Case History No. 9.13. San Joaquin Valley, California, U.S.A., by Joseph F. Poland, U.S. Geological Survey, Sacramento, California, and Ben E. Lofgren, Woodward-Clyde Consultants, San Francisco, California

9.13.1 INTRODUCTION

The principal areas of land subsidence due to ground-water withdrawal in California are in the San Joaquin Valley and the Santa Clara Valley (Figure 9.13.1). A case history for the Santa Clara Valley is included elsewhere in this publication. In the San Joaquin Valley, subsidence due to ground-water withdrawal occurs in three areas--the Los Banos-Kettleman City area on the central west side, the Tulare-Wasco area on the southeast border, and the Arvin-Maricopa area at the south end (Figure 9.13.1).

Since 1956, the U.S. Geological Survey has carried on two investigative programmes in the San Joaquin Valley. One, a study of land subsidence, was carried on in cooperation with the California Department of Water Resources. The other, a federally financed research project on the mechanics of aquifer systems, had two major goals: to determine the principles controlling the deformation of aquifer systems in response to change in grain-to-grain load, and to appraise the change in storage characteristics as the systems compact under increased effective stress. During the 20 years of research under these two projects, many of the causes and effects of land subsidence have been documented. Sixteen of the principal reports have been pub-

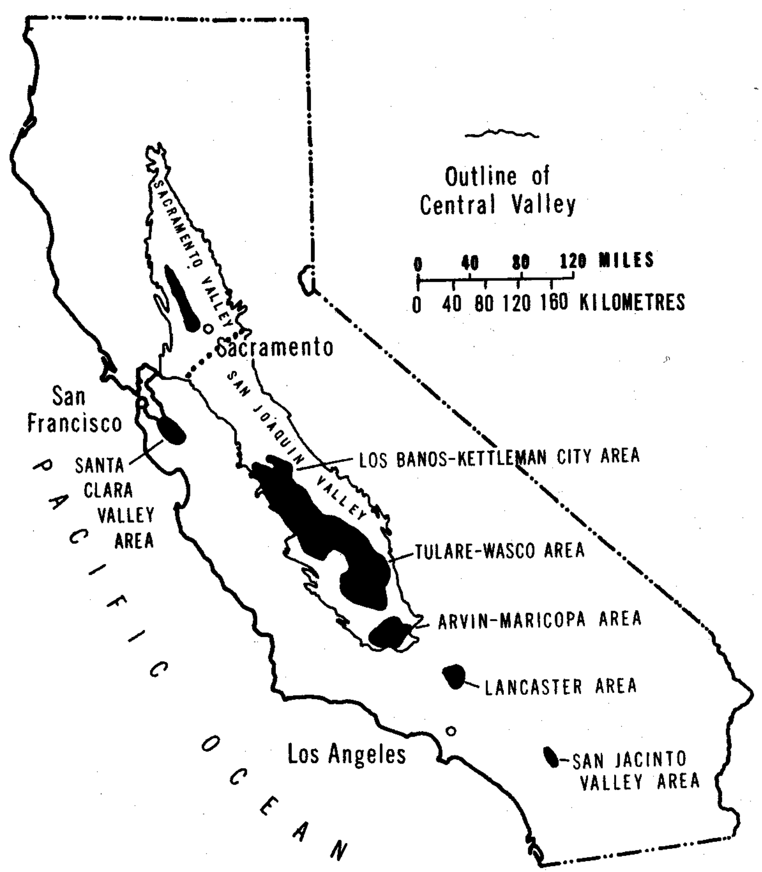

Figure 9.13.1 Areas of land subsidence in California due to ground-water withdrawal.

lished as professional papers of the Geological Survey, the subsidence reports in the Professional Paper 437 series, and the mechanics of aquifer systems papers in the Professional Paper 497 Series. The following case history concerning subsidence in the San Joaquin Valley is taken chiefly from the summary report by Poland, Lofgren, Ireland, and Pugh (U.S. Geol. Survey Prof. Paper 437-H, 1975). More detailed information is available in published reports on the three areas.

9.13.2 GEOLOGY

The San Joaquin Valley includes the southern two-thirds of the Central Valley, an area of 26,000 km^2. It is a broad structural downwarp bordered on the east by the granitic complex of the Sierra Nevada and on the west by the complexly folded and faulted Coast Ranges. The top of the basement complex of the Sierra Nevada block dips gently westward beneath the valley. Late Cenozoic continental deposits form the floor of the valley and attain maximum thickness of 5,000 m near the south edge.

The continental deposits are chiefly of fluvial origin but contain several extensive interbeds of lacustrine origin. The fluvial deposits consist of lenticular bodies of sand and gravel, sand, and silt deposited in stream channels, and sheetlike bodies of silt and clay laid down on flood plains by slow-moving overflow waters.

Along the east side of the valley the sediments deposited by the major streams issuing from the Sierra Nevada--from the Merced River south to the Kings River--have formed a series of coalescing alluvial fans, characterized by a mass of coarse permeable deposits, largely tongues and lenses of sand and gravel, that extend to and beyond the topographic trough of the valley.

In more than half of the San Joaquin Valley area that lies south of Los Banos, the deposits containing freshwater can be divided into: (1) an upper unit of clay, silt, sand, and gravel chiefly alluvial-fan and flood-plain deposits of heterogeneous character, (2) a middle unit consisting of a relatively impermeable diatomaceous lacustrine clay; and (3) a lower unit of clay, silt, sand, and some gravel, in part lacustrine deposits, that extends down to the beds containing saline water. The upper and middle units are Pleistocene age; the lower unit is of Pleistocene and Pliocene age. Together, these three units approximately constitute the Tulare Formation. The middle unit is the Corcoran Clay Member of the Tulare Formation (Miller, Green, and Davis, 1971).

9.13.3 HYDROLOGY

The continental freshwater-bearing deposits can be subdivided into two principal hydrologic units. The upper unit, a semiconfined aquifer system with a water table, also termed the "upper water-bearing zone," extends from the land surface to the top of the Corcoran Clay Member at a depth ranging from 0 to 275 m below the land surface. The lower unit, a confined aquifer system, also termed the "lower water-bearing zone," extends from the base of the Corcoran Clay Member down to the saline water body. The thickness of this confined system ranges from 60 to more than 600 m. The Corcoran Clay Member, which ranges in thickness from 0 to 40 m, is the principal confining bed beneath at least 13,000 km^2 of the San Joaquin Valley. The dotted line in Figure 9.13.2 defines the general extent of this principal confining bed in the valley. South of Bakersfield the confining bed has been designated the E clay by Croft (1972).

Yearly extraction of ground water for irrigation in the San Joaquin Valley increased slowly from 2,500 hm^3 in the middle 1920’s to 3,700 hm^3 in 1940. Then, during World War II and the following two decades, the rate of extraction increased more than threefold to furnish irrigation water to rapidly expanding agricultural demands. By 1966, pumpage of ground water was 12,000 hm^3 per year.

This very large withdrawal caused substantial overdraft on the central west side and in much of the southern part of the valley, mostly within the shaded area of Figure 9.13.2. The withdrawal in these overdraft areas in the 1950’s and early sixties was at least 5,000 hm^3 per year. During the period of long-continued excessive withdrawal, the head (potentiometric surface) in the confined aquifer system between Los Banos and Wasco was drawn down 60 to 180 M. South of Bakersfield the head decline was more than 100 m.

Importation of surface water to these areas of serious overdraft began in 1950 when water from the San Joaquin River was brought south through the Friant-Kern Canal, which extends to the Kern River (Figure 9.13.2).About 80 per cent of the average annual deliveries of 1,250

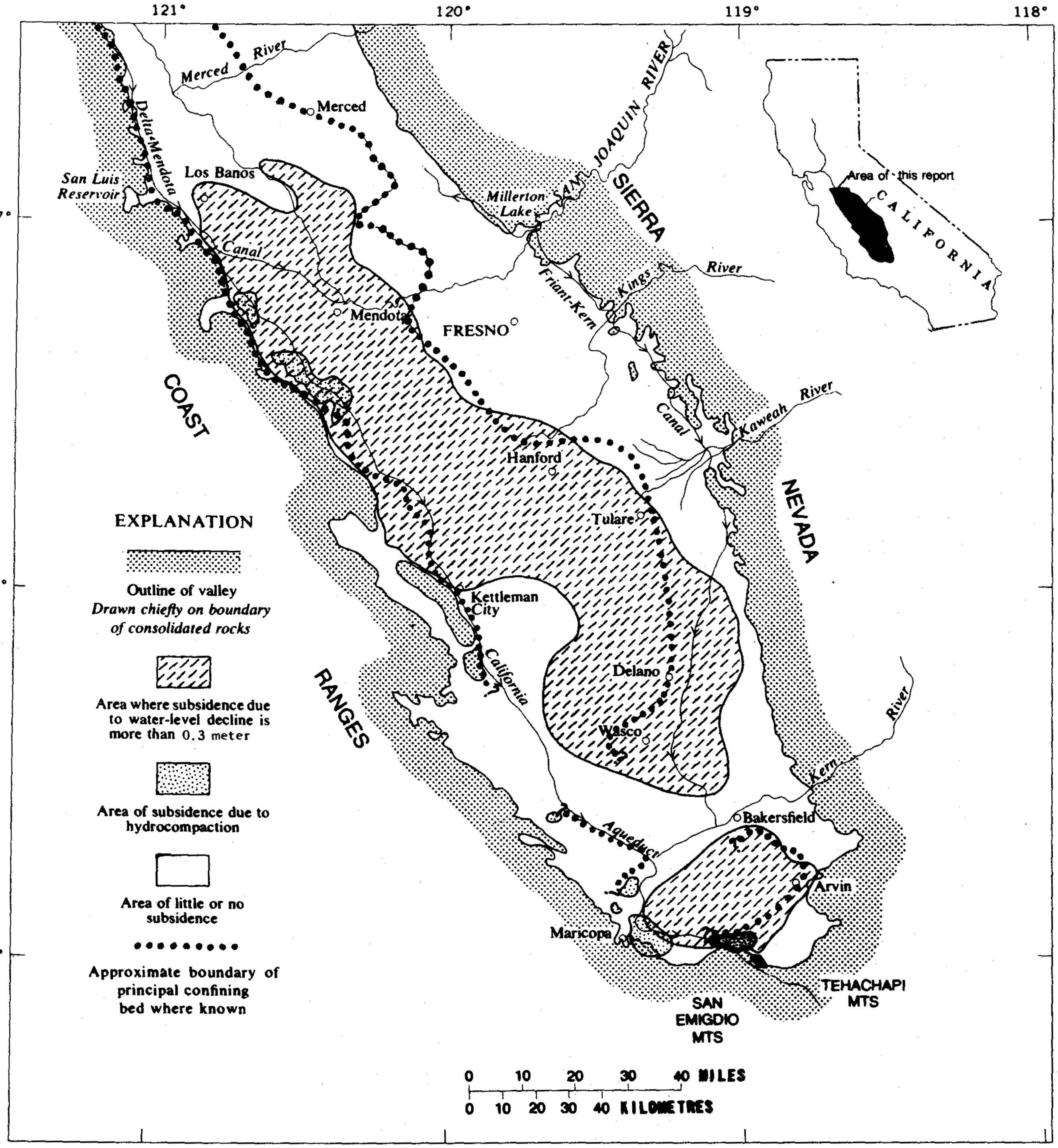

Figure 9.13.2 Pertinent geographic features of central and southern San Joaquin Valley and areas affected by subsidence.

hm^3 of water from this canal is sold to irrigation districts south of the Kaweah River, mostly in the Tulare-Wasco subsidence area.

Large surface-water imports from the northern part of the state to overdrawn areas on the west side and south end of the valley are being supplied through the California Aqueduct (Figure 9.13.2). The joint-use segment of the aqueduct between Los Banos and Kettleman City serves the San Luis project area of the U.S. Bureau of Reclamation and transports State-owned water south of Kettleman City. Surface-water deliveries to the San Luis project area increased from 250 hm^3 in 1968, the first year, to about 1,360 hm^3 in 1974. Also, by 1973 the California Aqueduct delivered 860 hm^3 to the southern part of the San Joaquin Valley (south of Kettleman City), and is scheduled eventually to supply 1,670 hm^3 under long-term contracts.

As a result of these large surface-water imports, the rate of ground-water withdrawal decreased sharply and the decline of artesian head was reversed in most of the areas of overdraft. By the early 1970’s many hundreds of irrigation wells were unused, artesian heads were recovering at a rapid rate, and rates of subsidence were sharply reduced.

9.13.4 LAND SUBSIDENCE

Subsidence in the San Joaquin Valley is of three types. In descending order of importance these are (1) subsidence due to the compaction of aquifer systems caused by the excessive withdrawal of ground water; (2) subsidence due to the compaction of moisture-deficient deposits when water is first applied--a process known as hydrocompaction; and (3) local subsidence caused by the extraction of fluids from several oil fields.

Oil-field subsidence is due to the same process as subsidence caused by excessive pumping of ground water--a lowering of fluid level and consequent increase of effective stress on the sediments within and adjacent to the producing beds. However, measured oil-field subsidence in the San Joaquin Valley, which has been discussed briefly by Lofgren (1975), is less than 0.6 m at the few oil fields where periodic releveling has defined its magnitude. This type of subsidence has not created any problems in the valley.

Hydrocompactible deposits occur locally on the west and south flanks of the valley (see Figure 9.13.2). These are near-surface alluvial-fan deposits, largely mud flows, still above the water table. They have been moisture deficient ever since deposition, chiefly because of the low rainfall in the area. When water is first applied, the clay bond is weakened and the deposits compact. Subsidence of 1.5 to 3 m is common and locally it exceeds 4.5 m (Lofgren, 1960; Bull, 1964). The California Aqueduct (Figure 9.13-2) passes through at least 65 km of deposits susceptible to hydrocompaction, and precompaction by prolonged wetting of the aqueduct alinement was carried on for about one year prior to the placing of the concrete lining.

Subsidence due to the compaction of aquifer systems in response to excessive decline of water levels had affected about 13,500 km^2 of the San Joaquin Valley by 1970. Figure 9.13.3 depicts the distribution and magnitude of subsidence exceeding 1 foot (0.3 m) that had occurred by 1970--affecting an area of 11,100 km^2. Three centers of subsidence are conspicuous on this map. The most conspicuous is the long narrow trough west of Fresno that extends 140 km from Los Banos to Kettleman City (referred to subsequently as the west-side area). Maximum subsidence in this area to 1977 was 29.5 feet (9.0 m), 16 km west of Mendota. The second center, between Tulare and Wasco, is defined by two closed 12-foot (3.7-m) lines of equal subsidence, 32 and 48 km south of Tulare, respectively. Maximum subsidence to 1970 was 4.3 m, at a benchmark 32 km south of Tulare. The third center, 32 km south of Bakersfield, has subsided a maximum of 9.2 feet (2-8 m), mostly since World War II. Note that the California Aqueduct was constructed through the full 140 km of the subsidence trough extending from Los Banos to Kettleman City, as well as through the southwestern edge of the subsidence bowl south of Bakersfield.

The cumulative volume of subsidence in the San Joaquin Valley (Figure 9.13.4) grew slowly until the end of World War II. With the great increase in ground-water extraction in the 1940’s and 1950’s, however, the cumulative volume of subsidence soared to 12,350 hm^3 by 1960, and reached 19,250 hm^3 by 1970. This very large volume is equal to one-half the initial storage capacity of Lake Mead or to the total discharge from all water wells in the San Joaquin Valley for 1.5 years at the 1966 rate. This volume of subsidence represents water of compaction derived almost wholly from compaction of the fine-grained highly compressible clayey interbeds (aquitards), in response to the increase in effective stress as artesian head in the confined system declined. The volume of subsidence for any interval of leveling control was obtained by planimetry of the subsidence map for that period. All leveling data used in the preparation of subsidence maps and graphs were by the National Geodetic Survey (formerly the Coast and Geodetic Survey).

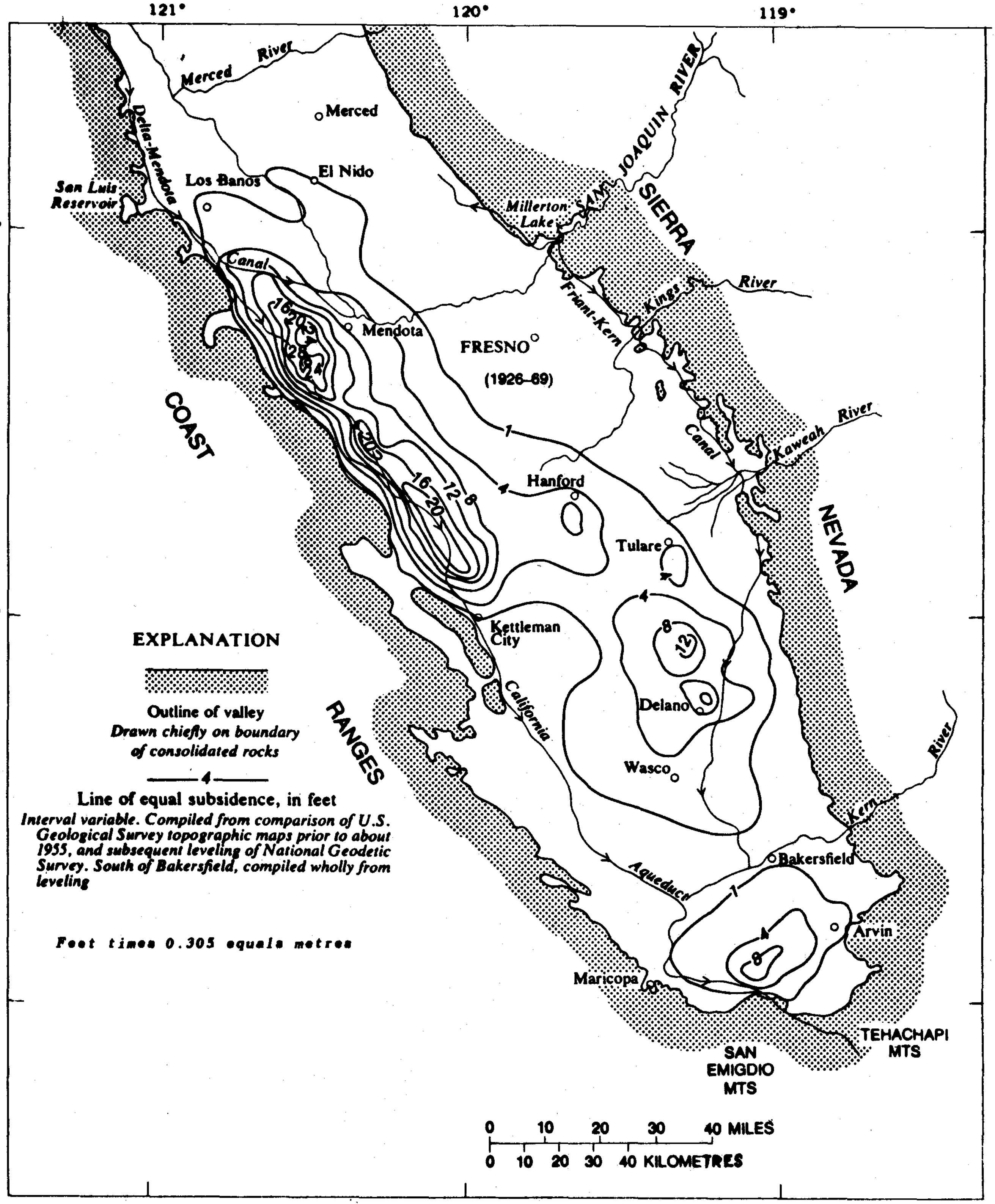

Figure 9.13.3 Land subsidence in the San Joaquin Valley, California, 1926-1970.

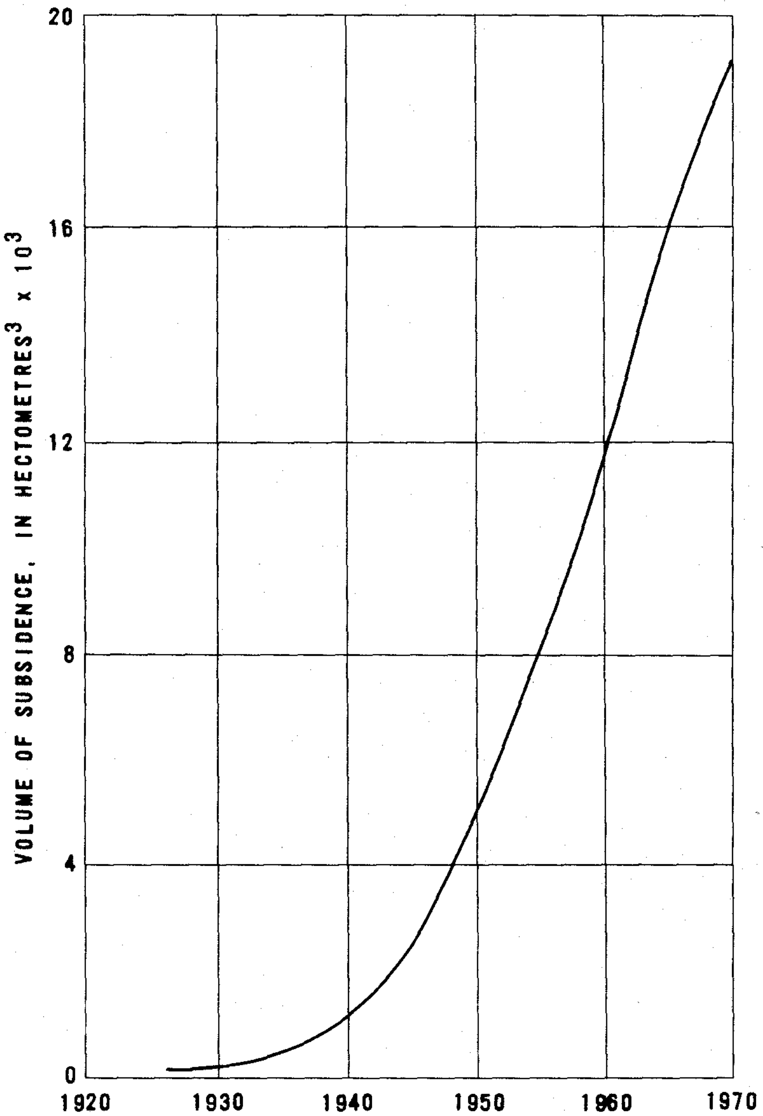

Figure 9.13.4 Cumulative volume of subsidence, San Joaquin Valley, California, 1926-70.

The west-side area has experienced the most severe subsidence (Figure 9.13.5); therefore several illustrations will be presented to show the relation between water-level change (stress change) and compaction or subsidence in that area. Subsidence has affected about 6,200 km^2 and the volume of subsidence, 1926-69, was about 11,850 hm^3, about two-thirds of the valley total. The cumulative volume of ground-water pumpage in the west-side area through March 1969 is estimated as 35,200 hm^3 (Figure 9.13.6). This cumulative pumpage has been plotted with cumulative subsidence at a scale of 3 to 1. The correlation is remarkably consistent, indicating that throughout the 43 years since subsidence began (1926 into 1969), about one-third of the water pumped has been water of compaction derived from the permanent reduction of pore space in the fine-grained compressible aquitards.

Figure 9.13.7 illustrates the relation of subsidence to artesian-head change since 1943 at a site 16 km southwest of Mendota. Bench mark S661, located within the 28-foot (8.5-m) line of equal subsidence in Figure 9.13.5, subsided 8 m from 1943 to 1969, in response to a water-level decline of nearly 125 m as measured in nearby wells. The rate of subsidence at this site reached a maximum of 0.54 m per year between 1953 and 1955 but decreased to 0.04 m per year between 1972 and 1975, due chiefly to substantial recovery of artesian head. Static water level began to recover in 1969 and by 1977 had risen 73 m above the 1968 summer low level because of

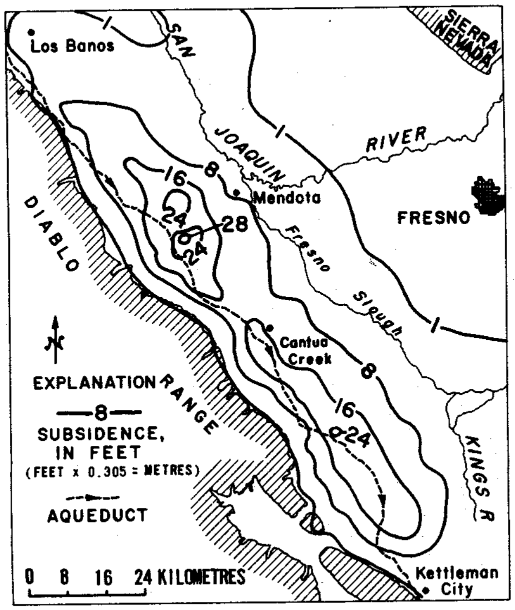

Figure 9.13.5 Land subsidence in the Los Banos-Kettleman City area, California, 1926-69.

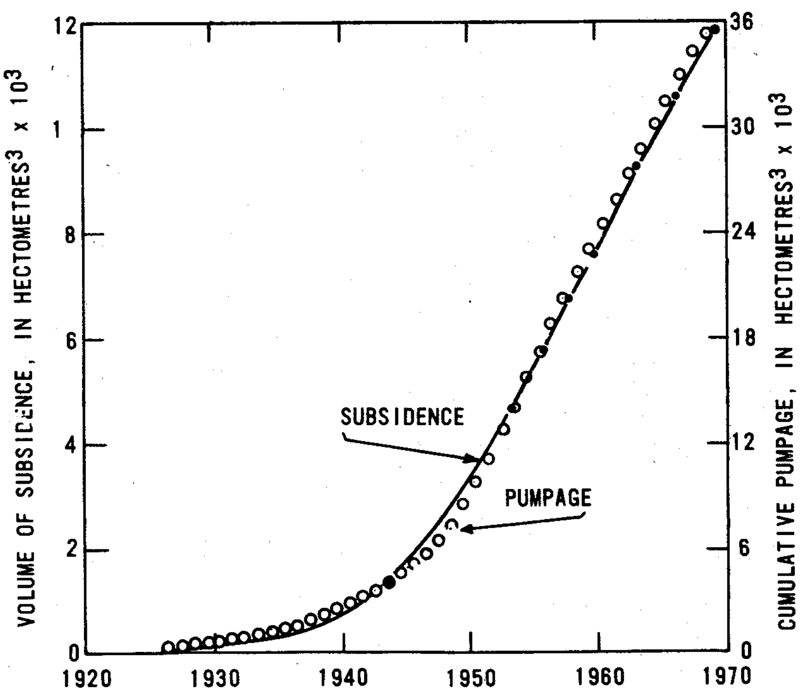

Figure 9.13.6 Cumulative volume of subsidence and pumpage, Los Banos-Kettleman City area, California. Points on subsidence curve indicate times of leveling control.

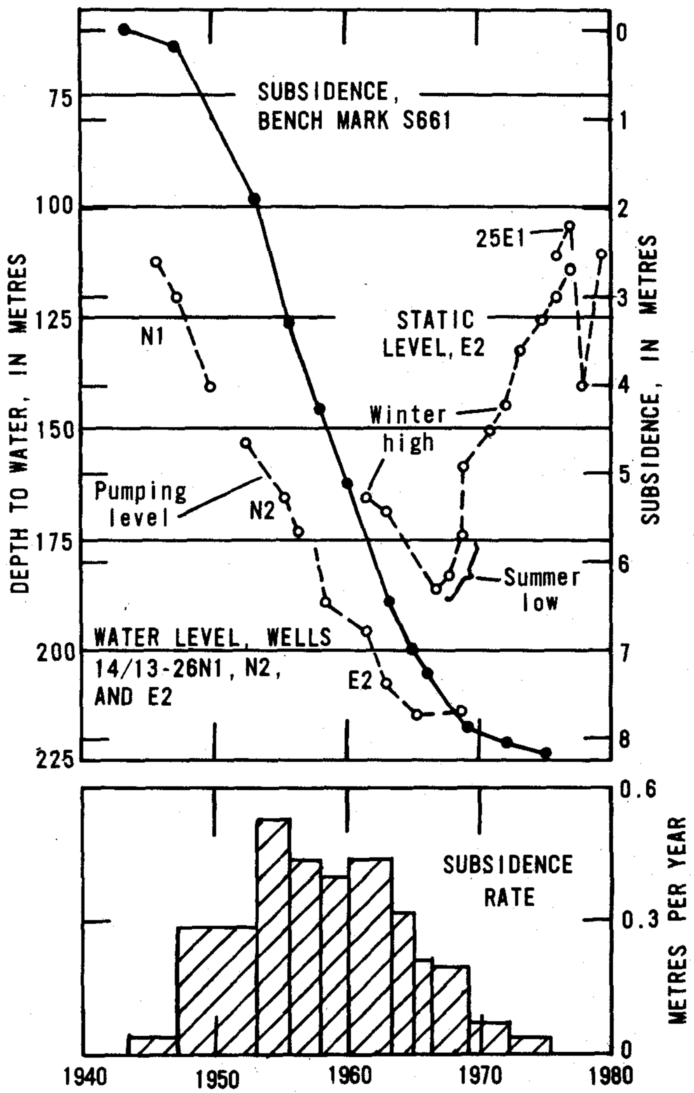

Figure 9.13.7 Subsidence and artesian-head change 16 kilometres southwest of Mendota.

the large imports of surface water through the California Aqueduct and the consequent reduction in pumpage.

If two or more extensometers (compaction recorders) are installed in adjacent wells of different depths, the records from the multiple-depth installation will indicate the magnitude and rate of compaction (or expansion), not only within the total depths of individual wells but also for the depth intervals between well bottoms. Figure 9.13.8 shows the record of compaction from 1958 through 1971 in three adjacent extensometer wells in the west-side area. The site is adjacent to the California Aqueduct at the north end of the southern 16-foot (4.9-m) line of equal subsidence in Figure 9.13.5. The wells are 152, 213, and 610 m deep. Measured compaction in the 13 years was about 0.42 m, 0.97 m, and 3.40 m, respectively. Thus the compaction in the 213-610-m depth interval was 2.43 m. The dashed line represents subsidence of a surface bench mark at this site as determined by repeated leveling from stable bench marks (black dotes on the dashed line show dates of leveling). In the early 1960's the rate of compaction measured in the 610-m well (Nl) was nearly equal to the rate of subsidence. Subsequently the rate of compaction of deposits below the 610-m depth gradually increased, due to increased pumping and declining pore pressures in deeper wells drilled in the 1960's. This deeper compaction caused the departure of the subsidence plot from the compaction plot for well Nl.

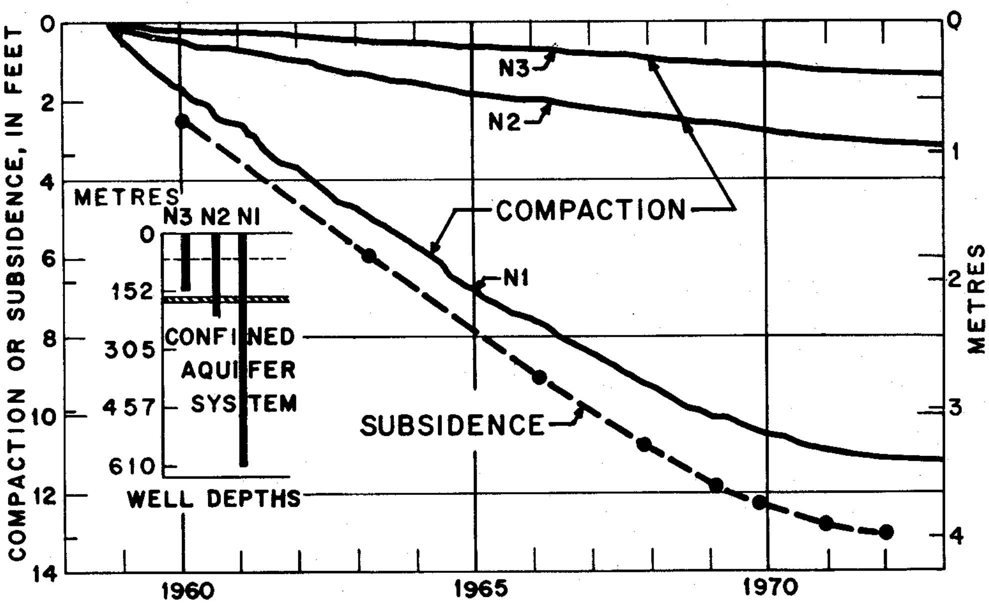

Figure 9.13.8 Compaction and subsidence at Cantua site, 65 kilometres southwest of Fresno, California.

9.13.5 COMPRESSIBILITY AND STORAGE PARAMETERS

In the late 1950's, as one phase of the research on land subsidence and compaction of aquifer sytems, the Geological Survey drilled four core holes in the Los Banos-Kettleman City (west side) area ranging in depth from 305 to 670 m, and two core holes in the Tulare-Wasco area to depths of 232 and 670 m. Cores were tested in the Hydrologic Laboratory for particle-size distribution, specific gravity of solids, dry unit weight, porosity and void ratio, hydraulic conductivity (normal and parallel to bedding) and Atterberg limits. Results have been published (Johnson, Moston, and Morris, 1968). X-ray diffraction studies of 85 samples from the westside cores and 26 samples from the Tulare-Wasco cores indicated that about 70 per cent of the clay-mineral assemblage in these deposits of Pliocene to Holocene age consists of montmorillonite (Meade, 1967, Tables 11-13).

Laboratory consolidation tests were made by the Bureau of Reclamation on 60 fine-grained cores from the four core holes in the west-side area and on 22 fine-grained cores from the two core holes in the Tulare-Wasco area. Parameters tested included the compression index, C_c, a measure of the compressibility of the sample, and the coefficient of consolidation, C_v, a measure of the time-rate of consolidation. Results have been published (Johnson and others, 1968, Tables 8 and 9). The range of the compression index, C_c, was much wider than for samples from the Santa Clara Valley: In the Los Banos-Kettleman City area the range was 0.09 to 1.13; in the Tulare-Wasco area it was 0.25 to 1.53. However, all values greater than 0.47 were either from lacustrine clays or from the fine-grained marine siltstone in the Richgrove core hole 12 km east of Delano.

The subsidence volume represents pore-space reduction occurring chiefly in the fine-grained compressible aquitards. In the west-side area, the volume of subsidence from 1926 to 1969 was about 11,850 hm^3, distributed over 6,200 km^2. If the subsidence had been distributed evenly over this area, it would average about 1.9 m. Roughly half the sediments in the principal aquifer system are fine-grained compressible aquitards. Assuming the average composite thickness of the compacting aquitard is 150 m and the average initial porosity is 40 per cent, a mean subsidence of 1.9 m would represent an average reduction in porosity of roughly 1 per cent in these fine-grained beds (from 40 to 39.2 per cent) - In the small area where the maximum 8.8 m of subsidence has occurred, the local reduction in pore space of aquitards would be roughly 4 per cent (from 40 to 36.3 per cent).

The subsidence/head-decline ratio (specific subsidence) is the ratio between land subsidence and the hydraulic head decline in the coarse-grained permeable beds of the compacting aquifer system, for a common time interval. It can be expressed as the change in thickness per unit change in effective stress (Δb/Δp′). This ratio is useful as a first approximation of compressibility; it is also useful for predicting a lower limit for the magnitude of subsidence in response to a step increase in virgin stress (stress greater than past maximum). If pore pressures in the fine-grained aquitards were eventually to reach equilibrium with those in adjacent aquifers after a step increase beyond preconsolidation stress, compaction would cease and the subsidence/head-decline ratio would indicate the true virgin compressibility of the system.

In the west-side area during the period 1943-60 the decline of artesian head for the lower zone ranged from 30 to 120 m (Bull and Poland, 1975, Figure 25), resulting in subsidence in the 17-year period of 0.3 to 4.9 m (Bull, 1975, Figure 10). The subsidence/head-decline ratio for that same period ranged areally from 0.01 to 0.08 (Bull and Poland, 1975, Figure 32). In other words, the head decline required to produce 1 metre of subsidence ranged from 100 to 12 m. A subsidence/head-decline ratio can be derived from Figure 9.13.7 for the period 1947 to 1965. In the 18 years, bench mark S661 subsided 6.86 m, and the pumping level in nearby wells declined 95 m. Thus, for that time span the ratio at that site equaled 0.07.

In the Tulare-Wasco area, the subsidence/head-decline ratio ranged from 0.01 to 0.06 (Lofgren and Klausing, 1969, Figure 69). In the Arvin-Maricopa area, the subsidence/head-decline ratio for the 8-year period 1957-65 ranged from 0.01 to 0.05 (Lofgren, 1975, Plate 5B).

Areal variation in the subsidence/head-decline ratio can be produced by one or more of several factors. These include variation in the individual, and gross aggregate thickness of the compacting aquitards and variation in compressibility and vertical hydraulic conductivity of the individual aquitards. Such areal variation in compressibility and hydraulic conductivity can be caused by variation in grain size, in depth of compacting beds (in overburden load), in geologic formation tapped, in existing preconsolidation stress, in clay-mineral assemblage, and in other diagenetic effects. Furthermore, because the subsidence values available for computing the ratio seldom represent ultimate subsidence for a designated change in stress within aquifers, time is an important factor. According to soil-consolidation theory, the time required for an aquitard that is draining to adjacent aquifers to reach a specified percentage of ultimate compaction varies directly as (1) the square of the draining thickness and (2) the ratio of compressibility to vertical hydraulic conductivity. Variation in the thicknesses of the many vertical-draining aquitards encountered at any selected site obviously makes that site unique in its rate of compaction, even if all other factors are equal. In the depth interval 214 to 610 m at west-side well 16/15-34N1, for example, interpretation of the microlog defined 60 aquitards ranging in thickness from 0.6 m to 15 m and averaging 4.5 m.

One other factor directly affecting the accuracy of the subsidence/head-decline ratio is the appropriateness or the accuracy of the change-in-stress value used. Even in a ground-water basin containing a single confined aquifer system it is difficult to obtain measurements of head change that truly represent the average stress change on aquitard boundaries within the full well-depth interval experiencing a measured compaction or subsidence. Thus, observation wells used to derive stress-change values, whether for subsidence/head-change ratios or for stress-strain plots, should be selected or constructed very carefully.

Bull (1975, p. 49-82) made a study of geologic factors that caused areal differences in specific unit compaction in the Los Banos-Kettleman City area for the period 1943-60. The factors included total applied stress, lithofacies, and source and mode of deposition.

Field measurements of compaction or expansion of sediments and the correlative change in fluid pressure(s) can be utilized to construct stress-strain curves and to derive storage and compressibility parameters. One example (Figure 9.13.9) is for a well 176 m deep on the west

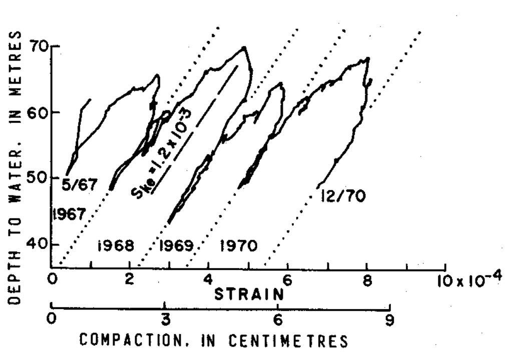

Figure 9.13.9 Stress change, compaction, and strain for a well in western Fresno County, California.

side of the valley. Depth to water is plotted increasing upward (increasing stress). Change in depth to water represents change in effective stress in the aquifers in the confined aquifer system (upper zone) that is 106 m thick. Along the abscissa the lower scale is the measured compaction and the upper scale is the strain (measured compaction/compacting thickness). The yearly fluctuation of water level caused by the seasonal irrigation demand and the permanent compaction that occurs each summer during the heavy pumping season when the depth to water is greatest produce a series of stress-strain loops. The lower parts of the descending segments of the annual loops for the three winters 1967-68 to 1969-70 are approximately parallel straight lines, indicating that the response is essentially elastic in both aquifers and aquitards when the depth to water is less than about 55 m. The heavy dashed line in the 1968 loop represents the average slope of the segments in the elastic range of stress. The reciprocal of the slope of the line is the component of the storage coefficient due to deformation of the aquifer-system skeleton, S_{ke}, and equals 1.2 x 10^{-3}. The component of average specific storage due to elastic deformation, S_{ske}, equals S_{ke}/106 m = 1.1 x $10^{-5}m^{-1}$. The average elastic compressibility of the aquifer system skeleton, α_{ke}, is S_{ske}/γ_w,; if γ_w, (the unit weight of water) equals 1, the numerical values Of α_{ke} and S_{ske} are identical.

For increase in effective stress in the range of loading exceeding preconsolidation stress, the "virgin" compaction of aquitards is chiefly inelastic--nonrecoverable upon decrease in stress. At Pixley, 27 km south of Tulare (Figure 9.13.3), compaction and change in stress for a confined aquifer system 108-231 m below land surface has been measured since 1958. Riley (1969) showed from a stress-strain plot that the mean virgin compressibility of the aquitards (aggregate thickness 75 m) in this confined aquifer segment 123 metres thick was 7.5 x $l0^{-4}m^{-7}$ and the mean elastic compressibility of the aquifer system was 9.3 x $10^{-6}m^{-1}$. Thus, for the aquifer system segment 123 metres thick at this site, the mean virgin compressibility of the aquitards is about 80 times as large as the mean elastic compressibility of the confined system.

Figure 9.13.10 shows a generalized plot of water level for the confined aquifer system 32 km south of Mendota (Figure 9.13.5) from 1905 to 1964 and the seasonal high and low in observation well 16/15-34N4 for 1961-77. This well taps the confined system. The regional water level declined about 120 m from 1905 to 1960 and the rate of decline accelerated as the groundwater withdrawal increased. By 1960 the seasonal low had declined below the base of the confining clay, producing a water-table condition. Surface-water imports to the west-side area began in 1968. As the imports increased, ground-water pumpage decreased and water levels recovered sharply. From 1968 to 1976 the water level at well 34N4 rose 82 metres. Then, during 1977, the second of two severe drought years, the imports decreased to 370 hm^3 and pumping draft from both old and newly drilled wells soared to about three times the 1976 rate. As a result the water level in well 34N4 fell 50 m in the 8 months to August 1977.

The changing stress as indicated by the hydrograph of well 34N4 and the resulting strain at this site as measured by an extensometer in well 34Nl since 1959 are clearly displayed in Figure 9.13.11. Well 16/15-34N1, 610 m deep, is equipped with an anchored-cable extensometer.

A time plot of cumulative measured compaction at this site was introduced earlier (Figure 9.13.8). in Figure 9.13.11, the measured compaction is plotted as an annual bar graph for comparison with the fluctuations of the water level in well N4. Note that the water level in well N4 began a sharp rise late in 1968 as surface-water imports began. In response to the sharp recovery of water level, compaction decreased rapidly after 1968 but did not cease until 1975. During this period of rising water levels in the coarse-grained aquifers, nonrecoverable virgin compaction continued through 1974 in the central parts of the thicker aquitards, exceeding the continuing small elastic expansion of the preconsolidated aquifers and the thinner aquitards. The water level in well N4 reached a seasonal high of 107 m below land surface in November 1976. Early in February 1977, when water level was 112 m below land surface (only 5 m below the seasonal high), virgin compaction resumed in well Nl. By March 30, 1977, when water level was 15 m below the seasonal high, the maximum compaction rate of the season was attained. The early February water level 112 m below land surface clearly defined the preconsolidation stress in the central segments of the thickest or least permeable aquitards or both. As the drawdown increased, more and more of the slow draining compressible beds began to contribute water of compaction. By yearend, about 12 cm of renewed nonrecoverable compaction had occurred.

During the first period of water-level decline (1905-68 in Figure 9.13.10), water of compaction represented about one-third of the total water pumped from west-side wells (Figure 9.13.6). By 1968, many of the aquitards were preconsolidated nearly to the 1968 stress level. Early in the second period of water-level decline (in 1977), the response of the preconsolidated sediments was chiefly elastic and the contribution of water of compaction was much less than one-third of the total pumpage. Hence the water level fell very rapidly.

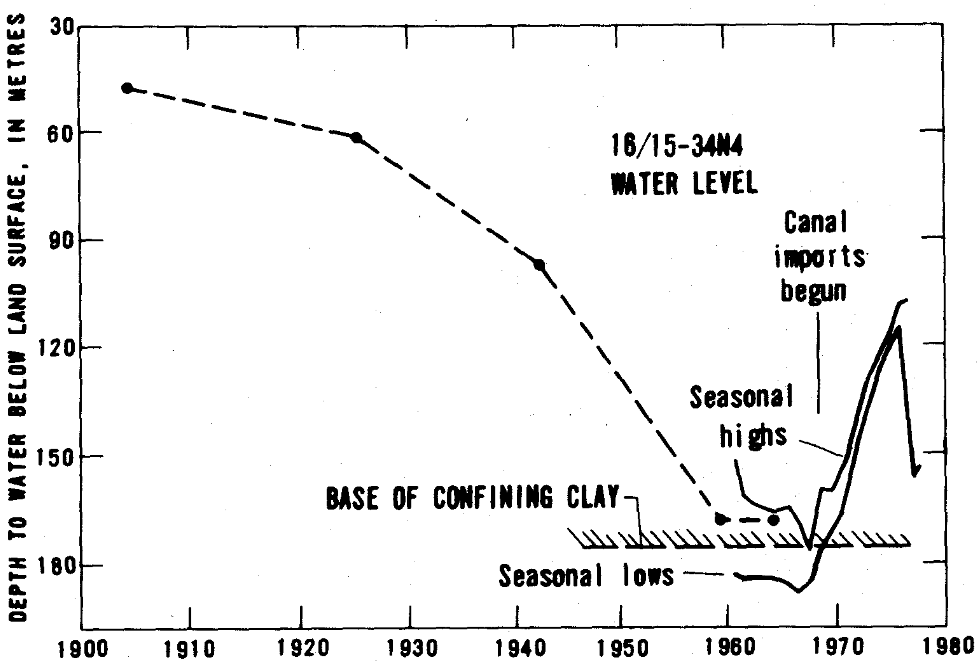

Figure 9.13.10 Long-term trend of water levels near Cantua Creek, and seasonal high and low levels in observation well 16/15-34N4 since 1960. (Modified from Lofgren, 1979,

Figure 9.13.12 displays a similar trend of water-level recovery and reduced compaction, followed by an abrupt head decline and renewed compaction during 1977. Observation well 20/18-6D1 is 25 km north of Kettleman City (Figure 9.13.4) and adjacent to the California Aqueduct. The abrupt head decline of 76 m in 1977 momentarily increased the stress in the aquifers to 1967 levels and stresses in the central parts of the aquitards once again exceeded preconsolidation stresses. In response, virgin compaction of the aquitards exceeded that of 1968. Such stressing and differential compaction in the vicinity of the aqueduct is of concern in sustaining the integrity of such structures. This particular problem appears to be of local extent, however--the intensity of the head decline in well 6Dl is due largely to pumping of a new irrigation well drilled early in 1977 within 60 m of the aqueduct.

9.13.6 ECONOMIC AND SOCIAL IMPACTS

The extensive major subsidence in the San Joaquin Valley has caused several problems. The differential change in elevation of the land surface has created problems in maintenance of water-transport structures, including canals, irrigation and drainage systems, and stream channels. Both the Delta-Mendota Canal and the Friant-Kern Canal (Figure 9.13-3), two major structures of the Central Valley Project of the Bureau of Reclamation, have required remedial work because of subsidence. Also in the period 1926-72, differential subsidence has steepened the channel of the San Joaquin River about 2 m in the 24 km before it reaches the valley trough and has flattened the channel about 2 m in the next 50 km downstream. These changes have affected the transport characteristics of the river and have altered levee requirements.

Another problem common to the subsiding areas in the San Joaquin Valley is the failure of water wells as a result of compressive rupture of casings caused by the compaction of the aquifer systems. In the west-side area, where subsidence has been greatest, many hundreds of deep irrigation wells have required costly repair or replacement. According to Wilson (1968), during 1950-61 approximately 1,200 casing failures were reported in 275 irrigation wells in an area of 1,600 km^2 that spans the region of most intensive subsidence. Well repair and replacement costs attributable to subsidence in the three subsiding areas have been many millions of dollars.

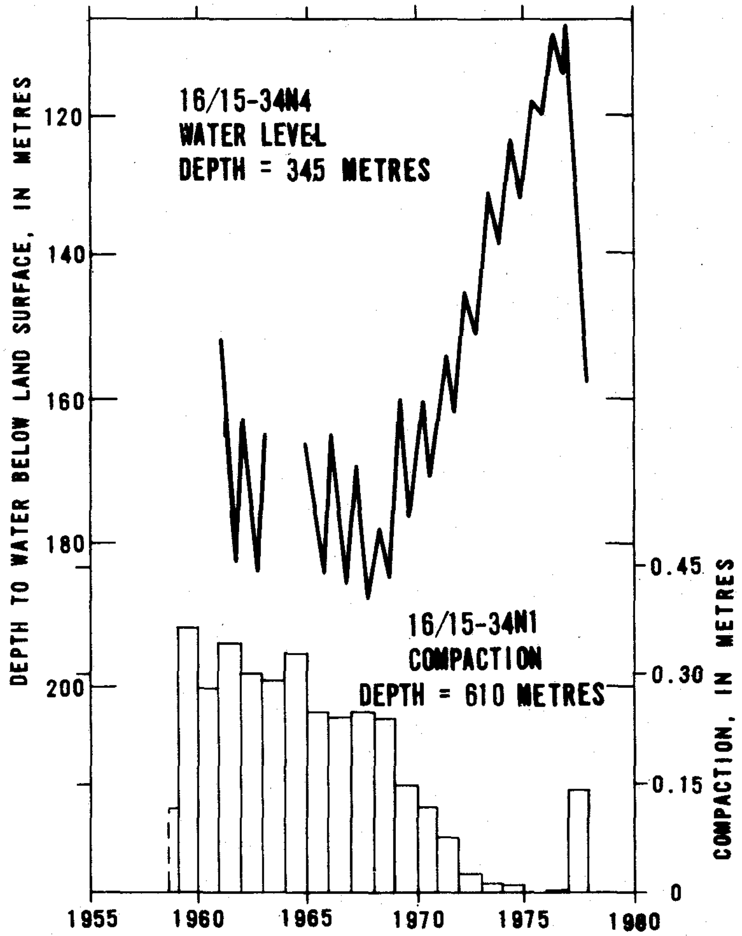

Figure 9.13.11 Seasonal fluctuations of water level in well 16/15-34N4 and measured compaction in observation well 16/15-34N1 near Cantua Creek. (Modified from Lofgren, 1979, Figure 10.)

The need for preconsolidation of deposits susceptible to hydrocompaction substantially increased the construction costs of the California Aqueduct. The aqueduct passes through about 65 km of susceptible deposits. The approximate cost for treatment by prewetting for the reach from Kettleman City to the Tehachapi Mountains has been estimated as $20 million (Lucas and James, 1976, p. 541). Preconsolidation of the susceptible areas between Los Banos and Kettleman City cost an additional estimated $5 million.

The subsidences have increased considerably the number and cost of surveys made by governmental agencies and by private engineering firms to determine the elevations of bench marks or construction sites and to establish grades. In addition, revision of topographic maps has been more frequent and more expensive than in nonsubsiding areas.

9.13.7 LEGAL ASPECTS

So far as known, no legal actions have been taken as a result of the subsidence.

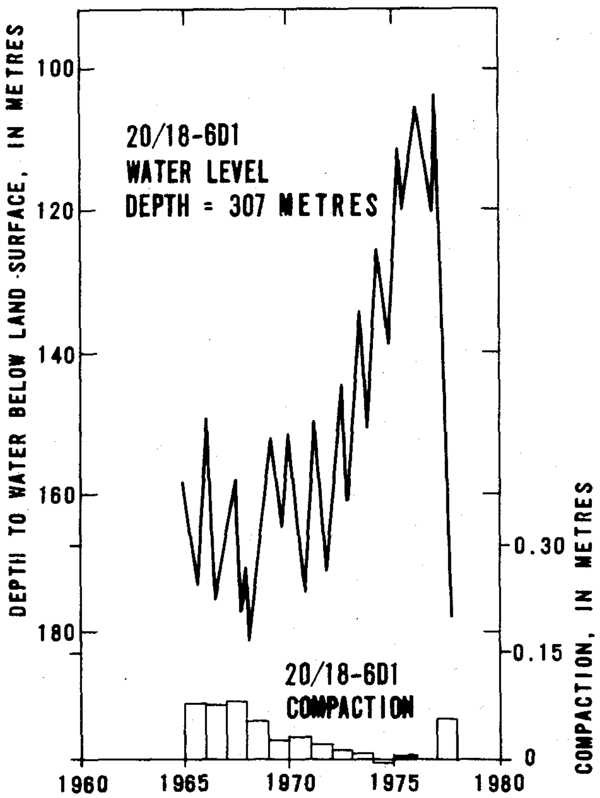

Figure 9.13.12 Seasonal fluctuations of water level and measured compaction in observation well 20/18-6D1 northeast of Huron.

9.13.8 MEASURES TAKEN TO CONTROL OR AMELIORATE SUBSIDENCE

The severe subsidence in all three areas in the San Joaquin Valley has been greatly reduced by the importation of surface water and the consequent decrease in ground-water pumping, as described earlier in this case history.

In the Tulare-Wasco area, the import of surface water from the San Joaquin River through the Friant-Kern Canal began in 1980. In the next 23 years, 1950-1972, the deliveries to this area from the canal averaged about 830 hm^3 per year, roughly 80 per cent of the surface-water supply to the area (Lofgren and Klausing, 1969). In the first 13 years of this period (1950-62), ground-water pumpage averaged about 1,230 hm^3 per year and continued at about this rate into the 1970's. Thus, the water imported from the San Joaquin River to the area during the 23-year period 1950-72 equaled about one-quarter of the total water supply and two-thirds of the ground-water pumpage.

Hydrographs of wells tapping the semiconfined to confined aquifer system in the eastern part of the Tulare-Wasco area show a water-level recovery of about 60 m from 1950 to 1970. As a result, subsidence decreased to less than 3 cm per year in most of the eastern area as 1962-70. On the other hand, hydrographs for wells tapping the confined aquifer system in the western part of the Tulare-Wasco area show continued decline of water levels since the 1950's; the supplemental irrigation supply from the Friant-Kern Canal to the western part has been insufficient to achieve a balance with ground-water pumping. As a result, subsidence has continued at rates locally exceeding 9 cm per year.

In the west-side area, the import of surface water through the California Aqueduct, which began in 1968, soon replaced most of the ground-water pumpage. For example, ground-water pumpage in the west-side area averaged 1,300 hm^3 per year from 1960 to 1967, before the imports began. By 1974, surface water imports to the west-side area reached 1,400 hm^3 per year and pumpage had decreased to roughly 250 hm^3 per year. The great decrease in ground-water pumpage and the consequent recovery of the artesian head in the confined aquifer system have nearly eliminated the subsidence problem for the present. However, any deficiency in surface-water imports could trigger renewed pumping, renewed head decline, and renewed subsidence, as in the severe drought year of 1977.

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