitude of groundwater-storage changes in the aquifer.

Introduction

Water sources for the city of Phoenix, Arizona, are surface water from the Salt, Verde, and Colorado Rivers; groundwater from basin-fill deposits, infiltrated streamflow, and managed aquifer recharge; and reclaimed water (effluent). The city lies within the Salt River Valley, a desert region home to more than 4 million people (U.S. Census Bureau, 2023) with a large and diverse economy (fig. 1). Cities in the Salt River Valley, which include Phoenix and 11 other cities of more than 75,000 inhabitants and several smaller towns and cities, have diverse water-use histories, water rights, and different groundwater, surface water, and reclaimed water-supply portfolios. They all are within the Phoenix Active Management Area (fig. 1), designated by the Arizona Department of Water Resources (ADWR) as an area with increased restrictions on groundwater pumping to achieve the goal of sustainable groundwater management (ADWR, 2024b).

The city of Phoenix water utility (Phoenix Water Services) is the largest water utility in the State, providing water to more than 1,700,000 customers in a 520 square mile service area (City of Phoenix, 2021). For the 2010–19 period, about 1,300,000 acre-feet of water were delivered annually, but only about 2 percent was groundwater, 26,000 acre-feet per year on average, for this period (ADWR, 2023a). To augment and strengthen the city's groundwater portfolio, in 2018 the city began drilling and installing additional artificial storage and recovery (ASR) wells for managed aquifer recharge in the northeast part of the city. In years with abundant surface-water supply, particularly from the Colorado River, these ASR wells are intended to inject (under gravity flow) excess water into the north Phoenix aquifer. In drier years, when Colorado River water or other supplies may be reduced, this stored water can be pumped and delivered to customers. As of 2023, the effort to construct and equip ASR wells is ongoing.

Groundwater monitoring in the study area includes metering the volume of water at each well where water is injected or pumped and depth-to-groundwater measurements at about 10 wells carried out by the ADWR. The part of the Salt River Valley basin-fill aquifer within the study area (the north Phoenix aquifer) is nearly equally shared between the cities of Phoenix and Scottsdale for pumping and recharge, but the

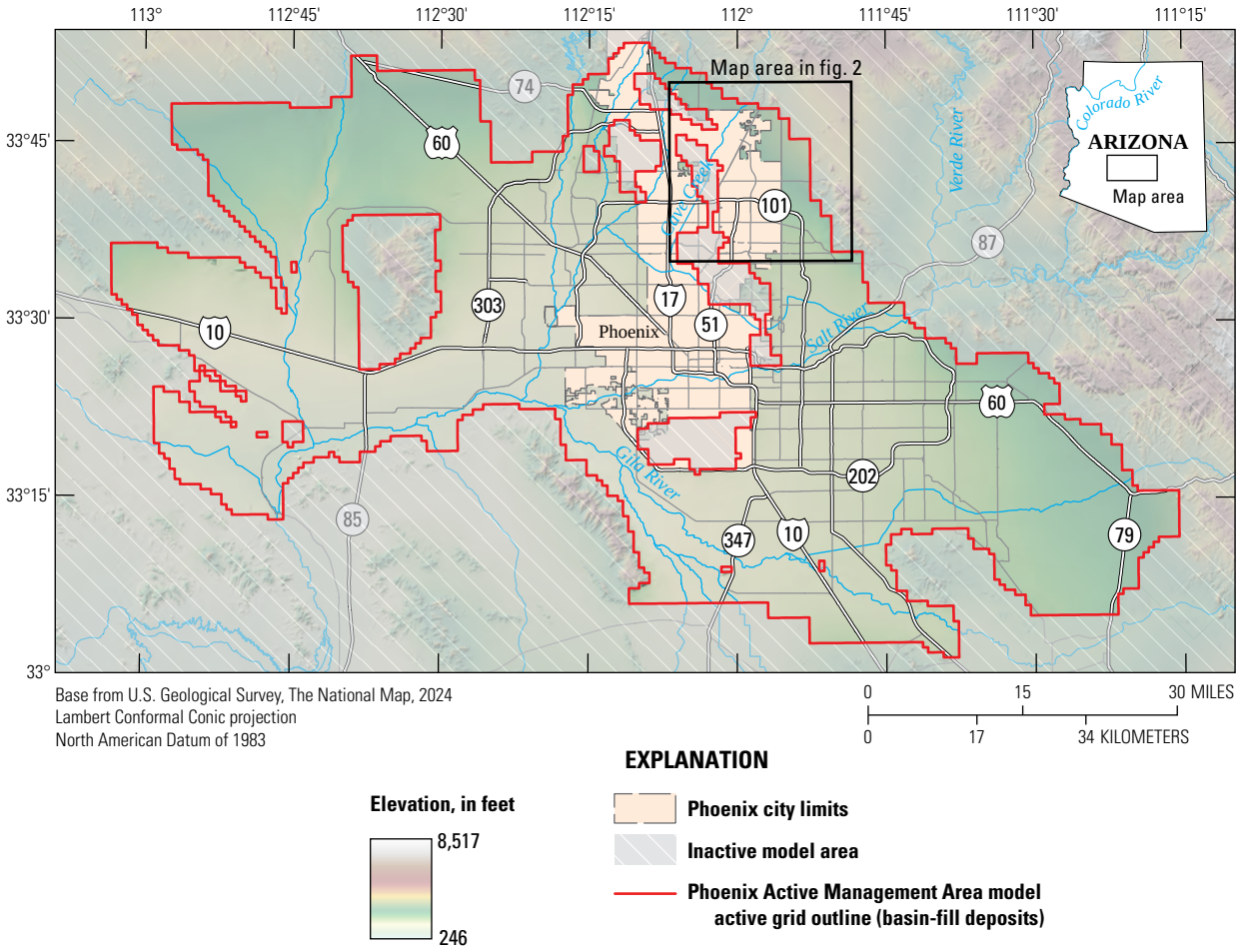


Figure 1. Regional map showing the extent of the basin-fill aquifer in the Salt River Valley, Arizona, simulated by the Arizona Department of Water Resources Phoenix Active Management Area groundwater-flow model (Arizona Department of Water Resources, 2023b).

effect on the aquifer of each city pumping from it is unknown. Pumping occurs at only a few high-capacity wells and more widely distributed residential wells are scarce. Therefore, groundwater pumped from any individual municipal well may affect groundwater storage over a large area.

To better understand groundwater-storage change in the north Phoenix aquifer, a repeat microgravity network comprising about 105 stations was established (fig. 2). Gravity surveys of this network were done annually in the winters of 2020, 2021, 2022, and 2023. Each survey represents a snapshot of Earth's gravity field at the time they were taken, and the change in gravity can be calculated between any two snapshots. Repeat microgravity provides a direct, non-invasive measurement of subsurface mass change. In desert alluvial basins, typically the only large source of mass change is from changes in aquifer storage or in soil-water content; therefore, the gravity changes can be interpreted directly as water-storage changes using a linear relation known as the horizontal infinite slab approximation. Unlike monitoring wells, gravity measurements are directly related to the change in "free-standing" water in the subsurface (in contrast, the change in groundwater level in a well for a given amount of storage change depends on the aquifer porosity). The microgravity network augments a limited number of monitoring wells within the study area where depth-to-groundwater is measured.

Purpose and Scope

The purpose of this report is to present the interpretation of repeat microgravity and groundwater-level data as they relate to groundwater-storage change in the north Phoenix aquifer. Data were collected at about 105 stations during annual surveys from 2020 through 2023 to measure changes in groundwater storage resulting from pumping and managed aquifer recharge in the aquifer. A subset of stations, approximately half, were observed in the first year. Microgravity and groundwater-level data are presented in context with groundwater pumping and recharge data reported by pumping entities to the ADWR.

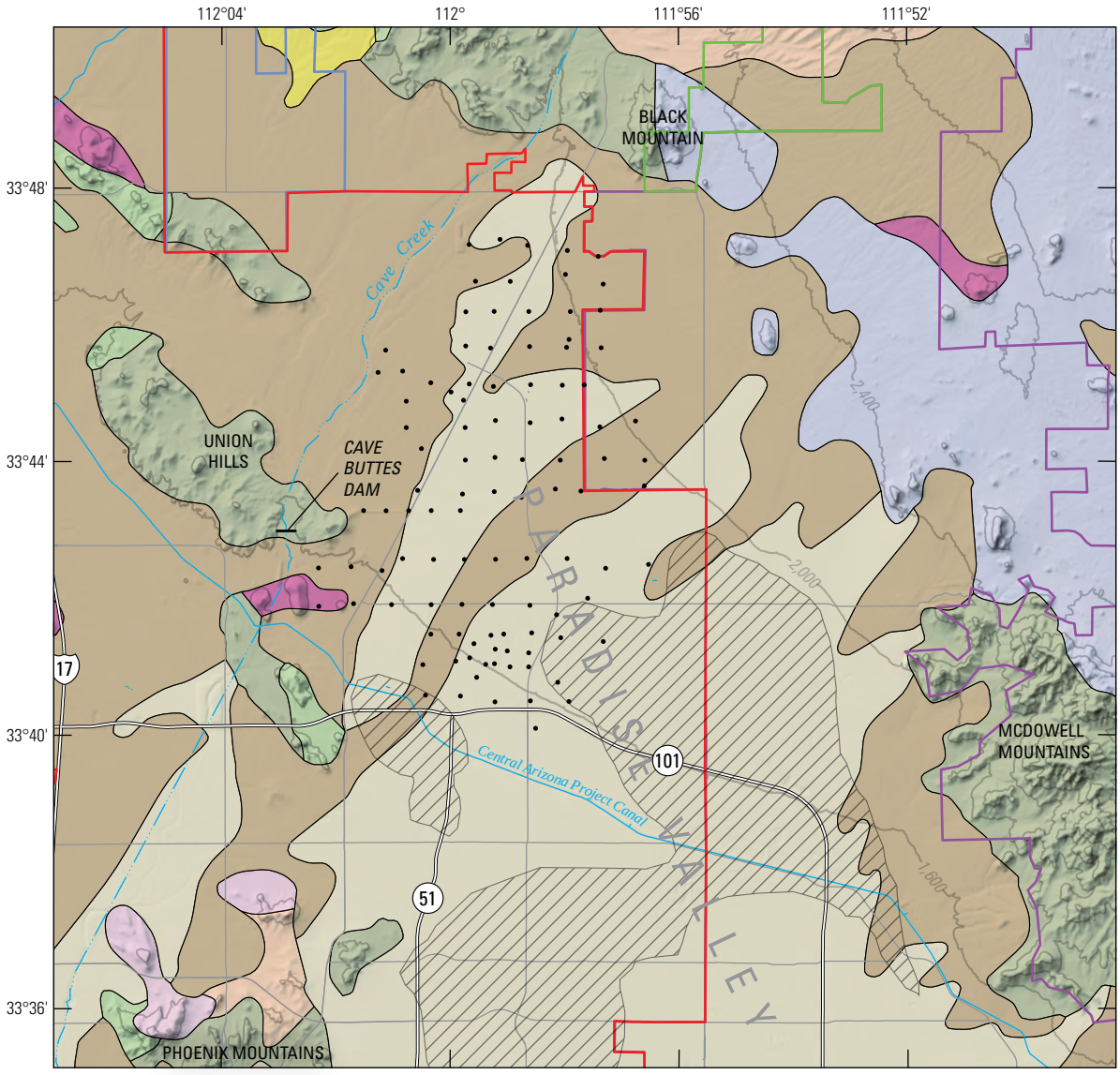


Figure 2. Map showing the geology in the study area (modified from Richard and others [2000]), subsidence features (Arizona Department of Water Resources, 2023c), and water service providers (Arizona Department of Water Resources, 2024a).

Study Area

The study area is in northeast Phoenix, at the north end of an alluvial fan setting historically known as Paradise Valley, one of several alluvial basins in the greater Salt River Valley. Today, the town of Paradise Valley occupies a relatively small (15.4 square miles) area at the far south end of the geographic Paradise Valley, which stretches roughly 25 miles north to south, from near Black Mountain and other ranges near the town of Cave Creek in the north, to the Salt River in the south, and 10 miles east to west between the McDowell Mountains and the Phoenix Mountains (fig. 2). The valley floor slopes downward from northeast to southwest throughout the study area, from an elevation around 2,200 feet (ft) above sea level to 1,200 ft (U.S. Geological Survey, 2024). The repeat microgravity network and the area where the city of Phoenix primarily pumps groundwater is in the northern part of Paradise Valley, an area bounded roughly by Cave Creek Road to the west, 64th Street to the east, Carefree Highway to the north, and the Loop 101 Freeway to the south.

The study area lies within the semiarid Sonoran Desert. The 30-year (1991–2020) average annual rainfall for the study area was 10.2 inches (PRISM Climate Group, 2023). Annual rainfall in 2020, 2021, and 2022 at a rainfall gage near the Scottsdale Airport (about 1 mile southeast of the intersection of Bell Road and Scottsdale Road, fig. 2) was 2.96 inches, 9.48 inches, and 12.91 inches, respectively (National Weather Service, 2023). The maximum average monthly high temperature is in July, 102 degrees Fahrenheit (°F), and the minimum monthly low temperature is in December, 42 °F. Temperatures routinely exceed 110 °F in summer.

The city of Phoenix is the primary water provider in the study area (fig. 2). The other significant water provider in the area is the city of Scottsdale, which borders Phoenix to the east and pumps and recharges in the same aquifer. The towns of Cave Creek and Carefree operate water utilities, including the Desert Hills Water Company, north of the study area, but deliver primarily Colorado River water by the Central Arizona Project (CAP) (CAP, 2024) and pump a smaller amount (less than 1,000 acre-feet per year) of groundwater (ADWR, 2024a).

Previous Studies

An early report by Meinzer and Ellis (1915) on the potential groundwater resources in Paradise Valley characterized depth to water and water quality. Agriculture and residential development in the study area at that time was minimal, although more than 50 new wells were noted south of the Old Verde Canal, which followed the alignment of the CAP canal in the southern part of the study area (fig. 2). Cave Creek was noted as ephemeral (“normally dry”), except for a short reach at Cave Creek Station (near the present-day town of Cave Creek, north of the study area), as it was by Lee (1905) 10 years earlier. Depth to water in the southernmost part of the study area, near the Old Verde/CAP Canals, was 300 ft or less. No data were available north of there, but it was noted depth to water would increase in the north as the land-surface elevation increased. Runoff from Cave Creek and the McDowell Mountains was noted as the primary source of recharge to the aquifer, with a particular focus on gravelly, buried former channels of Cave Creek as favorable pathways for subsurface flow.

A 1947 report on the groundwater resources of Paradise Valley (McDonald and others, 1947) showed just one groundwater well in the central part of the study area (near Dynamite Road and 56th Street; depth to water in 1946 was 626 ft); most wells at that time were south of the study area near Bell Road and along Scottsdale Road. Groundwater-level drawdown (change from initial conditions at a well) was as much as 40 ft in the southern part of Paradise Valley, but near zero further north (in the southern part of the present study area; no data were available farther north). Because of large depths to water in much of Paradise Valley, groundwater use for irrigation was limited to small areas with the shallowest water tables (McDonald and others, 1947).

Later, Arteaga and others (1968) did a comprehensive investigation on groundwater conditions in Paradise Valley, but most of their data and analyses focus on the southern part of the valley, south of the study area. Three informal alluvial units (upper, middle, and lower) forming a single aquifer system were identified; in northern Paradise Valley, wells were less productive than to the south because they did not penetrate the more permeable lower alluvium, and the upper alluvium was dry. Arteaga and others (1968) noted that in the southern part of Paradise Valley and near Scottsdale pumping greatly exceeded recharge and cones of depression had formed. In northern Paradise Valley (the study area), they noted groundwater from alluvium was the main source of water, and 2 public supply, 1 irrigation, and about 30 domestic wells were in the area. In total, less than 10,000 acre-feet were pumped in northern Paradise Valley from 1946 through 1965 and change in groundwater level from 1961 to 1966 was almost zero, although declines of 25 to 50 ft were observed in central and southern Paradise Valley.

Depth to bedrock (that is, the thickness of alluvial fill) throughout Paradise Valley was estimated by Lausten (1974) from 371 gravity stations and borehole logs. Low-density basin fill causes a gravity “low,” the magnitude of which is proportional to the thickness of fill. This depth-to-bedrock application of gravity data differs from the repeat microgravity surveys presented in this report to measure change in groundwater storage. It is an interpretation of the large-scale density features of a single “snapshot” of the gravity field and does not consider any change in gravity.

Laney and Hahn (1978) published a series of maps showing the distribution of sedimentary facies, groundwater-level contours, and aquifer transmissivity in the east Salt River Valley, including the southern part of Paradise Valley. The northernmost extent of their analysis barely overlaps with the southern part of the study area, but their work provides helpful descriptions of the alluvial units where applicable.

Geology

The study area is primarily an alluvial fan setting with Tertiary to Quaternary coarse-grained granitic sediment derived from mountains to the north, the McDowell Mountains to the east, and the Phoenix Mountains to the west and south. These

bounding mountain ranges are primarily Proterozoic igneous and metamorphic rocks and are not considered part of the groundwater flow system (ADWR, 2023b). The alluvial basin deepens from north to south through the study area, reaching a maximum thickness of 12,000 ft or more around Union Hills Road and Tatum Boulevard (Lausten, 1974). Farther north, along Pinnacle Peak Road, the maximum depth is about 5,000 ft; along Lone Mountain Road, it is about 2,500 ft; and along Carefree Highway, it is about 500 ft. Boreholes penetrating the entire alluvial fill are sparse, but an exploration well near Pinnacle Peak and Tatum Roads apparently met basement material at 5,150 ft below land surface (Laney and Hahn, 1978).

The alluvium is generally divided into informal lower, middle, and upper units (Arteaga and others, 1968), with the middle alluvium unit being generally the finest grained. The lower alluvium unit is generally coarse grained, well cemented, and interbedded with basaltic and andesitic lava flows (Arteaga and others, 1968). The middle alluvium unit includes playa, alluvial fan, and fluvial deposits and is estimated to be greater than 70 percent clay and silt south of the study area but coarsens considerably to more than 70 percent sand and gravel in the southernmost part of the study area (Laney and Hahn, 1978). In the southern part of Paradise Valley, it may be a source of naturally occurring nitrate (Silver and Fielden, 1980) and hexavalent chromium in groundwater (Robertson, 1975). The upper alluvium unit is in the upper few hundred feet of the subsurface and is dry in the study area (Arteaga and others, 1968).

Hydrology

The major surface-water feature in the study area is Cave Creek, an ephemeral wash (channel) originating in the central Arizona highlands north of Paradise Valley. An additional ephemeral wash, Apache Wash, parallels Cave Creek to the west. The drainage area of Cave Creek and Apache Wash at Cave Buttes Dam in the southwest part of the study area is approximately 195 square miles (U.S. Geological Survey, 2023). Cave Buttes Dam partially impounds ephemeral flows during periods of runoff, but impounded water drains quickly, and there is no significant surface reservoir most of the year. Other surface-water features in the study area are ephemeral washes that flow northeast to southwest, but only in response to rainfall. Although no direct streamgaging measurements are available for these washes, they can carry substantial flows occasionally (once every few years).

The CAP canal delivers water from the Colorado River to the Phoenix and Tucson metropolitan areas. The concrete-lined canal traverses the southern part of the study area from west to east following a similar alignment to the Old Verde Canal, a failed effort in the early 1900s to transport water east to west from the Verde River to the channel of Cave Creek, the goal of which was to establish irrigated agriculture in the Paradise Valley (Arteaga and others, 1968). Because the CAP is concrete lined through the study area, seepage and direct recharge from the canal is assumed to be minimal.

Groundwater in the study area is generally at depths greater than 500 ft below land surface—the greatest depths to groundwater in the entire Salt River Valley (ADWR, 2023b). There is little discussion in the historical references about confining or artesian conditions in the aquifer. McDonald and others (1947, p. 11) “found no structural features in the valley or in the bordering mountains that would indicate the presence of artesian water in Paradise Valley.” Arteaga and others (1968) mention a semiconfining layer in the southern part of Paradise Valley, south of the study area; however, they provide no discussion about this feature. Larson and Péwé (1986) describe unconfined conditions in their study area bordered by Bell Road in the north (south of the repeat microgravity network), but “near the northern boundary of the study area,” a clay layer 200 ft thick creates confining conditions. The presence of unconfined or confined conditions is significant for this study because it determines the relation between storage (measured by gravity) and groundwater-level change (measured in monitoring wells) according to equation 2. Confined conditions can also indicate a potential for Earth fissuring. Earth fissuring was observed at least since the early 1980s in the southern part of Paradise Valley, about 3 miles south of the study area (Larson and Péwé, 1986). Based on these references, well logs in the study area, and alluvial sediments that coarsen to the north in Paradise Valley, closer to the mountain fronts, unconfined aquifer conditions are inferred throughout the study area.

Several underground storage facilities, in the form of injection and vadose zone wells (the former screened at or below the water table, the latter above the water table), operate in and near the study area. Phoenix is permitted for 11 such wells, although only three operated during the study period (ADWR, 2024a). These wells are screened (open to the aquifer) at depths about 100 ft or more below the water table. Scottsdale operates three underground storage facilities near the study area: the Water Campus, West World Golf Course, and the North Scottsdale Aquifer Storage & Recovery Project (ADWR, 2024a). Each of these recharge water through vadose zone recharge wells.

Methods

Data collected for this project included repeat microgravity data from 108 stations and global navigation satellite system (GNSS) surveying of point locations. Additionally, groundwater elevation data from 10 wells were retrieved from the ADWR database.

Groundwater-Level Monitoring

Groundwater levels in the study area were monitored by ADWR at 10 locations in and near the study area (ADWR, 2023a; fig. 3). Groundwater levels were measured about once per year using an electric tape lowered in each well. Groundwater-level data were retrieved from the ADWR Groundwater Site Inventory database (ADWR, 2023a).

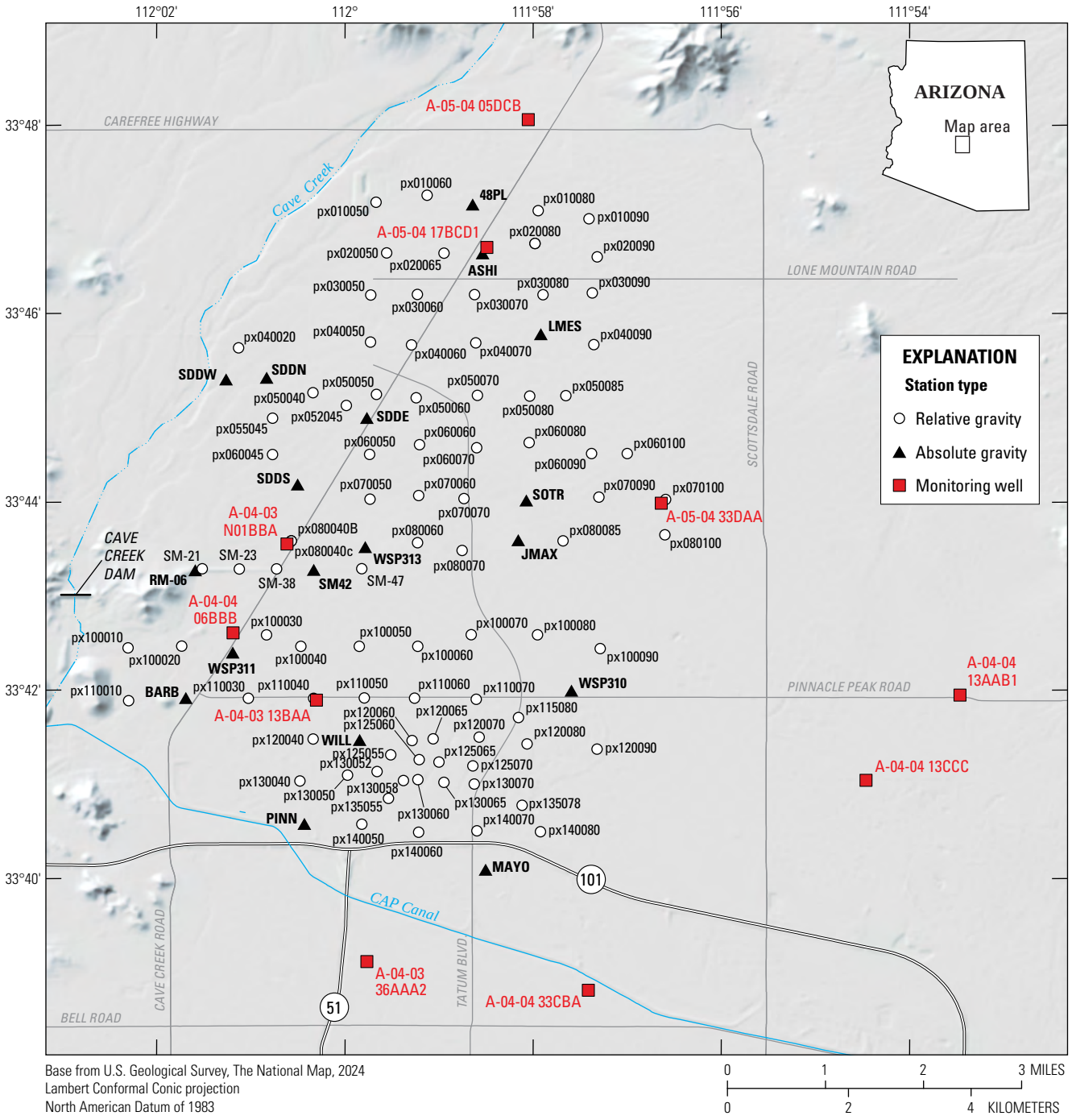


Figure 3. Map showing repeat microgravity (Kennedy, 2024) and groundwater-monitoring wells (Arizona Department of Water Resources, 2023a) in the study area.

Repeat Microgravity Monitoring

Gravity data were collected annually from 2020 to 2023, from January to February each year, at up to 108 locations. Not every location was surveyed each year. About half of the network was surveyed in 2020, and surveys of the full network began in 2021. Most gravity stations were on preexisting concrete sidewalks or other concrete features to provide vertical stability. Gravity stations where absolute-gravity data were collected are designated by capitalized station names in fig. 3; all other station names are in lowercase letters. Station density is limited in the central part of the study area because permission could not be obtained from the landowner to install new survey monuments.

Gravity data were collected using a combination of relative- and absolute-gravity meters following established

procedures (Kennedy and others, 2021). The absolute-gravity meter (Micro-g Lacoste, Inc. A–10, serial number 008, Lafayette, Colo.) measures the acceleration of a free-falling mass and provides reference ("base station") values for the relative surveys. Relative-gravity meters (ZLS Burris meters, serial numbers B–44, B–108, and E4D65, ZLS Corporation, Austin, Texas) measure the difference in gravity between two locations. Relative- and absolute-gravity meters are accurate to about 3–8 microGal (μGal; Crossley, 2013); 1 μGal is 1×10^{-8} meter per second squared and equivalent to about 2.38 centimeters of water using the horizontal-infinite slab approximation (eq. 1). Absolute-gravity measurements and relative-gravity differences were combined in a process known as least-squares network adjustment using GSadjust software (Kennedy, 2020). In 2021, a GNSS survey was done using a combination of static and real-time kinematic methods. Stations were positioned in the North American Datum of 1983 (2011) epoch 2010.00 datum using the Online Positioning User Service (National Geodetic Survey, 2023; Kennedy 2024).

Corrections to gravity data focus on accounting for the time-varying changes in the gravity field not related to water-mass change, including land-surface elevation change, Earth tides, ocean loading, and atmospheric pressure change (Kennedy and others, 2021). To evaluate land-surface elevation change, interferometric synthetic aperture radar (InSAR) data were processed by ADWR (ADWR, 2023c). Future GNSS surveys can be compared with the 2021 survey to further verify land-surface elevation change (or lack thereof). Earth tide and ocean loading corrections were done using standard models included with data collection software. The gravitational effect of atmospheric pressure change on absolute-gravity measurements is accounted for by measuring air pressure at the time of each measurement and applying a −0.30 μGal/millibar admittance (correction) factor. Relative-gravity data were not corrected for air pressure because only relative-gravity differences between stations observed close together in time are considered in the least-squares network adjustment, assuming that (large) air pressure changes occur more slowly than data are collected.

Once data have been corrected, and the least-squares network adjustment performed, changes in gravity are directly related to the change in water stored in the subsurface, modeled as a "horizontal infinite" (or "Bouguer") slab of free-standing water:

$$\Delta Storage = \Delta g/12.77 \quad (1)$$

where

$\Delta Storage$ is the change in thickness of free-standing water, in feet,

Δg is the change in gravity caused by a change in the thickness of a slab of free-standing water, in microgals, and

12.77 is a constant derived from the horizontal infinite slab approximation (Telford and others, 1990).

Equation 1 shows that the relation between water-storage change and gravity change does not depend on subsurface properties (including porosity), nor depth to water. Error in the horizontal infinite slab approximation is less than 10 percent if the water table is approximately flat to a distance (radius) equal to 10 times the depth to water (Pool and Eychaner, 1995). The change in storage is related to the change in groundwater level (for a single aquifer) as:

$$\Delta GWL = \Delta Storage/n_e \quad (2)$$

where

ΔGWL is the change in groundwater level measured in a well,

$\Delta Storage$ is the change in thickness of free-standing water, and

n_e is the aquifer effective porosity (approximately equal to specific yield in an unconfined aquifer).

The total volume of storage change between surveys was calculated by interpolating values within a polygon encompassing the repeat gravity network. This method converts the one-dimensional storage change at each measurement location to a three-dimensional volume of water and is equivalent to determining an anomalous mass from Gauss' law (Blakely, 1995; Pool and Anderson, 2007). Interpolation was done by kriging, a method that estimates the semi-variogram (the variance-distance relation) of the observed data and predicts a value (in this case, change in gravity between surveys) at all locations on a grid. This study used a spherical semi-variogram model, consistent with previous gravity kriging efforts (for example, Shamsipour and others, 2010; Arfaoui and Inoubli, 2013; Kennedy and Bell, 2023). The semi-variogram nugget, representing measurement error, was set to 0.28 ft of water. This nugget estimate represents the average error from each survey (about 2.5 μGal) summed in quadrature (because the quantity being kriged is the change in gravity between surveys, not the gravity value for each survey) and converted to feet of water using equation 1. The semi-variogram standard deviation, which represents interpolation error, was also set to 0.28 inches of water; total variance at each interpolation location is the nugget plus additional variance as a function of the location's distance from observation locations. The semi-variogram range, or distance at which spatial correlation approaches zero, was set to 6,000 ft or about 10 times the average depth-to-water in the study area. This distance represents the region over which individual gravity measurements are sensitive to subsurface mass change (Blakely, 1995). Prediction of the interpolated surface was done by universal kriging, which accounts for a linear trend in the interpolated surface.

An advantage of the kriging method for interpolation is that it also produces an estimate of the variance, or uncertainty, associated with the interpolated values. To estimate the uncertainty of the groundwater-storage-change volume estimates, the average variance of the kriged volume was calculated as:

$$\sigma^2_{\sum X} = \frac{\sum_i \sigma_i^2 + 2\sum_i \sum_{j<i} cov(X_i, X_j)}{n^2} \quad (3)$$

where

$\sigma^2_{\sum X}$ is the variance of the storage-change estimate (the sum of storage change across all grid cells in the interpolated raster),

σ_i^2 is the variance of the kriged prediction for each grid cell,

$cov(X_i, X_j)$ is the covariance between each pair of grid cells (non-diagonal elements of the covariance matrix), and

n is the number of grid cells.

The first term in the numerator represents the variance for independent estimates, and the second term in the numerator represents the cross-correlation between grid cells according to the kriging semi-variogram. Uncertainty results are presented as standard deviation ($\sqrt{\sigma^2_{\sum X}}$). The polygon over which storage is calculated, an example of a kriged storage-change surface, and the associated uncertainty is shown in figure 4.

Results

Presentation of study results is divided into groundwater pumping and elevation change, groundwater-level elevation, and groundwater storage.

Groundwater Pumping and Elevation Change

Pumping in the study area from 2020–22 was relatively low (table 1), particularly in comparison to the more than 800,000 acre-feet of groundwater pumped annually from the entire Salt River Valley (ADWR, 2023b) (fig. 5). Annual pumping at each well was relatively consistent over the 2020–22 period. Total pumping was less than the total amount of recharge through injection, although total recharge volumes were less in 2021 and 2022 than in previous years (table 2). Most of the recharged water is from the Colorado River, delivered by the CAP, although treated effluent is also recharged at the Scottsdale Water Campus. Thus, the recharged water is primarily additional water imported into the basin, rather than water that was originally pumped from the basin.

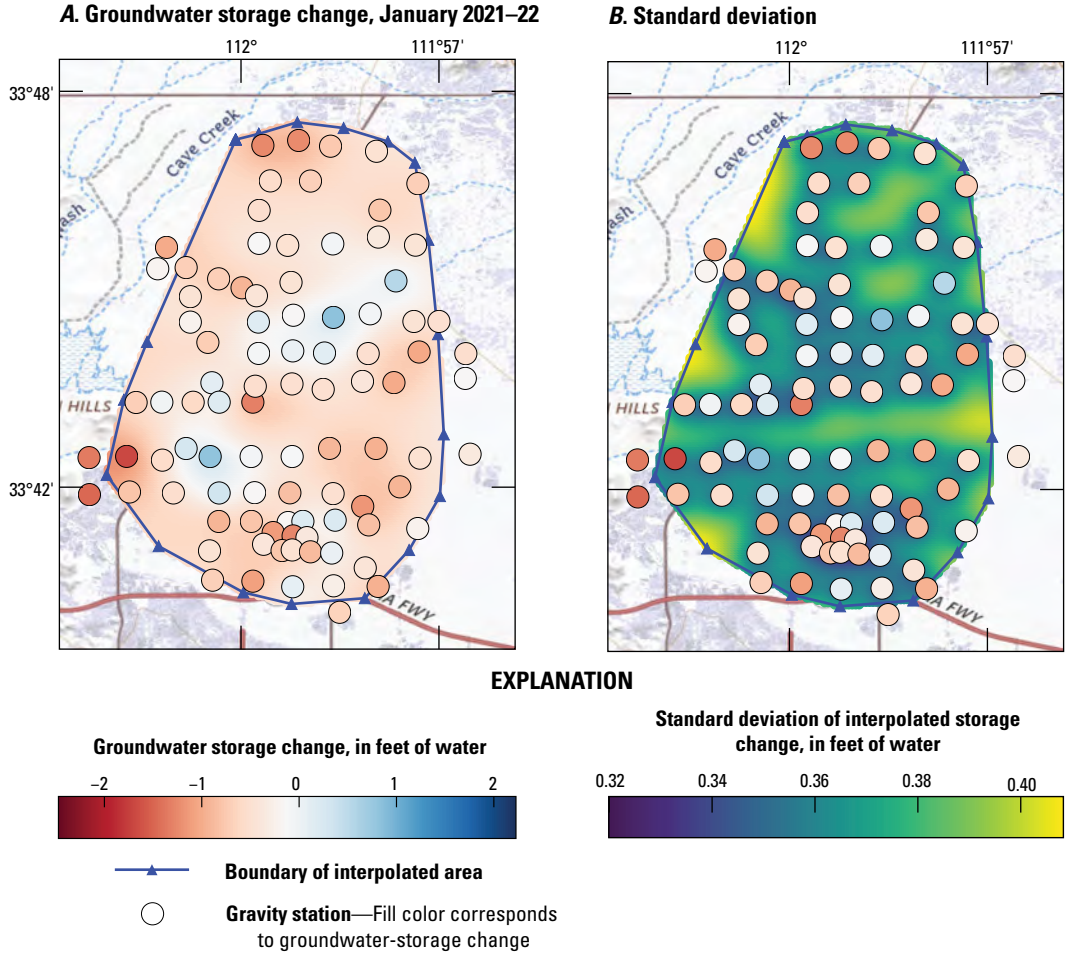


Figure 4. Graphs showing, *A*, an example of an interpolated (kriged) surface of groundwater-storage change within a polygon encompassing the repeat microgravity network and, *B*, the standard deviation of groundwater-storage change for the period from January 2021 to January 2022. Data from Kennedy (2024).

Satellite measurements of land-surface elevation change using InSAR during the study period showed small amounts of subsidence from 2020 to 2021 and from 2021 to 2023 (ADWR, 2023c) to the south and southeast of the study area (south of the Loop 101 Freeway along Frank Lloyd Wright Boulevard and centered along Scottsdale Road north of the Loop 101 Freeway and south of Pinnacle Peak Road). Maximum subsidence was about 2 centimeters over the study period (May 2020 to May 2023), but only within relatively small areas within known subsidence areas (fig. 2). Most of the study area did not have any subsidence during this period. These subsidence amounts are much smaller than historically reported amounts (Larson and Péwé, 1986) farther south in Paradise Valley—as much as 3 ft or more was reported in a region about 3 to 4 miles south of station MAYO (fig. 3), near Cactus and Thunderbird Road.

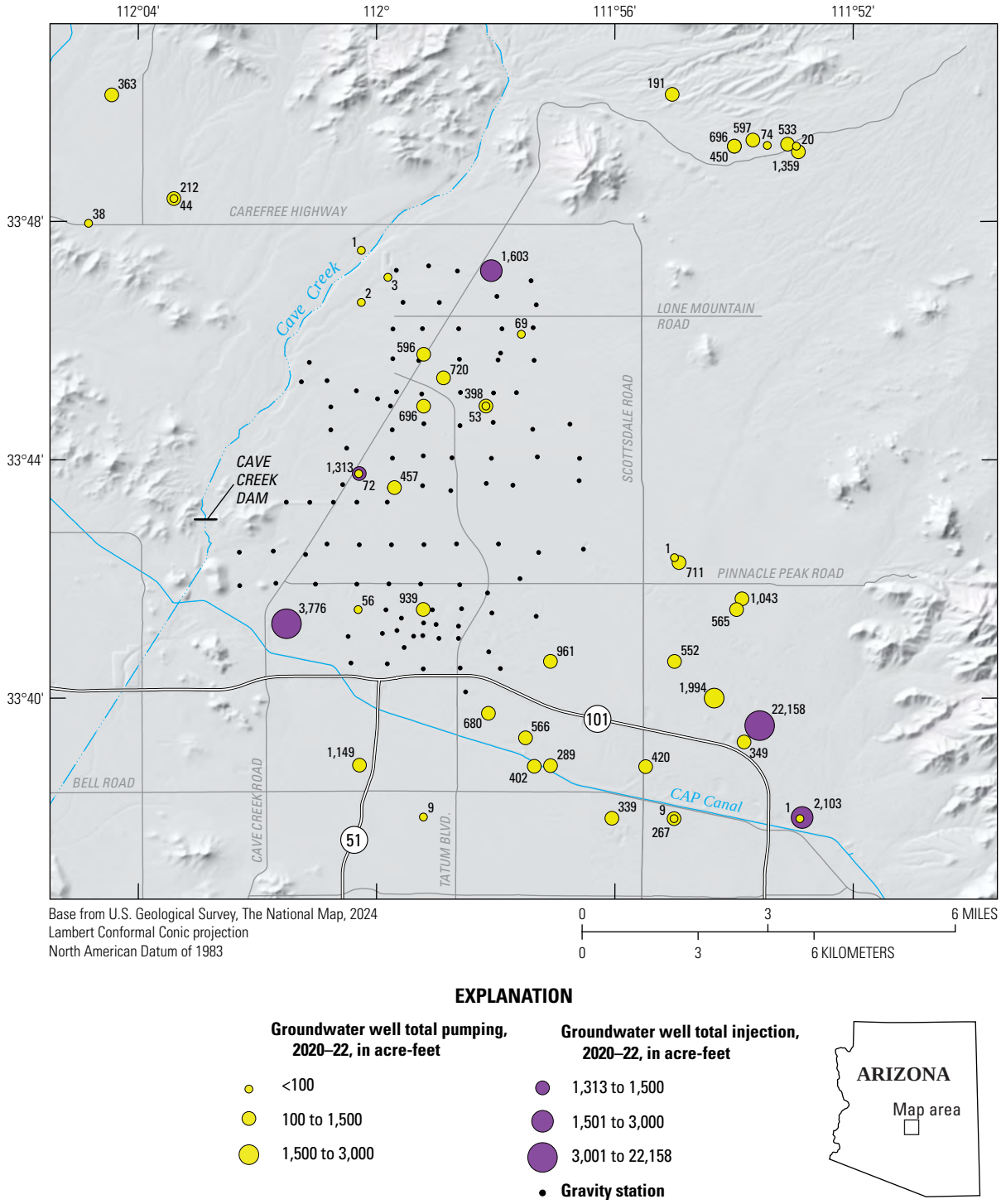


Figure 5. Map showing pumping and injection (recharge) data reported to the Arizona Department of Water Resources (2024a). <, less than; >, greater than.

Table 1. Volume of water pumped within the study area, as reported to the Arizona Department of Water Resources (2024a).

[ID, identification; ADWR, Arizona Department of Water Resources]

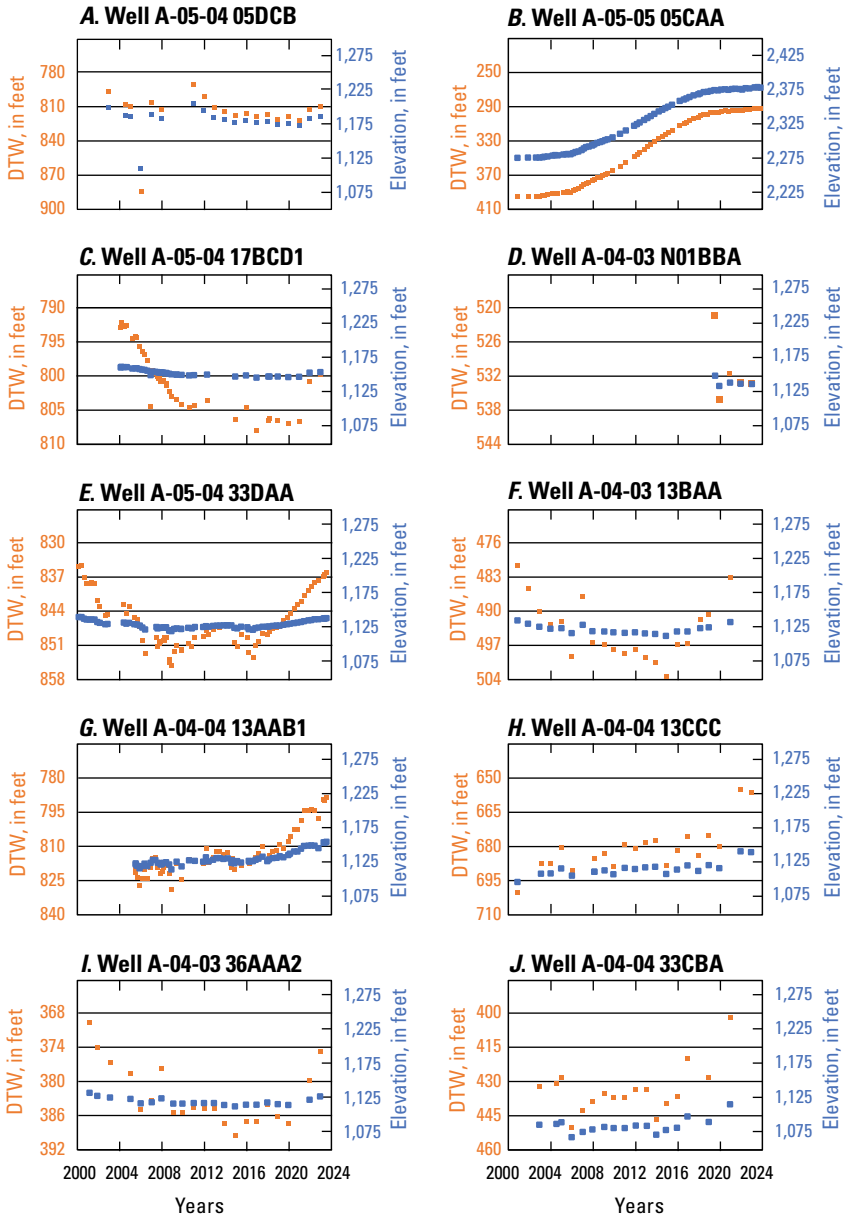
Cadastral ID	ADWR registry number	2020–22 pumpage, acre-feet
A-03-04 02AAA	55-617023	9
A-03-04 02DBB	55-626827	267
A-03-04 03BAA	55-501643	339
A-03-04 06CDC	55-626582	9
A-03-05 06DBB	55-573658	1
A-04-03 13BAA	55-503959	56
A-04-03 36AAA	55-606355	1,149
A-04-04 06BBB	55-623687	457
A-04-04 11CBB	55-550382	711
A-04-04 11CDD	55-626832	1
A-04-04 13ACB	55-584391	1,043
A-04-04 13CCC	55-602769	565
A-04-04 18DBC	55-560509	939
A-04-04 21CBA	55-508818	961
A-04-04 23BAB	55-554003	552
A-04-04 25BBC	55-214664	1,994
A-04-04 28CCC	55-583886	566
A-04-04 29CBA	55-560104	680
A-04-04 33CBA	55-504791	402
A-04-04 33CCC	55-87614	289
A-04-04 35BCC	55-587290	420
A-04-04 36ABA	55-564034	349
A-05-03 04	55-631199	212
A-05-03 04CDC	55-87697	44
A-05-03 05CCC	55-226119	38
A-05-03 12DDA	55-234983	1
A-05-03 13AAA	55-226136	3
A-05-03 13AAB	55-234984	2
A-05-03 36CDA	55-214540	72
A-05-04 19ACB	55-527549	596
A-05-04 19DDC	55-221450	720
A-05-04 21BBC	55-518789	69
A-05-04 29CCB	55-540078	398
A-05-04 29DAD	55-540079	53
A-05-04 30BAD	55-603807	696
A-06-03 29CCD	55-559936	363
A-06-04 26DCC	55-604779	191
Total		**15,215**
Wells in the Carefree/North Scottsdale area, shown in figure 5 but outside the gravity network		
A-06-04 36ADB	55-605050	696
A-06-04 36ADC	55-572380	597
A-06-04 36BDA	55-604781	450
A-06-05 31BCC	55-227879	74
A-06-05 31BDA	55-511578	1,359
A-06-05 31CCC	55-604782	533
A-06-05 31CDD	55-604783	20
Total		**18,944**

Table 2. Volume of water recharged by injection wells within the study area, as reported to the Arizona Department of Water Resources (2024a).

Underground storage facility permit number	Entity	Annual recharge through injection, acre-feet			
		2020	2021	2022	Total
71-216386.0001	City of Phoenix	1,309	4	0	1,313
71-220047.0001	City of Phoenix	568	566	469	1,603
71-222506.0001	City of Phoenix	2,001	1,743	32	3,776
71-560648.0003	City of Scottsdale	6,823	7,683	7,652	22,158
71-574911.0003	City of Scottsdale	794	817	492	2,103
Total		**11,495**	**10,813**	**8,645**	**30,953**

Groundwater-Level Elevation

Groundwater-level elevation increased during the study period at all monitoring wells but was variable in years before the study period. The maximum groundwater-level increase since the year 2000 was more than 100 ft, observed at well B (fig. 6). This increase was likely related to the start of artificial recharge and to the reduced pumping in this area since about 2000 (ADWR, 2024a). The groundwater level at several wells (C, E, F, I) drops during the first half of the hydrographs in figure 6 (roughly 2000–12), but later stabilizes or starts to increase. For the 2020–23 period, groundwater levels were stable (wells A, B, D, H) or increasing (wells C, E, G, I), in several cases by several feet or more (fig. 6). Only four wells overlap spatially with the repeat microgravity network (wells C, D, E, and F), and only well E, on the eastern boundary of the gravity network, has sufficient data to infer a definite upward groundwater-level trend (fig. 6). Data at the other wells (for example, F and J) reveal the limitation of annual measurements of groundwater levels; there are clearly within-year fluctuations in groundwater levels not captured by the annual measurements, and if even a single year's measurement is missed, the amount of information available from the record can be greatly reduced. Future analyses of the study area would benefit from the installation of continuously recording (for example, daily) pressure transducers to measure groundwater levels.



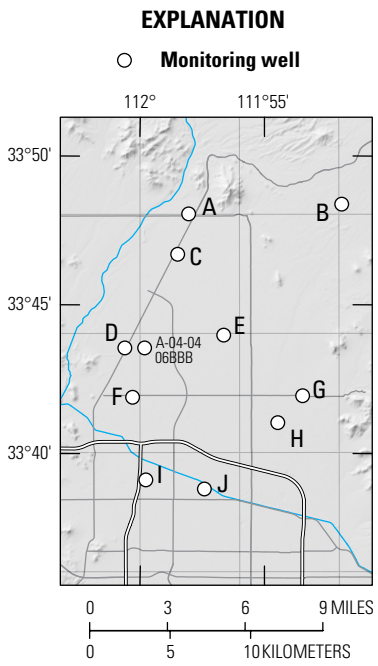


Figure 6. Hydrographs showing groundwater levels at monitoring wells (*A*–*J*). Depth to water (DTW) is shown in orange and has a variable range on each plot. Groundwater elevation (referenced to the National Geodetic Vertical Datum of 1929) is shown in blue and has a fixed range of 200 feet across all plots. Groundwater elevation is equal to the land-surface elevation minus depth to water. Data from Arizona Department of Water Resources Groundwater Site Inventory database (Arizona Department of Water Resources, 2023a).

The groundwater-level changes during the study period are small compared to changes observed in the mid-20th century (McDonald and others, 1947). Before then, in the early 20th century, groundwater-level changes were minimal and pumping for agriculture was impractical in the study area because of the large depth to water and high pumping costs (widespread irrigated agriculture was done elsewhere throughout the Salt River Valley). Increased pumping for municipal supply caused groundwater-level declines in the second half of the 20th century (Arteaga and others, 1968); hydrographs for two wells in the study area had changes in groundwater elevation of −5.5 and −4.0 feet per year (fig. 7) during the 1980s and 1990s. This decline continued until around 2010, after which groundwater level stabilized and eventually rebounded.

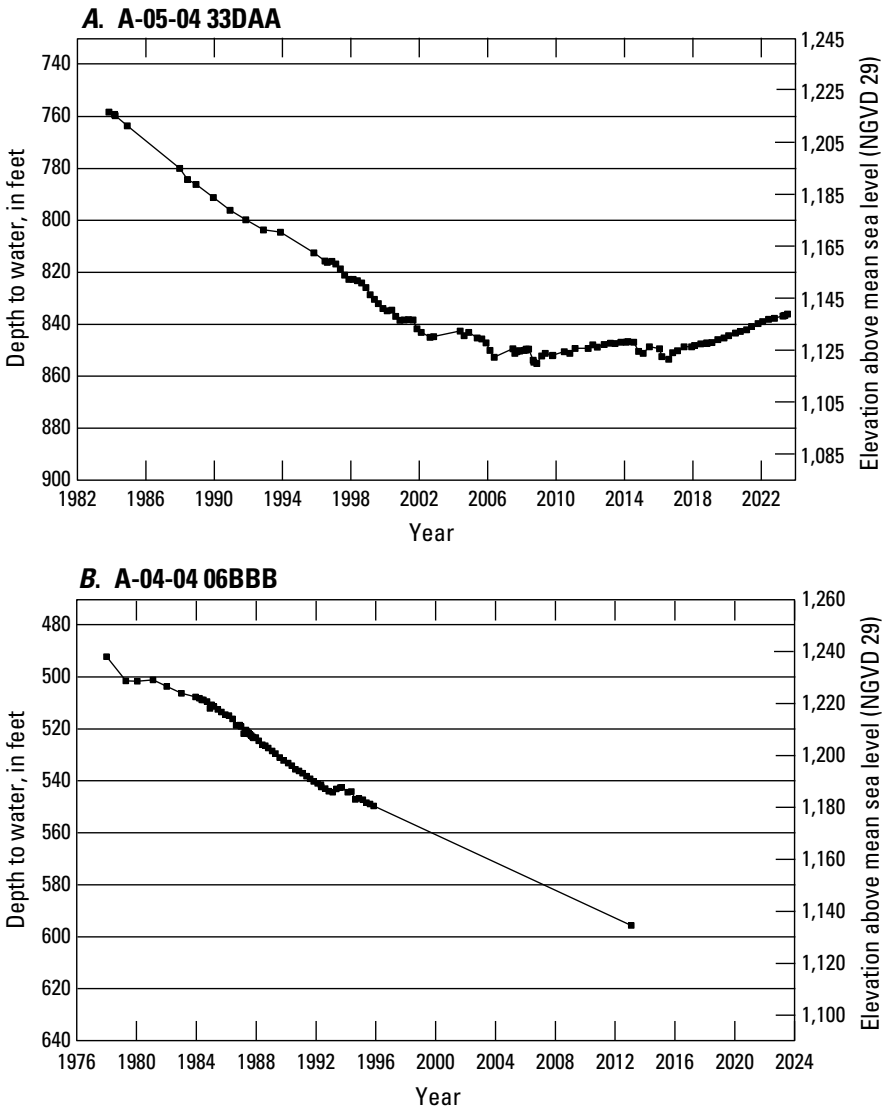


Figure 7. Long-term hydrographs showing groundwater levels since 1983 (*A*) and 1978 (*B*). Depth to water is shown on the left axis and groundwater elevation is shown on the right axis. Data from Arizona Department of Water Resources Groundwater Site Inventory database (Arizona Department of Water Resources, 2023a). NGVD 29, National Geodetic Vertical Datum of 1929.

Groundwater Storage

Repeat microgravity surveys were done each year from 2020 to 2023 in January–February. Relative- and absolute-gravity observations combined using least-squares network adjustment form a network of observations (fig. 8). The least-squares network adjustment represents the best-fit solution to the data, considering the uncertainty of each measurement type. Statistics for the network adjustments are provided in table 3. The average standard deviation of the adjusted gravity values across all surveys, 2.4 µGal, is equivalent to 0.19 ft of water according to equation 1. Details about gravity data collection and the data are available in the accompanying data releases (U.S. Geological Survey, 2021; Kennedy, 2024).

In calendar year 2020 (from January 2020 to January 2021), groundwater storage increased in the southwest part of the study area (fig. 9), near the city of Phoenix's largest injection well (fig. 5).

Table 3. Network-adjustment statistics for repeat microgravity surveys.

[Calibration coefficients are given for each Burris gravity meter serial number used. µGal, microGal; ±, plus or minus; *n*, number of observations]

Statistic	January 2020	January 2021	January 2022	January 2023
Relative-gravity observations				
n	151	219	244	273
Mean standard deviation	2.54 µGal	2.29 µGal	2.62 µGal	2.01 µGal
Relative-gravity meter calibration coefficients	B-44: 0.998777±0.000073	B-44: 0.998474±0.000099 E4D65: 1.000051±0.000094	B-44: 0.998954±0.000083 E4D65: 1.000252±0.000093 B-108: 0.999266±0.000090	B44: 0.999831±0.000052 E4D65: 1.000201±0.000055
Absolute-gravity observations				
n	18	27	33	26
Mean absolute residual	2.2 µGal	4.0 µGal	3.7 µGal	4.25 µGal

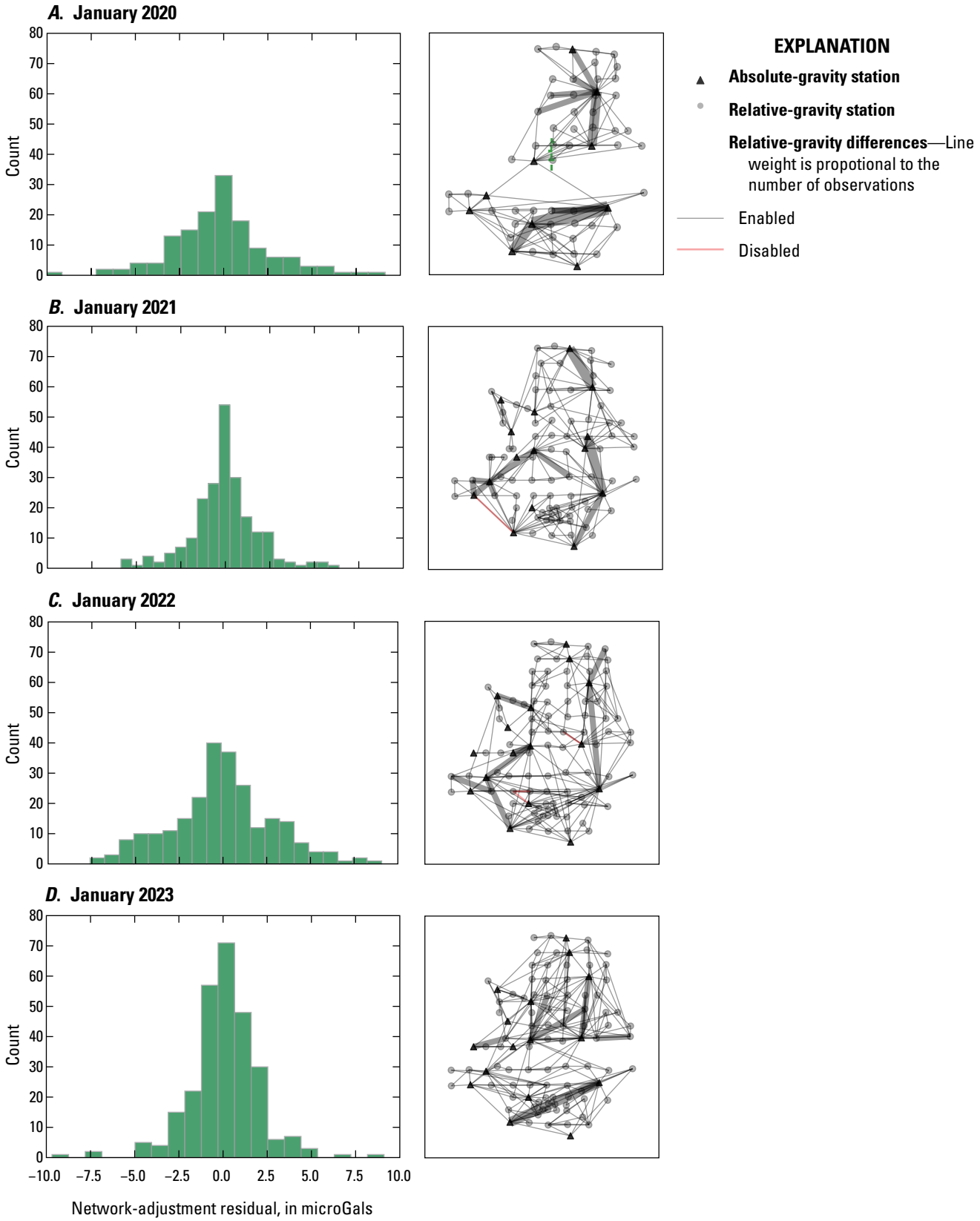


Figure 8. Graphs (left) showing network-adjustment residuals (difference between adjusted gravity difference between stations minus observed gravity difference) and images (right) showing the relative-gravity differences used in the network adjustment for years 2020–23 (Kennedy, 2024).

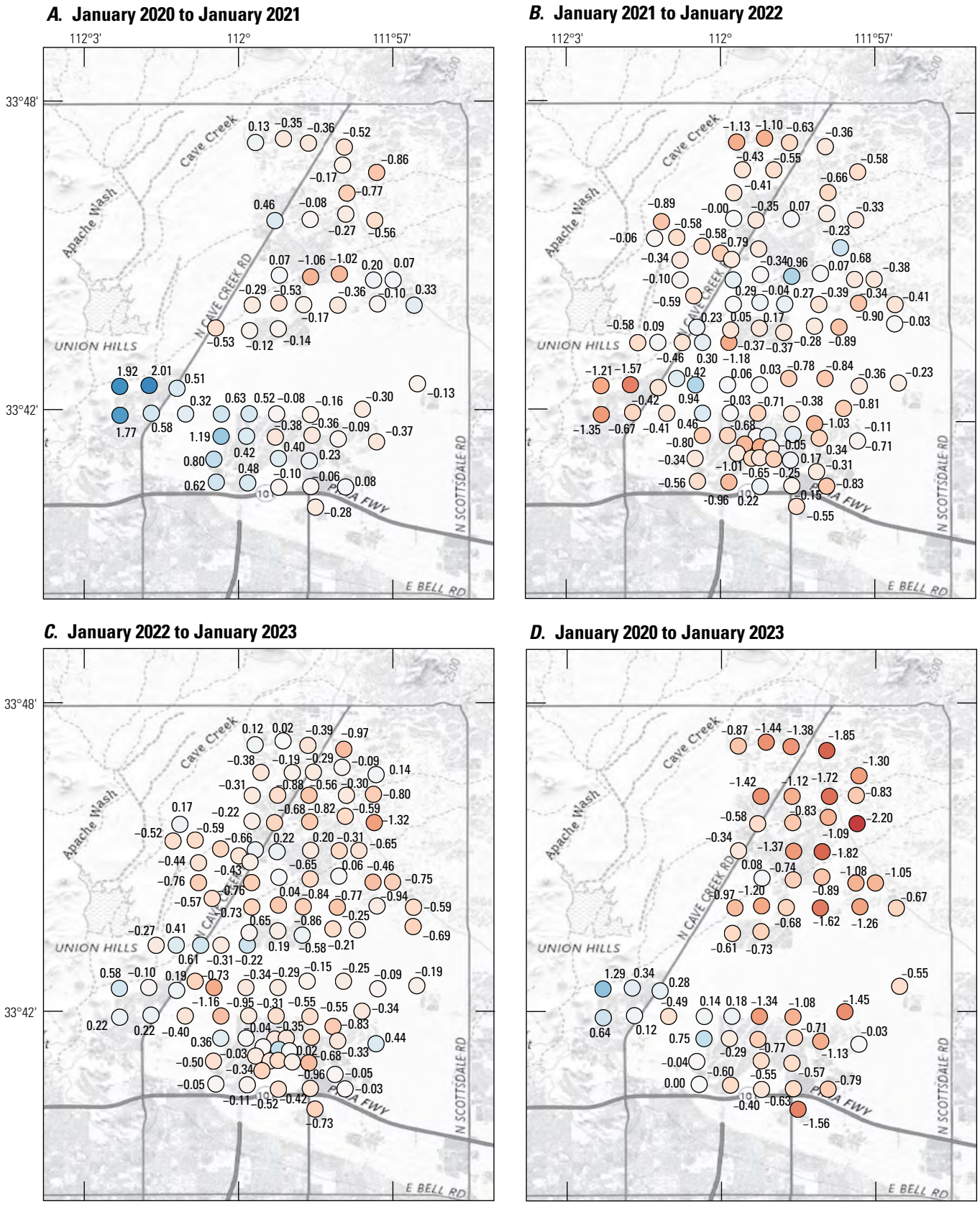
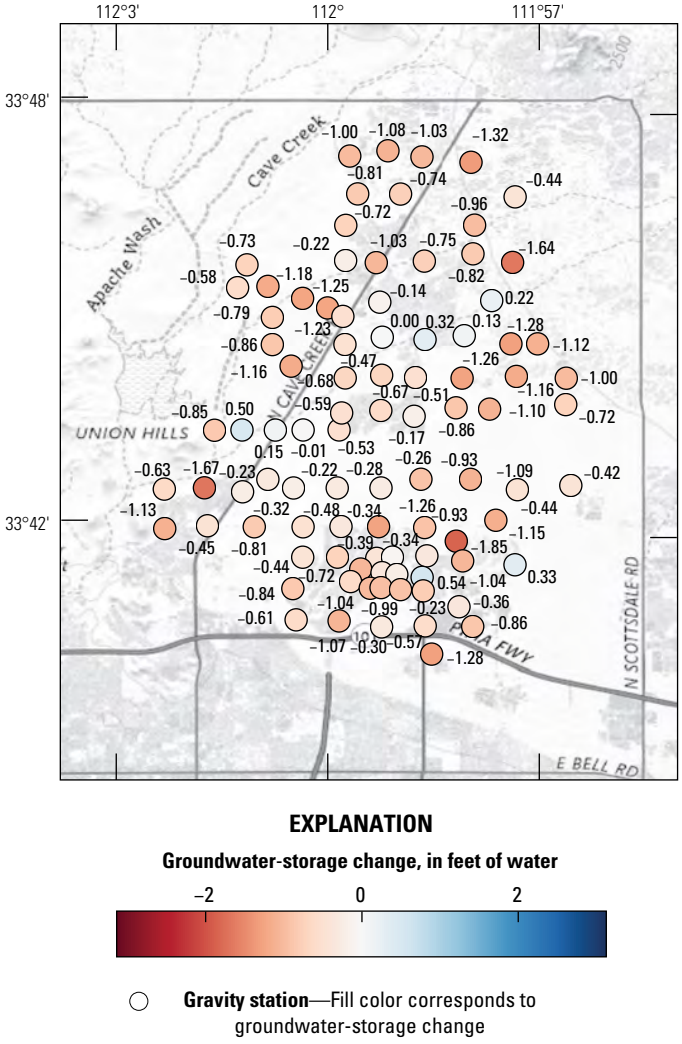


Figure 9. Maps showing aquifer storage change derived from repeat microgravity data in northeast Phoenix from 2020–21 (*A*), 2021–22 (*B*), 2022–23 (*C*), 2020–23 (*D*), and 2021–23 (*E*). Data from Kennedy (2024).

E. **January 2021 to January 2023**



EXPLANATION

Groundwater-storage change, in feet of water

−2 0 2

Gravity station—Fill color corresponds to groundwater-storage change

Figure 9—Continued

Changes elsewhere were small; a small decrease in storage was observed in the north-central part of the study area. In 2021 and 2022, changes in storage were small, generally negative, and lack large-scale spatial patterns. The largest gravity increases in the southwest part of the study area in 2020 were largely reversed in 2021. The locations of gravity changes were not closely related to pumping and injection well locations, consistent with these changes being small and localized owing to the small amount of water being pumped or injected.

Groundwater-storage changes during the study period (2020 to 2023) were negative overall, as seen in a time-series plot of gravity change at all stations (fig. 10) and volume calculations of year-to-year storage change (table 4). As shown in figure 10, gravity at 89 of 102 stations decreased during the study period (considering those stations that existed for the 2023 survey). The volume calculation is done over a polygon roughly encompassing the gravity network; it does not represent the entire region of the aquifer over which pumping and injection takes place (fig. 5). For the 19,750-acre area considered (fig. 4), groundwater storage increased by about 1,250 acre-feet in 2020 and decreased by about 6,700 acre-feet each year in 2021 and 2022 (table 4). During the 2020–22 period, the volume of injected water decreased from 11,495 to 8,695 acre-feet, but the volume of pumping increased.

Table 4. Groundwater-storage change in the north Phoenix aquifer within a 19,750-acre polygon encompassing the repeat microgravity network.

Groundwater-storage change	Jan. 2020 to Jan. 2021	Jan. 2021 to Jan. 2022	Jan. 2022 to Jan. 2023
Feet of water	0.063	−0.35	−0.34
Acre-feet	1,250	−6,820	−6,640
Standard deviation, acre-feet	860	860	860

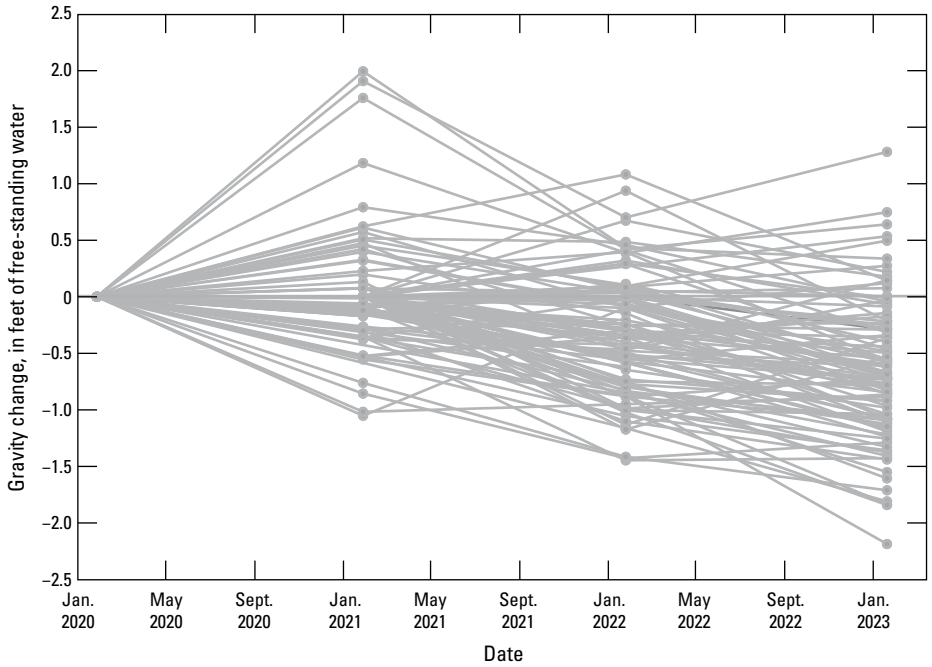


Figure 10. Time-series graph showing the change in gravity from the initial observation at each of 102 gravity stations. Data from Kennedy (2024).

These reported net changes (injection minus pumping) do not account for the full magnitude of the shift from positive storage change in 2020 to negative change in 2021–22 that is observed in the gravity data (fig. 9; table 4). The average annual net change in storage across the 19,950-acre interpolated area for 2020 through 2022 was −0.21 ft of free-standing water.

The decrease in storage indicated by the gravity data during the study period (fig. 10; table 4), together with injection volumes (table 2) that are greater than pumping (table 1), suggests aquifer subflow down-gradient, to the south and west, is greater than recharge and incoming subflow from the north and east. That is, outflow is greater than inflow. Although natural subflow and recharge are difficult or impossible to quantify, the upgradient recharge zone northeast of the study area is fairly small and includes a large expanse of Proterozoic granite at the land surface, which may limit recharge owing to potentially low porosity. Therefore, fluctuations in recharge and subflow in response to precipitation forcing may be relatively quick within that recharge zone, meaning that drought conditions since about 2000 (Leeper and others, 2022) may contribute toward reducing recharge and subflow.

Another cause of storage declines greater than that caused by net pumping may be drying of the unsaturated zone. This process—potentially caused by lower-than-average precipitation since about the year 2000 (Leeper and others, 2022)—may produce a change (decrease) in gravity without a corresponding change in groundwater level. Ultimately, a drying unsaturated zone will eventually result in a reduction in recharge to the aquifer and declining groundwater levels, but the thick unsaturated zone in the study area, over 500 ft in most areas, may make the reduction in recharge and declining groundwater levels from atmospheric forcing and precipitation less noticeable in the short term (Dickinson and Ferré, 2018).

Summary

A repeat microgravity network was established in 2020 for the purpose of quantifying aquifer storage change in the north Phoenix aquifer. Although relatively small volumes of groundwater are pumped from the aquifer as of 2023, the city has developed the well infrastructure and permitted capacity to increase pumping to more than 20,000 acre-feet per year. Our analysis demonstrates that the repeat microgravity network is well suited to capture the effects of potential increased pumping and (or) changes in aquifer storage resulting from managed aquifer recharge.

The repeat microgravity network comprises 108 stations established in 2020 and 2021, bounded roughly by Carefree Highway to the north, the Loop 101 freeway to the south, Cave Creek Road to the west, and 64th Street to the east. Stations were established on existing concrete surfaces, such as sidewalks. Gravity surveys were done using a combination of absolute- and relative-gravity meters. A Global Navigation Satellite System survey was done in 2021 to locate the stations and to allow stations to be evaluated for vertical movement in the future; vertical movement causes gravity changes independent of changes caused by change in subsurface mass (that is, groundwater-storage change). Satellite imagery (interferometric synthetic aperture radar [InSAR]) indicates minimal elevation change during the study period.

Gravity changes were generally small during the study period, commensurate with the relatively small volume of groundwater pumping and injection in and near the study area. From 2020 through 2022, groundwater storage changed on average by −0.21 feet per year within the study area, equivalent to −4,130±260 acre-feet over a 19,750-acre polygon encompassing the study area. This amount is less than the net 15,740 acre-feet difference between injection and pumping during this period. However, most of the injection is at one location: 22,158 acre-feet at the Scottsdale Water Campus during the study period. This relatively large amount appears to have little or no effect on storage change within the area of the repeat microgravity network. Because groundwater pumping and recharge in the basin is metered and reported—that is, no large, unknown sources withdraw or inject water—this suggests groundwater subflow out to adjacent basins is greater than incoming subflow, drying of the unsaturated zone, or both.

During the study period and the past two decades, widespread groundwater-level declines have largely leveled off or even rebounded as groundwater pumping was reduced and managed artificial recharge increased. Nonetheless, groundwater-flow model simulations indicate groundwater-storage losses will continue over the next 100 years in the north Paradise Valley Basin, including the study area (ADWR, 2023b). Storage losses are driven by pumping in the Salt River Valley as a whole, which can exceed 800,000 acre-feet per year (ADWR, 2023b). To observe these potential storage changes, barring site disturbance, repeat gravity surveys can be done at any time in the future. These measurements of gravity change are possible because the surveys are tied to the absolute datum of Earth's gravity field using absolute-gravity measurements rather than depending on "bedrock" stations for reference (that is, unchanging) values for relative-gravity-only surveys.

One limitation of the data in this report is that repeat microgravity and groundwater-level measurements were only done once per year and reported volumes of pumping and injection are only available as cumulative volumes for each calendar year. More frequent gravity monitoring and reporting of pumping/injections could help identify seasonal patterns. Often, water demand, and therefore groundwater pumping, is highest in summer months, but the distribution of pumping each year within the study area is unknown.

The reversal of groundwater declines in the study area in Paradise Valley can be seen as a positive result from sustainable groundwater management. Continued monitoring of the groundwater resource can support understanding of if this effect is short lived or sustainable; a previous microgravity investigation in Albuquerque tracked a multiyear increase in groundwater storage following surface-water importation, but this storage increase ceased when the surface-water supply decreased and groundwater

pumping resumed (Kennedy and Bell, 2023). Continued groundwater-level measurements (perhaps in an expanded monitoring-well network, with wells equipped with pressure transducers) beneficially augmented with continued repeat microgravity monitoring can help capture future groundwater-storage changes, especially if pumping and (or) injection increase.

References Cited

Arfaoui, M., and Inoubli, M.H., 2013, Advantages of using the kriging interpolator to estimate the gravity surface, comparison and spatial variability of gravity data in the El Kef-Ouargha region (northern Tunisia): Arabian Journal of Geosciences, v. 6, p. 3139–3147.

Arizona Department of Water Resources [ADWR], 2023a, Arizona groundwater site inventory (GWSI): Arizona Department of Water Resources website, accessed November 1, 2023, at https://azwatermaps.azwater.gov/gwsi.

Arizona Department of Water Resources [ADWR], 2023b, Groundwater flow model of the Phoenix active management area: Arizona Department of Water Resources Modeling Report No. 28, 124 p., accessed September 12, 2023, at https://infoshare.azwater.gov/docushare/dsweb/View/Collection-21998.

Arizona Department of Water Resources [ADWR], 2023c, Scottsdale and northeast Phoenix land subsidence feature—Land subsidence maps: Arizona Department of Water Resources web page, accessed October 12, 2023, at https://new.azwater.gov/hydrology/land-subsidence/scottsdale-and-northeast-phoenix.

Arizona Department of Water Resources [ADWR], 2024a, Interactive maps and data: Arizona Department of Water Resources web page, accessed July 26, 2024, at https://www.azwater.gov/gis-data-and-maps.

Arizona Department of Water Resources [ADWR], 2024b, Active Management Areas: Arizona Department of Water Resources web page, accessed November 19, 2024, at https://www.azwater.gov/ama/active-management-area-overview.

Arteaga, F.E., White, N.D., Cooley, M.E., and Sutheimer, A.F., 1968, Ground water in Paradise Valley Maricopa County, Arizona: Arizona State Land Department Water-Resources Report No. 35, 76 p.

Blakely, R.J., 1995, Potential theory in gravity and magnetic applications: Cambridge University Press, New York, 441 p.

Central Arizona Project [CAP], 2024, Central Arizona Project: Central Arizona Project web page, accessed November 19, 2024, at https://www.cap-az.com.

City of Phoenix, 2021, Water resource plan—2021 update: City of Phoenix Water Resource Plan, accessed August 23, 2023, at https://www.phoenix.gov/waterservicessite/Documents/2021%20City%20of%20Phoenix%20Water%20Resource%20Plan.pdf.

Crossley, D., Hinderer, J., and Riccardi, U., 2013, The measurement of surface gravity: Reports on Progress in Physics, v. 76, no. 4, p. 65–122.

Dickinson, J.E., and Ferré, T.P.A, 2018, Filtering of period infiltration in a layered vadose zone: 1—Approximation of damping and time lags: Vadose Zone Journal, v. 17, no. 1, p. 1–16.

Kennedy, J., 2020, GSadjust—A graphical user interface for processing combined relative- and absolute-gravity surveys (ver. 1.0): U.S. Geological Survey software release, accessed December 20, 2020, at https://doi.org/10.5066/P9YEIOU8.

Kennedy, J.R., Pool, D.R., and Carruth, R.L., 2021, Procedures for field data collection, processing, quality assurance and quality control, and archiving of relative- and absolute-gravity surveys: U.S. Geological Survey Techniques and Methods, book 2, chap. D4, 50 p., https://doi.org/10.3133/tm2D4.

Kennedy, J.R., and Bell, M.T., 2023, Measuring basin-scale aquifer storage change and mapping specific yield in Albuquerque, New Mexico, USA, with repeat microgravity data: Journal of Hydrology Regional Studies, v. 47.

Kennedy, J.R., 2024, Repeat microgravity data in the North Phoenix area, 2020-2023: U.S. Geological Survey data release, https://doi.org/10.5066/P96Q1OZG.

Laney, R.L., and Hahn, M.E., 1978, Hydrogeology of the eastern part of the Salt River Valley area, Maricopa and Pinal Counties, Arizona: U.S. Geological Survey Water-Resources Investigation Report 86-4147, 4 plates.

Lausten, C.D., 1974, Gravity methods applied to the geology and hydrology of Paradise Valley, Maricopa County: Tempe, Arizona State University, M.S. thesis, 137 p., 10 sheets, scale 1:62,500.

Larson, M.K., and Péwé, T.L., 1986, Origin of land subsidence and earth fissuring, northeast Phoenix, Arizona: Bulletin of the Association of Engineering Geologists, v. 23, no. 2, p. 139–165.

Lee, W.T., 1905, Underground water of the Salt River Valley, Arizona: U.S. Geological Survey Water-Supply and Irrigation Paper no. 136, 225 p., 2 sheets.

Leeper, R.D., Bilotta, R., Petersen, B., Stiles, C.J., Heim, R., Fuchs, B., Prat, O.P., Palecki, M. and Ansari, S., 2022, Characterizing U.S. drought over the past 20 years using the U.S. drought monitor: International Journal of Climatology, v. 42, no. 12, p. 6616–6630.

McDonald, H.R., Wolcott, H.N., and Bluhm, F.I., and Hem, J.D., 1947, Geology and ground-water resources of Paradise Valley Maricopa County, Arizona: U.S. Geological Survey Open-File Report 47-36, 38 p.

Meinzer, O.E., and Ellis, A.J., 1915, Ground water in Paradise Valley, Arizona: U.S. Geological Survey Water-Supply Paper 375-B, p. 51–75.

National Geodetic Survey, 2023, OPUS—Online positioning user service: National Oceanic and Atmospheric Administration web page, accessed May 4, 2023, at https://geodesy.noaa.gov/OPUS.

National Weather Service, 2023, NOWData–NOAA online weather data: National Oceanic and Atmospheric Administration web page, accessed November 3, 2023, at https://www.weather.gov/wrh/Climate?wfo=psr.

Pool, D.R., and Eychaner, J.H., 1995, Measurements of aquifer-storage change and specific yield using gravity surveys: Groundwater, v. 33, no. 3, p. 425–432.

PRISM Climate Group, 2023, PRISM gridded climate data: Oregon State University web page, accessed November 3, 2023, at https://prism.oregonstate.edu.

Richard, S.M., Reynolds, S.J., Spencer, J.E., and Pearthree, P.A., comps., 2000, Geologic map of Arizona: Arizona Geological Survey Map M-35, 1 sheet, scale 1:1,000,000.

Robertson, F.N., 1975, Hexavalent chromium in the ground water in Paradise Valley, Arizona: Groundwater, v. 13, no. 6, p. 516–527.

Shamsipour, P., Marcotte, D., Chouteau, M., and Keating, P., 2010, 3D stochastic inversion of gravity data using cokriging and cosimulation: Geophysics, v. 75, no. 1, p. I1–I10.

Silver, B.A., and Fielden, J.R., 1980, Distribution and probable source of nitrate in ground water of Paradise Valley, Arizona: Groundwater, v. 18, no. 3, p. 244–251.

U.S. Census Bureau, 2023, Incorporated places 2020 to 2023: U.S. Census Bureau database, accessed June 5, 2024, at https://www2.census.gov/programs-surveys/popest/tables/2020-2023/cities/totals/SUB-IP-EST2023-POP-04.xlsx.

U.S. Geological Survey, 2021, Southwest Gravity Program absolute-gravity database (updated 2023-10-31): U.S. Geological Survey data release, https://doi.org/10.5066/P984HN6J.

U.S. Geological Survey, 2023, StreamStats: U.S. Geological Survey website, accessed October 15, 2023, at https://streamstats.usgs.gov/ss.

U.S. Geological Survey, 2024, USGS 3D Elevation Program digital elevation model: U.S. Geological Survey data, accessed January 5, 2024, at https://elevation.nationalmap.gov/arcgis/rest/services/3DEPElevation/ImageServer.

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