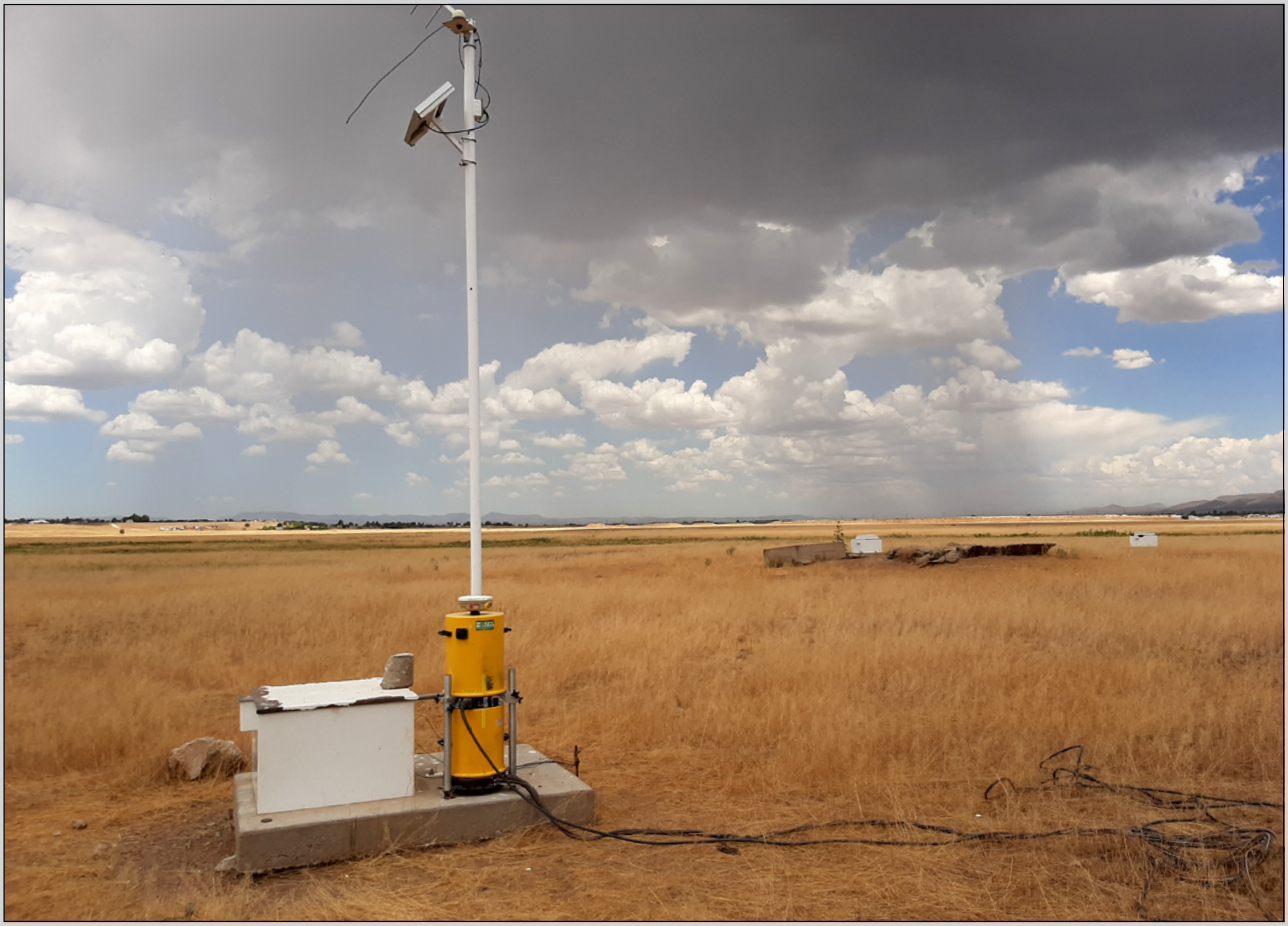
Prepared in Cooperation with the City of Prescott, the Town of Prescott Valley, and Salt River Project

# Aquifer Storage Change, 2018–2021, in the Big Chino Subbasin, Yavapai County, Arizona



Scientific Investigations Report 2022–5117

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

**Cover.** Photograph of an absolute gravity meter in the Paulden, Ariz., area at Arizona Department of Water Resources monitoring well B-17-02 S04DBC3 PZ1. U.S. Geological Survey photograph taken by Jeffrey R. Kennedy, July 6, 2020.

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U.S. Geological Survey, Reston, Virginia: 2023

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## Acknowledgments

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# Contents



# Figures



# Tables

# Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| | Flow rate | |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |
| cubic foot per second ($ft^3$/s) | 0.02832 | cubic meter per second ($m^3$/s) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |

International System of Units to U.S. customary units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Volume | |
| cubic meter ($m^3$) | 264.2 | gallon (gal) |
| cubic meter ($m^3$) | 35.31 | cubic foot ($ft^3$) |
| | Acceleration | |
| microGal (μGal) | 10 | nanometer per second squared (nm/$s^2$) |
| microGal (μGal) | $0.328\times10^{-9}$ | foot per second squared (ft/$s^2$) |

# Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) GEOID12B.

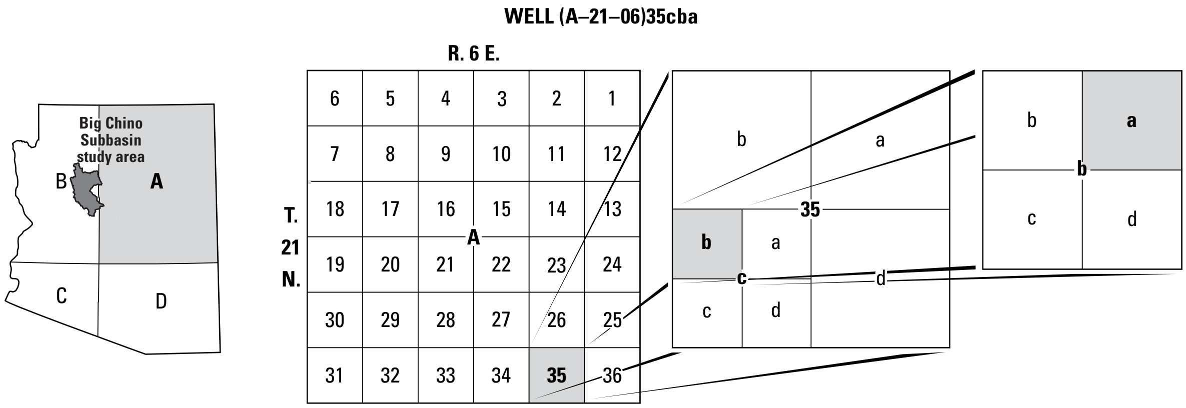
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) 2011 (epoch 2010.00).

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

# Supplemental Information

Water years begin on October 1 of the previous year, so water year 2018 covers October 1, 2017, through September 30, 2018.

**ARIZONA WELL-NUMBERING SYSTEM**




**Quadrant A, township 21 north, range 6 east, section 35, quarter section c, quarter section b, quarter section a**

The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants and are designated by capital letters A, B, C, and D in a counterclockwise direction beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes. In the example shown, well number (A–21–06)35cba designates the well as being in the northeast quarter, northwest quarter, southwest quarter, section 35, township 21 north, and range 6 east (NE1/4, NW1/4, SW1/4, sec. 35, T. 21 N., R. 6 E.).

# Abbreviations

| | |
|---|---|
| ADWR | Arizona Department of Water Resources |
| BCWR | Big Chino Water Ranch |
| CSAMT | controlled-source audio-frequency magnetotellurics |
| GPS | Global Positioning System |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| SMAP | Soil Moisture Active Passive (NASA) |
| USGS | U.S. Geological Survey |

# Aquifer Storage Change, 2018–2021, in the Big Chino Subbasin, Yavapai County, Arizona

By Jeffrey R. Kennedy

## Abstract

This report updates groundwater-storage and groundwater-level trends presented in U.S. Geological Survey (USGS) Scientific Investigations Report 2019–5060, in the Big Chino Subbasin, Yavapai County, Arizona. This earlier geophysical investigation of groundwater-storage change in the Big Chino Subbasin was conducted by the U.S. Geological Survey, in cooperation with the City of Prescott, the Town of Prescott Valley, and the Salt River Project from 2010 to 2017 to understand groundwater-level and groundwater-storage changes. Conclusions were based on precipitation, streamflow, groundwater level, and repeat microgravity data; the latter is a direct measurement of groundwater-storage change. This report focuses on the southern part of the Big Chino Subbasin for water years 2018–2021. These more recent data show relatively small changes in groundwater storage, consistent with the earlier monitoring presented in U.S. Geological Survey Scientific Investigations Report 2019–5060. In the Big Chino Water Ranch area, water levels have increased gradually owing to discontinued pumping for irrigation during summer months, and an in-channel recharge event in summer 2021. In the Paulden, Arizona, area, gradual water level declines have continued a downward trend that started in the 1990s. Seasonal variation is present in the Paulden area, with higher water levels in the winter months when pumping for irrigation and agricultural use is reduced. Two wells showed groundwater-level increases consistent with in-channel recharge in 2018 and 2021, whereas groundwater levels in a well screened in the deeper, confined to semi-confined carbonate aquifer showed no such discrete recharge events. In the area west of Big Chino Wash and east of the Juniper Mountains and Santa Maria Mountains, groundwater levels continued long-term declines, but storage changes were minimal.

## Introduction

The Big Chino Subbasin (fig. 1) is a groundwater basin in north-central Arizona that includes the Verde River headwaters in Yavapai County. The southern part of the subbasin, the focus of this report, consists of alluvial basins in the Big Chino and Williamson Valleys bounded by sedimentary and igneous rocks, with interbedded volcanic units (fig. 2). The Verde River, one of the major perennial rivers in Arizona, emanates from the subbasin. Verde River base flow relies on groundwater discharge, including discharge from the upper Verde River springs, believed to be a discharge zone of groundwater from basin-fill and Paleozoic carbonate aquifers in the Big Chino Subbasin (Blasch and others, 2006; Beisner and Jones, 2020). Ephemeral streams in the subbasin provide some recharge to the groundwater system, especially in years with high precipitation. Runoff, and therefore ephemeral-stream recharge, is near zero in dry years. Recharge also occurs at higher elevations in the surrounding mountain ranges, but land-surface recharge at the basin floor is likely minimal, owing to low precipitation and high evapotranspiration demand. Communities south of the Verde River headwaters, including Prescott and Prescott Valley, Arizona, are considering augmenting their water supplies by pumping groundwater from the Big Chino Subbasin (City of Prescott, 2022). However, downstream users of Verde River flows, including greater Phoenix area water provider Salt River Project, are concerned that Big Chino Subbasin groundwater withdrawals may eventually reduce the flow in the Verde River and their water availability (City of Prescott, Town of Prescott Valley, Salt River Valley Water Users Association, and Salt River Project Agricultural Improvement and Power District, 2012).

### Purpose and Scope

The purpose of this report is to update groundwater-storage and groundwater-level trends presented in Kennedy and others (2019a). The study area includes the Big Chino and Williamson Valley parts of the Big Chino Subbasin, Yavapai County, Arizona. Our analyses focus on water years 2018 to 2021 (water years begin on October 1 of the previous year, so water year 2018 covers October 1, 2017, through September 30, 2018). The groundwater-storage trends record current conditions under the current minimal pumping regime in the study area and will be useful for comparison to future trends if the amount of pumping changes in the future.

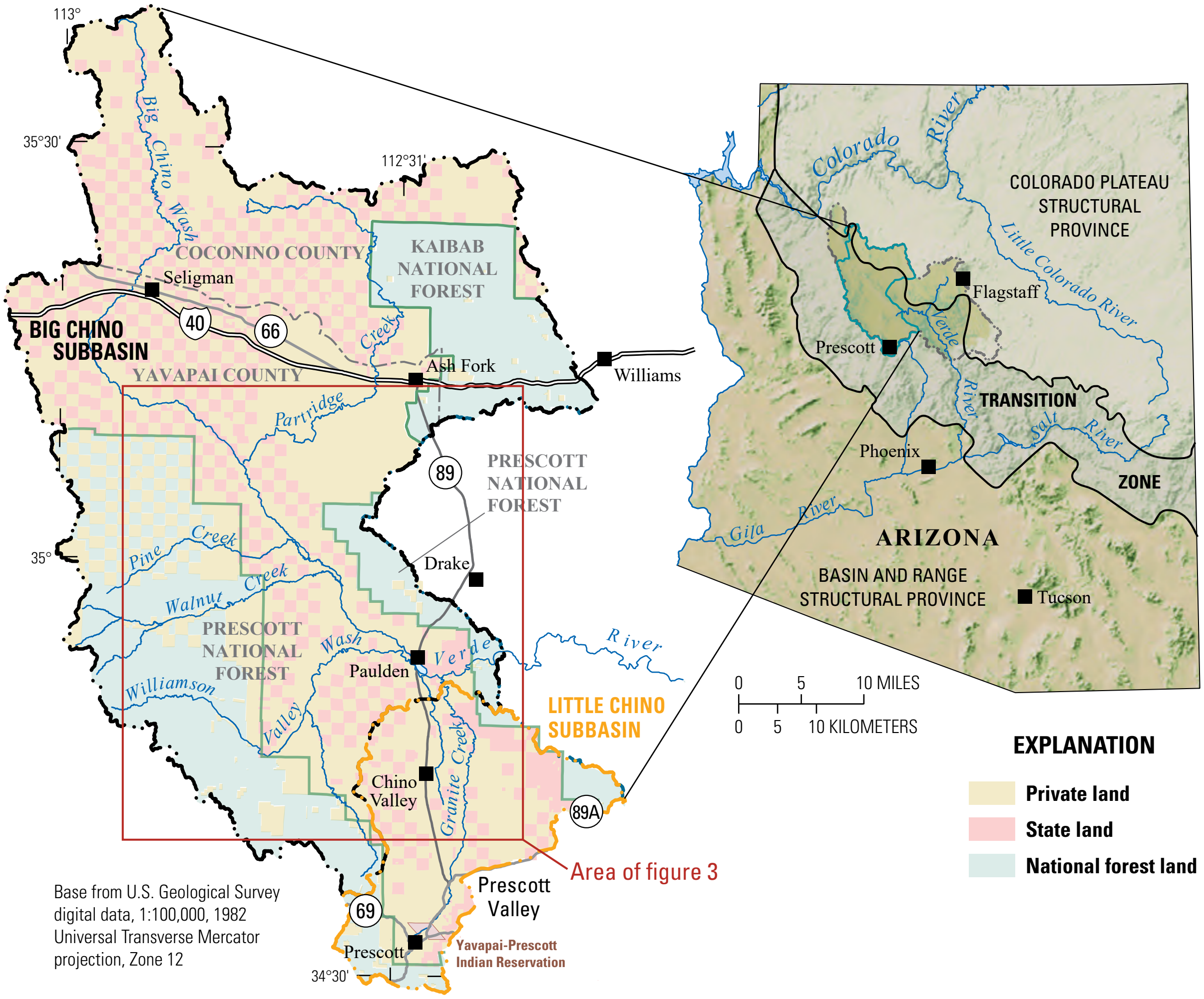



**Figure 1.** Map showing the location of the Big Chino and Little Chino Subbasins in north-central Arizona, including structural provinces and land ownership. Modified from Blasch and others, 2006.

This report summarizes aquifer-storage change, determined from repeat microgravity measurements, from 2018 to 2021 at 15 stations (fig. 3; table 1). Repeat microgravity data for 18 additional stations are presented in Kennedy and others (2019a) and the accompanying data release (Kennedy and others, 2019b). Repeat-microgravity data for this report are published in the Southwest Gravity Program Absolute Gravity Database (U.S. Geological Survey, 2021). Groundwater data are published by the U.S. Geological Survey (2022) and the Arizona Department of Water Resources (ADWR, 2021).

## Previous Investigations

Several previous hydrologic investigations of the Big Chino Subbasin have been carried out by the U. S. Geological Survey (USGS), the State of Arizona and other organizations. A selection of published studies are summarized here. For a comprehensive overview, refer to Blasch and others (2006) and Kennedy and others (2019a). A hydrogeologic framework of the subbasin based on geophysical methods, including the distribution of volcanic units and depth to bedrock based on aeromagnetic and gravity datasets, was completed by Langenheim and others (2005). A water-budget conceptualization for the subbasin, building on several previous water budgets, was completed by Blasch and others (2006). The most recent USGS groundwater-modeling project in the region, covering most of northern Arizona, concluded that more information about aquifer extents and aquifer-storage properties was needed to reduce modeling uncertainty and improve estimates of storage change in the Big Chino Subbasin (Pool and others, 2011). Estimates of storage change in the subbasin have typically been extrapolated from water-level changes assuming unconfined conditions in one or more index wells; such estimates require an assumed value of specific yield. In contrast, the repeat microgravity aquifer-storage-change measurements presented in this report are independent of specific yield.

In addition to Kennedy and others (2019a), recent studies have characterized Big Chino Subbasin geologic structure and geochemistry. A controlled-source audio-frequency magnetotellurics (CSAMT) investigation (Macy and others,

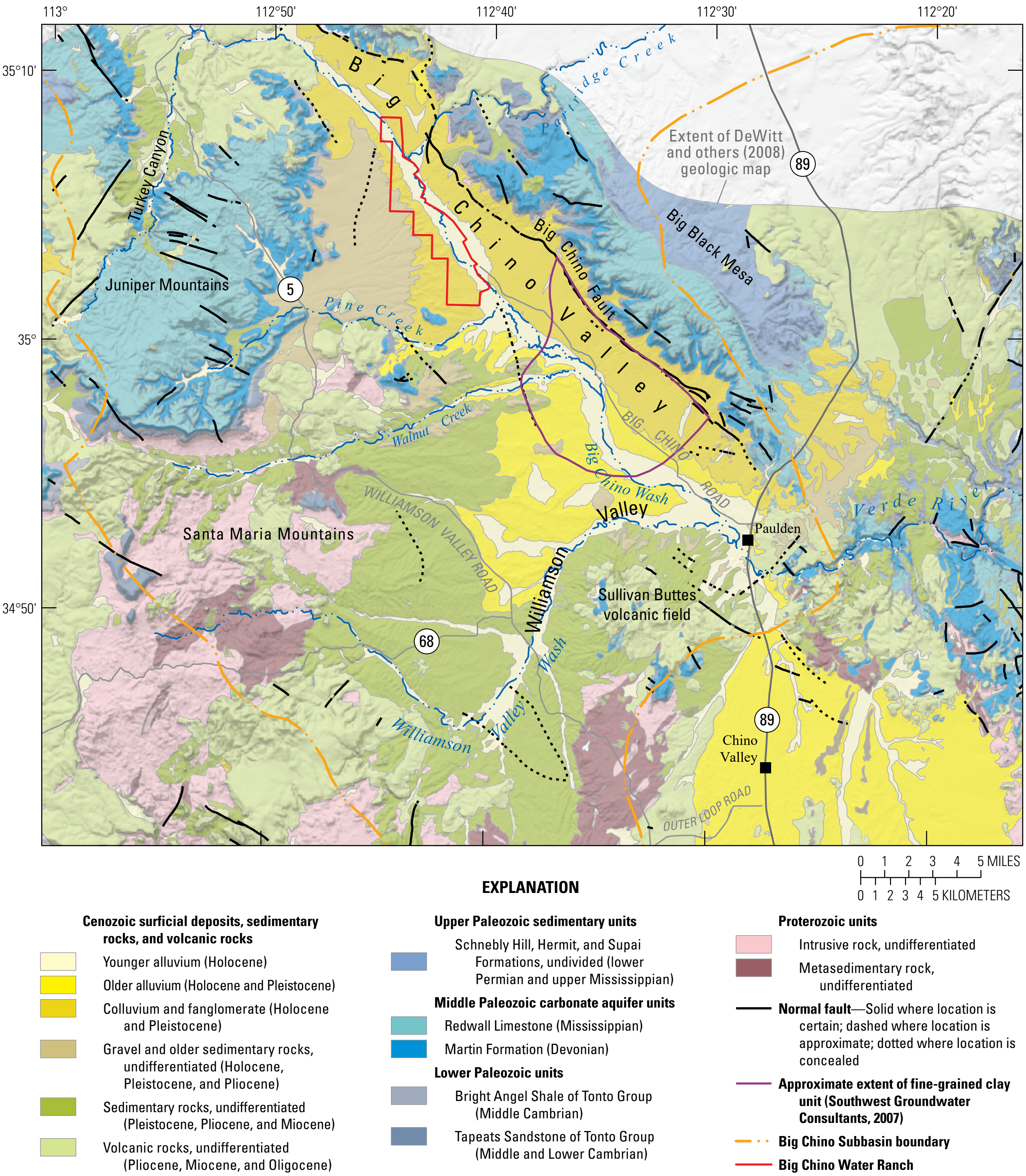



**Figure 2.** Map showing the area of this study of the Big Chino Subbasin in north-central Arizona, including geology, faults, and major geographic features. Modified from Kennedy and others, 2019a.

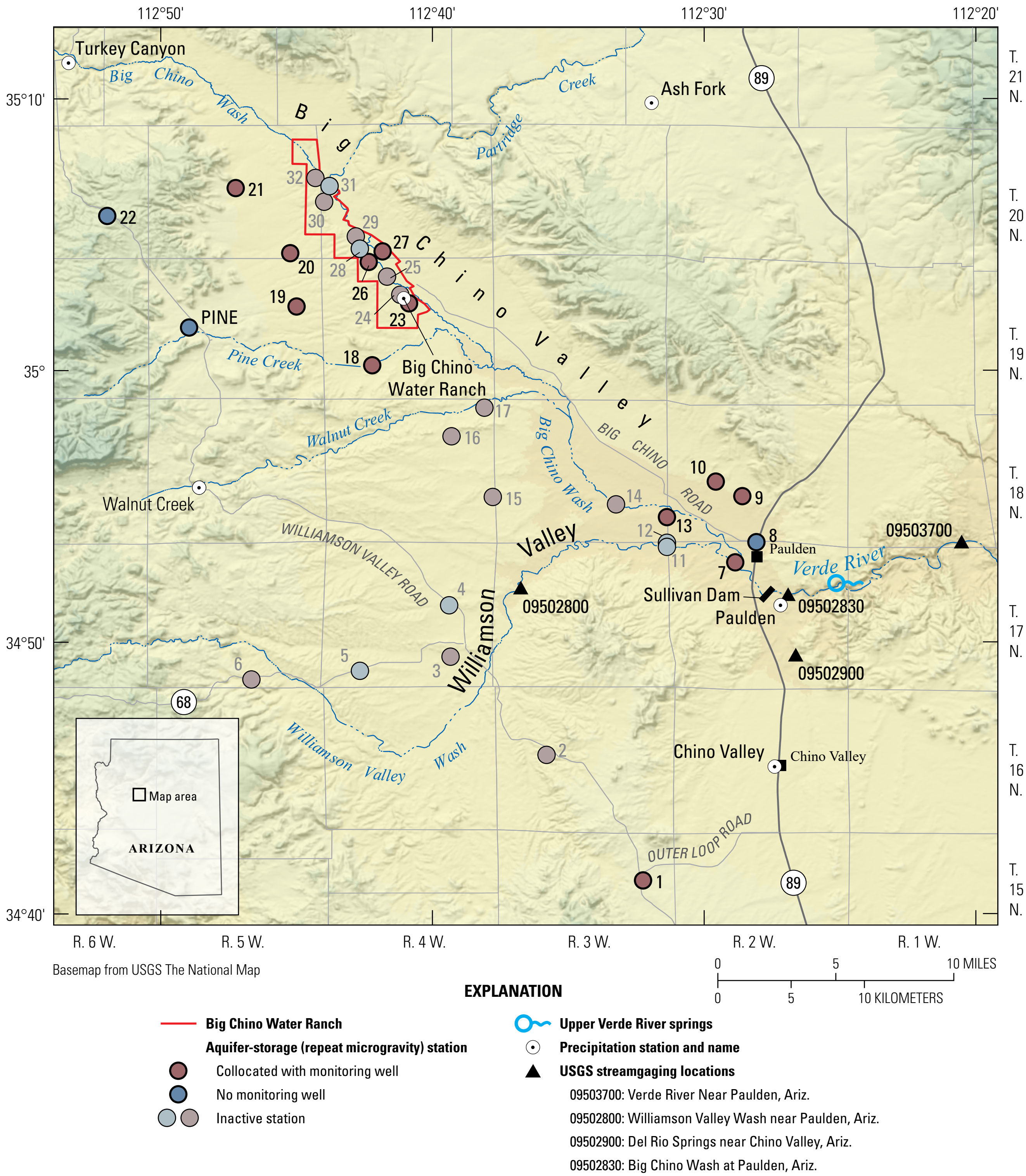



**Figure 3.** Map showing monitoring locations for this study in the Big Chino Subbasin in north-central Arizona. Data from inactive stations are presented in U.S. Geological Survey (USGS) Scientific Investigations Report 2019–5060 (Kennedy and others, 2019a). See figure 1 for map location. See table 1 for station information. Figure modified from Kennedy and others, 2019a.

**Table 1.** Stations used in the storage-change analysis for water years 2018–2021 in the Big Chino Subbasin, Yavapai County, Arizona.

[Station numbers were established in U.S. Geological Survey (USGS) Scientific Investigations Report 2019–5060 (Kennedy and others, 2019a). Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2017, for water year 2018). GWSI, Groundwater Site Inventory System; Arizona Department of Water Resources (ADWR, 2021); AZ014, ADWR site; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; Elevation refers to the distance above the vertical datum; ft, feet; NA, repeat microgravity station without co-located monitoring well; —, does not exist]

| Station no. (fig. 3) | Site name | Agency code[a] | USGS site number | Gravity-station coordinate NAD 83 (2011) epoch 2010.00, NAVD 88/GEOID12B | | |
|---|---|---|---|---|---|---|
| | | | | Latitude | Longitude | Elevation (ft) |
| | | | Williamson Valley Wash area | | | |
| 1 | B-15-03 11DDB | AZ014 | 344122112322201 | 34.68982[b] | −112.538463[b] | 5,072 |
| | | | Paulden area | | | |
| 7 | B-17-02 S04DBC3 PZ1 | AZ014 | 345300112283701 | 34.882353 | −112.478682 | 4,365.25 |
| 8 | PAULDEN | — | NA | 34.89570[b] | −112.46788[b] | 4,403 |
| 9 | B-18-02 28ABA | USGS | 345528112283201 | 34.923927 | −112.476498 | 4,493.06 |
| 10 | B-18-02 20DBB | USGS | 345557112294501 | 34.931629 | −112.496959 | 4,495.87 |
| 13 | B-18-02 31BCB | USGS | 345423112311901 | 34.904382 | −112.523015 | 4,400.21 |
| 14 | B-18-03 26BBC1 | USGS | 345518112332701 | 34.92169[c] | −112.55823[c] | 4,412.6[c] |
| | | | Area west of Big Chino Wash | | | |
| 18 | B-19-04 29DAB | USGS | 350016112421001 | 35.00422[b] | −112.70354[b] | 4,646 |
| 19 | B-19-05 13BBA | AZ014 | 350224112445801[d] | 35.040264 | −112.749957 | 4,902.62 |
| 20 | B-20-05 35DAD | USGS | 350423112451101 | 35.072975 | −112.753834 | 4,832.31 |
| 21 | B-20-05 15CCC | USGS | 350647112471101 | 35.112913 | −112.787294 | 4,979.24 |
| 22 | JUNIPER | — | NA | 35.095805 | −112.866067 | 5,783.33 |
| PINE | PINE | — | NA | 35.026049 | −112.811470 | 5,268.26 |
| | | | Big Chino Water Ranch area | | | |
| 23 | B-19-04 10CCB2 | AZ014 | 350232112404901 | 35.042192 | −112.680942 | 4,525.83 |
| 26 | B-19-04 05ABA1 | USGS | 350403112421801 | 35.067584 | −112.705678 | 4,569.24 |
| 27 | B-20-04 33CBD2 | AZ014 | 350427112414701 | 35.074071 | −112.697167 | 4,558.17 |

[a]Agency code refers to code in USGS-GWSI database.

[b]Position estimated from orthorectified imagery.

[c]Coordinates in Kennedy and others (2019a) are for the gravity station 1,620 ft southeast of the monitoring well.

[d]Site was referenced as USGS 345338112311801 in USGS Scientific Investigations Report 2019–5060 (Kennedy and others, 2019a).

2019) confirmed the presence of a relatively deep sedimentary basin along Big Chino Valley northwest of Paulden, Arizona, and complicated bedrock geology with abundant faulting in the Verde River headwaters area east of Paulden. A geochemical characterization of the Big Chino Subbasin (Beisner and Jones, 2020) found significant differences in water chemistry between wells representing basin-fill aquifers and wells and springs representing the deeper Paleozoic carbonate aquifer. Of the 11 samples from basin-fill wells, 5 contained significant amounts of tritium, indicating a modern (post-1950) recharge component of groundwater. The remaining basin-fill wells, and all nine of the wells completed in the underlying carbonate aquifer, had little to no tritium and much older radiocarbon dates, as old as 1,000 years (yrs). Using noble gas analysis, the recharge elevation of source water in many of the groundwater samples indicated recharge was occurring at higher elevations outside of the study area.

## Setting

The study area lies within the southern part of the Big Chino Subbasin (ADWR, 2010) in the transition zone between the Basin and Range and Colorado Plateau physiographic provinces (Wilson and Moore, 1959), which features extensive deformation caused by faulting and uplift resulting from periods of extension and compression. The southern part of the Big Chino Subbasin includes two connected alluvial-fill basins, one in the Big Chino Valley west and northwest of the community of Paulden beneath Big Chino Wash that is relatively deep and underlain primarily by Paleozoic sedimentary rocks, and a shallower basin in Williamson Valley west and southwest of Paulden beneath Williamson Valley Wash, underlain primarily by Proterozoic igneous and metamorphic rocks and bounded by several small faults and Tertiary volcanic formations (DeWitt and others, 2008). The Big Chino Valley part of the subbasin is bounded to the northeast by the Big Chino Fault (fig. 2), a northwest-southeast trending normal fault with little to no vertical displacement at its southeast end and maximum displacement of about 3,500 ft occurring to the northwest.

Nearly all water use in the subbasin is supplied by groundwater. Water is used for residential and agricultural use, including small vegetable farms, turf sod, and livestock. Average 2013–2016 water use in the Big Chino Valley, Paulden, Williamson Valley, and Walnut Creek areas was 3,481 acre-feet per year (Kennedy and others, 2019a), but this number varies widely because of variation in agricultural pumping.

Groundwater outside the study area in the northern part of the Big Chino Subbasin occurs primarily at depths greater than several hundred feet below land surface in Paleozoic sedimentary rocks. Groundwater development in this northern area is limited primarily to small water providers in Ash Fork and Seligman, Arizona (Arizona Corporation Commission, 2018), and rural wells pumping less than 35 gallons per minute. Groundwater data are sparse in this region, but groundwater flow is generally to the north towards springs and seeps in the Grand Canyon (ADWR, 2010). To the south of the study area, groundwater flows generally south to north through bedrock aquifers and the alluvial aquifer in the Little Chino Subbasin (fig. 2), contributing base flow to the Verde River (Blasch and others, 2006).

The Verde River, with headwaters just southeast of Paulden, is the primary perennial surface-water feature in the Big Chino Subbasin. Short reaches of Williamson Valley Wash north (downstream) of Williamson Valley Road are also perennial, and several small springs and seeps are found in the surrounding mountains. The Verde River begins about a mile below Sullivan Dam (fig. 3), where several springs (the upper Verde River springs) continuously discharge into the channel. Sullivan Dam impounds a sediment-filled reservoir just south of Paulden that holds a small amount of water when there is storm runoff in Big Chino Wash.

Surface-water runoff in response to precipitation drains through Big Chino Wash in the Big Chino Valley. The Big Chino Valley is roughly 28 miles (mi) long and ranges in width from 2 mi in the northwest to approximately 6 mi at its terminal end to the southeast, near Paulden. Major tributaries to Big Chino Wash in the Big Chino Valley include Partridge Creek, Walnut Creek, and Williamson Valley Wash. The alluvial-fill part of the Big Chino Subbasin is smaller than the watershed. The total watershed area at the confluence of Big Chino Wash and Williamson Valley wash is about 1,790 square miles ($mi^2$). Of this, 554 $mi^2$ in the Partridge Creek watershed, 480 $mi^2$ in the upper part of the subbasin (above the Big Chino Wash-Turkey Canyon confluence), and 82 $mi^2$ in the Walnut Creek watershed are largely outside the alluvial-fill subbasin (areas obtained from the USGS Streamstats application, USGS, 2018). There is approximately 225 $mi^2$ of Tertiary to Quaternary sedimentary rocks and alluvial fill mapped in the Big Chino Wash part of the subbasin and 150 $mi^2$ in the Williamson Valley Wash part of the subbasin (DeWitt and others, 2008). Major mountain ranges within the subbasin include Big Black Mesa to the northeast of Big Chino Valley and drained by Partridge Creek and the upper part of Big Chino Wash, the Juniper Mountains and the Santa Maria Mountains to the west of Big Chino Valley, drained by Pine Creek, Walnut Creek, and Williamson Valley Wash, and the Sullivan Buttes volcanic field, located between Williamson Valley Wash and the lower part of Big Chino Wash (fig. 2).

# Methods

Hydrologic data analyzed in this study include measurements of precipitation, streamflow, groundwater levels, and aquifer-storage change. Data collected by the USGS were augmented with additional data obtained from ADWR, the National Oceanic and Atmospheric Administration (NOAA), and Yavapai County Flood Control District (Mark Massis, Yavapai County Flood Control District, written commun., Dec. 21, 2021).

Precipitation data from 4 stations (NOAA, 2021) were evaluated for the magnitude of annual variability and in relation to groundwater level and storage changes. Discharge was measured at three USGS streamgaging stations (USGS, 2022) in the study area: Williamson Valley Wash near Paulden (station 09502800), Big Chino Wash near Paulden (station 09502830), and Verde River near Paulden (station 09503700). The drainage area for the Williamson Valley Wash streamgage is 255 $mi^2$, and the period of record is 1965–1985 and 2001–2022. The drainage area for the Big Chino Wash streamgage is 1,798 $mi^2$, and the period of record is 2018–2022. The drainage area for the Verde River streamgage is 2,507 $mi^2$, and the period of record is 1963–2022 (USGS, 2022). The Verde River streamgage drainage area includes the Big Chino Wash streamgage drainage area, which includes the Williamson Valley Wash streamgage drainage area. The Verde River and Big Chino Wash streamgage drainage areas include about 360 $mi^2$ of non-contributing area in Aubrey Valley west of Seligman.

Mean monthly base flow at the Verde River near Paulden station was calculated using the automated procedure HYSEP for hydrograph separation (Sloto and Crouse, 1996), following the same methodology as Blasch and others (2006) and Kennedy and others (2019a). The fixed-interval method was used, which has the effect of connecting lines through the low points in the hydrograph, thereby eliminating stormflow peaks from the discharge record.

## Groundwater-Level Monitoring

Groundwater levels are monitored in the Big Chino Subbasin by USGS (USGS, 2022) and ADWR (ADWR, 2021). USGS recorded groundwater levels at 6-hour intervals in 4 wells using vented pressure transducers. Discrete groundwater-level measurements at these wells were also recorded. ADWR collects continuous groundwater-level data at 6-hour intervals at additional wells. In addition, ADWR makes annual or semiannual measurements at about 88 index wells in and around the Big Chino Subbasin.

## Aquifer-Storage Monitoring

Changes in aquifer storage were monitored using the repeat microgravity method. The Earth's gravitational field, as described by Newton's law of gravitation, varies temporally because of changes in subsurface and atmospheric mass. In groundwater systems, changes in the amount of water stored in aquifers or in the unsaturated zone between an aquifer and the land surface cause changes in the magnitude of Earth's gravity. Measurements of changes in gravity ("repeat microgravity") have proven useful for many applications, including mapping aquifer storage change (Pool and Anderson, 2008), determining specific yield (Pool and Eychaner, 1995), resolving total water-storage-change into various partitions (Creutzfeldt and others, 2010), and monitoring the depth of the wetting front at an artificial recharge facility (Kennedy and others, 2014).

Gravity data are converted from acceleration, in units of microgal (µGal), to a thickness of free-standing water using the horizontal infinite-slab model. Using this approximation, also known as the Bouguer slab model, 12.77 µGal of gravity change is equivalent to 1 ft of free-standing water, regardless of aquifer porosity or depth to groundwater (Torge, 1989). The gravity method thus has the advantage of not being sensitive to the aquifer-storage coefficient, because it directly measures the change in the mass of water stored in the aquifer. In contrast, groundwater levels measured in wells require a storage-coefficient estimate to convert the measured change in water level to the change in aquifer storage; an unconfined aquifer with high specific yield may store a large amount of water with a relatively small change in water level, whereas a confined aquifer with a low storativity (storage coefficient) may show a much larger change in water level in a well for the same change in storage.

Absolute-gravity data were collected using an A-10 free-fall absolute gravity meter (Micro-g LaCoste, Inc., Lafayette, Colo., https://microglacoste.com/). This meter measures the position of a falling mass using a length scale determined by a laser interferometer and a time scale determined by a rubidium oscillator. Standard corrections for air pressure, Earth tide, and polar motion were applied (Kennedy and others, 2021). For further information, refer to Kennedy and others (2019a). Station positions were located using a differential Global Positioning System (GPS) receiver mounted on top of the A-10 absolute-gravity meter. GPS occupations were between 30 and 60 minutes. Station positions in the North American Datum of 1983 (NAD 83) 2011 (epoch 2010.00) datum were determined using the Online Positioning User Interface (National Geodetic Survey, 2021). Gravity data are published in an online database (U.S. Geological Survey, 2021). Storage changes are measured relative to the initial observation at a station.

### Soil-Moisture Correction

Gravity data provide an integrative measurement of all water-storage changes in the subsurface, from the land surface to the water table. Mass changes below the water table were considered negligible, as changes that occur through compression/decompression of an aquifer are generally too small to cause a measurable change in gravity. The effect of soil moisture variation on the gravity measurements was estimated using continuous root-zone time series from remote-sensing (satellite) products. The National Aeronautics and Space Administration (NASA), National Snow and Ice Data Center, Soil Moisture Active Passive (SMAP) Surface and Root Zone Soil Moisture Analysis Update (Reichle and others, 2021) provides soil moisture to 3.3-ft depth at 5.6 by 5.6-mi (9 by 9-kilometer [km]) spatial resolution at 3-hour intervals from 2015 through 2021 (fig. 4).

The SMAP root-zone soil moisture (volumetric water content) varies from 6.1 to 21.0 percent (cubic meter per cubic meter [$m^3/m^3$]; fig. 4), with an average 2018–2021 water year (data for 2021 are incomplete) soil moisture of 13.4 percent, higher than the 2010–2017 average, 7.7 percent. The daily departure from mean water content was converted to gravity units using a soil-moisture to gravity conversion factor, calculated using a digital elevation model by summing the gravitational attraction of a thin layer of water across the landscape (Kennedy and others, 2019a). The conversion factor varied from 28.4 to 46.3 µGal per meter of water across the 31 gravity stations used in the original 2010–2017 study. The soil-moisture gravity correction for each gravity measurement from 2018 to 2021 varied from 0.70 to 6.01 µGal (corrections are relative to the 2010–2017 mean). Uncertainty in the soil-moisture correction is estimated to be 20 percent of the maximum correction, or about 1.2 µGal.

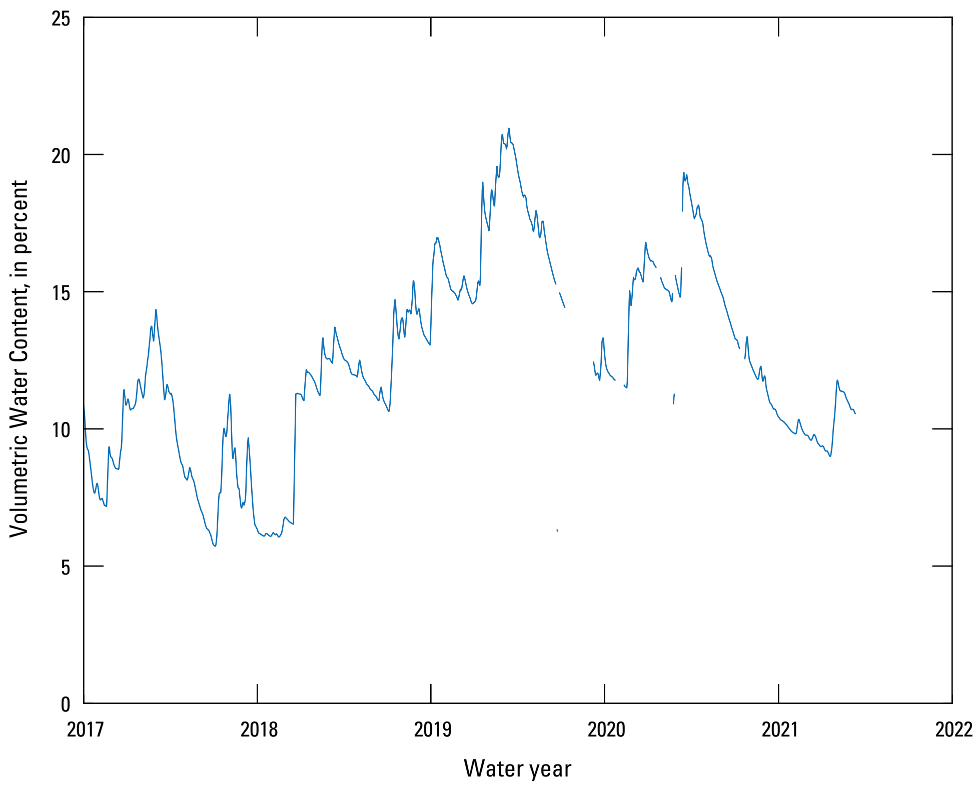



**Figure 4.** Graph of water-year time series showing root-zone soil-moisture satellite data used to correct gravity measurements from the Big Chino Subbasin in north-central Arizona for water years 2017–2021. Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2017, for water year 2018). Satellite data are from the National Aeronautics and Space Administration (NASA), National Snow and Ice Data Center, Soil Moisture Active Passive (SMAP) Surface and Root Zone So il Moisture Analysis Update (Reichle and others, 2021). Gaps represent periods of missing data.

# Results

Groundwater storage changes in the study area continue to be relatively small, consistent with the 2010–2017 period (Kennedy and others, 2019a). The following discussion focuses on the 2018–2021 period. For further discussion of aquifer-storage properties and groundwater-level trends, please refer to Kennedy and others, (2019a). Gravity-station numbering is maintained from Kennedy and others (2019a), but inactive stations (fig. 3) are not discussed in this report.

## Precipitation and Streamflow

Precipitation data were obtained for the Walnut Creek, Chino Valley, Paulden 2.3 SSE, and Ash Fork 4.9 SW stations (NOAA, 2021). Chino Valley and Ash Fork 4.9 SW had periods of missing data (the Ash Fork 4.9 SW station is not on figure 3 as it is north of the map area). Winter rainfall in 2019 and 2020, and summer rainfall in 2021 (fig. 5), caused substantial flow in ephemeral washes and increases in groundwater-level at some observation wells. At Walnut Creek, where the longest record is available, average annual rainfall for the 2018–2021 period was 14.7 inches per year (in/yr), below the 1964–2021 average for the period of record at this station, 15.4 in/yr (fig. 6*A*).

For the period of record for precipitation data and streamflow, conditions were generally wetter than average from the 1960s to 1990s, then drier than average from the 1990s through 2021 (fig. 6). Despite nearly average rainfall during the 2018–2021 period, estimated base flow discharge at the Verde River near Paulden streamgaging station (fig. 6*B*, station 09503700) was consistently below the 24.0 cubic feet per second ($ft^3/s$) average flow for the 1964–2021 period (average discharge was 24.2 $ft^3/s$ for the 1964–2017 period; Kennedy and others, 2019a). During the study period of 2018–2021, only one month, March 2020, had higher than average base flow. The months with the smallest departure from average (that is, the months that plot closest to zero in fig. 6*B*) are primarily the winter months January, February, and March, whereas the months with the greatest departure from average are the early summer months June and July.

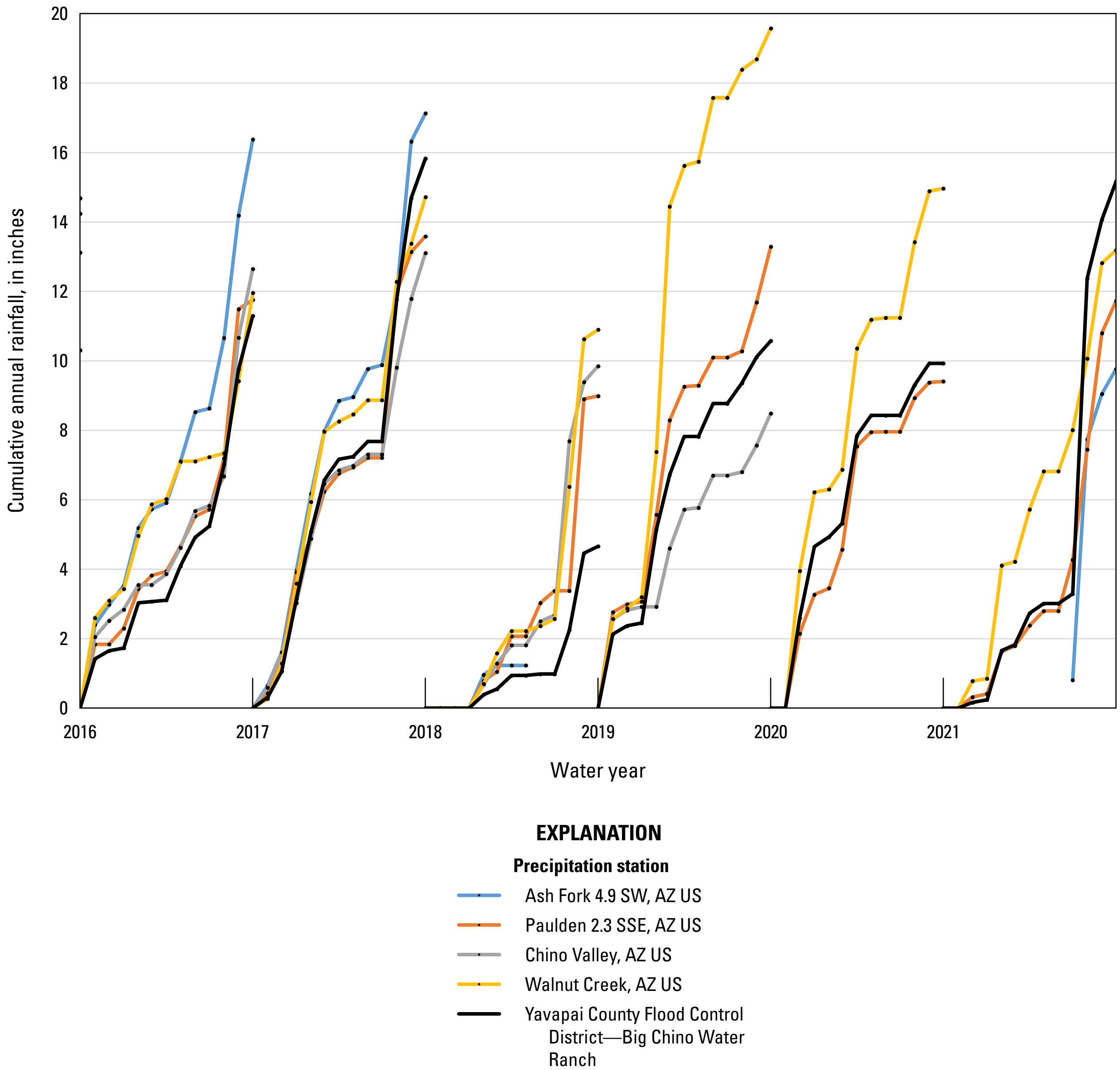



**Figure 5.** Graph showing precipitation at five stations in the Big Chino Subbasin in north-central Arizona for water years 2016–2021. Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2015, for water year 2016). Data for Ash Fork and Chino Valley were unavailable for 2019 and parts of other years. Precipitation data from National Oceanic and Atmospheric Administration (2021) and Yavapai County Flood Control District (Mark Massis, Yavapai County Flood Control District, written commun., Dec. 21, 2022). See figure 3 for station locations.

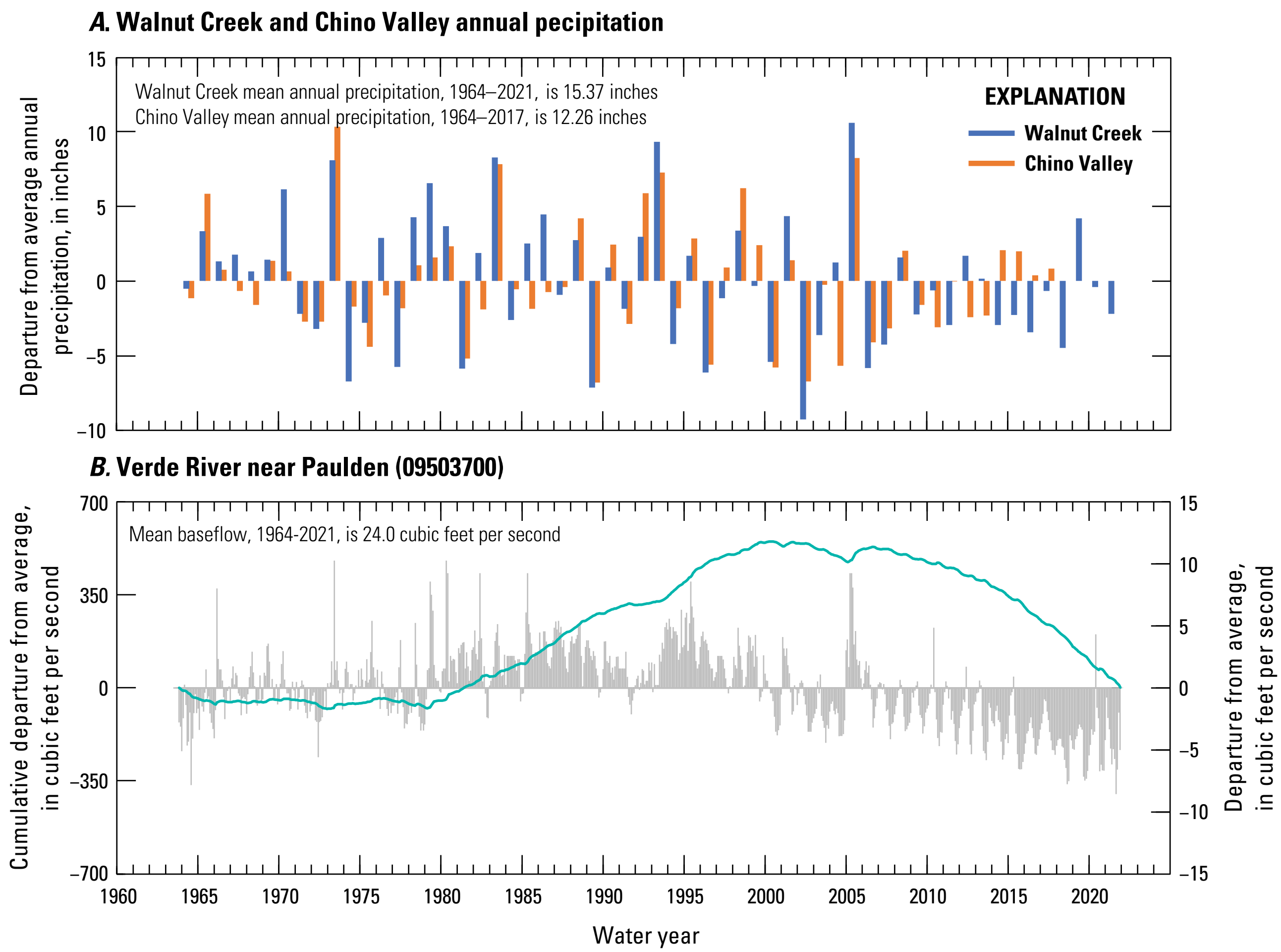



**Figure 6.** Graphs of mean annual precipitation (National Oceanic and Atmospheric Administration, 2021; Mark Massis, Yavapai County Flood Control District, written commun., Dec. 21, 2022) and monthly base flow at U.S. Geological Survey (USGS) streamgaging station Verde River near Paulden, Arizona (09503700) in the Big Chino Subbasin in north-central Arizona (USGS, 2022). *A*, Time series showing annual (water year) precipitation departure from average and cumulative departure from average. *B*, Hydrograph showing monthly base flow determined using HYSEP software (Sloto and Crouse, 1996) and cumulative departure from average for Verde River near Paulden. Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2009, for water year 2010). For location of streamgaging stations see figure 3. in, inch.

Streamflow was absent or nearly absent during most months at the two ephemeral-channel streamgaging stations, Big Chino Wash at Paulden (09502830) and Williamson Valley Wash near Paulden (05602800) (fig. 7). Periods of elevated flow occurred in winter 2019, spring 2020, and summer 2021. No summer monsoon flows (July, August, and September) were recorded in 2019 or 2020; the only sustained flows were in 2021.

## Groundwater-Level Change and Storage Change

Repeat microgravity data were collected at 15 stations (table 1). Groundwater-level data were available at 12 of these stations (fig. 8). Like the initial analysis (Kennedy and others, 2019a), storage changes are generally too small to accurately estimate specific yield based on the relation between storage change and groundwater-level change. Uncorrelated storage and groundwater-level change is an indication that groundwater-levels at a well may indicate confined or semi-confined conditions, and (or) large changes in unsaturated-zone storage (see Kennedy and others, 2019a, for further discussion of confining conditions in the subbasin). Storage changes are calculated relative to the initial measurement at each station, which in some cases is prior to the start of data shown in figure 8 (at these stations, the initial data point shown on fig. 8 is a non-zero value). Refer to Kennedy and others (2019a) and USGS (2021) for the complete time series.

In the Williamson Valley Wash area, monitoring continued at only one location (station 1 of fig. 8). Groundwater levels rose in 2020 and 2021 relative to the low (since data collection began in 1999) in 2019, but groundwater-level dynamics are likely poorly represented by

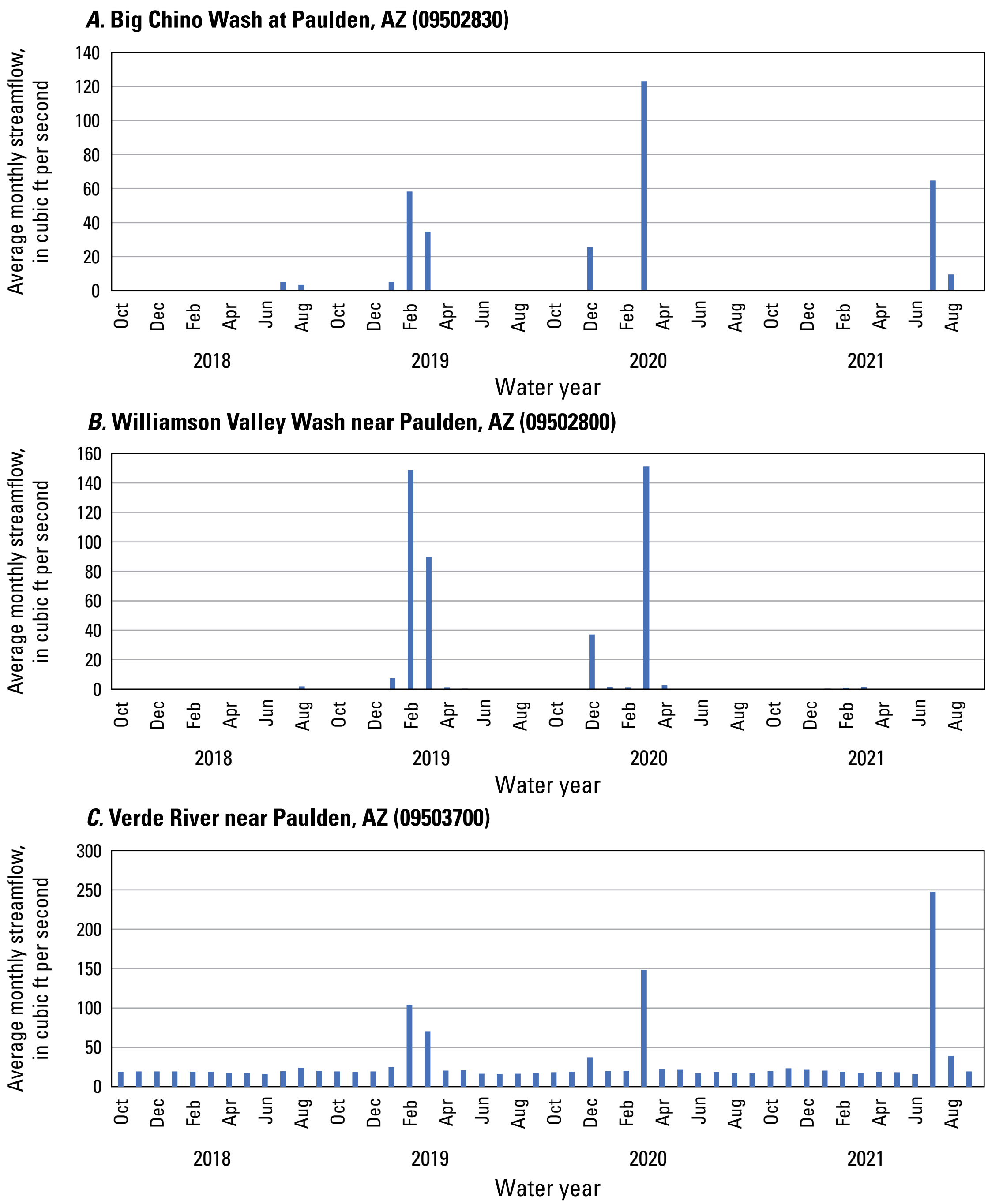



**Figure 7.** Graphs of average monthly streamflow, water years 2018–2021, at three U.S. Geological Survey (USGS) streamgaging stations in the Paulden, Arizona, area. Streamflow was absent or nearly absent during most months at the two ephemeral-channel streamgaging stations of Big Chino Wash and Williamson Valley Wash (USGS, 2022). Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2017, for water year 2018). See figure 3 for location of gaging stations.

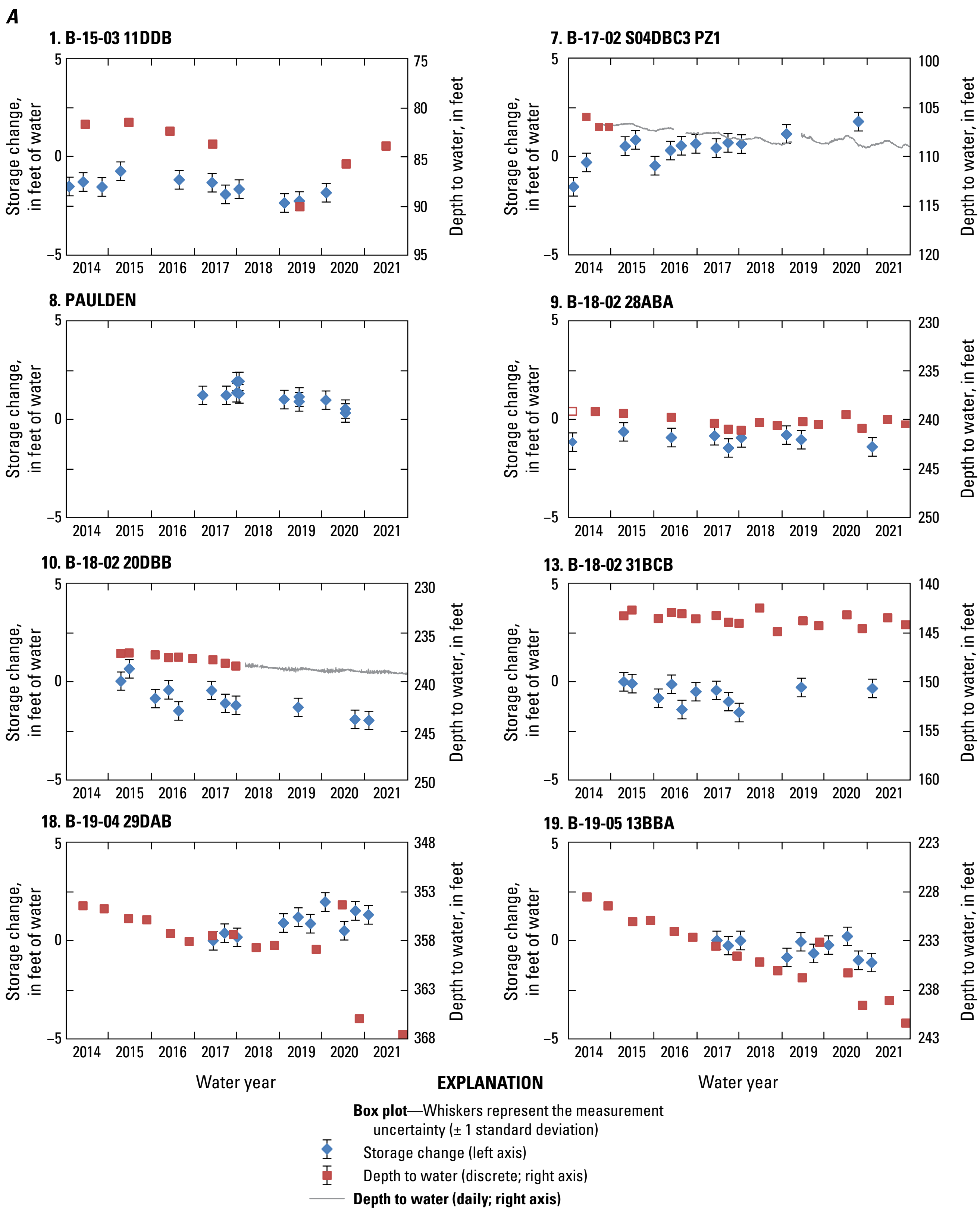



**Figure 8.** Graphs showing storage change and groundwater-level change (where applicable) by water year at locations in the Big Chino Subbasin in north-central Arizona. No water-level data were collected at stations 8, 22, and PINE. *A*, Stations 1, 7–10, 13, 18, and 19 in the Williamson Valley Wash, Paulden, and west of Big Chino Wash areas. *B*, Stations 20–22, PINE, 23, 26, and 27 in the areas west of Big Chino Wash and Big Chino Ranch. Year is start (October 1 of previous year) of indicated water year (for example, October 1, 2009, for water year 2010). See table 1 for explanation of station numbers. See figure 3 for index map of station locations. Error bars on gravity measurements represent the measurement uncertainty (1 standard deviation, about 10 μGal).

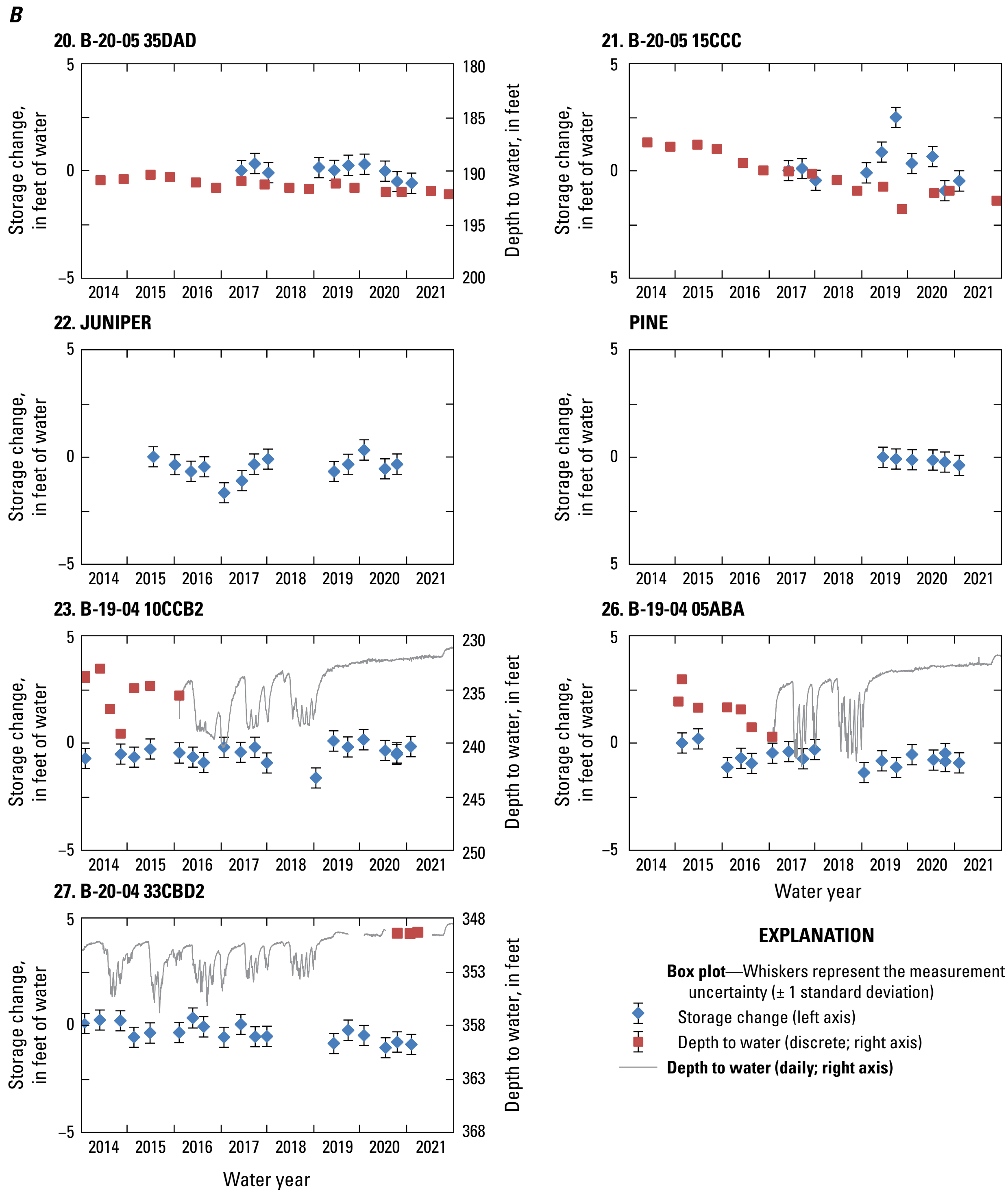



**Figure 8.**—Continued

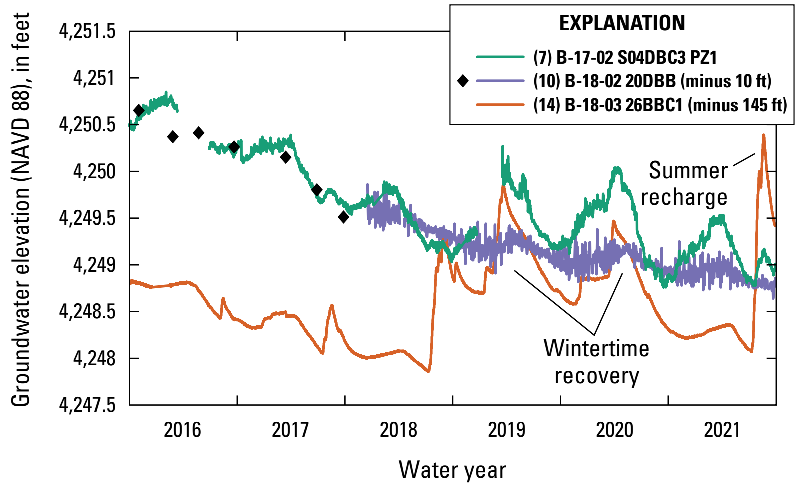



**Figure 9.** Hydrograph showing groundwater levels at stations 7, 10, and 14 in the Paulden area, Big Chino Subbasin, Yavapai County, Arizona. Groundwater elevations for B-18-03 26BBC1 and B-18-02 20DBB were shifted downward by the indicated amount to plot on the same scale as B-17-02 S04DBC3. Note: site B-18-03 26BBC1 is site number 345518112332701 (USGS, 2022). See table 1 for further station information.

annual sampling at this well. Several residential-use wells nearby pump groundwater and could influence groundwater levels. Storage at this location also increased slightly in 2020. In the Paulden area (stations 7, 8, 9, 10, 13 of fig. 8), storage and groundwater levels were generally steady. At station 7, gravity measurements indicate an upward trend, opposite to the slightly downward trend in groundwater levels. This likely arises because the water-level record at this well represents the deeper confined to semi-confined carbonate aquifer (Beisner and Jones, 2020). Satellite root-zone soil moisture (fig. 4) indicates elevated soil moisture during this period, and at this location the gravitational effect of soil moisture may be underestimated because the station is in an often-inundated low area, which may be inadequately represented in the satellite product. Finally, site access to this station is often impossible and data are insufficient. The remaining four gravity stations in the Paulden area showed little overall change. Trends were either steady (stations 9, 13 of fig. 8) or slightly declining (stations 8, 10 of fig. 8).

In the Paulden area groundwater levels show seasonal fluctuations, with generally higher levels in winter months when pumping for irrigation and agriculture is reduced. The declining trend—apparently less in the most recent years, likely related to the decline in storage from the last large recharge event in 2004–2005 (Kennedy and others, 2019a)—continues a longer-term downward trend in the Paulden area starting in the 1990s (Kennedy and others, 2019a). During dry periods (2016 through most of 2018 in fig. 9) the well nearest a recharge source, B-18-03 26BBC1 (fig. 3) at 900 ft northeast of Big Chino Wash, fluctuates consistently along with the other two wells, B-18-02 20DBB (station 10) and B-17-02 S04DBC3 PZ1 (station 7). During wet periods, and summer months in particular (end of water years 2018 and 2021 in fig. 9), groundwater levels increase rapidly at B-18-03 26BBC1, indicating recharge from surface water. Groundwater levels increased little or not at all at the other two wells, which, based on lack of tritium (derived from precipitation following nuclear weapons testing in the 1950s and 1960s) and groundwater age based on radiocarbon dating (17,000 to 6,000 years before present), represent the deeper Paleozoic aquifer (Beisner and Jones, 2020; well B-18-02 20DBB was not sampled, but is of similar depth [400 ft, compared to 410 ft] to well B-18-02 21BAB1, 1.0 mile to the northeast]). The similar seasonal and long-term water-level patterns between a well that represents the uppermost basin-fill aquifer, which receives surface water recharge (B-18-03 26BBC1), and two wells that represent the deeper carbonate aquifer, suggests hydrologic connectivity between these aquifer units.

In the area west of Big Chino Wash (stations 18, 19, 20, 21, 22, and PINE of fig. 8), groundwater-level declines have continued but groundwater storage has remained relatively constant, a relation that indicates a low aquifer storage coefficient (representative of confined or semi-confined conditions) and (or) large storage changes in the unsaturated zone (that is, water that the gravity meter "sees" but has not yet reached the aquifer). Stations 18, 19, 20, and 21 are co-located with wells with low-volume solar pumps; at 18 and 19 in particular, the water levels that depart from the long-term trend appear to be affected by pumping. Gravity data collected at station 21 were apparently affected by ground noise, or other unknown factors that contributed to the high values measured in 2019. Station 22 (JUNIPER), located on a Redwall Limestone outcrop, was established to evaluate storage changes where the basin-fill aquifer is absent. Storage changes at this station show similar variability to all other stations, indicating unconfined storage-changes can occur in the carbonate aquifer, at least where it is at the land-surface elevation. Station PINE was established to evaluate storage change related to recharge in the Juniper Mountains to the west. Gravity measurements here were stable over the monitoring period. Overall, the small magnitude of storage change and relatively noisy repeat microgravity measurements at these stations (with access requiring substantial driving on rough roads) limits the ability to make hydrologic interpretations.

In the BCWR area (stations 23, 26, and 27 of fig. 8), storage changes were minimal (station 23 of fig. 8), or continued trends of slight downward declines (stations 26 and 27 of fig. 8). The end of pumping for irrigation in 2019 appears to have had little effect on storage change in this area of the Big Chino Subbasin; the rising water levels likely represent increasing head in a confined to semi-confined aquifer. Only one small discrete recharge event occurred in summer 2021.

# Summary and Conclusions

Beginning in 2009, the U.S. Geological Survey has carried out groundwater-level and repeat microgravity monitoring to understand and characterize groundwater resources in the Big Chino Subbasin in Yavapai County, Arizona. Additional geophysical surveys have characterized basin geology (Macy and others, 2019) and geochemical characteristics (Beisner and Jones, 2020).

During this period, aquifer storage change has been relatively small owing to minimal pumping and the absence of large recharge events. The last large recharge event to cause widespread groundwater-level increases was in winter 2004–2005. Base flow discharge to the Verde River has gradually declined since that time. Because the aquifer stress (pumping and recharge) during the entire study period (2010–2021; Kennedy and others, 2019a, this report) has been minimal, limited information exists to extrapolate hydrologic conditions under different recharge or pumping conditions.

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