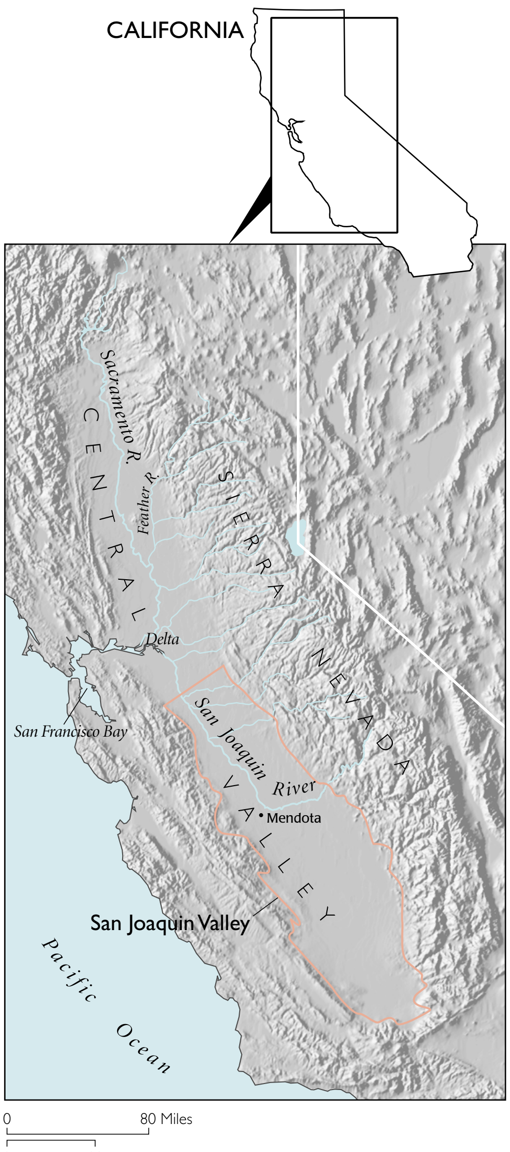
San Joaquin Valley, California

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.

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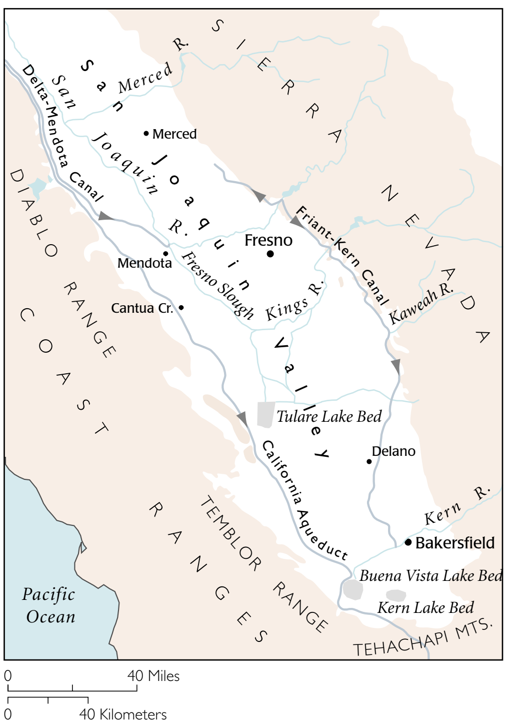
Since the early 1970s land subsidence has continued in some locations, but has generally slowed due to reductions in ground-water pumpage and the accompanying recovery of ground-water levels made possible by supplemental use of surface water for irrigation. The surface water is diverted principally from 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

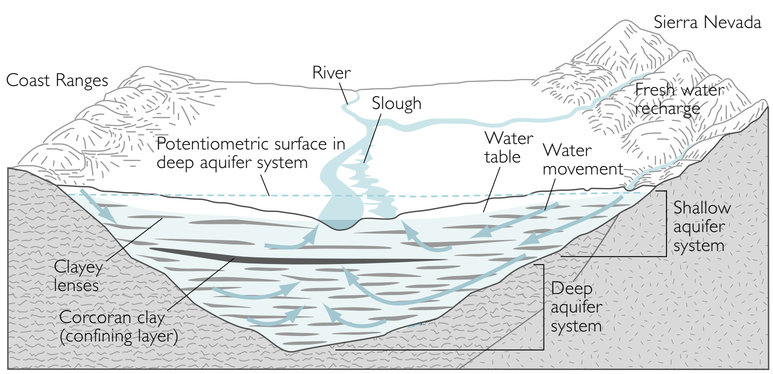
Ground water occurs in shallow, unconfined (water table) or partially-confined aquifers throughout the valley. Such aquifers are particularly important near the margins of the valley and near the toes of younger alluvial fans. A laterally extensive lacustrine clay known as the Corcoran Clay is distributed 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

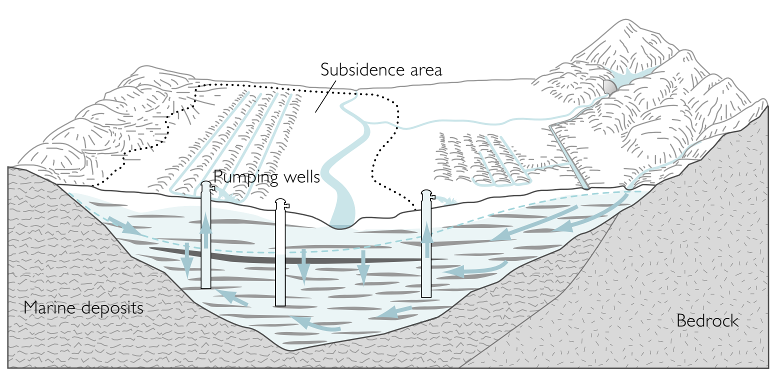
PREDEVELOPMENT

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.



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)

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.

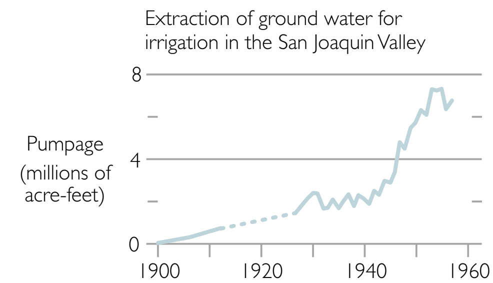
A STABLE WATER SUPPLY IS DEVELOPED FOR IRRIGATION

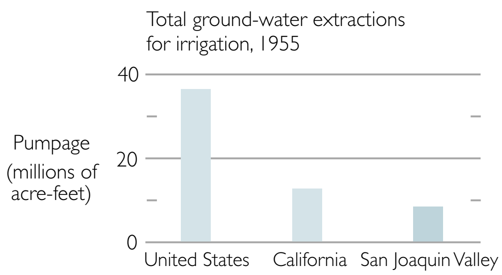
In the San Joaquin Valley, irrigated agriculture surged after the 1849 Gold Rush and again in 1857, when the California Legislature passed an act that promoted the drainage and reclamation of river-bottom lands (Manning, 1967). By 1900, much of the flow of the Kern River and the entire flow of the Kings River had been diverted through canals and ditches to irrigate lands throughout the southern part of the valley (Nady and Larragueta, 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)



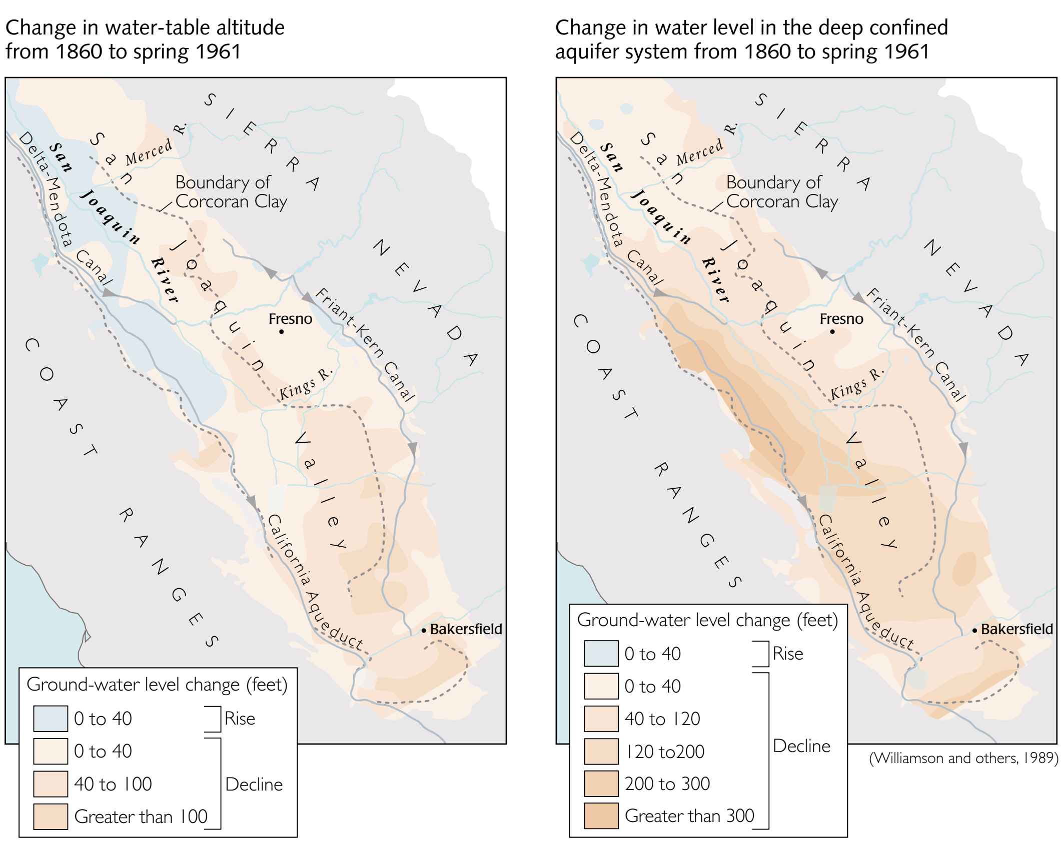


(Joseph F. Poland, U.S. Geological Survey, written communication, ca 1957)

WATER WITHDRAWAL CAUSED LAND SUBSIDENCE

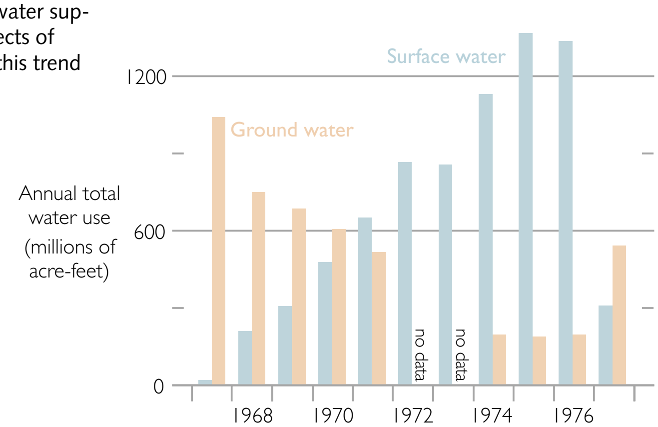
Shortly after the completion of the Delta-Mendota Canal by the U.S. Bureau of Reclamation in 1951, subsidence caused by withdrawal of ground water in the northern San Joaquin Valley had begun to raise concerns, largely because of the impending threat to the canal and the specter of remedial repairs. 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-

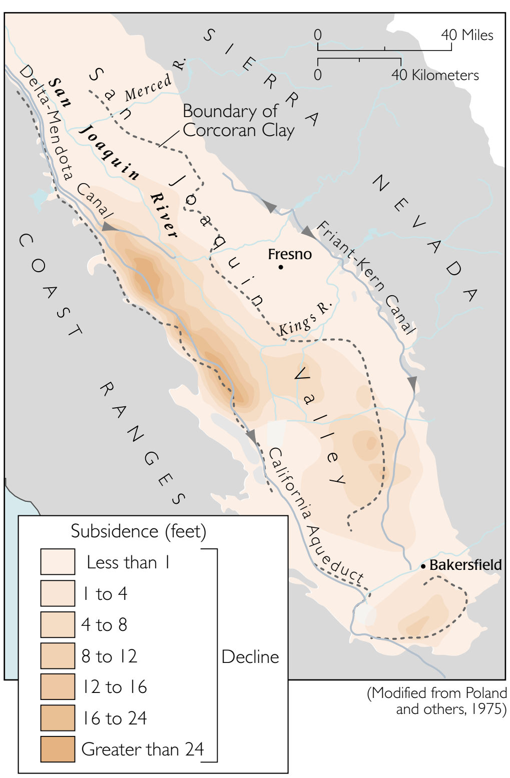


(Williamson and others, 1989)

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.



Land subsidence from 1926 to 1970



(Modified from Poland and others, 1975)

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

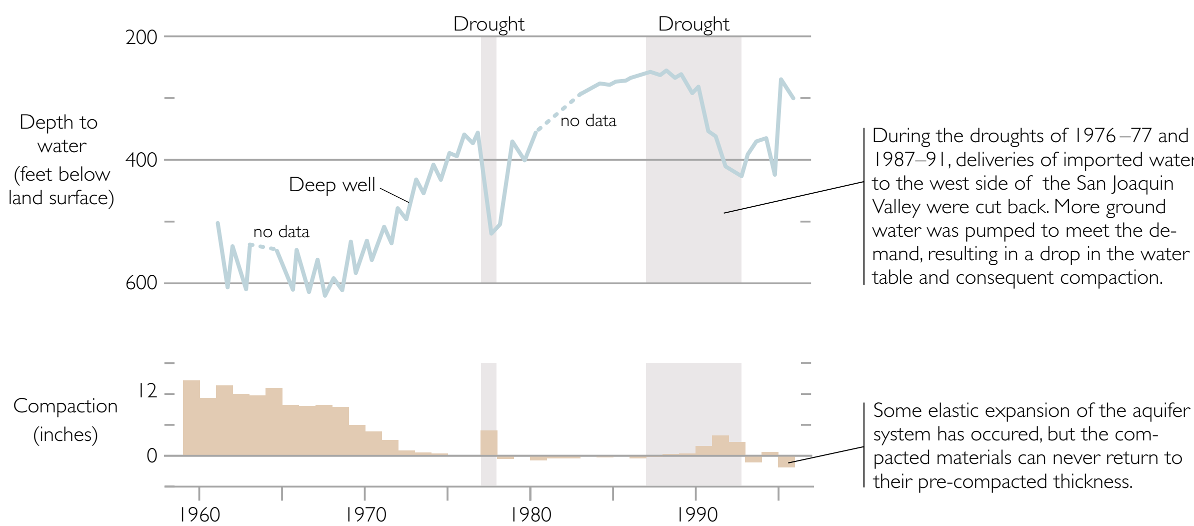
To supplement local ground-water supplies, the California Aqueduct (left) conveys water from the Delta to the dry southern valleys.

(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. . . ."

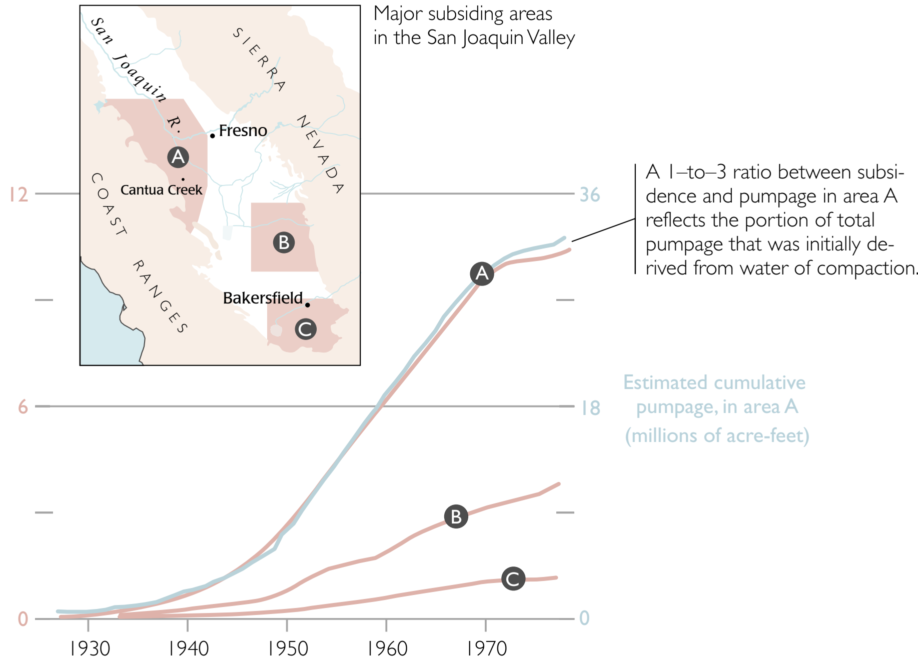
Since 1974, land subsidence has been greatly slowed or largely arrested but remains poised to resume. In fact, during the severe

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



(Modified from Swanson, 1998)

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



(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).