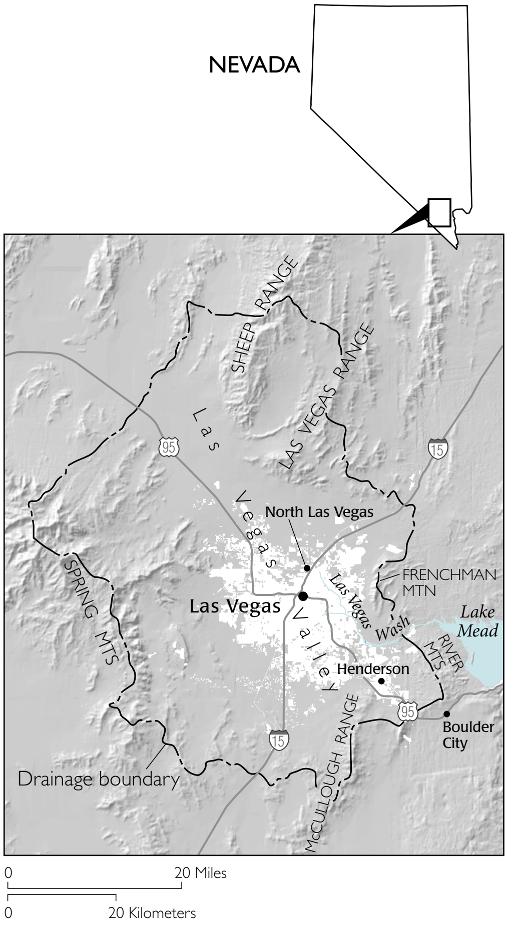
LAS VEGAS, NEVADA

Gambling with water in the desert



Las Vegas Valley is the fastest growing metropolitan area in the United States (U.S. Department of Commerce, accessed July 27, 1999). The accelerating demand for water to support the rapid growth of the municipal-industrial sector in this desert region is being met with imported Colorado River System supplies and local ground water. The depletion of once-plentiful ground-water supplies is contributing to land subsidence and ground failures. Since 1935, compaction of the aquifer system has caused nearly 6 feet of subsidence and led to the formation of numerous earth fissures and the reactivation of several surface faults, creating hazards and potentially harmful impacts to the environment.

In the near future, the current water supplies are expected not to satisfy the anticipated water demand. The federally mandated limit placed on imported water supplied from nearby Lake Mead, a reservoir on the Colorado River, will likely force a continued reliance on ground water to supplement the limited imported-water supplies. Water supply-and-demand dynamics in this growing desert community will likely perpetuate problems of land subsidence and related ground failures in Las Vegas Valley, unless some balanced use of the ground-water resource can be achieved.

Michael T. Pavelko, David B. Wood, and Randell J. Laczniak
U.S. Geological Survey, Las Vegas, Nevada

“THE MEADOWS” WAS AN IMPORTANT DESERT OASIS

Las Vegas Valley is located in southern Nevada and lies within both the Great Basin and Mojave Desert sections of the Basin and Range physiographic province. The arid, northwest-trending valley is bounded on the west by several mountain ranges and drains a 1,564-square-mile watershed southeastward through Las Vegas Wash into Lake Mead.

More than 24 inches of precipitation fall annually in the Spring Mountains bounding the valley to the west, but less than 4 inches of rain fall annually on the valley floor; measurable amounts (greater than 0.01 inch) seldom occur more than 30 days each year. Temperatures range from below freezing in the mountains to more than 120° F on the valley floor. There are typically more than 125 days of 90° F or warmer temperatures each year in Las Vegas Valley (Houghton and others, 1975).

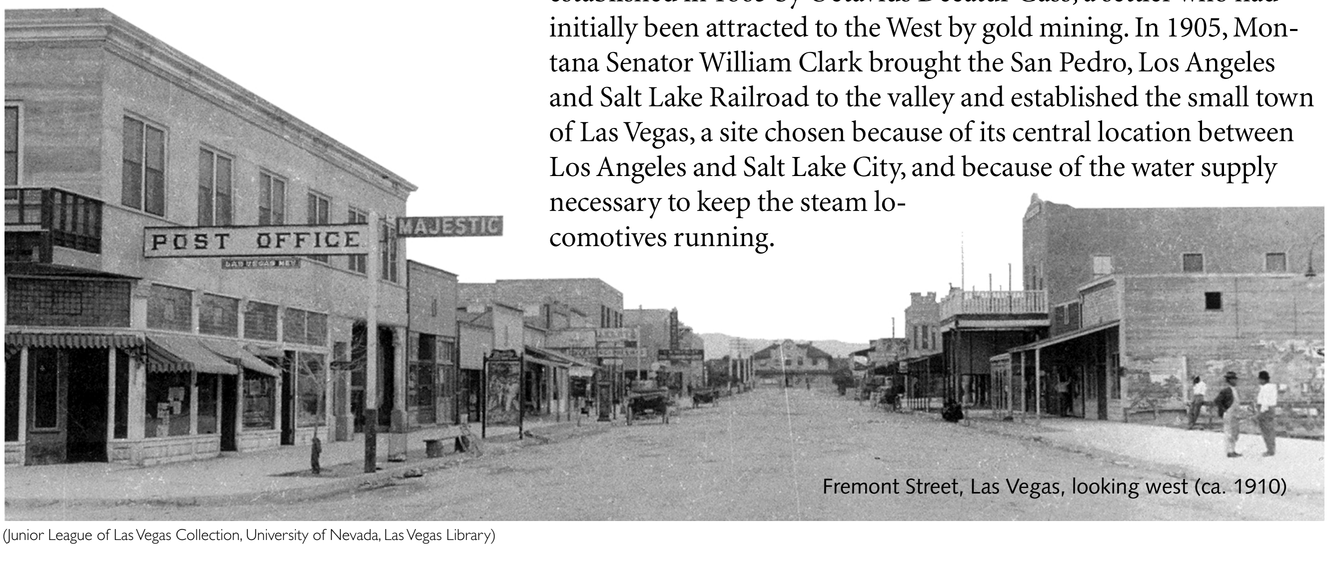
The desert oasis of Las Vegas Valley has been a source of water for humans for more than 13,000 years. Native Americans of the Mojave and Paiute tribes were among the earliest known users. Named by an unknown trader for its grassy meadows, Las Vegas, Spanish for “the meadows,” was a watering stop along the Old Spanish Trail that connected the settlements in Los Angeles and Santa Fe. In 1844, the renowned explorer John C. Fremont stopped here and spoke of the waters as “two narrow streams of clear water, 4 or 5 feet deep, with a quick current, from two singularly large springs” (Mendenhall, 1909). Others were similarly moved by the refreshing contrast of these welcome meadows in the otherwise barren landscape.

> *Wednesday Oct. 11th 1848*
>
> *[…] Camped about midnight at a spring branch called Cayataus. Fair grass. This is what is called the “Vegas”.*
>
> *Thursday Oct. 12th 1848*
>
> *[…] Staid [sic] in the camp we made last night all day to recruit the animals. They done finely. There is the finest stream of water here, for its size, I ever saw. The valley is extensive and I doubt not [,] would by the aid of irrigation be highly productive. There is water enough in this rapid little stream to propel a grist mill with a dragger run of stones! And oh! such water. It comes, too, like an oasis in the desert, just at the termination of a 50 m. [mile] stretch without a drop of water or a spear of grass. […]”*

Orville C. Pratt (from The Journal of Orville C. Pratt, 1848 in Hafen and Hafen, 1954)

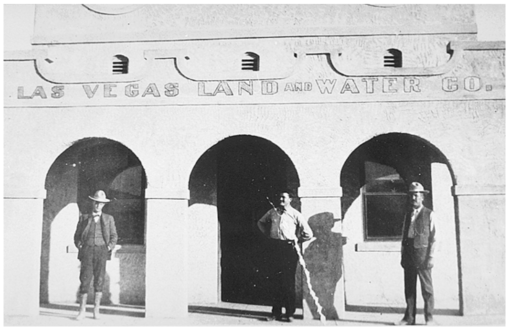
The railroad initiates a period of rapid growth

After failed attempts by Mormon settlers to mine lead from the nearby Spring Mountains and to establish farming in the valley, a flourishing ranch supported by springs and Las Vegas Creek was established in 1865 by Octavius Decatur Gass, a settler who had initially been attracted to the West by gold mining. In 1905, Montana Senator William Clark brought the San Pedro, Los Angeles and Salt Lake Railroad to the valley and established the small town of Las Vegas, a site chosen because of its central location between Los Angeles and Salt Lake City, and because of the water supply necessary to keep the steam locomotives running.



Fremont Street, Las Vegas, looking west (ca. 1910)

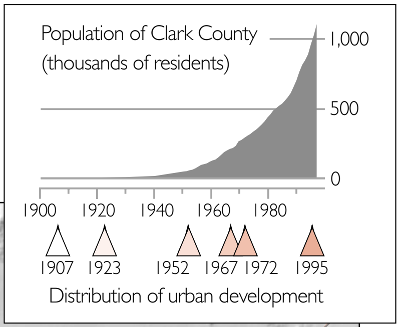
(Junior League of Las Vegas Collection, University of Nevada, Las Vegas Library)

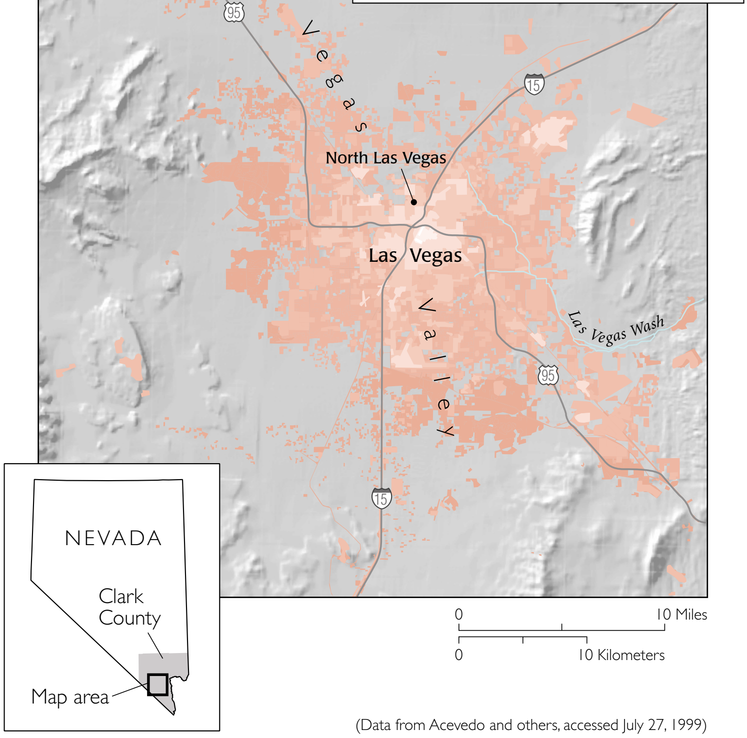


The Las Vegas Land and Water Company, established in 1905, was the area's first water purveyor.

As the railroad grew, so did Las Vegas and its thirst for water (Jones and Cahlan, 1975). To help meet the increasing demand, the Las Vegas Land and Water Company was formed in 1905. A new period of growth began in 1932 with the construction of Boulder Dam (later renamed Hoover Dam) and Lake Mead on the Colorado River, southeast of Las Vegas. Boulder Dam brought workers to Las Vegas from throughout America, and provided a seemingly unlimited supply of water and power in one of the most unlikely places. The wealth of land, water, and power resources attracted industry, the military, and gambling to the valley during the 1940s and 1950s. The population of Las Vegas was growing steadily, and by 1971 the heightened water demand required importing additional water from Lake Mead through a newly constructed Southern Nevada Water Project pipeline. At present, Las Vegas Valley is home to 1.2 million people, about two-thirds of Nevada's population, and hosts more than 30 million tourists each year.

Today Las Vegas sprawls across the valley.

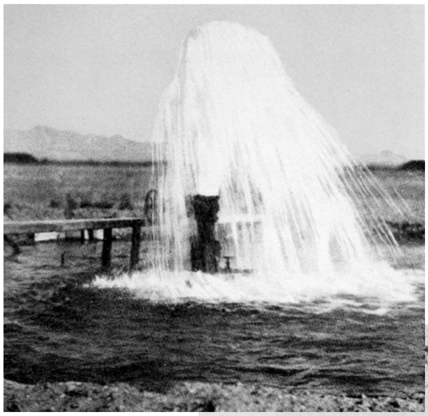




Urban growth in the Las Vegas Valley has soared in the last few decades.

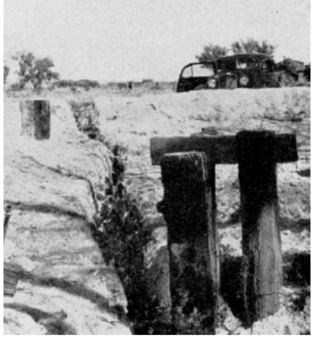
(Data from Acevedo and others, accessed July 27, 1999)

In 1912, the Eglington well, one of several uncapped artesian wells, was allowed to flow freely. (It is shown here flowing at about 615 gallons per minute.)



(Carpenter, 1915)

By 1938 the Eglington well had ceased flowing. The water level was then 3.3 feet below land surface.



(Livingston, 1941)

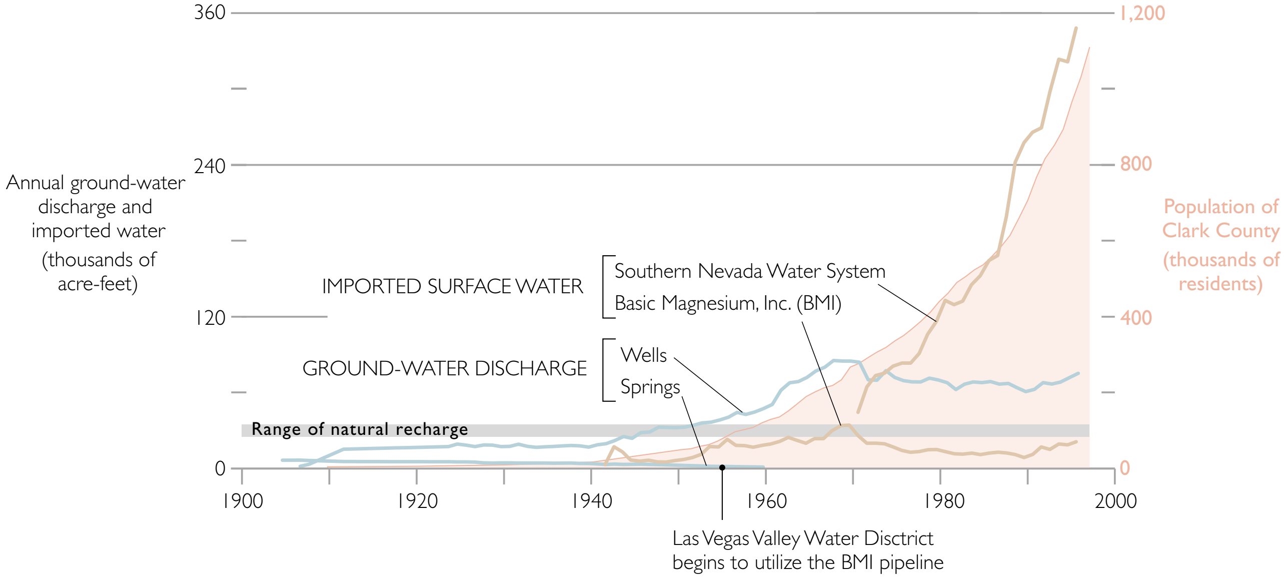
BROWNING OF "THE MEADOWS": DEMAND FOR WATER DEPLETES THE AQUIFER SYSTEM

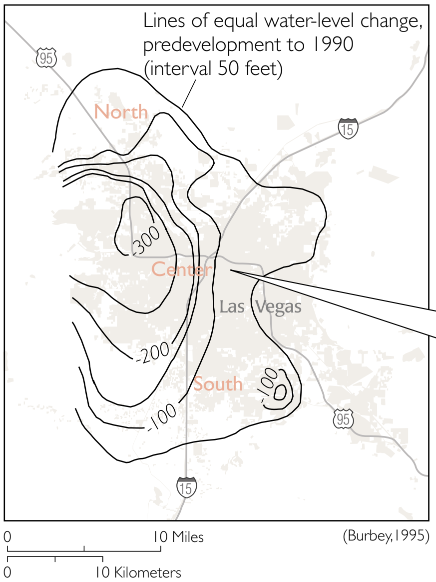
Prior to development in Las Vegas Valley, there was a natural, albeit dynamic, balance between aquifer-system recharge and discharge. Over the short term, yearly and decadal climatic variations (for example, drought and the effects of El Niño) caused large variations in the amount of water available to replenish the aquifer system. But over the long term, the average amount of water recharging the aquifer system was in balance with the amount discharging, chiefly from springs and by evapotranspiration. Estimates of the average, annual, natural recharge of the aquifer system range from 25,000 to 35,000 acre-feet (Maxey and Jameson, 1948; Malmberg, 1965; Harrill, 1976; Dettinger, 1989).

In 1907, the first flowing well was drilled by settlers to support the settlement of Las Vegas, and there began to be more ground-water discharge than recharge (Domenico and others, 1964). Uncapped artesian wells were at first permitted to flow freely onto the desert floor, wasting large quantities of water. This haphazard use of ground water prompted the State Engineer, W.M. Kearney, to warn in 1911 that water should be used "… with economy instead of the lavish wasteful manner, which has prevailed in the past" (Maxey and Jameson, 1948).

Intensive ground-water use led to steady declines in spring flows and ground-water levels throughout Las Vegas Valley. Spring flows began to wane as early as 1908 (Maxey and Jameson, 1948). By 1912 nearly 125 wells in Las Vegas Valley (60 percent of which were flowing-artesian wells) were discharging nearly 15,000 acre-feet per year.

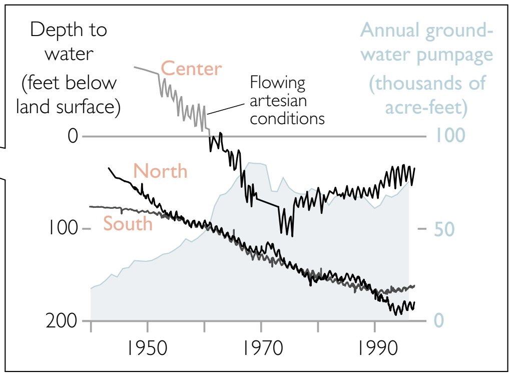
Las Vegas' water supply has kept pace with the demand.





(Burbey,1995)

By 1990 areas of the valley that had once supported flowing artesian wells experienced water level declines of more than 300 feet.



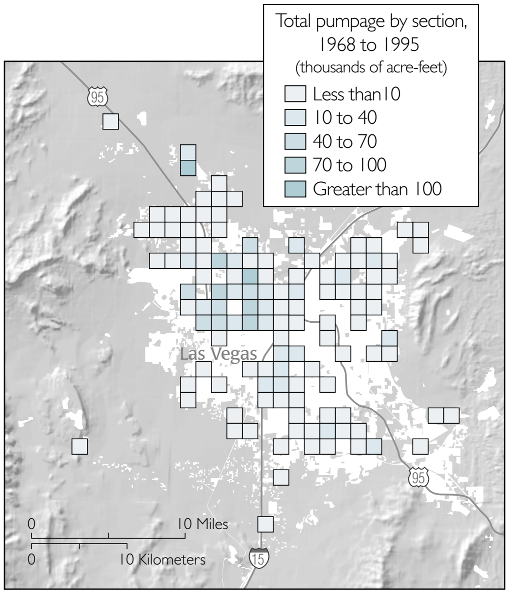
Increasing pumpage through the 1960s caused water levels to drop throughout Las Vegas Valley. Presently, due to some stabilization in the pumpage amounts and artificial ground-water recharge programs, water levels are recovering in many areas of the valley.

With the construction of Boulder Dam came development of the military and industrial sectors and a rapidly increasing demand for water. In 1942 a water pipeline was constructed to bring water from Lake Mead to the Basic Magnesium Project (now called Basic Management, Inc.) in the City of Henderson. This pipeline marked the first supplementation of Las Vegas Valley ground water and the beginning of surface-water imports to the valley. In 1955 the Las Vegas Valley Water District (LVVWD) began to use this pipeline to supplement the growing water demands. By this time, the amount of ground water pumped annually from wells had reached nearly 40,000 acre-feet, surpassing the estimated natural recharge to the valley aquifer system (Mindling, 1971). By 1968 the annual ground-water pumpage in the valley reached nearly 88,000 acre-feet (Harrill, 1976).

In 1971, the capacity to import surface water into the valley was greatly expanded when a second, larger pipeline was constructed between Lake Mead and Las Vegas by the Southern Nevada Water Project (Harrill, 1976). However, despite the steady increases in imported surface-water deliveries, rising demand for water and federally stipulated limits on Lake Mead imports encouraged a continued dependence on the local ground-water resource.

Ground-water levels decline as Las Vegas expands

Between 1912 and 1944, ground-water levels declined at an average rate of about 1 foot per year (Domenico and others, 1964). Between 1944 and 1963, some areas of the valley experienced water-level declines of more than 90 feet (Bell, 1981a). The City of North Las Vegas was the first area to experience large water-level declines but, as Las Vegas expanded, new wells were drilled, pumping patterns changed, and ground-water-level declines spread to areas south and west of the City of North Las Vegas. Between 1946 and 1960, the area of the



(Data compiled from unpublished Las Vegas Valley water usage reports, Nevada Department of Conservation and Natural Resources, Divison of Water Resources)

valley that could sustain flowing-artesian wells shrank from more than 80 square miles (Maxey and Jameson, 1948) to less than 25 square miles (Domenico and others, 1964). By 1962, the springs that had supported the Native Americans, and those who followed, were completely dry (Bell, 1981a).

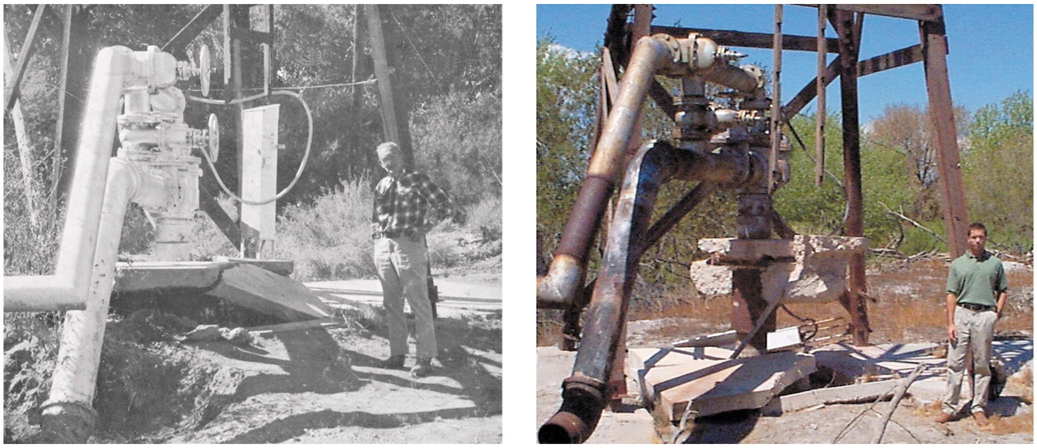
Since the 1970s annual ground-water pumpage in the valley has remained between 60,000 and 90,000 acre-feet; most of that has been pumped from the northwestern part of the valley. By 1990 areas in the northwest experienced more than 300 feet of decline, and areas in the central (including downtown and The Strip) and southeastern (Henderson) sections experienced declines between 100 and 200 feet (Burbey, 1995).

In 1996, imports from Lake Mead provided Las Vegas Valley with approximately 356,000 acre-feet of water (Coache, 1996) and represented the valley's principal source of water. This amount included 56,000 acre-feet of return-flow credits for annual streamflow discharging into Lake Mead from Las Vegas Wash.

DEPLETION OF THE AQUIFER SYSTEM CAUSES SUBSIDENCE

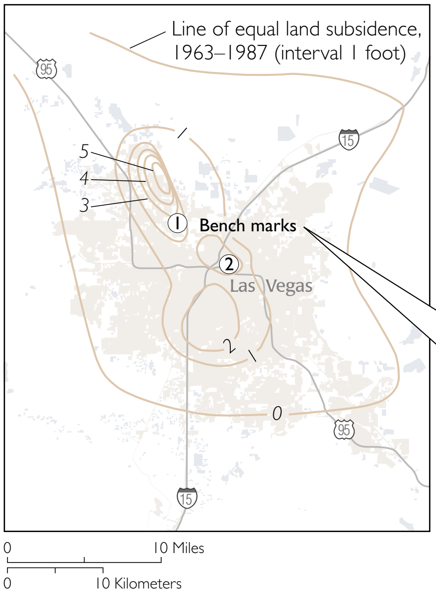
Land subsidence and related ground failures in Las Vegas Valley were first recognized by Maxey and Jameson (1948) based on comparisons of repeat leveling surveys made by the USGS and the U.S. Coast and Geodetic Survey between 1915 and 1941. Since then, repeat surveys of various regional networks have shown continuous land subsidence throughout large regions within the valley.

The surveys have revealed that subsidence continued at a steady rate into the mid-1960s, after which rates began increasing through 1987 (Bell, 1981a; Bell and Price, 1991). Surveys made in the 1980s delineate three distinct, localized subsidence bowls, or zones, superimposed on a larger, valley-wide subsidence bowl. One of these smaller subsidence bowls, located in the northwestern part of the valley, subsided more than 5 feet between 1963 and 1987. Two

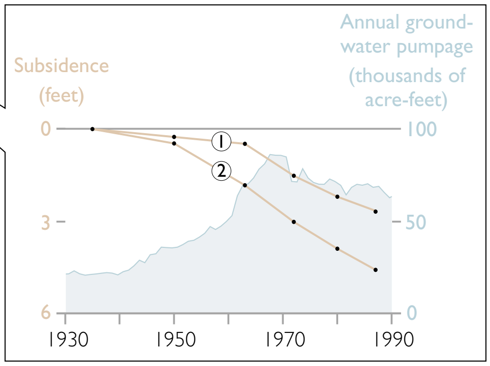

1964

1997

These photographs of a protruding well just west of downtown Las Vegas show evidence of subsidence. The 1964 photograph shows that the ground has subsided enough, relative to the well casing, to suspend the broken concrete foundation of the well head above land surface. Thirty three years later well head protrudes farther as the ground has continued to subside.



Three subsidence bowls were identified between 1963 and 1987. These bowls are caused by a combination of ground-water declines and the presence of compressible sediments in the aquifer system at these locations.



(Subsidence data from Bell and Price, 1991)

Subsidence measured at two bench marks continued beyond 1970, although ground-water pumpage was slightly reduced.

other localized subsidence bowls, in the central (downtown) and southern (Las Vegas Strip) parts of the valley, subsided more than 2.5 feet between 1963 and 1987. The areas of maximum subsidence do not necessarily coincide with areas of maximum water-level declines. One likely explanation is that those areas with maximum subsidence are underlain by a larger aggregate thickness of fine-grained, compressible sediments (Bell and Price, 1991).

Aquifer-system compaction creates earth fissures and reduces storage

All the impacts of subsidence in Las Vegas Valley have not yet been fully realized. Two important impacts that have been documented are (1) ground failures—localized ruptures of the land surface; and (2) the permanent reduction of the storage capacity of the aquifer system. Other potential impacts that have not been studied extensively are:

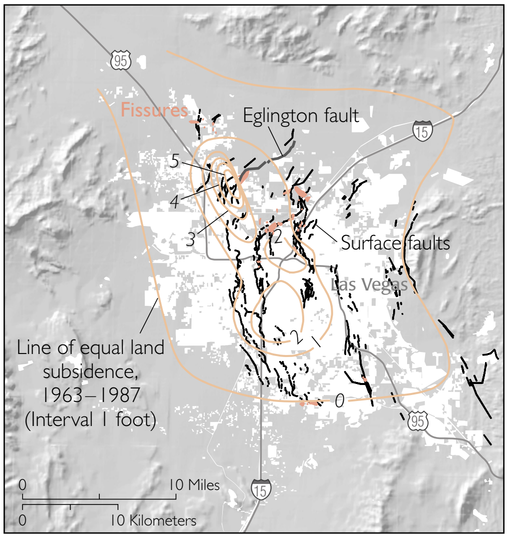
- Creation of flood-prone areas by altering natural and engineered drainage ways;
- Creation of earth fissures connecting nonpotable or contaminated surface and near-surface water to the principal aquifers; and
- Replacement costs associated with protruding wells and collapsed well casings and well screens.

All of these potential damages create legal issues related to mitigation, restoration, compensation, and accountability.

Ground failures Earth fissures are the dominant and most spectacular type of ground failure associated with ground-water withdrawal in Las Vegas Valley. Earth fissures are tensile failures in subsurface materials that result when differential compaction of sediments pulls apart the earth materials. Buried, incipient earth fissures be-

Bench Marks

The determination of subsidence trends in time and in space is limited in part by the inherently sparse distribution of available bench marks from which comparisons can be made. Subsidence is determined by comparing two elevations made at a vertical reference point—a bench mark—at two different times. The destruction and loss of historical bench marks inevitably accompanies the march of time and cultural developments such as building and road construction. The loss of comparable reference points reduces the spatial detail of subsidence determinations and disrupts the continuity of subsidence monitoring unless care is taken to preserve bench marks. These factors have limited the spatial detail of subsidence maps in Las Vegas and will continue to pose serious challenges to subsidence monitoring in the years to come. In 1990 the Nevada Bureau of Mines and Geology established more than 100 new bench marks in Las Vegas Valley.



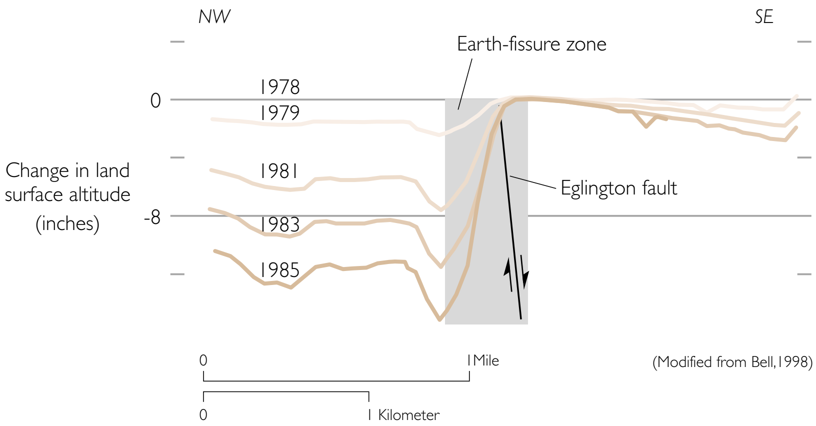
(Data from Bell and Price, 1991)

Earth fissures have occurred near areas of greater differential subsidence, and many fissures are associated with surface faults.

come obvious only when they breach the surface and begin to erode, often following extreme rains or surface flooding conditions. Earth fissures have been observed in Las Vegas Valley as early as 1925 (Bell and Price, 1991), but were not linked directly to subsidence until the late 1950s (Bell, 1981a). Most of the earth fissures are areally and temporally correlated with ground-water level declines.

Movement of preexisting surface faults has also been correlated to ground-water level changes and differential land subsidence in numerous alluvial basins (Holzer, 1979; Bell, 1981a; Holzer, 1984). In Las Vegas Valley, earth fissures often occur preferentially along preexisting surface faults in the unconsolidated alluvium. They tend to form as a result of the warping of the land surface that occurs when the land subsides more on one side of the surface fault than the other. This differential land subsidence creates tensional stresses that ultimately result in fissuring near zones of maximum warping. The association of most earth fissures with surface faults suggests a causal relationship. The surface faults may act as partial barriers to ground-water flow, creating a contrast in ground-water levels across the fault, or may offset sediments of differing compressibility.

The associated land-surface displacements and tilts are often sufficient to damage rigid or precisely leveled structures. Damage to homes in a 241-home subdivision in the north-central part of the valley has already cost more than $6 million, and the total cost projections are in excess of $14 million (Marta G. Brown, City of North Las Vegas, written communication, 1997). Other damage related to fissuring includes cracking and displacement of roads, curbs, sidewalks, playgrounds, and swimming pools; warped sewage lines; ruptured water and gas lines; well failures resulting from shifted, sheared, and/or protruded well casings; differential settlement of railroad tracks; and a buckled drainage canal (Bell, 1981b; Marta G. Brown, City of North Las Vegas, written communication, 1997). Earth fissures are also susceptible to erosion and can form wide, steep-walled gullies capable of redirecting surface drainage and creating floods and other hazards. Adverse impacts of ground failures may worsen as the valley continues to urbanize and more developed areas become affected.



(Modified from Bell,1998)

This cross section of the Eglington fault zone and accompanying fissure zone shows that land-surface elevations on the upthrown side of the fault are decreasing due to subsidence.

A fissure displaces pavement (far right) and damages a building (near right) on Harrison Street, Las Vegas.

(Fred B.Houghton, 1961)

Reduced storage capacity Reduction of storage capacity in the Las Vegas Valley aquifer system is another important consequence of aquifer-system compaction. The volume of ground water derived from the irreversible compaction of the aquifer system —"water of compaction"—is approximately equal to the reduced storage capacity of the aquifer system and represents a one-time quantity of water "mined" from the aquifer system.

Loss of aquifer-system storage capacity is cause for concern, especially for a fast-growing desert metropolis that must rely in part on local ground-water resources. A study conducted by the Desert Research Institute (Mindling, 1971) estimated that, at times, up to 10 percent of the ground water pumped from the Las Vegas Valley aquifer system has been derived from water of compaction. Assuming conservatively that only 5 percent of the total ground water pumped between 1907 and 1996 was derived from water of compaction, the storage capacity of the aquifer system has been reduced by about 187,000 acre-feet. This may or may not be considered "lost" storage capacity: arguably, if this water is derived from an irreversible process, this storage capacity has been used in the only way that it could have been. In any case, producing water of compaction represents mining ground water from the aquifer system. Further, the reduced storage implies that, even if water levels recover completely, any future drawdowns will progress more rapidly.

An estimated 187,000 acre-feet (61 billion gallons) of water (enough water to supply almost 10,000 households in Las Vegas for nearly 20 years) may have been derived from a permanent reduction in the storage capacity of the Las Vegas Valley aquifer system due to compaction of the aquifer system and land subsidence between 1907 and 1996.

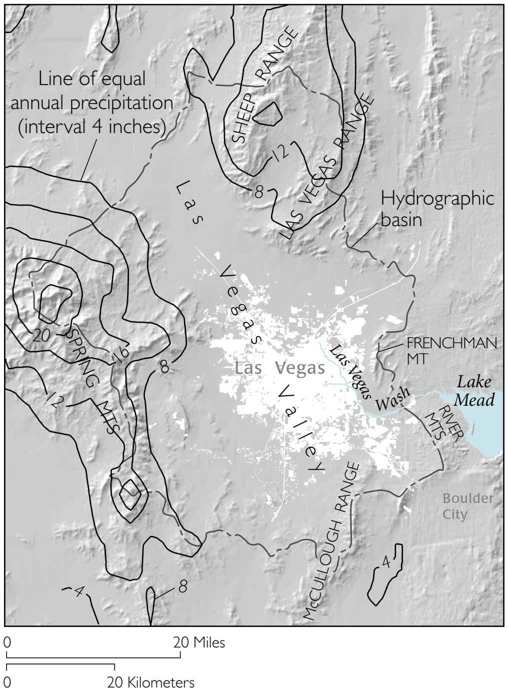
LAS VEGAS VALLEY IS UNDERLAIN BY A GROUND-WATER RESOURCE

Las Vegas Valley is a sediment-filled structural trough that has formed over many millions of years through compression, extension, and faulting of the original flat-lying marine sediments that form the bedrock. Some bedrock blocks were down-dropped between the faults along the eastern and western margins of the present-day valley.

Sediment eroded by wind and water from the surrounding bedrock highlands began filling the trough with gravel, sand, silt, and clay.

During some of the wetter periods in the past 1 million years or so, extensive playa lakes and spring-fed marshes covered the lower parts of the valley floor, depositing variably thick sequences of fine-grained sediment (Mifflin and Wheat, 1979 and Quade et al., 1995). Coarse-grained sand and gravel tend to rim the valley, forming alluvial fans and terraces, especially in the northern, western, and southern parts. The deposits generally thicken and become finer-textured toward the central and eastern part of the valley, where their total thickness exceeds 5,000 feet (Plume, 1989).

Most precipitation in the watershed falls in the mountains surrounding Las Vegas



Ground water flows through the aquifers

Ground water is generally pumped from the upper 2,000 feet of unconsolidated sediments that constitute the aquifer system in the central part of the valley. The deeper aquifers, generally below 300 feet, are capable of transmitting significant quantities of ground water, and have been referred to variously as the "principal," "artesian," or "developed-zone" aquifers (Maxey and Jameson, 1948; Malmberg, 1965; Harrill,1976; Morgan and Dettinger, 1996). In places, these principal aquifers are more than 1,000 feet thick and consist mainly of sands and gravels beneath the terraces along the margins of the valley. In the central and eastern parts, clays and silts predominate (Plume, 1989). Overlying the principal aquifers, in most places, is a 100-to-300 foot-thick section of extensive clay, sand, and gravel deposits known as the "near-surface reservoir." The principal aquifers and the near-surface reservoir are separated by a variably-thick, laterally discontinuous aquitard, or confining unit.

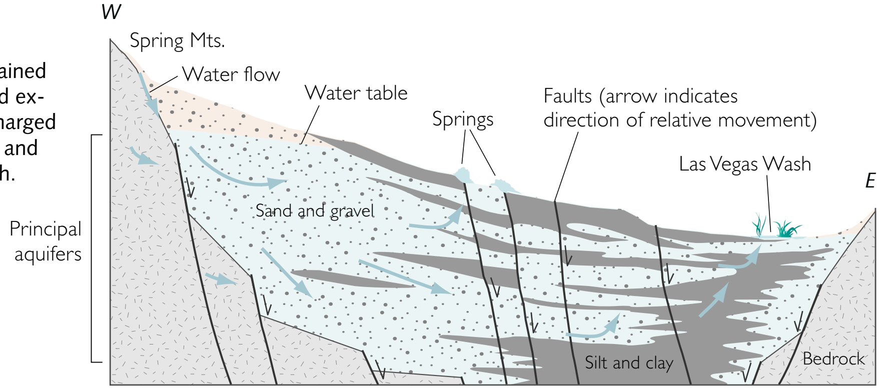
Much of the ground water found in the aquifer system originates as rain or snow falling on the Spring Mountains to the west or on the Sheep and Las Vegas Ranges to the northwest. Some of the precipitation infiltrates into the underlying bedrock through faults and fractures, eventually moving into the deposits comprising the principal aquifers. The remainder of the precipitation runs off onto the sloping alluvial terraces and rapidly enters the sand and gravel deposits, where it either recharges the underlying principal aquifers or is evaporated or transpired into the atmosphere.

Near the margins of the valley, ground water moves freely through the coarse-grained sand and gravel deposits, but as it moves

> *"The settlement [subsidence] in Las Vegas Valley as a whole appears to be the result of compaction of the sediments of the valley fill, and the faults, … are probably caused by the differential compaction of the fine-grained and coarse-grained sediments."*
>
> *—1948, George B. Maxey and C. Harry Jameson*

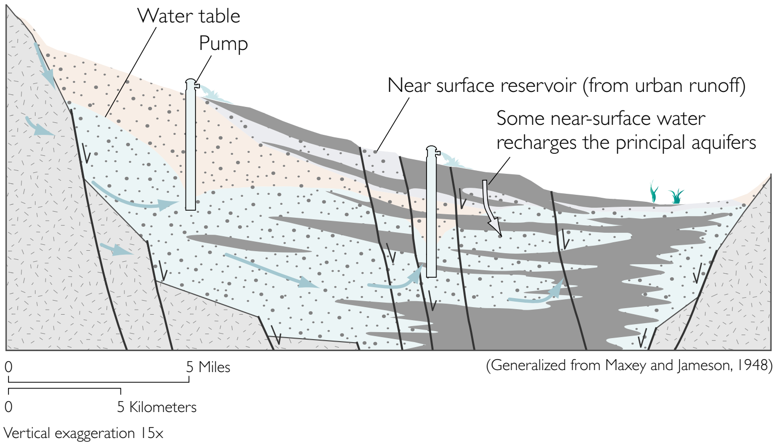
Predevelopment

Ground water was sustained by natural recharge, and excess ground water discharged through several springs and into the Las Vegas Wash.



Postdevelopment

Excessive pumping has caused the water table to drop and springs to dry up. Urban runoff has created a reservoir of poorer quality, potentially contaminated water just below the surface that now recharges the principal aquifers.



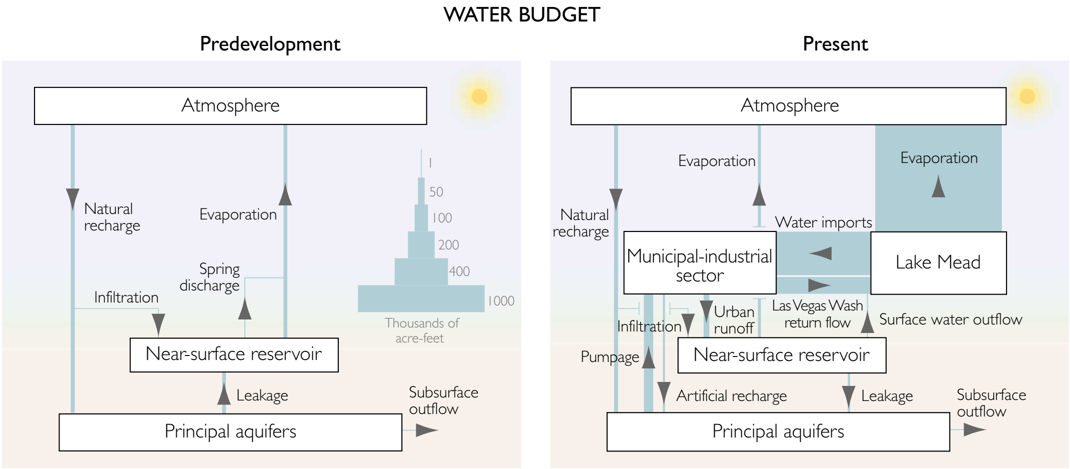
(Generalized from Maxey and Jameson, 1948)

basinward it begins to encounter increasingly greater percentages of lower permeability, fine-grained clay and silt. The increasing proportion of fine-grained deposits retards lateral flow, and the low-permeability deposits effectively impede the vertical flow of ground water. As ground water recharges the aquifer system from the higher elevations, fluid pressures in the principal aquifers can build to create artesian conditions at lower elevations in the basin.

Prior to development of the ground-water resource, artesian pressure in the aquifer system forced water slowly upward through confining zones and more rapidly along faults. Flow from these conduits formed the springs on the valley floor and supported thriving grassy meadows with an estimated annual flow of 7,500 acre-feet (Malmberg, 1965). Most of the spring flow and precipitation falling on the valley floor was consumed by evapotranspiration, but some infiltrated downward into the surficial deposits.

The changing balance between recharge and discharge

Development of the ground-water resource to support the local population and its land uses drastically altered the way water cycles through the basin. The present water budget reveals that only a small fraction of the water used in Las Vegas Valley is actually consumed, and therefore removed from the water cycle, by domestic,



agricultural and municipal/industrial uses. Most is either returned to the aquifer system, evaporated, or discharged into the Colorado River system. Large quantities of this generally poorer-quality water drain from overwatered lawns, public sewers, paved surfaces, and other drainage ways. Much of this urban runoff flows onto open ground where it evaporates, is transpired by plants, or recharges the near-surface reservoir. Large amounts of treated sewage water are discharged into the Colorado River system by way of the Las Vegas Wash. Ground water has been depleted in the principal aquifers and aquitards, causing land subsidence, while the shallow, near-surface reservoir has been recharged with poor-quality urban runoff.

LAS VEGAS IS DEALING WITH A LIMITED WATER SUPPLY

> *"All data available from this and other studies strongly indicate that the quantities of water presently developed, if removed entirely from the ground-water reservoir on a permanent basis, would eventually result in critical depletion"*
>
> *—Domenico and others, 1964*

Managing land subsidence in Las Vegas Valley is linked directly to the effective use of ground-water resources. At present more ground water is appropriated by law and is being pumped in Las Vegas Valley than is available to be safely withdrawn from the ground-water basin (Nevada Department of Conservation and Natural Resources, 1992; Coache, 1996). Historic and recent rates of aquifer-system depletion caused by overuse of the ground-water supply cannot be sustained without contributing further to land subsidence, earth fissures, and the reactivation of surface faults.

In order to arrest subsidence in the valley, ground-water levels must be stabilized or maintained above historic low levels. Stabilization or recovery of ground-water levels throughout the valley will require that the amount of ground water pumped from the aquifers be less than or equal to the amount of water recharging the system. Eliminating any further decline will reduce the stresses contributing to the compaction of the aquifer system. Even so, a significant amount of land subsidence (residual compaction) will continue to occur until the aquifer system equilibrates fully with the stresses imposed by lowered ground-water levels in the aquifers (Riley, 1969). This equilibrium may require years, decades, or even centuries to be realized.

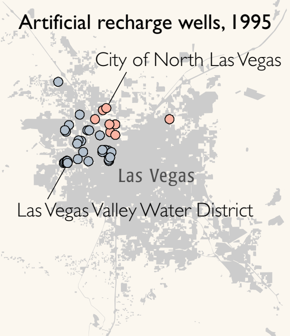
Replenishing the aquifer system artificially

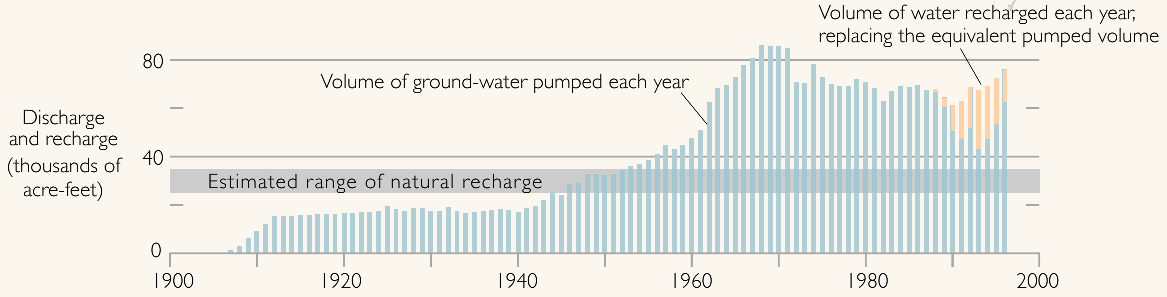
Las Vegas Valley Water District (LVVWD) and the City of North Las Vegas have developed artificial recharge programs

The artificial recharge programs serve two primary purposes:

- To store surplus imported surface water in the principal aquifers during winter months when demand is relatively low, so that it can later be pumped to supplement any shortfalls in the supply and delivery of imported water during the high-demand summer months
- To replenish the principal aquifers, if only temporarily, thus raising ground-water levels and forestalling subsidence in the local area.

Recharging began in 1988 and by 1995 a total of nearly 115,000 acre-feet of treated, imported Lake Mead water had been injected through more than 40 wells, at an annual rate of up to 25,000 acre-feet. Additional recharge wells constructed since 1995 have significantly enlarged the recharge area and increased the number of injection-well sites.

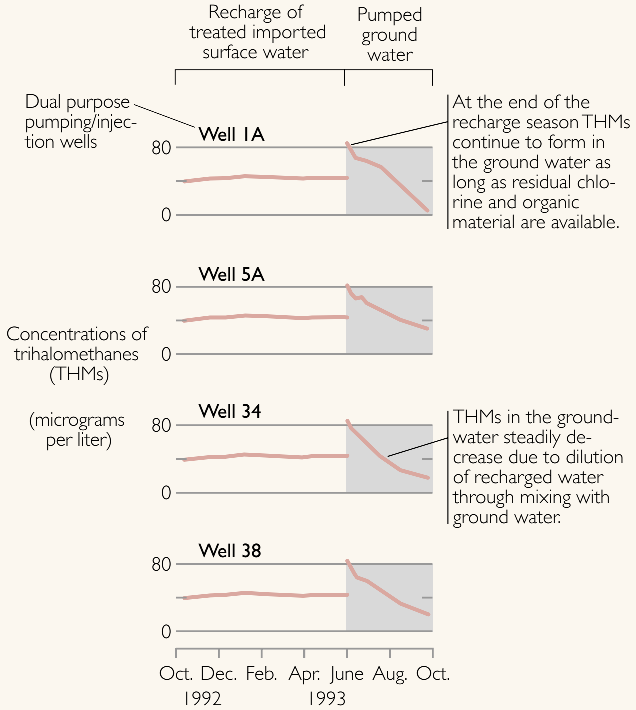




DISINFECTION BYPRODUCTS

The artificial recharge program poses a potential for contamination of the Las Vegas Valley aquifer system. The problem arises because it is necessary to disinfect the recharge water prior to injecting it through the wells into the aquifer system. Disinfection byproducts (DBPs), chiefly trihalomethanes (THMs), form when chlorine is introduced into the water-treatment process. The dissolved and particulate organic material in the water reacts with the chlorine and other halogens to form DBPs, of which THMs are specifically regulated by State and Federal standards. THMs have been shown to cause cancer in laboratory animals, and may pose other health risks to humans. Presently, the total THM maximum contaminant level allowed under the drinking-water standards is 100 µg/l (micrograms per liter), but the U. S. Environmental Protection Agency is strongly considering a lower limit.

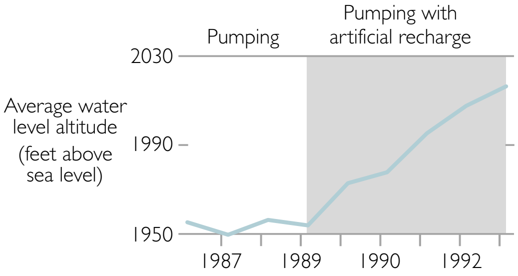
Native ground waters in arid alluvial basins are typically low in dissolved organics compared to surface waters, so that even if they are chlorinated prior to use, few if any THMs form. In contrast, the imported surface water is high in organics, and when it is disinfected before injection into the aquifer system, an average of 45 µg/l of THMs are produced. This concentration eventually becomes diluted within the aquifer. But when the mixture is pumped for use, disinfection is still needed, and the chlorine raises THM levels about 25 µg/l, potentially near the drinking-water standard. To lower the THMs to acceptable levels, further treatment or blending (dilution) may be needed.



(Modified from Bernholtz and others, 1994)

The natural recharge is augmented "artificially"

Since 1988, the LVVWD and the City of North Las Vegas have implemented artificial ground-water-recharge programs in an attempt to increase local water supplies during periods of high demand. These aquifer-recharge programs replenish the aquifers by injecting treated surface water imported from Lake Mead through dual-purpose wells. Water is recharged primarily during cooler months, when water demand is lowest, thereby raising ground-water levels above typical winter conditions. Recently, annual artificial recharge of nearly 20,000 acre-feet has succeeded in raising ground-water levels in some local areas to the extent that they are generally higher both at the beginning and end of the peak water-demand (summer) season.



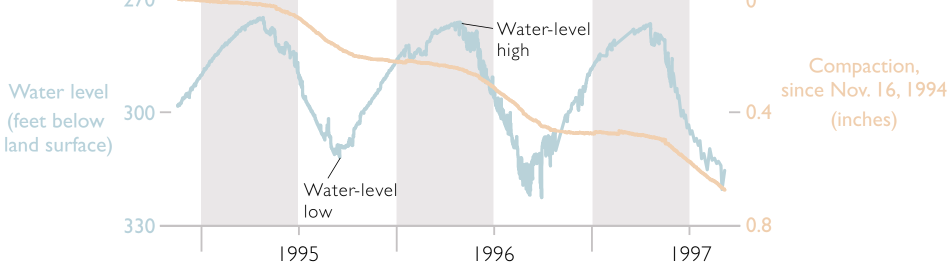
Water levels at the Las Vegas Valley Water District's main well field have increased with artificial recharge.

Despite the ambitious efforts to artificially recharge the aquifer system, valleywide net ground-water pumpage still exceeds the estimated natural recharge. To minimize any future subsidence, some combination of increased recharge and reduced pumpage is needed, especially in areas prone to subsidence. These options depend largely on the seasonal availability of additional imported water, to compensate for any additional water recharged, and on the amount of reduced pumpage required to maintain ground-water levels above critical levels.

Both the ground water and surface water of Nevada belong to the public and are managed on their behalf by the State of Nevada, the Colorado River Compact, and the Bureau of Reclamation. Nevada water law is founded on the doctrine of prior appropriation—"first in time, first in right"—which grants the first user of a water course a priority right to the water. All the surface- and ground-water resources in the valley are currently fully appropriated. The State Engineer has established a perennial yield of 25,000 acre-feet for the Las Vegas Valley aquifer system (Malmberg, 1965; Nevada Dept. Of Conservation and Natural Resources, 1992), based on the minimum, average annual natural recharge to the aquifer system. Despite this legally established yield, more than 25,000 acre-feet have been pumped from the valley every year since 1945; a maximum yield of more than 86,000 acre-feet were pumped in 1968. As of

This typical artificial recharge well has the dual function of pumping and injecting. (The tall object on the far right is the electric motor for the pump).

Water levels and compaction fluctuate seasonally in response to natural and artificial recharge and pumpage.



During the winter and spring when demand for water is low, less ground water is pumped, and imported water is recharged into the aquifer system.

During the summer when demand for water is high, more ground water is pumped, and less imported water is recharged into the aquifer system.

To arrest subsidence, ground-water levels must recover or stabilize.

(Data is from an extensometer site near central Las Vegas.)

1996, State permits for an annual total of 90,000 acre-feet had been issued (Coache, 1996), and in that year nearly 76,000 acre-feet, more than three times the perennial yield, were pumped.

WATER MANAGERS ATTEMPT TO MEET GROWING WATER DEMAND

A limit on the amount of water that can be imported from the Colorado River system, and a growing local water demand, make it difficult to reduce the present reliance on the local ground-water supply. At the current rate of ground-water extraction, there may be insufficient surplus of imported water to control land subsidence. Water-use projections for southern Nevada have indicated that the region's available water supply likely will not meet projected demands beyond the year 2002, or 2006 provided responsible water-conservation programs are implemented (Water Resources Management Incorporated, 1991). After that time, the water supply will become extremely vulnerable to variability caused by droughts and potentially by contamination.

It is uncertain whether Nevada will be able to acquire, on a permanent basis, any additional Colorado River system water beyond the current annual allocation of 300,000 acre-feet. To help prevent water shortages, and thereby reduce additional stress on the aquifer system, the Southern Nevada Water Authority (SNWA) is pursuing several avenues to increase the future supply of water to southern Nevada and Las Vegas Valley. Primary sources might include importation of both in-state and out-of-state water and ground-water banking. Water from the Virgin and Muddy Rivers and ground-water banking in southern Nevada and Arizona are leading options. Stormwater recovery and desalination are also being considered.

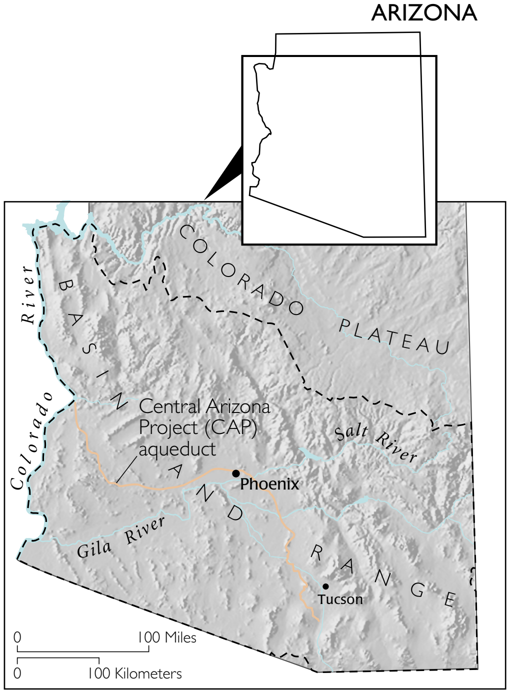
Perhaps the most desirable option to the SNWA would be the "wheeling" of Virgin and Muddy River water. Under this scenario, river water that is legally available for use is allowed to continue to flow into Lake Mead, rather than being piped directly out of the rivers. This would allow the SNWA to obtain approximately an additional 120,000 acre-feet, without constructing a pipeline. "Wheeling" of this water, however, is technically not permitted, because any river water that reaches Lake Mead is legally considered to be part of Nevada's Colorado River system water apportionment of 300,000 acre-feet. If legal solutions cannot be achieved in favor of "wheeling" water, a legal, and costly, pipeline could divert this water before it reaches Lake Mead.

Another important potential resource is ground-water banking, whereby aquifers could be artificially recharged with unused portions of Colorado River system water to be used during future high-demand periods. While this option is already being used in Las Vegas Valley, more water could be banked elsewhere in southern Nevada and, pending legal decisions, Nevada could buy water for banking from Arizona or other member states in the Colorado River Compact.

Given these expanded options, the SNWA has projected that there will in fact be enough water to meet the demands of southern Nevada beyond the year 2025.

SOUTH-CENTRAL ARIZONA

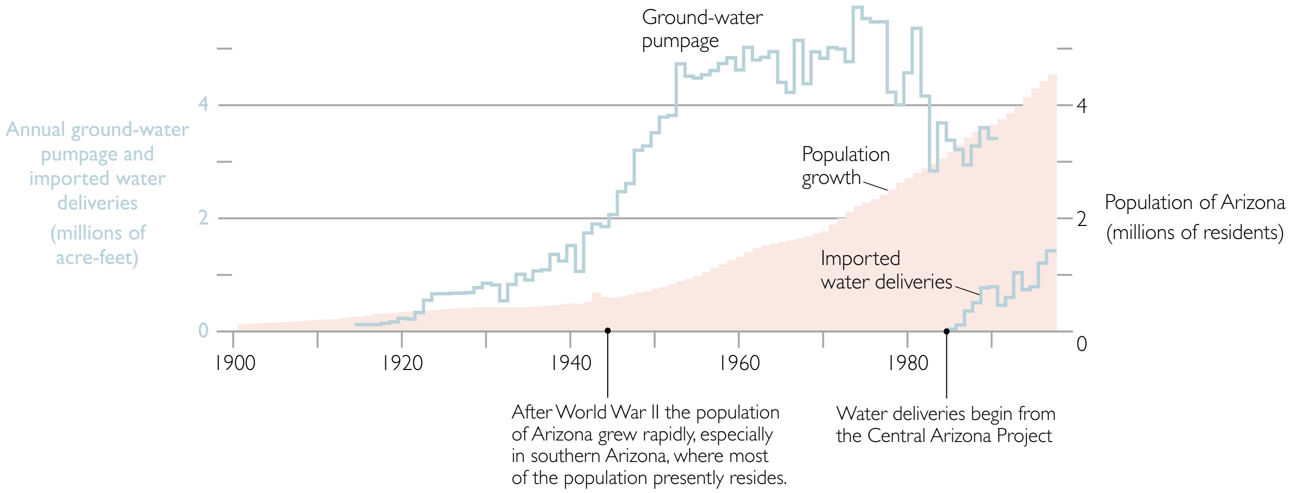
Earth fissures and subsidence complicate development of desert water resources



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

Michael C. Carpenter
U.S. Geological Survey, Tucson, Arizona



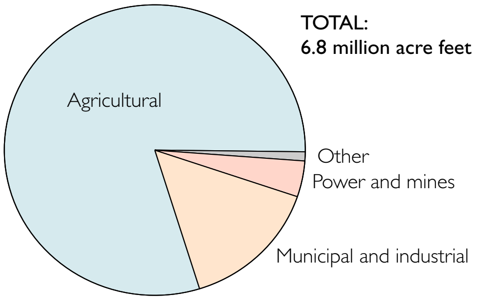
(Ground-water pumpage from Anning and Tuet, 1994; imported water deliveries from Arizona Department of Water Resources; population data modified from U.S. Census Bureau)

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.

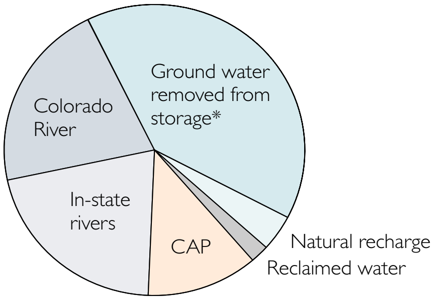
GROUND WATER HAS SUSTAINED AGRICULTURE

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

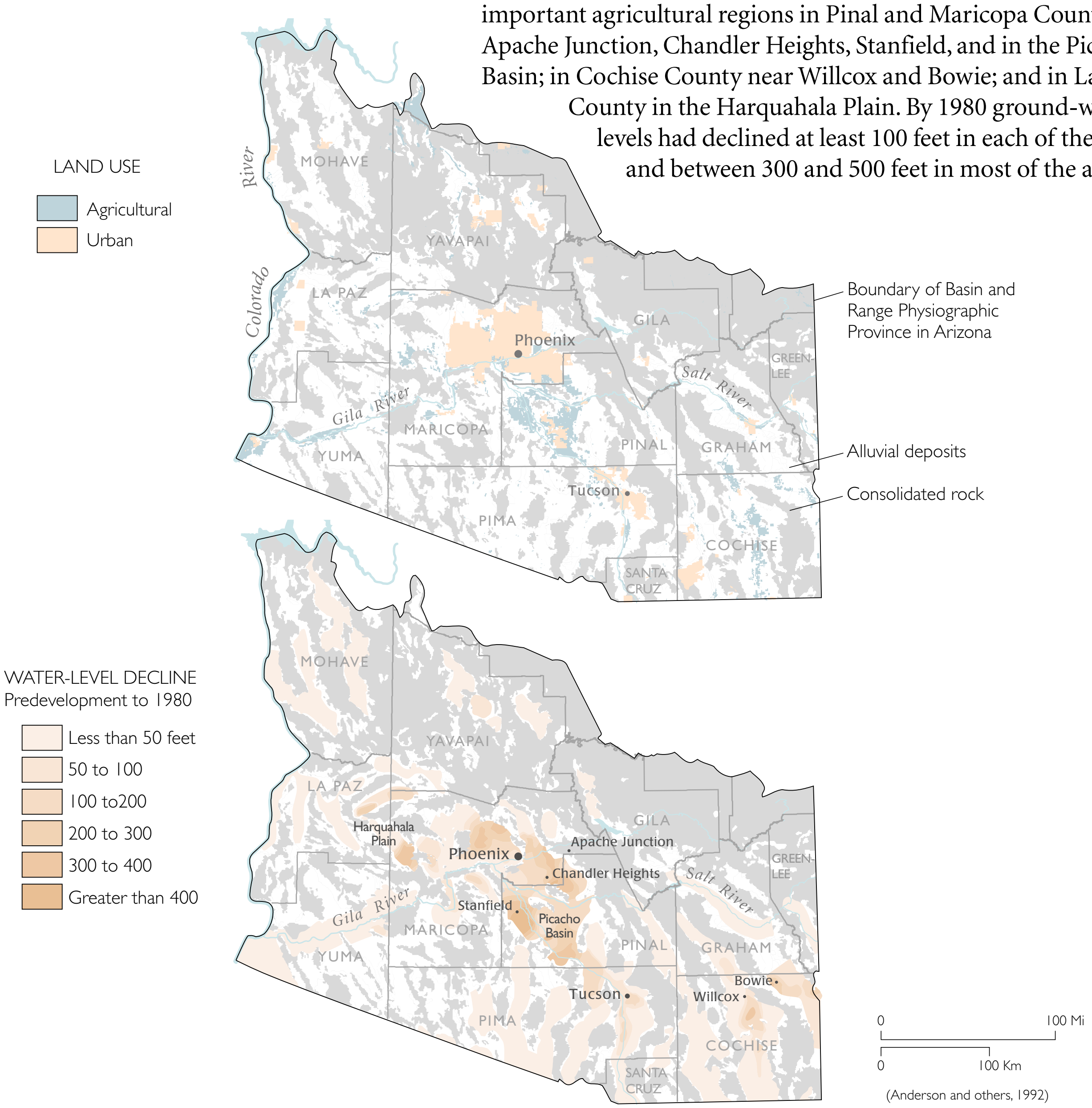
Agriculture in Arizona requires intensive irrigation.

(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)

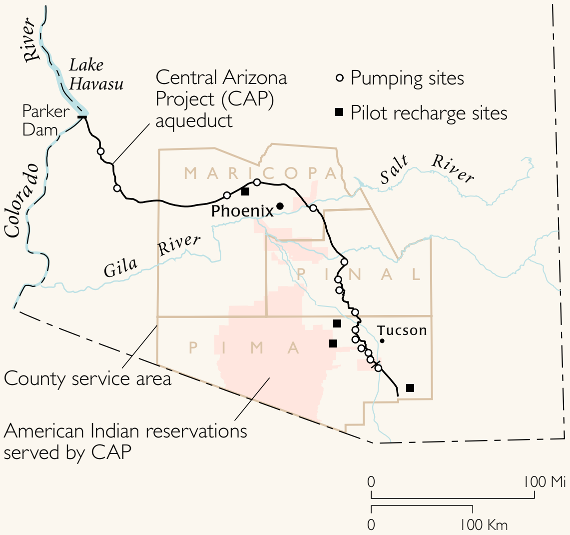
Central Arizona Project (CAP)

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.

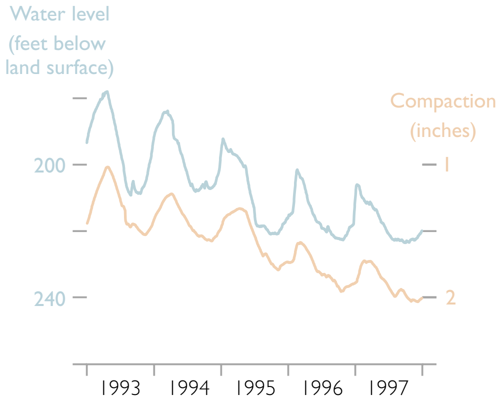

(U.S. Bureau of Reclamation)

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).

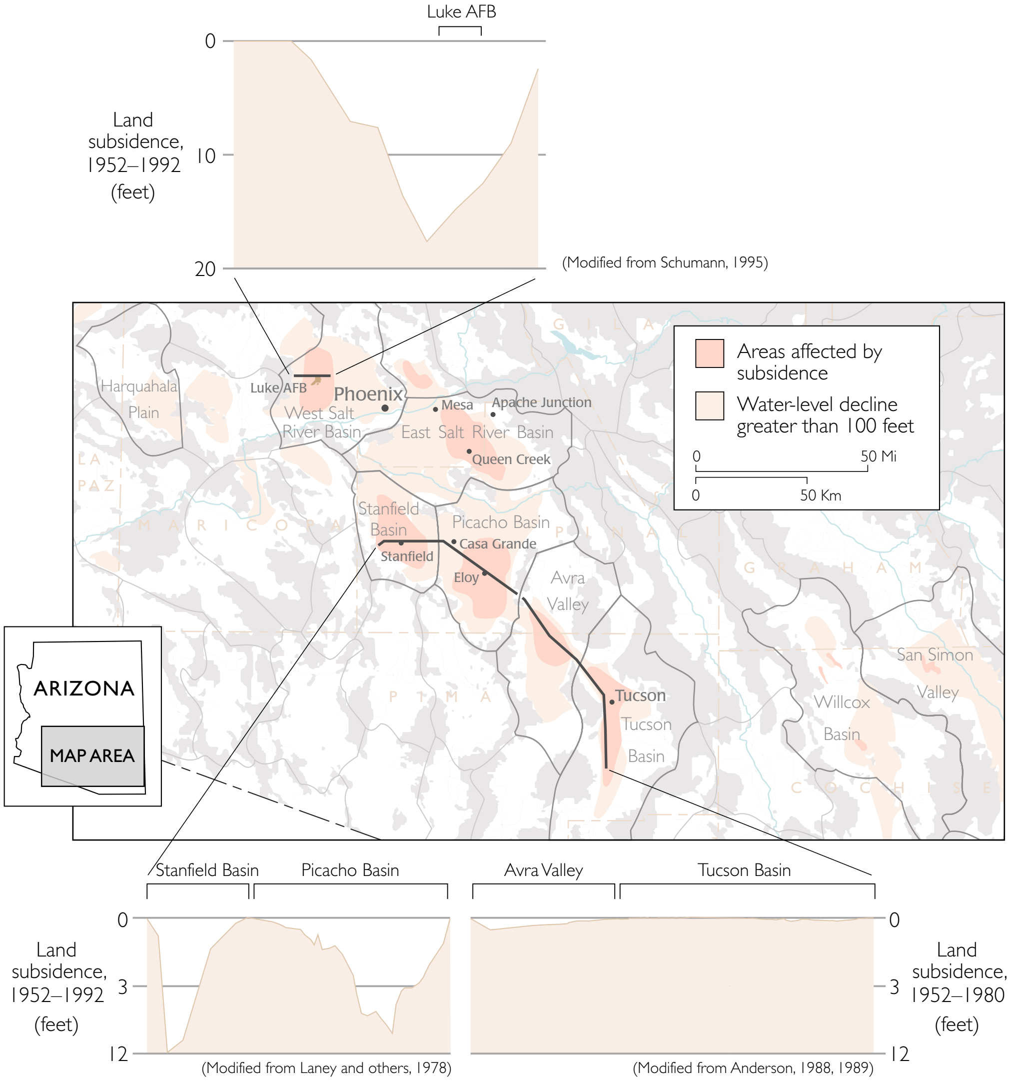
By 1977, nearly 625 square miles had subsided around Eloy, where as much as 12.5 feet of subsidence was measured; another 425 square miles had subsided around Stanfield, with a maximum sub-



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



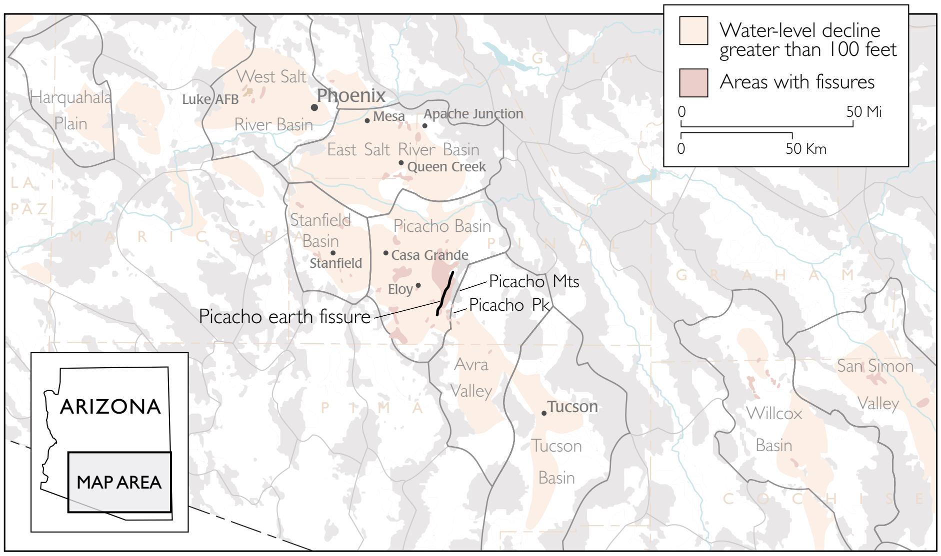
(Modified from Schumann, 1995)

(Modified from Laney and others, 1978)

(Modified from Anderson, 1988, 1989)

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.

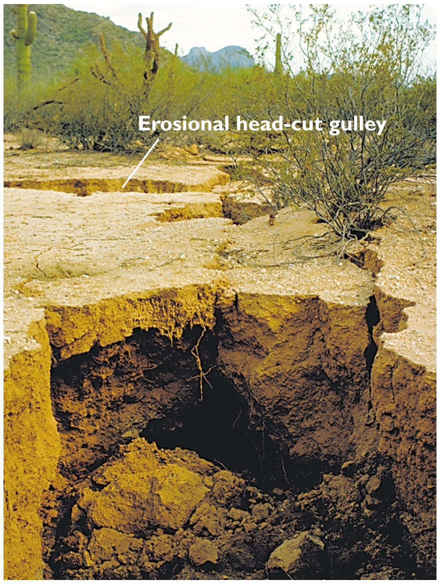


conveyance. On September 20, 1992, surface runoff from a rainstorm of 4 inches closed the base for 3 days. The sluggish Dysart Drain spilled over, flooding the base runways along with more than 100 houses and resulted in about $3 million in damage (Schumann, 1995).

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

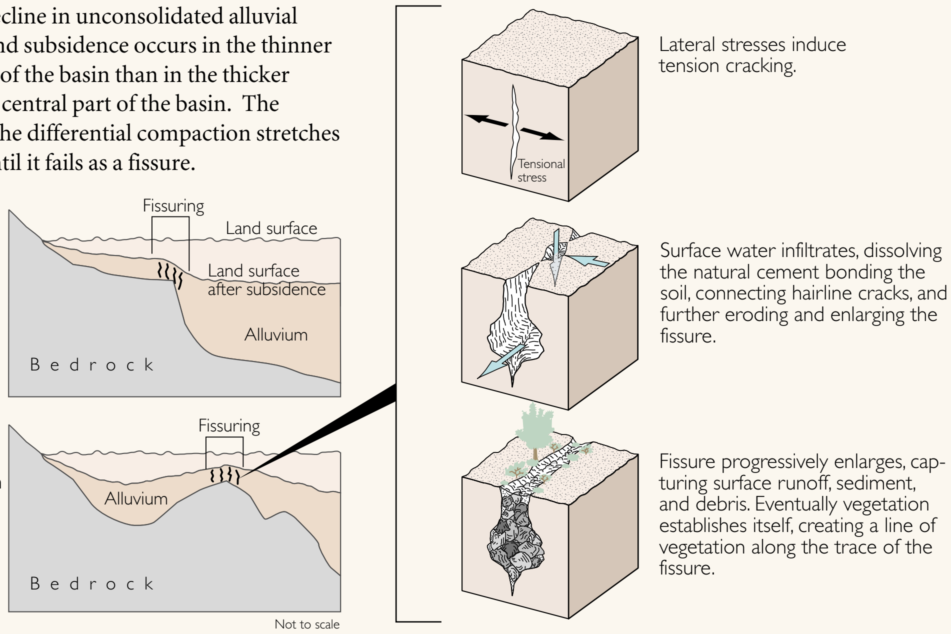
Several theories explain the mechanism of fissure formation

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)

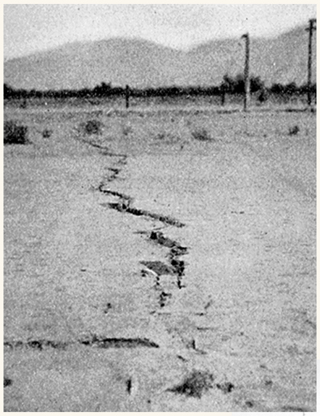
Discovering Arizona's early fissures

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

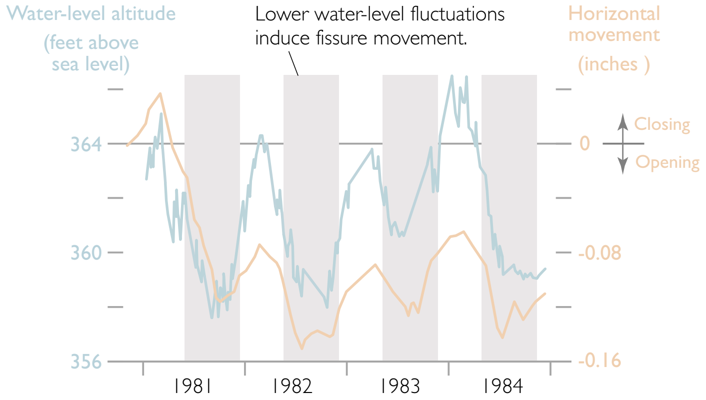
Douglas's view

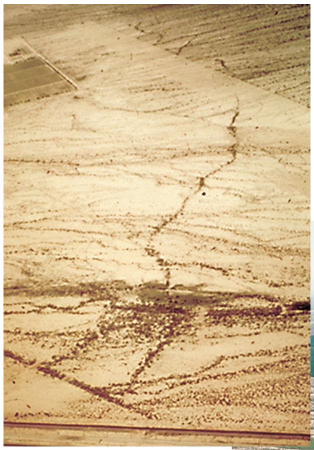
(University of Arizona Tree Ring Laboratory photographs GEOL 27-2)

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

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





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.

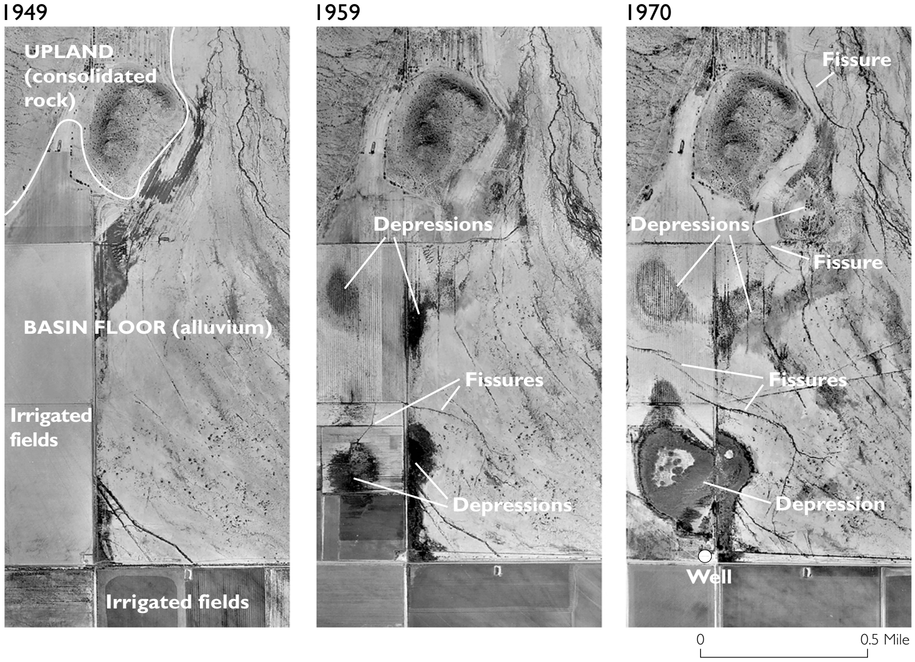
The Picacho fissure is Arizona's most studied

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.

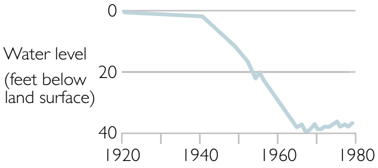
In the early 1950s Feth (1951) attributed formation of earth fissures west of the Picacho Mountains to differential compaction caused by ground-water-level decline in unconsolidated alluvium over the edge of a buried pediment or bedrock bench. He observed that fissures typically open during and after 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,

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

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).

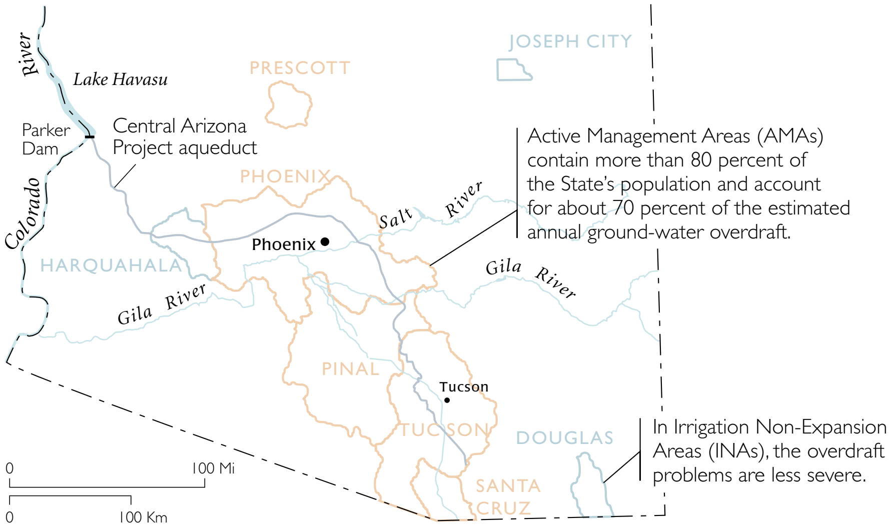
Engineering measures can also mitigate damage where fissures undercut roads. At Apache Junction, a trench was dug to a depth of about 30 feet, backfilled by about 10 feet of compacted fill, and then draped by a reinforced plastic grid, geotextile felt, and an impermeable membrane. The membrane was buried 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



Active Management Areas (AMAs) contain more than 80 percent of the State's population and account for about 70 percent of the estimated annual ground-water overdraft.

In Irrigation Non-Expansion Areas (INAs), the overdraft problems are less severe.

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.

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/**

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 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

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.


(U.S. Bureau of Reclamation)