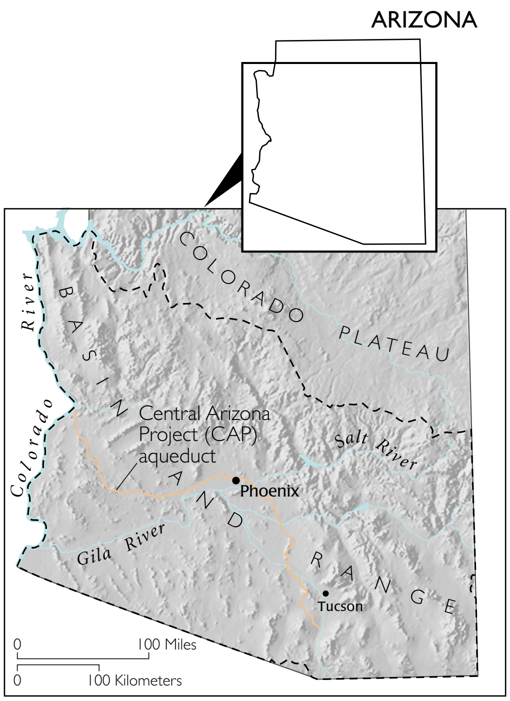
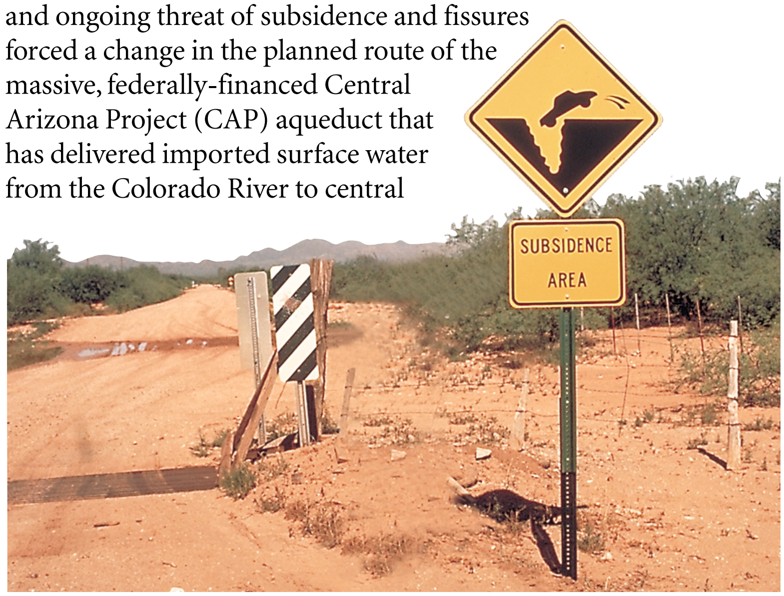
SOUTH-CENTRAL ARIZONA

Earth fissures and subsidence complicate development of desert water resources



Earth fissures that rupture the Earth's surface and widespread land subsidence in deep alluvial basins of southern Arizona are related to ground-water overdrafts. Since 1900 ground water has been pumped for irrigation, mining, and municipal use, and in some areas more than 500 times the amount of water that naturally replenishes the aquifer systems has been withdrawn (Schumann and Cripe, 1986). The resulting ground-water-level declines—more than 600 feet in some places—have led to increased pumping costs, degraded the quality of ground water in many locations, and led to the extensive and uneven permanent compaction of compressible fine-grained silt- and clay-rich aquitards. A total area of more than 3,000 square miles has been affected by subsidence, including the expanding metropolitan areas of Phoenix and Tucson and some important agricultural regions nearby.

Earth fissures, a result of ground failure in areas of uneven or differential compaction, have damaged buildings, roads and highways, railroads, flood-control structures, and sewer lines. The presence and ongoing threat of subsidence and fissures forced a change in the planned route of the massive, federally-financed Central Arizona Project (CAP) aqueduct that has delivered imported surface water from the Colorado River to central



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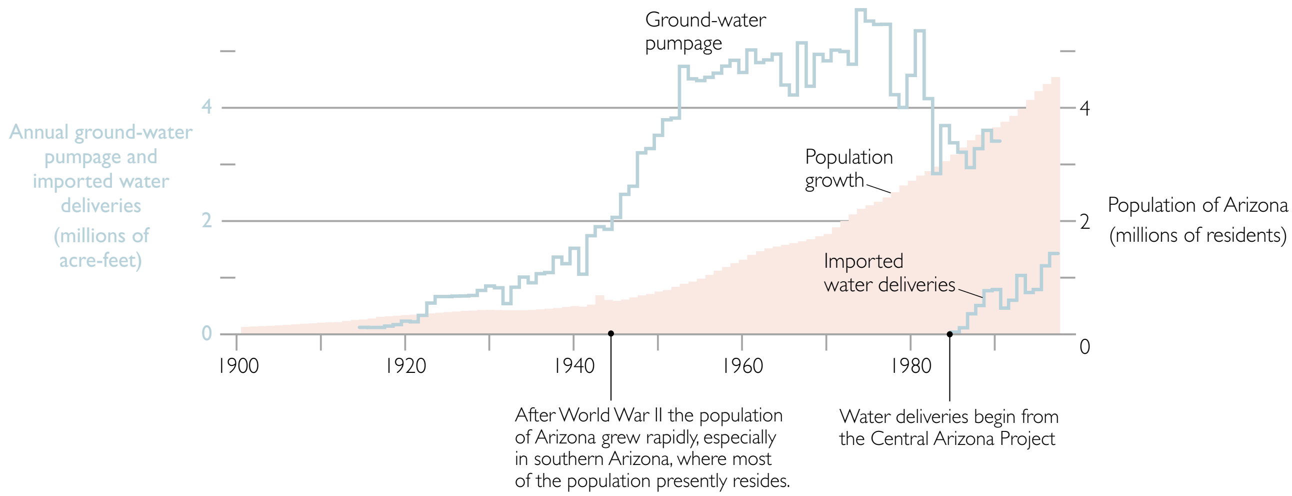


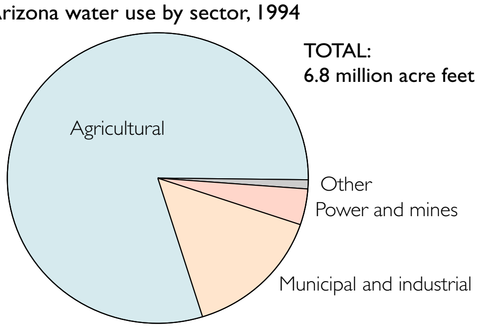
(Ground-water pumpage from Anning and Tuet, 1994; imported water deliveries from Arizona Department of Water Resources; population data modified from U.S. Census Bureau)

Arizona since 1985. In the CAP, Arizona now has a supplemental water supply that has lessened the demand and overdraft of ground-water supplies. Some CAP deliveries have been used in pilot projects to artificially recharge depleted aquifer systems. When fully implemented, recharge of this imported water will help to maintain water levels and forestall further subsidence and fissure hazards in some areas.

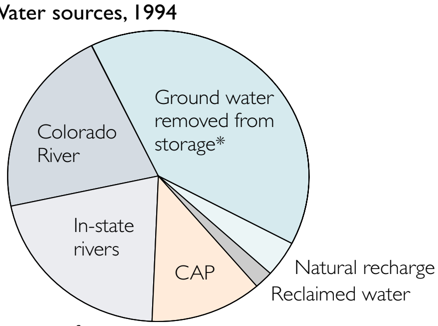
GROUND WATER HAS SUSTAINED AGRICULTURE

Irrigation is needed to grow crops in Arizona because of the low annual rainfall and the high rate of potential evapotranspiration—more than 60 inches per year. Precipitation in south-central Arizona ranges from as low as 3 inches per year over some of the broad flat alluvial basins to more than 20 inches per year in the rugged mountain ranges. Large volumes of water can be stored in the intermontane basins, which contain up to 12,000 feet or more of sediments eroded from the various metamorphic, plutonic, volcanic, and consolidated sedimentary rocks that form the adjacent mountains. Ground water is generally produced from the upper 1,000 to 2,000 feet of the basin deposits, which constitute the aquifer systems. Ground water pumped from the aquifer systems became a reliable and heavily tapped source of irrigation water that fueled the development of agriculture during the early and mid-20th century. In many areas, the aquifer systems include a large fraction of fine-grained deposits containing silt and clay that are susceptible to compaction when the supporting fluid pressures are reduced by pumping.

Arizona water use by sector, 1994



Water sources, 1994



*In excess of natural recharge

(Arizona Department of Water Resources, accessed July 27, 1999)

CAP water sustains urban growth

Pumping for irrigation began prior to 1900, and increased markedly in the late 1940s. By the mid-1960s the expected growth in the metropolitan Phoenix and Tucson areas, coupled with the already large

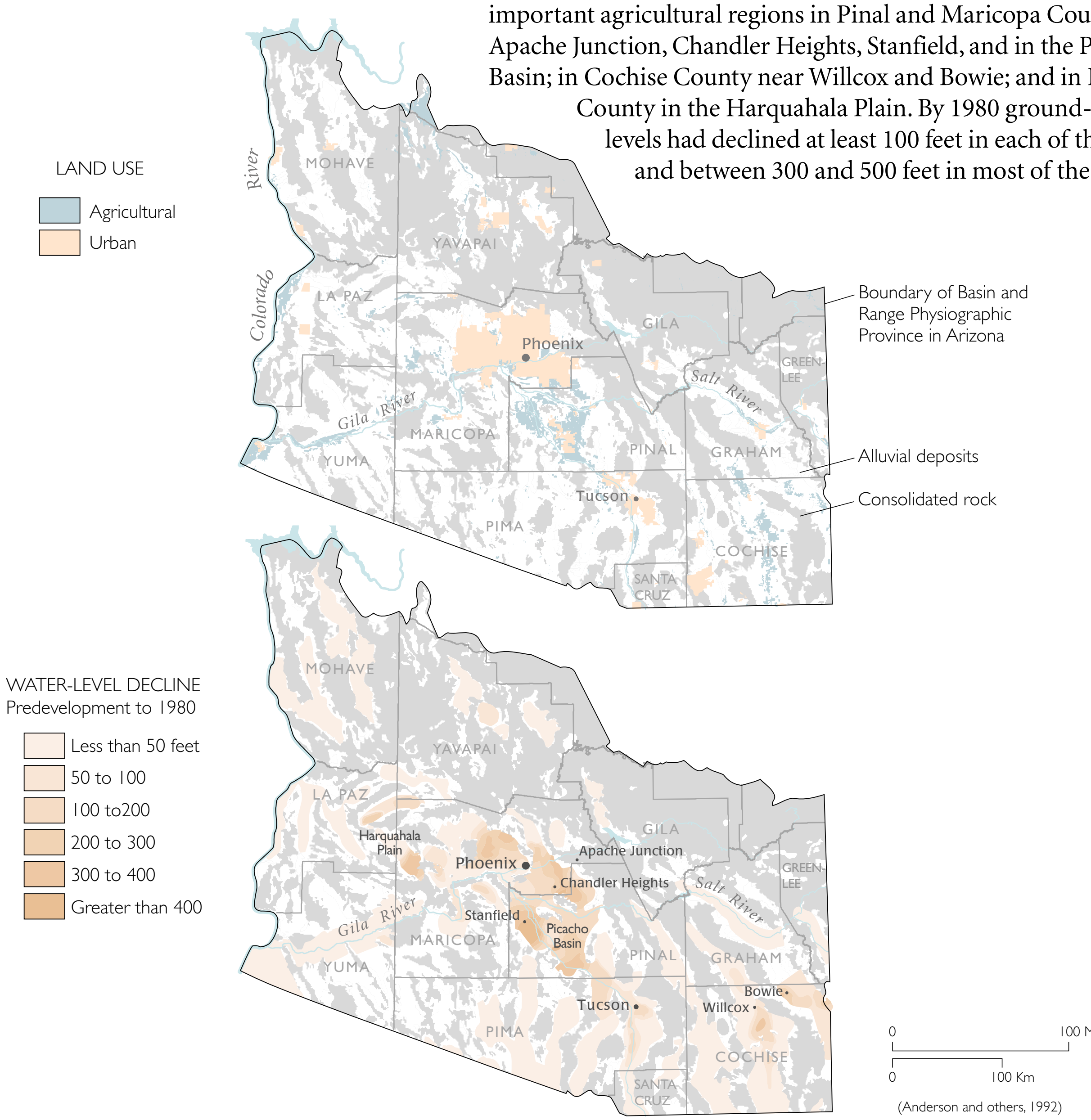
Agriculture in Arizona requires intensive irrigation.

(U.S. Bureau of Reclamation)

ground-water-level declines and worsening subsidence problems, prompted Arizona water officials to push for and receive congressional approval for the CAP. Since then, growth in the metropolitan areas has exceeded expectations, and municipal-industrial and domestic water use presently accounts for nearly 20 percent of Arizona's water demand.

Subsidence follows water-level declines

Subsidence first became apparent during the 1940s in several alluvial basins in southern Arizona where large quantities of ground water were being pumped to irrigate crops. By 1950, earth fissures began forming around the margins of some of the subsiding basins. The areas affected then and subsequently include metropolitan Phoenix in Maricopa County and Tucson in Pima County, as well as important agricultural regions in Pinal and Maricopa Counties near Apache Junction, Chandler Heights, Stanfield, and in the Picacho Basin; in Cochise County near Willcox and Bowie; and in La Paz County in the Harquahala Plain. By 1980 ground-water levels had declined at least 100 feet in each of these areas and between 300 and 500 feet in most of the areas.



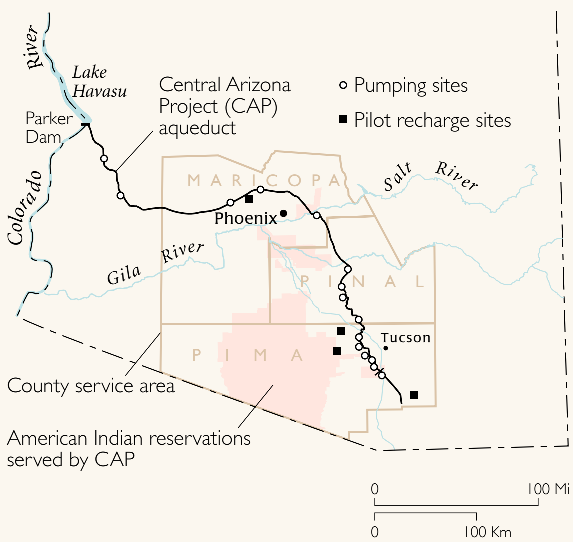
(Anderson and others, 1992)

Central Arizona Project (CAP)

Delivering water to the interior basins

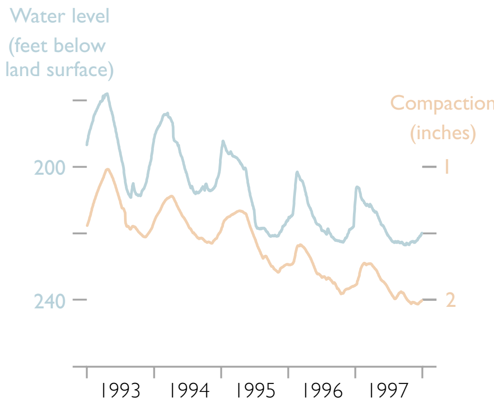
The primary purpose of The Central Arizona Project (CAP) is to help conserve the ground-water resources of Arizona by extending the supply of Colorado River water to interior basins in Arizona that are heavily dependent on the already depleted ground-water supplies. A body of legal doctrine collectively known as the "Law of the River" allots Arizona up to 2.85 million acre-feet of Colorado River water yearly, depending on availability. The Central Arizona Project was designed to deliver about 1.5 million acre-feet of Colorado River water per year to Maricopa, Pinal, and Pima Counties. Colorado River water fills the aqueduct at Lake Havasu near Parker and flows 336 miles to the San Xavier Indian Reservation southeast of Tucson, with the aid of pumping plants and pumping-stations with lifts that total about 3,000 feet. Of the more than 80 major customers, 75 percent are municipal or industrial, 13 percent are irrigation districts, and about 12 percent are Native American communities. CAP water was first delivered to Phoenix in 1986 and to Tucson in 1992. Having a higher salinity than the natural ground-water supplies it augments, CAP water is generally used in three ways—direct treatment and delivery; treatment, blending and delivery; and spread in percolation basins to artificially recharge the aquifer systems. Before it is distributed as drinking water, CAP water is disinfected and generally "softened." Of the 1.5 million acre-feet annual capacity of the CAP, only about 1 million acre-feet were being directly utilized as of 1997. Much of the balance was used to augment natural aquifer-system recharge through artificial-recharge pilot projects, in order to store water for future use and mitigate water-level declines and limit subsidence.

A segment of the CAP aqueduct snakes through the desert west of Phoenix.



Land subsidence was first verified in south-central Arizona in 1948 using repeat surveys of bench marks near Eloy (Robinson and Peterson, 1962). By the late 1960s, installation and monitoring of borehole extensometers at Eloy, Higley Road south of Mesa, and at Luke Air Force Base, as well as analysis of additional repeat surveys, indicated that land subsidence was occurring in several areas. The areas of greatest subsidence corresponded with the areas of greatest water-level decline (Schuman and Poland, 1970).

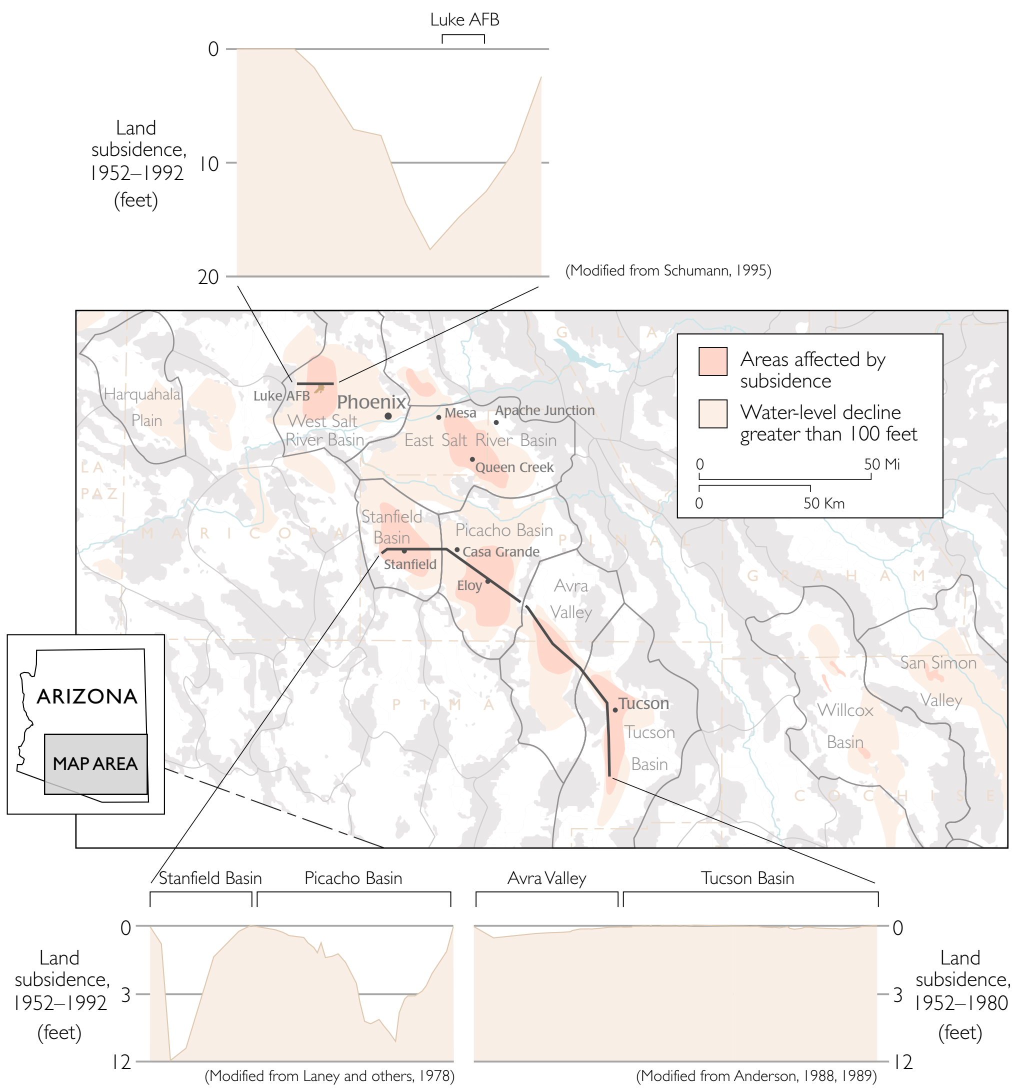
By 1977, nearly 625 square miles had subsided around Eloy, where as much as 12.5 feet of subsidence was measured; another 425 square miles had subsided around Stanfield, with a maximum sub-



Data from a borehole extensometer site in the Tucson Basin shows how compaction can respond to water level changes. Seasonal fluctuations are related to patterns of ground-water pumping.

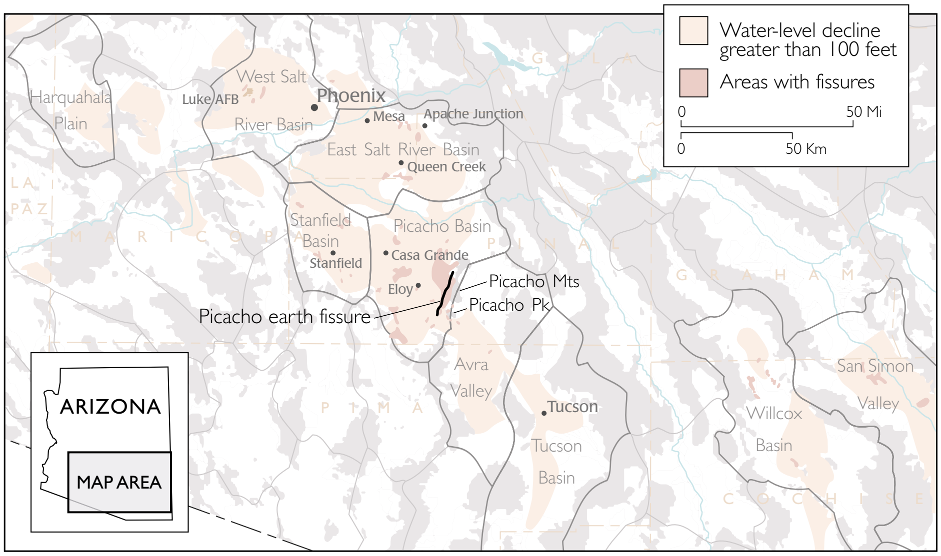
sidence of 11.8 feet (Laney and others, 1978). Near Queen Creek, an area of almost 230 square miles had subsided more than 3 feet. In northeast Phoenix, as much as 5 feet of subsidence was measured between 1962 and 1982. By contrast, in the Harquahala Plain, only about 0.6 feet of subsidence occurred in response to about 300 feet of water-level decline, whereas near Willcox, more than 5 feet of subsidence occurred in response to 200 feet of water-level decline (Holzer, 1980; Strange, 1983; Schumann and Cripe, 1986). The relation between water-level decline and subsidence varies between and within basins because of differences in the aggregate thickness and compressibility of susceptible sediments.

By 1992, ground-water level declines of more than 300 feet had caused aquifer-system compaction and land subsidence of as much as 18 feet on and near Luke Air Force Base, about 20 miles west of Phoenix. Associated earth fissures occur in three zones of differential subsidence on and near the base. Local flood hazards have greatly increased due to differential subsidence at Luke, which led to a flow reversal in a portion of the Dysart Drain, an engineered flood



Subsidence has occurred in basins with large water-level declines, but the relation between the magnitude of water-level decline and subsidence varies between and within basins. Representative profiles show that subsidence is greater near the center of basins, where the aggregate thickness of fine-grained sediments is generally greater.

Fissures tend to develop near the margins of subsiding basins.

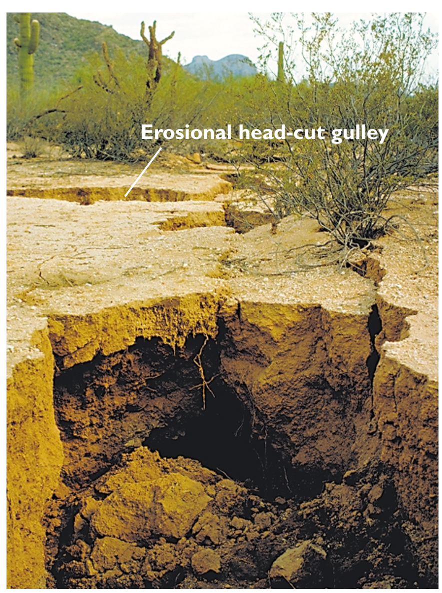


conveyance. On September 20, 1992, surface runoff from a rainstorm of 4 inches closed the base for 3 days. The sluggish Dysart Drain spilled over, flooding the base runways along with more than 100 houses and resulted in about $3 million in damage (Schumann, 1995).

EARTH FISSURES ARE COMMON IN MANY BASINS

Some of the most spectacular examples of subsidence-related earth fissures occur in south-central Arizona. Earth fissures are the dominant mode of ground failure related to subsidence in alluvial-valley sediments in Arizona and are typically long linear cracks at the land surface with little or no vertical offset. The temporal and spatial correlation of earth fissures with ground-water-level de-

Fissures have vertical sides, and typically first appear following severe rainstorms. Opening or movement is rarely more than 1 inch in any particular episode, although erosion and collapse of the sides during the initial episode may leave a fissure gully more than 10 feet wide, 30 feet deep, and hundreds of feet long. The apparent 1-foot width of the fissure that opened on July 23, 1976, near the Picacho Mountains, is due to erosion, collapse, and disintegration of down-dropped blocks. Several blocks remain wedged about 1 foot below land surface.



In another fissure that opened July 23, 1976, near the Picacho Mountains, an erosional gully 6 feet wide, 5 feet deep, and 20 feet long was cut in less than 16 hours. The head-cut gully developed perpendicular to the fissure in a wash on its upstream side. In subsequent storms, both the head-cut gully in the wash and the fissure were widened, deepened, and lengthened. It may take years or decades before a wash again carries water or sediment past a fissure that has cut across it.

clines indicates that many of the earth fissures are induced, and are related to ground-water pumpage. More than 50 fissure areas had been mapped in Arizona prior to 1980 (Laney and others, 1978).

Most fissures occur near the margins of alluvial basins or near exposed or shallow buried bedrock in regions where differential land subsidence has occurred. They tend to be concentrated where the thickness of the alluvium changes markedly. In a very early stage, fissures can appear as hairline cracks less than 0.02-inch wide interspersed with lines of sink-like depressions resembling rodent holes. When they first open, fissures are usually narrow vertical cracks less than about 1-inch wide and up to several hundred feet long. They

Fissure formation

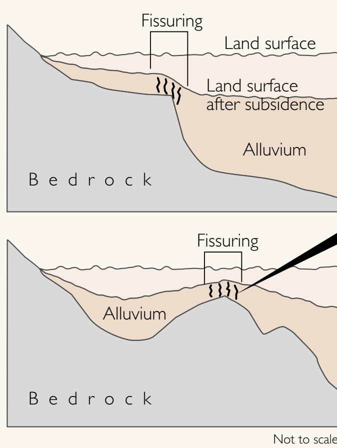
Several theories explain the mechanism of fissure formation

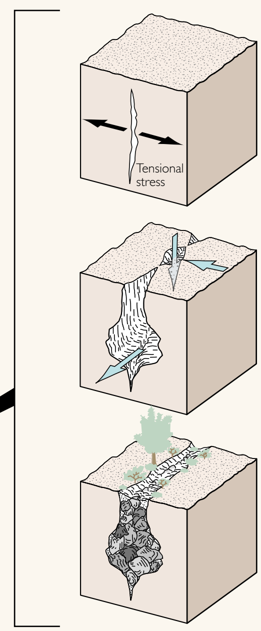
Several mechanisms have been proposed for earth fissures, the most widely accepted of which is differential compaction. As ground-water levels decline in unconsolidated alluvial basins, less compaction and subsidence occurs in the thinner alluvium near the margin of the basin than in the thicker alluvium near the deeper, central part of the basin. The tension that results from the differential compaction stretches the overlying sediment until it fails as a fissure.

Differential compaction

As the land surface subsides, alluvium stretches and eventually fails, generally in a region of abrupt change in alluvium thickness.

Fissures are concentrated in areas where the thickness of the alluvium changes, such as near the margin of basins or where bedrock is near the surface.





Lateral stresses induce tension cracking.

Surface water infiltrates, dissolving the natural cement bonding the soil, connecting hairline cracks, and further eroding and enlarging the fissure.

Fissure progressively enlarges, capturing surface runoff, sediment, and debris. Eventually vegetation establishes itself, creating a line of vegetation along the trace of the fissure.

OTHER POSSIBLE MECHANISMS

Horizontal seepage stresses and rotation of a rigid slab over an incompressible edge are other mechanisms that have been suggested. The observation that new fissures have formed between existing fissures and the mountain front argues against these two hypotheses. Hydrocompaction, or collapse of low-density soils upon complete wetting, and increased soil-moisture tension have also been suggested as possible mechanisms. Hydrocompaction in fact did occur during construction of sections of the CAP Aqueduct between the Picacho Mountains and Marana.

Other proposed mechanisms include piping erosion, soil rupture during earthquakes, renewed faulting, collapse of caverns or mines, oxidation of organic soils, and diapirism. Piping (subsurface soil erosion) along the trace of a fissure certainly plays a part in the opening, progressive enlargement and subsequent development of fissure gullies.

(Eaton and others, 1972; Carpenter, 1993)

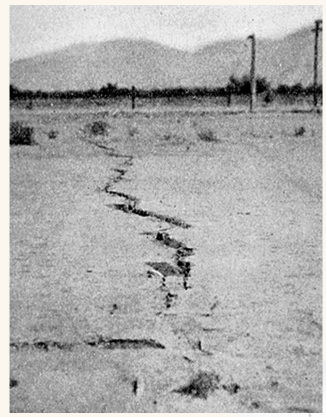
Discovering Arizona's early fissures

Two fissures, two scientists, and their one discovery

On September 12, 1927, Professor R.J. Leonard from the University of Arizona visited and photographed an earth fissure south of the town of Picacho that was observed following a severe thunderstorm. After considering several possible causes for the fissure, Leonard tentatively concluded that an earthquake which had occurred on September 11, 1927, 170 miles from Tucson, caused the fissure by triggering the release of preexisting, accumulated strain. Leonard, a mining engineer, was probably influenced by his knowledge of the occurrence of unusual cracks at the El Tiro Mine near Silver Bell, Arizona, about 20 miles to the south (Leonard, 1929).

Two months later on November 13, 1927, Professor A.E. Douglas, also from the University of Arizona, visited and photographed what he probably thought was the same fissure that Leonard had photographed. In fact, it was not. The mountain skyline on Douglas's photographs lines up from a viewpoint about 1 mile to the southwest of Leonard's viewpoint. Leonard and Douglas discovered two separate earth fissures, and it was Douglas's photo that captured the precursor to the present-day Picacho earth fissure (Carpenter, 1993).

These early discoveries of multiple earth fissures at a time when ground-water withdrawals were just beginning raise some doubts about their origin. Although there is little doubt that ground-water-level declines since the 1940s have caused earth fissures, the cause of the Leonard and Douglas fissures remains a mystery.

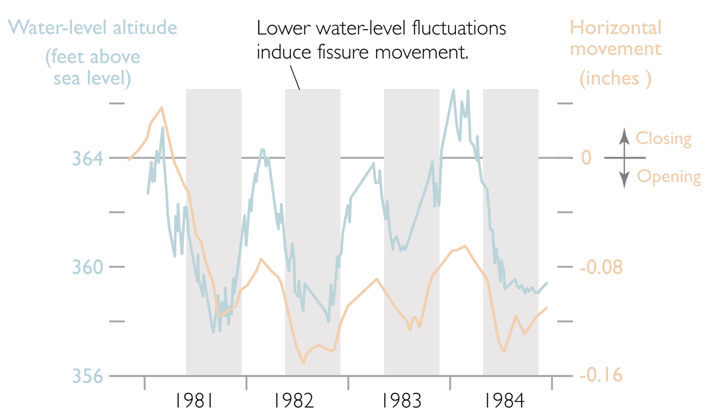


Leonard's fissure

Douglas's view

(University of Arizona Tree Ring Laboratory photographs GEOL 27-2)

A fissure moves with the seasonal fluctuation of water levels (data from the Picacho Basin).



can progressively lengthen to thousands of feet. Apparent depths of fissures range from a few feet to more than 30 feet; the greatest recorded depth is 82 feet for a fissure on the northwest flank of Picacho Peak (Johnson, 1980). Fissure depths of more than 300 feet have been speculated based on various indirect measurements including horizontal movement, volume-balance calculations based on the volume of air space at the surface, and the amount of sediment transported into the fissures.

Widening of fissures by collapse and erosion results in fissure gullies (Laney and others, 1978) that may be 30-feet wide and 20-feet deep. No horizontal shear (strike-slip movement) has been detected at earth fissures, and very few fissures show any obvious vertical offset. However, fissures monitored by repeated leveling surveys commonly exhibit a vertical offset of a

This aerial view taken in October 1967 shows the Picacho earth fissure as a single crack. A citrus grove is visible in the upper left.

By June 1989 the fissure had developed into a system of multiple parallel cracks. A fissure scarp developed as much as 2 feet of vertical offset, with the west or left side of the fissure (as pictured) downdropped.

A lateral canal in the upper left skirts a citrus grove. This canal originates from the Central Arizona Project Aqueduct (not visible) at the base of the mountains in the background and crosses the fissure north of the citrus grove.

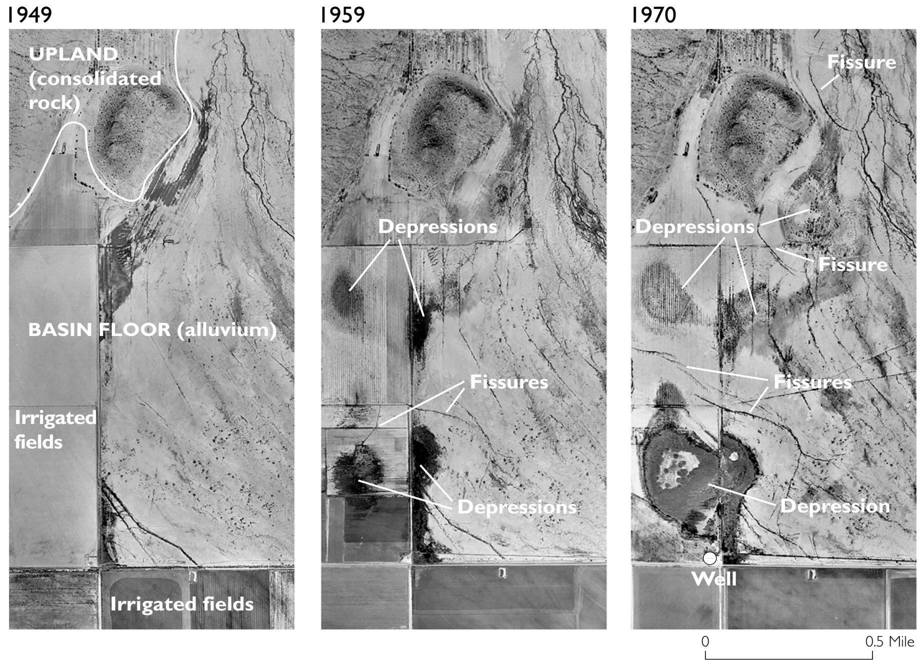
few inches. Two notable exceptions are the Picacho earth fissure, which has more than 2 feet of vertical offset at many places along its 10-mile length, and a fissure near Chandler Heights, which has about 1 foot of vertical offset.

The Picacho fissure is Arizona's most studied

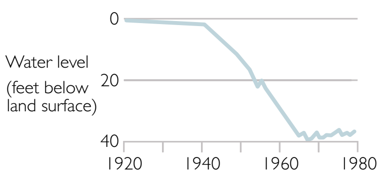
The Picacho earth fissure, perhaps the most thoroughly investigated earth fissure (Holzer and others, 1979; Carpenter, 1993), began to creep vertically in 1961, forming a scarp. The scarp initially grew at a rate of more than 2 inches per year, before progressively slowing to about one-third inch per year by 1980 (Holzer, 1984). The observed opening and closing correlated with seasonal ground-water-level fluctuations from 1980 to 1984 (Carpenter, 1993). Surface deformation near the fissure indicated that formation of the vertical scarp was preceded by differential land subsidence and the formation of other earth fissures distributed over an approximately 1,000-foot-wide zone. Local geophysical and geologic surveys indicated that the Picacho earth fissure is associated with a preexisting high-angle, normal fault.

This fissure near the Picacho Mountains is undergoing erosional widening to become a fissure gully.

In the early 1950s Feth (1951) attributed formation of earth fissures west of the Picacho Mountains to differential compaction caused by ground-water-level decline in unconsolidated alluvium over the edge of a buried pediment or bedrock bench. He observed that fissures typically open during and after storms and potentially intercept large quantities of surface runoff. A decade later, the occurrence of subsidence-related fissures near Picacho, Chandler Heights, Luke Air Force Base, and Bowie was well known (Robinson and Peterson, Another area experiencing subsidence-related earth fissures is near Casa Grande. This series of photographs shows how irrigation and pumping over a period of 22 years resulted in subsidence, surface depressions, and fissures possibly related to hydrocompaction.



A hydrograph from the well shown in the 1970 photo shows a sudden drop in water level after 1940.



1962). Subsidence-related earth fissures also have occurred in McMullen Valley (northwest of the Harquahala Plain), Avra Valley, the east Salt River Valley near Apache Junction, Willcox Basin (Schumann and Genauldi, 1986) and, as recently as 1997, in the Harquahala Plain (Al Ramsey, Arizona Department of Water Resources, written communication, 1998). Subsurface conditions beneath many subsidence-related earth fissures have been inferred principally from geophysical surveys and indicate that most occur above ridges or "steps" in the bedrock surface (Peterson, 1962; Holzer, 1984). In recent years, with introduction of CAP irrigation water, retirement of some farm lands, and the consequent recovery of water levels, earth fissures have apparently ceased to be active in some areas.

The Central Main Lateral Canal of the CAP was damaged where it crosses the Picacho earth fissure. Opening of the fissure is evident as a dark line in the lower middle of the photograph.

FISSURES CAN UNDERCUT AND DAMAGE INFRASTRUCTURE

Structures damaged by fissures include highways, railroads, sewers, canals, aqueducts, buildings, and flood-control dikes. The threat of damage from earth fissures forced a change in the proposed route of the CAP aqueduct. Erosionally enlarged fissure gullies present hazards to grazing livestock, farm workers, vehicles, hikers, and wildlife. Aquifer contamination may also occur as a result of ruptured pipelines, dumping of hazardous waste into fissures, and capture of surface runoff containing agricultural chemicals and other contaminants.

Where Interstate 10 crosses the Picacho earth fissure, more than 2 feet of vertical offset and several inches of horizontal opening have damaged the highway, requiring repeated pavement repairs. Where a natural gas pipeline crosses a fissure near the Picacho Mountains, erosional enlargement of the fissure left the pipeline exposed. The

Part of this fissure south of Apache Junction has been trenched and backfilled for a land bridge.

30-foot-wide hole was simply backfilled, but was repeatedly eroded for several years thereafter during summer and winter rains and had to be repeatedly refilled.

The CAP aqueduct and associated canals have been affected by earth fissures at several localities. Near Apache Junction, the U.S. Bureau of Reclamation installed vertical sheet piles on both sides of the CAP aqueduct in a fissure that undercuts the aqueduct. Soil beneath the aqueduct was compacted to reduce erosion. Erosional damage at this site and at another similarly treated site south of the Casa Grande Mountains has been minimal (Cathy Wellendorf, U.S. Bureau of Reclamation, written communication, 1988).

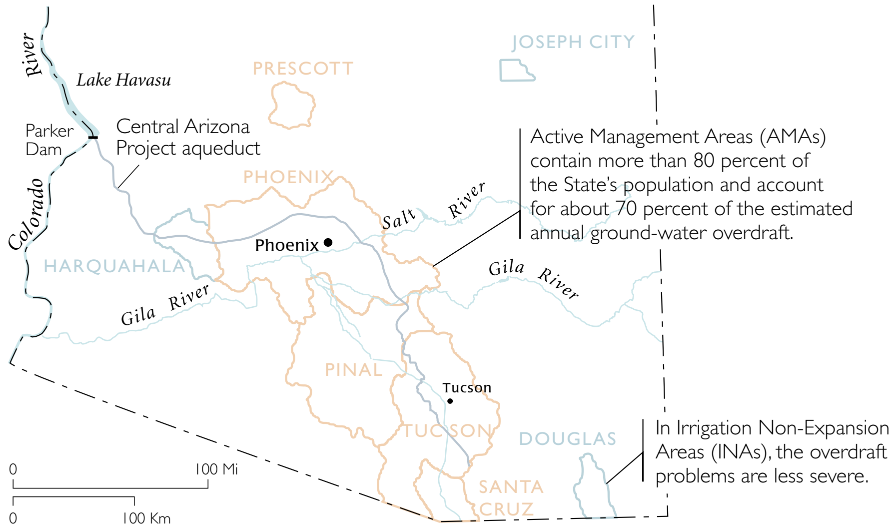
Engineering measures can also mitigate damage where fissures undercut roads. At Apache Junction, a trench was dug to a depth of about 30 feet, backfilled by about 10 feet of compacted fill, and then draped by a reinforced plastic grid, geotextile felt, and an impermeable membrane. The membrane was buried by additional compacted fill. This treatment protects the road from subsurface erosion by enhancing its structural strength and by restricting the upward flow of water from the fissure into the land bridge during flooding.

A natural-gas pipeline undercut by an earth fissure was exposed through erosional widening of the fissure. The pipeline was evacuated and cut to determine the stresses on it. Tension was evident, but no shear.

ARIZONA ACTS TO PROTECT THE AQUIFER SYSTEM

To ensure the future viability of the State's critical ground-water resources, the Arizona Groundwater Management Act was passed in 1980. This innovative law has three primary goals: (1) to control the severe overdraft of depleted aquifer systems, (2) to provide a means for allocating the limited ground-water resources among competing demands and effectively meet the changing needs of the State, and (3) to augment Arizona's ground-water resource through development of additional water supplies. The Act recognized ground water in Arizona as a public resource that must be managed for the benefit of everyone, and in 1986 was named one of the Nation's ten most innovative programs in State and local government by the Ford Foundation.

Based upon recommendations of the Groundwater Management Study Commission, which included representatives from cities and



towns, Native American communities, and mining, agricultural, and electric utilities industries, the Act focuses on limiting ground-water-level declines. Although it specifically mentions subsidence only three times, measures that limit ground-water-level declines will ultimately help to control compaction of the aquifer system and land subsidence. The Act provides for two levels of water management to respond to geographic regions where ground-water overdraft is a problem. Active Management Areas (AMAs) are designated where problems are most severe and Irrigation Non-Expansion Areas (INAs) are designated where problems are least severe. The Act established the Arizona Department of Water Resources (ADWR) to administer the Act. The State Director of the ADWR can designate additional AMAs for several reasons, including land subsidence or fissuring that is endangering property or potential ground-water-storage capacity (Carpenter and Bradley, 1986). The Act includes these six key provisions:

1. A program of ground-water rights and permits.
2. Restriction on new agricultural irrigation within AMAs.
3. Water conservation and management plans for AMAs that constitute 5 consecutive and progressively more stringent phases implemented during the periods 1980–1990, 1990–2000, 2000–2010, 2010–2020, and 2020–2025.
4. Assured water supply for new growth in AMAs before land may be marketed to the public.
5. Metering of ground-water pumpage for designated wells in AMAs.
6. Annual reporting of ground-water pumpage and assessment of withdrawal fees for designated wells in AMAs.

The original four AMAs were Phoenix, Pinal, Prescott, and Tucson. Subsequently, the Santa Cruz AMA was created by separation from the Tucson AMA in 1994. The two original INAs were Douglas and Joseph City, followed by Harquahala in 1982. The AMAs contain

For more information concerning the Arizona Groundwater Management Act, visit the Arizona Department of Water Resources web site at **http://www.adwr.state.az.us/**

more than 80 percent of the State's population and account for about 70 percent of the estimated annual ground-water overdraft in the State.

In the Tucson and Phoenix AMAs, which include the large urban areas of the State, and in the Prescott AMA, the primary management goal is to achieve safe yield by January 1, 2025. The goal in the Pinal AMA, where a predominantly agricultural economy exists, is to extend the life of the agricultural economy for as long as feasible and to preserve water supplies for future nonagricultural uses. In the Santa Cruz AMA, where significant ground-water/surface-water, international, and riparian water issues exist, the goal is to maintain safe yield and prevent the long-term decline of local unconfined aquifers.

A section of the Central Arizona Project passes through Apache Junction.

(U.S. Bureau of Reclamation)

Increasingly stringent conservation measures are being implemented in each of the AMAs during the five management periods. Municipal conservation measures include reductions in per capita water use measured in gallons per capita per day (GPCD). The requirements apply to the water providers, who must achieve target GPCDs through water-use restrictions or incentive-based conservation programs. Conservation for irrigated agriculture is being achieved by prohibiting new ground-water-irrigated acreage and by reductions in ground-water allotment, based on the quantity of water needed to irrigate the crops historically grown in the particular farm unit. There are also programs for augmenting water supplies, including incentives for artificial recharge, for purchase and retirement of irrigation rights, and for levying fees of up to $2.00 per acre-foot (Carpenter and Bradley, 1986).

A SUBSIDENCE-MONITORING PLAN WAS ESTABLISHED

In 1983, the National Geodetic Survey, with advice from an interagency Land Subsidence Committee, created a subsidence-monitoring plan for the Governor of Arizona. The plan summarized known subsidence and recognized hazards caused by subsidence, differential subsidence, and earth fissures in Arizona. The objectives of the plan were (1) "Documentation of the location and magnitude of existing subsidence and subsidence-induced earth fissures;" and (2) "Development of procedures for estimating future subsidence as a function of water-level decline and defining probable areas of future fissure development." The plan proposed a central facility at a State agency for compilation and organization of leveling, compaction, gravity, and other geophysical and stratigraphic information. There were plans to coordinate the analysis of existing data, to produce estimates of future subsidence and earth-fissure development, and to identify observation requirements. Other provisions included (1) "[a]n initial observation program designed to obtain a limited amount of additional leveling data, gravity observations, compaction measurements, and horizontal strain determinations;" and (2) "[a] cooperative effort between State and Federal agencies to evaluate new measurement technologies which offer the potential of being faster and more cost effective than current methods of subsidence monitoring." Also included were proposals for directions in research, some initial monitoring plans, and an advisory committee to oversee the formation of the central data facility and provide continuing guidance. (Strange, 1983). The recommendations have been only partially implemented. The Arizona Geological Survey has a Center for Land Subsidence and Earth Fissure Information. The USGS, the Arizona Department of Water Resources, the City of Tucson, and Pima County maintain cooperative programs for monitoring subsidence using global positioning system (GPS) surveying, microgravity surveys, and borehole extensometers. The ADWR has also started its own program of GPS surveying and microgravity surveys in the Phoenix metropolitan area.

In 1997, 19 of 29 borehole extensometers installed in south-central Arizona to measure aquifer-system compaction were still in operation. In the early 1990s, water levels in the Tucson basin continued to decline by as much as 3 to 6 feet per year, and a small amount of subsidence, generally less than 0.2 inch per year, was occurring in some areas. During the same period, water levels in Avra Valley continued to decline by 3 feet per year, and some subsidence, generally less than 0.1 inch per year, was occurring in some areas (City of Tucson Water Department, 1995). In the Picacho Basin, despite water-level recoveries of as much as 150 feet, some areas continue to subside at rates of up to 0.3 inches per year, most likely due to residual compaction of slowly equilibrating aquitards.

RISING WATER LEVELS OFFER SOME HOPE FOR THE FUTURE


(U.S. Bureau of Reclamation)

Importation of CAP water for consumptive use and ground-water recharge, retirement of some farmlands, and water-conservation measures have resulted in cessation of water-level declines in many areas and the recovery of water levels in some areas. However, some basins are still experiencing subsidence, because much of the aquifer-system compaction has occurred in relatively thick aquitards. It can take decades or longer for fluid pressures to equilibrate between the aquifers and the full thickness of many of these thick aquitards. For this reason, both subsidence and its abatement have lagged pumping and recharge. A glimmer of hope exists from data at the borehole extensometer near Eloy, where water levels have recovered more than 150 feet and compaction has decreased markedly.