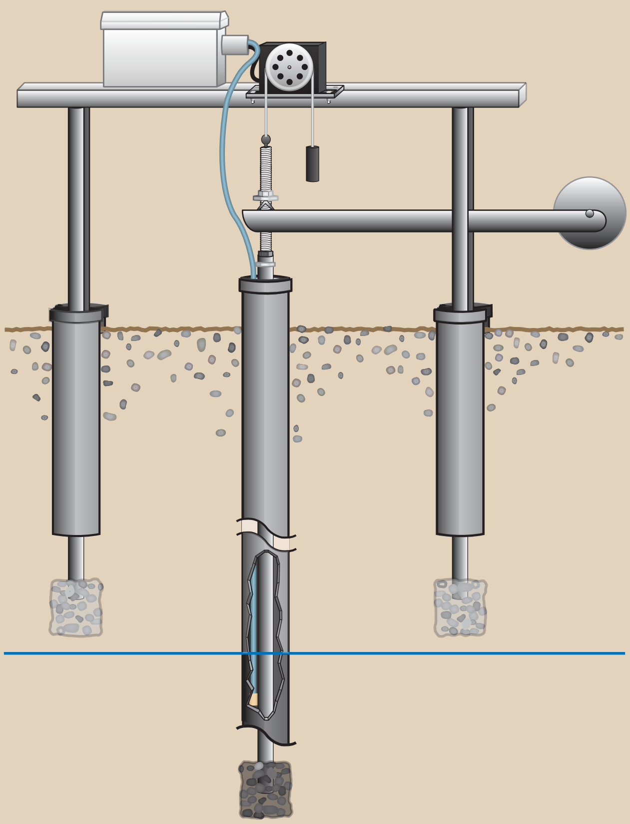
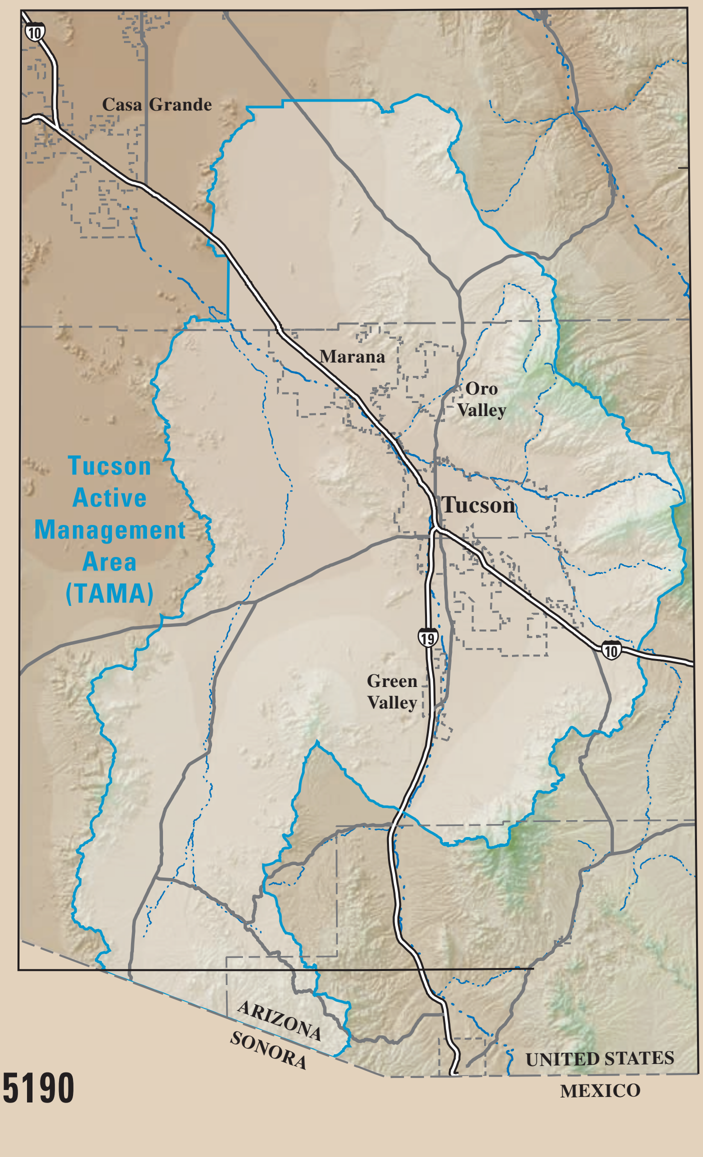
Prepared in cooperation with the
ARIZONA DEPARTMENT OF WATER RESOURCES, CITY OF TUCSON WATER DEPARTMENT, PIMA COUNTY, THE TOWN OF ORO VALLEY, THE TOWN OF MARANA, and the METROPOLITAN DOMESTIC WATER IMPROVEMENT DISTRICT

Land Subsidence and Aquifer-System Compaction in the Tucson Active Management Area, South-Central Arizona, 1987–2005





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By Robert L. Carruth, Donald R. Pool, and Carl E. Anderson

Prepared in cooperation with the Arizona Department of Water Resources, City of Tucson Water Department, Pima County, the Town of Oro Valley, the Town of Marana, and the Metropolitan Domestic Water Improvement District

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FRONT COVER

Left, diagrammatic sketch of a borehole extensometer used in the Tucson Active Management Area.
Right, map of the Tucson Active Management Area in south-central Arizona.

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Conversion Factors

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)
yard (yd)	0.9144	meter (m)
Area		
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Land Subsidence and Aquifer-System Compaction in the Tucson Active Management Area, South-Central Arizona, 1987–2005

By Robert L. Carruth, Donald R. Pool, and Carl E. Anderson

Abstract

The U.S. Geological Survey monitors land subsidence and aquifer-system compaction caused by ground-water depletion in Tucson Basin and Avra Valley—two of the three alluvial basins within the Tucson Active Management Area. In spring 1987, the Global Positioning System was used to measure horizontal and vertical positions for bench marks at 43 sites to establish a network for monitoring land subsidence in Tucson Basin and Avra Valley. Between 1987 and 2005, the original number of subsidence monitoring stations was gradually increased to more than 100 stations to meet the need for information in the growing metropolitan area. Data from approximately 60 stations common to the Global Positioning System surveys done after an initial survey in 1987 are used to document land subsidence. For the periods of comparison, average land-surface deformation generally is less than the maximum subsidence at an individual station and takes into account land-surface recovery from elastic aquifer-system compaction. Between 1987 and 1998, as much as 3.2 inches of subsidence occurred in Tucson Basin and as much as 4 inches of subsidence occurred in Avra Valley. For the 31 stations that are common to both the 1987 and 1998 Global Positioning System surveys, the average subsidence during the 11-year period was about 0.5 inch in Tucson Basin and about 1.2 inches in Avra Valley.

For the approximately 60 stations that are common to both the 1998 and 2002 Global Positioning System surveys, the data indicate that as much as 3.5 inches of subsidence occurred in Tucson Basin and as much as 1.1 inches of subsidence occurred in Avra Valley. The average subsidence for the 4-year period is about 0.4 inch in Tucson Basin and 0.6 inch in Avra Valley. Between the 2002 and the 2005 Global Positioning System surveys, the data indicate that as much as 0.2 inch of subsidence occurred in Tucson Basin and as much as 2.2 inches of subsidence occurred in Avra Valley. The average subsidence for the 3-year period is about 0.7 inch in Avra Valley.

Between 1987 and 2004-05, land subsidence was greater in Avra Valley than in Tucson Basin on the basis of the average cumulative subsidence for the stations that were common to the original Global Positioning System survey in 1987. The average total subsidence during the 17- to 18-year period was about 1.3 inches in Tucson Basin and about 2.8 inches in Avra Valley. Three stations in Tucson Basin showed subsidence greater than 4 inches for the period—5 inches at stations C45 and X419 and 4.1 inches at station PA4. In Avra Valley, two stations showed subsidence for the 17- to 18-year period greater than 4 inches—4.3 inches at station AV25 and 4.8 inches at station SA105.

In 1983, fourteen wells were fitted with borehole extensometers to monitor water-level fluctuations and aquifer-system compaction. Continuous records of water level and aquifer-system compaction indicate that as much as 45 feet of water-level decline and 4 inches of aquifer-system compaction occurred in Tucson Basin from January 1989 through December, 2005. In Avra Valley, extensometer data indicate that as much as 55 feet of water-level decline and 1.7 inches of aquifer-system compaction occurred during the same time period. Rates of compaction vary throughout the extensometer network, with the greater rates of compaction being associated with areas of greater water-level decline and more compressible sediments. In Avra Valley, data from the Global Positioning System surveys indicate that more than half of the total subsidence of the land surface may be the result of aquifer-system compaction below the portion of the aquifer instrumented with the vertical extensometers.

For the area in the northern part of Tucson Basin between the Rillito and Santa Cruz rivers, an Interferometric Synthetic Aperture Radar interferogram indicates that about 1.65 inches of subsidence occurred between 2003 and 2006. Between 2002 and 2004, the Global Positioning System station at C45, in the same northern area of Tucson basin, shows subsidence of 1.2 inches, indicating a good correlation between the Global Positioning System data and the Interferometric Synthetic Aperture Radar data.

Introduction

The Tucson Active Management Area (TAMA) encompasses about 3,900 mi^2 in south-central Arizona (fig. 1). The TAMA is one of five Active Management Areas established

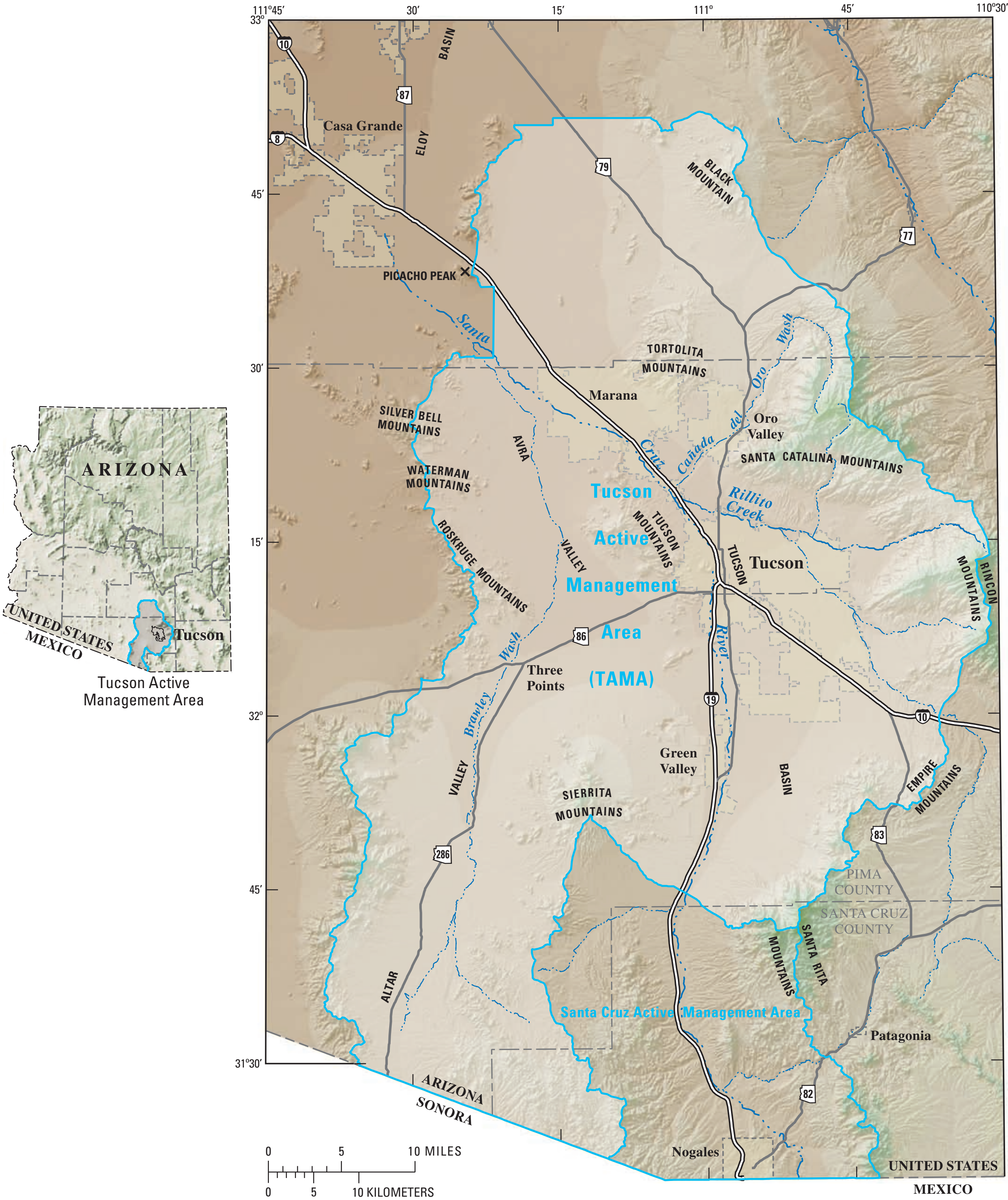


Figure 1. Tucson Active Management Area in south-central Arizona.

pursuant to Arizona's 1980 Groundwater Management Act and is administered by the Arizona Department of Water Resources. There are three alluvial basins within the TAMA: Tucson Basin, Avra Valley, and Altar Valley. Land use varies significantly within the three basins. Tucson Basin is heavily urbanized with a rapidly growing population. Avra Valley is mostly rural, having been primarily agricultural in the past. Land use in the Avra Valley basin presently is mixed use, as much of the agricultural land has been retired for use in housing development and for use by the City of Tucson Water Department for artificial recharge of Central Arizona Project water and other municipal water-supply projects. Altar Valley, located in the southeastern portion of the TAMA, has many ranches and a wildlife refuge. Land subsidence and aquifer-system compaction is not monitored presently in Altar Valley owing to the largely undeveloped nature of the area,

The TAMA has been dependent upon ground water for urban and agricultural consumption, and ground-water withdrawal has exceeded natural recharge for many decades. As a result, between 1989 and 2005, water levels in the TAMA declined by as much as 45 ft in Tucson Basin, and 55 ft in Avra Valley. Water levels in Altar Valley, where residential and commercial development are minimal, have remained largely unchanged.

Background

Ground water is a critical resource in the TAMA, providing drinking water to urban and rural communities, supporting irrigation, mining, and industry, and sustaining baseflow in small streams along mountain fronts that support riparian ecosystems. Land subsidence and aquifer-system compaction can occur when water is removed from alluvial-aquifer systems. Land subsidence is the loss of surface elevation as the result of the removal of subsurface support (Galloway and others, (1999). Decisions by stakeholders concerning the sustainable development of land and water resources within the TAMA could benefit from improved scientific understanding, detection, and monitoring of aquifer-system compaction and land subsidence.

According to Galloway and others (2000), more than 80 percent of the identified subsidence in the United States is a consequence of human impact on subsurface water and is dominated by three distinct processes—compaction of aquifer systems, drainage and subsequent oxidation of organic soils, and dissolution and collapse of susceptible rocks. In the TAMA, ground-water pumping in excess of natural recharge is the major cause of aquifer-system compaction and associated land subsidence.

The focus of this report is on compaction of sediments within the saturated ground-water system. It is important to note, however, that other processes can cause land-surface movement in the area. In particular, near-surface compaction or expansion of soils from wetting and drying has been known to cause damage to houses and other structures in the TAMA, particularly in areas that are underlain by soils with a high clay content. The Natural Resources Conservation Service has produced maps of soil-shrink/swell potential for the greater Tucson area (http://www.az.nrcs.usda.gov/technical/soils/shrinkswell.html). Shrink/swell potential is the relative change in volume to be expected with changes in moisture content. Platt (1963) found that mapped zones with a high frequency of building fractures in the Tucson area had a positive correlation with the Tucson Loam soil type when superimposed on the county soil map. In the Tucson area, urban wetting and drying of soils with a high shrink/swell potential is an important issue in terms of realized and potential damage to buildings and foundations; however, the study of this process is beyond the scope of this report.

As early as the 1940s, water-level declines of up to several feet per year have resulted in aquifer-system compaction and measurable land subsidence in Tucson Basin and Avra Valley (Evans and Pool, 2000). Conventional first-order leveling surveys showed that ground-water pumping resulted in about 0.5 ft of land subsidence in Tucson Basin between 1952 and 1980 and about 1 ft of land subsidence in the northwestern part of Avra Valley between 1948 and 1980 (Schumann and Anderson, 1988).

In 1979, the U.S. Geological Survey (USGS), in cooperation with the City of Tucson, began an investigation to determine the potential for aquifer-system compaction, land subsidence, and earth fissures in Tucson Basin. This USGS-City of Tucson study lead to the construction of a network of 14 vertical extensometers, seven in Tucson Basin and seven in Avra Valley. In 1987, a network of vertical control stations was established in cooperation with the City of Tucson and the National Geodetic Survey to use the Global Positioning System (GPS). The vertical-control network consisted of 43 benchmarks, and the network was designed to map land subsidence in Tucson Basin and Avra Valley.

In 1996, the USGS began a cooperative study with Metropolitan Domestic Water Improvement District and the town of Oro Valley to monitor aquifer-storage change in the Lower Cañada del Oro subbasin. In 1998, the USGS began a cooperative study with the Arizona Department of Water Resources (ADWR), Pima County, and the City of Tucson to monitor land subsidence and aquifer-storage change in the TAMA. In 2003, these two monitoring studies were combined, and the town of Marana joined the study. This report documents the results of analyses made from measurements at a vertical-control network and a vertical-extensometer network established to determine the relation between ground-water depletion, aquifer-system compaction and land subsidence in Tucson Basin and Avra Valley.

Purpose and Scope

The purpose of this report is to describe aquifer-system compaction and land subsidence caused by ground-water depletion in Tucson Basin and Avra Valley between 1987 and 2005. Land-surface elevation was measured approximately annually by using GPS-survey methods at a network of stable-benchmark monitoring stations in Tucson Basin and Avra Valley. Rates and magnitude of aquifer-system compaction and water-level change were measured by using a network of vertical extensometers.

Previous Investigations

Evans and Pool (2000), provide a comprehensive summary of Federal, State, county, municipal, and university studies that have focused on various aspects of the hydrogeologic framework and water resources of alluvial basins in southern Arizona. In the TAMA, the hydrogeology and water resources were described by Davidson (1973), Pool (1984), and Schmidt (1985), and stratigraphy was described by Allen (1981) and Anderson (1987a). Models of ground-water flow were developed by Anderson (1972), Moosburner (1972), Clifton (1981), Travers and Mock (1984), Mock and others (1985), and Mason and Bota (2006). The potential for aquifer-system compaction, land subsidence, and earth fissures was evaluated by Platt (1963), Caito and Sogge (1982), Anderson (1987a, 1989), Carpenter (1988, 1993), Hanson (1989), Hanson and others (1990), and Hanson and Benedict (1994). General ground-water conditions were defined by White and others (1966), Reeter and Cady (1982), Whallon (1983), and Cuff and Anderson (1987). Hydrologic and geologic terms used in this report are summarized by Poland and others (1972), and Laney and Davidson (1986). Holzer and others (1979) and Jachens and Holzer (1979) describe fissuring and subsidence related to ground-water withdrawal.

Using GPS methods, Schumann and Anderson (1988) established the original land-subsidence monitoring network in Tucson Basin and Avra Valley. A ground-water storage monitoring project in the Tucson Basin, incorporating stations from the original land-subsidence monitoring network, was also begun in the late-1980s by Dr. John Sumner of the University of Arizona Geosciences Department.

Acknowledgments

This investigation and report is the result of cooperation among several individuals and agencies. Cooperating agencies include the Tucson Active Management Area of the Arizona Department of Water Resources, the City of Tucson Water Department, Pima County Department of Transportation, and the Pima County Regional Flood Control District. The Pima County Surveyors office organized and conducted the majority of the GPS surveys from 1998 to 2002. Support from several other agencies, including Metropolitan Domestic Water Improvement District, the Town of Oro Valley, and the Town of Marana was helpful in the development of this project.

Description of the Study Area

The alluvial basins of Tucson and Avra Valley are in the Basin and Range physiographic province of Arizona. The basins are partly surrounded by mountains that include ranges that are more than 9,000 ft above sea level. Tucson Basin and Avra Valley, the focus of this study, lie to the southeast of the Eloy Basin within the boundaries of the TAMA, except for a small area near Picacho Peak (fig. 1). The watershed area for the Tucson Basin extends beyond the study area and the southern boundary of the TAMA and encompasses about 2,870 mi^2 in northern Sonora, Mexico, and in Santa Cruz, Pima, and Pinal, Counties, Arizona. Tucson Basin is bounded on the west by the Tucson and Sierrita Mountains, on the north by the Tortolita and Santa Catalina Mountains, on the east by the Rincon and Empire Mountains, and on the south by the Santa Rita Mountains. The southern drainage-area boundary is south of the study area in Mexico. The mountains range in altitude from about 3,000 ft to about 9,500 ft above sea level. Within the basin, the valley floor ranges in altitude from 2,000 ft above sea level near Rillito and the northwestern edge of the basin to 3,500 ft near the international boundary with Mexico. Annual precipitation ranges from about 10 in. to 12 in. on the valley floor to as much as 30 in. in the surrounding mountains.

Avra Valley encompasses about 520 mi^2 and is bounded on the south by the Sierrita Mountains and Altar Valley, on the west by Silverbell, Waterman, and Roskruge Mountains, on the northwest by Picacho Peak, and on the northeast by the Tortolita Mountains. The surrounding mountains range in altitude from about 4,500 ft to 6,000 ft above sea level. The valley floor ranges from 1,800 ft above sea level near Picacho Peak to 2,600 ft near Three Points. Annual precipitation in Avra Valley ranges from less than 10 in. on the valley floor to about 12 in. in the mountains.

The Santa Cruz River is the major surface-water drainage in the Tucson Basin and Avra Valley. Before large-scale ground-water pumping began in the basin, the Santa Cruz River was perennial in sections of the study area. As of 1998, the baseflow in the river is effluent and occurs in reaches below the three water-treatment plants located where the river intersects with Roger Road, Ina Road, and Tangerine Road. Natural flow occurs only during periods of runoff from storms. Other streams in the study area generally flow only in response to local precipitation and include the Rillito River and the Cañada del Oro Wash in Tucson Basin and Brawley Wash in Avra Valley.

Methods of Data Collection

In Tucson Basin and Avra Valley, land-surface elevation change is monitored approximately annually by using GPS surveys. The GPS is a United States Department of Defense satellite-based system designed to provide continuous worldwide positioning capability. The system comprises a full constellation of at least 24 satellites that act as reference points so that a GPS receiver can be used to calculate accurate position information. In GPS surveying, the satellite-based system with Earth-based reference stations is used to determine accurately the position of geodetic monuments. The vertical positions of stations are monitored by using repeat GPS surveys to determine any changes in elevation.

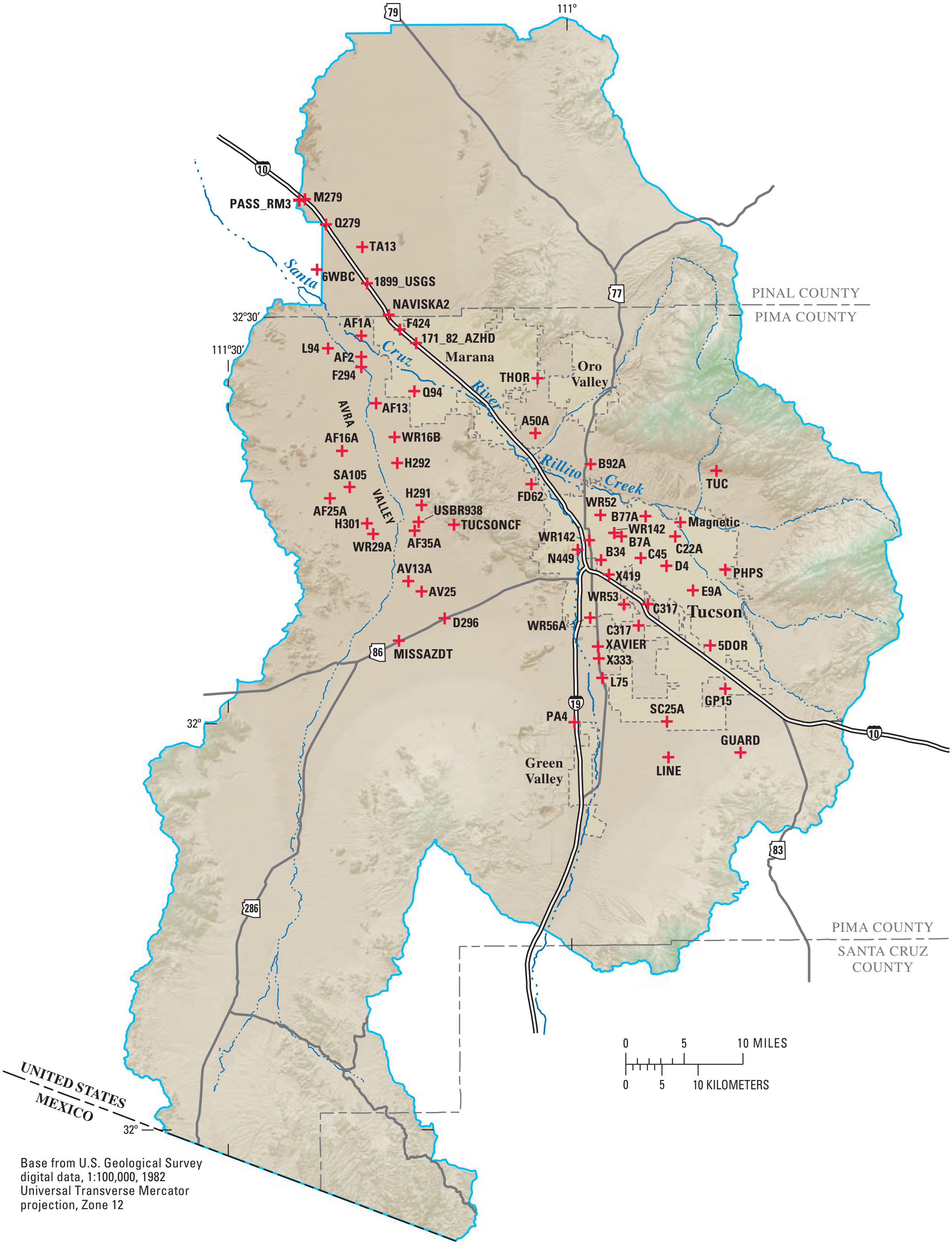


Figure 2. Long-term elevation-change monitoring stations in the Tucson Active Management Area.

Figure 3. Photograph of a typical setup of a geodetic GPS receiver in the Tucson Active Management Area.

In the spring of 1987, the GPS was used to establish a vertical-control network for monitoring land subsidence in Tucson Basin and Avra Valley (fig. 2). The initial survey was done by using satellite receivers and antennas from the Motorola, Inc., Government Electronics Group. Presently, survey instruments are Trimble 4800 and 5700 geodetic-grade receivers. Receivers are placed on fixed-height tripods at most stations to minimize errors in antenna-height measurements (fig. 3).

The initial GPS survey consisted of a series of measurements at bench marks at 43 sites; however, at least 11 of the original benchmarks had been destroyed by the time annually repeated surveys had begun (table 1). In 1998, approximately annual GPS surveys began, using as much of the original network as possible. Many new stations were added to the network between 1998 and 2005 to provide additional information on both amounts and areal distribution of land-surface elevation change in the growing metropolitan areas of the TAMA.

Surveys of the Tucson Basin and Avra Valley networks were made by using static-surveying techniques. Static surveying is the most precise GPS-surveying technique and is performed with dual-frequency receivers. A static survey requires the use of at least two receivers; one receiver at each of two (or more) stations defines the baseline. Each receiver logs observations simultaneously from at least four common satellites. Static surveying requires that observations be logged at each station for an extended period of time. In the TAMA, the GPS surveys were performed by using multiple overlapping subnetworks of three to six stations. A single base station was common to every subnetwork. Stations were occupied for a minimum of 30 minutes, and many stations were occupied for several hours. Generally, about 20 percent of the stations were reoccupied for redundancy and quality assurance.

The GPS data were post-processed to achieve an accuracy of 0.8 in. or better. GPS data were downloaded and processed by using software that calculates differential positions between stations. A least-squares network adjustment was performed by using stations on bedrock with known positions that are assumed to be stable from year to year. Additionally, one to several stations within the basins with little to no historical movement also were used in the network adjustment. Stable, stationary stations included TUC, N419, POST, GUARD, and THOR in the Tucson Basin and H291 and PASS in Avra Valley. Resulting station positions generally were accurate to within 0.8 in. in the vertical position and 0.4 in. in the horizontal position. Results of the network adjustments of each annual survey were differenced to determine changes in station vertical position and land subsidence.

In order to directly compare data sets from year to year, the same set of points were used in the network adjustments. Using different points for network adjustments could introduce some error by allowing the entire network to “rotate” in order to fit a new set of control points. If analogous points are used each year for the network adjustment, the network is fixed to the same place each time, allowing for the best possible comparison of station positions from each successive survey.

Surveys from 2004 and 2005 did not contain some control points used historically in the network adjustment, and therefore, could not be processed to the same level of certainty. To allow for a full network adjustment, control points missing from 2004 and 2005 data sets were imported from the 2002 GPS data set. Bedrock control points (their positions and vectors) from past surveys can be included in more recent surveys if those points are stable as assumed.

In order to compare the annual GPS surveys from 1998 through 2005 to the original 1987 GPS survey documented in Schumann and Anderson (1988), it was necessary to adjust the original 1987 vectors to the control stations used in post-processing the surveys from 1998 to 2005. Additionally, it was necessary to re-project the original survey coordinates and ellipsoid heights from datum WGS-72 to NAD-83. The original survey, National Geodetic Survey (NGS) project GPS082, was performed in 1987 in support of the USGS project to monitor subsidence in the Tucson Basin and Avra Valley (Dave Minkel, NGS State Geodesist, oral commun.).

Dave Minkel used program ADJUST, version 4.30, for the adjustment. The original 1987 vector components and station coordinates were edited to resolve issues with the older format no longer supported by the program ADJUST. Two adjustments were performed; a free (minimally constrained) adjustment, and a constrained adjustment using coordinates and ellipsoid heights for two stations (N 419 and TUC) provided by the authors. The free adjustment shows the original survey results were surprisingly good considering the size of the GPS constellation and capability of GPS equipment in 1987 (Dave Minkel, NGS State Geodesist, oral commun., 2007).

In addition to the annual GPS surveys of the vertical-control network of benchmarks in the TAMA, a borehole-extensometer network was established for measuring and monitoring aquifer-system compaction and land subsidence caused by ground-water depletion. The network of 14 borehole extensometers was established in 1983 to monitor the rates and magnitude of aquifer-system compaction and water-level change. Seven extensometers are in Tucson basin and seven are in Avra Valley (fig. 4).

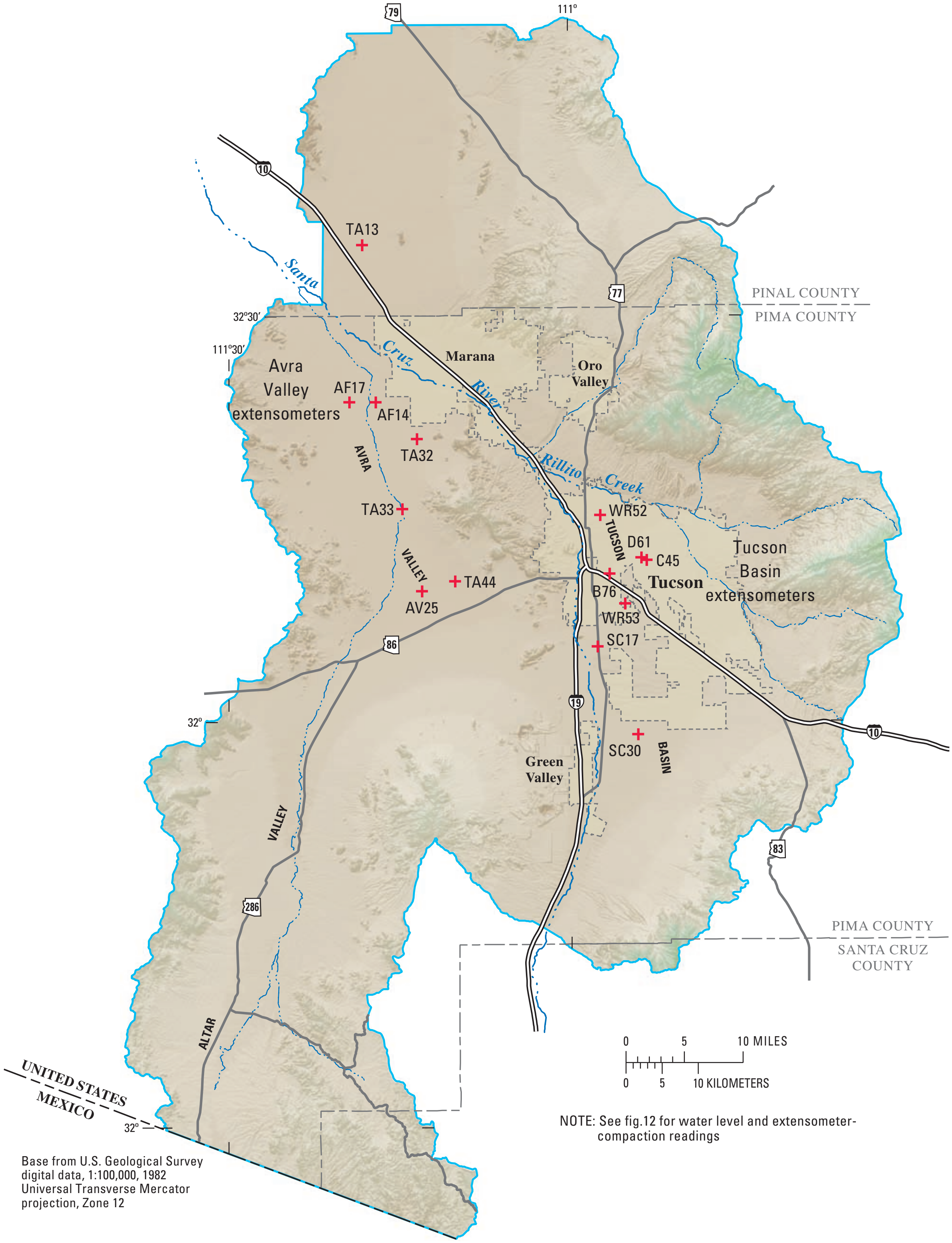


Figure 4. Tucson Active Management Area borehole extensometer stations.

Table 1. Positions and elevations of monitoring stations in the Tucson Active Management Area and changes in vertical position from 1987 to 2005.

Station	NAD83 horizontal coordinates, meters		Ellipsoid height, feet								Elevation change since 1987, inches			E levation change since 1998, inches				Elevation change since 1999, inches			Elevation change since 2002, inches	
	UTME	UTMN	1987	1998	1999	2000	2001	2002	2004	2005	1998	2004	2005	1999	2000	2001	2002	2000	2001	2002	2004	2005
TUCSON BASIN																						
5DOR	519252	3550967	2853.5	2853.5	2853.5	2853.5	2853.5	2853.4	--	--	0.4	--	--	-0.6	-0.2	-0.2	-1.4	0.4	0.4	-0.8	--	--
A50A	495343	3579970	--	2244.5	2244.4	2244.4	2244.5	2244.4	2244.5	2244.5	--	--	--	-0.7	-0.9	-0.6	-1.1	-0.1	0.2	-0.3	1.1	0.5
B34	504329	3562633	--	2358.6	2358.5	2358.5	2358.5	2358.4	2358.4	--	--	--	--	-0.6	-0.7	-1.3	-1.5	-0.1	-0.6	-0.8	-0.8	--
B77A	510486	3568617	--	2361.4	2361.5	2361.4	2361.4	2361.4	2361.4	--	--	--	--	0.8	-0.3	-0.2	-0.3	-1.1	-1.0	-1.1	-0.0	--
B7A	507136	3565844	--	2398.4	2398.4	2398.3	2398.3	2398.2	--	--	--	--	--	0.3	-1.4	-1.5	-2.6	-1.7	-1.8	-2.9	--	--
B92A	502941	3575697	--	2404.8	2404.7	2404.7	2404.8	2404.7	2404.7	2404.7	--	--	--	-0.5	-1.0	0.5	-1.0	-0.5	1.0	-0.5	0.5	-0.0
C22A	514583	3565813	--	2490.8	2490.8	2490.8	2490.8	2490.7	2490.7	--	--	--	--	1.1	0.3	0.0	-0.1	-0.8	-1.1	-1.2	-0.2	--
C317	510739	3556597	2573.1	2573.0	2573.0	2573.0	2573.0	2573.0	2572.9	--	-0.6	-2.1	--	-0.4	-0.6	0.0	-0.8	-0.2	0.4	-0.4	-0.7	--
C45	509759	3562889	2458.7	2458.4	2458.5	2458.4	2458.4	2458.4	2458.3	--	-3.2	-5.0	--	0.9	0.0	-0.0	-0.6	-0.9	-0.9	-1.5	-1.2	--
COT1	502651	3565315	--	2409.2	2409.4	2409.4	2409.4	2409.4	2409.3	2409.0	--	--	--	2.1	2.1	2.1	1.9	0.0	-0.0	-0.2	-0.7	--
D4	513302	3561800	--	2557.9	2558.0	2557.9	2557.8	2557.9	2557.8	--	--	--	--	1.3	0.4	-0.2	0.2	-0.8	-1.5	-1.1	-0.6	--
E9A	516983	3558461	--	2710.9	2710.9	2710.9	2710.8	2710.9	2710.8	--	--	--	--	-0.4	-0.3	-0.9	-0.1	0.0	-0.5	0.2	-0.7	--
FD62	494738	3573014	2247.7	2247.7	2247.7	2247.7	2247.7	2247.6	2247.7	2247.7	0.4	0.4	0.4	0.0	0.0	0.0	-0.6	0.0	0.0	-0.6	0.6	0.6
GP15	521344	3545062	--	2985.4	2985.3	2985.3	2985.3	2985.3	--	--	--	--	--	-0.7	-1.4	-1.1	-0.5	-0.7	-0.4	0.2	--	--
GUARD	523374	3536344	3338.8	3338.9	3338.9	3338.9	3338.9	3338.9	3338.9	--	1.1	1.1	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	--
L75	504365	3546580	2507.6	2507.7	2507.5	2507.6	2507.7	2507.6	2507.6	--	1.3	0.5	--	-1.8	-1.3	-0.1	-1.3	0.5	1.7	0.5	0.5	--
LINE	513387	3535747	--	2821.0	2820.9	2820.9	2820.9	2820.9	2820.8	--	--	--	--	-1.2	-1.3	-0.9	-1.4	-0.1	0.2	-0.2	-0.4	--
MAGNETIC	515284	3567735	--	2452.6	2452.6	2452.7	2452.6	2452.6	--	--	--	--	--	-0.2	0.6	0.2	0.1	0.9	0.4	0.4	--	--
N419	501108	3564098	2281.4	2281.4	2281.4	2281.4	2281.4	2281.4	2281.4	2281.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PA4	500510	3540597	2700.8	2700.7	2700.5	2700.5	2700.6	2700.5	2700.5	--	-1.0	-4.1	--	-2.6	-2.4	-1.4	-3.3	0.2	1.2	-0.7	0.2	--
PHPS	521453	3561262	2801.8	2801.8	2801.8	2801.8	2801.8	2801.8	2801.8	--	-0.6	-0.4	--	0.2	0.5	0.5	0.1	0.2	0.2	-0.1	0.2	--
SC25A	513261	3540610	--	2750.6	2750.5	2750.5	2750.5	2750.4	2750.5	--	--	--	--	-0.7	-1.1	-0.7	-1.4	-0.4	0.0	-0.6	0.4	--
THOR	495638	3587453	2598.9	2598.9	2598.9	2598.9	2598.9	2598.9	2598.9	2598.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TUC	520271	3574775	2870.2	2870.2	2870.2	2870.2	2870.2	2870.2	2870.2	--	0.0	0.0	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	--
WR142	506108	3566327	--	2373.9	2373.9	2373.8	2373.8	2373.7	--	--	--	--	--	0.2	-0.8	-1.4	-2.5	-1.0	-1.6	-2.7	--	--
WR175A	509387	3553709	--	2580.2	2580.1	2580.1	2580.2	2580.1	2580.1	--	--	--	--	-1.0	-1.0	-0.0	-1.0	0.0	0.9	-0.0	0.3	--
WR52	504242	3568767	2299.6	2299.5	2299.5	2299.5	2299.5	2299.5	2299.5	2299.5	-0.9	-0.8	-1.2	0.4	-0.2	0.5	-0.1	-0.6	0.1	-0.5	0.2	-0.2
WR53	507443	3556554	2506.2	2506.2	2506.2	2506.2	2506.2	2506.2	2506.2	--	-0.5	-0.8	--	0.2	0.2	0.6	0.1	0.1	0.4	-0.0	-0.4	--
WR56A	502734	3554784	--	2431.4	2431.3	2431.2	2431.2	2431.1	2430.9	--	--	--	--	-0.8	-1.4	-1.6	-3.5	-0.6	-0.8	-2.8	-1.4	--
X333	503930	3549284	2496.0	--	--	2496.0	2496.0	2495.9	--	--	--	--	--	--	--	--	--	0.0	0.0	0.0	--	--
X419	505349	3560633	2406.2	2405.9	2405.9	2405.9	2405.9	2405.8	2405.7	--	-2.7	-5.0	--	0.2	-0.2	-0.3	-1.4	-0.4	-0.5	-1.5	-0.9	--
XAVIER	503806	3550860	2491.9	2491.8	2491.8	2491.8	2491.8	2491.7	2491.7	--	-0.4	-1.7	--	-0.9	-0.9	-0.5	-1.3	-0.0	0.4	-0.4	0.0	--

Table 1. Positions and elevations of monitoring stations in the Tucson Active Management Area and changes in vertical position from 1987 to 2005—Continued.

Station	NAD83 horizontal coordinates, meters		Ellipsoid height, feet								Elevation change since 1987, inches			Elevation change since 1998, inches				Elevation change since 1999, inches			Elevation change since 2002, inches	
	UTME	UTMN	1987	1998	1999	2000	2001	2002	2004	2005	1998	2004	2005	1999	2000	2001	2002	2000	2001	2002	2004	2005
AVRA VALLEY																						
171+82 AZHD	478981	3592341	1874.5	1874.4	1874.6	1874.4	1874.5	1874.5	--	--	-0.9	--	--	2.0	-0.2	0.4	0.3	-2.2	-1.6	-1.7	--	--
1899 USGS	472267	3600476	1815.2	1815.2	1815.2	1815.1	1815.2	1815.2	--	--	-0.8	--	--	0.0	-0.1	0.2	0.3	-0.2	0.2	0.3	--	--
6WBC	465409	3602421	1730.2	--	1729.9	1729.9	1729.9	1730.0	--	--	--	--	--	0.0	--	--	--	0.0	0.1	0.5	--	--
AF13	473365	3584136	--	1901.1	1901.0	1901.0	1901.0	--	--	1899.3	--	--	--	-0.7	-0.8	-0.1	--	-0.1	0.6	0.0	0.0	--
AF16A	468661	3577661	--	1972.6	1972.6	1972.6	1972.6	1972.5	1972.6	1972.4	--	--	--	0.4	-0.2	0.2	-0.3	-0.5	-0.2	-0.6	0.3	-1.7
AF1A	471385	3593356	--	1812.8	1812.8	1812.8	1812.8	1812.8	1812.9	1812.7	--	--	--	0.0	-0.1	0.2	0.3	-0.1	0.2	0.3	1.2	-0.9
AF2	471385	3590499	--	1822.0	1822.0	1822.0	1822.1	1822.0	1822.2	1822.0	--	--	--	0.3	-0.2	0.8	0.1	-0.4	0.5	-0.2	1.5	-0.9
AF25A	466979	3571262	--	2051.1	2051.1	2051.1	2051.2	2051.1	2051.2	2051.1	--	--	--	0.2	-0.3	1.3	0.2	-0.5	1.1	0.0	0.7	-0.4
AF35A	478616	3566732	--	2166.8	2166.8	2166.8	2166.8	2166.8	2166.8	2166.7	--	--	--	-0.4	-0.9	-0.6	-0.7	-0.4	-0.1	-0.3	0.1	-0.4
AV13A	477727	3559980	--	2224.2	2224.2	2224.1	2224.2	2224.2	2224.3	2224.1	--	--	--	0.4	-0.4	0.4	0.4	-0.8	0.0	-0.1	0.8	-1.1
AV25	479566	3558472	2228.3	2227.9	2227.9	2227.9	2227.9	2227.9	2228.0	2227.9	-4.2	-3.8	-4.3	0.0	-0.7	0.0	-0.4	-0.7	0.0	-0.4	0.8	0.2
D296	482709	3554826	2330.1	2329.9	2329.9	2330.0	2330.0	2329.9	2329.9	2329.9	-2.2	-1.8	-2.6	0.5	1.0	1.2	0.3	0.5	0.7	-0.2	0.0	-0.8
F294	471394	3589144	1832.6	1832.6	1832.6	1832.6	1832.6	1832.6	--	--	-0.3	--	--	0.2	0.3	1.1	0.4	0.0	0.9	0.1	--	--
F424	476803	3594162	1849.7	1849.7	1849.8	1849.7	1849.8	1849.8	--	--	-0.1	--	--	0.3	-0.4	0.1	0.5	-0.7	-0.2	0.2	--	--
H291	479609	3570295	--	2309.3	2309.3	2309.3	2309.3	2309.3	2309.3	2309.3	--	--	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H292	476275	3576032	2017.1	2017.0	2016.9	2017.0	2016.9	2016.9	2017.0	2016.9	-1.3	-0.7	-2.4	-0.1	0.0	-0.1	-0.6	0.1	0.0	-0.6	1.3	-0.4
H301	472123	3567811	2123.2	2123.2	2123.1	2123.0	2123.2	2123.1	2123.1	2123.0	-0.7	-1.2	-2.4	-0.5	-1.5	-0.1	-0.6	-1.0	0.4	-0.1	0.3	-0.9
L94	466769	3591697	1819.1	1819.1	1819.1	1819.1	1819.1	1819.1	1819.2	1819.0	0.4	1.4	-1.4	-0.4	-0.7	-0.6	-0.5	-0.2	-0.2	0.0	1.4	-1.4
M279	463734	3611992	1699.4	1699.4	1699.3		1699.3	1699.3	--	--	-0.2	--	--	-0.4	--	-0.6	-0.5	--	-0.2	0.0	--	--
MISSAZDT	476391	3551790	2400.3	2400.1	2400.1	2400.1	2400.1	2400.0	2400.1	2400.1	-3.1	-2.4	-2.9	0.5	0.4	0.8	-0.5	-0.1	0.3	-0.9	1.2	0.7
NAVISKA2	475248	3596193	1852.5	1852.5	1852.5	1852.5	1852.5	1852.5	--	--	-0.1	--	--	0.3	0.4	0.3	0.0	0.0	0.0	-0.3	--	--
PASS	462945	3611845	--	1886.1	1886.1	1886.1	1886.1	1886.1	1886.1	--	--	--	--	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	--
Q279	466601	3608533	1720.3	1720.3	1720.2	1720.2	1720.2	1720.2	1720.3	1720.1	-1.1	-1.1	-3.1	-0.3	-0.3	-0.6	-0.2	0.0	-0.3	0.1	0.3	-1.7
Q94	478704	3585792	1916.6	1916.5	1916.5	1916.5	1916.6	1916.5	1916.6	1916.4	-0.8	0.6	-1.4	0.5	0.4	0.6	-0.2	-0.1	0.1	-0.6	1.4	-0.6
SA105	469731	3572810	2048.5	2048.3	2048.3	2048.2	2048.2	2048.2	2048.3	2048.1	-3.3	-3.3	-4.8	-0.2	-0.6	-0.7	-0.8	-0.4	-0.5	-0.6	0.8	-0.7
TA13	471579	3605427	--		1827.5	1827.5	1827.5	1827.6	1827.5	1827.4	0.0	--	--		--	--	--	0.2	0.1	0.0	-0.4	-2.2
USBR938	479244	3567997	--	2222.1	2222.1	2222.0	2222.0	2222.0	--	--	--	--	--	0.0	-0.5	-0.1	-0.3	-0.5	-0.1	-0.2	--	--
WR16B	475937	3579485	--	1955.7	1955.6	1955.6	1955.6	1955.6	1955.7	1955.5	--	--	--	-0.4	-0.7	-0.8	-1.1	-0.2	-0.4	-0.6	0.9	-0.5
WR29A	472926	3566350	--	2148.1	2148.1	2148.0	2148.1	2148.1	2148.1	2148.0	--	--	--	-1.0	-1.1	-0.7	-1.0	-0.2	0.3	0.0	0.6	-0.6

Aquifer-system compaction is measured by the borehole-extensometer pipes that extend from the land surface to the bottom of cased wells or test holes (fig. 5). The extensometer pipes are isolated from the well casings and are jetted into the formation, or are set on 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, borehole extensometers measure compaction for the portion of the aquifer system between the land surface and the depth at which the bottom of the extensometer is anchored. The design and operation of borehole extensometers is described in detail by Schumann (1986) and Anderson and others (1982).

In the TAMA, the base of the extensometer pipes are jetted into bedrock as stated previously, or are grouted at the bottom of the well into less compressible alluvium. Most of the extensometers are anchored in alluvium at depths between 800 and 1,400 ft. Extensometers measure aquifer-system compaction in the depth interval of the extensometer pipe which might represent only a portion of the total compaction, whereas GPS surveys measure land subsidence. Aquifer-system compaction occurring beneath the base of the extensometer is not measured by the extensometer but is represented in the GPS-measured land subsidence (Amelung and others, 1999; Evans and Pool, 2000).

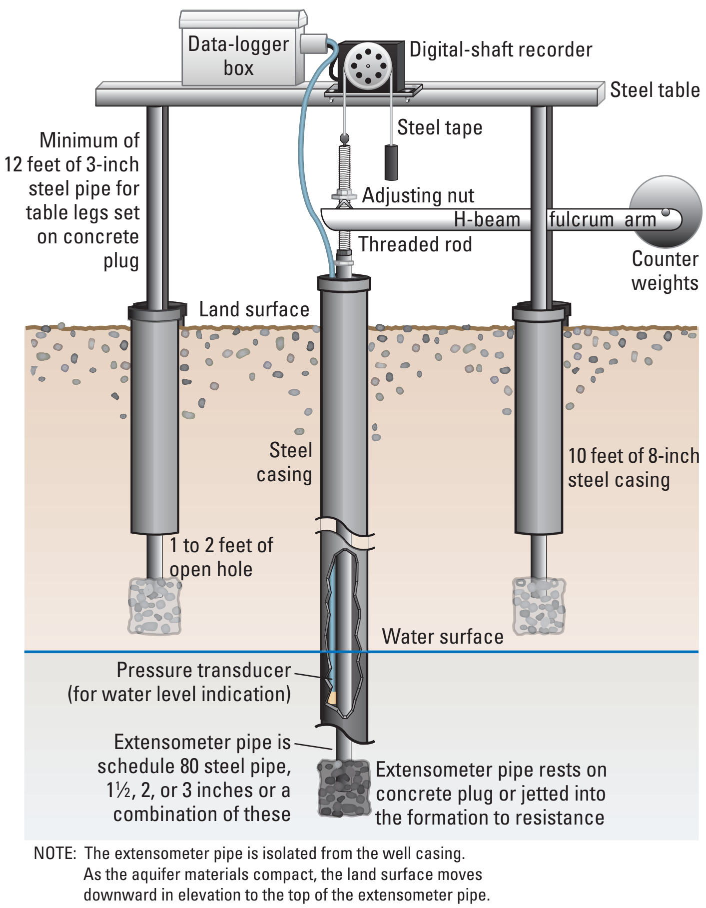


Figure 5. Diagrammatic sketch of a borehole extensometer in the Tucson Active Management Area.

Effective monitoring of the extent and rate of land subsidence is a continuous challenge owing to the cost, time, and resources needed to perform ground-based GPS surveys and maintain the borehole-extensometer network. Interferometric Synthetic Aperture Radar (InSAR) is a satellite technology that can provide high-resolution mapping of earth-surface topography and deformation. The 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 acquisition. Isolating the deformation signal by applying phase corrections to satellite position and surface topography produces a differential interferogram in which one cycle of phase change represents a half-wavelength (about 1.1 in. for C-band radar) of surface movement in the range or line-of-sight of the radar transmitter. The ADWR presently is using InSAR to map sub-centimeter deformation in Phoenix and Tucson (Brian Conway, ADWR, oral commun., 2007).

Hydrogeology

Basins in the TAMA were formed as a result of crustal extension during the Cenozoic Basin and Range orogeny. The Basin and Range orogeny was accompanied by block faulting, the formation of a horst-and-graben terrain, and the accumulation of sedimentary basin fill. The Basin and Range orogeny transformed the landscape of the basins in the TAMA from an area of generally moderate relief into one of high relief characterized by deep structural basins bounded by high mountain ranges (Anderson, 1987a).

Published reports from studies of the Tucson Basin were used as references for describing the hydrogeologic conditions within the TAMA. Alluvial deposits that accumulated in the structural basins can be grouped into three stratigraphic units of basin fill on the basis of structural relations (fig. 6). The three sedimentary units compose the alluvial-aquifer system (Davidson, 1973; Allen, 1981; Anderson, 1987a, 1987b, 1989; and Hanson 1989) and are correlative with the lower, middle, and upper hydrostratigraphic units of adjacent basins within the region.

The lower stratigraphic unit was deposited before and during the early phases of extensional tectonism associated with low-angle faulting and includes the Pantano Formation in the TAMA. The Pantano Formation consists of conglomerate, sandstone, mudstone, and gypsiferous mudstone, as well as megabreccia, bedded tuffs, and interbedded volcanic flows (Anderson, 1987a). The Pantano Formation yields small to moderate amounts of water to wells.

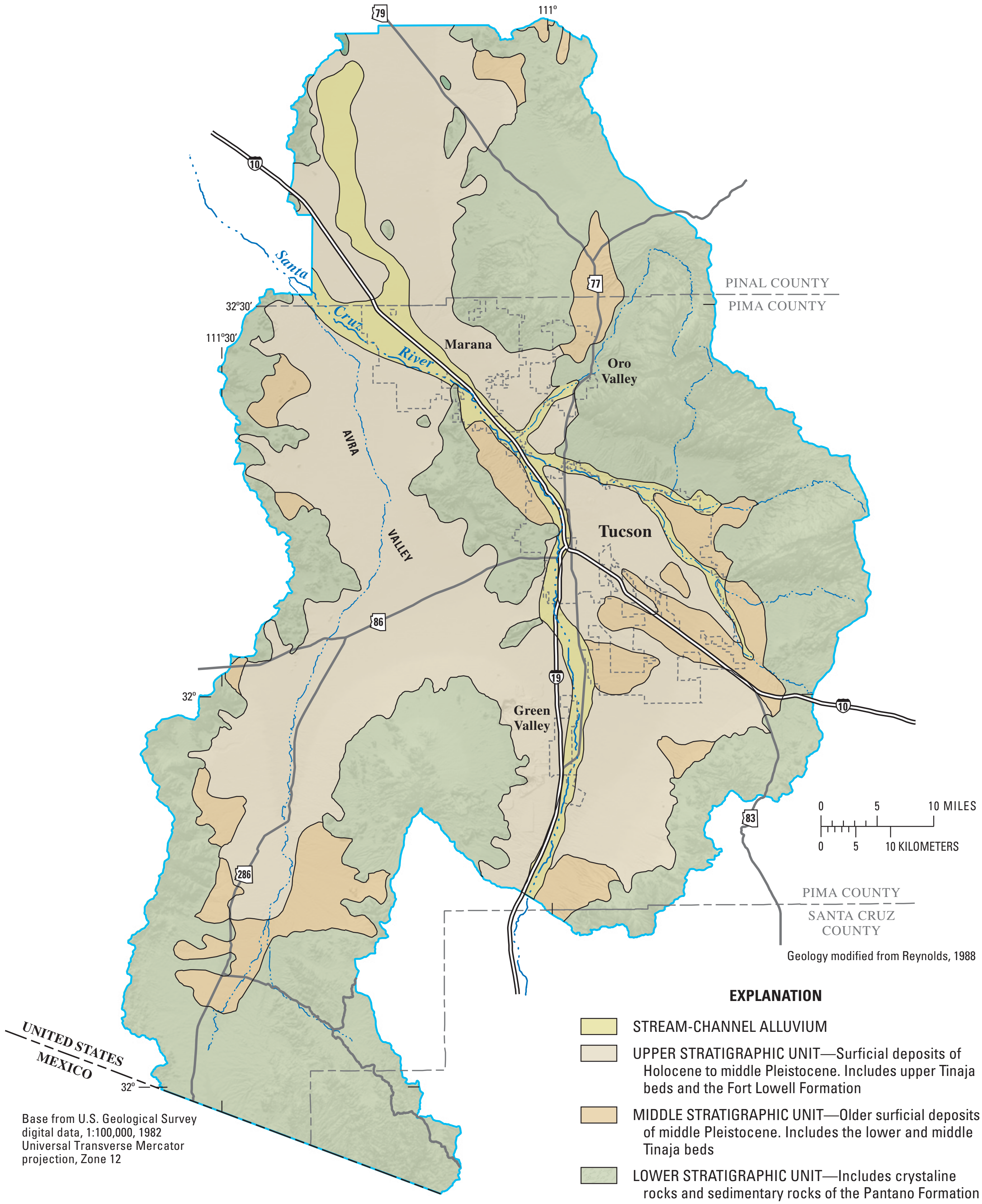


Figure 6. Generalized geology of the Tucson Active Management Area.

The middle stratigraphic unit was deposited during the transition from low- to high-angle faulting and includes the lower and middle Tinaja beds in the TAMA. The lower Tinaja beds consist of gravel and conglomerate to clayey silt and mudstone and are hundreds of feet thick. The middle Tinaja beds consist of gravel conglomerate to gypsiferous and anhydritic clayey silt and mudstone and are hundreds to thousands of feet thick. The lower and middle Tinaja beds yield small to moderate amounts of water to wells (Anderson, 1987a).

The upper stratigraphic unit is relatively undisturbed by faulting in comparison to the older units and includes the upper Tinaja beds and Fort Lowell Formation in the TAMA. The upper Tinaja beds are gravel to clayey silt and are hundreds to thousands of feet thick. The Fort Lowell Formation consists of gravel to clayey silt and includes thin surficial alluvial deposits of late Pleistocene and Holocene age. The Fort Lowell Formation ranges in thickness from several feet to several hundreds of feet (Anderson, 1987a). The Fort Lowell Formation is the most permeable unit of the aquifer and yields moderate to large amounts of water to wells (Davidson, 1973). Subsequent to the accumulation of the three stratigraphic units of basin fill, a thin layer of alluvium was deposited along major drainage channels.

Ground water is replenished by mountain-front recharge and underflow in the TAMA (Hanson, 1989). Additional streamflow infiltration from effluent and floods contributes to recharge along the Santa Cruz River and its tributaries. The Santa Cruz River and ground-water outflow from the Tucson Basin enter Avra Valley northwest of Rillito. Additional underflow enters Avra Valley from Altar Valley to the south. Ground-water outflow from Avra Valley occurs between the Silverbell Mountains and Picacho Peak and enters the Eloy Basin in the southern part of the Lower Santa Cruz River Basin. Natural ground-water flow paths and head distributions have been altered by ground-water withdrawals (Hanson, 1989).

In some places, continued withdrawal of ground water and infiltration of irrigation water have created perched zones of local saturation atop low-permeability deposits above the zone of regional saturation. Cuff and Anderson (1987) outlined an area of perched ground water in the north-central part of Avra Valley that is similar to an area in west-central Tucson. Perched zones, which are caused by irrigation return flow or artificial recharge, can increase geostatic load (stress), and transient-vertical gradients can result in seepage stresses (Hanson, 1989). Both conditions can inrease the effective (intergranular) stress on aquitards, potentially affecting the magnitude, rate and distribution of land subsidence.

Potential for Land Subsidence

Permanent land subsidence can occur in alluvial basins when water is removed from aquifer systems (Galloway and others, 1999). The geostatic loads in aquifer systems such as those in the TAMA are supported in part by the granular skeleton of the aquifer system and in part by the pore-fluid pressure. Under conditions of constant geostatic stress, when ground water is withdrawn and the pore-fluid pressure is reduced, the stress on the granular skeleton (effective stress) is increased by an equivalent amount and the aquifer system compacts, causing some lowering of the land surface. The compaction[1] may be permanent (inelastic) or reversible (elastic) depending on the stress history of aquifer system. The magnitude of effective stress that determines whether the skeleton will undergo elastic or inelastic compaction is known as the preconsolidation stress and is approximated by the previous maximum effective stress or in terms of hydraulic head, the historic minimum head—critical head. Inelastic compaction occurs when the preconsolidation stress is exceeded or in terms of head—when head falls below the critical head. For equal incremental changes in effective stress, compaction in the elastic range of stress is typically much less than compaction in the inelastic range of stress.

Both the aquifers (sand and gravel) and aquitards (clay and silt) of aquifer systems deform as a result of changes in effective stress, but to different degrees. Elastic compaction occurs in both the aquifers and aquitards in the aquifer systems. For example, when ground-water levels are raised fluid pressure increases and effective stress decreases. Some support previously provided by the aquifer and (or) aquitard skeleton is transferred to the fluid pressure, and the skeleton expands. This fully recoverable deformation commonly results in seasonal, reversible displacements in land surface (uplift and subsidence) of more than 1 in. (Amelung and others, 1999; Galloway and others, 1999). Conversely, most permanent compaction and land subsidence occurs due to the inelastic compaction of aquitards.

Potential for aquifer-system compaction in the TAMA was investigated by Anderson (1987a) and Hanson (1989). The Pantano Formation, lower Tinaja beds, and middle Tinaja beds consist largely of moderately indurated to indurated deposits that generally are resistant to deformation related to ground-water withdrawal (Anderson, 1987a). Thus, the potential for aquifer-system compaction and its effects in the TAMA may depend more on the character of the upper units of the Tinaja beds and the Fort Lowell Formation (which contain a higher percentage of silt and clay) than on the character of the lower units in the TAMA.

In addition to the higher silt and clay content of the upper units, the thickness and the relation between the upper units and bedrock affect the potential for aquifer-system compaction in the TAMA. The thickness of the Fort Lowell Formation and the upper Tinaja beds varies throughout the TAMA as a result of structural deformation of the underlying rock. Generally, areas of greater rates of inelastic compaction are those areas that contain a larger percentage of silt and clay in the saturated zones and are associated with ground-water withdrawals.

Land subsidence and aquifer-system compaction in the TAMA has not been as great as that in the nearby Eloy and Stanfield Basins because alluvial basins in the TAMA have not

[1] In this report, the term "compaction" refers to a decrease in thickness of sediments as a result of increase in vertical compressive stress. The identical physical process is referred to as "consolidation" by soils engineers.

been pumped as extensively as the Eloy and Stanfield Basins where ground water has been used extensively for agriculture (Anning and Duet, 1994). In addition, the Fort Lowell Formation and the upper Tinaja beds do not contain as much compressible clay as the upper hydrostratigraphic units of the Eloy Basin do and, therefore, would not be expected to compact as much under similar ground-water withdrawal conditions. The Fort Lowell Formation and the upper Tinaja beds do, however, contain compressible clay layers that have compacted inelastically in response to ground-water withdrawals.

Long-term ground-water withdrawal rates in the TAMA that are greater than rates of inflow to the ground-water system have resulted in removal of water from ground-water storage and in water-level declines during the last several decades. Superimposed on the long-term water-level declines are short-term increases in storage and water levels that occur over periods of months to years after occasional significant increases in the rate of recharge (Pool, 2005). Additionally, long-term water-level declines have stabilized or reversed since 2000 at some monitoring wells (figs. 7 and 8) in Tucson Basin (wells B76, C45, D61, and SC17) and Avra Valley (wells AF14, AF17, TA32, and TA33). These areas of water-level increase—likely a result of decreases in ground-water withdrawal and redistribution of pumpage as Central Arizona Project water has become available for artificial recharge and municipal consumption—reduce the potential for continued land subsidence due to aquifer-system compaction in the TAMA.

Land Subsidence and Aquifer-System Compaction

Permanent subsidence, seasonal elastic deformation, and uplift have been observed during the period of data collection from 1987 to 2005. In the spring of 1987, a GPS survey was used to measure horizontal and vertical positions for bench marks at 43 sites to establish a network for monitoring land subsidence in Tucson Basin and Avra Valley. Between 1987 and 2005, the original number of subsidence-monitoring stations was gradually increased to more than 100 stations to meet the need for information in the growing metropolitan area. Data from approximately 60 stations common to the GPS surveys done after 1987, in addition to the remaining stations from the original survey, were used to document land subsidence in the TAMA.

Between 1987 and 1998, land subsidence was greater in Avra Valley than in Tucson Basin on the basis of the average subsidence at 31 stations that were common to the original GPS survey in 1987. The average subsidence in the Tucson Basin during the 11-year period from 1987 to 1998 was 0.5 in., and the maximum subsidence of 3.2 in. and 2.7 in. occurred in the middle of Tucson Basin at stations C45 and X419, respectively (fig. 9 and table 1). In the southern portion of Tucson Basin, several stations showed uplift, and two stations (L75 and GUARD) showed uplift in excess of 1 in. In Avra Valley, the average subsidence during the 11-year period was 1.2 in. Most of the stations in Avra Valley showed subsidence, with the greatest amounts of subsidence occurring at stations in the southern part of the valley. About 4 in. of subsidence occurred at station AV25, and three stations, D296, MISSAZDT, and SA105, showed more than 2 in. of subsidence (fig. 9 and table 1).

For the approximately 60 stations that are common between the 1998 and 2002 GPS surveys, the data indicate that up to 3.5 in. of subsidence occurred in Tucson Basin, and as much as 1.1 in. of subsidence occurred in Avra Valley (fig. 10 and table 1). Land subsidence was greater in Tucson Basin than in Avra Valley between 1998 and 2002—the average subsidence for the 4-year period was about 0.4 in. in Tucson Basin and 0.1 in. in Avra Valley. In contrast to the 11-year period from 1987 to 1998 where most of the subsidence in Tucson Basin occurred in the middle of the basin between the Rillito and Santa Cruz Rivers, the greatest amount of subsidence for the 4-year period between 1998 and 2002 occurred in the southern portion of the basin along the Santa Cruz River at stations WR56A (3.5 in. of subsidence) and PA4 (3.3 in. of subsidence). In Avra Valley, most of the stations showed subsidence during the 4-year period between 1998 and 2002; however, the magnitude of subsidence was less than 1 in. at all stations except WR16B, which showed 1.1 in. of subsidence.

Between 2002 and 2005, the GPS surveys were conducted largely at newer stations within the TAMA, and thus, fewer data points were available for comparison with the earlier surveys. For 2005, there were 19 stations in Avra Valley available for comparison with the 2002 survey, but only 6 stations in the Tucson Basin common to the 2002 survey (fig. 11 and table 1). Of the available stations from the 2005 survey in the Tucson Basin, station WR52, in the northern part of Tucson Basin, had the most subsidence (0.2 in.), consistent with the area that showed active subsidence in previous surveys. In Avra Valley, more data were available for comparison with the 2002 survey (fig. 11 and table 1). The average subsidence for the 19 stations surveyed in Avra Valley between 2002 and 2005 is about 0.7 in.; however, three stations in the northern part of the valley showed subsidence of more than 1 in.—2.2 in. at station TA13 and 1.7 in. at both station Q279 and AF16A. Data from station MISSAZDT in the southern part of the valley showed 3.1 in. of subsidence between 1987 and 1998 and another 0.5 in. of subsidence between 1998 and 2002; however, MISSAZDT showed 0.7 in. of uplift between 2002 and 2005.

A comparison of the original 1987 GPS survey to the 2004–05 surveys was done to determine (1) the approximate magnitude of subsidence during the 17- to 18-year period, and (2) the areas of the TAMA where the most subsidence has occurred (fig. 12 and table 1). From the surveys in 2004–05 for Tucson Basin, there were 14 stations in common with the 1987 survey. In Avra Valley, there were 9 stations from the 2004–05 surveys in common with the 1987 survey. The 2004–05 GPS-survey data were combined for the comparison with the original 1987 survey in order to maximize the number of stations for the comparison during the period of record.

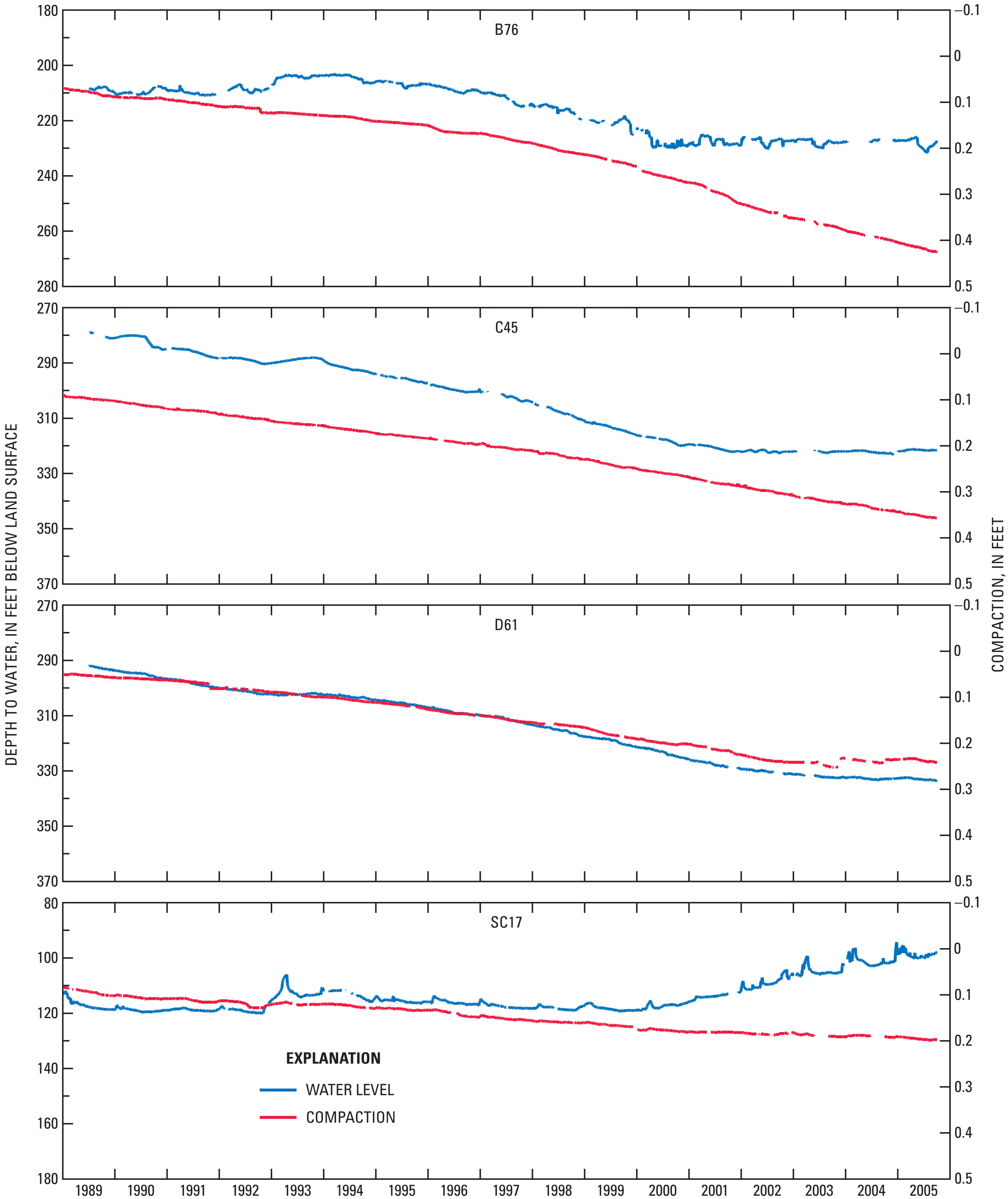


Figure 7. Water level and compaction readings at extensometers in Tucson Basin, 1989 to 2005.

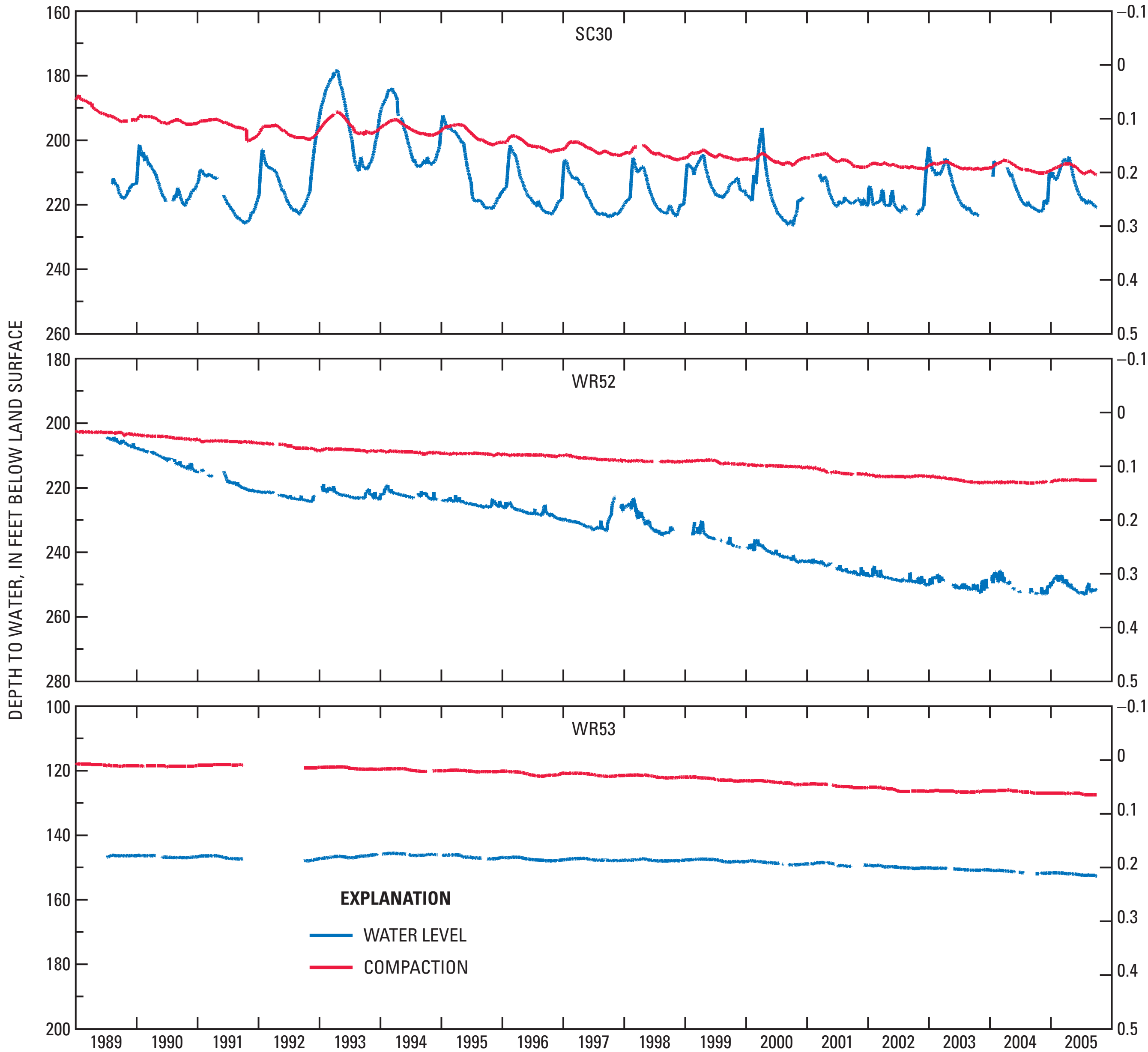


Figure 7. Water level and compaction readings at extensometers in Tucson Basin, 1989 to 2005—Continued.

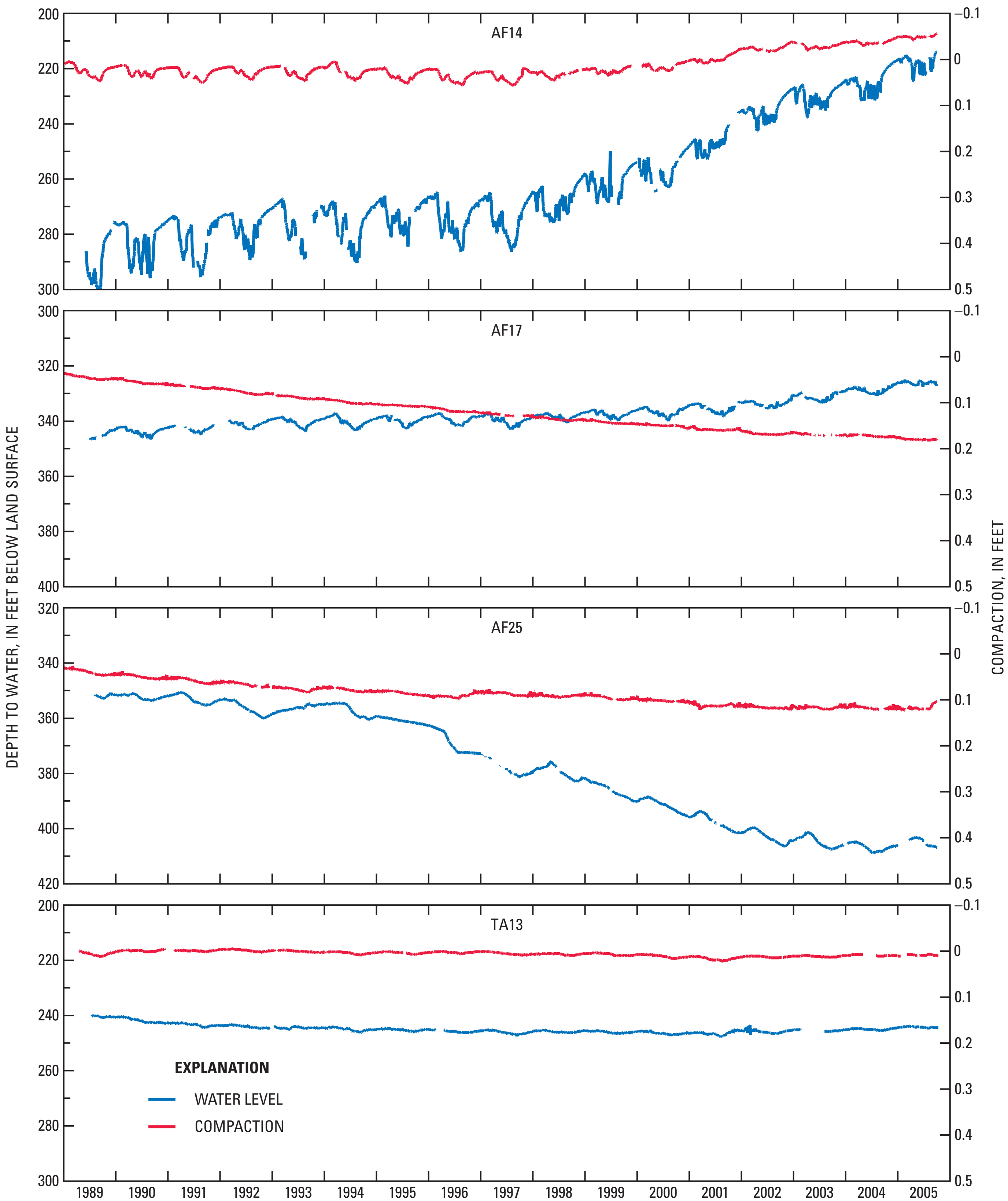


Figure 8. Water level and compaction readings at extensometers in Avra Valley, 1989 to 2005.

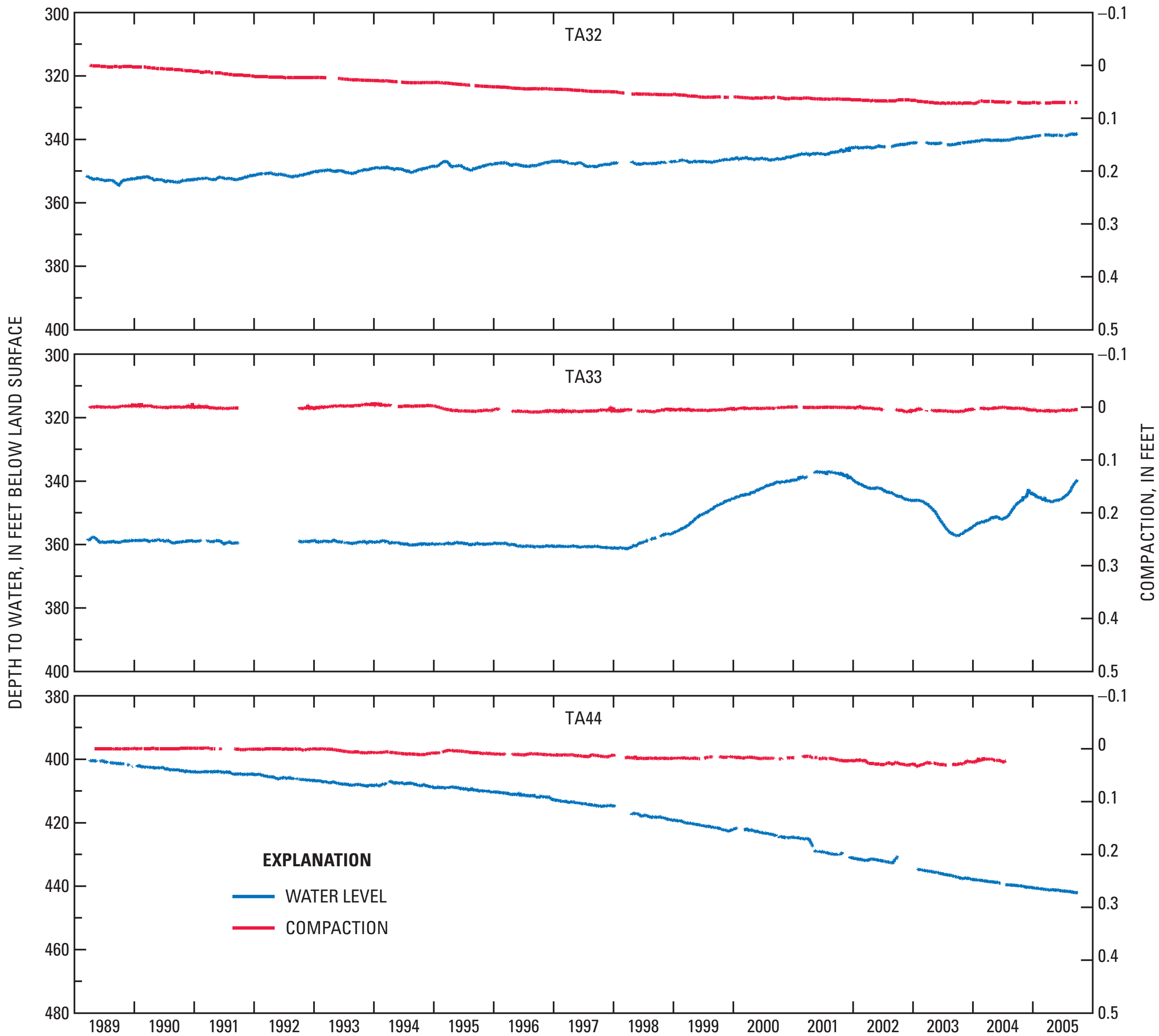


Figure 8. Water level and compaction readings at extensometers in Avra Valley, 1989 to 2005—Continued.

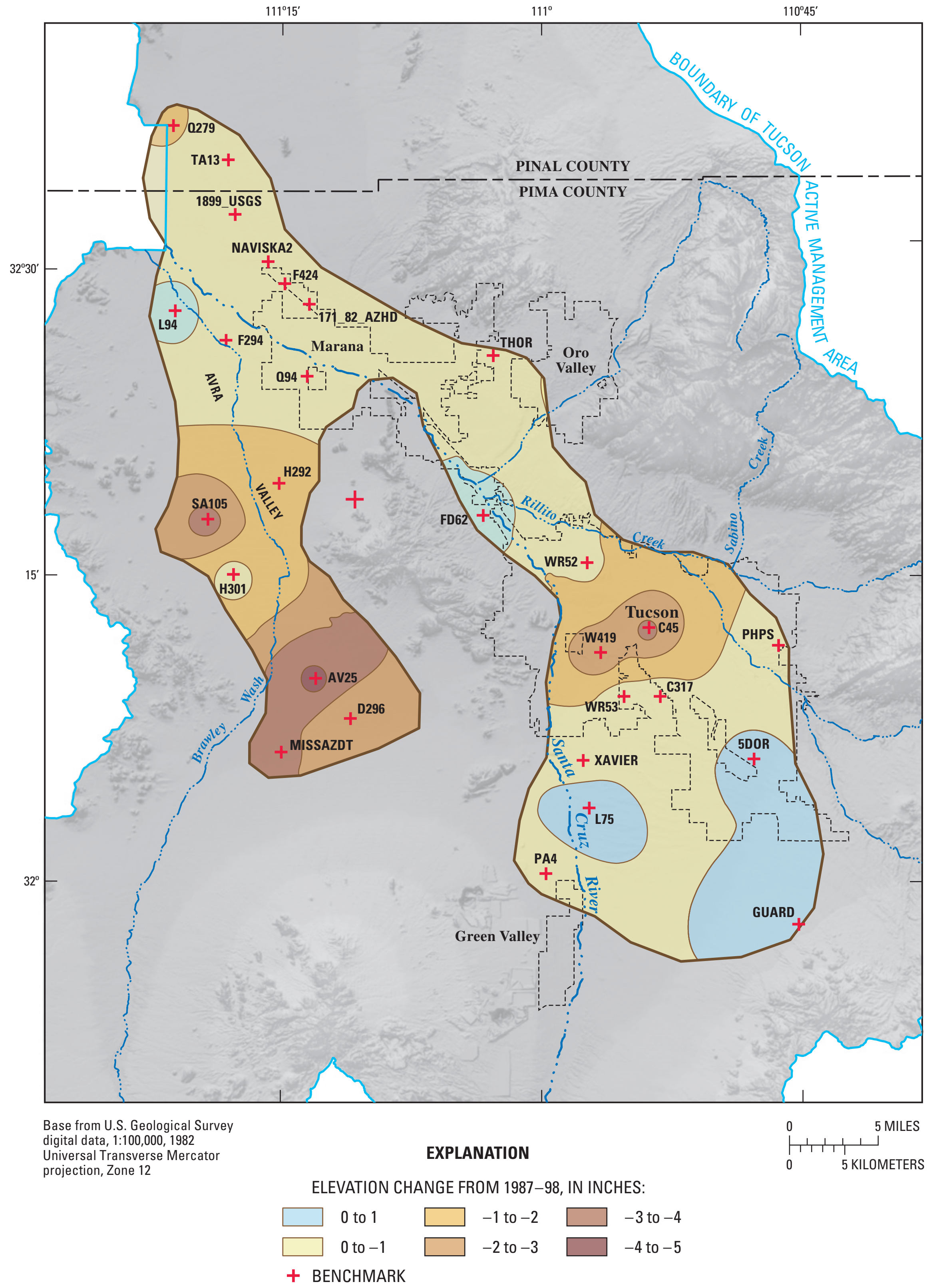
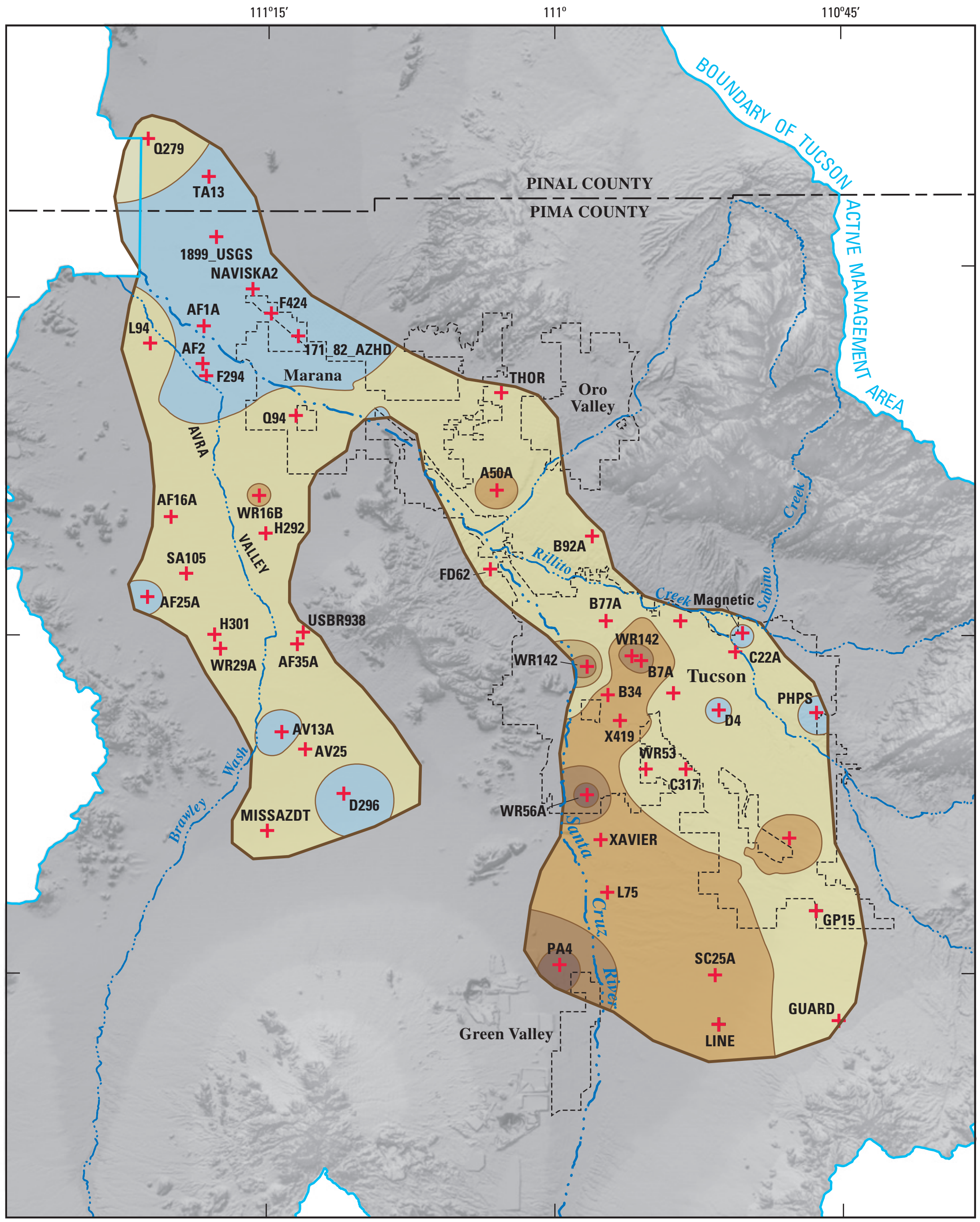


Figure 9. Land-surface elevation change in the Tucson Active Management Area from 1987 to 1998.



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

0 5 MILES
0 5 KILOMETERS

EXPLANATION

ELEVATION CHANGE FROM 1998–2002, IN INCHES:

0 to 1
0 to –1
–1 to –2
–2 to –3
–3 to –4
BENCHMARK

Figure 10. Land-surface elevation change in the Tucson Active Management Area from 1998 to 2002.

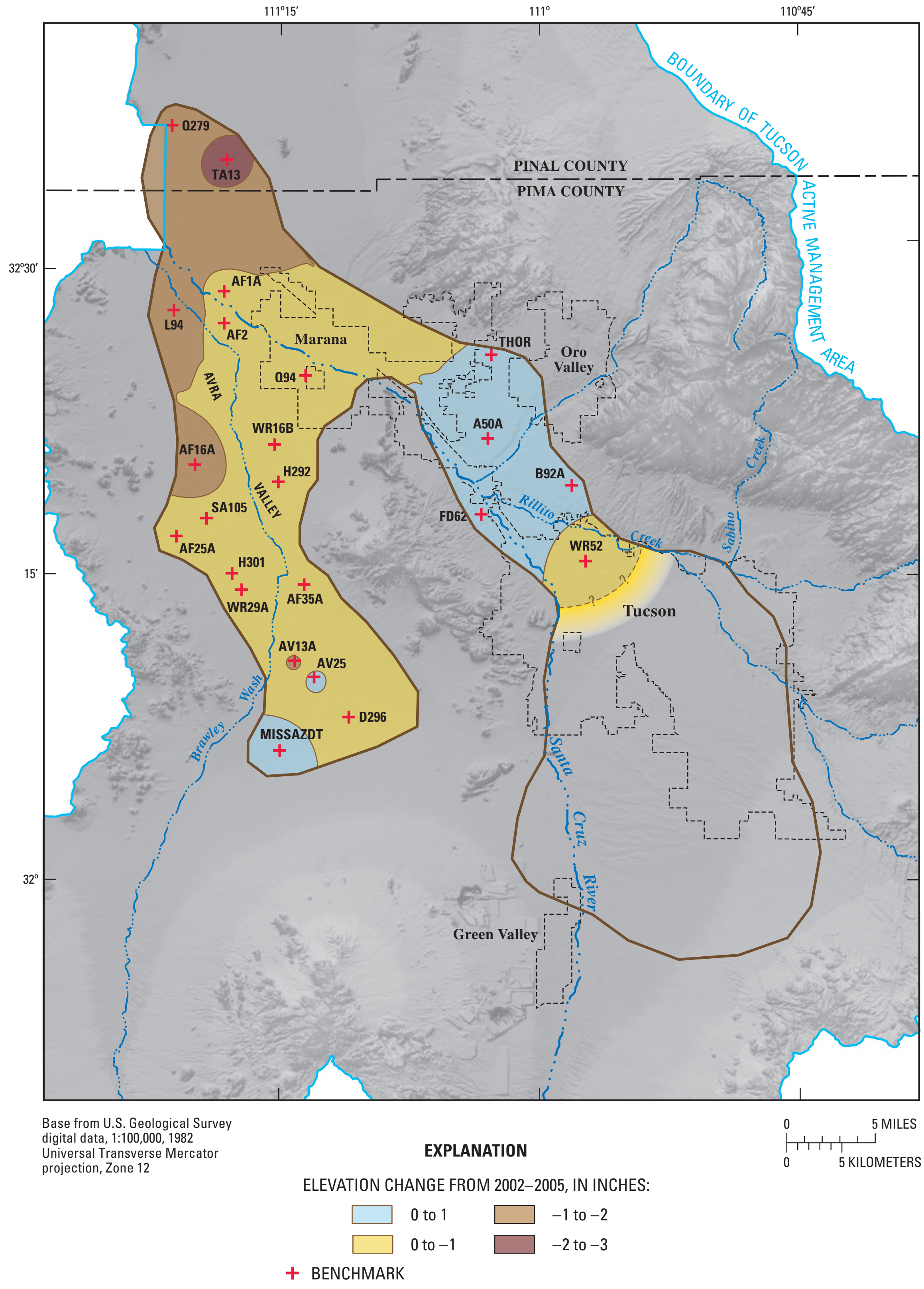


Figure 11. Land-surface elevation change in the Tucson Active Management Area from 2002 to 2005.

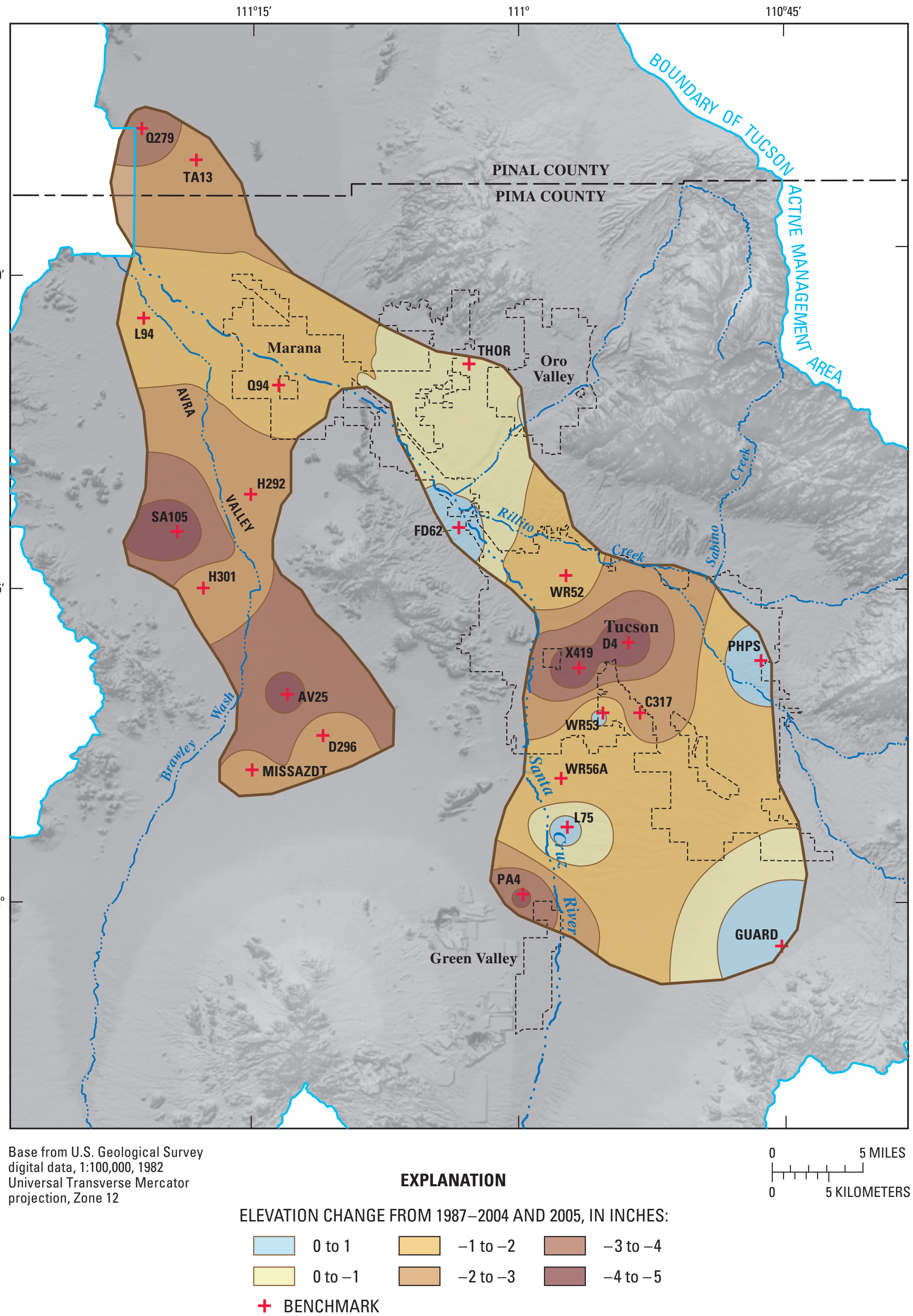


Figure 12. Land-surface elevation change in the Tucson Active Management Area from 1987 to 2004 and 2005.

Between 1987 and 2004–05, land subsidence was greater in Avra Valley than in Tucson Basin on the basis of the average subsidence for the stations that were common to the original 1987 GPS survey. The average total subsidence during the 17- to 18-year period was about 1.3 in. in the Tucson Basin and about 2.8 in. in Avra Valley. Three stations in the Tucson Basin displayed subsidence greater than 4 in. for the 17- to 18-year period—5 in. at stations C45 and X419 and 4.1 in. at station PA4. In Avra Valley, two stations showed subsidence greater than 4 in. for the 17- to 18-year period greater than 4 in.—4.3 in. at station AV25 and 4.8 in. at station SA105.

On the basis of the GPS-survey data, the area with the greatest magnitude of subsidence in Tucson Basin is the northern portion of the basin bounded by the Rillito and Santa Cruz rivers, and in the southwestern portion of the basin along the Santa Cruz River. In Avra Valley, GPS-survey data indicate that the greatest magnitude of subsidence occurred in the middle of the basin near station SA105 and in the southern portion of the basin near station AV25. All Avra Valley stations showed cumulative subsidence for the 17- to 18-year period. In the Tucson Basin, station GUARD in the southeastern portion of the basin, showed a cumulative uplift of 1.1 in.; and station FD62, near the confluence of the Rillito and Santa Cruz rivers, showed a cumulative uplift of 0.4 in.

The GPS-survey data also indicate that there are several areas within the TAMA where the measured subsidence is recoverable, an indication that the history of stress on the granular skeleton of the aquifer system in these areas is within the elastic range of compaction (i.e. the preconsolidation stress has not been exceeded). Reversible compaction has occurred at stations within Tucson Basin during the periods of comparison between 1987 and 2004–2005. Station L75 showed uplift of 1.3 in. between 1987 and 1998, subsidence of 1.3 in. between 1998 and 2002, followed by 0.5 in. of uplift between 2002 and 2004 (figs. 9–11 and table 1). Station FD62, near the confluence of the Rillito and Santa Cruz rivers, showed 0.4 in. of uplift between 1987 and 1998, subsidence of 0.6 in. between 1998 and 2002, followed by 0.6 in. of uplift between 2002 and 2005 (figs. 9–11 and table 1).

In Avra Valley, there also are areas where reversible compaction has occurred at stations during the periods of comparison between 1987 and 2004–2005. Station D296 showed subsidence of 2.2 in. between 1987 and 1998, uplift of 1.3 in. between 1998 and 2002, followed by 0.8 in. of subsidence between 2002 and 2005 (figs. 9–11 and table 1). In the northern portion of Avra Valley, several stations showed subsidence of 0 to 1 in. between 1987 and 1998, a period of uplift from 1998 to 2002, followed by another period of subsidence of 0 to 2 in. from 2002 to 2005 (figs. 9–11 and table 1).

Results from the aquifer-compaction monitoring at the network of 14 borehole extensometers, seven in Tucson Basin and seven in Avra Valley, are displayed in figures 7-8 and table 2. The extensometers provide a continuous record of water level and aquifer-system compaction for the part of the aquifer system penetrated by each well. At the seven extensometers in Tucson Basin, aquifer-system compaction from 1989 and 2005 ranged from 0.7 in. to 4.3 in., while in Avra Valley, aquifer-system compaction for the same period ranged from 0.1 in. at TA13, to 1.7 in. at AF17 (table 2). Additionally, the extensometer at AF14 measured about –0.6 in. of compaction for the 1989 to 2005 period.

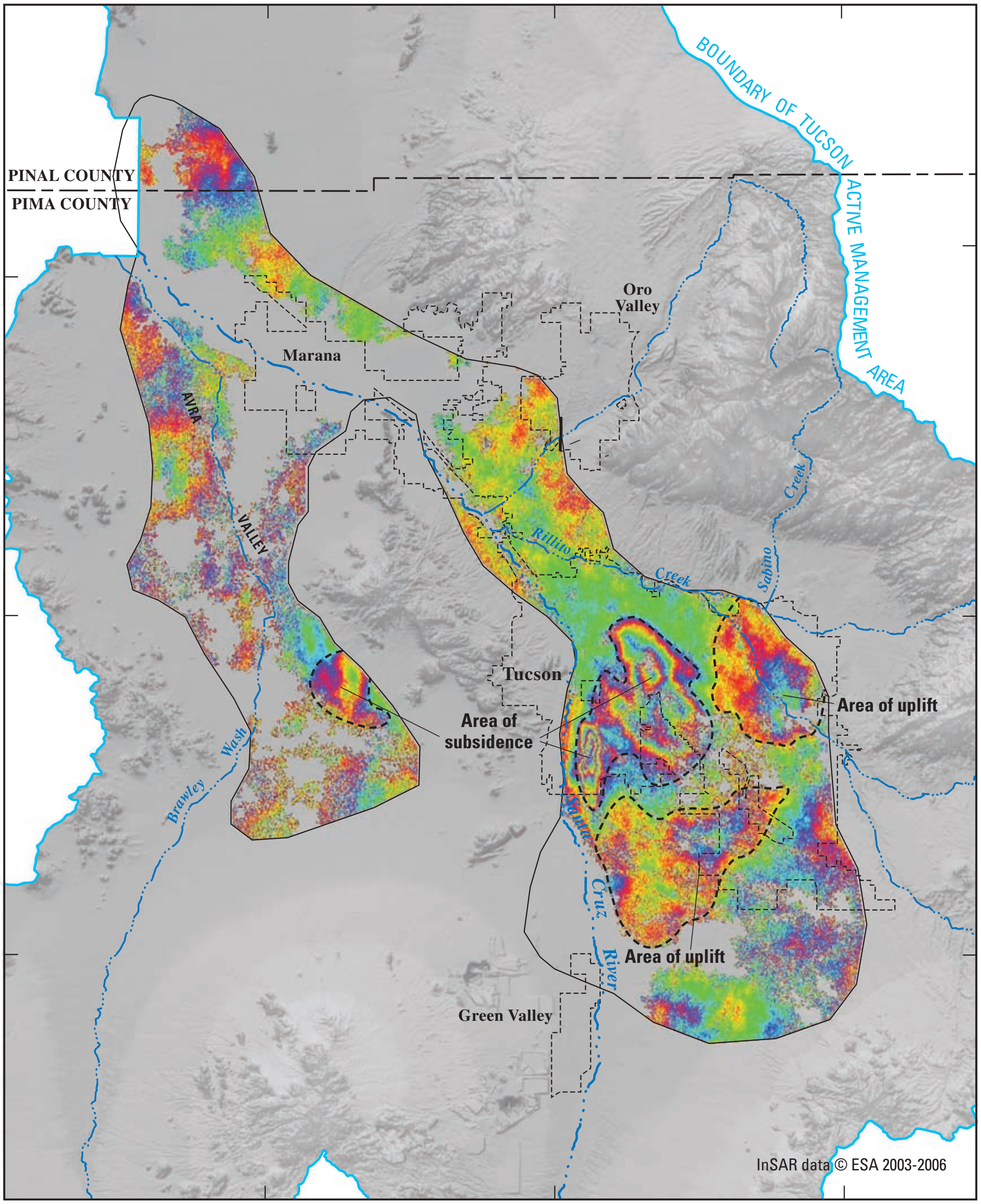
In Tucson Basin, the greatest cumulative aquifer-system compaction occurred in the northern portion of the basin at extensometers B76, C45, and D61 (4.3, 3.2, and 2.3 in., respectively). Cumulative water-level change at these stations for the same period was –18.8, –42.53, and –41.6 ft., respectively. These results agree with data from the GPS surveys, which indicate the greatest magnitude of subsidence in Tucson Basin is in the northern portion of the basin between the Rillito and Santa Cruz Rivers.

The extensometer at C45 also is a station measured annually by using GPS-survey methods. For about the same period (1987 to 2005), GPS survey data indicated that station C45 had a cumulative subsidence of 5 in., versus 3.2 in. of aquifer-system compaction measured by the extensometer from 1989 to 2005. Thus, the data indicate that most of the subsidence occurring in the vicinity of station C45 is due to aquifer-system compaction within the zone measured by the extensometer. As noted previously, aquifer-system compaction measured at borehole extensometers generally is less than the subsidence measured by repeated GPS surveys for the same time period because extensometers measure compaction between the land surface and the depth at which the bottom of the extensometer is anchored, and repeated GPS surveys measure total land subsidence due to fluid withdrawal throughout the entire thickness of the aquifer system, including any portion that is below the level of the extensometer.

As noted previously, aquifer-system compaction at the seven extensometers in Avra Valley ranged from 0.1 in. at station TA13 to 1.7 in. at station AF17 for the period between 1989 and 2005 (table 2). The extensometer at station AF14 measured a cumulative compaction of about –0.6 in. for the period of record. Most of this occurred from 1997 to 2005 during a corresponding increase in water level of more than 70 ft.

At station AV25 in Avra Valley, the aquifer-system compaction measured by the extensometer from 1989 to 2005 was 0.9 in. During the period of record there was a water-level decline of 55 ft. GPS-survey data from 1987 to 2005 indicate that more than1989 and 2005 4 in. of subsidence has occurred at station AV25. Thus, the data indicate that most of the subsidence occurring in the vicinity of station AV25 is due to aquifer-system compaction below the depth measured by the extensometer.

A review of the time-series records of the extensometer data also show evidence of residual compaction due to delayed drainage of aquitards following a net increase in water level in the surrounding aquifer system. The equilibrium of hydraulic heads in the aquitards of an aquifer system typically lag head changes in the surrounding aquifer because of the low vertical hydraulic conductivity of the fine-grained silts and clays that make up the aquitards (Hoffmann and others, 2003). In Tucson Basin, the time-series data for the extensometer at well SC17



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

0 5 MILES
0 5 KILOMETERS

EXPLANATION

APPROXIMATE ELEVATION CHANGE , IN INCHES:

–1.1 0 1.1
Subsidence Uplift

Figure 13. Land-surface elevation change in the Tucson Active Management Area based on a 3-year, 8-month interferogram, February 2003 to October 2006.

Table 2. Aquifer-system compaction and water-level data for the Tucson Active Management Area, 1989-2005.

Name	Latitude	Longitude	Compaction data					Water-level data				
			Start date	End date	Land surface compaction (ft)		Total (in)	Start date	End date	Depth-to-water (ft)		Delta
					Start	End				Start	End	Water level (ft)
Avra Valley												
AF14	32.394	-111.283	1/1/1989	9/30/2005	0.008	-0.056	-0.576	6/5/1989	9/30/2005	286.20	213.80	72.40
AF17	32.394	-111.322	1/1/1989	9/30/2005	0.039	0.181	1.704	9/28/1989	9/30/2005	345.50	327.00	18.50
AV25	32.162	-111.216	1/1/1989	9/30/2005	0.032	0.105	0.876	8/8/1989	9/30/2005	351.67	406.80	-55.13
TA13	32.587	-111.303	4/6/1989	9/30/2005	0.000	0.010	0.120	7/6/1989	9/30/2005	240.20	244.30	-4.10
TA32	32.349	-111.223	4/16/1989	9/30/2005	0.000	0.070	0.840	3/16/1989	9/30/2005	351.50	338.10	13.40
TA33	32.263	-111.244	4/6/1989	9/30/2005	0.000	0.005	0.060	3/24/1989	9/30/2005	358.60	339.60	19.00
TA44	32.174	-111.168	5/4/1989	7/19/2004	0.000	0.023	0.276	4/5/1989	9/30/2005	400.60	442.00	-41.40
Tucson Basin												
B76	32.183	-110.943	1/1/1989	9/30/2005	0.070	0.426	4.272	7/7/1989	9/30/2005	208.40	227.20	-18.80
C45	32.202	-110.896	1/1/1989	9/30/2005	0.094	0.357	3.156	7/7/1989	9/30/2005	278.97	321.50	-42.53
D61	32.199	-110.888	1/1/1989	9/30/2005	0.051	0.241	2.280	7/7/1989	9/30/2005	291.90	333.50	-41.60
SC17	32.094	-110.960	1/1/1989	9/30/2005	0.084	0.197	1.356	1/5/1989	9/30/2005	113.14	97.71	15.43
SC30	31.986	-110.902	1/1/1989	9/30/2005	0.065	0.204	1.668	8/8/1989	9/30/2005	213.20	220.80	-7.60
WR52	32.255	-110.955	1/1/1989	9/30/2005	0.035	0.126	1.092	7/7/1989	9/30/2005	204.68	251.50	-46.82
WR53	32.146	-110.920	1/1/1989	9/30/2005	0.008	0.065	0.684	7/7/1989	9/30/2005	146.85	152.70	-5.85

shows continued compaction during a net water level rise of about 20 ft for the period between 2000 and 2005 (fig. 7). Similarly in Avra Valley, the time-series data for the extensometer at well AF17 shows continued compaction during a net water level rise of about 15 ft for the period between 1998 and 2005 (fig. 8).

InSAR interferograms are a powerful mapping tool in the assessment and monitoring of subsidence. The method has been used successfully to measure and map subsidence and uplift of the earth's surface (as small as a a few tenths of an inch) caused by aquifer-system compaction (Bawden and others, 2003, Galloway and others, 2000, Galloway and Hoffmann, 2007). In Arizona, the ADWR has added InSAR to its program of subsidence monitoring with repeated GPS surveys in Phoenix and Tucson with encouraging results (Brian Conway, ADWR, oral commun., 2007). Figure 13, provided by the ADWR, is a portion of an interferogram from February 2003 to October 2006 that shows the same area in the TAMA where subsidence is monitored by using the network of GPS stations and borehole extensometers.

To read the interferogram, count the number of InSAR fringes between two points on the interferogram, where one fringe is one complete color cycle (that is, blue, red, yellow, green, and blue). Then multiply the number of fringes by 1.1 in. and determine if the ground moved closer (uplift) or further away (subsidence) by matching how the colors change on the InSAR scale bar. For the area in the northern part of the Tucson Basin between the Rillito and Santa Cruz rivers, there are about 1.5 fringes or 1.65 in. of subsidence indicated by the interferogram. This northern area includes the GPS station C45. Between 2002 and 2004, the GPS surveys at station C45 show a subsidence of 1.2 in., indicating a good correlation between the GPS-survey and InSAR data. InSAR technology has the potential to enhance the capability to assess and monitor subsidence and allow for better understanding of the seasonal elastic deformation in the TAMA.

Summary

The U.S. Geological Survey monitors land subsidence and aquifer-system compaction caused by ground-water depletion in the Tucson Basin and Avra Valley. In southern Arizona, ground-water pumping in excess of natural recharge is the primary cause of aquifer-system compaction and associated land subsidence. Improved scientific understanding, detection, and monitoring of aquifer-system compaction and land subsidence could prove useful for stakeholders concerned with the sustainable development of land and water resources within the TAMA.

Compaction of sediments within the saturated ground-water system is the focus of this report; however, near-surface compaction or expansion of soils from wetting and drying has been documented as contributing to subsidence in the TAMA, particularly in areas that are underlain by soils with a high clay content.

In the spring of 1987, GPS-survey methods were used to measure horizontal and vertical positions for bench marks at 43 sites to establish a network for monitoring land subsidence in the TAMA. The average subsidence in Tucson Basin during the 11-year period from 1987 to 1998 was 0.5 in., and the maximum subsidence of 3.2 in. occurred in the northern part of the basin at station C45. In the southern portion of Tucson Basin, several stations showed uplift, and two stations (L75 and GUARD) showed uplift in excess of 1.0 in. In Avra Valley, the average subsidence during the 11-year period was 1.2 in., and the maximum subsidence of 4.0 in. occurred at station AV25 in the southern part of the valley.

A comparison of the GPS surveys between 1998 and 2002 indicates that up to 3.5 in. of subsidence occurred in Tucson Basin, and as much as 1.1 in. of subsidence occurred in Avra Valley. Between 2002 and 2005, the maximum subsidence of 0.2 in occurred in Tucson Basin at station WR52 in the northern part of the basin. In Avra Valley, the average subsidence for the 3-year period between 2002 and 2005 was about 0.7 in.; however, three stations showed subsidence of more than 1.0 in. in the northern part of the valley.

Between 1987 and 2004–05, land subsidence was greater in Avra Valley than in Tucson Basin on the basis of the average subsidence for the stations that were common to the original 1987 GPS survey. The average total subsidence during the 17- to 18-year period was about 1.3 in. in Tucson Basin and about 2.8 in. in Avra Valley. Three stations in Tucson Basin displayed subsidence greater than 4.0 in. for the period—5.0 in. at stations C45 and X419 and 4.1 in. at station PA4. In Avra Valley, two stations showed subsidence for the 17- to 18-year period greater than 4.0 in.—4.3 in. at station AV25 and 4.8 in. at station SA105.

Results from aquifer-compaction monitoring at borehole extensometers in Tucson Basin show that aquifer-system compaction ranged from 0.7 in. to 4.3 in. between 1989 and 2005. The greatest cumulative aquifer-system compaction in Tucson Basin, 4.3, 3.2, and 2.3 in., occurred in the northern part of the basin at extensometers B76, C45, and D61, respectively. Cumulative water-level change at these stations for the 1989–2005 period was –18.8, –42.53, and –41.6 ft., respectively. These results are in agreement with the area shown by the GPS surveys to have the greatest magnitude of subsidence in Tucson Basin.

At the seven extensometers in Avra Valley, aquifer-system compaction ranged from 0.1 in. at TA13, to 1.7 in. at AF17 between 1989 and 2005. The extensometer at AF14 measured a cumulative uplift of about 0.6 in. for the period of record. Most of the uplift occurred from 1997 to 2005 during a corresponding increase in water level of more than 70 ft. At AV25 in Avra Valley, the aquifer-system compaction measured by the extensometer from 1989 to 2005 was less than 0.9 in. During the period of record there was a water-level decline of 55 ft. The GPS surveys between 1987 and 2005 show that more than 4.0 in. of subsidence has occurred at AV25. The data indicate that most of the subsidence occurring in the vicinity of AV25 is due to aquifer-system compaction below the portion of the aquifer measured by the extensometer.

For the area in the northern part of Tucson Basin between the Rillito and Santa Cruz rivers, an InSAR interferogram indicates that about 1.65 in. of subsidence occurred between 2003 and 2006. Between 2002 and 2004, the GPS station at C45 in the same northern part of the basin shows a subsidence of 1.2 in., indicating a good correlation between the GPS and the InSAR data. InSAR is a tool that promises to enhance the capability to assess and monitor subsidence and allow for a better understanding of the seasonal elastic deformation in the TAMA.

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