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

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Introduction

The U.S. Geological Survey monitors land subsidence and aquifer compaction caused by ground-water depletion in Tucson Basin and Avra Valley—two of the three alluvial basins within the Tucson Active Management Area (TAMA). The TAMA encompasses about 3,900 mi^2 in south-central Arizona (fig. 1). 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 sustain riparian ecosystems.

Sustainable development of land and water resources within the TAMA depends upon scientific understanding, detection, and monitoring of land subsidence. Land subsidence and aquifer compaction can occur when water is removed from alluvial-aquifer systems. Land subsidence is the lowering of surface elevation as the result of the removal of subsurface support (Galloway and others, 1999).

As early as the 1940s, water-level declines of up to several feet per year resulted in aquifer compaction and measurable land subsidence in Tucson Basin and Avra Valley (Evans and Pool, 2000). Conventional first-order leveling surveys showed that ground-water mining 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) began an investigation to determine the potential for aquifer compaction, land subsidence, and earth fissures in Tucson Basin. This 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 43 vertical control stations was established to utilize Global Positioning System (GPS)

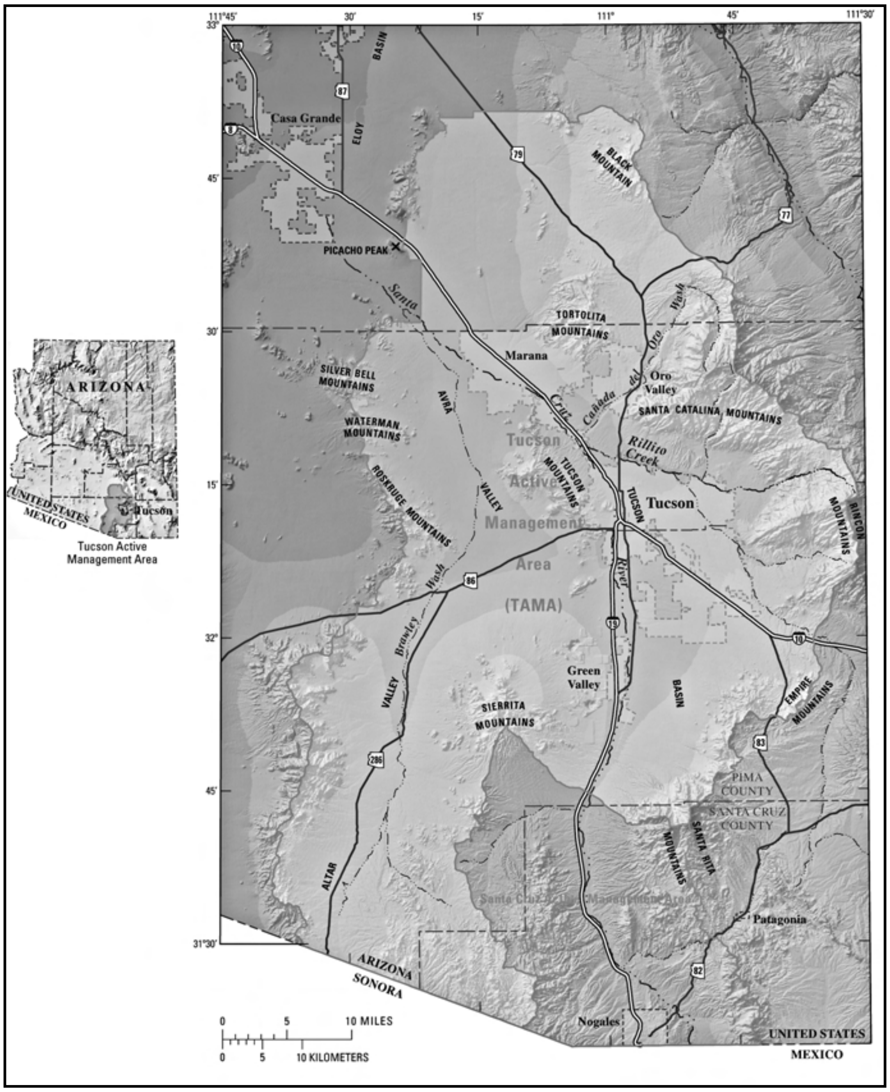

Figure 1. Tucson Active Management Area in south-central Arizona.

technology for measurement of land-surface elevation change. The GPS network was designed to enhance knowledge of the amount and distribution of land subsidence in Tucson Basin and Avra Valley.

Methods of Data Collection

The initial 1987 GPS survey consisted of a series of measurements at bench marks at 43 sites. In 1998, approximately annual GPS surveys began, using as much of the original network as possible. In addition, many new stations were added to the network between 1998 and 2005 to provide additional information on both amounts and aerial distribution of land-surface elevation change in the growing metropolitan areas of the TAMA (fig. 2).

In addition to the annual GPS surveys, a vertical-extensometer network is used to measure land subsidence and for monitoring aquifer compaction caused by ground-water depletion. Aquifer compaction is measured by the vertical-extensometer pipes that extend from the land surface to the bottom of cased wells or test holes (fig. 3). 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, vertical extensometers measure aquifer compaction for the portion of the aquifer between the land surface and the depth at which the bottom of the extensometer is anchored. Extensometers may measure less vertical displacement than GPS surveys because the GPS measures total subsidence, whereas some compaction may occur beneath the base of the extensometer (Amelung and others, 1999; Evans and Pool, 2000).

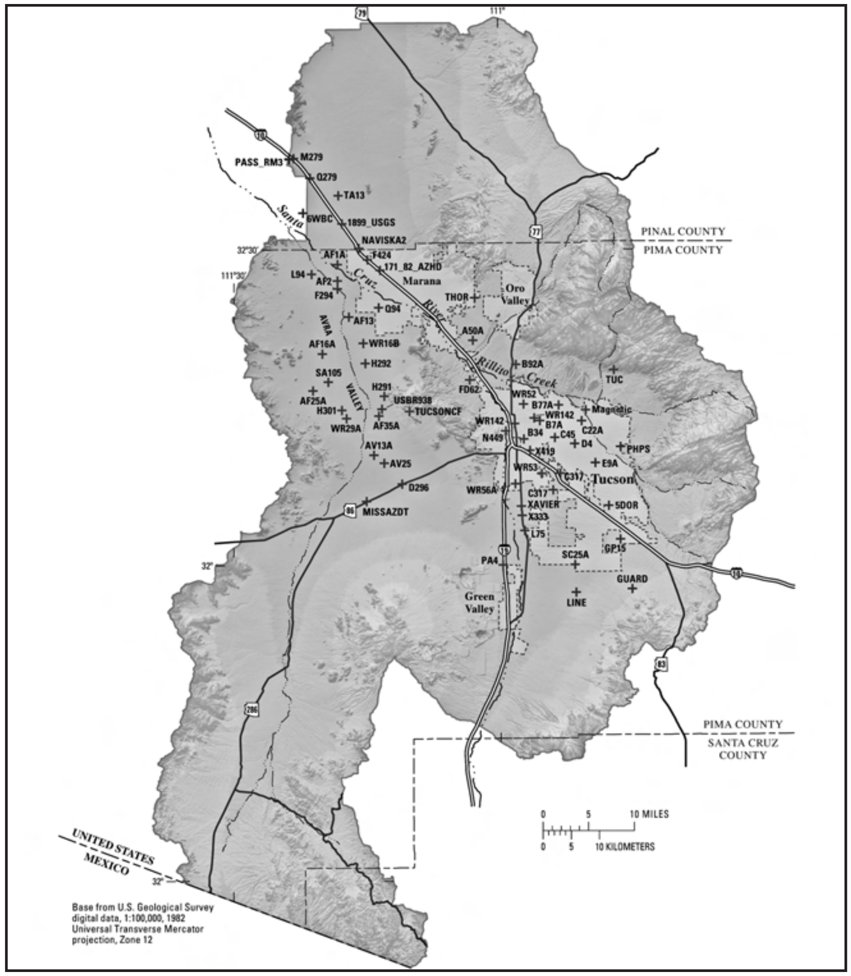

Figure 2. Long-term elevation-change monitoring stations in the Tucson Active Management Area, south-central Arizona.

Name	Latitude	Longitude	Compaction data: start date	end date	land surface compaction (ft) start	end	total (in)	Water level data: start date	end date	depth-to-water (ft) start	end	delta 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

Table 1. Aquifer-compaction and water-level data for the Tucson Active Management Area, 1989-2005.

Potential for Land Subsidence

Permanent land subsidence can occur in alluvial basins when water is removed from aquifer systems. Aquifer systems in unconsolidated rocks such as those in the TAMA are supported by the granular skeleton and the pore-fluid pressure. When ground water is withdrawn and the pore-fluid pressure is reduced, the granular skeleton compresses, causing some lowering of the land surface. Both the aquifers (sand and gravel) and aquitards (clay and silt) of aquifer systems deform as a result of changes to the pore-fluid pressure and skeleton, but to different degrees. Most permanent subsidence occurs due to the irreversible compression of aquitards during the slow (years) process of aquitard drainage.

Reversible deformation also occurs in all aquifer systems. When ground-water levels are lowered, the pore-fluid pressure is decreased, support provided by the water is transferred to the skeleton, and the skeleton compresses. Conversely, when ground-water levels are raised, some support provided by the skeleton is transferred to the fluid-pore pressure, and the skeleton expands. This fully recoverable deformation commonly results in seasonal, reversible displacements in land surface of more than 1 in. (Amelung and others, 1999; Galloway and others, 1999).

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). Long-term water-level declines have stabilized or reversed since 2000 at several monitoring wells 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—will decrease the potential for continued land subsidence due to aquifer compaction in the TAMA.

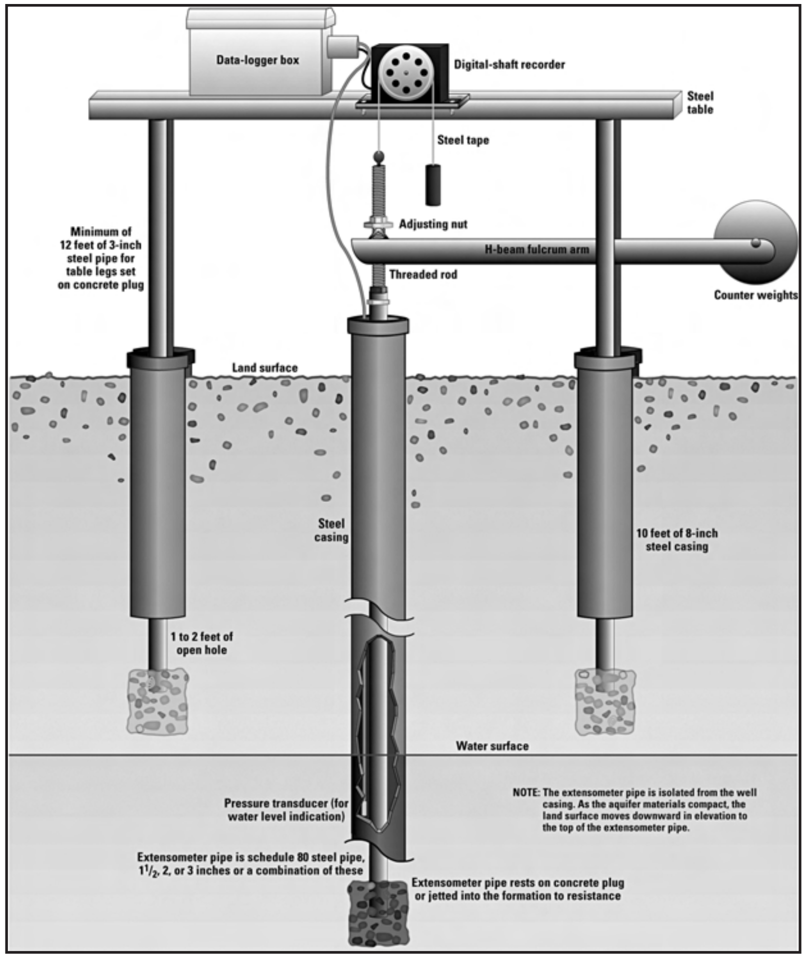

Figure 3. Diagrammatic sketch of a vertical extensometer installation in the Tucson Active Management Area, south-central Arizona.

Land Subsidence and Aquifer Compaction

Permanent subsidence, seasonal elastic deformation, and uplift have been observed during the period of data collection from 1987 to 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 17–18 year period, and (2) the areas of the TAMA where the most subsidence has occurred (fig. 4 and table 1). GPS survey data for 2004 and 2005 were combined for the comparison with the original 1987 survey in order to maximize the number of stations common to the original survey.

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 17–18 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 in. for the 17–18 year period—5 in. at stations C45 and X419 and 4.1 in. at station PA4. In Avra Valley, two stations showed subsidence for the 17–18 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 17–18 year period. In 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 extensometers provide a continuous record of water level and aquifer compaction for the part of the aquifer penetrated by each well. At the seven extensometers in Tucson Basin, aquifer compaction from 1989 and 2005 ranged from 0.7 in. to 4.3 in., while in Avra Valley, aquifer compaction for the same period ranged from 0.1 in. at TA13, to 1.7 in. at AF17 (table 1). Additionally, the extensometer at AF14 measured a cumulative uplift of about 0.6 in. for the 1989 to 2005 period.

In Tucson Basin, the greatest cumulative aquifer 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 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

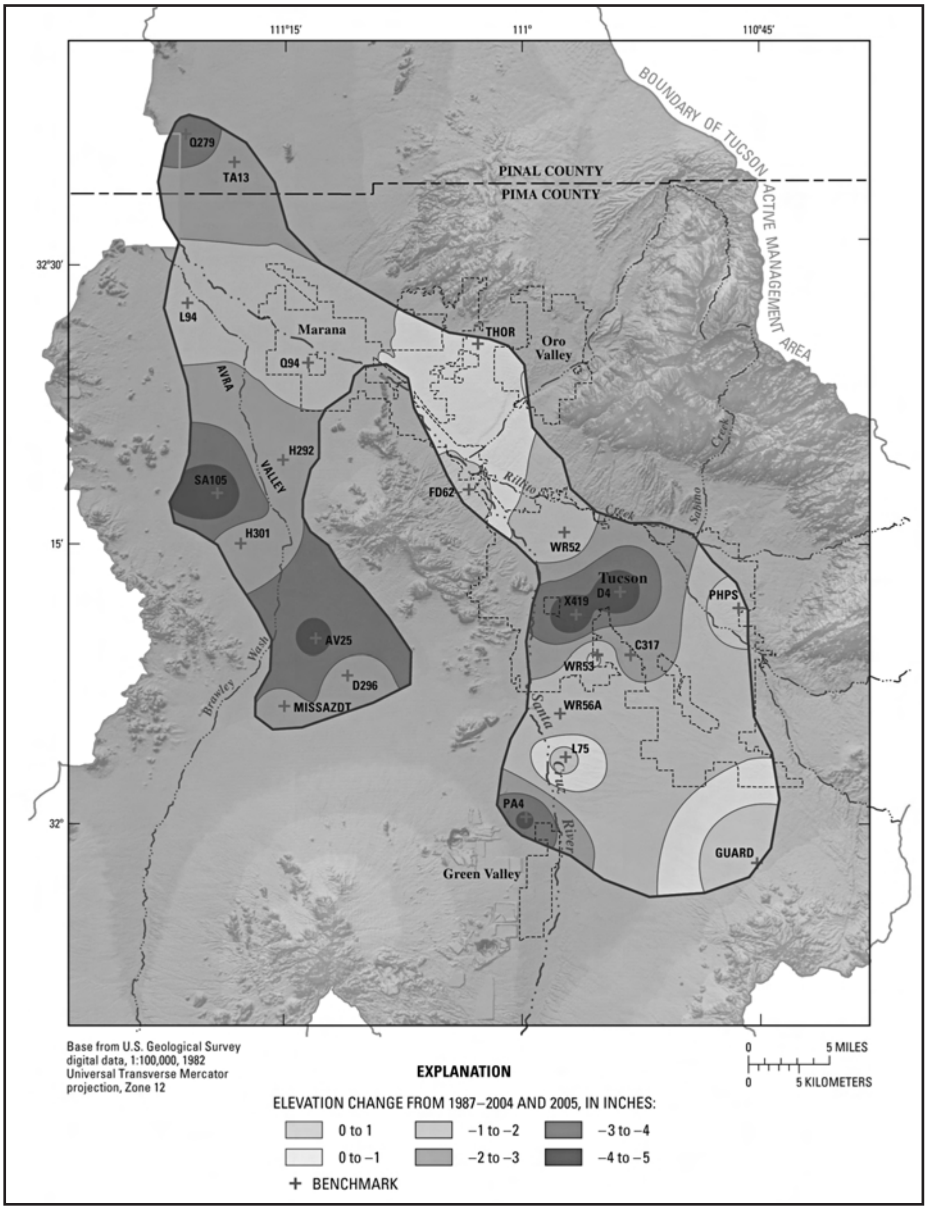

Figure 4. Land-surface elevation change in the Tucson Active Management Area, south-central Arizona, from 1987 to 2004.

due to aquifer compaction within the zone measured by the extensometer. As noted previously, aquifer compaction measured at vertical 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, whereas repeated GPS surveys measure total land subsidence due to fluid withdrawal throughout the entire aquifer, including any portion of the aquifer that is below the level of the extensometer.

Aquifer 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 1). The extensometer at station 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 station AV25 in Avra Valley, the aquifer 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 than 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 compaction below the portion of the aquifer measured by the extensometer.

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