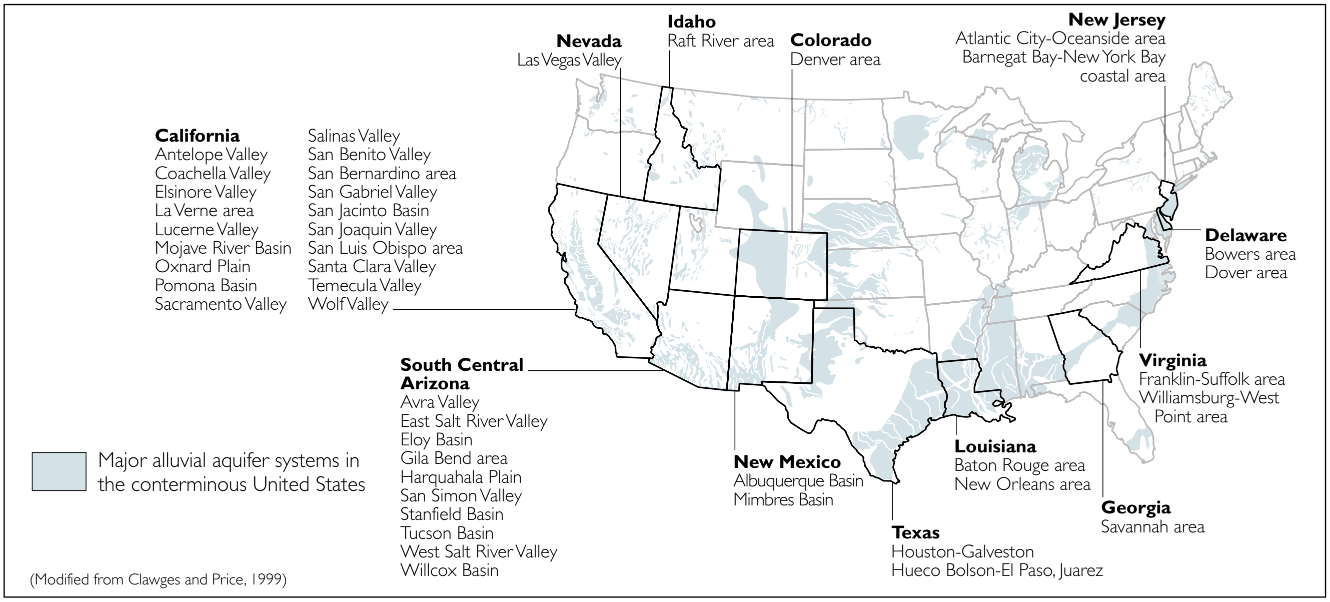
PART I

Mining Ground Water

Santa Clara Valley, California
San Joaquin Valley, California
Houston-Galveston, Texas
Las Vegas, Nevada
South-Central Arizona

Permanent subsidence can occur when water stored beneath the Earth's surface is removed by pumpage or drainage. The reduction of fluid pressure in the pores and cracks of aquifer systems, especially in unconsolidated rocks, is inevitably accompanied by some deformation of the aquifer system. Because the granular structure—the so-called "skeleton"—of the aquifer system is not rigid, but more or less compliant, a shift in the balance of support for the overlying material causes the skeleton to deform slightly. Both the aquifers and aquitards that constitute the aquifer system undergo deformation, but to different degrees. Almost all the permanent subsidence occurs due to the irreversible compression or consolidation of aquitards during the typically slow process of aquitard drainage (Tolman and Poland, 1940). This concept, known as the aquitard-drainage model, has formed the theoretical basis of many successful subsidence investigations.*

Areas where subsidence has been attributed to ground-water pumpage



(Modified from Clawges and Price, 1999)

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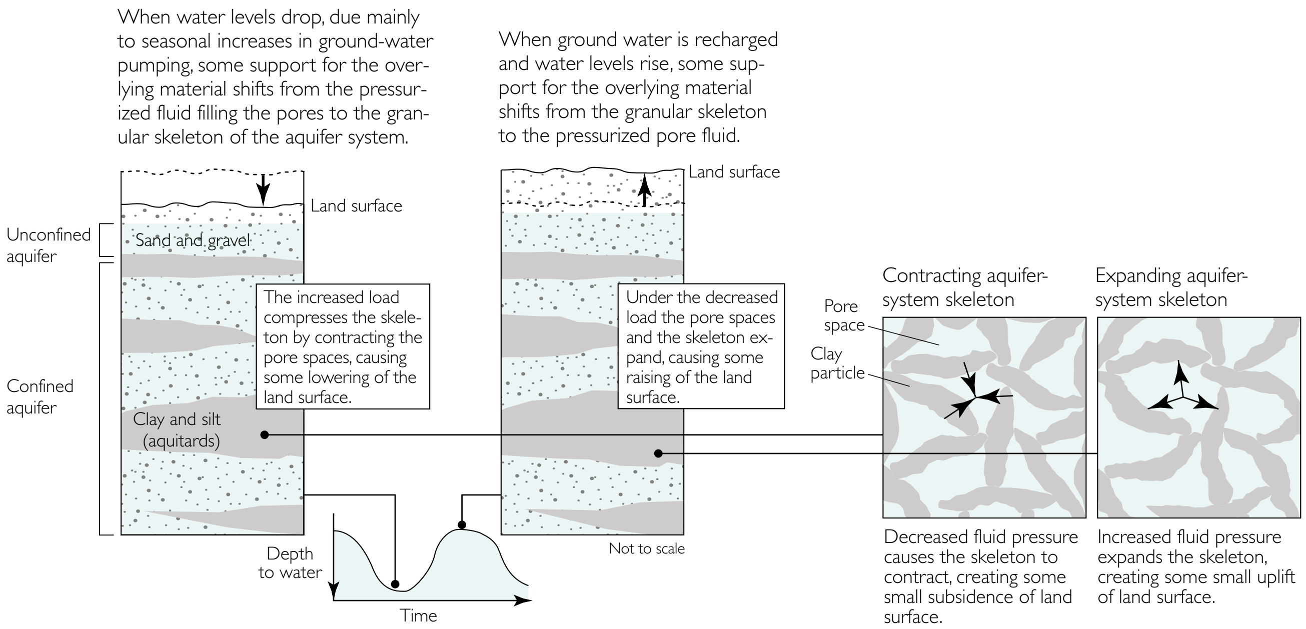
* Studies of subsidence in the Santa Clara Valley (Tolman and Poland, 1940; Poland and Green, 1962; Green, 1964; Poland and Ireland, 1988) and San Joaquin Valley (Poland, 1960; Miller, 1961; Riley, 1969; Helm, 1975; Poland and others, 1975; Ireland and others, 1984) in California established the theoretical and field application of the laboratory derived principle of effective stress and theory of hydrodynamic consolidation to the drainage and compaction of aquitards. For reviews of the history and application of the aquitard drainage model see Holzer (1998) and Riley (1998).

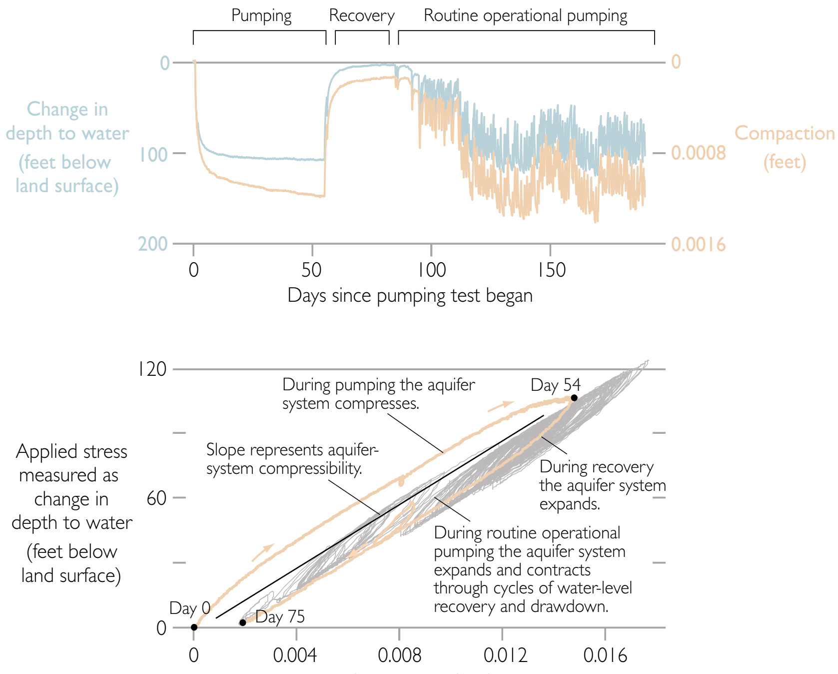


REVERSIBLE DEFORMATION OCCURS IN ALL AQUIFER SYSTEMS

The relation between changes in ground-water levels and compression of the aquifer system is based on the principle of effective stress first proposed by Karl Terzaghi (Terzaghi, 1925). By this principle, when the support provided by fluid pressure is reduced, such as when ground-water levels are lowered, support previously provided by the pore-fluid pressure is transferred to the skeleton of the aquifer system, which compresses to a degree. Conversely, when the pore-fluid pressure is increased, such as when ground water recharges the aqui-

Mostly recoverable (elastic) deformation was observed during and following a pumping test near Albuquerque, New Mexico. Changes in the water level due to cyclic pumping were accompanied by alternating cycles of compression and expansion of the aquifer system.

A measure of the change in applied stress is the change in water level.



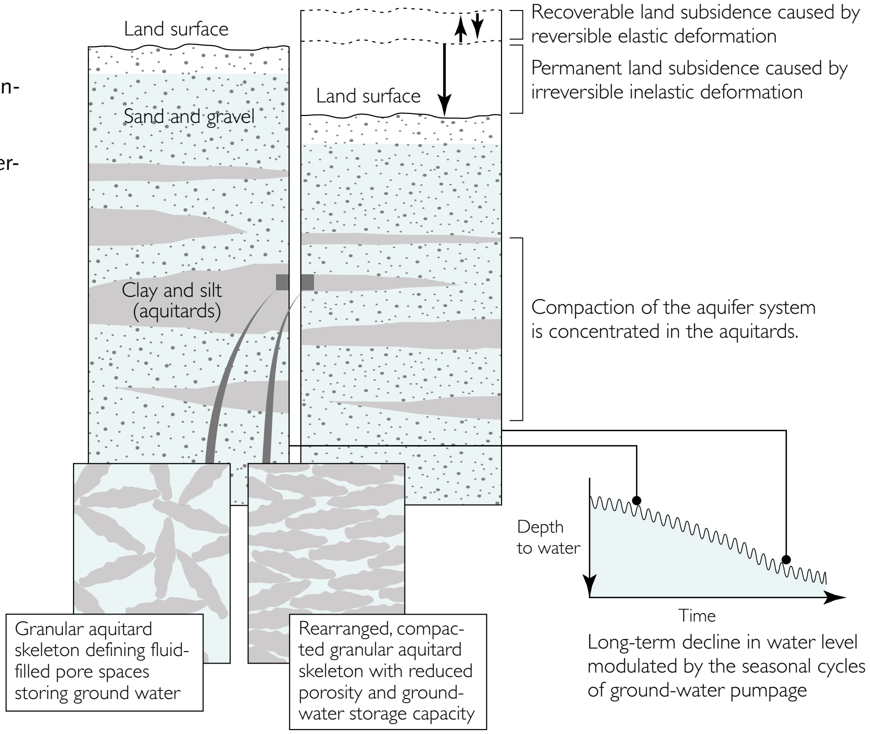
(Heywood, 1997)

fer system, support previously provided by the skeleton is transferred to the fluid and the skeleton expands. In this way, the skeleton alternately undergoes compression and expansion as the pore-fluid pressure fluctuates with aquifer-system discharge and recharge. When the load on the skeleton remains less than any previous maximum load, the fluctuations create only a small elastic deformation of the aquifer system and small displacement of land surface. This fully recoverable deformation occurs in all aquifer systems, commonly resulting in seasonal, reversible displacements in land surface of up to 1 inch or more in response to the seasonal changes in ground-water pumpage.

INELASTIC COMPACTION IRREVERSIBLY ALTERS THE AQUIFER SYSTEM

The maximum level of past stressing of a skeletal element is termed the preconsolidation stress. When the load on the aquitard skeleton exceeds the preconsolidation stress, the aquitard skeleton may undergo significant, permanent rearrangement, resulting in irreversible compaction. Because the skeleton defines the pore structure of the aquitard, this results in a permanent reduction of pore volume as the pore fluid is "squeezed" out of the aquitards into the aquifers. In confined aquifer systems subject to large-scale overdraft, the volume of water derived from irreversible aquitard compaction is essentially equal to the volume of subsidence and can typically range from 10 to 30 percent of the total volume of water pumped. This represents a one-time mining of stored ground water and a small permanent reduction in the storage capacity of the aquifer system.

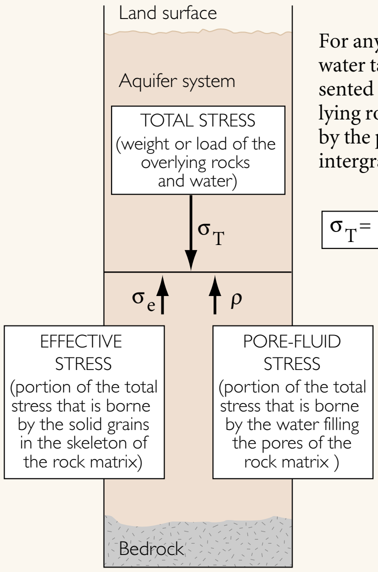
When long-term pumping lowers ground-water levels and raises stresses on the aquitards beyond the preconsolidation-stress thresholds, the aquitards compact and the land surface subsides permanently.



Aquitard Drainage and Aquifer-System Compaction

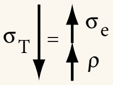
The Principle of Effective Stress

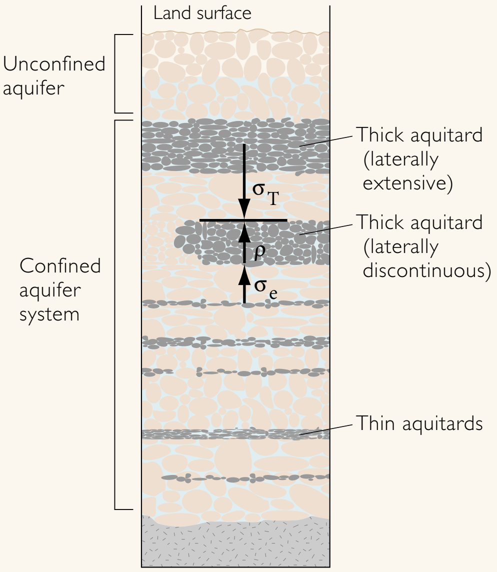
This principle describes the relation between changes in water levels and deformation of the aquifer system.



For any arbitrary plane below the water table, the total stress represented by the weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

$$\boxed{\sigma_T = \sigma_e + \rho}$$



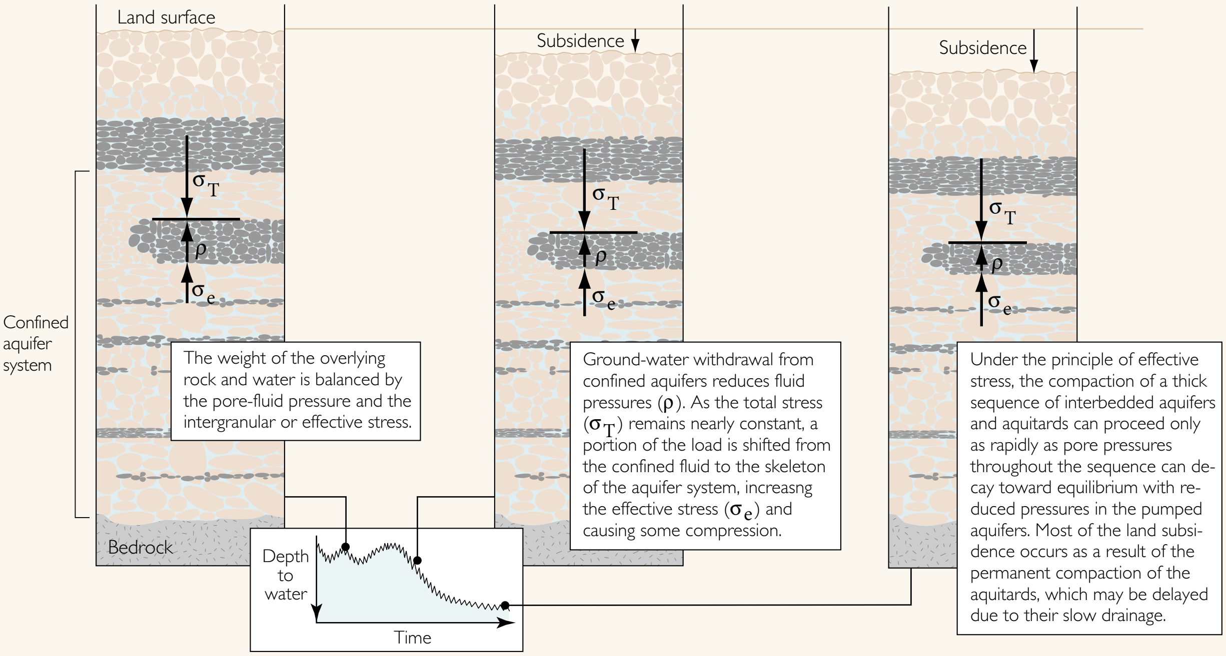


PROLONGED CHANGES IN GROUND-WATER LEVELS INDUCE SUBSIDENCE

Prior to the extensive development of ground-water resources, water levels are relatively stable—though subject to seasonal and longer-term climatic variability.

During development of ground-water resources, water levels decline and land subsidence begins.

After ground-water pumping slows or decreases, water levels stabilize but land subsidence may continue.



The weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

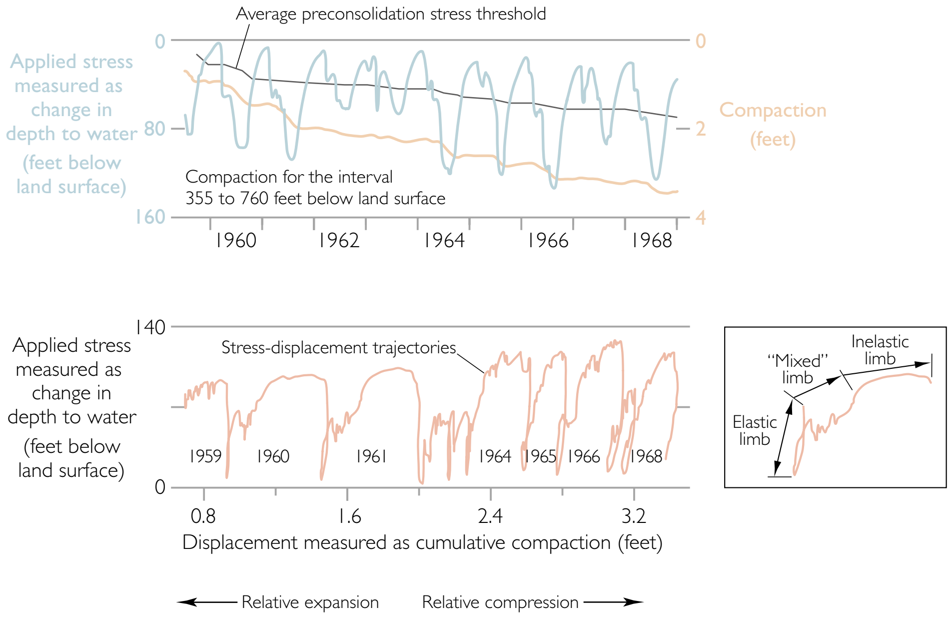
Ground-water withdrawal from confined aquifers reduces fluid pressures (ρ). As the total stress (σ_T) remains nearly constant, a portion of the load is shifted from the confined fluid to the skeleton of the aquifer system, increasng the effective stress (σ_e) and causing some compression.

Under the principle of effective stress, the compaction of a thick sequence of interbedded aquifers and aquitards can proceed only as rapidly as pore pressures throughout the sequence can decay toward equilibrium with reduced pressures in the pumped aquifers. Most of the land subsidence occurs as a result of the permanent compaction of the aquitards, which may be delayed due to their slow drainage.

More than 2.5 feet of permanent (inelastic) compaction was observed near Pixley, San Joaquin Valley, California during a 10-year period.

The high summer demand for irrigation water combined with the normally wetter winters causes ground-water levels to fluctuate in response to seasonal pumpage and recharge. The annual cycles of alternating stress increase and decrease are accompanied by cycles of compression and slight expansion of the aquifer system.

Compression proceeds most rapidly when the stress is larger than the preconsolidation stress threshold. Beyond this threshold almost all of the compression is permanent (inelastic) and attributed to the compaction of fine-grained aquitards.



(Riley, 1969)

Aquitards play an important role in compaction

In recent decades increasing recognition has been given to the critical role of aquitards in the intermediate and long-term response of alluvial aquifer systems to ground-water pumpage. In many such systems interbedded layers of silts and clays, once dismissed as nonwater yielding, comprise the bulk of the ground-water storage capacity of the confined aquifer system! This is by virtue of their substantially greater porosity and compressibility and, in many cases, their greater aggregate thickness compared to the more transmissive, coarser-grained sand and gravel layers.

Because aquitards are by definition much less permeable than aquifers, the vertical drainage of aquitards into adjacent pumped aquifers may proceed very slowly, and thus lag far behind the changing water levels in adjacent aquifers. The duration of a typical irrigation season may allow only a modest fraction of the potential yield from aquitard storage to enter the aquifer system, before pumping ceases for the season and ground-water levels recover in the aquifers. Typically, for thick aquitards, the next cycle of pumping begins before the fluid pressures in the aquitards have equilibrated with the previous cycle. The lagged response within the inner portions of a thick aquitard may be largely isolated from the higher frequency seasonal fluctuations and more influenced by lower frequency, longer-term trends in ground-water levels. Because the migration of increased internal stress into the aquitard accompanies its drainage, as more fluid is squeezed from the interior of the aquitard, larger and larger internal stresses propagate farther into the aquitard.

When the internal stresses exceed the preconsolidation stress, the compressibility increases dramatically, typically by a factor of 20 to

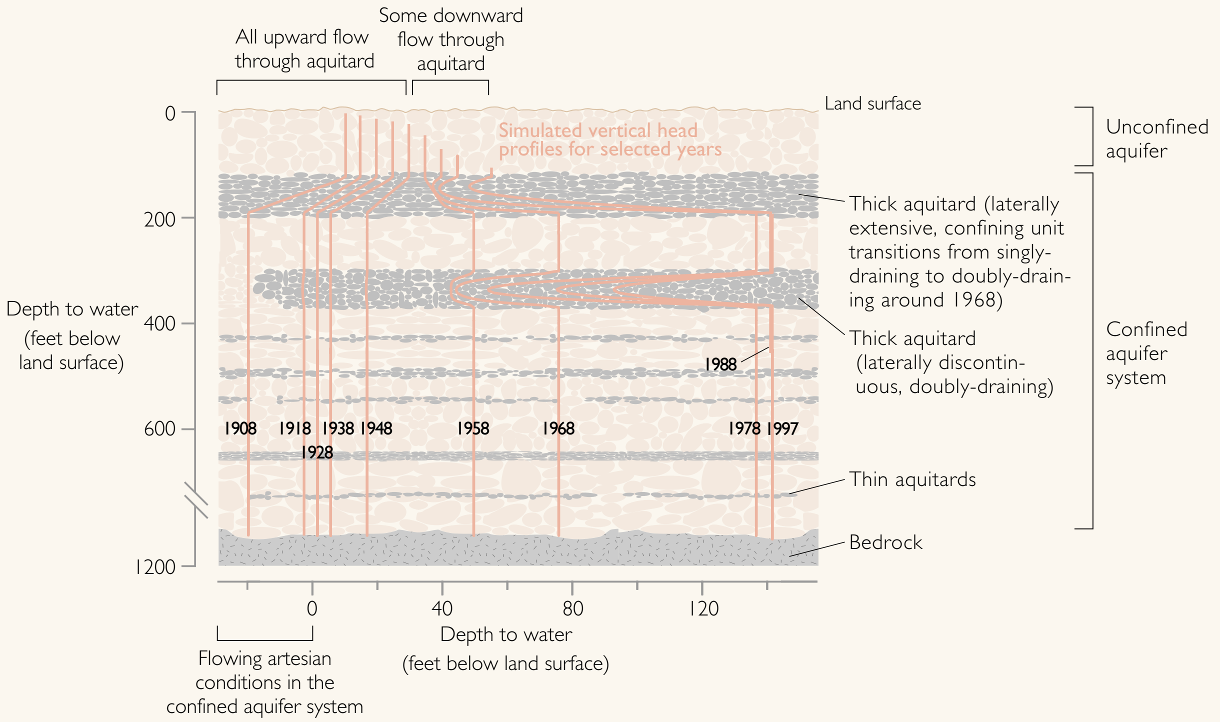
> *". . . the term **aquitard** has been coined to describe the less-permeable beds in a stratigraphic sequence. These beds may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow, but their permeability is not sufficient to allow the completion of production wells within them."*
>
> *—Freeze and Cherry, 1979*

Aquitard Drainage and Aquifer-System Compaction

The Theory of Hydrodynamic Consolidation

The theory describes the delay in draining aquitards when water levels are lowered in adjacent aquifers, as well as the residual compaction that may continue long after water levels are initially lowered.

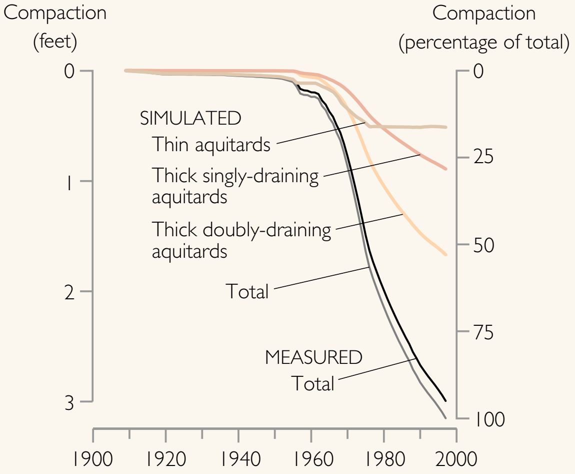
During a 90-year period (1908–1997) of ground-water development in the Antelope Valley, California, the response of water levels in two thick aquitards lags the declining water level in the aquifer. A laterally discontinuous aquitard draining from both upper and lower faces approaches fluid-pressure equilibrium with the adjacent aquifers more rapidly than an overlying laterally extensive aquitard that has a complex drainage history, including a gradient reversal.*



RESIDUAL COMPACTION

Significant amounts of compaction began occurring in the late 1950s after water levels in the aquifers had fallen some 60 feet. Initially, most of the compaction occured in the faster-draining thin aquitards within the aquifers. Subsequently most of the compaction occured in the two thickest and most slowly draining aquitards. Despite stabilization of ground-water levels in the aquifers, more than 0.3 feet of compaction has occurred since 1990, due to residual compaction.

Simulations predict that another 1.3 feet of compaction may ultimately occur even if ground-water levels remain at 1997 levels.



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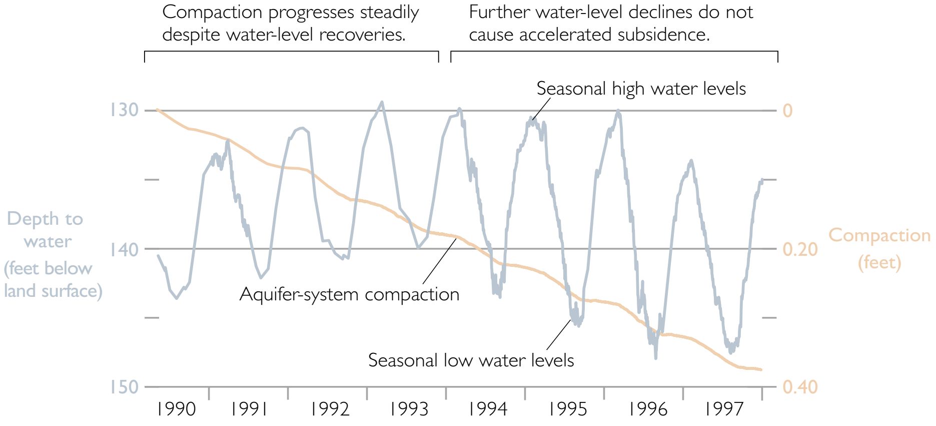
*These results from an aquifer system in Antelope Valley, Mojave Desert, California are based on field measurements and computer simulations of aquitard drainage. They illustrate the history of ground-water-level changes and compaction in the aquifers and aquitards throughout the period of ground-water resource development, 1908-97.

(Michelle Sneed, USGS. written communication, 1998)

100 times, and the resulting compaction is largely nonrecoverable. At stresses greater than the preconsolidation stress, the lag in aquitard drainage increases by comparable factors, and concomitant compaction may require decades or centuries to approach completion. The theory of hydrodynamic consolidation (Terzaghi, 1925)—an essential element of the "aquitard drainage model"—describes the delay involved in draining aquitards when heads are lowered in adjacent aquifers, as well as the residual compaction that may continue long after drawdowns in the aquifers have essentially stabilized. Numerical modeling based on Terzaghi's theory has successfully simulated complex histories of compaction observed in response to measured water-level fluctuations (Helm, 1978).

Hydrodynamic lag, which is a delay in the propagation of fluid-pressure changes between the aquifers and aquitards, can be seen at this site in the Antelope Valley, Mojave Desert, California.

The responses to changing water levels following eight decades of ground-water development suggest that stresses directly driving much of the compaction are somewhat insulated from the changing stresses caused by short-term water-level variations in the aquifers.



(Michelle Sneed, USGS, written communication, 1998)

SANTA CLARA VALLEY, CALIFORNIA

A case of arrested subsidence

The Santa Clara Valley is part of a structural trough that extends about 90 miles southeast from San Francisco. The northern third of the trough is occupied by the San Francisco Bay, the central third by the Santa Clara Valley, and the southern third by the San Benito Valley. The northern Santa Clara Valley, roughly from Palo Alto to the Coyote Narrows (10 miles southeast of downtown San Jose), is now densely populated and known as "Silicon Valley," the birthplace of the global electronics industry.

In the first half of this century, the Santa Clara Valley was intensively cultivated, mainly for fruit and vegetables. The extensive orchards, dominated by apricots, plums, cherries, and pears, led local boosters to dub the area a Garden of Eden or "The Valley of Heart's Delight." In the post-World War II era (circa 1945–1970), rapid population growth was associated with the transition from an agriculturally based economy to an industrial and urban economy. The story of land subsidence in the Santa Clara Valley is closely related to the changing land and water use and the importation of surface water to support the growing urban population.

San Jose and its surrounding communities sprawl across the Santa Clara Valley. The view is looking southeast from downtown San Jose.

(Air Flight Service)

S.E. Ingebritsen and David R. Jones
U.S. Geological Survey, Menlo Park, California

The Santa Clara Valley was a premier fruit growing region in the early part of the 20th century. The landscape was dotted with family orchards, each with its own well (note well house far right).

(Alice Iola Hare, Bancroft Library, UC Berkeley)

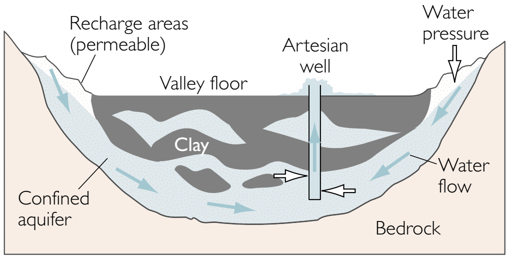
(George E. Hyde & Co. 1915-1921, Bancroft Library, UC Berkeley)

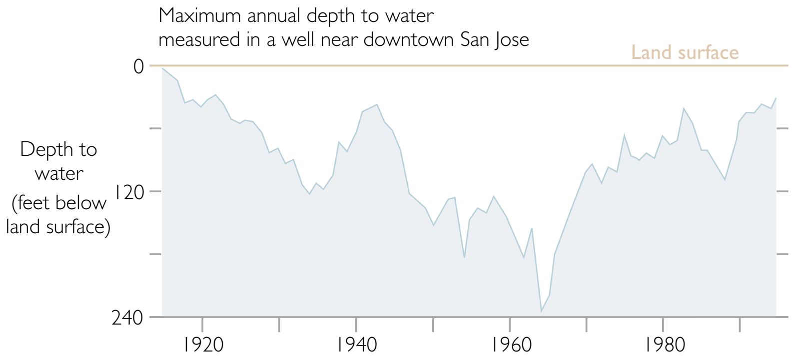
The Santa Clara Valley was the first area in the United States where land subsidence due to ground-water withdrawal was recognized (Tolman and Poland,1940). It was also the first area where organized remedial action was undertaken, and subsidence was effectively halted by about 1969. The ground-water resource is still heavily used, but importation of surface water has reduced ground-water pumping and allowed an effective program of ground-water recharge that prevents ground-water levels from approaching the historic lows of the 1960s. The unusually well-coordinated and effective conjunctive use of surface water and ground water in the Santa Clara Valley is facilitated by the fact that much of the Valley is served by a single water-management agency, the Santa Clara Valley Water District.

GROUND-WATER PUMPING SUPPLIED ORCHARDS AND, EVENTUALLY, CITIES

This free-flowing artesian well was capped to prevent waste (1910).

The moderate climate of the Santa Clara Valley has distinct wet and dry periods. During the wet season (November to April), average rainfall ranges from a high of about 40 inches in the low, steep mountain ranges to the southwest to a low of about 14 inches on the valley floor—rates that are generally insufficient to support specialty crops. Early irrigation efforts depended upon local diversions of surface water, but the acreage that could be irrigated in this manner was very limited. By the 1860s, wells were in common use.





In the late 1800s construction of railroads, refrigerator cars, and improved canning techniques gave farmers access to the growing California and eastern markets for perishable crops. The planting of orchards and associated ground-water pumping increased rapidly into the 1900s.

In the late 1880s most wells in the area between downtown San Jose and Alviso and along the Bay northwest and northeast of Alviso were artesian. That is, water flowed freely without needing to be pumped. In fact, there was substantial waste of ground water from uncapped artesian wells. The widespread artesian conditions were due to the natural hydrogeology of the Santa Clara Valley. Water levels in the artesian wells rose above the land surface because they tapped confined aquifers that have permeable connections to higher-elevation recharge areas on the flanks of the Valley but are overlain by low-permeability clay layers.

By 1920, two-thirds of the Santa Clara Valley was irrigated, including 90 percent of the orchards, and new wells were being drilled at the rate of 1,700 per year (California History Center, 1981). By the late 1920s, about 130,000 acre-feet of ground water was pumped annually to irrigate crops and support a total population of about 100,000.

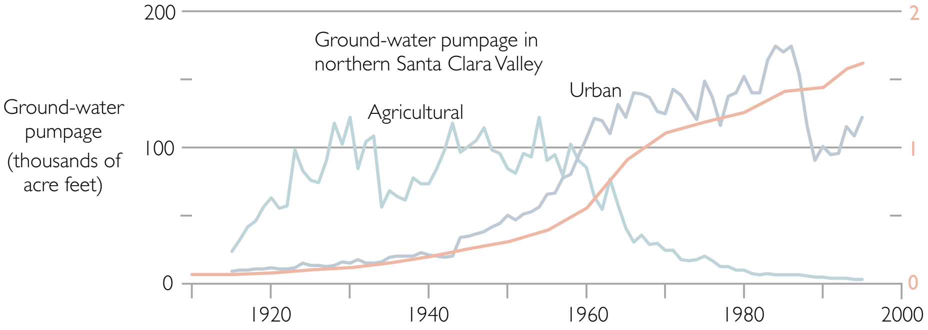
Acre-Feet

Hydrologists frequently use the term acre-feet to describe a volume of water. One acre-foot is the volume of water that will cover an area of one acre to a depth of one foot. The term is especially useful where large volumes of water are being described. One acre-foot is equivalent to 43,560 cubic feet, or about 325,829 gallons!

Ground-water levels drop

Ground water was being used faster than it could be replenished. As a result, water levels were dropping and artesian wells becoming increasingly rare. By 1930, the water level in a formerly artesian USGS monitoring well in downtown San Jose had fallen 80 feet below the land surface.

Between 1920 and 1960 an average of about 100,000 acre-feet per year of ground water was used to irrigate crops. Nonagricultural use of ground water began to increase substantially during the 1940s, and by 1960 total ground-water withdrawals approached 200,000 acre-feet per year. In 1964 the water level in the USGS monitoring well in downtown San Jose had fallen to a historic low of 235 feet below the land surface.



These photographs of the South Bay Yacht Club in Alviso show dramatic evidence of subsidence.

1914—The Yacht Club (building to the right) is practically at sea level.

1978—The Yacht Club is now about 10 feet below sea level, and a high levee keeps bay water from inundating Alviso.

(Santa Clara Valley Water District)

MASSIVE GROUND-WATER WITHDRAWAL CAUSED THE GROUND TO SUBSIDE

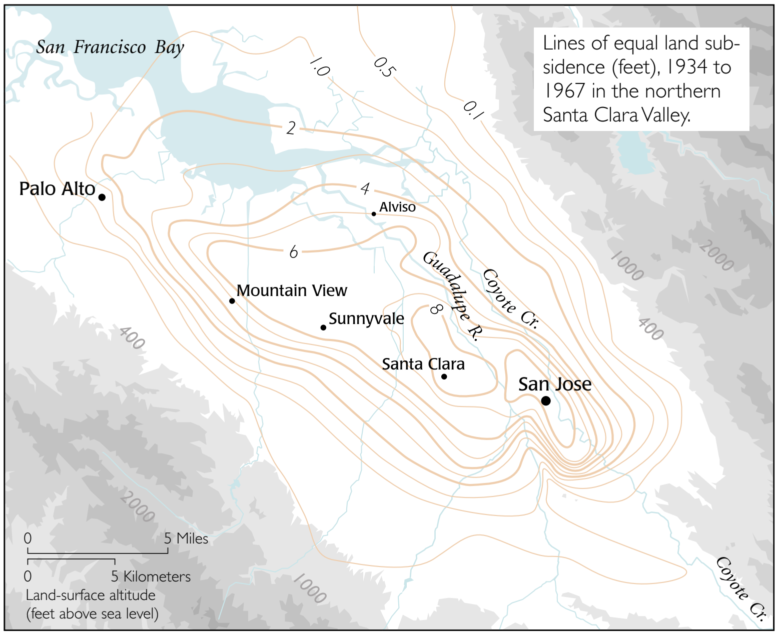
Substantial land subsidence occurred in the northern Santa Clara Valley as a result of the massive ground-water overdrafts. Detectable subsidence of the land surface (greater than 0.1 feet) took place over much of the area. The maximum subsidence occurred in downtown San Jose, where land-surface elevations decreased from about 98 feet above sea level in 1910 to about 84 feet above sea level in 1995.

Lands adjacent to the southern end of San Francisco Bay sank from 2 to 8 feet by 1969, putting 17 square miles of dry land below the high-tide level. The southern end of the Bay is now ringed with dikes to prevent landward movement of saltwater, and flood-control levees have been built to control the bayward ends of stream channels. The stream channels must now be maintained well above the surrounding land in order to provide a gradient for flow to the Bay. In the land that has sunk below the high-tide level, local storm discharge must be captured and pumped over levees in order to prevent widespread flooding.

The fact that Santa Clara Valley was subsiding became generally known in 1933, when bench marks in San Jose that were established in 1912 were resurveyed and found to have subsided 4 feet. This finding motivated the U.S. Coast and Geodetic Survey to establish a network of bench marks tied to stable bedrock on the edges of the Valley. The bench-mark network was remeasured many times between 1934 and 1967, and forms the basis for mapping subsidence.

During the 33-year period, subsidence ranged from 2 feet under the Bay and its tideland to 8 feet in San Jose and Santa Clara.

Total land subsidence, which probably began in the 1920s and continued to 1969 or later, is likely greater than shown on this map.



Lines of equal land subsidence (feet), 1934 to 1967 in the northern Santa Clara Valley.

(Modified from Poland and Ireland, 1988)

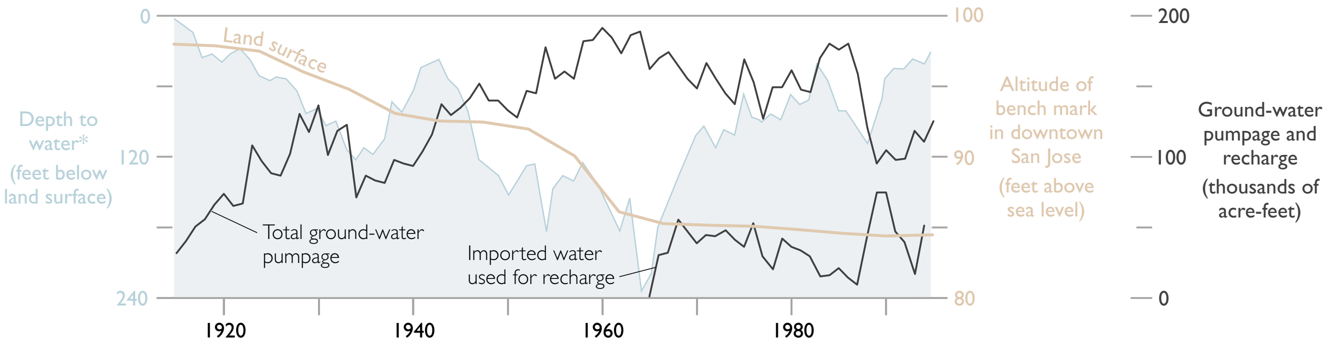
Subsidence had to be stopped

In 1935 and 1936, the Santa Clara Valley Water District built five storage dams on local streams to capture storm flows. This permitted controlled releases to increase ground-water recharge through streambeds. Wet years in the early 1940s enhanced both natural and artificial recharge. Although subsidence was briefly arrested during World War II, these measures proved inadequate to halt water-level declines over the long term, and, between 1950 and 1965, subsidence resumed at an accelerated rate. In 1965, increased imports of surface water allowed the Santa Clara Valley Water District to greatly expand its program of ground-water recharge, leading to substantial recovery of ground-water levels, and there has been little additional subsidence since about 1969.

In fact, as of 1995, water levels in the USGS monitoring well in downtown San Jose were only 35 feet below land surface, the highest levels observed since the early 1920s. A series of relatively wet years in the mid-1990s even caused a return to artesian conditions in some areas near San Francisco Bay. Some capped and long-forgotten wells near the Bay began to leak and were thereby rediscovered!

Subsidence in the Santa Clara Valley was caused by the decline of artesian pressures and the resulting increase in the effective overburden load on the water-bearing sediments. The sediments compacted under the increasing stress and the land surface sank. Most of the compaction occurred in fine-grained clay deposits (aquitards), which are more compressible, though less permeable, than coarser-grained sediments. The low permeability of the clay layers retards and smooths the compaction of the aquifer system relative to the water-level variations in the permeable aquifers. Since 1969, despite water-level recoveries, a small amount of additional residual com-

Land subsidence was a result of intensive ground-water pumping and the subsequent drop in water levels. Once pumping was stabilized by the introduction of imported surface water, subsidence was arrested.



Subsidence slowed briefly due to a recharge program instituted by the Santa Clara Valley Water District.

Reduced ground-water pumping and recharge using imported surface water has raised ground-water levels and effectively arrested subsidence.

From 1960 to 1963 subsidence attained its greatest average rate (about 8 inches per year).

*In USGS monitoring well in downtown San Jose paction and subsidence has accrued. The total subsidence has been large and chiefly permanent, but future subsidence can be controlled if ground-water levels are maintained safely above their subsidence thresholds.

The South Bay aqueduct conveys water from the Sacramento-San Joaquin Delta to the Santa Clara Valley.

(Santa Clara Valley Water District)

Surface water is delivered for use in the Valley

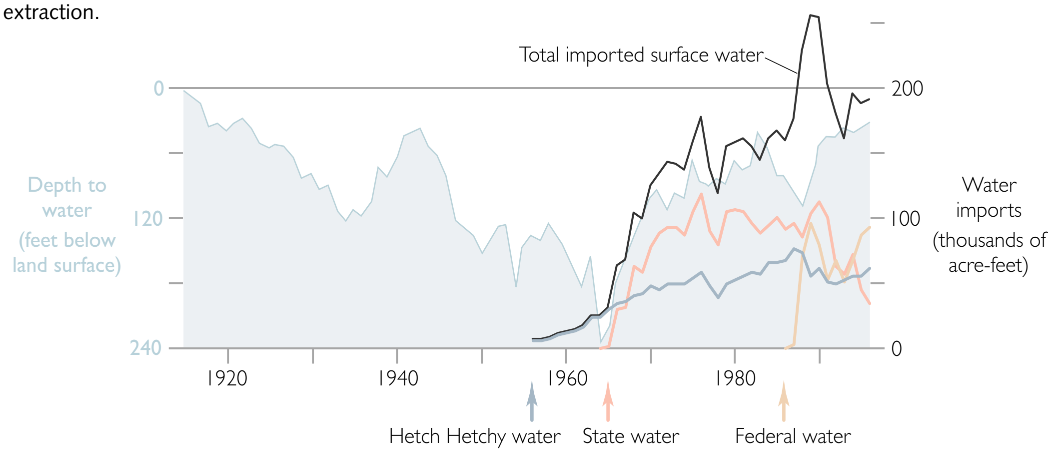
To balance Santa Clara Valley's water-use deficit, surface water has been imported from northern and eastern California via aqueducts—Hetch Hetchy (San Francisco Water Department, 1951-), the California State Water Project (1965-), and the Federal San Felipe Water Project (1987-). Much of the imported water also feeds into various local distribution lines. But presently about one-fourth of the water imported by the Santa Clara Valley Water District (about 40,000 of the 150,000 acre-feet total) is used for ground-water recharge.

The aquifer systems are used for natural storage and conveyance, in preference to constructing expensive surface-storage and conveyance systems. In order to avoid recurrence of the land subsidence that plagued the Valley prior to 1969, ground-water levels are maintained well above their historic lows, even during drought periods. For example, ground-water levels beneath downtown San Jose were maintained even during the major California droughts of 1976–77 and 1987–91. In order to avoid large ground-water overdrafts, the Water District aggressively encourages water conservation during drought periods. Per-capita water use under current conditions is much lower than in the agrarian past. Today, about 350,000 acre-feet of surface and ground water meet the annual requirements of a countywide population of about 1,600,000, and per-capita water use is only about one-fifth of the 1920 level.

The economic impact can only be approximated

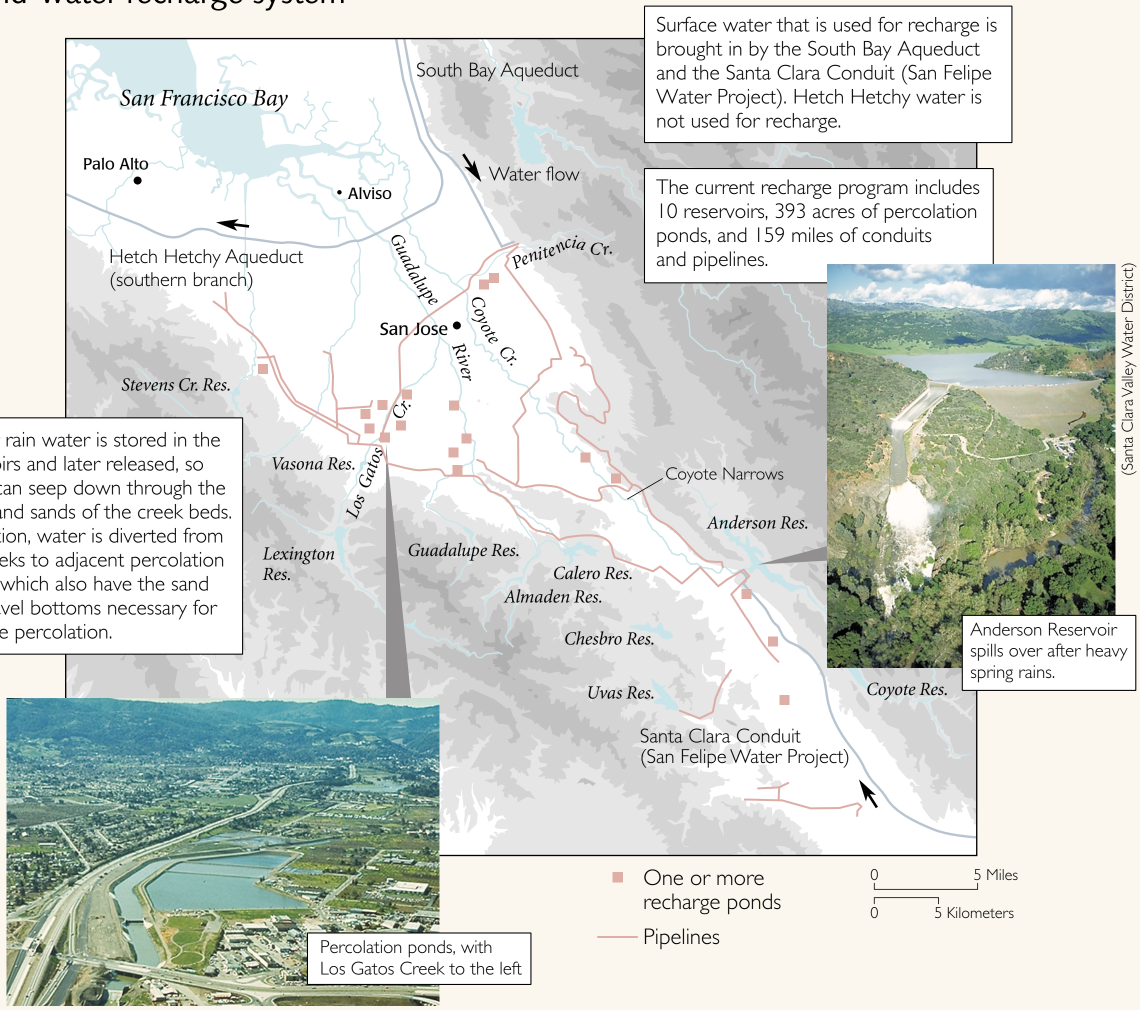
The direct costs of land subsidence in the Santa Clara Valley include the cost of constructing levees around the southern end of San Francisco Bay and the bayward ends of stream channels, main-

Water imports allow water managers to raise ground-water levels by reducing net ground-water extraction.



Santa Clara Valley Water District

Ground-water recharge system



Surface water that is used for recharge is brought in by the South Bay Aqueduct and the Santa Clara Conduit (San Felipe Water Project). Hetch Hetchy water is not used for recharge.

The current recharge program includes 10 reservoirs, 393 acres of percolation ponds, and 159 miles of conduits and pipelines.

Winter rain water is stored in the reservoirs and later released, so that it can seep down through the gravel and sands of the creek beds. In addition, water is diverted from the creeks to adjacent percolation ponds, which also have the sand and gravel bottoms necessary for effective percolation.

Anderson Reservoir spills over after heavy spring rains.

(Santa Clara Valley Water District)

Percolation ponds, with Los Gatos Creek to the left

(Santa Clara Valley Water District)

■ One or more recharge ponds

— Pipelines

NATURAL CONDITIONS

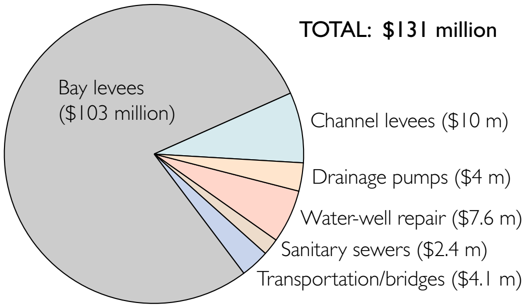
Conditions are favorable for recharge in the upper reaches of several streams because there is an abundance of coarse sand and gravel deposits and the aquifer system is generally unconfined; that is, fluid pressure in the aquifer is not confined by any overlying lenses of low-permeability clay. Nearer to the Bay, sediments tend to be finer-grained, and the exploited ground-water system is generally confined by low-permeability materials that impede recharge.

RECHARGE FACILITIES

The first percolation facilities in the Santa Clara Valley were built in the 1930s. They relied on capturing local surface runoff, and proved inadequate to keep pace with the rate of ground-water extraction. The volume of artificial recharge was increased significantly when additional imported surface water became available in 1965. Artificial recharge rates in the 1970s were sufficient to reverse ground-water level declines and arrest subsidence.

COST-BENEFIT

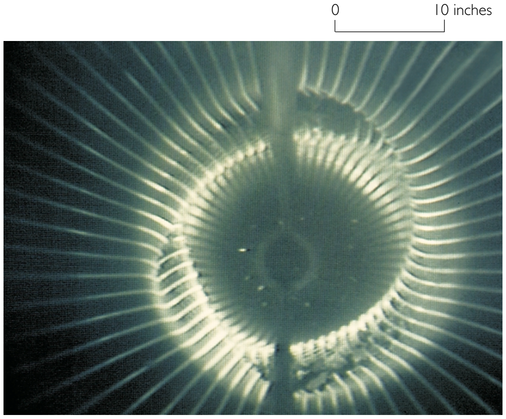
In 1984, a cost-benefit approach was used to estimate the value of artificial ground-water recharge in the Santa Clara Valley (Reichard and Bredehoeft, 1984). The benefits of reduced ground-water pumping costs and reduced subsidence were found to be greater than the total costs of continuing the artificial recharge program. A second analysis compared the costs of artificial recharge with the cost of a surface system that would achieve the same storage and conveyance of water. The costs of artificial recharge proved to be much less than the costs of an equivalent surface system.



Direct costs of land subsidence in the Santa Clara Valley in 1979 dollars.

taining salt-pond levees, raising grades for railroads and roads, enlarging or replacing bridges, enlarging sewers and adding sewage pumping stations, and constructing and operating storm-drainage pumping stations in areas that have subsided below the high-tide level. Most of these direct costs were incurred during the era of active subsidence. In 1981 Lloyd C. Fowler, former Chief Engineer of the Santa Clara Valley Water District, estimated the direct costs of subsidence to be $131,100,000 in 1979 dollars, a figure that translates to about $300,000,000 in 1998 dollars. The ongoing cost of maintaining levees and pumping facilities can also be attributed mainly to subsidence. In fact, as of this writing, the U.S. Army Corps of Engineers is building a substantial system for flood control along the lower Guadalupe River channel, with design requirements (and associated expense) influenced by past subsidence.

Some of Fowler's estimates of direct costs deserve further explanation. Land subsidence was estimated to have damaged or destroyed about 1,000 wells in the 5-year period 1960 to 1965, and the cost estimate was based on the cost of repair. By the 1960s most large wells in the Santa Clara Valley extended to depths of 400 feet or more. Many well casings were buckled or collapsed by the compaction of clay lenses at depths more than 200 feet below the land surface. The compacting clay caused the casing to buckle and eventually collapse. The cost estimate cited for the Bay levees as of 1979 applies only to the publicly maintained flood-protection levees, and likely underestimates the total cost. An additional, unknown cost was incurred by a salt company that maintained levees on 30 square miles of salt ponds within the original bayland area. Land subsidence has permanently increased the risk of saltwater flooding in case of levee breaks and the potential for saltwater intrusion of shallow aquifers.



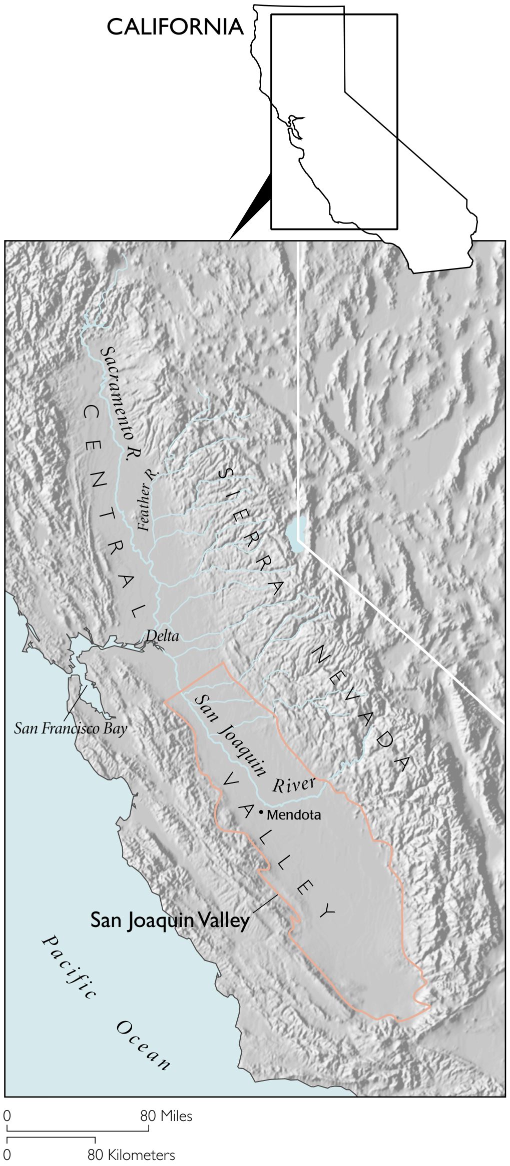
This view looking into a typical collapsed well screen shows the damage caused by compaction. This photograph was made by lowering a light into the well, followed by a camera; the crumpled vertical ribbing of the steel well screen produced this radiating effect.

Careful management will continue

The Santa Clara Valley Water District is currently managing the ground-water basin in a conservative fashion in order to avoid further subsidence. Their management strategy depends on continued availability of high-quality surface water from State and Federal projects that import water from massive diversion facilities in the southern part of the Sacramento-San Joaquin Delta. As we describe in another case study, these diversion facilities themselves are threatened by land subsidence within the Delta. Thus the prognosis for land subsidence in the Santa Clara Valley depends in part on subsidence rates and patterns in the Delta. Because much of California relies on large-scale interbasin water transfers, subsidence and water-quality issues in many parts of the State are complexly interrelated.

SAN JOAQUIN VALLEY, CALIFORNIA

Largest human alteration of the Earth's surface



Mining ground water for agriculture has enabled the San Joaquin Valley of California to become one of the world's most productive agricultural regions, while simultaneously contributing to one of the single largest alterations of the land surface attributed to humankind. Today the San Joaquin Valley is the backbone of California's modern and highly technological agricultural industry. California ranks as the largest agricultural producing state in the nation, producing 11 percent of the total U.S. agricultural value. The Central Valley of California, which includes the San Joaquin Valley, the Sacramento Valley, and the Sacramento-San Joaquin Delta, produces about 25 percent of the nation's table food on only 1 percent of the country's farmland (Cone, 1997).

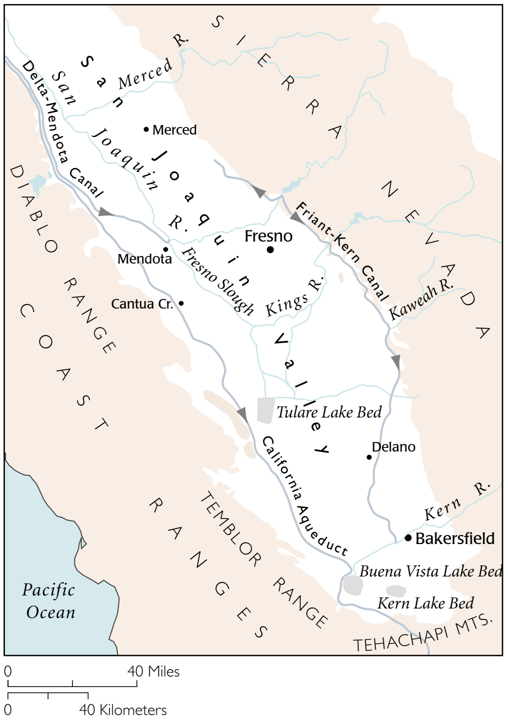
In 1970, when the last comprehensive surveys of land subsidence were made, subsidence in excess of 1 foot had affected more than 5,200 square miles of irrigable land—one-half the entire San Joaquin Valley (Poland and others, 1975). The maximum subsidence, near Mendota, was more than 28 feet.

Approximate location of maximum subsidence in United States identified by research efforts of Joseph Poland (pictured). Signs on pole show approximate altitude of land surface in 1925, 1955, and 1977. The pole is near benchmark S661 in the San Joaquin Valley southwest of Mendota, California.

Devin Galloway and Francis S. Riley
U.S. Geological Survey, Menlo Park, California

Since the early 1970s land subsidence has continued in some locations, but has generally slowed due to reductions in ground-water pumpage and the accompanying recovery of ground-water levels made possible by supplemental use of surface water for irrigation. The surface water is diverted principally from the Sacramento-San Joaquin Delta and the San Joaquin, Kings, Kern and Feather Rivers. Two droughts since 1975 have caused surface-water deliveries in the valley to be sharply curtailed, and demonstrated the valley's vulnerability to continued land subsidence when ground-water pumpage is increased.

The history of land subsidence in the San Joaquin Valley is integrally linked to the development of agriculture and the availability of water for irrigation. Further agricultural development without accompanying subsidence is dependent on the continued availability of surface water, which is subject to uncertainties due to climatic variability and pending regulatory decisions.



Land subsidence in the San Joaquin Valley was first noted in 1935 when I. H. Althouse, a consulting engineer, called attention to the possibility of land subsidence near the Delano (Tulare-Wasco) area. The process was first described in print by Ingerson (1941, p. 40–42), who presented a map and profiles of land subsidence based on comparison of leveling of 1902, 1930, and 1940. Four types of subsidence are known to occur in the San Joaquin Valley. In order of decreasing magnitude they are (1) subsidence caused by aquifer-system compaction due to the lowering of ground-water levels by sustained ground-water overdraft; (2) subsidence caused by the hydrocompaction of moisture-deficient deposits above the water-table; (3) subsidence related to fluid withdrawal from oil and gas fields; and (4) subsidence related to crustal neotectonic movements. Aquifer-system compaction and hydrocompaction have significantly lowered the land surface in the valley since about the 1920s, and our review of the subsidence problems there is limited to these two primary causes.

THE SAN JOAQUIN VALLEY IS PART OF A GREAT SEDIMENT-FILLED TROUGH

The San Joaquin Valley comprises the southern two-thirds of the Central Valley of California. Situated between the towering Sierra Nevada on the east, the Diablo and Temblor Ranges to the west, and the Tehachapi Mountains to the south, the valley occupies a trough created by tectonic forces related to the collision of the Pacific and North American Plates. The trough is filled with marine sediments overlain by continental sediments, in some places thousands of feet deep, deposited largely by streams draining the mountains, and partially in lakes that inundated portions of the valley floor from time to time. More than half the thickness of the continental sediments is composed of fine-grained (clay, sandy clay, sandy silt, and silt) stream (fluvial) and lake (lacustrine) deposits susceptible to compaction.

Meltwater from the Sierra snowpack recharges ground water in the San Joaquin Valley and supplies surface water during the dry summer months.

(California Department of Water Resources)

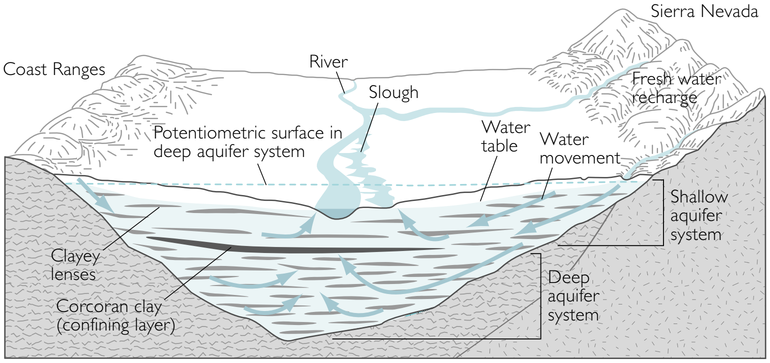
The valley floor, comprising about 10,000 square miles, is arid to semiarid, receiving an average of 5 to 16 inches of rainfall annually. Most of the streamflow in the valley enters from the east side in streams draining the western Sierra Nevada, where much of the precipitation occurs as snow. The San Joaquin River begins high in the Sierra Nevada and descends onto the valley floor, where it takes a northerly flow path toward the Sacramento-San Joaquin Delta. On its course northward to the Delta it collects streamflow from the central and northern portions of the valley. The southern valley receives streamflow from the Kings, Kaweah, and Kern Rivers, which issue from steeply plunging canyons onto broad, extensive alluvial fans. Over many thousands of years, the natural flow of these rivers distributed networks of streams and washes on the slopes of the alluvial fans and terminated in topographically closed sinks, such as Tulare Lake, Kern Lake, and Buena Vista Lake. Streams draining the drier western slopes and Coast Ranges adjacent to the valley are intermittent or ephemeral, flowing only episodically. Precipitation and streamflow in the valley vary greatly from year to year.

Pumping for irrigation altered the ground-water budget

Ground water occurs in shallow, unconfined (water table) or partially-confined aquifers throughout the valley. Such aquifers are particularly important near the margins of the valley and near the toes of younger alluvial fans. A laterally extensive lacustrine clay known as the Corcoran Clay is distributed throughout the central and western valley. The Corcoran Clay, which varies in thickness from a feather edge to about 160 feet beneath the present bed of Tulare Lake, confines a deeper aquifer system that comprises fine-grained aquitards interbedded with coarser aquifers. Most of the subsidence measured in the valley has been correlated with the distribution of ground-water pumpage and the reduction of water levels in the deep confined aquifer system.

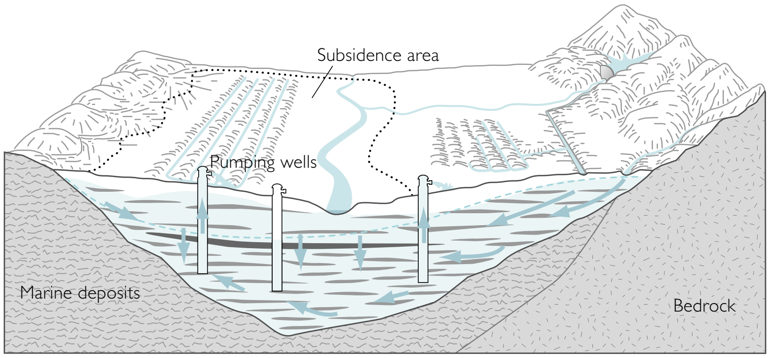
Under natural conditions before development, ground water in the alluvial sediments was replenished primarily by infiltration through stream channels near the valley margins. The eastern-valley streams carrying runoff from the Sierra Nevada provided most of the recharge for valley aquifers. Some recharge also occurred from precipitation falling directly on the valley floor and from stream and lake seepage occurring there. Over the long term, natural replenishment was dynamically balanced by natural depletion through ground-water discharge, which occurred primarily through evapotranspiration and contributions to streams flowing into the Delta. The areas of natural discharge in the valley generally corresponded with the areas of flowing, artesian wells mapped in an early USGS investigation (Mendenhall and others, 1916). Direct ground-water outflow to the Delta is thought to have been negligible.

Today, nearly 150 years since water was first diverted at Peoples Weir on the Kings River and more than 120 years after the first irrigation colonies were established in the valley, intensive development of ground-water resources for agricultural uses has drastically altered the valley's water budget. The natural replenishment of the aquifer systems has remained about the same, but more water has discharged than recharged the aquifer system; the deficit may have amounted to as much as 800,000 acre-feet per year during the late 1960s (Williamson et al., 1989). Most of the surface water now being imported is transpired by crops or evaporated from the soil. The amount of surface-water outflow from the valley has actually been



PREDEVELOPMENT

Ground water flowed from the mountains toward the center of the valley where it discharged into streams or through evapotranspiration.



POSTDEVELOPMENT

Ground water flows generally downward and toward pumping centers.

reduced compared to predevelopment conditions. Ground water in the San Joaquin Valley has generally been depleted and redistributed from the deeper aquifer system to the shallow aquifer system. This has created problems of ground-water quality and drainage in the shallow aquifer system, which is infiltrated by excess irrigation water that has been exposed to agricultural chemicals and natural salts concentrated by evapotranspiration.

By pumping the vast reserves of ground water, farmers have developed the San Joaquin Valley into a major agricultural region.

(California Department of Water Resources)

A STABLE WATER SUPPLY IS DEVELOPED FOR IRRIGATION

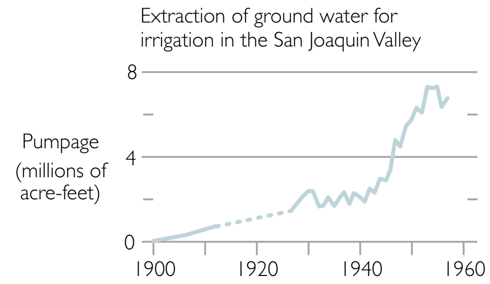
In the San Joaquin Valley, irrigated agriculture surged after the 1849 Gold Rush and again in 1857, when the California Legislature passed an act that promoted the drainage and reclamation of river-bottom lands (Manning, 1967). By 1900, much of the flow of the Kern River and the entire flow of the Kings River had been diverted through canals and ditches to irrigate lands throughout the southern part of the valley (Nady and Laragueta, 1983). Because no significant storage facilities accompanied these earliest diversions, the agricultural water supply, and hence crop demand, was largely limited by the summer low-flows. The restrictions imposed by the need for constant surface-water flows, coupled with a drought occurring around 1880 and the fact that, by 1910, nearly all the available surface-water supply in the San Joaquin Valley had been diverted, prompted the development of ground-water resources.

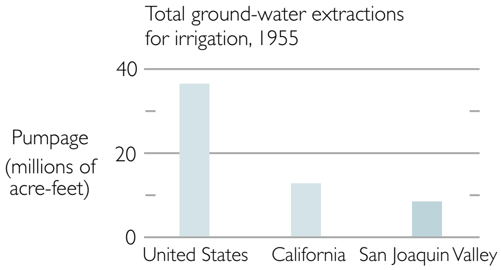
The first development of the ground-water resource occurred in regions where shallow ground water was plentiful, and particularly where flowing wells were commonplace, near the central part of the valley around the old lake basins. Eventually, the yields of flowing wells diminished as water levels were reduced, and it became necessary to install pumps in wells to sustain flow rates. Around 1930, the development of an improved deep-well turbine pump and rural electrification enabled additional ground-water development for irrigation. The ground-water resource had been established as a reliable, stable water-supply for irrigation. Similar histories were repeated in many other basins in California and throughout the Southwest, where surface water was limited and ground water was readily available.

Overhead and flood irrigation supply water to a wide range of crops.

(California Department of Water Resources)

WATER WITHDRAWAL CAUSED LAND SUBSIDENCE





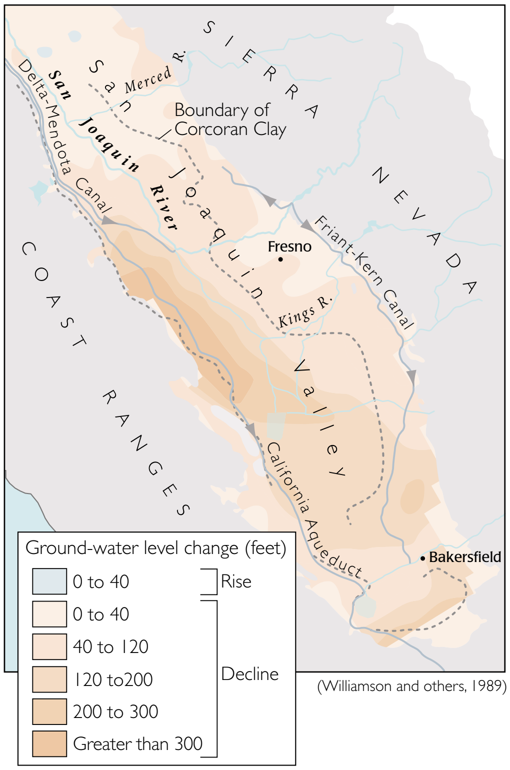
(Joseph F. Poland, U.S. Geological Survey, written communication, ca 1957)

Shortly after the completion of the Delta-Mendota Canal by the U.S. Bureau of Reclamation in 1951, subsidence caused by withdrawal of ground water in the northern San Joaquin Valley had begun to raise concerns, largely because of the impending threat to the canal and the specter of remedial repairs. Because of this threat to the canal, and in order to help plan other major canals and engineering proposed for construction in the subsiding areas, the USGS, in cooperation with the California Department of Water Resources, began an intensive investigation into land subsidence in the San Joaquin Valley. The objectives were to determine the causes, rates, and extent of land subsidence and to develop scientific criteria for the estimation and control of subsidence. The USGS concurrently began a federally funded research project to determine the physical principles and mechanisms governing the expansion and compaction of aquifer systems resulting from changes in aquifer hydraulic heads. Much of the material presented here is drawn from these studies.

In 1955, about one-fourth (almost 8 million acre-feet) of the total ground water extracted for irrigation in the United States was pumped in the San Joaquin Valley. The maximum changes in water levels occurred in the western and southern portions of the valley, in the deep confined aquifer system. More than 400 feet of water-

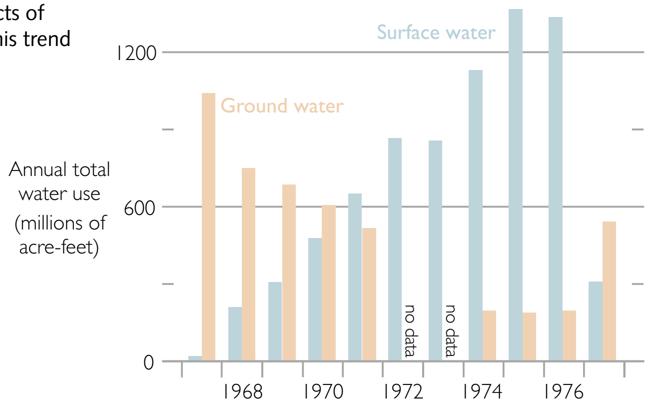
Change in water-table altitude from 1860 to spring 1961

Change in water level in the deep confined aquifer system from 1860 to spring 1961



(Williamson and others, 1989)

By 1971 the growing use of imported surface-water supplies surpasses the use of local ground-water supplies, but the effects of drought reverse this trend in 1977.

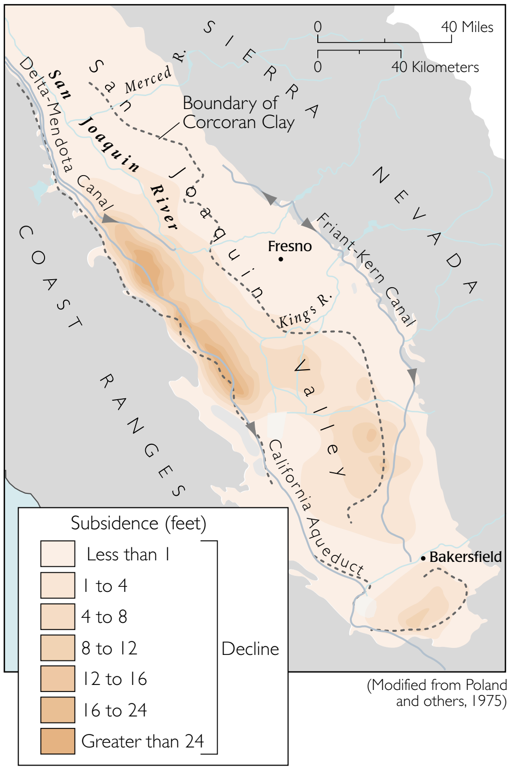


level decline occurred in some west-side areas in the deep aquifer system. Until 1968, irrigation water in these areas was supplied almost entirely by ground water. As of 1960, water levels in the deep aquifer system were declining at a rate of about 10 feet per year. Western and southern portions of the valley generally experienced more than 100 feet of water-level decline in the deep aquifer system. Water levels in the southeastern and eastern portions of the valley were generally less affected because some surface water was also available for irrigation. In the water-table aquifer, few areas exceeded 100 feet of water-level decline, but a large portion of the southern valley did experience declines of more than 40 feet. In some areas on the northwest side, the water-table aquifer rose up to 40 feet due to infiltration of excess irrigation water.

Accelerated ground-water pumpage and water-level declines, principally in the deep aquifer system during the 1950s and 1960s, caused about 75 percent of the total volume of land subsidence in the San Joaquin Valley. By the late 1960s, surface water was being diverted to agricultural interests from the Sacramento-San Joaquin Delta and the San Joaquin River through federal reclamation projects and from the Delta through the newly completed, massive State (California) Water Project. Less-expensive water from the Delta-Mendota Canal, the Friant-Kern Canal, and the California Aqueduct largely supplanted ground water for crop irrigation. Ground-water levels began a dramatic period of recovery, and subsidence slowed or was arrested over a large part of the affected area. Water levels in the deep aquifer system recovered as much as 200 feet in the 6 years from 1967 to 1974 (Ireland and others, 1984).

When water levels began to recover in the deep aquifer system, aquifer-system compaction and land subsidence began to abate, although many areas continued to subside, albeit at a lesser rate. During the period from 1968 to 1974, water levels measured in an observation well near Cantua Creek recovered more than 200 feet while another 2 feet of subsidence continued to accrue. This apparent contradiction is the result of the time delay in the compaction

Land subsidence from 1926 to 1970



(Modified from Poland and others, 1975)

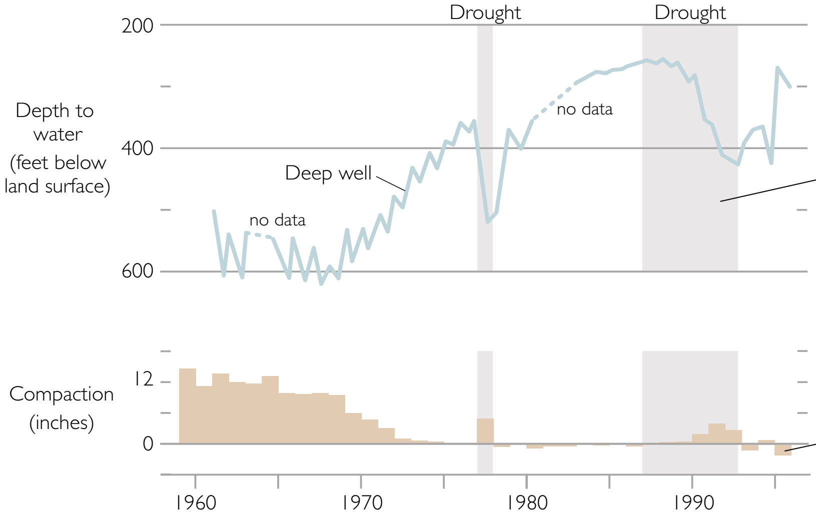
To supplement local ground-water supplies, the California Aqueduct (left) conveys water from the Delta to the dry southern valleys.

(California Department of Water Resources)

of the aquitards in the aquifer system. The delay is caused by the time that it takes for pore-fluid pressures in the aquitards to equilibrate with the pressure changes occurring in the aquifers, which are much more responsive to the current volume of ground-water being pumped (or not pumped) from the aquifer system. The time needed for pressure equilibration depends largely on the thickness and permeability of the aquitards. Typically, as in the San Joaquin Valley, centuries will be required for most of the pressure equilibration to occur, and therefore for the ultimate compaction to be realized. Swanson (1998) states that "Subsidence is continuing in all historical subsidence areas. . . , but at lower rates than before. . . ."

Since 1974, land subsidence has been greatly slowed or largely arrested but remains poised to resume. In fact, during the severe

When water levels recover, compaction and land subsidence can abate.

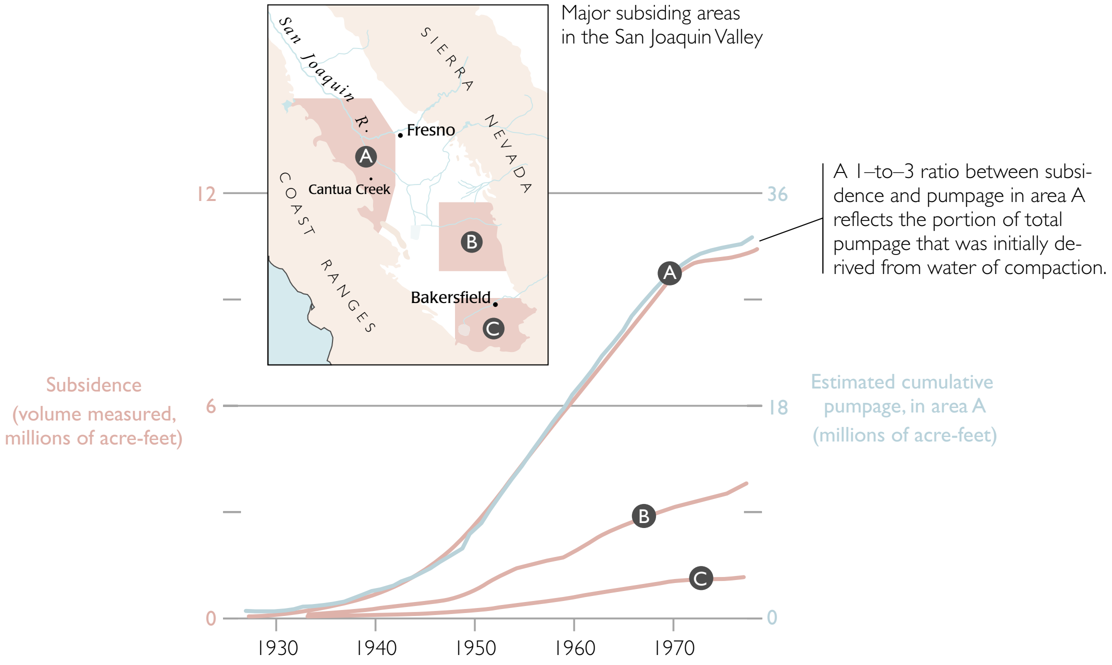


During the droughts of 1976–77 and 1987–91, deliveries of imported water to the west side of the San Joaquin Valley were cut back. More ground water was pumped to meet the demand, resulting in a drop in the water table and consequent compaction.

Some elastic expansion of the aquifer system has occured, but the compacted materials can never return to their pre-compacted thickness.

(Modified from Swanson, 1998)

In the major subsiding areas, subsidence has continued except for a slight leveling off in the mid 1970s.



Major subsiding areas in the San Joaquin Valley

A 1–to–3 ratio between subsidence and pumpage in area A reflects the portion of total pumpage that was initially derived from water of compaction.

(Modified from Poland and others, 1975)

droughts in California in 1976–77 and 1987–91, diminished deliveries of imported water prompted some water agencies and farmers, especially in the western valley, to refurbish old pumping plants, drill new wells, and begin pumping ground water to make up for cutbacks in the imported water supply. The decisions to renew ground-water pumpage were encouraged by the fact that ground-water levels had recovered nearly to predevelopment levels. During the 1976–77 drought, after only one-third of the peak annual pumpage volumes of the 1960s had been produced, ground-water levels rapidly declined more than 150 feet over a large area and subsidence resumed. Nearly 0.5 feet of subsidence was measured in 1977 near Cantua Creek. This scenario was repeated during the more recent 1987–91 drought. It underscores the sensitive dependence between subsidence and the dynamic state of imported-water availability and use.

That a relatively small amount of renewed pumpage caused such a rapid decline in water levels reflects the reduced ground-water storage capacity—lost pore space—caused by aquifer-system compaction. It demonstrates the nonrenewable nature of the resource embodied in the "water of compaction." It emphasizes the fact that extraction of this resource, available only on the first cycle of large-scale drawdown, must be viewed, like more traditional forms of mining, in terms not only of its obvious economic return but also its less readily identifiable costs.

Hydrocompaction

Compaction near the surface

Hydrocompaction produces an undulating surface of hollows and hummocks with local relief, typically of 3 to 5 feet. In this view of a furrowed field, the hollows are filled with irrigation water.

Hydrocompaction—compaction due to wetting— is a near-surface phenomenon that produces land-surface subsidence through a mechanism entirely different from the compaction of deep, overpumped aquifer systems. Both of these processes accompanied the expansion of irrigated agriculture onto the arid, gentle slopes of the alluvial fans along the west side and south end of the San Joaquin Valley. Initially, the distinction between them, and their relative contributions to the overall subsidence problem, were not fully recognized.

In the 1940s and 50s farmers bringing virgin valley soils under cultivation found that standard techniques of flood irrigation caused an irregular settling of their carefully graded fields, producing an undulating surface of hollows and hummocks with local relief, typically of 3 to 5 feet. Where water flowed or ponded continuously for months, very localized settlements of 10 feet or more might occur on susceptible soils. These consequences of artificial wetting seriously disrupted the distribution of irrigation water and damaged pipelines, power lines, roadways, airfields, and buildings. In contrast to the broad, slowly progressive and generally smooth subsidence due to deep-seated aquifer-system compaction, the irregular, localized, and often rapid differential subsidence due to hydrocompaction was readily discernible without instrumental surveys. Recognition of its obvious impact on the design and construction of the proposed California Aqueduct played a major role in the initiation in 1956 of intensive studies to identify, characterize, and quantify the subsidence processes at work beneath the surface of the San Joaquin Valley.

MECHANISMS OF COMPACTION WERE ANALYZED

The mechanisms and requisite conditions for hydrocompaction, initially known as "near-surface subsidence," were investigated by means of laboratory tests on soil cores from depths to 100 or more feet, and by continuously flooded test plots equipped with subsurface benchmarks at various depths and, in some cases, with soil-moisture probes.

The combined field and laboratory studies demonstrated that hydrocompaction occurred only in alluvial-fan sediments above the highest prehistoric water table and in areas where sparse rainfall and ephemeral runoff had never

Hydrocompaction caused surface cracks and land subsidence at experimental Test Plot B, Fresno County.

Mudflow containing hydrocompactible sediments, western Fresno County (1961)

penetrated below the zone subject to summer desiccation by evaporation and transpiration. Under these circumstances the initial high porosity of the sediments (often enhanced by numerous bubble cavities and desiccation cracks) is sun-baked into the deposits and preserved by their high dry strength, even as they are subjected to the increasing load of 100 or more feet of accumulating overburden. In the San Joaquin Valley, such conditions are associated with areas of very low average rainfall and infrequent, flashy, sediment-laden runoff from small, relatively steep upland watersheds that are underlain by easily erodable shales and mudstones. The resulting muddy debris flows and poorly sorted stream sediments typically contain montmorillonite clay in proportions that cause it to act, when dry, as a strong interparticulate bonding agent. When water is first applied in quantities sufficient to penetrate below the root zone the clay bonds are drastically weakened by wetting, and the weight of the overburden crushes out the excess porosity. The process of densifying to achieve the strength required to support the existing overburden may reduce the bulk volume by as much as 10 percent, the amounts increasing with increasing depth and overburden load.

Most of the potential hydrocompaction latent in anomalously dry, low-density sediments is realized as rapidly as the sediments are thoroughly wetted. Thus the progression of a hydrocompaction event is controlled largely by the rate at which the wetting front of percolating water can move downward through the sediments. A site underlain by a thick sequence of poorly permeable sediments may continue to subside for months or years as the slowly descending wetting front weakens progressively deeper deposits. If the surface water source is seasonal or intermittent, the progression is further delayed.

Localized compaction beneath a water-filled pond or ditch often leads to vertical shear failure at depth between the water-weakened sediments and the surrounding dry material. At the surface this process surrounds the subsiding flooded area with an expanding series of concentric tensional fissures having considerable vertical offset—a severely destructive event when it occurs beneath an engineered structure.

The hazards presented by hydrocompaction are somewhat mitigated by the fact that the process goes rapidly to completion with the initial thorough wetting, and is not subject to reactivation through subsequent cycles of decreasing and increasing moisture content. However, if the volume of water that infiltrates the surface on the first wetting cycle is insufficient to wet the full thickness of susceptible deposits, then the process will propagate to greater depths on subsequent applications, resulting in renewed subsidence. Also, an increase in the surface load such as a bridge footing or a canal full of water can cause additional compaction in prewetted sediments.

Studies undertaken in the mid-1950s led to a better understanding of hydrocompaction and to the identification of long reaches of the California Aqueduct route that were underlain by deposits susceptible to hydrocompaction. Construction of the aqueduct through these reaches was preceded by prewetting, and thus compacting to a nearly stable state, the full thickness of susceptible deposits beneath the aqueduct alignment. These measures added more than two years and tens of millions of dollars to the cost of the project.

Prewetting a new section of the California Aqueduct to precompact shallow deposits susceptible to hydrocompaction (near toe of Moreno Gulch, 1963)

MANY COSTS OF LAND SUBSIDENCE ARE HIDDEN

The economic impacts of land subsidence in the San Joaquin Valley are not well known. Damages directly related to subsidence have been identified, and some have been quantified. Other damages indirectly related to subsidence, such as flooding and long-term environmental effects, merit additional assessment. Some of the direct damages have included decreased storage in aquifers, partial or complete submergence of canals and associated bridges and pipe crossings, collapse of well casings, and disruption of collector drains and irrigation ditches. Costs associated with these damages have been conservatively estimated at $25,000,000 (EDAW-ESA, 1978). These estimates are not adjusted for changing valuation of the dollar, and do not fully account for the underreported costs associated with well rehabilitation and replacement. When the costs of lost property value due to condemnation, regrading irrigated land, and replacement of irrigation pipelines and wells in subsiding areas are included, the annual costs of subsidence in the San Joaquin Valley soar to $180 million per year in 1993 dollars (G. Bertoldi and S. Leake, USGS, written communication, March 30, 1993).