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Groundwater-Storage Change and Land-Surface Elevation Change in Tucson Basin and Avra Valley, South-Central Arizona—2003–2016

Scientific Investigations Report 2018–5154

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

Cover. A flooded recharge basin at Southern Avra Valley Storage and Recovery Project underground storage facility in south-central Arizona (U.S. Geological Survey photograph by Jeffrey Kennedy).

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By Robert L. Carruth, Libby M. Kahler, and Brian D. Conway

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This investigation and report is the result of cooperation among several individuals and agencies. The Arizona Department of Water Resources provided Interferometric Synthetic Aperture Radar interferograms of land surface elevation change for the Tucson Active Management Area. The Pima County Surveyors office provided funding for a Global Navigation Satellite System survey. The National Geodetic Survey of the National Oceanic and Atmospheric Administration provided a part of the absolute-gravity data. Project development was aided by several other agencies, including Arizona Department of Water Resources, Tucson Water, Pima County, Metropolitan Domestic Water Improvement District, the Town of Oro Valley, and the Town of Marana.

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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)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)

International System of Units to U.S. customary unitsw

Multiply	By	To obtain
	Acceleration	
microgal (μGal)	10	nanometer per second squared (nm/s^2)
microgal (μGal)	0.328×10^{-9}	Feet per second squared (ft/s^2)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Datum

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

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

Supplemental Information

Tucson Basin as used in this report refers to the hydrologic basin, not a geographic feature.

Abbreviations

ADWR	Arizona Department of Water Resources
AMA	active management area
CAP	Central Arizona Project
CAVSARP	Central Avra Valley Storage and Recovery Project
GNSS	Global Navigation Satellite System
GSF	groundwater savings facility
InSAR	interferometric synthetic aperture radar
SAVSARP	Southern Avra Valley Storage and Recovery Project
TAMA	Tucson Active Management Area
USF	underground storage facility
USGS	U.S. Geological Survey

Groundwater-Storage Change and Land-Surface Elevation Change in Tucson Basin and Avra Valley, South-Central Arizona—2003–2016

By Robert L. Carruth,[1] Libby M. Kahler,[1] and Brian D. Conway[2]

Abstract

The U.S. Geological Survey monitors groundwater-storage change and land-surface elevation change caused by groundwater withdrawal in Tucson Basin and Avra Valley—the two most populated alluvial basins within the Tucson Active Management Area. The Tucson Active Management Area is one of five active management areas in Arizona established by the 1980 Groundwater Management Act and governed by the Arizona Department of Water Resources. Gravity and land-surface elevation change were monitored every 1 to 3 years at wells and benchmarks in Tucson Basin and Avra Valley from 2003 to 2016. Monitoring resulted in estimates of land-surface elevation change and groundwater-storage change. Interferometric synthetic aperture radar (InSAR) interferograms showing land-surface elevation change were constructed for the Tucson metropolitan area from (1) May 2003 to July 2006, (2) July 2006 to June 2008, (3) June 2008 to April 2011, (4) April 2011 to November 2014, and (5) November 2014 to March 2016. For the Tucson metropolitan area, maximum subsidence of about 2 inches occurred during May 2003 to July 2006. From July 2006 to June 2008, maximum subsidence of approximately 0.8 inches occurred in two regions in the Tucson metropolitan area. From June 2008 to April 2011, about 0.8 inches of subsidence also occurred in two regions. Additionally, for the period April 2011 to November 2014, a maximum of about 0.9 inches of subsidence occurred in the same two regions of Tucson Basin. For the entire monitoring period from May 2003 to March 2016, maximum subsidence of as much as 5.3 inches occurred in the Tucson metropolitan area south of Irvington Road between south 12th Avenue and south Park Avenue, and as much as 4 inches in central Tucson south of Broadway between Country Club Road and Craycroft Road. The InSAR data indicated that there was no significant land-surface deformation from 2003 to 2016 in Avra Valley, and no change in either basin from 2014 to 2016.

The volume of stored groundwater in the monitored part of Tucson Basin showed net zero change from spring 2003 to summer 2006. From summer 2006 to summer 2008 the volume of stored groundwater in the monitored part of Tucson Basin increased approximately 50,000 acre-feet; however, overdraft conditions resumed from summer 2008 to spring 2011, resulting in decreased storage of approximately 178,000 acre-feet. From spring 2011 to fall 2014, the volume of stored groundwater in Tucson Basin decreased about 200,000 acre-feet, following a period of lower than average rainfall in 2012 and 2013. The volume of stored groundwater in the monitored part of Tucson Basin increased approximately 167,000 acre-feet from fall 2014 to spring 2016.

Groundwater storage in Avra Valley increased during the entire monitoring period from spring 2003 to spring 2016, largely as a result of managed recharge of Central Arizona Project water in the monitored region. From 2003 to 2016, artificial recharge in Avra Valley totaled approximately 1,788,000 acre-feet, and in Tucson Basin artificial recharge for the entire period was about 636,790 acre-feet. Artificial recharge exceeded pumping in Avra Valley for each time interval. Pumping in Tucson Basin exceeded artificial recharge for every period except 2014 to 2016. Overall, long-term water-level declines have stabilized or reversed since 2000 at most areas in Tucson Basin and Avra Valley.

Introduction

The Tucson Active Management Area (TAMA) encompasses most of Tucson Basin and Avra Valley within Pima County in south-central Arizona and includes the metropolitan area of the City of Tucson and several other incorporated towns and agricultural areas (fig. 1). TAMA is one of five active management areas (AMAs) established following the 1980 Arizona Groundwater Management Act, which are governed by the Arizona Department of Water Resources (ADWR). The regulatory goal for TAMA under the Arizona Groundwater Management Act of 1980 is to create a balanced groundwater budget by the year 2025, whereby groundwater withdrawals are equal to recharge—both natural and artificial.

[1]U.S. Geological Survey.

[2]Arizona Department of Water Resources.

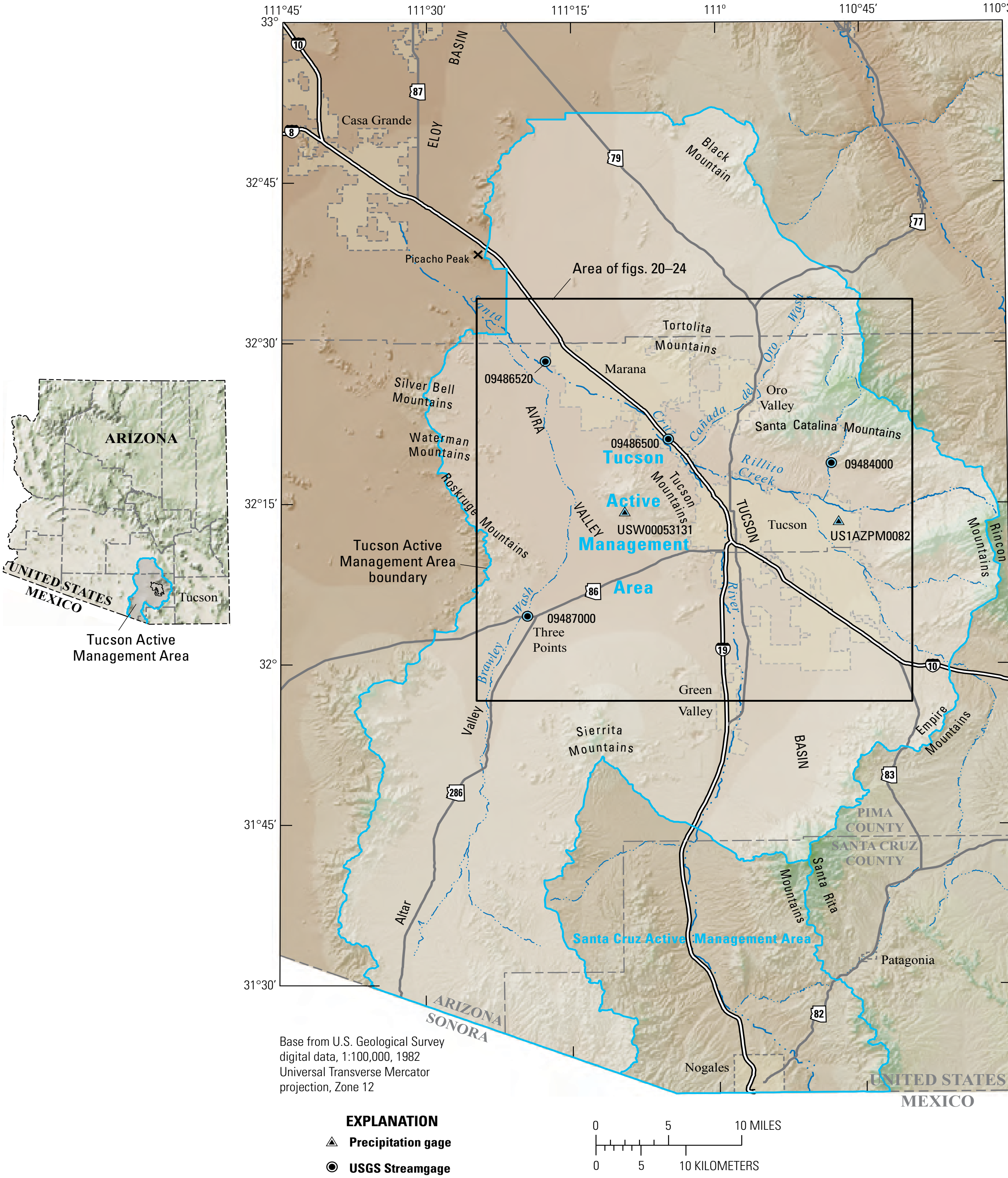


Figure 1. Map of the Tucson Active Management Area in south-central Arizona.

Artificial recharge in TAMA—particularly in Avra Valley—has increased since the beginning of this project, with significant changes occurring in 2008, when the Southern Avra Valley Storage and Recovery Project (SAVSARP) was first used. SAVSARP and its neighbor facility, the Central Avra Valley Storage and Recovery Project (CAVSARP) are underground storage facilities (USFs) operated by Tucson Water, a division of the city of Tucson. Together they total 543 acres of recharge basins in Avra Valley (Tucson Water, SAVSARP), and both recharge Central Arizona Project (CAP) water allotted to the City of Tucson (or other agencies with valid CAP entitlements) to the aquifer. Tucson Water also operates a USF in the northwest part of Tucson Basin, which recharges treated effluent to the Santa Cruz River channel at Cortaro and to several basins near the treatment plant (fig. 2). Other utilities or agencies in TAMA also operate recharge projects, typically smaller but still potentially significant to local storage change.

Groundwater savings facilities (GSFs) have also been added to TAMA since 2003, and although these facilities do not directly recharge water to the aquifer, they authorize the purchase and use of CAP water or treated effluent in lieu of groundwater pumping. A significant part of the agricultural areas in northern Avra Valley are classified as GSFs as of 2016. Pumping near CAP-supplied USFs provides Tucson Water customers with a blend of native groundwater and CAP water. This pattern of recharge and pumping has allowed Tucson Water to limit withdrawals from the central Tucson wellfield that experienced significant declines in water levels until 2000 (Tucson Water).

Historically, groundwater pumping in TAMA exceeded recharge for decades, thereby depleting aquifer storage and resulting in areas of land subsidence. Between 2003 and 2016, an overall decreasing trend in pumping and increase in artificial recharge resulted in net positive storage change in TAMA as a whole. However, comparing only recharge and pumping is insufficient for water managers in TAMA to assess progress toward the regulatory goal of safe yield, where withdrawals are equal to recharge for some time period. Additional information about unmonitored changes in storage and in spatial patterns of storage change are also necessary in order to account for variable components of the water budget. Pool and Anderson (2008) found that gravity-derived aquifer-storage change estimates were responsive to interannual variations in natural recharge, enabling a more accurate estimate of the groundwater-budget for a given time interval. Improved groundwater-budget information will reduce uncertainty and improve management of the groundwater resource by the ADWR, Pima County, and the municipalities of Tucson, Oro Valley, Marana, and the Metropolitan Domestic Water Improvement District. Some of the groundwater-budget components are measured directly, including the amount of water that is artificially recharged and withdrawals from wells that pump more than 35 gallons per minute (gpm; the Arizona Groundwater Management Act of 1980 mandates that all wells pumping more than 35 gpm be metered). Estimations based on indirect methods must be used for other groundwater-budget components, including withdrawals by small capacity (<35 gpm) wells, evapotranspiration, groundwater underflow from adjacent basins, incidental recharge from effluent recharge and other sources, and natural recharge from many sources including mountain fronts and ephemeral streams. This estimation of several groundwater-budget components results in large uncertainty in the groundwater budget. The greatest uncertainty can be attributed to a lack of information about natural recharge and groundwater-storage change. Estimates of the natural recharge rates are highly uncertain and depend on accurate measurements of annual precipitation and streamflow, which have high interannual variation (Pool, 2005). Estimates of groundwater-storage change are also highly uncertain when computed as residuals in the water budget equations because the storage term includes the cumulative uncertainty of all other components.

Gravity methods can be used to directly and independently measure groundwater-storage change, which reduces uncertainty in the groundwater budget by eliminating a large source of error. In conjunction with gravity methods, land-surface elevation change associated with declining water levels (and any land-surface rise associated with water-level recovery) must be measured at the same monitoring stations as the gravity measurements. The land-surface elevation change information, when combined with gravity methods, can be used to estimate the part of storage loss that results from compaction of pore space in the aquifer. Another benefit of using gravity methods is the ability to estimate the specific yield of the aquifer at monitoring sites where groundwater levels are measured. Specific yield is a measure of the volume of water that can be released from storage and can be difficult to estimate using other methods such as aquifer tests.

Purpose and Scope

This report summarizes changes to land-surface elevation and gravity-derived aquifer storage for the Tucson and Avra Valley parts of TAMA, from 2003 to 2016. Groundwater-storage change and land-surface elevation change have been monitored in parts of TAMA every 1 to 3 years since December 1997. Data used in this report are combined from surveys at a network of gravity stations across large parts of the primary aquifers in Tucson Basin and Avra Valley (fig. 2).

Similarly, monitoring at 23 stations in Avra Valley was conducted as a single regional network that has been surveyed every 1 to 3 years since December 1997. The distribution of gravity stations in Avra Valley is not as dense as the network in the Tucson Basin and was not specifically designed to identify aquifer-storage changes due to ephemeral-stream recharge or MFR. Land-surface elevation change was measured between the intervals specified in this report using interferometric synthetic aperture radar (InSAR) and was monitored continuously by a network of 13 vertical extensometers in TAMA. Several stations in each network were collocated with observation

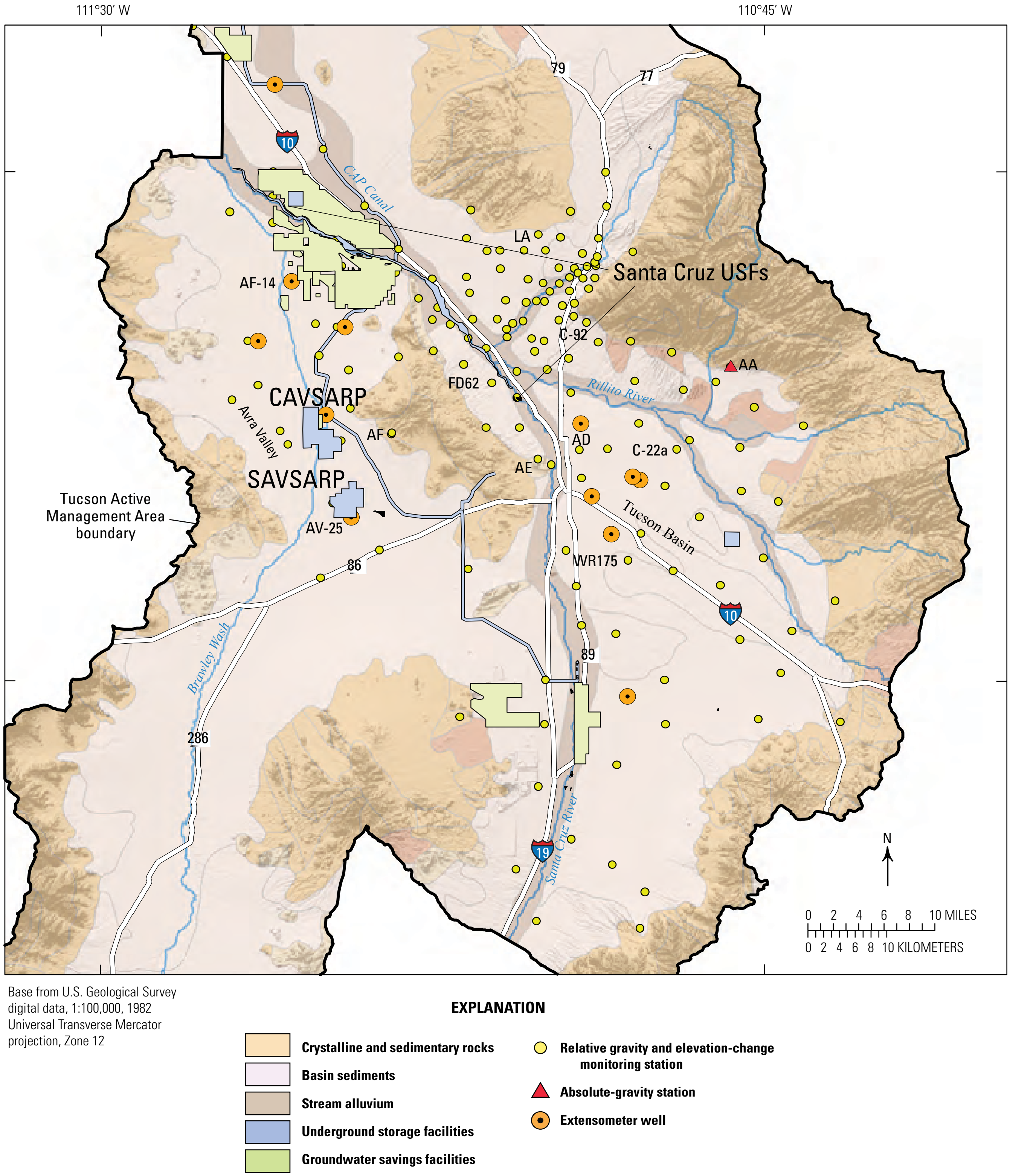


Figure 2. Map of study area, general geology, and groundwater-storage monitoring stations within the Tucson Active Management Area, south-central Arizona. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project; SAVSARP, Southern Avra Valley Storage and Recovery Project; USF, underground storage facility.

wells used to monitor water levels. Annual groundwater-storage change in Tucson Basin and Avra Valley was estimated by interpolation of gravity-derived storage change across the area of each network.

Hydrogeology

The primary aquifer materials in TAMA are thick alluvial deposits that are bounded by crystalline rocks in the surrounding mountains (fig. 3). Water is stored in the pore spaces between grains of gravel, sand, silt, and clay in the alluvial deposits. Water is transmitted primarily through permeable pore spaces between grains of sand and gravel, with little transmission occurring through the poorly permeable pores between particles of silt and clay. Groundwater enters the TAMA region as infiltration of streamflow in ephemeral streams, as recharge along mountain fronts, and as groundwater underflow from adjacent basins along the southern and northern boundaries of TAMA (Mason and Bota, 2006). Groundwater outflow primarily occurs through groundwater withdrawals from wells, but also occurs as groundwater outflow at the northwestern margin of TAMA. Outflow from the groundwater system through evapotranspiration is minimal in comparison to other water-budget components (Hanson and Benedict, 1994). Long-term groundwater withdrawal rates that are greater than recharge rates to the groundwater system have resulted in a reduction in groundwater storage and water-level declines during the last several decades. Short-term increases in storage and water levels have occurred for periods of months to years after short-term increases in the volume of recharge resulting from periods of above normal precipitation (Pool, 2005). Additionally, artificial recharge projects managed by Tucson Water have increased groundwater storage in Avra Valley and the southern part of TAMA. Annual average natural recharge in Avra Valley is typically estimated at 30,000 acre-feet, and 70,000 acre-feet for Tucson Basin (Pool and Anderson 2008).

The alluvial deposits are heterogeneous and include layers of poorly permeable silt and clay that are interbedded with highly permeable layers of gravel and sand. The silt and clay layers form aquitards that restrict the flow of water between adjacent aquifers of sand and gravel (fig. 4). The interbedded layers are part of an aquifer system that includes multiple aquifers that are generally hydraulically connected and thick aquitards that impede vertical flow of water between aquifers in places. Aquitards are common in the basin center but also occur on the basin margins. Local perched aquifers occur in places above silt and clay layers that are above the water table. Several local perched aquifers occur near major ephemeral streams where percolating water from streamflow infiltration is held up by silt and clay layers. Perched aquifers near ephemeral streams are often ephemeral as well. Perched aquifers develop following infiltration, but drain as the temporarily available water flows across the margin of silt and clay, or permeates through the deposit to the underlying unsaturated zone and aquifer (Pool, 2005).

Groundwater-storage change occurs through three mechanisms in the study area:

1. Changes in the water content of pore spaces in the unsaturated zone,
2. Saturated/unsaturated changes at the water table in regional and perched aquifers, and
3. Expansion and contraction of saturated pore volume in compressible parts of the aquifer (fig. 5).

The focus of this investigation is only quantification of the aquifer storage-change part of groundwater-storage change. Changes in unsaturated-zone storage that are not transmitted to the aquifer system but instead are evaporated from the soil and transpired by vegetation are of little interest to the quantification of aquifer-storage change because the water is unavailable for withdrawal except by vegetation. Groundwater flows into and out of storage in pore spaces in the zone of water-table variation as water levels rise and fall, respectively. Groundwater also flows in and out of pore-space storage with compression of the aquifer through changes in the volume of the saturated pores. Most of the compressible storage change occurs in the most compressible parts of the aquifer, which are intervals primarily comprised of silt and clay-sized particles. Water is released from storage in compressible intervals as water levels decline in adjacent coarse-grained intervals. The amount of water released from storage is equivalent to the volume of pore-space compaction, which manifests as lowering of the land surface, a process known as subsidence. Generally, compaction may be permanent (inelastic) or reversible (elastic) depending on how easily pore-fluid pressure within the granular skeleton of the aquifer system can be re-established. Typically, less water can return to storage in the compressible pores, because compaction has permanently rearranged the silt and clay particles.

Changes in unsaturated-zone water storage normally are restricted to the root zone, except beneath ephemeral channels, where infiltration of concentrated runoff often exceeds root-zone water demand and results in deep percolation of infiltrated water and temporary changes in storage between the water table and the root zone. The thickness of the root zone varies from only a few feet in areas outside of stream channels to as much as 50 feet (ft) near ephemeral-stream channels where phreatophytes, primarily mesquite, may tap groundwater supplies (Leenhouts and others, 2006). Significant amounts of unsaturated storage change can occur through transpiration processes where vegetation can access soil moisture within the root zone. Unsaturated-zone storage change occurs with infiltration of excess precipitation that is beyond vegetative-transpiration demands.

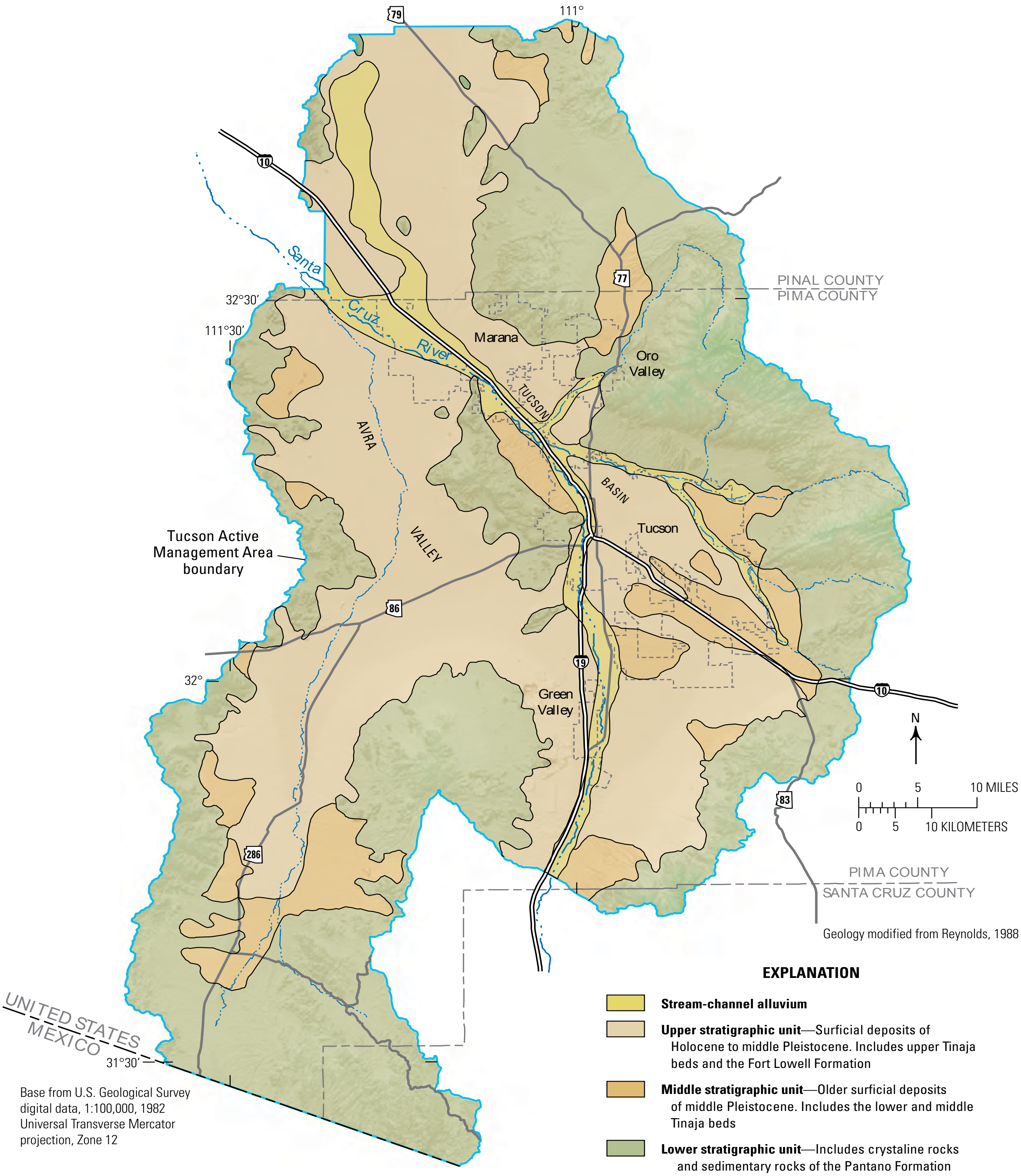


Figure 3. Map of general surface geology of the Tucson Active Management Area, south-central Arizona. See figure 1 for map location.

Direct infiltration of precipitation rarely exceeds the root-zone soil-moisture deficit, resulting in little variation in storage below the root zone. Total soil-moisture variation in the upper 40 inches (in.) of the root zone typically is less than 1 in., but on the basis of monitoring near Tombstone, Ariz., it can briefly increase to 3 in. following intense summer precipitation before returning to preexisting conditions over a period of 1–2 months (Garry Schaefer, hydrologist, U.S. Department of Agriculture, Agricultural Research Service, written commun., as cited in Pool and Anderson, 2008).

In contrast, infiltration often exceeds transpiration demands where runoff is concentrated in ephemeral channels, resulting in deep percolation of infiltrated water and changes in water storage between the water table and the root zone. Changes in unsaturated-zone water storage can be large, as much as several feet, because depths to water are typically 50 to 300 ft or more. These changes can persist for a period of several months following summer precipitation and following periods of extreme winter precipitation (Leenhouts and others, 2006). Much of the water that infiltrates the unsaturated zone beneath ephemeral channels likely continues to percolate and recharge the aquifer and can be considered water available for withdrawal from the aquifer.

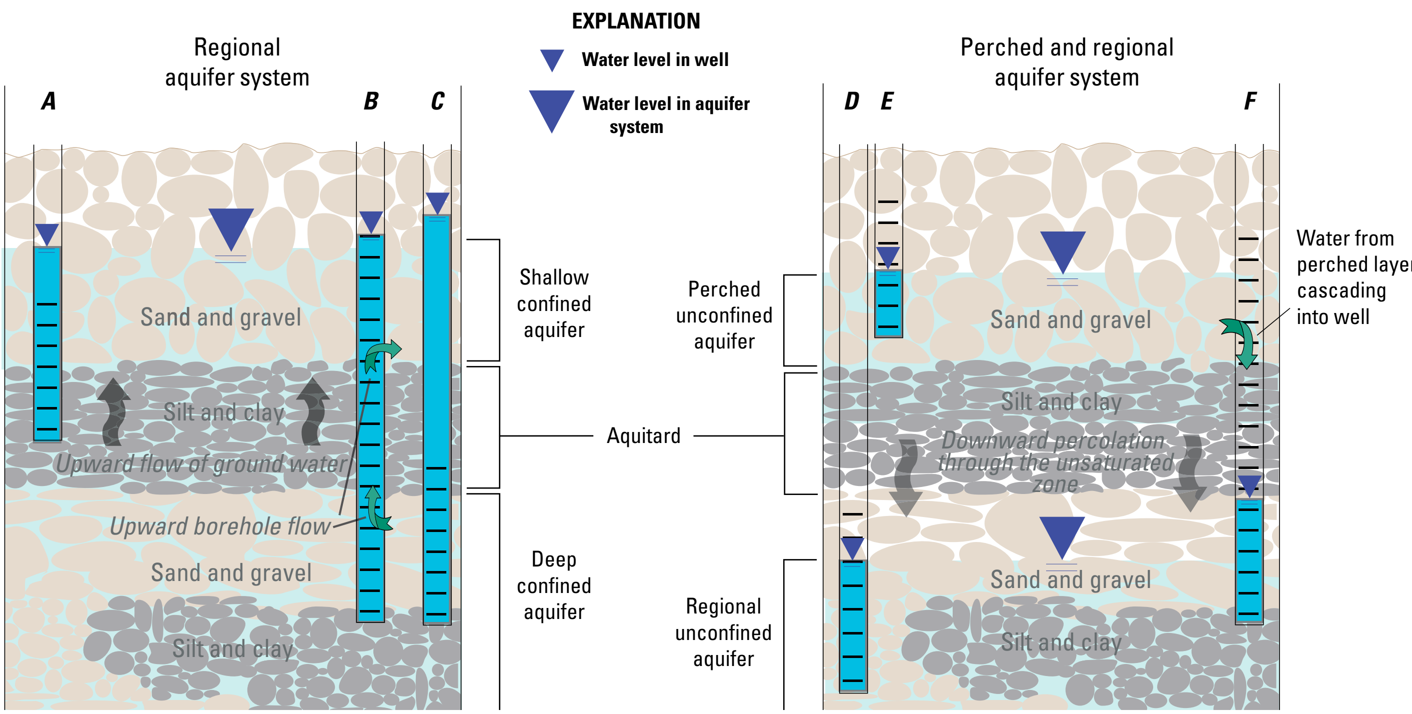


Figure 4. Diagram showing selected well-construction scenarios in a multi-aquifer system, including representations of common relations between hydraulic head, screened intervals, and water levels in wells in the Tucson Active Management Area, south-central Arizona (modified from Pool and Anderson, 2008). *A,* Well screened in shallow unconfined aquifer with lower hydraulic head than in the deep confined aquifer; water level in the well represents hydraulic head in the shallow aquifer and approximates regional aquifer water table. *B,* Well screened in shallow unconfined aquifer and deep confined aquifer with higher hydraulic head than in the shallow aquifer; upward flow occurs in borehole; water level in the well represents a hydraulic head that is a composite of the two aquifers and does not approximate the shallow aquifer water table. *C,* Well screened in deep confined aquifer with higher hydraulic head than shallow unconfined aquifer; water level in the well represents hydraulic head in deep confined aquifer and does not approximate water table. *D,* Well screened in regional unconfined aquifer; water level in the well represents hydraulic head in the regional aquifer and approximates regional aquifer water table. *E,* Well screened in perched unconfined aquifer; water level in the well represents hydraulic head in the perched aquifer and approximates perched aquifer water table. *F,* Well screened in perched and regional aquifers with water cascading into well from the perched aquifer through screened intervals; water level in the well represents hydraulic head that is greater than the hydraulic head in the regional aquifer and does not approximate the regional or perched aquifer water table.

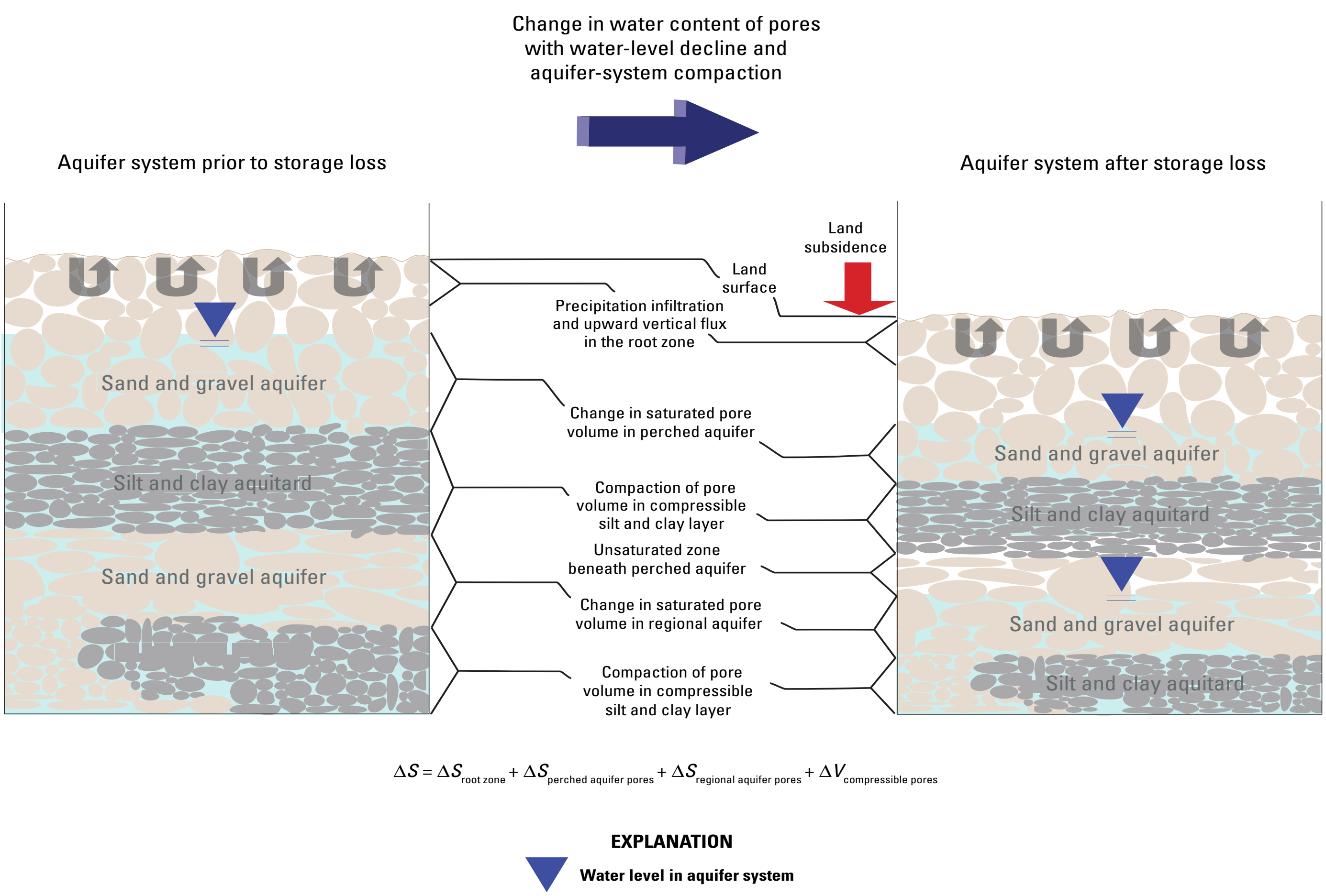
Methods

For this study, annual variations in groundwater storage and land-surface elevation in TAMA were monitored at the network of stations in Tucson Basin and Avra Valley from 2003 to 2016 (fig. 2). Land-surface elevation change was measured using InSAR, and storage change was measured using gravity methods (Pool and Eychaner, 1995; Pool and Schmidt, 1997) (fig.6). Combined use of gravity and InSAR methods results in more complete measurement of the components of groundwater-storage change. InSAR interferograms are used to resolve the part of storage change that occurs because of expansion or contraction of saturated pore volume, and the gravity data are used to resolve the total storage change. The difference in storage change from the two methods is the storage change because of drainage or filling of pore spaces.

Accurate repeat monitoring of groundwater storage and land-surface elevation change requires vertically and horizontally stable monuments that are not susceptible to movement because of soil shrink and swell. Thus, suitable network stations require a concrete pad or monument that is well anchored to stable soil at depth. Many existing vertical and horizontal control monuments met the stability criteria and were chosen as stations. Other stations were constructed by using 2-in. brass caps placed in building foundations, concrete well pads, or crystalline rock.

InSAR and Vertical Extensometers

InSAR interferograms are a powerful mapping tool in the assessment and monitoring of land-surface elevation change. InSAR has been used successfully to measure and map land-surface elevation change and uplift of the Earth's



$$\Delta S = \Delta S_{\text{root zone}} + \Delta S_{\text{perched aquifer pores}} + \Delta S_{\text{regional aquifer pores}} + \Delta V_{\text{compressible pores}}$$

Figure 5. Diagram of primary groundwater-storage and storage-loss mechanisms within the Tucson Active Management Area, south-central Arizona (modified from Pool and Anderson, 2008). ΔS, total change in aquifer storage; ΔV, expansion or contraction of saturated pore volume in compressible parts of the aquifer.

surface caused by aquifer-system compaction (Galloway and others, 2000; Bawden and others, 2003; Carruth and others, 2007; Galloway and Hoffmann, 2007).

InSAR is a satellite technology that provides high-resolution mapping of earth-surface topography and deformation. The satellite radar transmits a series of microwave pulses and records both the amplitude and phase of the backscattered responses from the surface. The phase difference between two radar images (interferogram) taken at different times, contains signals associated with surface topography and deformation, as well as differences in the atmosphere and satellite position at the time of each response. Isolating the deformation signal by applying phase corrections to satellite position and surface topography produces a differential interferogram where one cycle of phase change represents a half-wavelength (1.1 in.) of surface movement toward or away from the radar (Galloway and Hoffmann, 2007). The ADWR is presently using InSAR data to create interferograms to map deformation in the Phoenix AMA and TAMA with a vertical resolution of ±1/2 in. or less (Arizona Department of Water Resources, 2018).

In addition to the InSAR interferograms, a vertical-extensometer network was used to measure land-surface elevation change and monitor aquifer compaction caused by groundwater depletion at point locations. The network of 13 vertical extensometers was established in 1983 to monitor the rates and magnitude of aquifer compaction and water-level change at different locations in TAMA. Seven extensometers are in the Tucson Basin and six are in the Avra Valley (fig. 7).

Aquifer compaction is measured by vertical-extensometer pipes that extend from the land surface to the bottom of cased wells or test holes (fig. 8). The extensometer pipes are isolated from the well casings and are jetted into the formation, or are set into concrete plugs placed at the bottom of the well. As the aquifer materials compact, the land surface moves downward in relation to the top of the extensometer pipe. Thus, vertical extensometers measure aquifer compaction for the part of the aquifer between the land surface and the depth where the bottom of the extensometer is anchored. The design and operation of vertical extensometers is described in detail by Anderson and others (1982) and Schumann (1986).

In TAMA, the bases of the extensometer pipes are in bedrock or are grouted into a stationary platform in less compressible alluvium. Most of the extensometers are anchored in alluvium at depths between 800 and 1,400 ft. Extensometers may not measure as much vertical displacement as InSAR because that method measures total land-surface elevation change, while the extensometer may measure less change because some compaction could occur beneath the base of the extensometer (Amelung and others, 1999; Evans and Pool, 2000). Accuracy of the vertical displacement measured by extensometers is ±0.012 inches, but these values are valid at point locations and cannot be extrapolated to significant areal extents. A combination of extensometer and InSAR monitoring is useful for assessing land-surface elevation changes across large regions such as the monitoring area of this report.

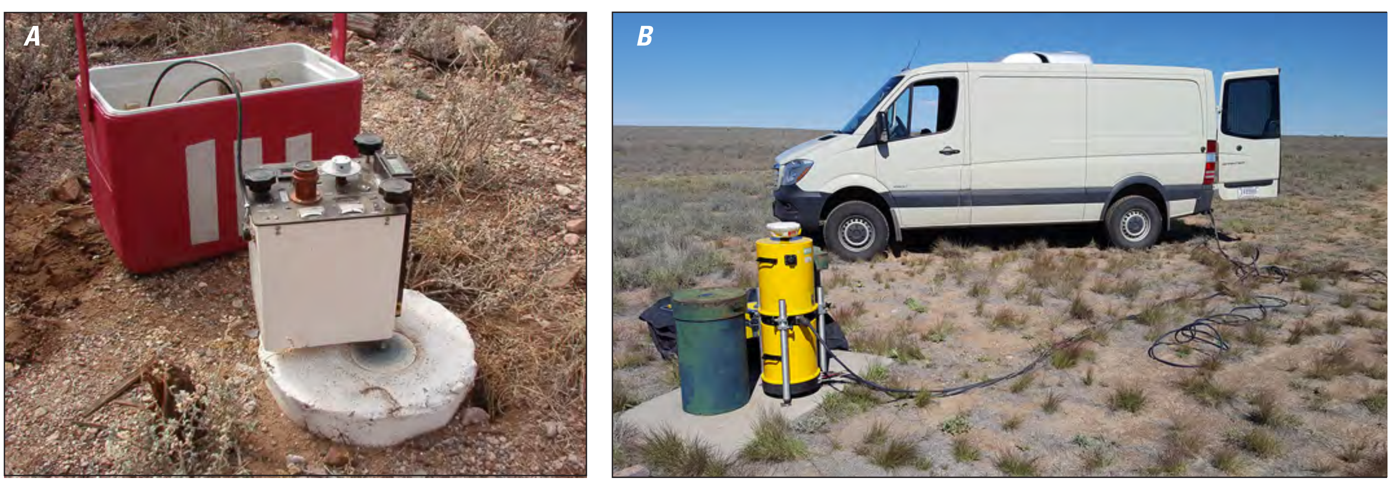


Figure 6. Photographs of gravity-monitoring equipment deployed in the field by the U.S. Geological Survey. *A*, LaCoste and Romberg Model D relative-gravity meter; *B*, Micro-g LaCoste A-10 absolute-gravity meter deployed from a van. (U.S. Geological Survey photographs.)

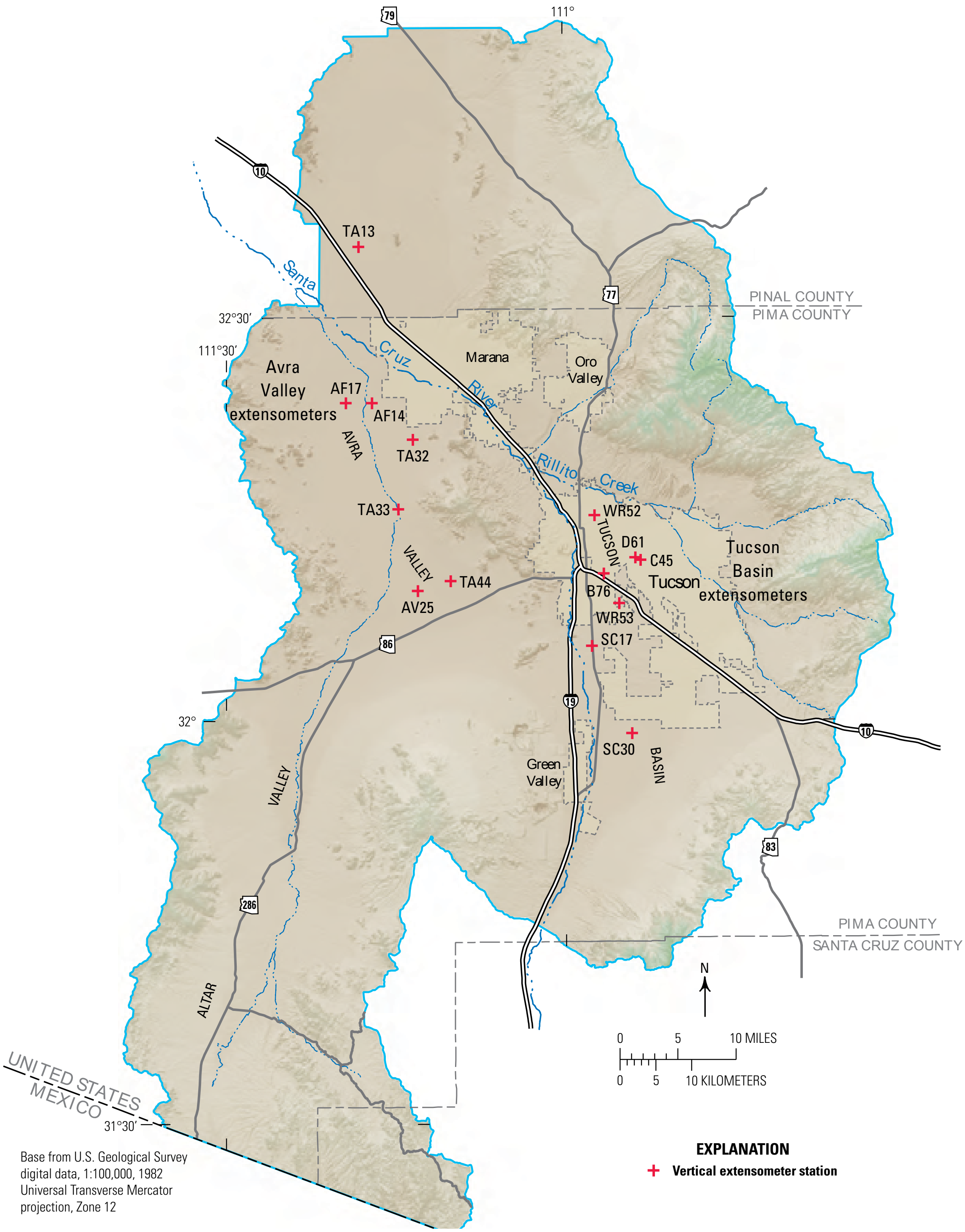


Figure 7. Map of Tucson Active Management Area vertical extensometer stations (red crosses), south-central Arizona. See figure 1 for map location.

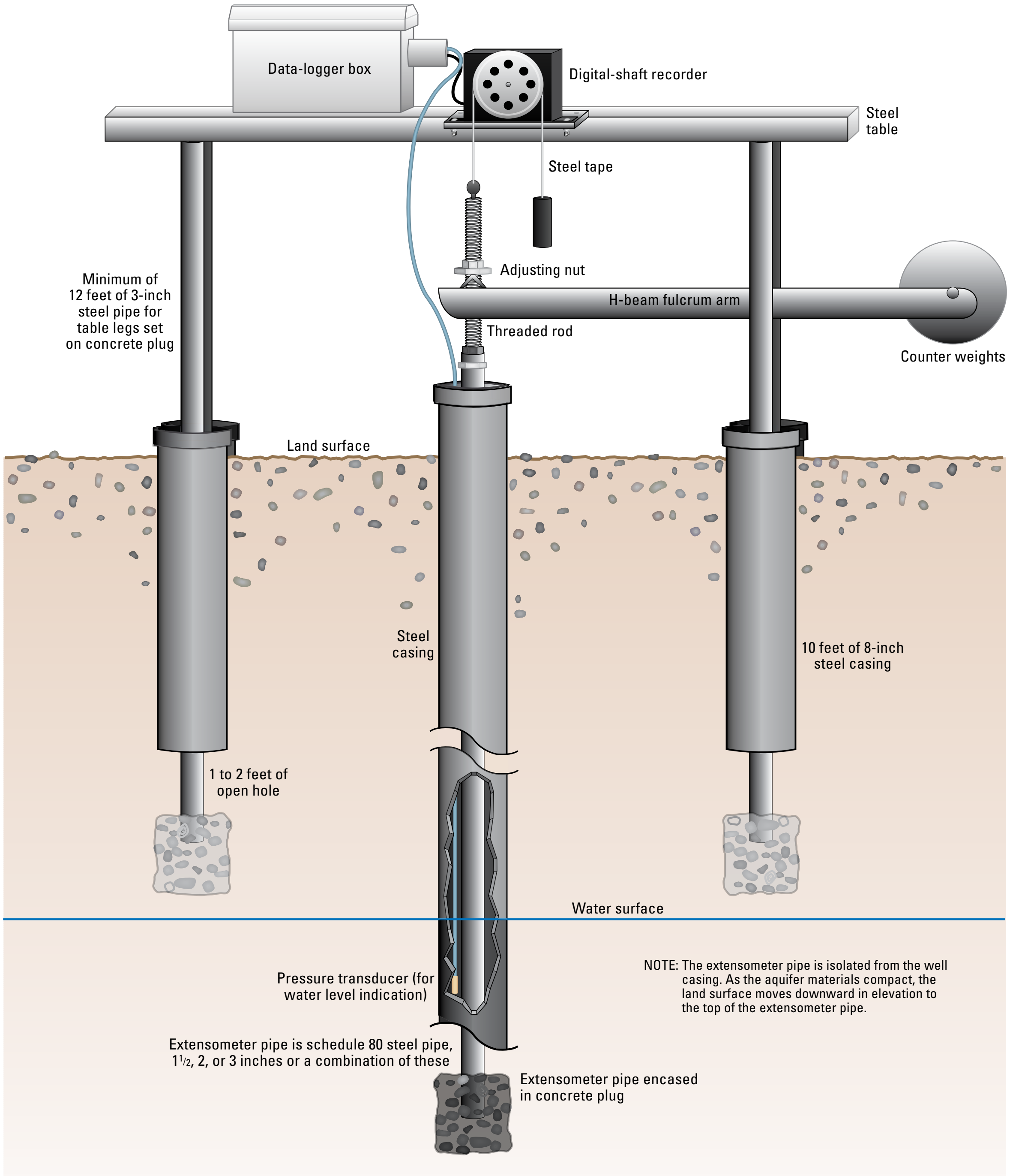


Figure 8. Diagrammatic sketch of a vertical extensometer installation in the Tucson Active Management Area, south-central Arizona.

Gravity

Gravity methods are based on the principles of Newton's Law of Gravitation (Telford and others, 1976), which states that the acceleration of gravity within an object's gravitational field is directly related to the mass of the object and inversely related to the square of the distance to the center of the object. Thus, the greater an object's mass, the stronger the gravitational field. The object that produces the gravitational field in this case is the Earth, including groundwater stored in aquifers and the unsaturated zone between the land surface and aquifer. Changes in the Earth's gravitational field at any location on the surface can be caused by changes in the amount of groundwater in storage. Other subsurface mass change can also result in gravity change at the surface of the Earth, such as movement of mass in magma and geothermal reservoirs. However, changes in groundwater storage are the only likely cause of subsurface-mass change in TAMA during the time scale of this study.

Gravity measurements were made by using relative- and absolute-gravity meters (gravimeters; fig. 6). Most gravity-data collection was done using relative gravimeters, which measure the relative difference in gravitational acceleration between stations. The absolute acceleration of gravity at selected control stations was established by measuring the value using an absolute gravimeter. The absolute acceleration of gravity at other stations is then determined on the basis of the difference in gravity measured by using relative gravimeters. Measurements of the relative difference in gravity among stations were made by the U.S. Geological Survey (USGS) using two Lacoste and Romberg Model D relative gravimeters (fig. 6). Measurements of absolute gravity were made by the USGS using an A-10 falling-mass gravimeter or by the National Geodetic Survey using an FG-5 falling-mass gravimeter. Both of the absolute gravimeters are manufactured by Micro-g LaCoste, Inc,. of Lafayette, Colorado (fig. 6).

The absolute acceleration of gravity was measured at 5 or more stations every 1 to 3 years (fig. 2). Additional absolute-gravity stations were added to the network from 2003 to 2016 to increase the resolution of the combined absolute and relative gravity-data sets. Observations at the absolute-gravity stations included sets of several hundred individual measurements made during a period of 20 minutes or more. Data are corrected for theoretical Earth tides, location of the rotational axis of the Earth, and barometric pressure. Resulting values of gravitational acceleration are the average of the individual measurements reduced to the height at which the falling mass is released, known as the instrument drop height. Observations under ideal conditions generally are accurate to within ±5 microgal (μGal; a unit of acceleration used in gravimetry), which is equivalent to the change in gravity resulting from the addition or removal of an extensive layer of water that is about 5 in. thick. This number is based on the assumption that all mass change in the subsurface is due to a change in water storage. It is derived from the Bouguer slab approximation, which can be used to relate a change in gravity (g) to a change in a thickness of free-standing water in the subsurface by $\Delta Storage = \Delta g/12.77$, independent of the depth to water or porosity of the aquifer or unsaturated zone. The approximation applies because vertical mass changes are small relative to their horizontal extent. This assumption is a reasonable approximation in the case of many aquifers because storage change typically occurs in the interval of water-table fluctuation, which typically is shallow in comparison to the lateral extent of mass change. Accuracy may be degraded by ground motion caused by local construction activity, seismic activity, atmospheric disturbances, and large variations in temperature. Temperature variations were minimized by collecting data during temperature-stable seasons or locating stations in buildings where the temperature is controlled or varies minimally.

The inclusion of absolute-gravity observations in both aquifer and bedrock areas provided quality control for observation of gravity change from the relative-gravity surveys and for the possibility of observing gravity variations that are caused by mass change outside of the aquifer. Initially, one station—TUCSON AD—was located on alluvium and within the extent of the regional aquifer. Additional absolute stations—C22, C92, WR175, and AF14 were added to monitor storage changes in areas of alluvial basin fill. Stations on the margins of the alluvial fill—FD62 and LATUCS—were also added to the network between 2003 and 2016. Three stations—TUCSON AA, TUCSON AE, and TUCSON CF—were located on bedrock areas that lie outside the aquifer extent where gravity variations caused by groundwater-storage changes were thought likely to be smaller than the accuracy of the measurement. However, Pool and Anderson (2008) found that annual gravity changes at these locations of 8 to 9 μGal did occur, though these changes were less than those detected from stations over thick alluvium. Changes at these bedrock stations during the time span represented in this report were also observed, specifically at TUCSON CF, which is located on the bank of a wash. The detection of variations in gravity at stations located on low porosity bedrock could be caused by non-aquifer storage-related changes, such as elevation change or nearby soil-moisture variations. Fractures in the rock can also give rise to short-term storage below these sites. Simple gravity models, constrained by nearby water-level variations and extents of aquifers, can also be used to establish the likely causes of significant variations in gravity in areas of low-porosity rock.

Relative-gravity surveys at the network of stations in Tucson Basin and Avra Valley were completed every 1 to 3 years by completing many subsurveys of 2 to 4 stations to establish gravity differences among stations. Inclusion of stations where the absolute acceleration of gravity was also measured allowed for the calculation of absolute gravity at each station in the network. Before 2014, specific meters were dedicated to relative-gravity surveys of the network in each basin to maintain consistency in meter calibration. Gravimeter D-127 was used in Tucson Basin, and gravimeter D-209 was used in Avra Valley. In 2014, gravimeter D-209 calibrations showed instabilities in the meter and it was removed from service. Therefore, the 2014 and 2016 relative surveys for Tucson Basin and Avra Valley used gravimeter D-127. Surveys were reduced to gravity differences between stations by converting meter readings to gravity units and correcting for estimated Earth-tides (Longman, 1959) and linear-meter drift.

Estimates of groundwater-storage change were made for periods between surveys for Tucson Basin and Avra Valley by using the excess-mass method (Telford and others, 1976). The excess-mass method sums the gravity or storage change across the monitored area to determine the total mass change, which can be converted to a volume of water assuming a density of 1.0 grams per cubic centimeter (g/cm^3). Two important assumptions apply to the use of the excess-mass method for these data sets, (1) the distribution of gravity change is adequately sampled and (2) gravity change outside of the monitored region that is caused by mass change within the region is small. Accurate estimates of storage change require that the spacing between stations be sufficiently small (typically 1 to 3 miles) so that gravity change among stations is spatially correlated. Variations in gravity change that occur at distances less than the station spacing result in under sampling of the gravity change and greater uncertainty in resulting estimates of storage change. Unmeasured gravity change that is outside of the monitored area and caused by groundwater-storage change within the monitored area can result in underestimation of total storage change.

The magnitude of this error is small where the area of unmonitored gravity change is small in comparison to the area of the monitored region. Estimation of the unmonitored-gravity change area requires estimation of the maximum distance that gravity change may be detected beyond the monitored region, which can be made on the basis of the estimated maximum depth to the storage change—approximately 500 ft in the study area. The gravity change caused by the addition or removal of 1 ft of water at a depth of 500 ft throughout the monitored region would be undetectable at a distance of about1,000 ft from the edge of the mass change (the edge of the aquifer). The area within 1,000 ft of the monitored regions represent approximately 8 percent of the monitored area for Tucson Basin and approximately 6 percent of the monitored area for Avra Valley. The average gravity change within 1,000 ft of the aquifer is about one-half of the change measured at the edge of the monitored area on the basis of a semi-infinite horizontal slab approximation for the aquifer-storage change (Telford and others, 1976). Accordingly, the total storage-change error contributed by the unmonitored region is about 4 percent for the Tucson Basin network and approximately 3 percent for the Avra Valley network.

Land-Surface Elevation Change

Historically, groundwater-level declines have resulted in aquifer-system compaction and subsidence of the land surface in parts of Tucson Basin and Avra Valley (Hanson, and others, 1990; Hanson and Benedict, 1994; Carruth and others, 2007). Strange (1983) analyzed repeated spirit-level surveys and documented less than 0.5 ft of subsidence near the center of Tucson Basin from 1952 to 1980 in an area where water levels declined as much as 160 ft from 1940 to 1981 (Anderson, 1989a). Documented subsidence of as much as 2.1 ft east of Picacho Peak in Avra Valley occurred from 1948 to 1980 in an area where water levels declined as much as 140 ft from 1940 to 1985 (Anderson, 1989b). Rates of subsidence from 1976 to 1980 were 0.6–0.8 in. per year near the center of Tucson Basin based on spirit-level surveys conducted by the National Geodetic Survey (Anderson, 1989a). For this study, land-surface elevation change was monitored continuously at the network of vertical extensometers in Tucson Basin and Avra Valley, and every 2 to 3 years in the Tucson metropolitan area using InSAR data. Long-term water-level declines have stabilized or reversed since 2000 at most areas in Tucson Basin and Avra Valley as indicated by the time-series data from the extensometer wells (figs. 9 and 10).

The extensometers in Tucson Basin and Avra Valley (fig. 7) provide a continuous record of water level and aquifer compaction (and in some cases, recovery) for the part of the aquifer penetrated by each well. At the seven extensometers in Tucson Basin, aquifer compaction from 2003 to 2016 ranged from 0.3 in. to 2.51 in., whereas in Avra Valley aquifer compaction for the same period ranged from 0.072 in. at TA32, to 0.42 in. at AF17. Additionally, the extensometer at AF14 in Avra Valley measured a cumulative uplift of about 0.23 in. for the period between 2003 and 2016.

In Tucson Basin, the greatest cumulative aquifer compaction occurred in the northern part of the basin at extensometers B76, C45, and D61 (2.37, 2.5, and 1.47 in., respectively). Cumulative water-level change at these stations for the same period was −18.8, −42.53, and −41.6 ft, respectively.

As noted previously, aquifer compaction at the seven extensometers in Avra Valley ranged from about 0.16 in. at station TA13 to 0.42 in. at station AF17 for the period between 2003 and 2016. The extensometer at station AF14 measured a cumulative uplift of 0.23 in. for the study period. Most of the uplift occurred from 2000 to 2010 during a corresponding increase in water level of about 70 ft. At station AV25 (located on the southern edge of the SAVSARP recharge facility in Avra Valley) the aquifer compaction measured by the extensometer from 2003 to 2016 indicated a small uplift of 0.06 in.

A

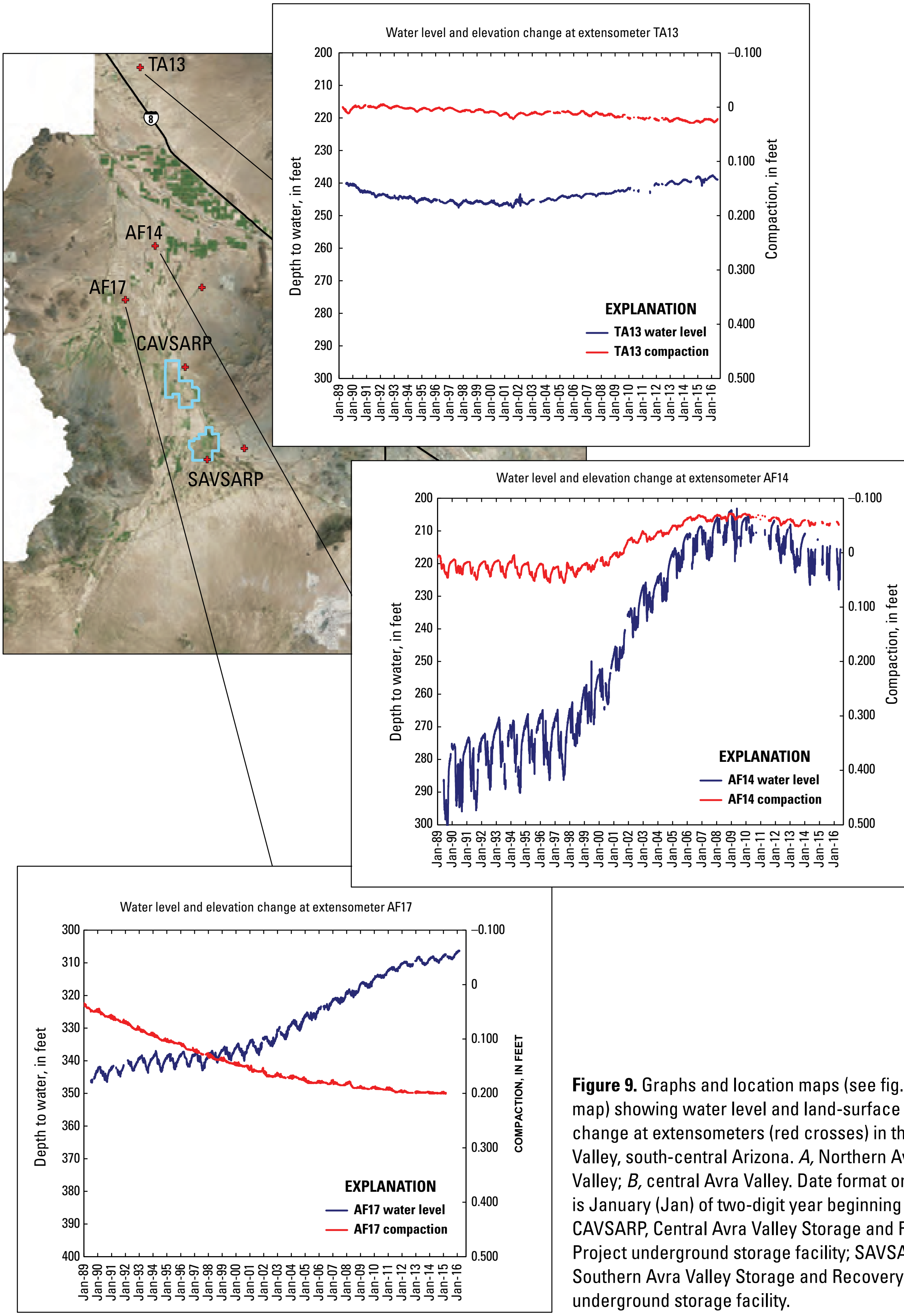


Figure 9. Graphs and location maps (see fig. 7 for full map) showing water level and land-surface elevation change at extensometers (red crosses) in the Avra Valley, south-central Arizona. *A,* Northern Avra Valley; *B,* central Avra Valley. Date format on graphs is January (Jan) of two-digit year beginning in 1989. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

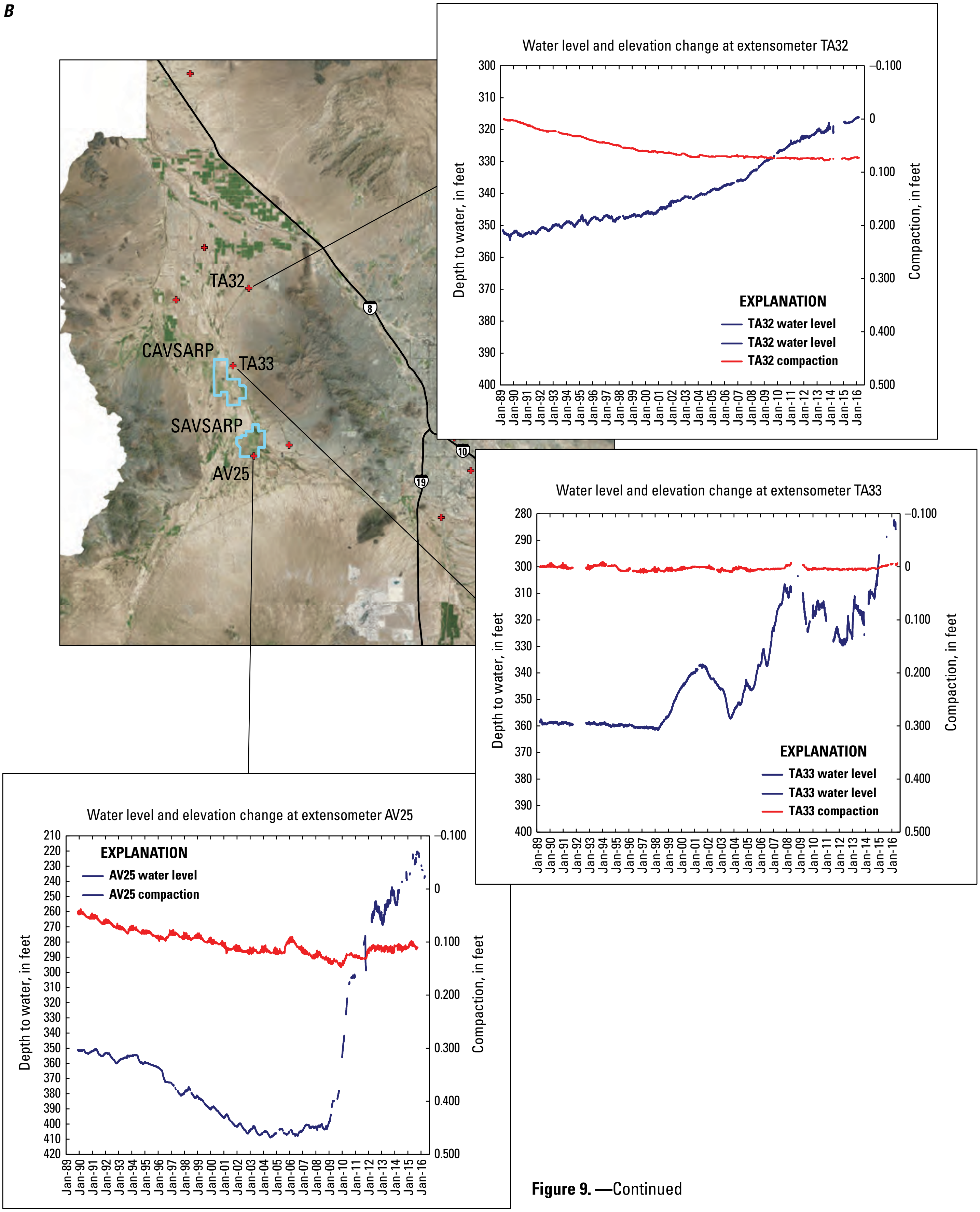


Figure 9. —Continued

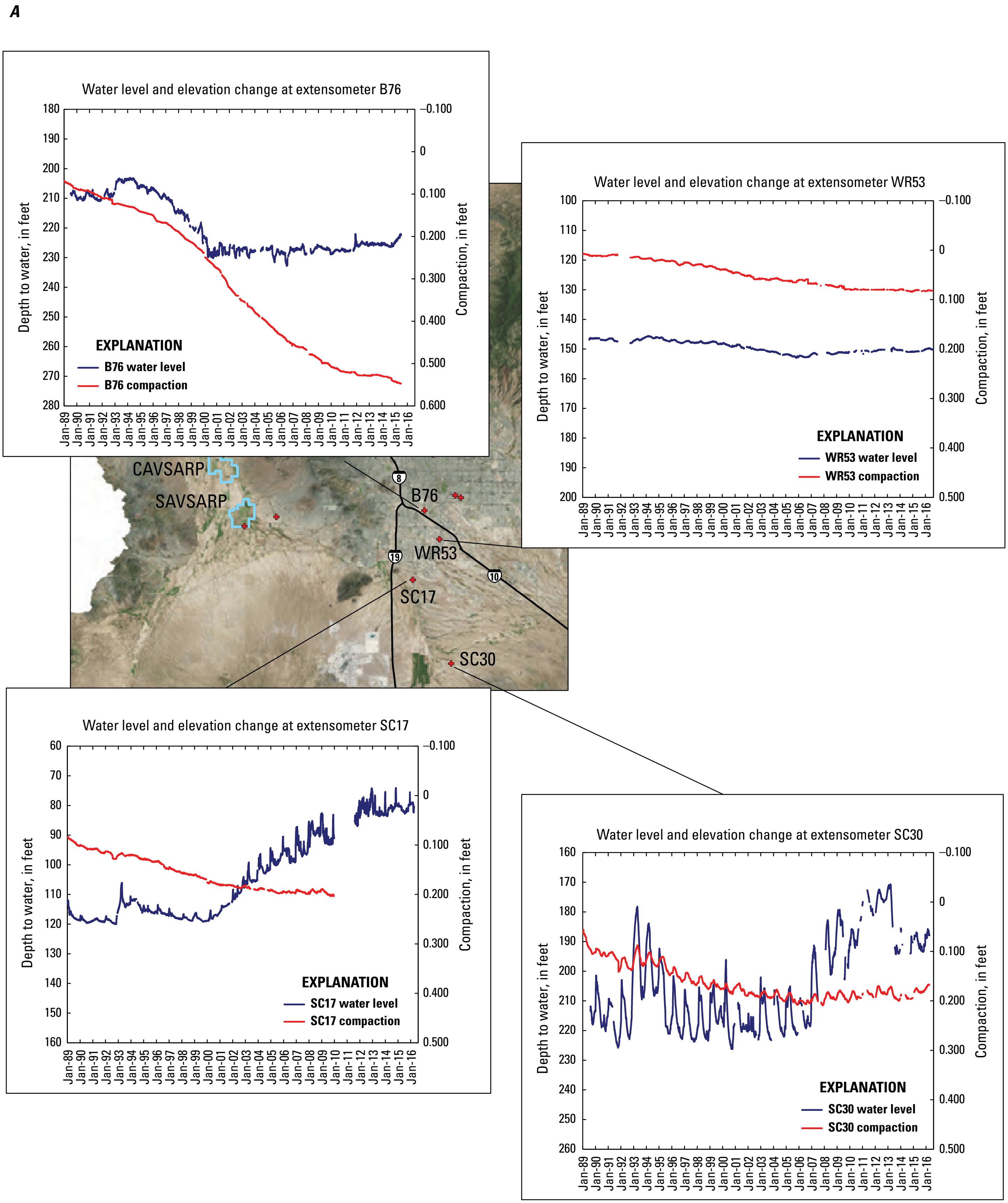


Figure 10. Graphs and location maps (see fig. 7 for full map) showing water level and land-surface elevation change at extensometers (red crosses) in the Tucson Basin, south-central Arizona. *A*, Extensometers B76, WR53, SC17, and SC30; *B*, extensometers WR52, C45, and D61. Date format on graphs is January (Jan) of two-digit year beginning in 1989. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

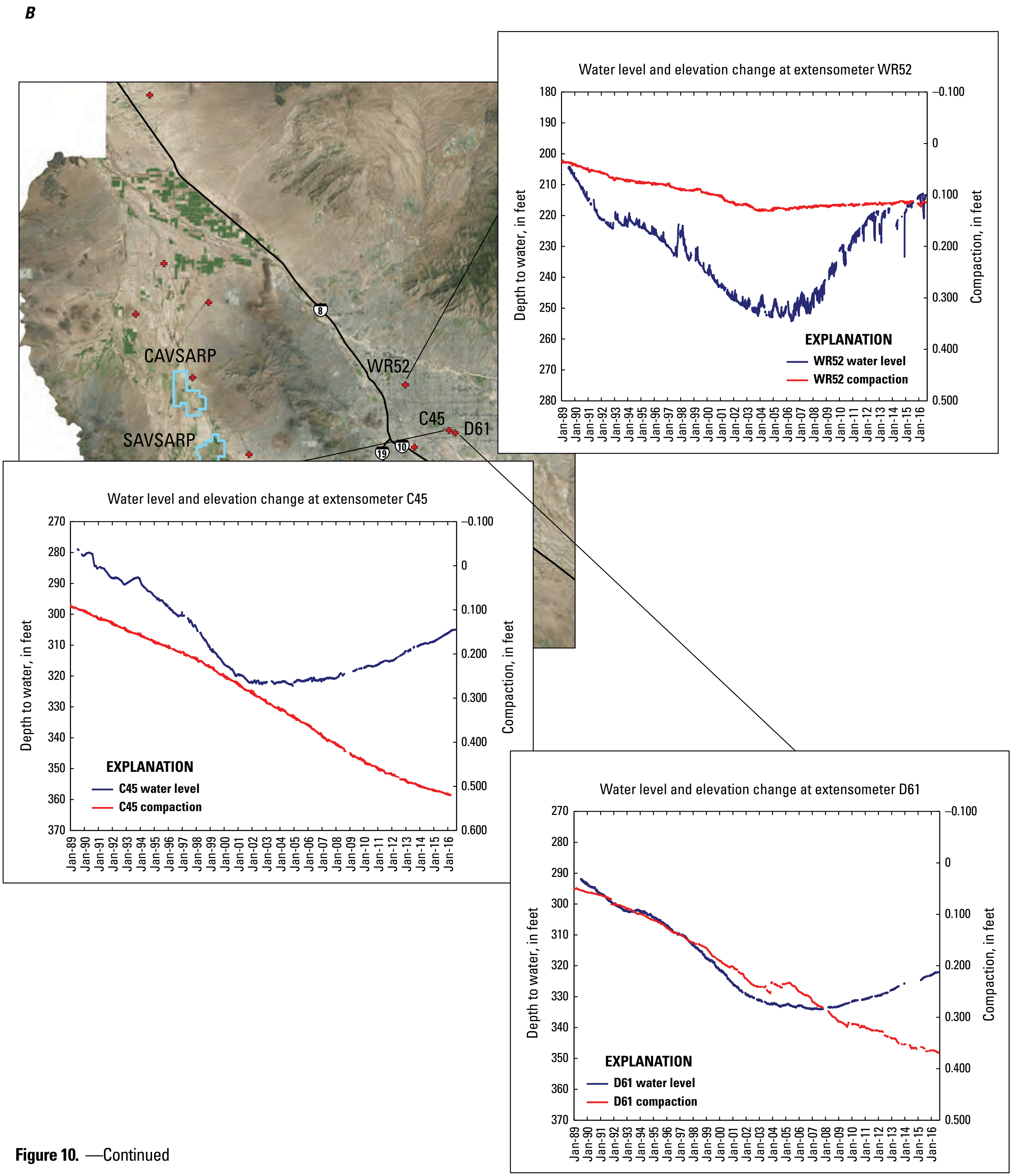


Figure 10. —Continued

During 2003 to 2016 there was a water-level rise of approximately 180 ft at AV25. The small amount of uplift measured at AV25 during a period of a large water-level rise due to recharge at SAVSARP indicates there may be some delayed drainage and associated compaction of fine-grained units in the vicinity of station AV25 from water-level decline that occurred prior to the current study period, and prior to active artificial recharge in that area.

The extensometer records shown in figures 9 and 10 also highlight the varied response of compaction to changes in water levels throughout the basin. Seasonal water-level fluctuations at AF14 and SC30—at diametrically opposite ends of the study area—are great enough to highlight the seasonal response of compaction to changes in water levels. Smaller fluctuations at other sites mask this seasonal response over the time shown, but it is typical behavior at some scale for all of the extensometers. AF14 and SC30 also show a marked change in compaction as water levels rise, whereas significant increases in water levels at AV25 and TA33 demonstrate a minimal change in compaction with time.

In general, the plots in figure 10 show that although changes in depth to water with time in the Tucson Basin have leveled off or slightly decreased over the period of record, largely as a result of decreased pumping in the central Tucson wellfield, compaction continues due to delayed drainage and response. Similarly, in Avra Valley, most locations with rising groundwater levels over time do not demonstrate proportional uplift, or significant decreases in compaction—even when located near artificial recharge facilities. Northern Avra Valley station AF14 is the only one in that region that shows a marked change from compaction to uplift, and yet it is much further from the main recharge facilities in Avra Valley. This uplift may be due in part to the transition of significant agricultural acreage in the area to operation as GSF facilities, which decrease pumping due to in lieu use of CAP water to irrigate. Taken as whole, the extensometer network demonstrates minimal uplift or compaction for the time period of 2003 to 2016 but given the range of responses distributed through the region, is not useful for quantifying land surface elevation change at gravity stations that are not located at extensometer sites.

Figures 11–15 show InSAR interferograms (using data provided by the ADWR) of land-surface elevation change in TAMA from:

- May 2003 to July 2006 (fig. 11),
- July 2006 to June 2008 (fig. 12),
- June 2008 to April 2011 (fig. 13),
- April 2011 to November 2014 (fig. 14), and
- November 2014 to March 2016 (fig. 15).

For the Tucson metropolitan area, maximum subsidence of about 2 inches occurred from May 2003 to July 2006. From July 2006 to June 2008, maximum subsidence of about 0.8 inches occurred in two regions in the Tucson metropolitan area. From June 2008 to April 2011, approximately 0.8 inches of subsidence also occurred in two regions. Additionally, from April 2011 to November 2014, a maximum of about 0.9 inches of subsidence occurred in the same two regions of Tucson Basin. For the entire monitoring period from May 2003 to March 2016, maximum subsidence of as much as 5.3 inches occurred in the Tucson metropolitan area south of Irvington Road between south 12th Avenue and south Park Avenue, and as much as 4 inches in central Tucson south of Broadway between Country Club Road and Craycroft Road. The InSAR data indicated that there was no significant land-surface deformation from 2003 to 2016 in Avra Valley, and no significant change in either basin from 2014 to 2016. Areas of water-level increase—a result of decreases in groundwater withdrawal and redistribution of pumping as CAP water has become available for managed recharge and municipal consumption—will decrease the potential for continued subsidence because of aquifer compaction in TAMA.

Gravity and Groundwater-Storage Change

Gravity surveys of the groundwater-storage monitoring stations were generally completed during spring to early summer or in the fall in Tucson Basin and Avra Valley every 1 to 3 years. Gravity control for the relative gravity station surveys during each measurement campaign was established with observations of absolute gravity at five or more stations (fig. 2). The absolute acceleration of gravity was calculated for each of the relative-gravity stations by summing the absolute acceleration of gravity measured at a control station and the measured difference in gravity between the control and relative-gravity stations. Gravity values for stations were corrected for measured land-surface elevation change by using the worldwide average vertical gradient of gravity, −93 microgal per foot (μGal/ft). Local vertical-gravity gradients in subsiding areas may be a few percent less than this average value, but more accurate estimates of vertical-gravity gradients would only marginally improve the accuracy of land-surface elevation change corrections for the observed magnitude of land-surface elevation change.

In the Tucson Basin from 2003–2016, changes in water level and groundwater storage were associated with precipitation and streamflow patterns. For example, increases in water-level values occurred from summer 2006 to summer 2008 in central Tucson following a large precipitation event during the summer of 2006 (fig. 16). Variations in precipitation throughout the basin can result in large runoff events that affect local recharge through stream channels that may not occur in all parts of the AMA (fig. 17). The Santa Cruz USFs constantly recharge reclaimed effluent through the part of the managed river channel, while other ephemeral channels

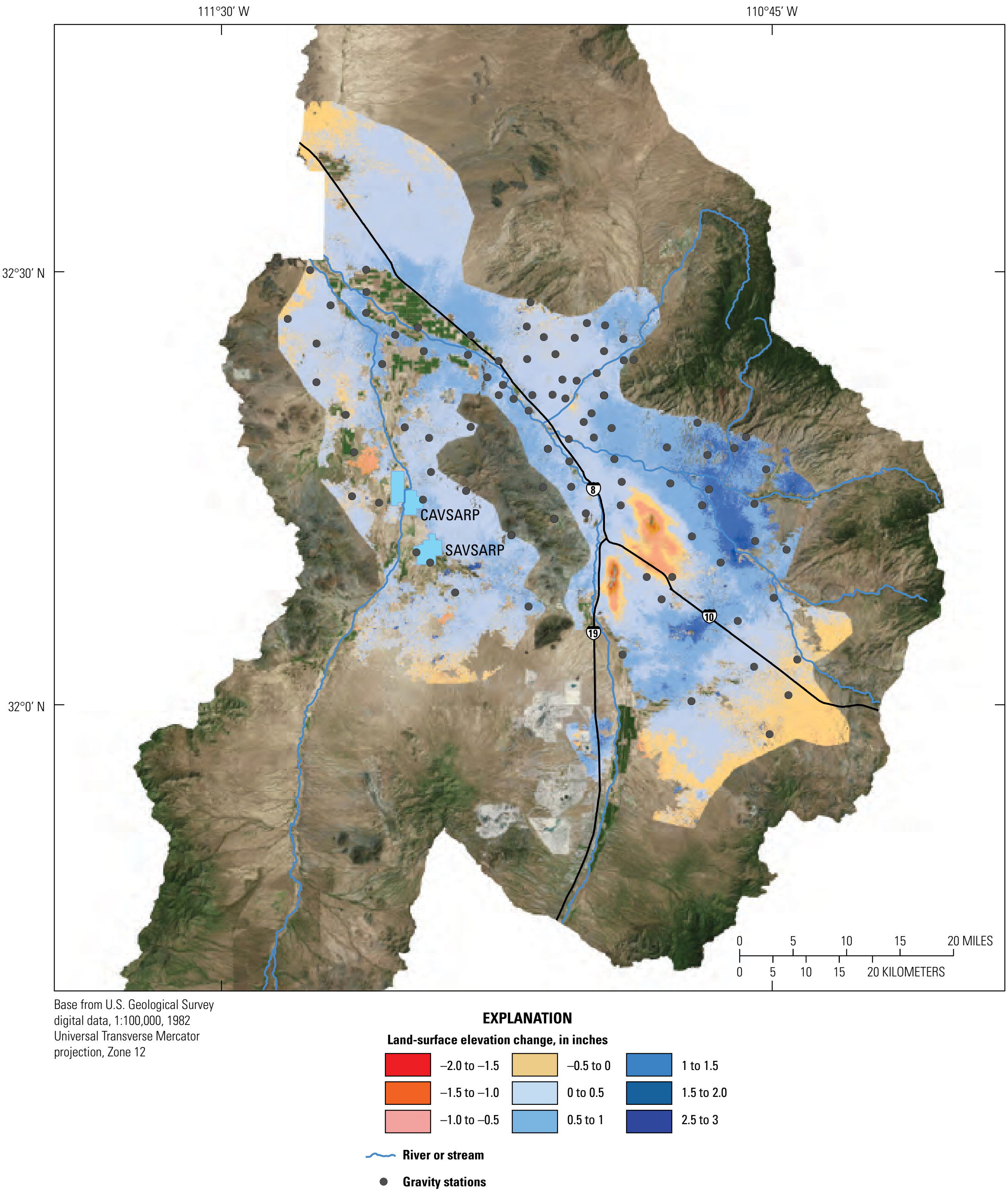


Figure 11. Map showing land-surface elevation change generated from InSAR (interferometric synthetic aperture radar) data in the Tucson Active Management Area, south-central Arizona, from May 2003 to July 2006. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

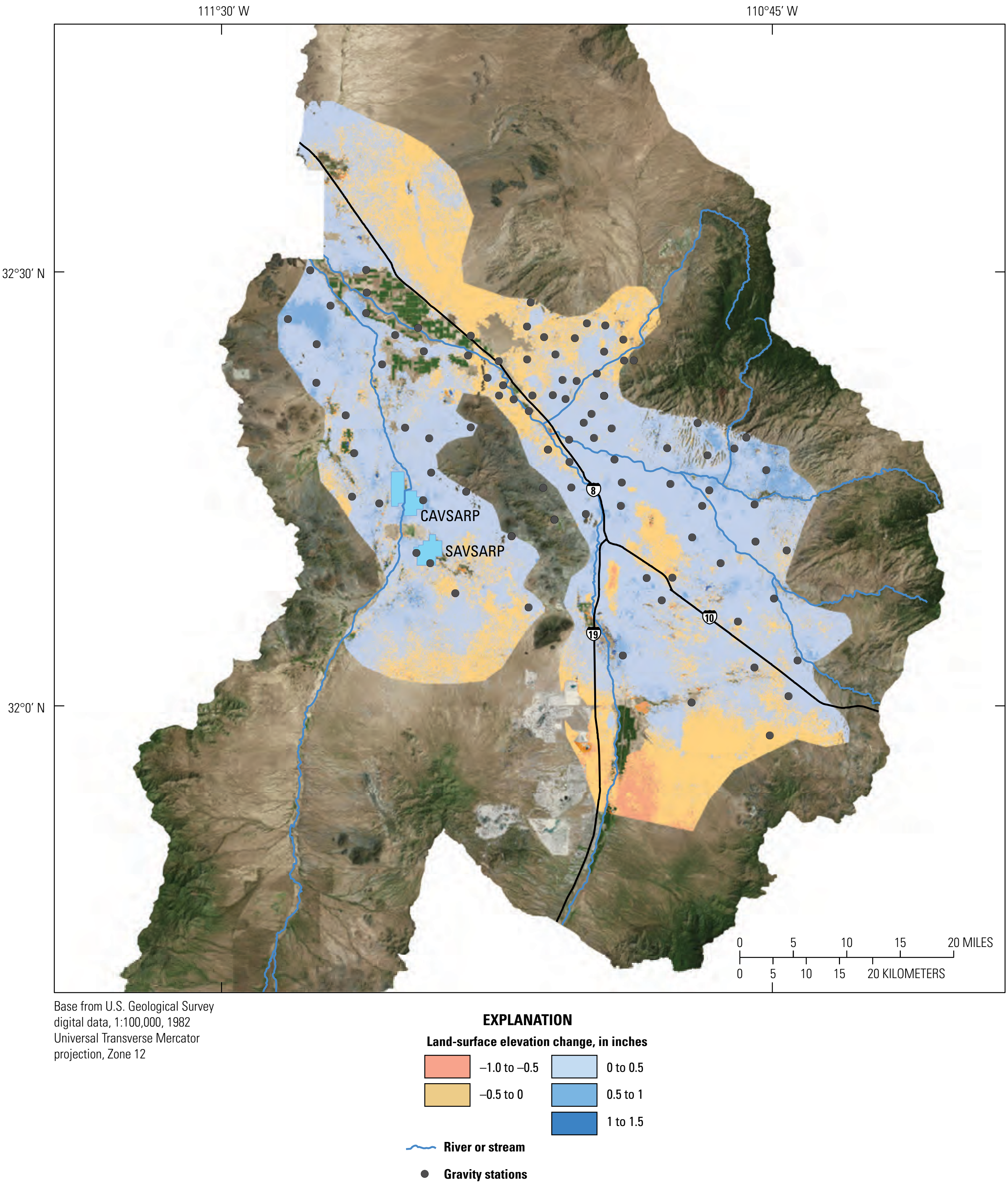


Figure 12. Map showing land-surface elevation change generated from InSAR (interferometric synthetic aperture radar) data in the Tucson Active Management Area, south-central Arizona, from July 2006 to June 2008. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

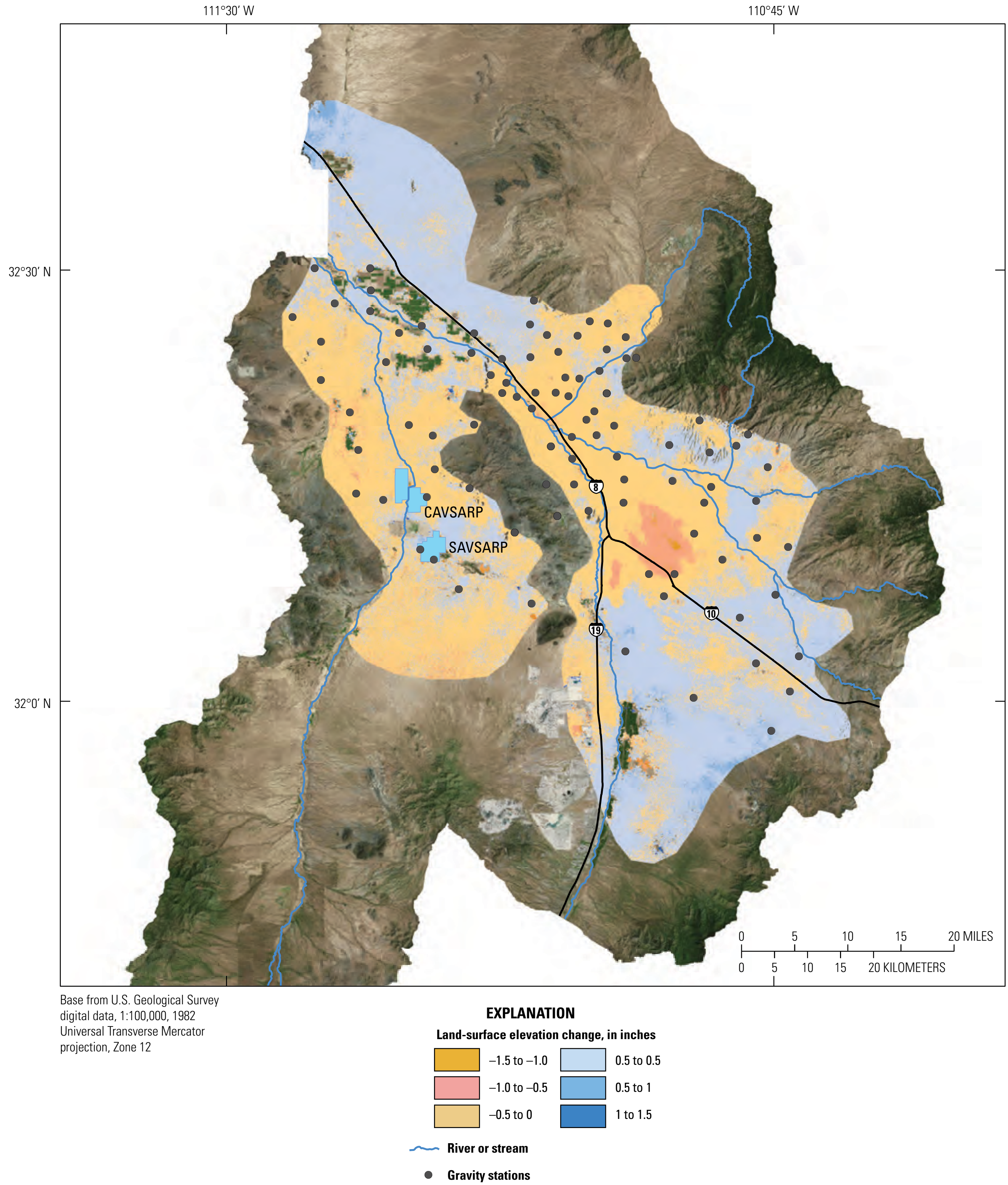


Figure 13. Map showing land-surface elevation change generated from InSAR (interferometric synthetic aperture radar) data in the Tucson Active Management Area, south-central Arizona, from June 2008 to April 2011. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

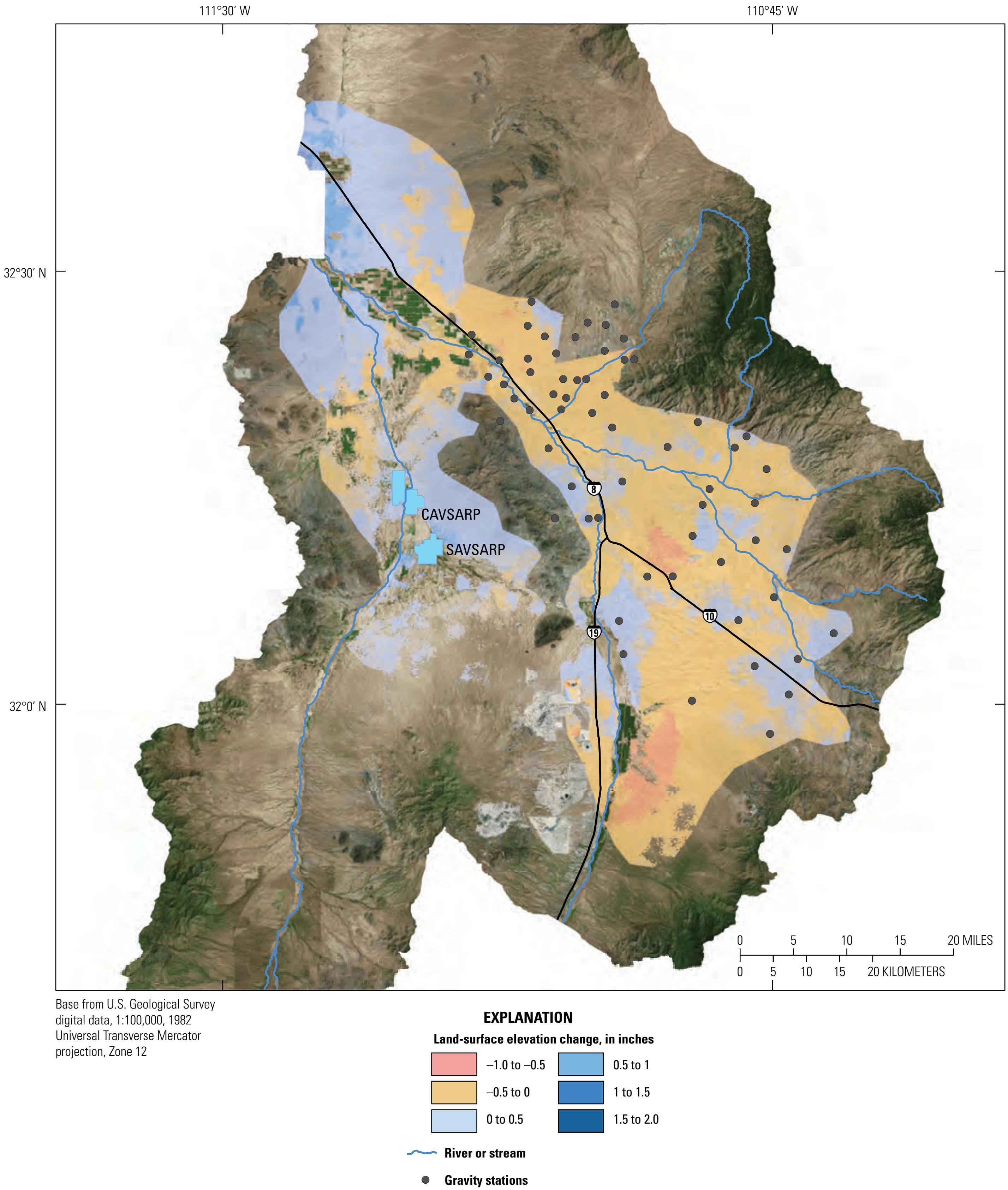


Figure 14. Map showing land-surface elevation change generated from InSAR (interferometric synthetic aperture radar) data in the Tucson Active Management Area, south-central Arizona, from April 2011 to November 2014. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

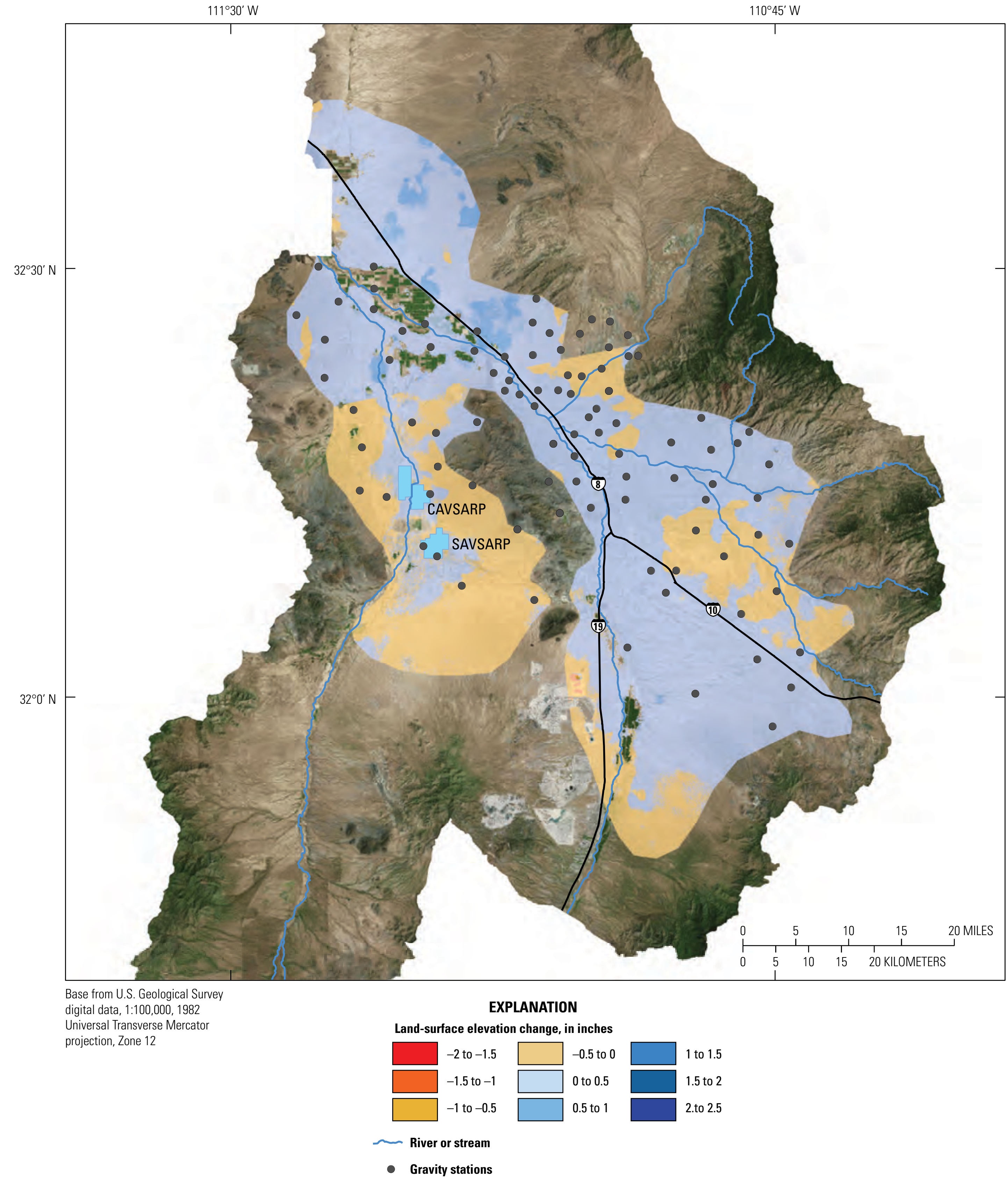


Figure 15. Map showing land-surface elevation change generated from InSAR data (interferometric synthetic aperture radar) in the Tucson Active Management Area, south-central Arizona, from November 2014 to March 2016. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

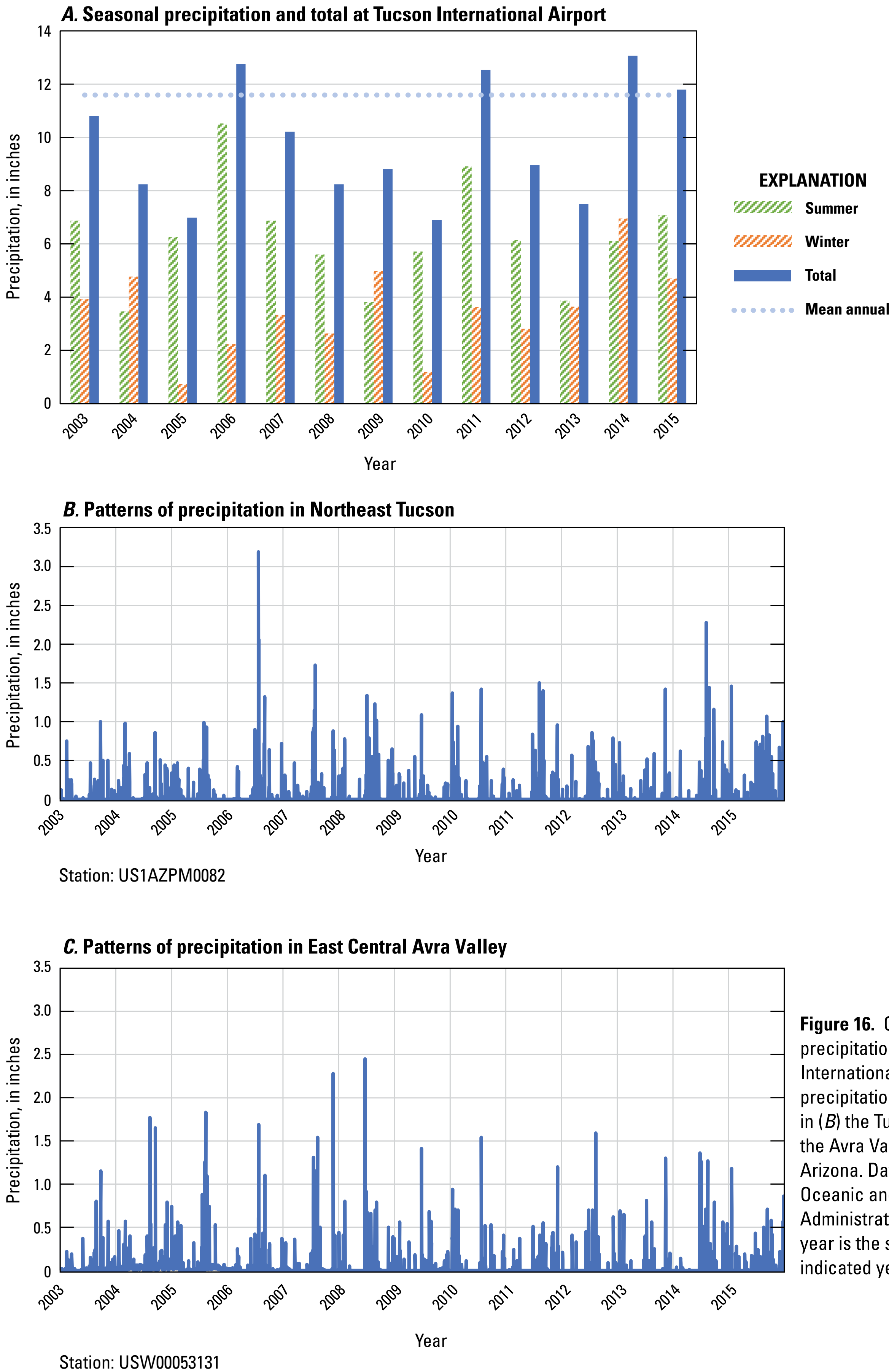


Figure 16. Graphs of seasonal precipitation at (*A*) the Tucson International Airport and precipitation patterns at locations in (*B*) the Tucson Basin and (*C*) the Avra Valley in south-central Arizona. Data from National Oceanic and Atmospheric Administration (2016). For *B* and *C*, year is the start (January 1) of the indicated year.

are only active in response to heavy precipitation events in patterns that vary spatially and temporally (fig. 17).

From fall 2014 to spring 2016, water-level rise occurred following higher than average precipitation in 2014 (fig. 16), a trend toward a reduction in groundwater withdrawal in the Tucson Basin (fig. 18), and an increase in artificial recharge (fig. 19).

The volume of stored groundwater in the monitored part of Tucson Basin was not estimated due to limited coverage between spring 2003 to summer 2006, but the average value of storage change for stations in the central part of Tucson Basin monitoring area was about 0.06 feet (fig. 20). Total recharge minus pumping for the entire Tucson Basin in this period was approximately –275,965 acre-ft (table 1). This discrepancy between positive change indicated in the monitored region and the Basin as a whole is likely due to the location of the area monitored between 2003 to 2006, which is roughly centered on a wellfield managed for recovery by Tucson Water (fig. 20). The wells in this area are only pumped during times of highest demand and water levels in this area have recovered by more than 50 feet in places (Tucson Water, Groundwater Recovery). A large precipitation and streamflow event in 2005 (figs. 16*B*, 17) also likely increased the natural recharge in this time period above the 70,000 acre-ft per year average used here, based on Pool and Anderson (2008), possibly resulting in an overestimate of groundwater loss given by the water budget components. Gravity data in Avra Valley for this time period were incomplete due to an absolute-gravity value in 2003 that could not be tied into the relative network sufficiently. During this 3-year period pumping exceeded estimated total recharge by about 97,536 acre-ft, but relative data collected in Avra Valley suggests there was some negative storage change in places as well.

From summer 2006 to summer 2008, the volume of stored groundwater in the monitored part of Tucson Basin increased approximately 50,000 acre-feet, with another 71,000 acre-feet of positive storage change in the monitored part of Avra Valley (fig. 21). An even greater precipitation and streamflow event in 2006, relative to the one in 2005, contributed to the increase in storage, and redistribution of recharge from the 2005 event continued. Pumping in both basins also went down significantly in this time period as well (table 1). Overdraft conditions resumed from summer 2008 to spring 2011, resulting in decreased storage of about 178,000 acre-feet (fig. 22) in the monitored part of Tucson Basin. Gravity data in Avra Valley for this interval were only

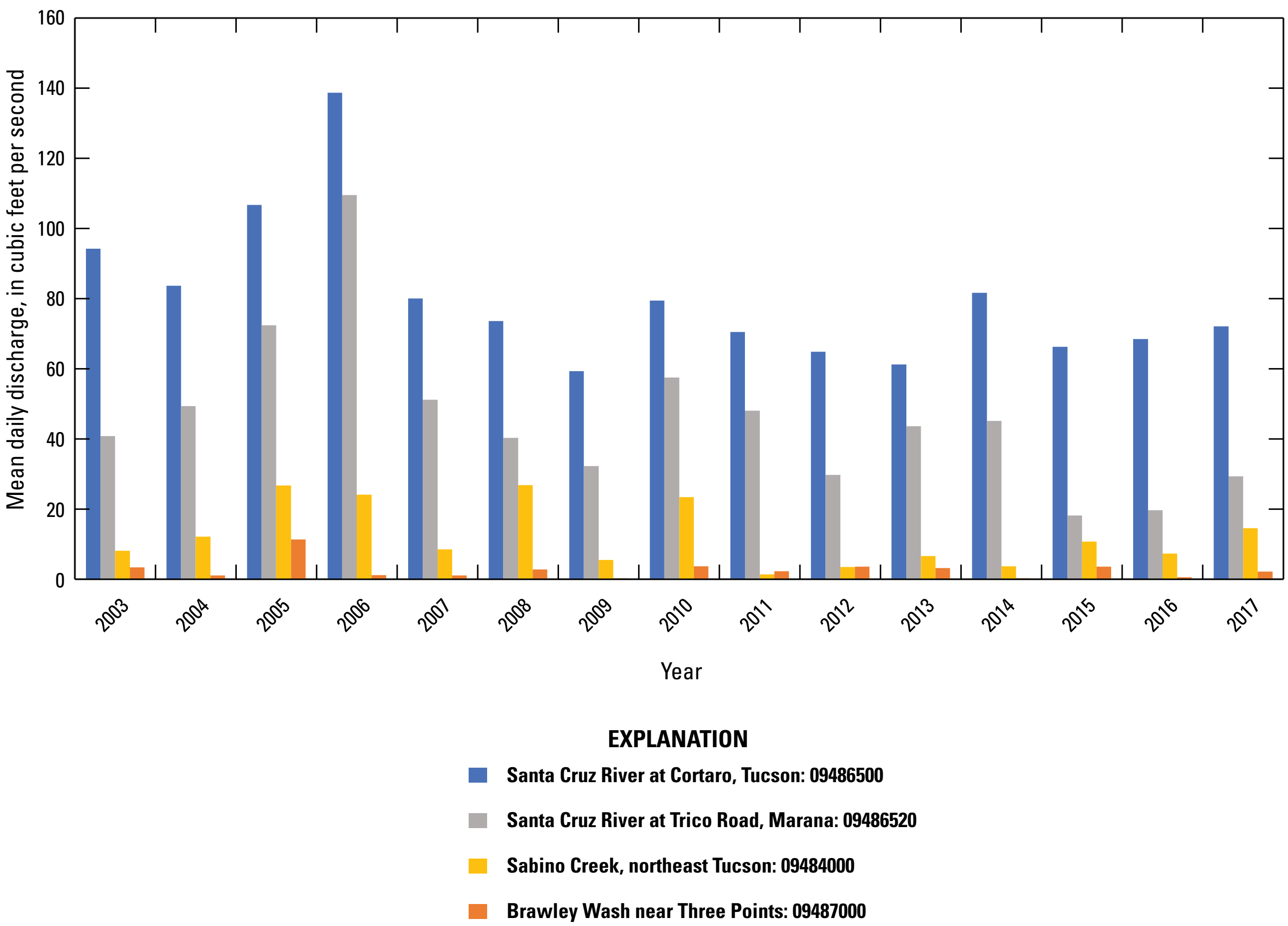


Figure 17. Graph of annual mean streamflow in channels throughout the Tucson Active Management Area, south-central Arizona.

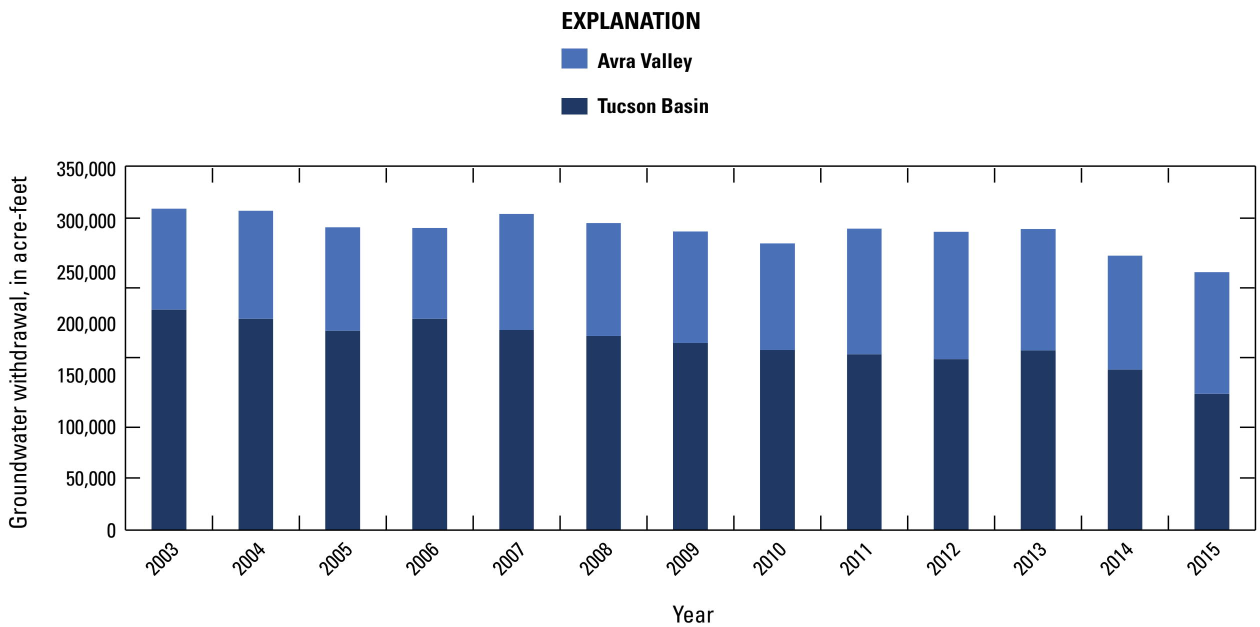


Figure 18. Graph of annual groundwater withdrawals from subbasins of the Tucson Active Management Area, south-central Arizona. Data from Arizona Department of Water Resources (2017).

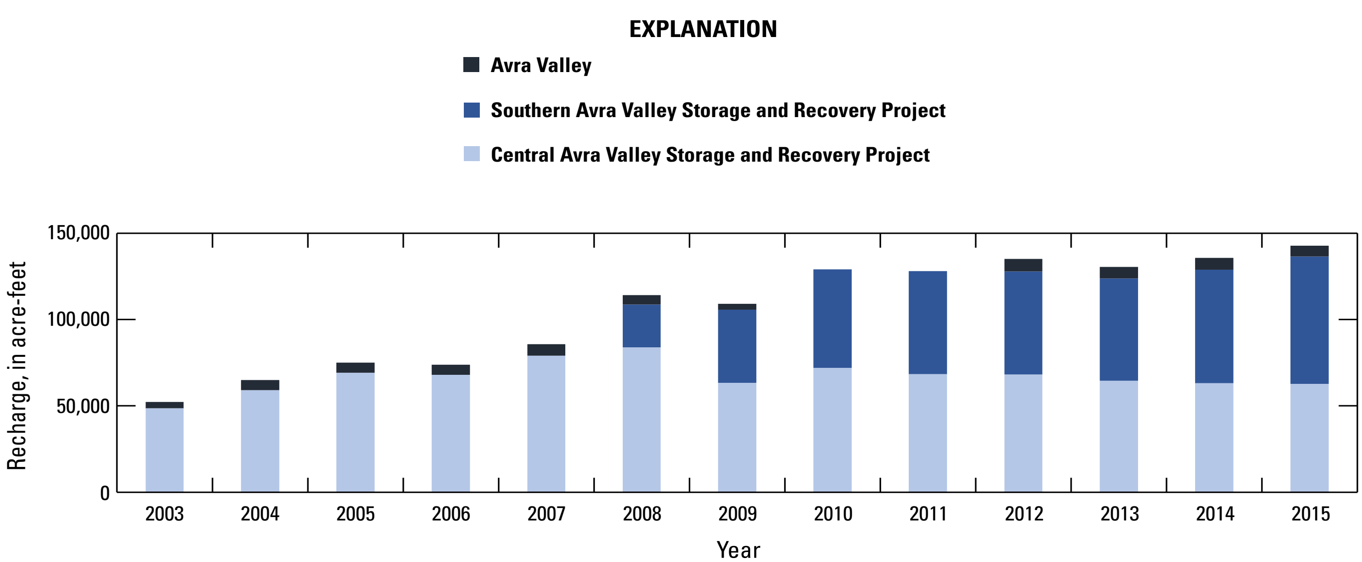


Figure 19. Graph of select annual Central Arizona Project recharge volumes in Avra Valley, south-central Arizona. Data from an Arizona Department of Water Resources (ADWR) public records request response, November 9, 2016; data are subject to amendment and revision by ADWR.

Table 1. Recharge and pumping volumes for the Avra Valley and Tucson Basin, south-central Arizona.

[Recharge and pumping volumes are from an Arizona Department of Water Resources (ADWR) public records request response, November 9, 2016, and are subject to amendment and should be considered preliminary and subject to revision. Natural recharge is based on Pool and Anderson (2008), which estimated an average annual natural-recharge rate of 70,000 acre-feet in the Tucson Basin and 30,000 acre-feet in the Avra Valley]

Recharge and pumping	Volume, in acre-feet				
	2003–2006	2006–2008	2008–2011	2011–2014	2014–2016
Avra Valley					
Artificial recharge	308,490	232,630	465,075	468,151	313,677
Pumping	300,954	198,545	318,462	360,272	226,220
Total estimated recharge: artificial and natural recharge minus pumping	97,536	94,085	236,614	197,879	147,457
Tucson Basin					
Artificial recharge	120,600	101,360	149,023	137,424	128,383
Pumping	606,565	395,811	539,777	506,259	285,558
Total estimated recharge: artificial and natural recharge minus pumping	–275,965	–154,451	–180,753	–158,835	42,825
Total: Avra Valley+Tucson Basin					
Total	–178,429	–60,367	55,860	39,044	190,282
Gravity-derived change in aquifer storage (Δ*S*)					
Δ*S* in monitored area of Avra Valley	unknown	71,000	14,000	unknown	100,000
Δ*S* in monitored area of Tucson Basin	net 0	50,000	–178,000	–200,000	167,000
Δ*S* in monitored area, total	unknown	121,000	–164,000	unknown	267,000

available in the northern part, but indicated small positive storage change for that area (fig. 22). Depth to water in wells near SAVSARP recovered by over 80 feet between 2008 and 2011, but water levels declined in wells around CAVSARP by 20 to 30 ft in some places. SAVSARP began recharging CAP water in 2008, and artificial recharge in Avra Valley almost doubled from 2008 to 2011, compared to 2006 to 2008.

From spring 2011 to fall 2014, the volume of stored groundwater in Tucson Basin decreased about 200,000 acre-feet (fig. 23), following a period of lower than average rainfall in 2012 and 2013 (fig. 16). A comparison in Avra Valley for this time period was not possible due to an issue with the meter used to monitor that part of the basin. The volume of stored groundwater in the monitored part of Tucson Basin increased about 167,000 acre-feet from fall 2014 to spring 2016 (fig. 24). Pumping for this time period was approximately 40,000 acre-feet per year under the long-term average, but the gravity-derived storage change estimate is greater than total recharge minus pumping (table 1). There were no extreme precipitation and streamflow events in this period, but lower flow events in the TAMA have been shown to result in greater infiltration through the streambed (Keith, 1981), so the greater frequency of precipitation events during this time interval likely caused an increase in natural recharge for this period (fig. 16*B*). In the monitored part of Avra Valley, the volume of stored groundwater increased approximately 100,000 acre-feet between 2014 and 2016. Estimates of changes in the stored volume of groundwater for Avra Valley are likely always underestimates due to the areal extent that is monitored. It often appears that additional increases in stored groundwater volumes are occurring south of SAVSARP, but there are only 1 to 3 gravity stations in that area, and they are spaced too far apart to justify spatial interpolation into that part of Avra Valley.

Groundwater storage in Avra Valley increased an unknown amount during the entire monitoring period from spring 2003 to spring 2016 but showed an increase in storage for every monitored time period, largely as a result of managed recharge in the monitored region (fig. 19). Groundwater storage over the monitored part of Tucson Basin decreased at least 161,000 acre-feet from 2003 to 2016, but this likely an underestimate since much of the observed negative storage changes occur in the southern part of the Basin, which was not monitored in every time interval. Storage change to south of the monitored area is also not known.

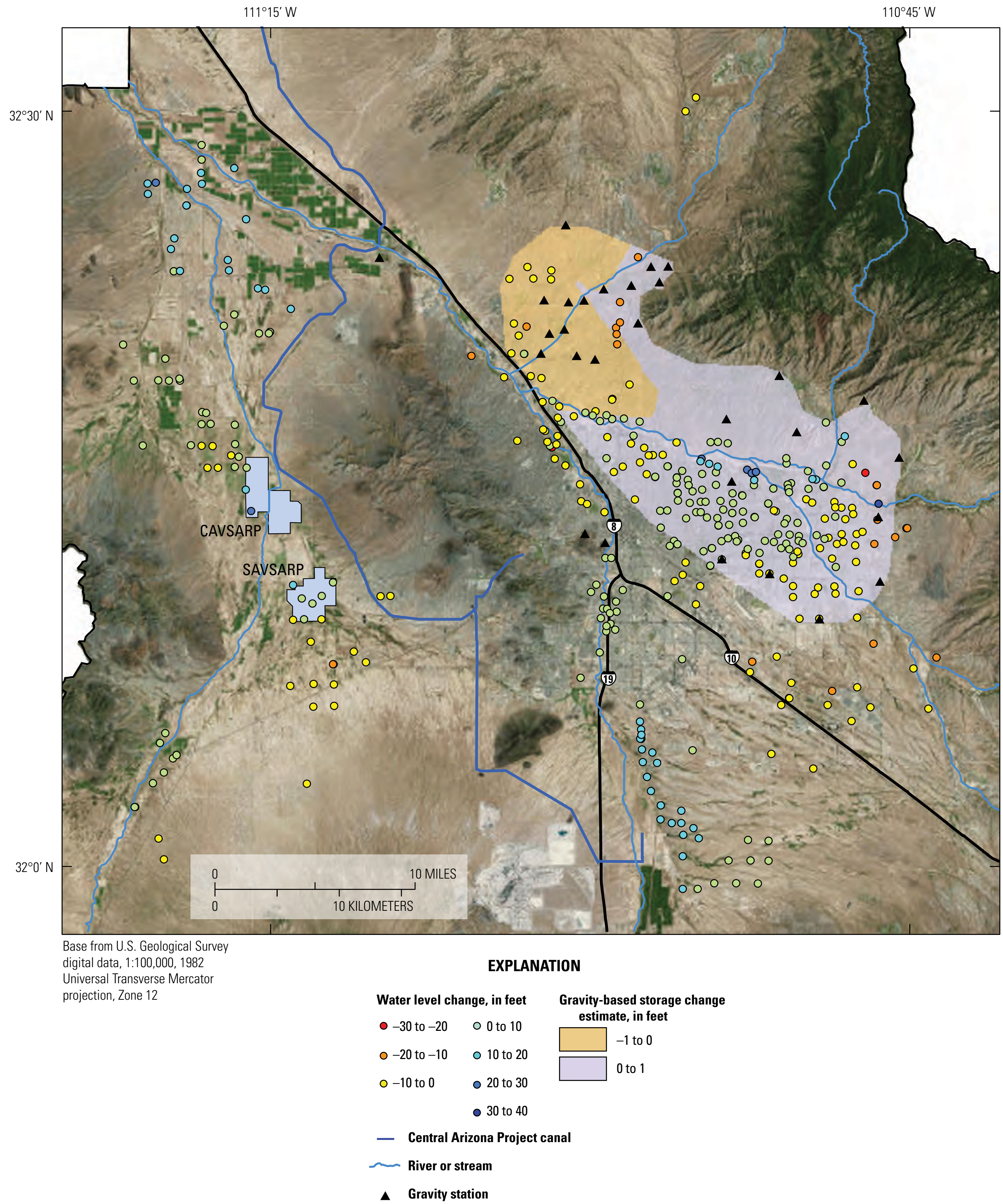


Figure 20. Map showing gravity-based groundwater-storage and water-level change in the Tucson Active Management Area, south-central Arizona, from spring 2003 to summer 2006. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

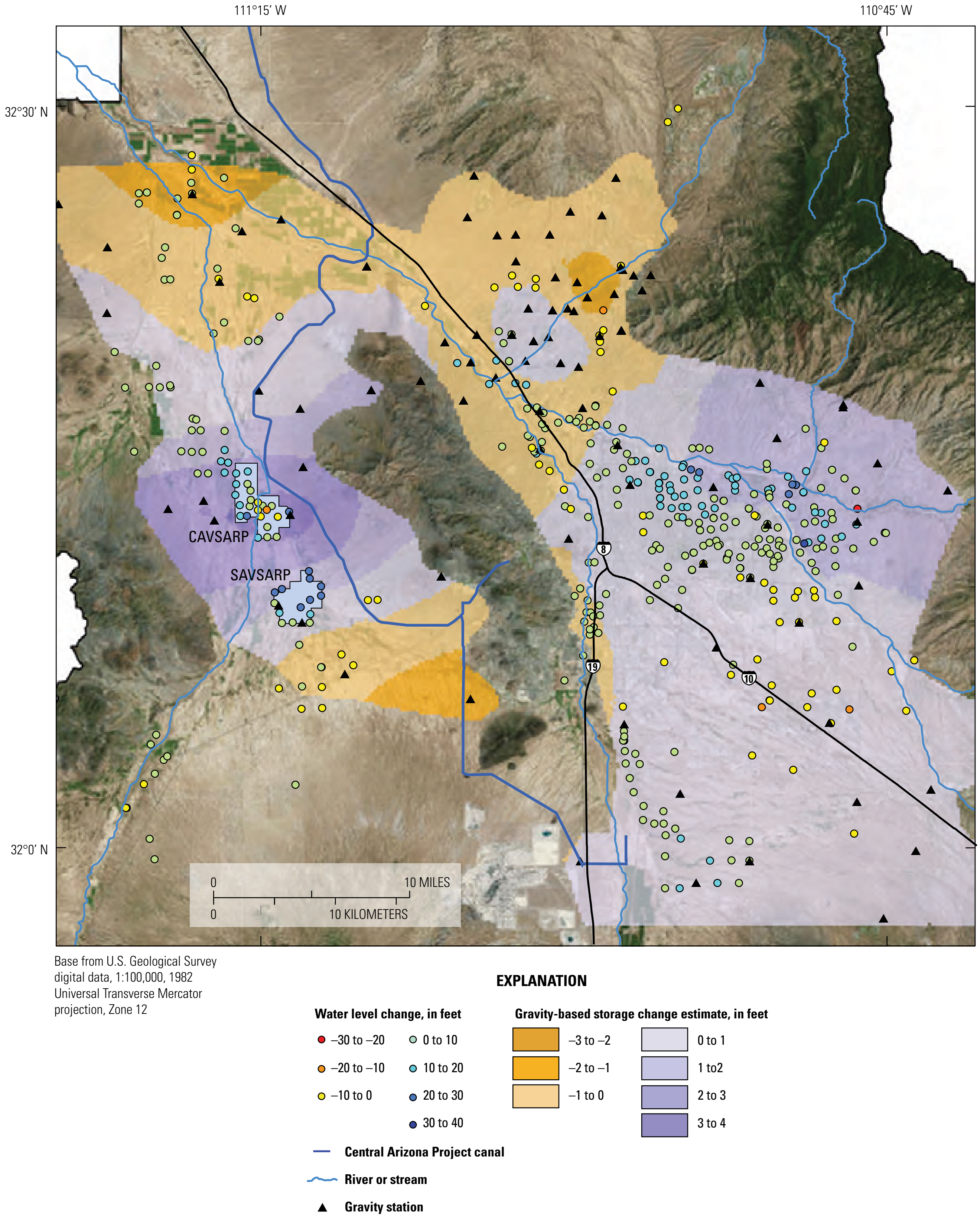
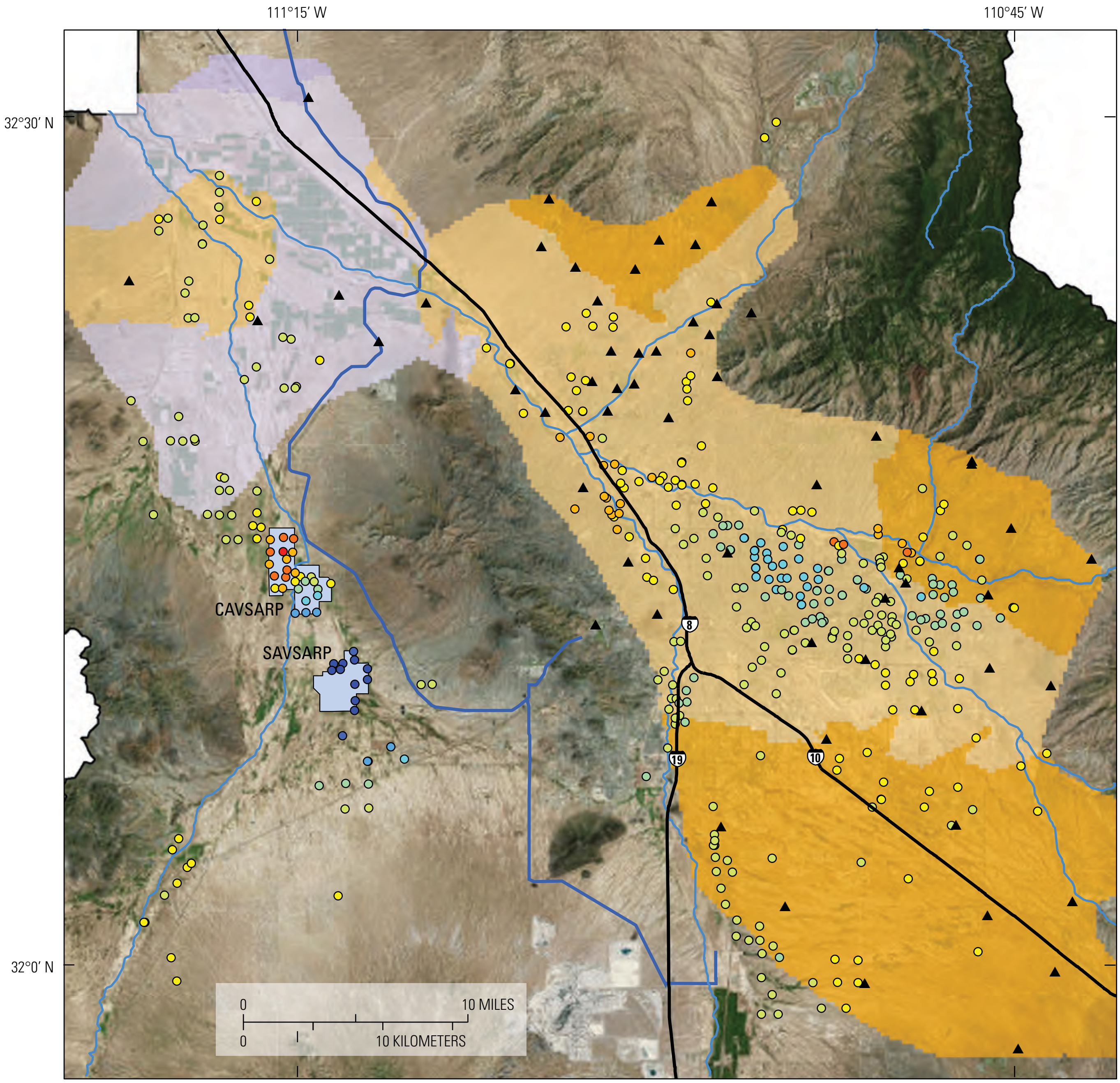


Figure 21. Map showing gravity-based groundwater-storage and water-level change in the Tucson Active Management Area, south-central Arizona, from summer 2006 to summer 2008. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.



Base from U.S. Geological Survey digital data, 1:100,000, 1982
Universal Transverse Mercator projection, Zone 12

EXPLANATION

Water level change, in feet

- −30 to −20
- −20 to −10
- −10 to 0
- 0 to 10
- 10 to 20
- 20 to 30
- 30 to 40

Gravity-based storage change estimate, in feet

- −3 to −2
- −2 to −1
- −1 to 0
- 0 to 1
- 1 to2
- 2 to 3
- 3 to 4

Central Arizona Project canal

River or stream

Gravity station

Figure 22. Map showing gravity-based groundwater-storage and water-level change in the Tucson Active Management Area, south-central Arizona, from summer 2008 to spring 2011. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

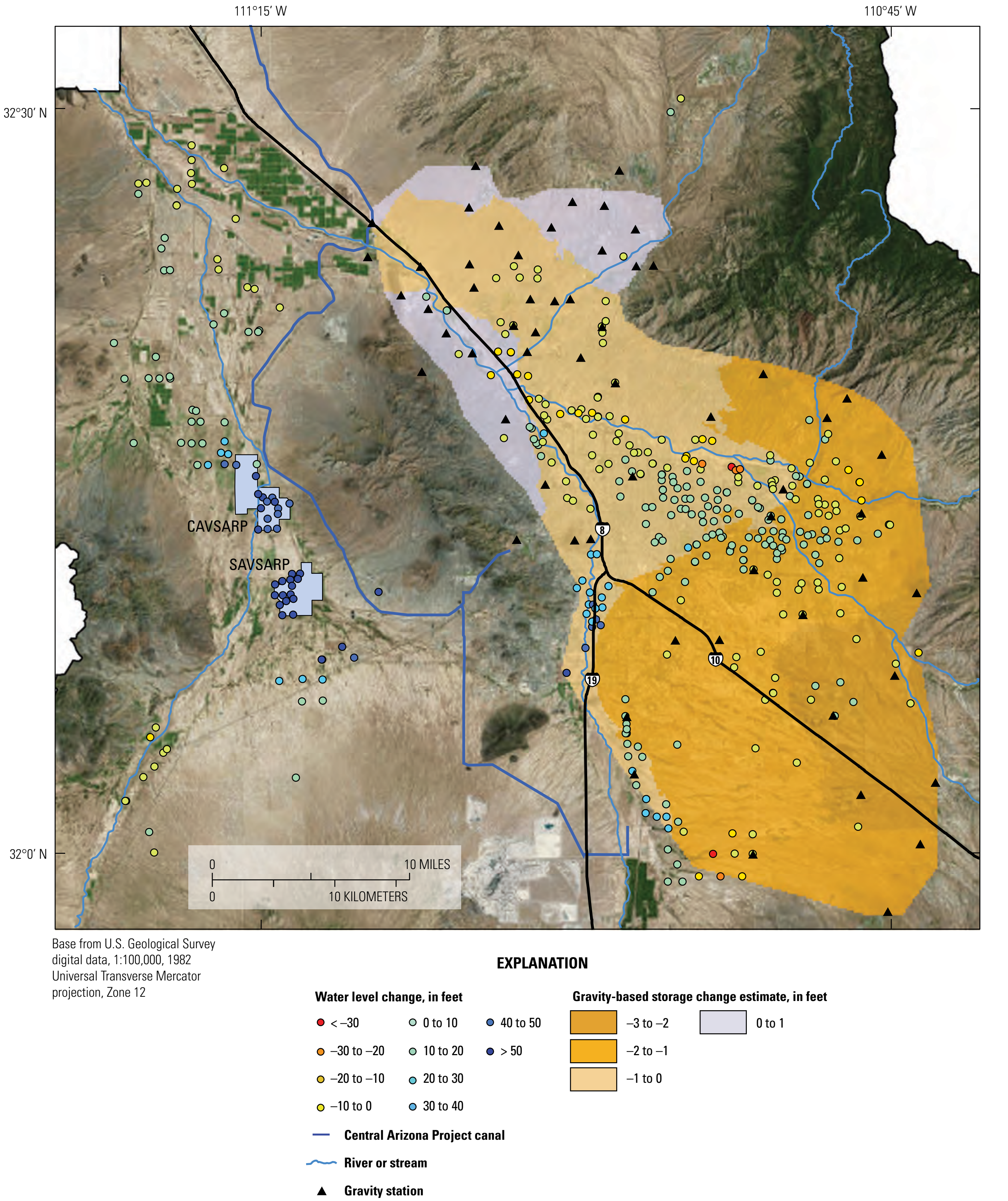


Figure 23. Map showing gravity-based groundwater-storage and water-level change in the Tucson Active Management Area, south-central Arizona, from spring 2011 to fall 2014. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

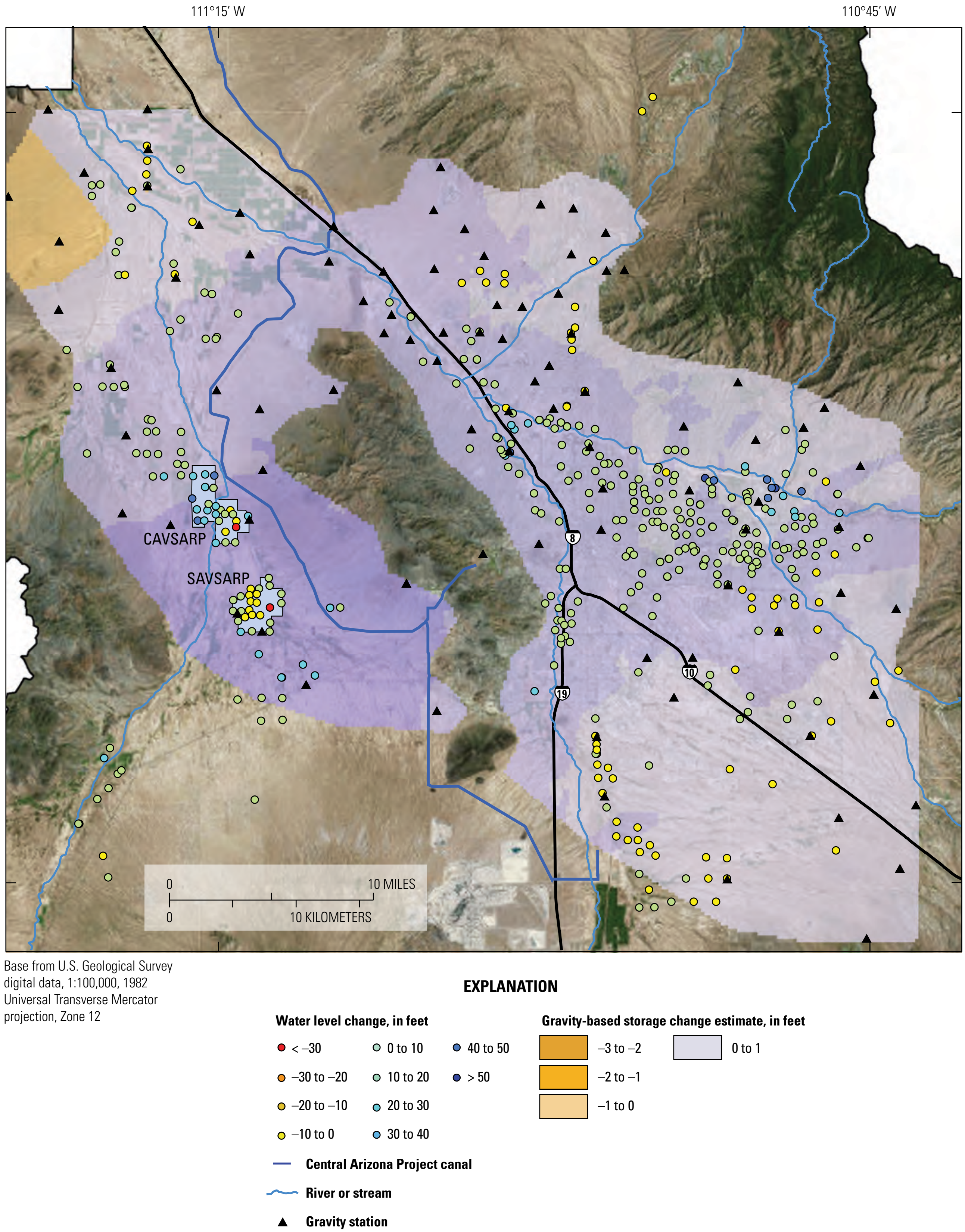


Figure 24. Map showing gravity-based groundwater-storage and water-level change in the Tucson Active Management Area, south-central Arizona, from fall 2014 to spring 2016. See figure 1 for map location. CAVSARP, Central Avra Valley Storage and Recovery Project underground storage facility; SAVSARP, Southern Avra Valley Storage and Recovery Project underground storage facility.

Summary

Gravity and land-surface elevation change were monitored every 1 to 3 years at wells and gravity stations in Tucson Basin and Avra Valley from 2003 to 2016. Monitoring resulted in estimates of land-surface elevation change and groundwater-storage change. Interferograms (from InSAR) showing land-surface elevation change were constructed for the Tucson metropolitan area from (1) May 2003 to July 2006, (2) July 2006 to June 2008, (3) June 2008 to April 2011, (4) April 2011 to November 2014, and (5) November 2014 to March 2016. For the Tucson metropolitan area, maximum subsidence of about 2 in. occurred from May 2003 to July 2006. From July 2006 to June 2008, maximum subsidence of approximately 0.8 in. occurred in two regions in the Tucson metropolitan area. From June 2008 to April 2011, about 0.8 in. of subsidence also occurred in two regions. Additionally, for the period from April 2011 to November 2014, a maximum of about 0.9 in. of subsidence occurred in the same two regions of Tucson Basin. For the entire monitoring period from May 2003 to March 2016, maximum subsidence of as much as 5.3 in. occurred in the Tucson metropolitan area south of Irvington Road between south 12th Avenue and south Park Avenue, and as much as 4 in. in central Tucson south of Broadway between Country Club Road and Craycroft Road. The InSAR data indicated there was minimal land-surface deformation from 2003 to 2016 in Avra Valley, and no significant change in either basin from 2014 to 2016.

In the Tucson Basin, increases in gravity and water-level occurred from summer 2006 to summer 2008 in central Tucson following a large natural recharge event during the summer of 2006. Overall however, declining gravity and water-level trends from spring 2003 through fall 2014 in Tucson Basin reflected general overdraft conditions and redistribution of recent recharge throughout a larger region of the aquifer. From fall 2014 to spring 2016, water-level rise and corresponding increases in gravity occurred following higher than average precipitation in 2014 and a trend toward a reduction in groundwater withdrawal in the Tucson Basin.

The volume of stored groundwater in the monitored part of Tucson Basin experienced net zero change in acre-feet from spring 2003 to summer 2006, largely due to the limited extent of the monitored area, which was located around a recovering well field. From summer 2006 to summer 2008, the volume of stored groundwater in the monitored part of Tucson Basin increased approximately 50,000 acre-feet; however, overdraft conditions resumed from summer 2008 to spring 2011, resulting in a loss from storage of about 178,000 acre-feet. From spring 2011 to fall 2014, the volume of stored groundwater in Tucson Basin decreased approximately 200,000 acre-feet, following a period of lower than average rainfall in 2012 and 2013. The volume of stored groundwater in the monitored part of Tucson Basin increased about 167,000 acre-feet from fall 2014 to spring 2016, mostly due to a decrease in pumping and also a likely increase in natural recharge in this period.

Groundwater storage in Avra Valley increased during the entire monitoring period from spring 2003 to spring 2016, largely as a result of managed recharge of Central Arizona Project water in the monitored region. The largest observed increase in groundwater storage in Avra Valley occurred during fall 2014 to spring 2016, a period when the volume of stored groundwater in the monitored area increased by about 100,000 acre-feet. The cumulative change in groundwater stored in the Tucson Basin from 2003 to 2016 is approximately −161,000 acre-feet, though this is an underestimate of loss of groundwater given that the total Basin was not monitored between 2003 and 2006 and total recharge less pumping for that time period alone was approximately −275,965 acre-feet.

Historically, groundwater withdrawal rates in TAMA that were greater than rates of inflow to the groundwater system resulted in net removal of water from groundwater storage and water-level declines during the last several decades; however, long-term water-level declines have stabilized or reversed since 2000 at most areas in Tucson Basin and Avra Valley, as indicated by the time-series data from the network of 13 extensometers. These areas of water-level increase—a result of decreases in groundwater withdrawal and redistribution of pumping as Central Arizona Project water has become available for managed recharge and recovery—will decrease the potential for continued subsidence due to aquifer compaction in TAMA.

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