Land Subsidence due to Ground-Water Withdrawal Tulare-Wasco Area California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-B

Prepared in cooperation with the California Department of Water Resources

Land Subsidence due to Ground-Water Withdrawal Tulare-Wasco Area California

By B. E. LOFGREN *and* R. L. KLAUSING

STUDIES OF LAND SUBSIDENCE

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Prepared in cooperation with the California Department of Water Resources

A study of land subsidence caused by water-level changes in complex aquifer systems, including analysis of stresses and appraisal of parameters for estimating subsidence

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CONTENTS

ILLUSTRATIONS

TABLES

GLOSSARY

In the studies of water-bearing deposits that compact sufficiently in response to change in effective stress (caused by changes in water levels) to produce significant land subsidence, certain terms have been used in the literature to cover a broad span of physical conditions and rock units are defined and explained as used for purposes of these studies. In addition, several terms utilized by soil-mechanics engineers and a few terms introduced as a result of the subsidence investigations are defined here for readers who have diverse backgrounds.

The compactible deposits or sediments that have undergone sufficient compaction to produce significant subsidence in California or elsewhere are clastic sediments. The definitions given in this glossary are directed toward this type of sediment; they do not attempt to span the full range of rock types that contain and yield ground water.

In this report, the stresses causing compaction are expressed in equivalent "feet of water" (1 ft of water=0.433 psi). Thus, the unit weight of water, γ_w, equals 1 foot of water. In this glossary, dimensions are listed first in the usual convention, and second in parentheses, with stresses expressed in "feet of water."

Aquiclude. An areally extensive body of saturated but relatively impermeable material that functions as an upper or lower boundary to an aquifer system and does not yield appreciable quantities of water to wells or to adjacent aquifers.

Aquifer. A body of saturated relatively permeable material that conducts significant ground-water flow and is capable of yielding water to wells in economic quantities.

Aquifer system. A heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more interconnected aquifers separated by laterally discontinuous aquitards that locally impede ground-water movement but do not greatly affect the overall hydraulic continuity of the system.

Aquitard. A saturated, but poorly permeable, interbed within an aquifer system that impedes ground-water movement and does not yield freely to wells, but which may transmit appreciable water to or from adjacent aquifers and, where sufficiently thick, may function as an important ground-water storage unit.

Coefficient of volume compressibility. The compression of a clay (aquitard), per unit of original thickness, per unit increase of pressure. Symbol m_v (Terzaghi and Peck, 1948 p. 64).

Dimensions: L^2/F
(L)

Compaction. "Decrease in volume of sediments, as a result of compressive stress, usually resulting from continued deposition above them" (American Geological Institute, 1957, p. 58). In this report, compaction is defined as the decrease in thickness of sediments as a result of increase in vertical compressive stress and is synonomous with "one-dimensional consolidation" as used by engineers. The term "compaction" is applied both to the process and to the measured change in thickness.

In thick fine-grained beds, compaction is a delayed process involving the slow escape of pore water and the gradual transfer of stress from neutral to effective. Until sufficient time has passed for ultimate compaction to occur, measured values of compaction are transient.

Consolidation. In soil mechanics, consolidation is the adjustment of a saturated soil in response to increased load, involving the squeezing of water from the pores and the decrease in void ratio (American Society of Civil Engineers, 1962, p. 85). In this report, the geologic term "compaction" is used in preference to consolidation, except in reporting and discussing results of laboratory consolidation tests made in accordance with soil-mechanics techniques.

Effective pressure or stress. Stress that is transmitted through the grain-to-grain contacts of a deposit and that thus affects its porosity, or void ratio, and other physical properties is called effective stress. Effective stress is the average grain-to-grain load per unit area borne by the granular skeleton of the sediments. Above the water table, the effective stress at any given depth is equal to the weight per unit area of the overlying sediments and their contained moisture. Below the water table, the effective stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight of overlying sediments below the water table, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the sediments.

The total stress, p, normal to any horizontal plane of reference in a saturated deposit can be resolved into two components: a neutral stress, u_w, and an effective stress, p'. Therefore, $p=p'+u_w$ (Terzaghi and Peck, 1948, p. 52.)

In a complex aquifier system containing compressible aquitards, a given decline of head in the aquifers results in an immediate increase in effective stress in the aquifers. Within the aquitards, however, the transfer from neutral to effective stress occurs only as rapidly as drainage from the aquitard takes place. Months or years may be required to reach equilibrium—that is, for the applied stress to become fully effective within the aquitard.

Dimensions: F/L^2
[L(feet of water)]

Geostatic load. The total load of sediments and water above some plane of reference. It is the sum of (1) the unit weight of sediments and moisture above the water table multiplied by their thickness and (2) the unit weight of saturated sediments (solids plus water) below the water table multiplied by their thickness.

Neutral pressure. Pressure produced by the head of water. Hydrostatic pressure does not have a measurable influence on the void ratio or on any other mechanical property of the deposits and is called a neutral pressure. The neutral pressure is equal to the hydraulic head multiplied by the unit weight of water (Terzaghi and Peck, 1948, p. 52), or

$$u_w=\gamma_w \cdot h_w$$

where

u_w=neutral pressure,
γ_w=unit weight of water, and
h_w=hydraulic head.

Neutral pressures are transmitted to the base of the deposit through the pore water.

Dimensions: F/L^2
(L)

Seepage stress. When water flows through a porous medium, energy is transferred from the water to the medium by viscous friction. This energy is equal to the loss of hydraulic head. The force corresponding to this energy transfer is called the seepage force. (See Harr, 1962, p. 23.)

The total seepage force, F, at the base of an aquiclude across which a hydraulic head differential, H, exists, can be expressed as

$$F=H\cdot\gamma_w\cdot A$$

where γ_w equals the unit weight of water and A equals the cross sectional area. The total seepage force per unit area, J, referred to in this report as the seepage stress, is

$$J=\frac{F}{A}=\gamma_w\cdot H$$

Dimensions: F/L²

If γ_w is expressed in feet of water, then

$$J=H$$

(L)

This seepage stress is algebraically additive with gravitational stresses and is transmitted downward through the granular structure of the aquifer system below the aquiclude.

Specific compaction. The ratio between compaction during a specified period of time and the responsible increase in applied stress.

Dimensions: L³/F
(L/L)

Specific rebound. The ratio between rebound and the decrease in applied stress.

Dimensions: L³/F
(L/L)

Specific unit compaction. The ratio between unit compaction (compaction per unit thickness) and the increase in applied stress, which is equal to the increase in effective stress in the coarse-grained beds of the aquifer system. For a given decline of head in the aquifers of a complex aquifer system containing compressible aquitards, ultimate specific unit compaction is attained when pore pressures in the aquitards have reached hydraulic equilibrium with pore pressures in the aquifers; at that time specific unit compaction equals gross compressibility of the system.

Dimensions L²/F
(L/L²)

Specific unit rebound. The ratio between the unit rebound (rebound per unit thickness) and the decrease in applied stress, which is equal to the decrease in effective stress in the coarse-grained beds of the aquifer system.

Dimensions: L²/F
(L/L²)

Subsidence to head-decline ratio. The ratio between land subsidence and the hydraulic head decline in the coarse-grained beds of the compacting aquifer system.

Dimensions: L/L

Unit compaction. The amount of compaction per unit thickness of the compacting deposits. Usually computed as the measured compaction in a given depth interval during a specified period of time divided by the thickness of the interval.

Dimensions: L/L

Unit compaction to head-decline ratio. The ratio between the amount of compaction per unit thickness of the compacting deposits and the head decline in the coarse-grained beds of the compacting aquifer system.

Dimensions: $L/L^2=L^{-1}$

STUDIES OF LAND SUBSIDENCE

LAND SUBSIDENCE DUE TO GROUND-WATER WITHDRAWAL TULARE-WASCO AREA, CALIFORNIA

By B. E. Lofgren and R. L. Klausing [1]

ABSTRACT

Intensive pumping of ground water has caused more than 800 square miles of irrigable land to subside in the Tulare-Wasco area, which is in the southeastern part of the San Joaquin Valley, Calif. Locally, ground-water levels declined as much as 200 feet between 1905 and 1964, and the maximum subsidence was about 12 feet by 1964. Subsidence was due to the compaction of the water-yielding deposits as the intergranular effective stresses increased.

The compacting deposits include a thick sequence of unconsolidated Quaternary continental deposits from the Sierra Nevada and, in the eastern part of the area, semiconsolidated and consolidated upper Pliocene and Pliocene(?) marine strata. Within the continental sequence, a thin lacustrine clay underlying the western half of the area separates a confined aquifer system for an overlying semiconfined aquifer system.

The magnitude and rate of subsidence are directly related to (1) the change in effective stress within the various compacting beds that results from water-level changes and (2) the thickness and compressibility of the compacting deposits. The compressibility of the deposits can be approximated either by testing selected cored samples in the laboratory or by measuring in the field the compaction that results from a given change in effective stress in a subsiding area.

The annual rate of subsidence varies greatly in direct response to seasonal pumping. This rate varied from an average of about 136,000 acre-feet per year from 1948 to 1954, to 45,000 acre-feet per year from 1957 to 1959, and to 173,000 acre-feet per year from 1959 to 1962. During the 13 years from 1950 to 1962, the volume of subsidence (1.40×10^6 acre-ft) was roughly 10 percent of the total ground-water pumpage (13.5×10^6 acre-ft).

Subsidence to head-decline ratios range from about 0.5×10^{-2} foot of subsidence per foot of head decline in outlying areas to more than 5.0×10^{-2} foot of subsidence per foot of head decline where subsidence has been the most intense. This ratio, established during periods of continuing subsidence and water-level decline, is the best means now available of estimating future subsidence.

Subsidence at a given location will continue as long as declining water levels continue to cause increased effective stresses. Subsidence will stop as soon as excess pore pressures in the aquitards are dissipated. In the southeastern part of the Tulare-Wasco area, subsidence was arrested in the late fifties, when water levels recovered as much as 130 feet in response to reduced pumping and increased recharge resulting from importation of water through the Friant-Kern Canal. Additional subsidence caused by lowering of water levels can be kept at a minimum by reducing withdrawal or by wider dispersal of withdrawal wells. Slight rebound of the land surface has been observed in areas of large water-level recovery.

[1] All sections were written by B. E. Lofgren except for those on "Geology" and "Ground water," which were co-authored.

INTRODUCTION

STATEMENT OF PROBLEM

Land subsidence in the San Joaquin Valley, Calif., has been an increasing problem for the past two decades. Most of this subsidence has been attributed to intensive pumping of ground water and to the resultant water-level decline. Ground-water pumpage for irrigation in this valley amounts to about one-fourth of all ground water pumped for irrigation in the continental United States. This intensive withdrawal has developed extensive areas of overdraft, where water-level declines are 100 feet to more than 400 feet in some areas. As a consequence, at least 3,500 square miles in the central and southern parts of the valley has subsided more than a foot. This subsidence is most severe in three major areas (fig. 1): the Los Banos-Kettleman City area on the central west side, the Tulare-Wasco area on the southeast, and the Arvin-Maricopa area at the south end of the valley. As of 1962, maximum subsidence was 23 feet in the Los Banos-Kettleman City area and at least 6 feet in the Arvin-Maricopa area. In the Tulare-Wasco area, as of 1962, 800 square miles had undergone more than 1 foot of subsidence, and as much as 12 feet of subsidence had occurred locally since the first detailed topographic maps were prepared in 1926.

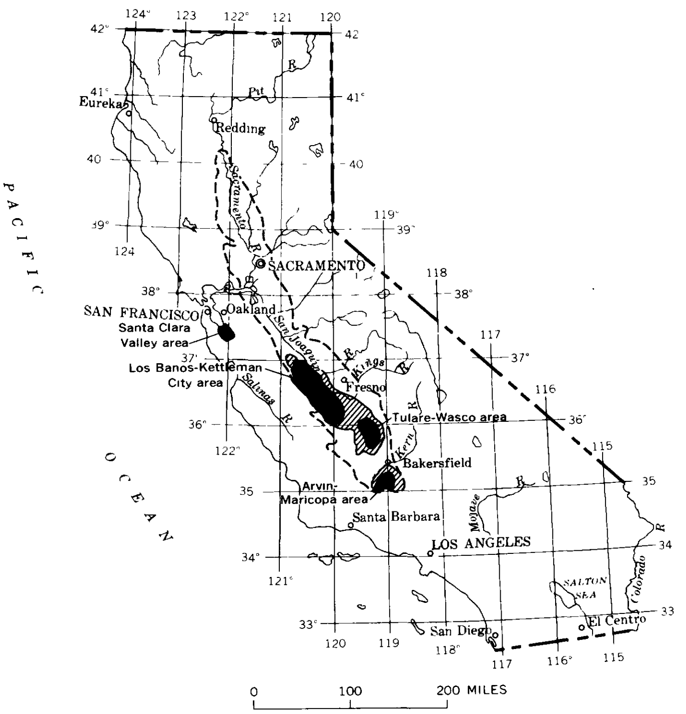

FIGURE 1.—Principal areas in California where ground-water withdrawal has caused land subsidence. Outline of Central Valley dashed; areas of major subsidence shaded black; areas of lesser subsidence hatched.

Although land subsidence has been occurring in the Tulare-Wasco area for more than 40 years and has been recognized by engineers since the late thirties, the causes, the rate and magnitude, and the areal extent of the subsidence have not been clearly understood. Settlement has occurred over such a broad area and so gradually that it has gone unnoticed to most residents. The detrimental and costly effects of subsidence, however, have been of serious concern to design and construction engineers, irrigation districts, and landowners for more than 20 years.

When this investigation was initiated in 1957, the need for an interpretive study of the causes and effects of the land subsidence was readily apparent. Ground-water levels in areas of concentrated pumping had declined more than 200 feet, and the land had subsided more than 10 feet. Already the Friant-Kern Canal, constructed by the U.S. Bureau of Reclamation in the early 1950's on a gentle gradient of less than 0.5 foot per mile, had suffered differential settlement of as much as 2 feet. Water-distribution systems and drainage and flood-control structures were becoming less effective owing to subsidence. Water-well casings were breaking under the compressive stresses imposed by subsidence, and altitudes on topographic maps were out of date before the maps were published. The costly effects of subsidence were of concern to many people and agencies.

LOCATION AND GENERAL FEATURES OF THE AREA

The Tulare-Wasco area is in the southeastern part of the San Joaquin Valley, Calif., north of Bakersfield (fig. 2). It includes roughly 1,500 square miles of intensively farmed land on the gently westward-sloping alluvial plain between the lofty Sierra Nevada on the east and the valley trough on the west.

Designated by cities near its north and south limits, the project area is bounded on the north by the north line of T. 20 S., on the south by the center line of T. 27 S., on the west by a line roughly through the center of R. 22 E. (Dairy Avenue), and on the east by the 119°00′ west longitude line. (See fig. 6.) The area is traversed by U.S. Highway 99, by a network of secondary roads, and by main lines of two major railroads. The cities of Tulare and Delano, with respective 1960 populations of 13,284 and 11,913, are the principal centers of commerce and, with Porterville (7,991), Wasco (6,841), and a dozen smaller communities, serve the social and commercial needs of the dominantly agricultural economy.

The climate of the Tulare-Wasco area is characterized by hot, dry summers and mild winters. Precipitation occurs principally as rain between December and March and averages about 9 inches a year. Occasional violent thunderstorms over local areas of the foothills contribute the only summer rainfall. Summer midday temperatures frequently exceed 100°F, and day and night temperatures may differ by more than 40 degrees.

Water for irrigation in the Tulare-Wasco area is obtained both from surface-water sources and from wells. Irrigation diversions from the Tule, Kaweah, and Kern Rivers and from the Friant-Kern Canal since 1950 constitute the principal surface-water supply (fig. 13). Three secondary streams, Deer Creek, White River, and Poso Creek, also are significant sources of irrigation water. Ground water has been used for irrigation in this part of the valley since about 1885, largely to supplement surface-water supplies. Ground-water withdrawal increased greatly from the 1920's to 1950 and far exceeded the natural and artificial replenishment to the ground-water reservoir until the large import of surface water through the Friant-Kern Canal, beginning in 1950, decreased demand from wells and supplied a new source of replenishment to the ground-water body.

SCOPE OF INVESTIGATION AND PURPOSE OF REPORT

In December 1954, after several preliminary planning conferences, an Inter-Agency Committee on Land Subsidence in the San Joaquin Valley was formed by concerned Federal and State agencies to plan and coordinate subsidence investigations. As one result of the

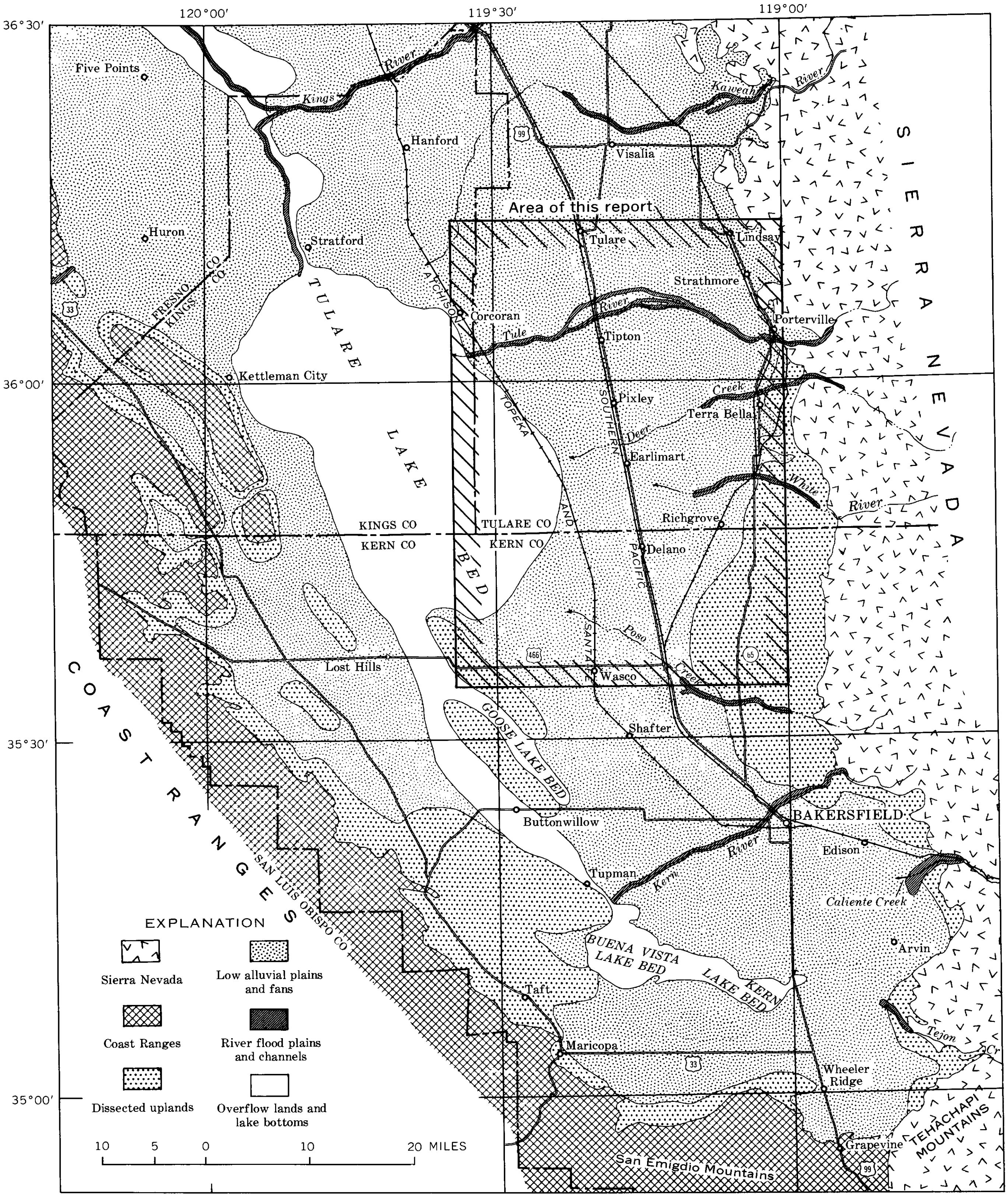

FIGURE 2.—Principal geomorphic features of southern San Joaquin Valley and area of this report. Modified from Davis and others, 1959, pl. 1.)

interagency planning, an intensive investigation of land subsidence in the San Joaquin Valley was begun by the U.S. Geological Survey in 1956, in financial cooperation with the California Department of Water Resources. The objectives of the cooperative investigation are:

1. To obtain vertical control on the land surface adequate to define the extent, rate, and magnitude of subsidence. The vertical control program is a companion project of the U.S. Coast and Geodetic Survey, which that agency has carried on since 1960 in financial cooperation with the California Department of Water Resources.
2. To determine causes of the subsidence, the relative magnitude attributable to the different causes, and the depth range within which compaction is occurring.
3. To furnish criteria for estimating the rates and amounts of subsidence that might occur under assumed hydrologic change; to determine whether any part of the subsidence is reversible and, if so, to what extent; and to suggest methods for decreasing or stopping subsidence.

Because the subsidence in the San Joaquin Valley is concentrated in three nearly independent areas, the cooperative studies by the Geological Survey were divided into three project areas spanning the areas of major subsidence. These are the Los Banos-Kettleman City, Tulare-Wasco, and Arvin-Maricopa areas of figure 1. The Tulare-Wasco area of this report is the central of these three project areas. Cooperative subsidence studies in the other two areas are continuing and interpretive reports are in preparation. The objectives just listed are common to the investigations in all three areas.

The purpose of this report is to describe the geologic framework and the aquifer systems of the ground-water reservoir; to present the history of ground-water withdrawal and its effects on water levels in the several aquifer systems; to describe the land subsidence; to report on the field measurements of compaction; to show the relation of land subsidence and the compaction of the sediments to water-level decline and recovery; to furnish criteria for estimating subsidence that might occur under assumed hydrologic change; to furnish evidence on whether any part of the subsidence is reversible; and to suggest methods for decreasing or stopping the subsidence.

Concurrently with the cooperative subsidence studies, the Geological Survey is carrying on a closely allied Federal research project on the Mechanics of Aquifer Systems, which is directed toward determining the principles controlling the compaction or expansion of aquifer systems resulting from change in grain-to-grain load caused by change in internal fluid pressure. This Federal project has been utilizing areas of rapid land subsidence, including those in the San Joaquin Valley, as field laboratories for the study of compaction of sediments in response to decrease in fluid pressure. The two projects, Federal and cooperative, have benefited mutually from the closely allied studies.

Four reports prepared as a part of the Federal project on Mechanics of Aquifer Systems are pertinent to land-subsidence studies in the Tulare-Wasco area. The first report (Johnson, Moston, and Morris, 1968) describes the results of laboratory tests on cores from eight core holes in subsiding areas in central California, including two drilled in the Tulare-Wasco area. For these two core holes, the laboratory studies included tests of physical and hydrologic properties for 157 samples by the Denver Hydrologic Laboratory of the Geological Survey and consolidation and rebound tests for 22 cores by the Earth Laboratory of the U.S. Bureau of Reclamation. Results of the tests have been utilized in this report, in particular for the computation of compaction by means of Terzaghi's soil-mechanics theory (Terzaghi and Peck, 1948).

The second Federal report (Meade, 1964) is a review of the pertinent literature on the factors influencing the water content and clay-particle fabric of clayey sediments under increasing overburden pressures.

The third Federal report (Meade, 1967) describes the petrology of the cored sediments with special reference to particle-size distribution and clay-mineral assemblages (determined by X-ray diffraction methods). The characters of the clay-mineral assemblage in sediments is one of the factors that determines the amount of compaction that occurs in response to an increase in effective stress. Meade's findings with respect to clay-mineral assemblages in cored sediments in the Tulare-Wasco area are summarized briefly at the end of the geologic section of this report.

The fourth Federal report (Meade, 1968) is a study, partly statistical, of the factors that influence the pore volume and the compaction of the water-bearing sediments in the subsiding areas of central California. For the Tulare-Wasco area, Meade examined the effect of particle size on void ratio of alluvial-fan samples. Also, for fine-grained sediments from the Richgrove core hole, he examined the relations of void ratio to depth of burial, type of deposit, and overburden load and the relations of montmorillonite particle orientation to depth of burial and type of deposit.

The investigation in the Tulare-Wasco area, which was started in August 1957, was made under the general direction of J. F. Poland, research geologist in charge of subsidence studies. B. E. Lofgren, the project chief, was assisted by R. L. Klausing intermittently from September 1957 to September 1962. Klausing made a field canvass of wells and collected well records in the northern part of the area and contributed substantially to the interpretive work and to the sections of the report on geology and ground water. R. L. Ireland assisted in the installation of compaction and water-level recorders and has had primary responsibility for their maintenance and for the plotting and filing of records.

Although the principal investigation of subsidence in the Tulare-Wasco area is completed, the operation of field installations for measuring compaction and water-level change will probably be continued to obtain more specfic information on compaction and subsidence in certain critical areas. These are areas where field data collected to date have not adequately resolved the problem of the depth distribution of compaction and also areas where sensitive compaction recorders are supplying information critical to a better understanding of the response of sediments to changes in effective stress as defined by water-level change. Periodic releveling of the Tulare-Wasco area at about 5-year intervals should be continued as long as water levels continue to decline and land subsidence remains a problem. Subsidence maps for these intervals will define the extent of the subsidence and will serve as a basis for interpreting the continuing compaction-recorder data.

PREVIOUS INVESTIGATIONS

During the 1880's, W. H. Hall[2] made hydrologic studies in the San Joaquin Valley and described early ground-water conditions in the Tulare-Wasco area. Grunsky (1898) reported on the early irrigation methods in the area between Bakersfield and Visalia. Between 1905 and 1910, field studies were made by the Geological Survey (Mendenhall and others, 1916) on the ground-water resources of the San Joaquin Valley describing occurrence and use of ground water before extensive exploitation began.

Hydrologic data utilized in this study are contained in several reports by the State of California, including the following: California Department of Engineering (1921), California Department of Public Works (1922, 1929), and California Water Resources Board (1951). Additional hydrologic data have been reported in studies by Harding (1927, 1949).

Several investigations of ground-water conditions and occurrence in the southern part of the San Joaquin Valley, made by the Geological Survey since 1950 in cooperation with the California Department of Water Resources, have furnished basic data pertinent to this investigation. An extensive study of ground-water conditions and storage capacity in the San Joaquin Valley (Davis and others, 1959) included the Tulare-Wasco area and thus furnished background information. A detailed study by the Geological Survey (Hilton and others, 1963) of ground-water conditions in the Terra Bella-Lost Hills area, which includes the southern two-thirds of the Tulare-Wasco area, resulted in the collection and assembling of much of the basic well data used in this present study. A detailed investigation of the ground-water conditions in the Hanford-Visalia area, which includes the northern third of the Tulare-Wasco area, is currently in progress (M. G. Croft, oral commun., 1965). Data on wells within the Tulare-Wasco area, derived from the investigations of Hilton and Croft, have been assembled in two open-file reports (Hilton and others, 1960; Gordon and Croft, 1964).

Ingerson (1941) published the first report describing land subsidence in the Tulare-Wasco area. Poland and Davis (1956) outlined three areas of active subsidence in the San Joaquin Valley and prepared a 1948–54 subsidence map for the Tulare-Wasco area. This study was followed by a progress report through 1957 (Inter-Agency Committee, 1958) of subsidence investigations by a committee representing several Federal and State agencies. The background data from all these earlier studies have been freely drawn on for this present report.

WELL-NUMBERING SYSTEM

The well-numbering system used in California by the Geological Survey and the State of California shows the locations of wells according to the rectangular system for the subdivision of public land. For example, in the number 23/25–16N1, the part of the number preceding the slash indicates the township (T. 23 S.), the part between the slash and the hyphen shows the range (R. 25 E.), the number between the hyphen and the letter indicates the section (sec. 16), and the letter following the section number indicates the 40-acre subdivision of the section as shown in figure 3. Within each 40-acre tract, wells are numbered serially, as indicated by the final digit of the well number. Thus, well 23/25–16N1 is the first well to be listed in the SW¼ SW¼ sec. 16, T. 23 S., R. 25 E. Wells other than water

[2] Unpublished reports, field notes, and hydrologic maps of the San Joaquin Valley, Calif., on file in the archives of the California Department of Water Resources.

wells and exploration test holes are indicated by location numbers without the final digit. For example, an oil test hole in the SW¼NW¼ sec. 33, T. 21 S., R. 25 E., 2 miles east of Pixley is designated as 21/25–33E. The entire Tulare-Wasco area lies south and east of the Mount Diablo base line and meridian; therefore, the foregoing abbreviation of the township and range is sufficient.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

FIGURE 3.—Well-numbering system.

COLLECTION OF DATA AND FIELD PROGRAM

When this investigation was begun, a large volume of basic data—drillers' logs, electric logs, core-hole logs, and water-level measurements—collected in earlier and concurrent studies by the Geological Survey was available to the authors. Most of these records had been obtained initially from the California Department of Water Resources, the U.S. Bureau of Reclamation, and the irrigation districts. A detailed field canvass of about 2,000 wells was made during the early part of the investigation, and this canvass included the assembling of additional electric and drillers' logs and water-level records. Also, several months were spent reviewing the general geology of the area and preparing the geologic sections used in this report. After review of these data, the principal hydrologic units of the area were defined, and a selection was made of representative observation wells tapping the various aquifers.

As part of this investigation, two core holes were drilled in areas of maximum subsidence: one (23/25–16N1) near Pixley, 760 feet deep and cored to 752 feet; the other (24/26–36A2) at Richgrove, 2,200 feet deep and cored to 2,180 feet. Results of tests of selected core samples from these two sites have been reported by Johnson, Moston, and Morris (1968) as part of the Mechanics of Aquifer Systems studies. Also, paleontologic studies made by Lohman (Klausing and Lohman, 1964) of fossils from cores of the Richgrove hole have assisted in the dating of the deposits in this part of the valley.

Eleven compaction recorders and six water-level recorders were installed between September 1957 and June 1959 to furnish specific data on compaction and on the relation of compaction of the water-bearing deposits to changes in ground-water level in areas of rapid subsidence. During the investigation, installation and maintenance of these recorders have represented a substantial part of the field program. Interpretive results from these installations have been the basis for many of the conclusions made in this report. Table 8 gives the location and length of records available for each of the recorders maintained during this investigation.

Unpublished data from 19 core holes drilled by the Bureau of Reclamation in 1950–52 have been used extensively in this study. These records include electric and descriptive logs of the core holes, together with particle-size analyses and permeability test data. Table 1 gives information on the core holes that have been drilled in the Tulare-Wasco area, and their locations are shown in figure 11.

TABLE 1.—*Core holes in the Tulare-Wasco area*

[Location of core holes shown in figure 11]

Core hole	Year drilled	Depth (ft)	Drilled by	Cored interval (ft)
20/23–8D	1952	730	USBR	12 to 700.
20/25–14F	1951	1,000	USBR	10 per 100.
20/26–24K1	1951	1,070	USBR	Continuous.
21/24–31D1	1950	1,180	USBR	10 per 100; continuous 340–430.
35M1	1950	1,490	USBR	1,200 to 1,330.
21/26–1Q1	1951	700	USBR	10 per 100 below 290.
6F1	1951	900	USBR	10 per 100.
35J2	1951	700	USBR	100 to 700.
22/26–6F1	1951	700	USBR	10 per 100.
23/23–33A1	1951	1,200	USBR	0 to 800.
23/24–16R1	1951	1,400	USBR	10 per 50 from 0–400; 10 per 100 below 400.
23/25–9Q2	1951	770	USBR	10 per 50.
16N1	1958	760	USGS	10 per 40 to 250; continuous 250–752.
23/26–8R1	1951	90	USBR	10 per 50.
24/25–2H1	1952	1,188	USBR	Do.
24/26–36A2	1959	2,200	USGS	50–1,900; 10 per 40 below 1,900.
25/23–29A1	1952	800	USBR	About 75 percent.
25/24–15H1	1952	600	USBR	10 per 50.
25/25–22D1	1952	1,291	USBR	Do.
25/26–16P1	1952	1,170	USBR	0–500; 10 per 100 below 500.
27/23–1R1	1952	1,160	USBR	0–800; 10 per 100 below 800.

ACKNOWLEDGMENTS

The cooperation of numerous landowners and irrigation districts in supplying information vital to this investigation is acknowledged. Special credit is expressed to the Pixley Irrigation District for purchasing the test site for the Pixley core hole and to Vincent B. Zaninovich and Sons for permission to drill the Richgrove core hole in their headquarters area. Particular assistance has been rendered by the Pacific Gas and Electric Co., the Southern California Edison Co., the Southern Pacific Co., and the Delano-Earlimart and Rag Gulch Irrigation Districts. To the various well drillers, oil

companies, and service companies, appreciation is extended for supplying drillers' logs and electric logs used in this study. Also, the cooperation and assistance of local, State, and Federal agencies in furnishing data throughout the investigation are gratefully acknowledged. The U. S. Bureau of Reclamation and the California Department of Water Resources have been particularly helpful throughout the investigation.

The U.S. Coast and Geodetic Survey provided the leveling data used in preparing almost all the subsidence maps and graphs in this report and has been most cooperative in extending level lines to compaction-recorder sites. In 1964, the Coast and Geodetic Survey made an unscheduled circuit through the area of most rapid subsidence. Since 1960, the vertical control program of the Coast and Geodetic Survey has been carried on in financial cooperation with the California Department of Water Resources.

GEOLOGY

GEOLOGIC SETTING

The San Joaquin Valley represents roughly the southern two-thirds of the Central Valley of California, extending from the combined delta of the San Joaquin and Sacramento Rivers on the north to the Tehachapi Mountains on the south, a distance of 250 miles. The relatively flat floor of the San Joaquin Valley overlies thousands of feet of alluvial, lacustrine, and marine deposits that have accumulated in the valley as the trough has been lowered and the adjacent mountains have been elevated.

The San Joaquin Valley is a structural trough, whose main axis trends northwest-southeast to the west of the valley's drainage axis. The valley is bordered on the east by the granitic complex of the Sierra Nevada and on the west by the folded and faulted sedimentary, volcanic, and metamorphic rocks of the Coast Ranges. The highly deformed sedimentary deposits and granitic rocks of the Tehachapi and San Emigdio Mountains form the south boundary of the valley. On the north the San Joaquin Valley is open to the Sacramento Valley, a northward extension of the same structural system.

Throughout Late Cretaceous and much of Tertiary time the San Joaquin Valley was the site of marine deposition, and thousands of feet of shallow-water marine sediments were deposited in this geosyncline. Presently, overlying these marine sedimentary deposits are continental deposits of late Tertiary and Quaternary age. In aggregate, these marine and continental deposits form an immense wedge which thickens from east to west, and from north to south, and attains a thickness in excess of 22,000 feet at the axis of the structural trough at Elk Hills (deLaveaga, 1952, p. 100). In the extreme south end of the valley, the maximum thickness of the sediments of Tertiary and Quaternary age is about 28,000 feet (deLaveaga, 1952, p. 103). The deposits of continental origin, whose thickness exceeds 15,000 feet at the south end of the valley, occur as successive layers of interfingering lacustrine, deltaic, floodplain, and fan deposits. These continental deposits have been tilted to the west and downwarped, and their base is now several hundred to many thousand feet below sea level. This very slow downwarping of the valley trough is probably continuing, but at a rate too small to be significant in this study.

The present form of the San Joaquin Valley is chiefly a result of tectonic movement during late Tertiary and Quaternary time. Structural deformation during Quaternary time has occurred principally along the south and west borders of the valley, where marine and continental rocks are tightly folded and faulted and where elevated stream terraces and deformed strata give ample evidences of recent tectonic activity. Deformation along the east side of the valley has consisted primarily of uplift and westward tilting of the Sierra Nevada block (which extends westward beneath much of the valley) and the resultant westward tilting of the overlying sediments. For a more extensive discussion of the general geology and ground-water conditions in the San Joaquin Valley, reference is made to earlier studies by Davis and coworkers (1959 and 1964).

PHYSIOGRAPHY

The Tulare-Wasco area is in the southeastern part of the San Joaquin Valley and is bordered on the east by the foothills and mountain block of the Sierra Nevada. Figure 2 delineates the principal geomorphic features of the southern third of the San Joaquin Valley and of the Tulare-Wasco area.

Except for the dissected uplands in its southeastern part, the Tulare-Wasco area is a gently westward-sloping plain ranging in altitude from 500 to 600 feet on its east margin to 200 feet on the dry bed of Tulare Lake. In large part, this plain represents a surface of aggradation immediately underlain by deposits of Recent age laid down by the westward-flowing streams. In the northeast corner of the area, deeply weathered granitic and metamorphic rocks of the Sierra Nevada rise abruptly above the valley surface. Also, inliers of old crystalline rocks project through the alluvium and form rocky hills above the valley plain near the mountain front. These inliers reveal the process of gradual burial of the rugged mountain block.

South of the Tule River, the dissected foothill belt of Tertiary and Quaternary marine and continental rocks separates the crystalline complex of the Sierra Nevada from the alluvial deposits of the valley plain. This dissected belt is in marked contrast to the alluvial plain with respect to physiography and underlying sediments as well as agricultural use and farming practices. Thus, a sharp line of demarcation separates the highly productive vineyards, citrus groves, and cultivated fields on the valley plain from the low-yield dry farms and parched ranges of the largely undeveloped foothills.

As shown in figure 2, the Tulare-Wasco area includes the following five geomorphic units as classified by Davis, Green, Olmsted, and Brown (1959, pl. 1): (1) overflow lands and lake bottoms in the west-central part of the area, representing the historically inundated lake bottom of Tulare Lake, (2) alluvial plains and fans of low relief that occupy three-quarters of the area, (3) flood-plain and channel deposits that occur as narrow strips along three streams extending onto the alluvial plain from the east, (4) dissected uplands (foothills) in the southeast corner of the area and in the ridge of older sediments in the southwest corner, and (5) bedrock outcrops of the Sierra Nevada near Porterville and Lindsay.

TULARE LAKE

Tulare Lake bed, which has been the site of lacustrine deposition during most of Quaternary time, has been largely dry since 1919. Today Tulare Lake receives water during high-water periods from the Kaweah and Tule Rivers and possibly, during exceptional floods, from the Kings and Kern Rivers, Deer Creek, and several small intermittent streams. Its natural boundary has been greatly altered by construction of levees and other reclamation work. The altitude of the lowest point of the lakebed, 10 miles west of the study area, is now about 180 feet above mean sea level.

According to Mendenhall, Dole, and Stabler (1916, p. 281), Tulare Lake filled and overflowed northward to the San Joaquin River three times during the period between 1848, the beginning of record, and 1906; these spills occurred in 1861–63, 1867–68, and 1878 (Harding, 1949, p. 30), when the water level rose to 220 feet above sea level. Since 1906, the maximum observed altitude of the lake surface occurred in late June 1941 at 196.8 feet above sea level (maximum depth of water about 17 ft). At this high stage, the shore of the transient lake was just west of the study area. The Tulare Lake bed has remained dry since August 1958. Today most of the lake bottom area is diked, drained, and intensively farmed. Most of the former inflow from the Kings River has been regulated since December 1952 by the Pine Flat Dam.

GEOLOGIC UNITS

The deposits penetrated by wells in the Tulare-Wasco area and also the underlying sediments and bedrock are divided, for purposes of this report, into five geologic units. In descending order of occurrence, these are: (1) a thick sequence of unconsolidated continental deposits derived from the Sierra Nevada that constitutes the principal ground-water reservoir in the area, (2) semiconsolidated and consolidated upper Pliocene and Pliocene(?) marine strata, tapped by water wells in the eastern part of the area, (3) the Santa Margarita Formation as used by Diepenbrock (1933), a thin marine sand that is tapped by water wells in the vicinity of Richgrove, (4) an undifferentiated sequence of lower Tertiary sands and silts, and (5) the crystalline basement complex. The age and general character of these geologic units are summarized in table 2 and are discussed in greater detail in succeeding pages.

CONTINENTAL DEPOSITS FROM THE SIERRA NEVADA

The gently sloping land surface of the Tulare-Wasco area is underlain everywhere by unconsolidated continental deposits derived from the Sierra Nevada; these deposits range in thickness from 0 feet to at least 3,000 feet. They consist chiefly of alluvial, lacustrine, and flood-plain deposits which form a westward-thickening wedge of Sierran detritus (figs. 4, 5). As shown in figure 5 and on east-west geologic sections *A–A″* and *B–B′* (figs. 4, 5; for location see fig. 6), this sequence of poorly bedded and generally poorly sorted sediments ranges in thickness from 0 to about 800 feet along the east boundary of the area and thickens abruptly to the west. The maximum thickness of about 3,200 feet was measured north of Alpaugh (geologic section *D–D′*, fig. 10). As shown in table 2, these continental deposits range in age from late Pliocene to the present, and are, in general, correlative with the Tulare Formation and younger deposits to the west, with the upper part of the Kern River Series of Diepenbrock (1933) to the south, and with the continental deposits, undifferentiated, and younger deposits of Hilton, McClelland, Klausing, and Kunkel (1963) in the Terra Bella-Lost Hills area. For the purposes of this investigation, these deposits are called continental deposits from the Sierra Nevada.

Three major facies are recognized in the continental deposits (figs. 4, 5): oxidized alluvial deposits, reduced flood-plain and lacustrine deposits, and lacustrine clays.

TABLE 2.—*Geologic units of the Tulare-Wasco area*

Geologic age		Depositional environment	Geologic unit	Thickness[1] (ft)	General character	Generally equivalent geologic units as described by others
Quaternary	Recent to Pliocene	Continental (alluvial fan, flood plain, and lacustrine)	Continental deposits from the Sierra Nevada	0–3,200	Interbedded gravel, sand, silt, and clay. Principal water-producing zone.	Upper part of Kern River Group of Park and Weddle (1959); upper part of Kern River Series of Diepenbrock (1933); Tulare Formation and overlying deposits (Woodring and others, 1940); Tertiary and Quaternary(?) deposits, undifferentiated, and overlying strata of Hilton, McClelland, Klausing, and Kunkel (1963).
Tertiary	Pliocene	Marine	Upper Pliocene and Pliocene(?) marine strata	630–2,500±	Siltstone, clayey, diatomaceous, with numerous thin interbeds of quartzose sand. Limited ground-water production.	Lower part of Kern River Group of Park and Weddle (1959); lower part of Kern River Series of Diepenbrock (1933); part of San Joaquin Formation (Woodring and others, 1940).
	Miocene		Unconformity Santa Margarita Formation as used by Diepenbrock (1933)	150–525	Sand, fine to coarse, arkosic, some gravel. Local water-producing zone.	
	Miocene and Eocene		Tertiary sedimentary deposits, undifferentiated	200–1,500+	Semiconsolidated to consolidated sand, silt, and clay.	Round Mountain Silt of Diepenbrock (1933); Olcese Sand of Diepenbrock (1933); Freeman-Jewett Silt of Weaver and others (1944); Vedder Sand of Wilhelm and Saunders (1927); Walker Formation of Wilhelm and Saunders (1927).
Pre-Tertiary			Unconformity Sierra Nevada basement complex		Granite, gneiss, and schist.	

[1] Thickness from geologic sections.

These facies represent distinct depositional environments and are differentiated by their color and texture and by the state of preservation of plant remains as revealed in well cores or samples. In general, the oxidized alluvial deposits are thickest in the eastern part of the area and interfinger with and overlie the reduced deposits; also, they are characterized by their yellow, red, and brown color and by highly weathered, crumbling feldspar grains. The reduced lacustrine and flood-plain deposits, on the other hand, are recognized by their drab green, blue, and dark-gray color, well-preserved plant remains, and an ever-present dissemination of iron sulfide.

Although several distinct tongues of lacustrine clay extend eastward and southward from the Tulare Lake bed area where a nearly continuous sequence of lake clays has accumulated, only the one most significant clay layer has been delineated in the geologic sections. This extensive diatomaceous clay, which is in the upper part of the Tulare Formation, has been designated the Corcoran Clay Member of the Tulare Formation (Inter-Agency Committee, 1958, p. 119–120). Except for the Corcoran Clay Member which represents nearly valley-wide lake deposition in part of Pleistocene time, all the continental deposits in the Tulare-Wasco area are believed to be derived from a Sierran source.

Within the Sierran continental sequence in the eastern part of the area (figs. 4, 5), 200–250 feet of slightly weathered permeable alluvial deposits is underlain by 300–700 feet of highly weathered less permeable alluvium. Data from several core holes indicate that for the most part the upper deposits are relatively fresh, sandy, and noncalcareous, whereas the lower weathered deposits are decomposed, much finer grained, and highly calcareous. The sharp break separating these two sequences, which probably represents both a lapse of time and a transition in weathering regime, is clearly shown on many electric logs. It is especially well displayed at a depth of about 255 feet in the electric log of core hole 24/26–36A2 near the east end of geologic section *B–B′* (fig. 5).

In core hole 23/25–16N1 (fig. 7), about 3 miles south of Pixley, the entire thickness of unconsolidated deposits penetrated was of continental origin. (Also see fig. 4.) All deposits, except the 16-foot thickness of the Corcoran Clay Member (280–296-foot depth interval, fig. 7) and a very thin clay layer at the 730-foot depth, are oxidized alluvial-fan deposits. In general, the deposits in this core hole consist of thin heterogeneous beds of yellowish-brown sand, silt, and sandy clay. The sand fraction predominates and consists largely of fine to coarse subangular grains of quartz and feldspar.

About 8 miles west of core hole 23/25–16N1, the oxidized fluvial deposits intertongue with poorly sorted, reduced flood-plain and lacustrine sediments (geologic section *A–A″*, fig. 4). Beneath Tulare Lake bed in the vicinity of Alpaugh (figs. 6, 10), well-sorted reduced lacustrine strata of clay, silt, and sand constitute the principal sediments in about the lower half of the continental deposits and indicate more or less continuous

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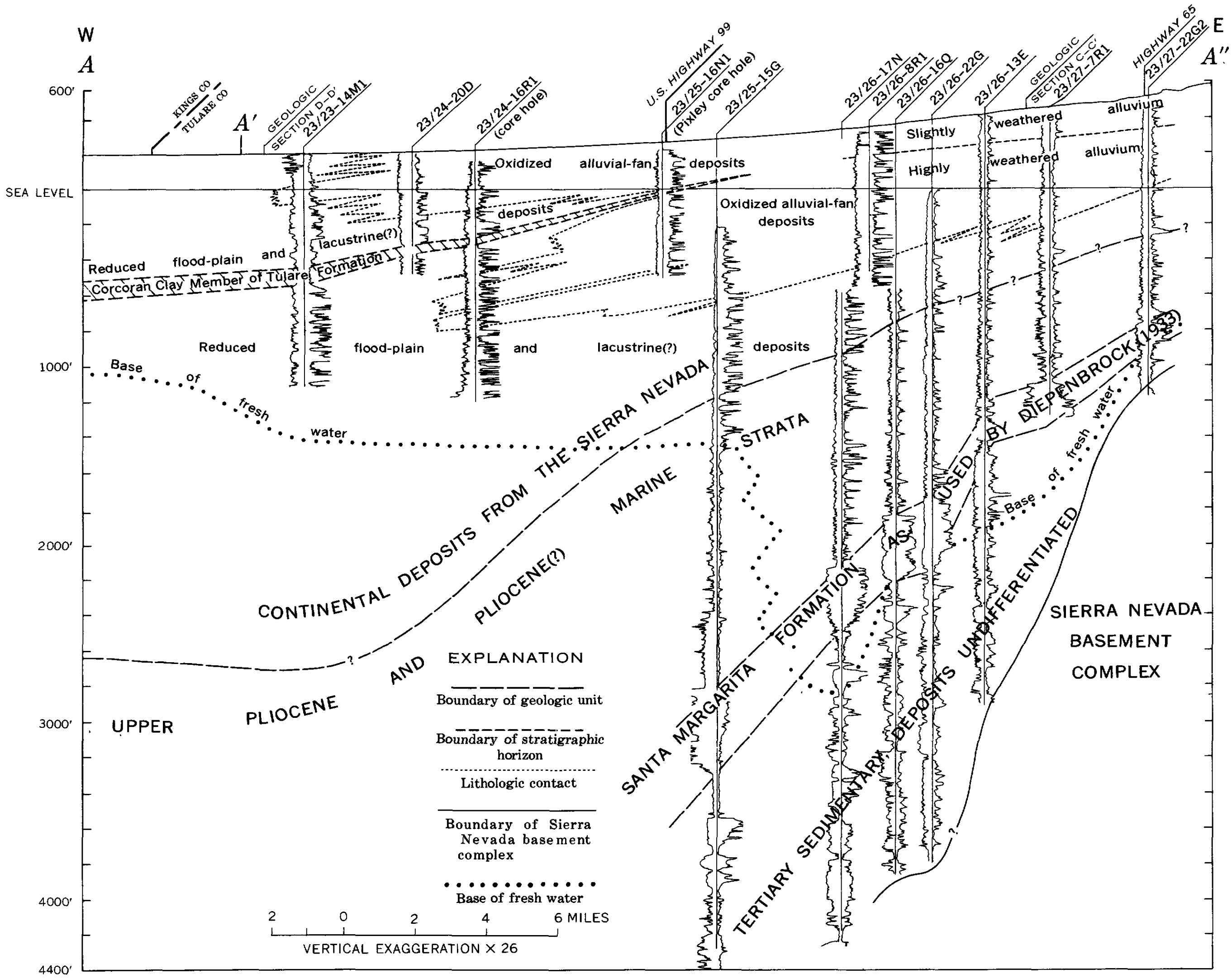


FIGURE 4.—Geologic section *A–A''* through the Pixley core hole. See figure 6 for well locations.

lake deposition through this interval. In general, evidence from electric logs of oil-test holes indicates that the water in these deposits is too saline for ordinary uses.

At Richgrove, core hole 24/26–36A2 (fig. 8) penetrated 744 feet of continental deposits overlying a thick sequence of marine siltstone. Oxidized alluvial-fan deposits, consisting predominantly of yellowish-brown poorly sorted sands, compose the upper 620 feet of the continental section (fig. 5). Underlying the oxidized zone is 124 feet of greenish-gray reduced flood-plain deposits. As shown in north-south geologic section *C–C'* through this core hole (fig. 9), the threefold sequence of upper slightly weathered oxidized alluvium, intermediate highly weathered calcareous oxidized alluvium, and lower reduced flood-plain deposits persists within the continental section along the east side of the Tulare-Wasco area.

As shown by north-south geologic section *D–D'* (fig. 10), the sequence of interbedded continental deposits attains a maximum thickness of about 3,200 feet north of Alpaugh. A thick tongue of oxidized alluvial deposits beneath the Corcoran Clay Member extends northward about 10 miles from the south end of section *D–D'*. This tongue is inferred to represent deposition on an ancestral Kern River fan.

Most of the ground water pumped in the Tulare-Wasco area comes from the unconsolidated continental deposits (figs. 4, 5, 9, 10). These deposits, for the most part, are moderately permeable, and the yields of most wells tapping this geologic unit range from 400 to 1,500 gpm (gallons per minute).

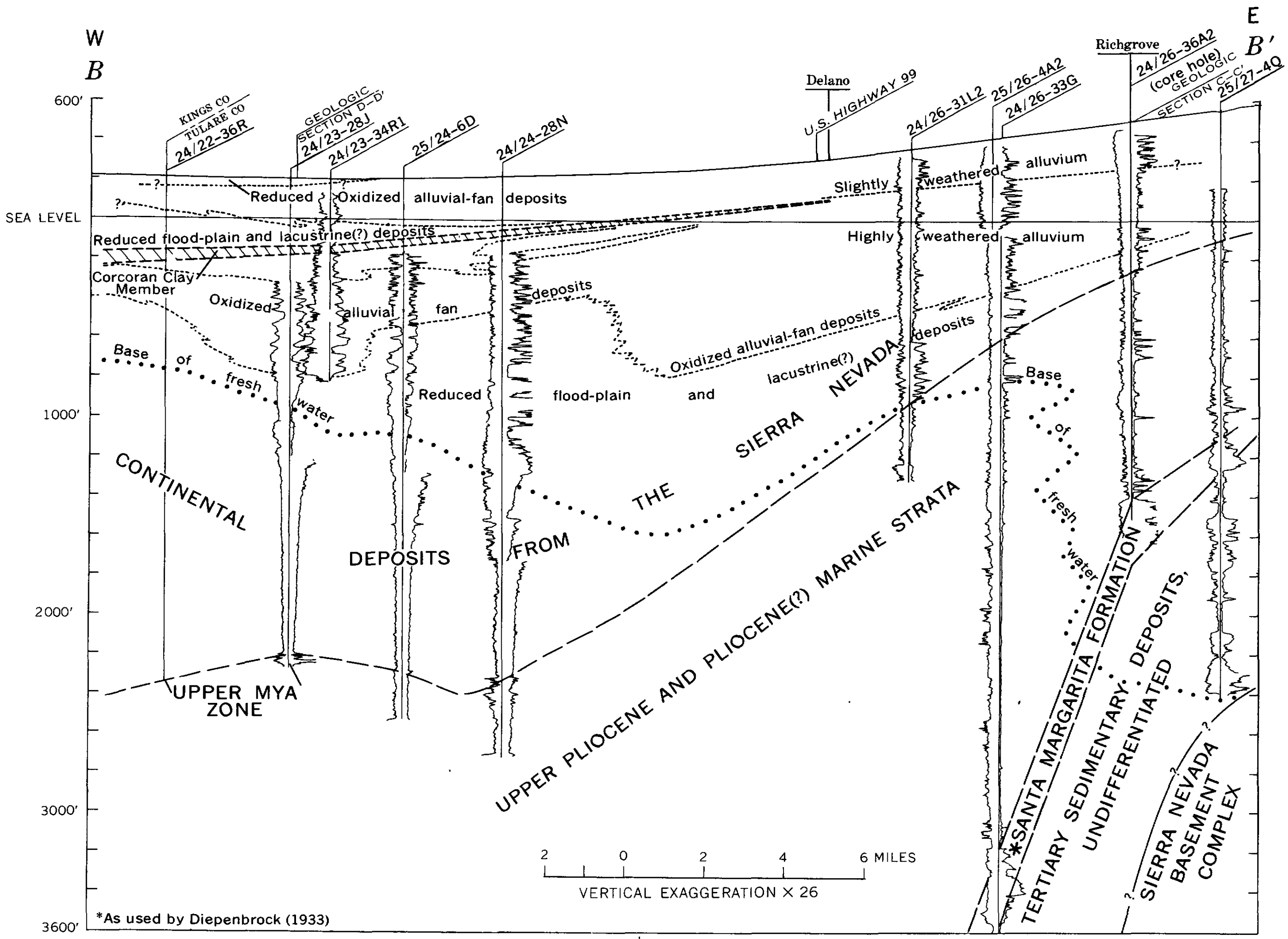


Figure 5.—Geologic section *B–B′* through the Richgrove core hole. See figure 6 for location of wells and figure 4 for explanation.

CORCORAN CLAY MEMBER OF THE TULARE FORMATION

A well-sorted bed of diatomaceous lake clay occurs within the continental deposits in the western part of the Tulare-Wasco area. This clay bed was first identified and described by Frink and Kues (1954) and later was mapped in more detail by Davis, Green, Olmstead, and Brown (1959, p. 76–81, pl. 14), who showed that it extended beneath at least 5,000 square miles of the San Joaquin Valley. It has been designated the Corcoran Clay Member of the Tulare Formation (Inter-Agency Committee, 1958, p. 119–120). The Corcoran serves not only as the one distinctive geologic marker in the continental deposits but also as the principal confining bed beneath about half the San Joaquin Valley.

The Corcoran Clay Member underlies about half of the Tulare-Wasco area (fig. 11), mostly west of U.S. Highway 99. The boundary of the Corcoran is 2–3 miles east of U.S. Highway 99 from Tulare to Earlimart; there it swings to the southwest crossing the south boundary of the study area west of Wasco. Near the outer margin, the lake clays give way to well-sorted sand and silt which in turn grade into, and interfinger with, poorly sorted reduced flood-plain and oxidized alluvial deposits.

The thickness of the Corcoran ranges from 0 feet at its east boundary to about 110 feet at Alpaugh (fig. 10). Within most of its extent, core logs and electric logs indicate it to be a well-defined and distinct silty clay or clayey silt, bounded above and below by coarser, more permeable deposits. At some places, however, the upper or lower contact is indefinite and subject to more than one interpretation. North of Alpaugh, for ex-

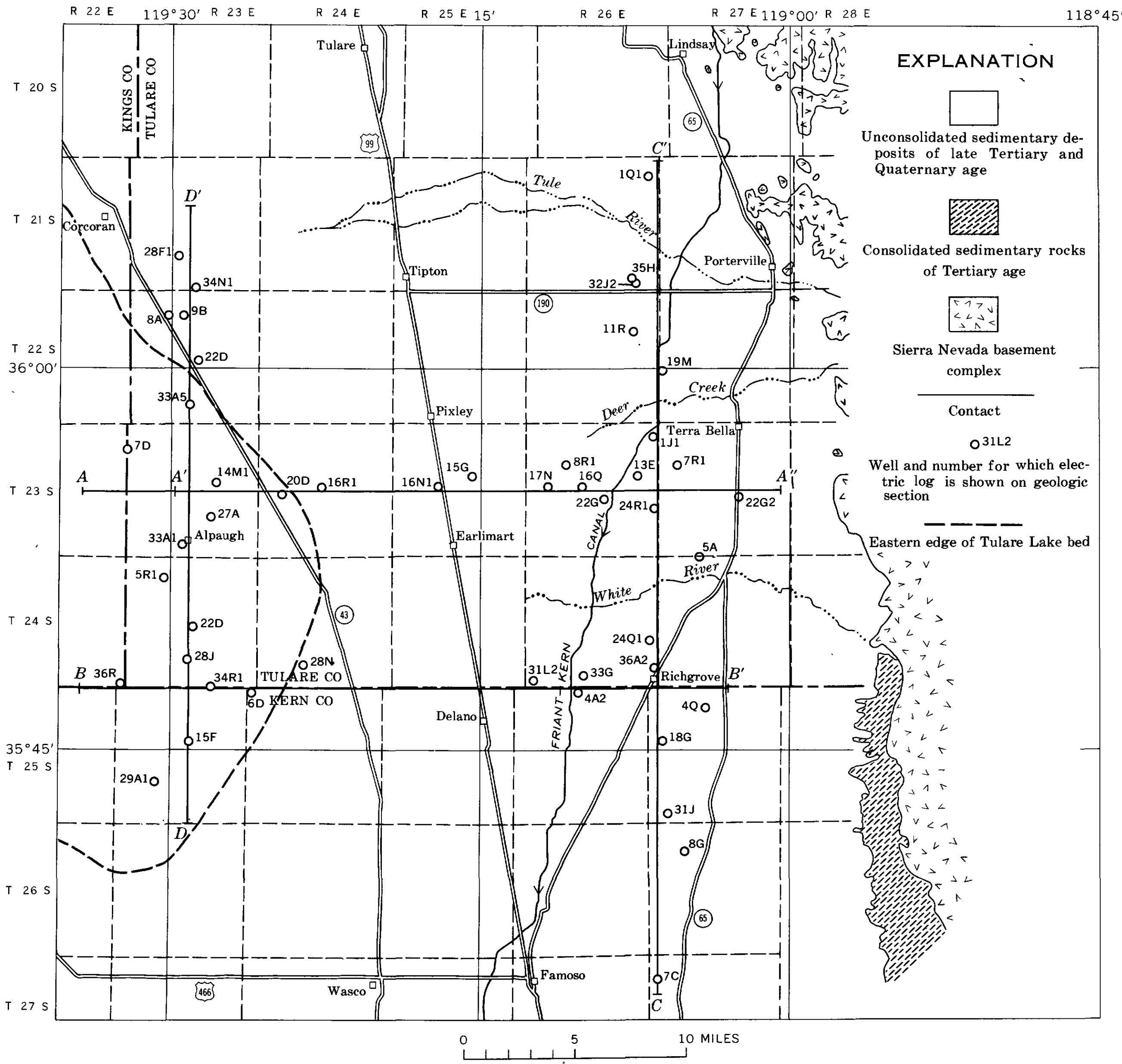


FIGURE 6.—Location of geologic and hydrologic sections shown in figures 4, 5, 9, and 10.

ample, the Corcoran as defined in figure 10 is immediately overlain by clay as much as 90 feet thick. (See electric logs for wells 22/23–33A5, 22D, and 9B, fig. 10.) Although this overlying clay is not considered a part of the Corcoran in this report, it does add substantially to the overall thickness of the principal confining stratum where present. To the east, between Pixley and Wasco, a clay tongue beneath the Corcoran as here delimited extends beyond the east boundary shown in figure 11. In the Pixley core hole, the lower tongue is a yellowish-brown silty clay containing thin sand interbeds 330–360 feet below the land surface (fig. 7). M. G. Croft (oral commun., 1966) considers this tongue to represent an earlier phase of deposition near the shore of Corcoran lake. Hydraulic data from a series of piezometers installed near the Pixley core hole (23/25–16N1) indicate that this lower tongue is the principal confining bed locally. Throughout most of the western half of the Tulare-Wasco area, however, the Corcoran Clay Member as mapped in figures 4, 5, 10, and 11 is the principal confining bed in the continental deposits.

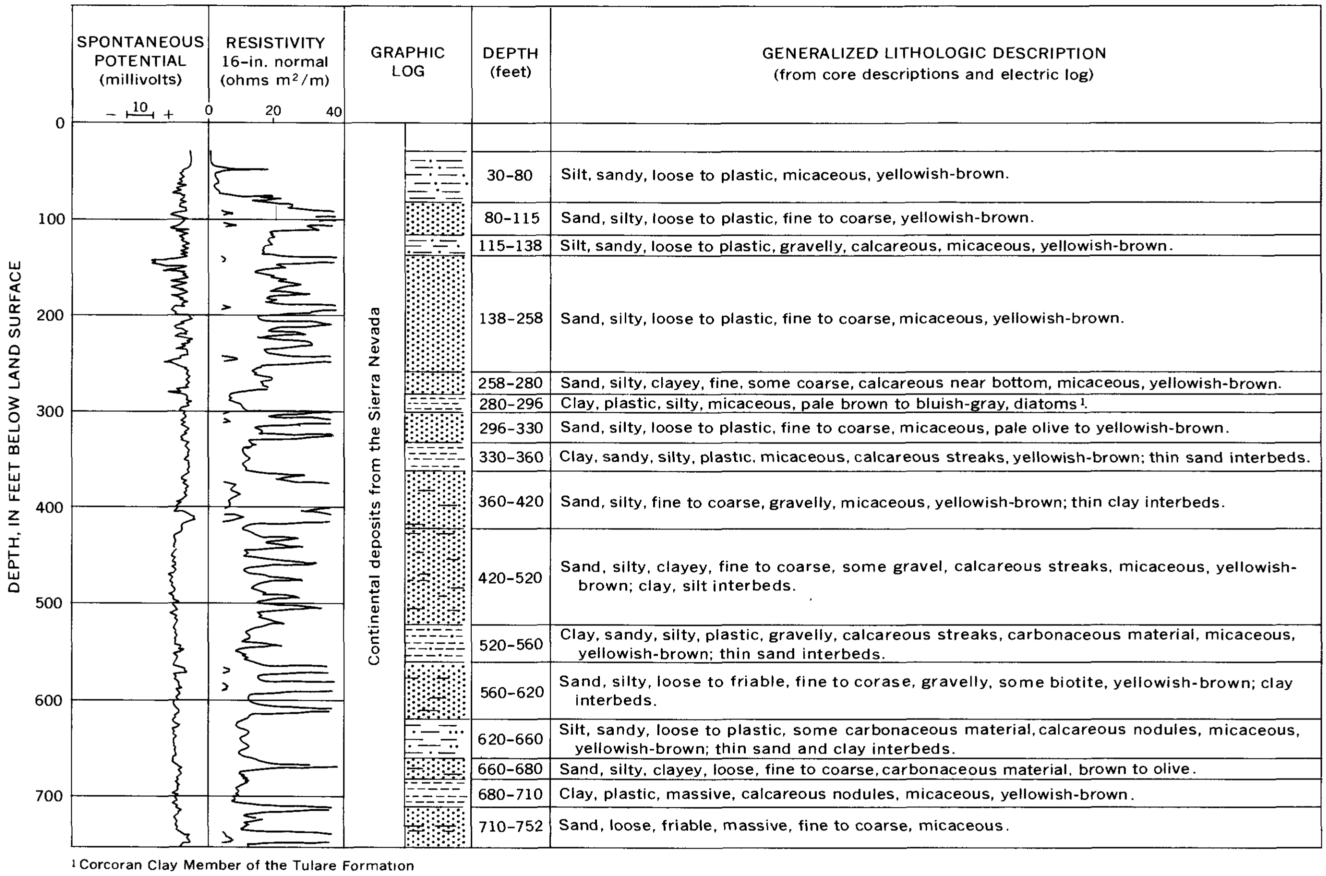


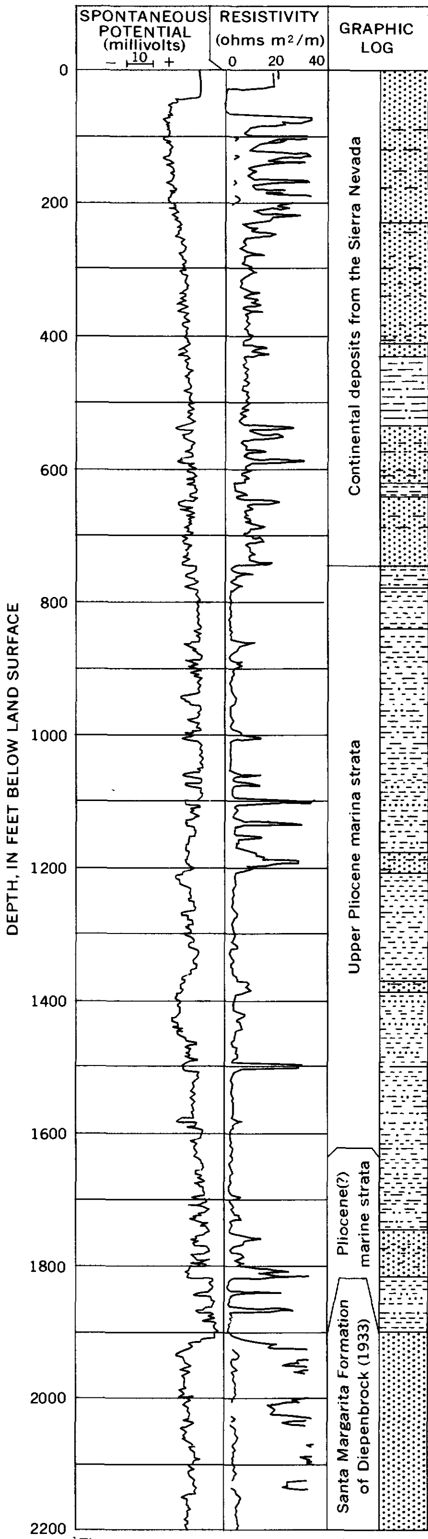
FIGURE 7.—Composite logs of core hole 23/25-16N1 near Pixley.

The structural contours drawn on the base of the Corcoran Clay Member (fig. 11) show its configuration and altitude. The base of the Corcoran ranges in altitude from slightly above sea level at its east edge to more than 600 feet below sea level northwest of Alpaugh. The well-defined trough trending northwest from the vicinity of Delano (fig. 11) represents either the configuration of the surface of the pre-Corcoran lake bottom or a downwarping of the lake deposit since Corcoran time. The sharpness of the trough suggests that the second interpretation is the more likely one.

UPPER PLIOCENE AND PLIOCENE(?) MARINE STRATA

Underlying the unconsolidated continental deposits throughout the Tulare-Wasco area is a thick section of marine strata, chiefly siltstone, of late Pliocene and Pliocene(?) age (figs. 4, 5, 9, 10). In the Richgrove core hole, this siltstone, which is diatomaceous in part, is differentiated from the overlying continental deposits by a marked change in lithology. This lithologic transition was recognized in the electric log of core hole 24/26-36A2 (fig. 8) and was correlated with other electric logs through much of the area. On the basis of fossils recognized in a number of oil-test holes, the top of the upper Pliocene strata is tentatively correlated with the upper *Mya* zone described by Woodring, Stewart, and Richards (1940, p. 28). (Also see fig. 5.)

At Richgrove (fig. 8), the marine strata extend in depth from 744 to 1,900 feet. Partially cemented clayey siltstone (logged from core inspection as claystone, but particle-size analyses indicate mostly silt sizes) dominates the interval, but thin sand beds occur at several intervals. K. E. Lohman examined a marine diatom assemblage in the depth interval between 1,141 and 1,641 feet (Klausing and Lohman, 1964), assigned a late Pliocene age to this interval, and concluded that it may be the equivalent of the late Pliocene San Joaquin Formation of the Kettleman Hills area. The lithologic similarity of the siltstone through the full thickness from 744 to 1,900 feet suggests that the entire marine section from 744 to 1,641 feet should be assigned to the upper Pliocene; the marine siltstone from 1,641 to 1,900 feet has been tentatively assigned to the Pliocene(?) (Klausing and Lohman, 1964).



DEPTH (feet)	GENERALIZED LITHOLOGIC DESCRIPTION (from core descriptions and electric logs)
0–230	Sand, clean to silty, yellowish-brown; silt and sandy silt interbeds; several gravelly layers.
230–412	Sand, silty and clayey, fine to coarse, yellowish-brown; calcareous toward bottom, carbonaceous material.
412–429	Sand, clean to silty, medium, loose, dark-yellowish-brown.
429–535	Silt, sandy, fine to coarse, moderate-yellowish-brown; some gravel, calcareous zones.
535–620	Sand, silty and clayey, fine to coarse, yellowish-brown to olive-gray.
620–637	Clay and silt, sandy, firm to lithified, brownish- to olive-gray.
637–744	Sand, silty, greenish- to bluish-gray; thin interbeds of silt, clay, and claystone; some cementation.
744–779	Claystone[1], siltstone, and silty sand, calcareous streaks, dark-bluish- to greenish-gray.
779–841	Claystone and clay, silty, with sandy layers, greenish-gray.
841–1176	Claystone, silty to sandy, dark-greenish- to bluish-gray; thin interbeds of clay, silt, and loose sand, plant remains; rhyolitic ash zone at 1058 ft.
1176–1206	Sand, silty, clayey, fine to medium, dark-greenish- to bluish-gray.
1206–1369	Claystone, silty, sandy, dark-greenish- to bluish-gray; thin interbeds of silt, sand, and fine gravel, diatomaceous, plant remains.
1369–1384	Sand, silty, clayey, fine to medium, bluish-gray.
1384–1500	Claystone and sand interbedded, firm to loose, dark-bluish- to greenish-gray; 10-ft sand layer at base, diatomaceous.
1500–1745	Claystone, silty, sand, bluish- to greenish-gray; interbeds of silt, sand, and fine gravel, more sand toward bottom, carbonaceous material, mollusk shells, crab remains, diatomaceous above 1641 ft.
1745–1818	Sand, silty, clayey, bluish-gray; claystone interbeds, mollusk shells and fish remains.
1818–1900	Claystone, sandy, silty, bluish-gray; sand interbeds, mollusk shells, fish scales and teeth, carbonaceous material.
1900–2200	Sand, slightly clayey, some gravel, fine to coarse, greenish-gray; carbonaceous material, shell fragments.

[1] The many beds in the depth interval 744–1900 feet described as claystone from field examination of cores are shown by particle-size analyses to be chiefly siltstone

Figure 8.—Composite logs of core hole 24/26–36A2 at Richgrove. Modified from Klausing and Lohman, 1964.

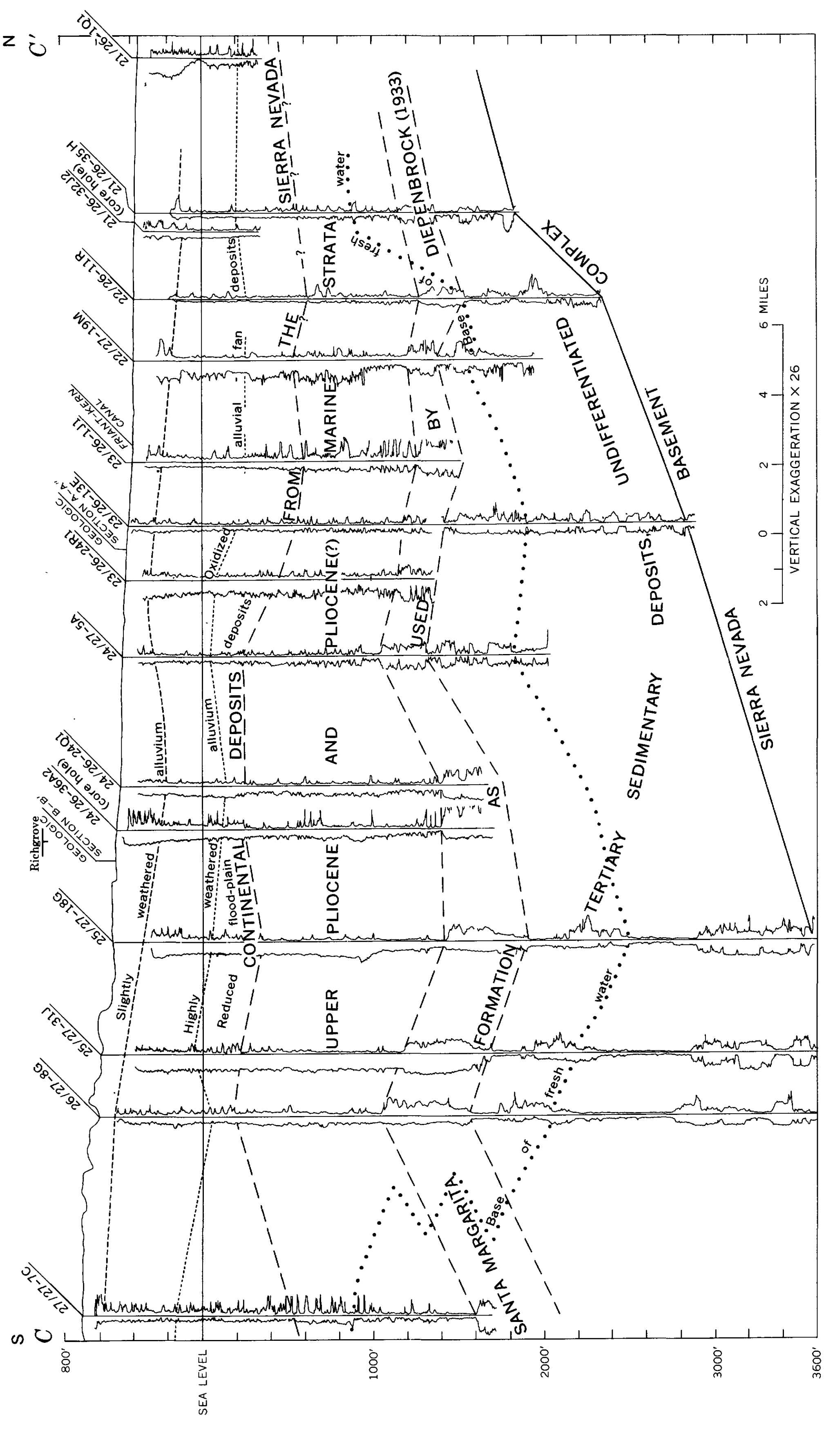


FIGURE 9.—Geologic section C–C′ through the Richgrove core hole. See figure 6 for location of wells and figure 4 for explanation.

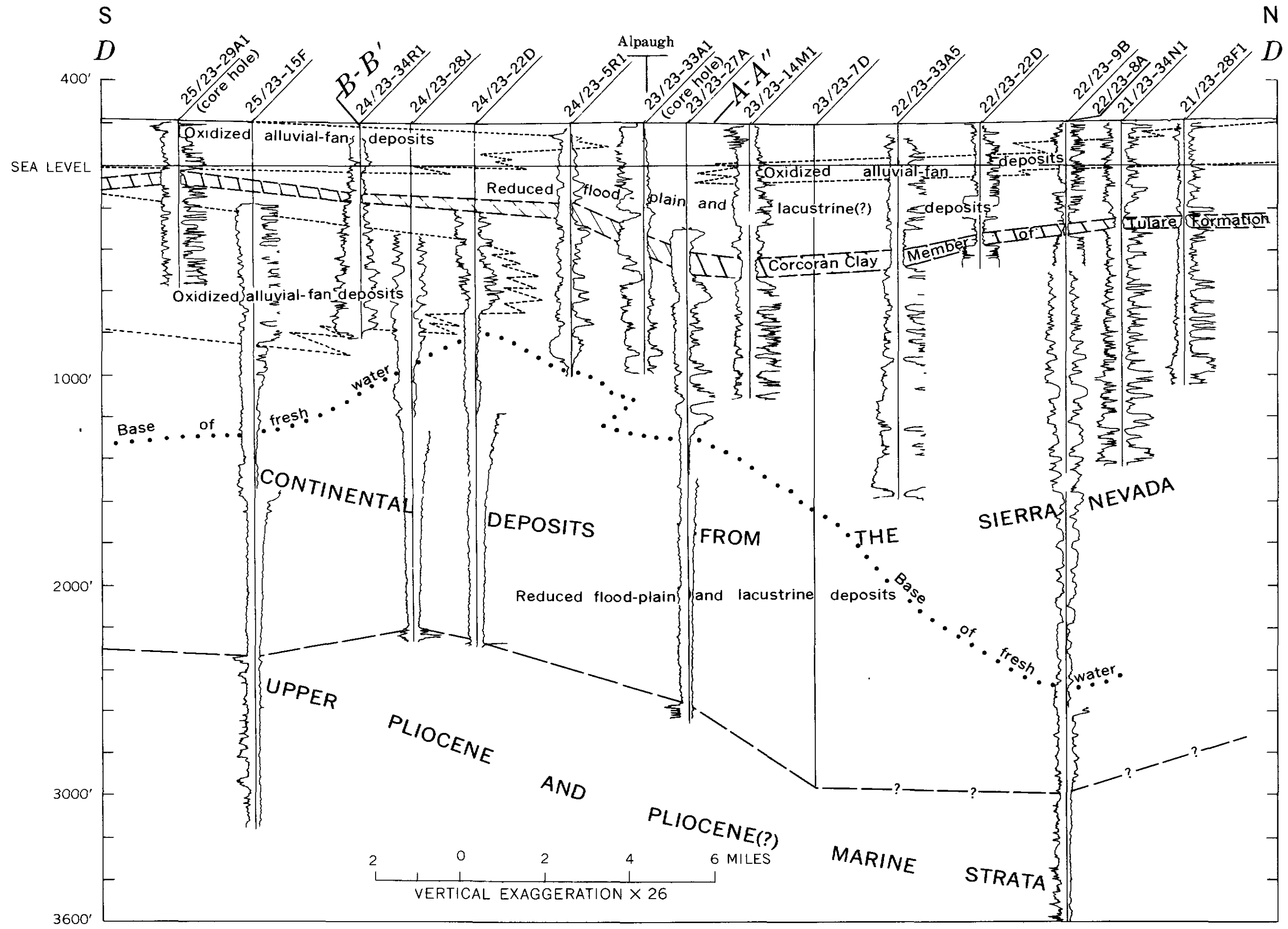


FIGURE 10.—Geologic section *D–D′* through Alpaugh. See figure 6 for location of wells and figure 4 for explanation.

As shown in geologic section *A–A″* (fig. 4), the marine strata were not penetrated by the Pixley core hole, 23/25–16N1, or by other wells on the western half of the section. The upper *Mya* zone, and thus the top of the marine strata, has been identified, however, in other deep oil-test holes in the vicinity (fig. 5), and the dashed formational contact of figure 4 is projected into the section from wells not shown.

The thin sandstone beds in this Pliocene marine siltstone sequence are tapped by a few wells, but the overall transmissibility of the siltstone unit is very low; thus it contributes little ground water to wells. Beneath about two-thirds of the Tulare-Wasco area, the sands still contain saline water that is unusable for ordinary purposes. Therefore, this unit is not important as a source of fresh water, nor is it an appreciable factor in the problem of land subsidence in most of the area.

SANTA MARGARITA FORMATION AS USED BY DIEPENBROCK (1933)

On the basis of electric-log correlations north from the Mount Poso oil field, the marine sand immediately

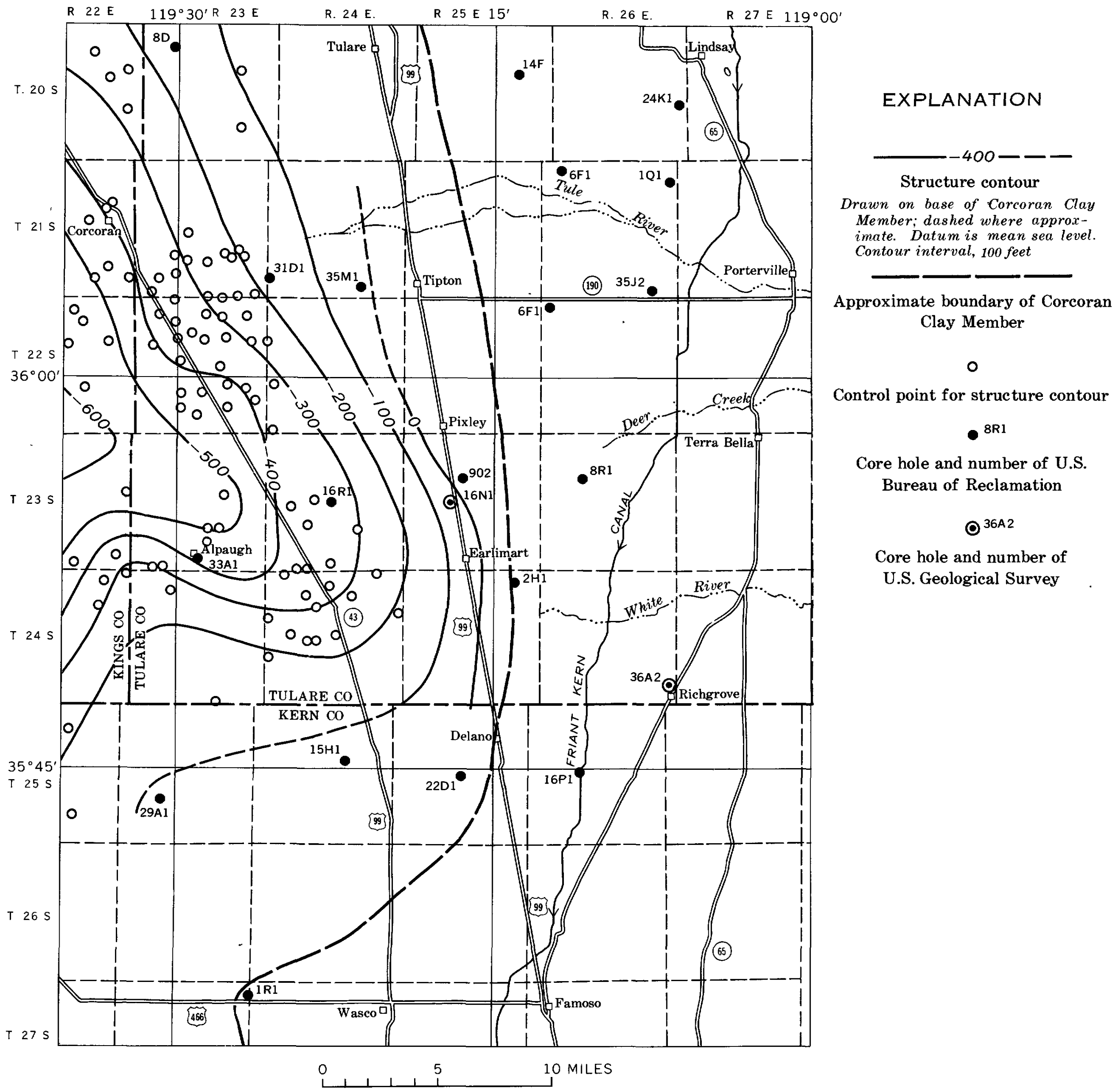


Figure 11.—Structure and extent of the Corcoran Clay Member of the Tulare Formation, and location of core holes.

below the siltstone sequence is correlated with the Miocene Santa Margarita Formation as used by Diepenbrock (1933). He noted (1933, p. 13) that the name, as he used it, is of local significance and therefore that this unit may not be correlative with the type Santa Margarita Formation as defined in the vicinity of Santa Margarita.

Along the east side of the Tulare-Wasco area, Diepenbrock's Santa Margarita occurs as a well-defined subsurface unit. It ranges in thickness from about 150 feet (geologic section *A–A″*, fig. 4) to as much as 520 feet (geologic section *C–C′*, fig. 9). Basinward the formation is represented by organic shale facies that may be as much as 6,000 feet thick (Hoots and others, 1954, p. 122). About 300 feet of the Santa Margarita was penetrated by the Richgrove core hole, 24/26–36A2 (figs. 5, 8). Core samples show the formation to consist of greenish-gray to bluish-gray loose to well-indurated clayey very fine to coarse arkosic sand and thin streaks of fine gravel.

About 20 water wells tap the Santa Margarita in the vicinity of Richgrove. Most of these wells are also perforated in overlying aquifers and do not give specific information on the water-yielding characteristics of the Santa Margarita. Six deep irrigation wells perforated exclusively in the Santa Margarita, however, yield up to 1,950 gpm; they indicate that this unit is highly permeable. The Santa Margarita also serves as an important ground-water aquifer in a limited area near Richgrove.

TERTIARY SEDIMENTARY DEPOSITS, UNDIFFERENTIATED

Beneath the sands of Diepenbrock's (1933) Santa Margarita Formation along the east edge of the valley is a sequence of semiconsolidated to consolidated sand, silt, and clay of Miocene or greater age which is here termed Tertiary sedimentary deposits undifferentiated. This sequence crops out in the foothills south of White River and is shown in figure 6 as consolidated sedimentary rocks of Tertiary age. Although oil in several nearby oil fields is derived from sediments of this unit, no water wells in the Tulare-Wasco area are known to tap these deposits. For the most part, water in these deposits is highly saline and unusable for most purposes.

Park and Weddle (1959, pl. 2) have subdivided this sequence of Tertiary deposits overlying the basement complex into the Round Mountain Silt, Olcese Sand, Freeman-Jewett Silt, Pyramid Hill Sand, Vedder Sand, and Walker Formation. All except the Walker Formation are of marine origin. Of these, Hilton, McClelland, Klausing, and Kunkel (1963, table 3) consider only the Olcese Sand and the Pyramid Hill and Vedder Sands as potential sources of ground water. Potable water from these sands would be limited to a narrow belt east of Richgrove (fig. 5).

As observed in geologic sections *A–A″* (fig. 4) and *B–B′* (fig. 5) the undifferentiated Tertiary sedimentary deposits dip steeply valleyward and range in thickness from about 200 feet to more than 2,000 feet. These deposits crop out near Poso Creek and in this area have been described by Albright, Hluza, and Sullivan (1957, p. 13) and Diepenbrock (1933, p. 14–16). For a more detailed description of the deposits beneath the Santa Margarita, reference is made to Hilton, McClelland, Klausing, and Kunkel (1963).

SIERRA NEVADA BASEMENT COMPLEX

Rocks of the Sierra Nevada basement complex crop out along part of the east margin of the Tulare-Wasco area (fig. 6) and extend westward beneath the area. The dominant rock types are igneous rocks ranging in composition from granite to gabbro and metamorphic rocks consisting of quartzite, schist, gneiss, and crystalline limestone. That the basement complex is found in wells at increasing depths in a westward direction indicates that the westward-tilted Sierran mountain block dips beneath the younger sedimentary deposits in this part of the valley (figs. 4, 5).

In general, the structural contours on top of the basement complex (Smith, 1964) roughly parallel the surface contours but do so with an apparent westward dip of 400–800 feet per mile. This dip generally steepens toward the west and also toward the south and thus suggests that tectonic warping in the valley trough accompanied the tectonic uplift of the mountain block. The depth of the basement complex below the land surface increases from 0 feet east of Porterville to 7,200 feet at Pixley and about 11,000 feet at Corcoran. For the purposes of this investigation, the Sierran basement rocks are considered both non-water bearing and noncompactible under changes in load.

CLAY-MINERAL ASSEMBLAGE IN CORED SEDIMENTS

As summarized by Meade (1964, p. 20), the removal of water and the compaction of clayey sediments under increased effective stress are complex functions of particle size, clay minerals and associated ions, interstitial-electrolyte concentration, acidity, temperature, and the arrangement of particles at the onset of compaction. Of these, particle size is perhaps the most significant factor.

The response of water-saturated clayey sediments to compacting stresses is directly related to forces associated with clay-mineral surfaces. Because of the large surface areas of clay minerals, these forces are more effective than are the gravitational forces associated with the particle mass. Surface effects are especially significant in the very fine grained montmorillonitic clay minerals, which have a specific surface (surface area per unit mass) 10–100 times as great as other clay minerals (Meade, 1964, p. 6). The finer grained clayey sediments are more porous under a given load and more compressible under a given change in load than the coarser silty sediments (Meade, 1964, fig. 3). Also, clays rich in montmorillonite are more porous and more compressible under a given load or change in load than clays that consist mainly of the other clay minerals (Meade, 1964, fig. 4).

From detailed study of core samples from the Pixley and Richgrove core holes (figs. 7, 8), Meade (1967, p. 116) found that the principal clay mineral of the sediments tapped by water wells in the Tulare-Wasco area is montmorillonite. Subsidiary minerals include illite, a kaolinite-type mineral, and vermiculite, with lesser amounts of chlorite and a low-grade illite-montmorillonite mixture. The average clay-mineral composition of these sediments is approximately as follows (Meade, 1967, p. 117):

	Nonmarine sediments (nearest 5 percent)	*Marine siltstones (nearest 5 percent)*
Montmorillonite	60	80
Illite	20	5
Kaolinite-type mineral	10	5
Vermiculite	10	0
Chlorite	0	5
Mixed-layer illite-montmorillonite	Trace	Trace

The total clay-mineral content of the sediments from the Pixley and Richgrove core holes is estimated (Meade, 1967, p. 120) to be as follows:

	Total clay minerals (percent)	*Total montmorillonite and vermiculite (percent)*
Nonmarine sediments	15	10
Marine siltstones and sands	25	20
Santa Margarita Formation as used by Diepenbrock (1933)	<2	<2

SURFACE WATER

NATURAL STREAMS

Four natural streams enter the Tulare-Wasco area from the Sierra Nevada on the east (fig 2). Tule River, the only major stream, has long been an important source of irrigation supply. The other streams—Deer Creek, White River, and Poso Creek—flow only intermittently and in most years supply only small quantities of water to the valley.

The Tule River is the only natural stream for which long-term discharge records are available. Figure 12 shows the discharge of Tule River for the period of record 1902–64. During this period the locations of gaging stations along Tule River were moved several times, and the recorded discharge measurements are not entirely comparable throughout the period. The inconsistencies, however, are relatively small. The annual discharge of the river is here reported for the water year October 1 through September 30. Inasmuch as changes in ground-water level, subsidence of surface bench marks, and computations of land subsidence and compaction are considered primarily on a calendar-year basis in subsequent chapters, stream discharge also is reported by calendar year hereafter. As shown in figure 12, the yearly discharge fluctuates widely from a high of about 340,000 acre-feet in 1906 (excluding South Fork runoff) to less than 20,000 acre-feet in 1931 and 1961 (South Fork runoff included). Since the completion of Success Reservoir on the Tule River (partial regulation began in 1961), the discharge has been regulated.

Streamflow measurements of Deer Creek, White River, and Poso Creek were made by the Bureau of Reclamation for a number of years between 1952 and 1960. In those years the annual discharge of Tule River represented between 65 and 75 percent of the combined flow of the four streams entering the Tulare-Wasco area. The flows of Deer Creek, White River, and Poso Creek composed the remaining 25–35 percent of the natural surface inflow. In this report the combined flow of these three intermittent streams has been estimated as three-sevenths of the annual discharge of Tule River. This quantity was the basis for the estimate of combined discharge of Deer Creek, White River, and Poso Creek shown in figure 14.

CANALS

In addition to discharge from the natural streams, canal diversions from the Kern and Kaweah Rivers and, since 1950, from the Friant-Kern Canal have been an important source of irrigation supply. Water is imported from the Kern River via the Lerdo and Calloway Canals of the Kern County Land Company. Prior to deliveries from the Friant-Kern Canal, surface water generally was not available after June of each year, so during the late summer and autumn months ground water was usually the only source of supply.

The Friant-Kern Canal was constructed by the Bureau of Reclamation as part of the Central Valley Project. Diverting water from Millerton Lake (storage capacity 520,500 acre-ft) on the San Joaquin River, the Friant-Kent Canal has provided a major part of the irrigation water used in the Tulare-Wasco area since 1950. Water from the Friant-Kern Canal has supplemented surface supplies from the natural streams and has greatly reduced the ground-water pumpage within the canal service area.

The first 70 miles of the Friant-Kern Canal was in operation by July 1949. Deliveries of water were first made to the Tulare and the Lindsay-Strathmore Irrigation Districts (fig. 13) in the fall of that year. By 1950, construction had progressed, so that deliveries were being made as far south as White River and the Delano-Earlimart Irrigation District. During 1951, water deliveries extended into Kern County, and construction was virtually completed in 1952. Contracted surface-water deliveries were made throughout the area as rapidly as distribution systems in the individual districts could be provided. The actual water deliveries to the various irrigation districts from the Friant-Kern Canal through 1964, as reported by the Bureau of Reclamation, are given in table 3. The locations of the districts are shown in figure 13.

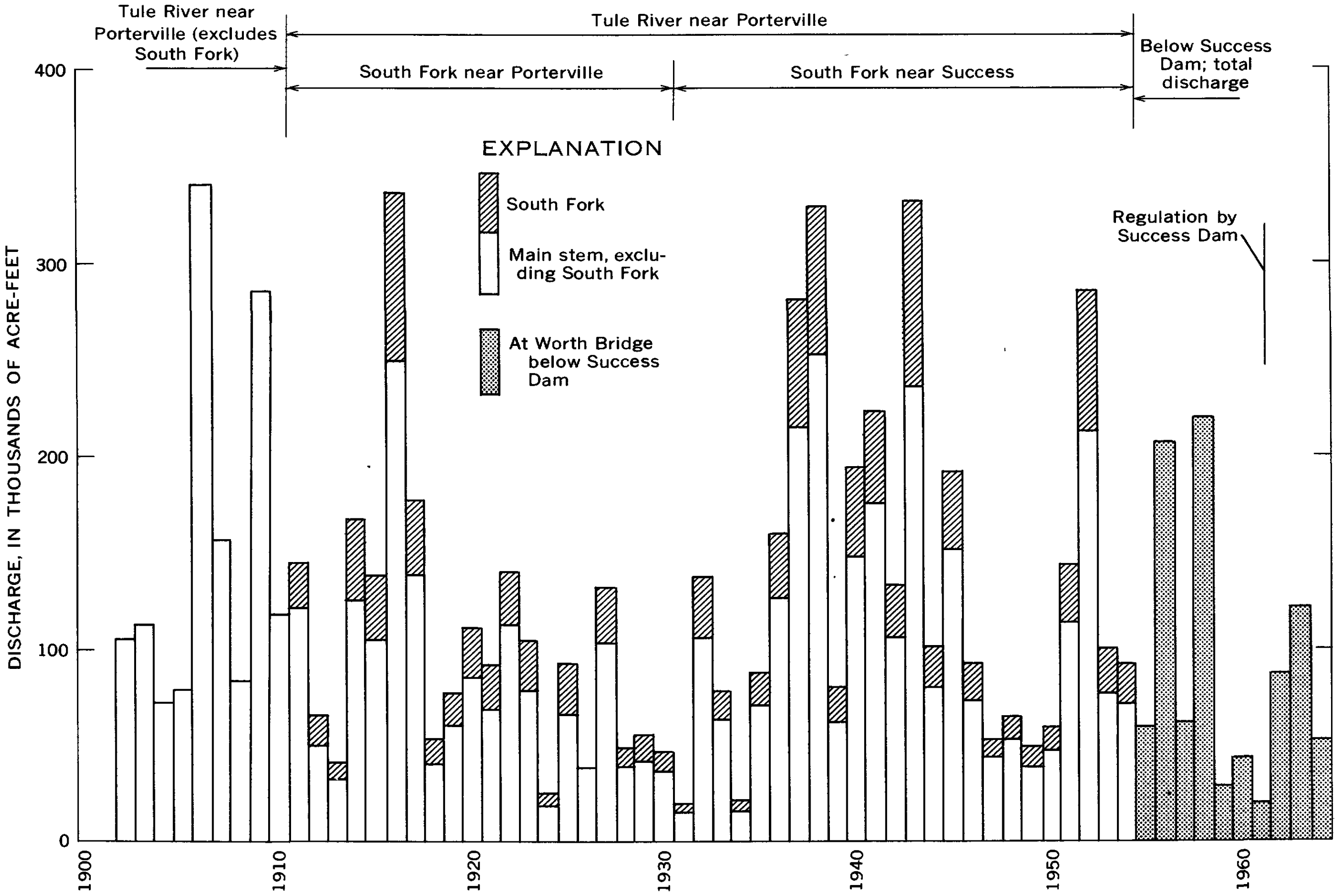


Figure 12.—Discharge of Tule River, 1902–64. For water year October 1 through September 30. Data from U.S. Geological Survey Water-Supply Papers 1315–A and 1735, and annual summaries since 1960.

Table 3.—*Surface-water deliveries from the Friant–Kern Canal to irrigation districts in the Tulare–Wasco area, 1949–64*

[In thousands of acre-feet per calendar year; data from U.S. Bur. Reclamation]

District [1]	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964
Alpaugh										3.0		1.2				
Cloer								0.4		0.2	0.1			0.1	0.2	
Delano-Earlimart		5.4	33.6	64.8	72.6	98.0	135.7	172.3	162.0	150.4	151.3	109.8	87.1	169.5	162.3	127.7
Lindmore		1.7	8.8	29.0	44.8	48.0	52.4	47.5	47.3	44.5	41.5	34.1	27.4	53.3	45.0	40.6
Lindsay-Strathmore	4.3	2.2	11.0	7.0	13.2	17.0	17.2	15.6	16.9	17.1	24.0	20.1	21.5	18.5	12.7	19.1
Lower Tule River		76.1	94.2	153.0	196.5	170.0	211.6	271.4	245.7	226.6	194.4	64.8	49.0	326.6	307.7	124.7
Pixley										23.2	20.3			48.5	51.8	6.0
Porterville		7.4	5.3	8.2	8.0	4.9	4.7	6.6	5.0	5.8	7.2	9.1	10.2	21.1	19.6	18.9
Rag Gulch					2.0	5.9	0.3	6.4	2.9	6.0	4.2		5.4	6.3	8.9	1.0
Saucelito		8.0	23.5	29.6	29.3	29.6	29.4	33.7	33.4	30.8	26.7	20.1	16.2	48.4	46.7	28.9
Shafter-Wasco									2.1	32.9	42.5	45.9	36.2	46.9	45.3	54.9
South San Joaquin			22.3	40.4	72.2	94.9	105.9	124.0	114.9	101.3	101.6	94.7	76.6	130.3	124.5	114.6
Tea Pot Dome												0.4	3.6	3.6	3.2	4.4
Terra Bella		1.9	5.0	4.7	5.4	7.3	7.6	7.1	8.0	6.1	9.0	9.6	8.6	11.3	9.6	14.5
Tulare	26.5	60.0	100.1	75.0	129.0	151.5	159.0	182.9	150.1	152.0	101.3	31.4	32.3	211.4	204.0	82.2
Total (rounded)	31	163	304	412	573	627	724	868	788	800	724	441	374	1,096	1,042	638

[1] For district location and complete name, see fig. 13.

Several of the districts listed in table 3 extend beyond the boundaries of the Tulare-Wasco area. The amount of water shown in table 3 that is used outside the area, however, is small in proportion to the total deliveries. The tabulated deliveries of table 3 are thus used herein as an approximation of the total Friant-Kern deliveries within the Tulare-Wasco area.

SURFACE-WATER SUPPLY

Figure 13 shows schematically the quantities of surface water that were diverted for irrigation and ground-water recharge from the various sources in the Tulare-Wasco area during 1960; it also shows the boundaries and names of the incorporated districts that received and distributed this water. Several of the quantities

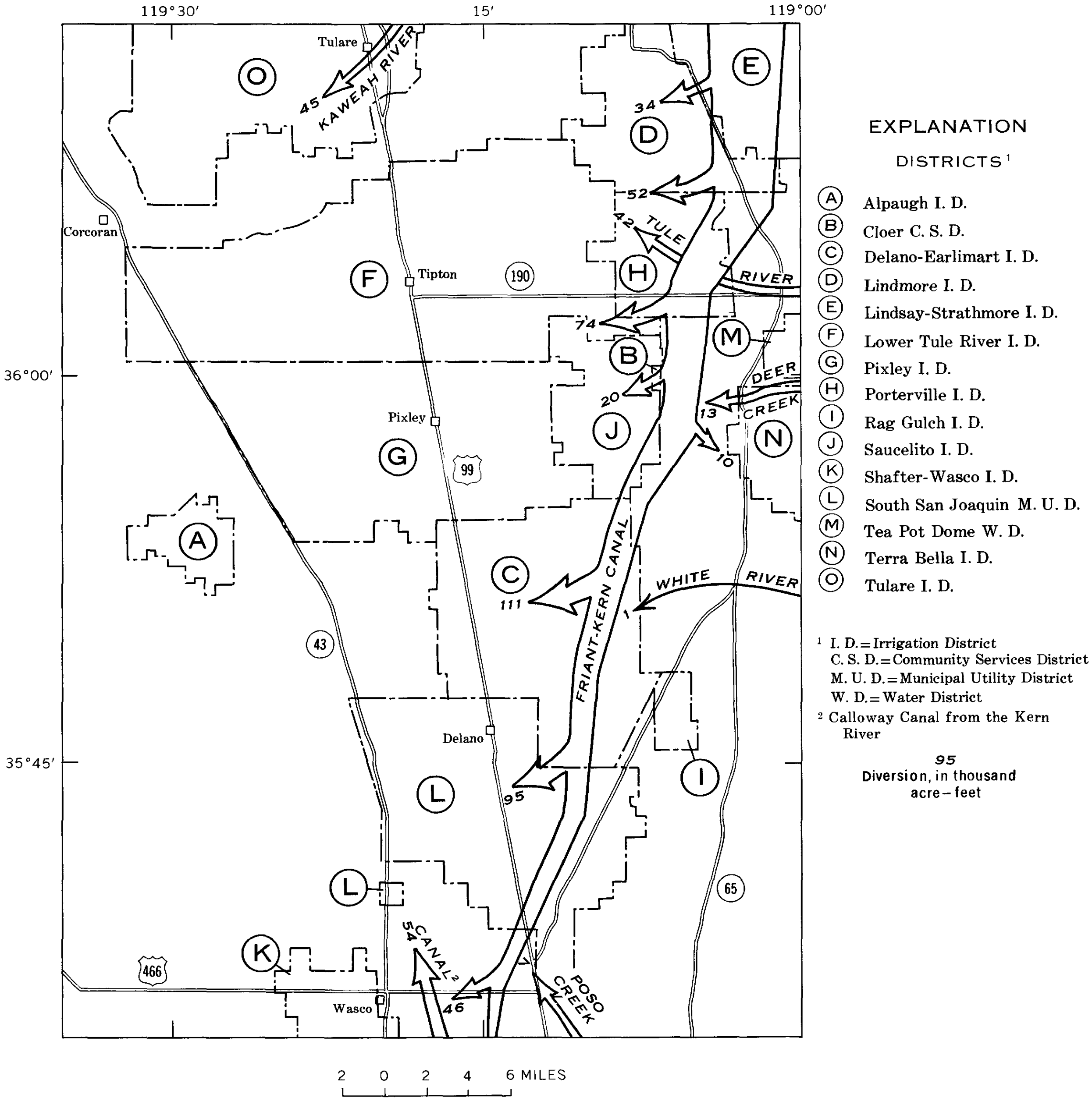


FIGURE 13.—Surface-water diversions during 1960, in thousands of acre-feet, and boundaries of incorporated districts receiving water from the Friant-Kern Canal.

given in figure 13 are not identical to quantities in table 3 because, at some places, diversions to several districts have been lumped to simplify the diagram.

The approximate amounts of surface water distributed for irrigation and ground-water recharge in the Tulare-Wasco area from 1930 through 1964 are shown in figure 14. Canal imports from the Kern and Kaweah Rivers are not included. Neither is the measured discharge (inflow) of Tule River corrected for outflow to Tulare Lake. Prior to closure of Success Dam on the Tule River in 1962, part of the discharge of Tule River flowed out of the Tulare-Wasco area to Tulare Lake bed in years when Tule River discharge exceeded about 130,000 acre-feet (California Department of Public Works, 1922, p. 40). In years of high stream discharge, however, canal imports from the Kaweah and Kern Rivers to the Tulare-Wasco area probably compensated for much of the outflow of Tule River discharge to Tulare Lake. Furthermore, Tule River discharge has appreciably exceeded 130,000 acre-feet only in 2 years since 1950 (fig. 14).

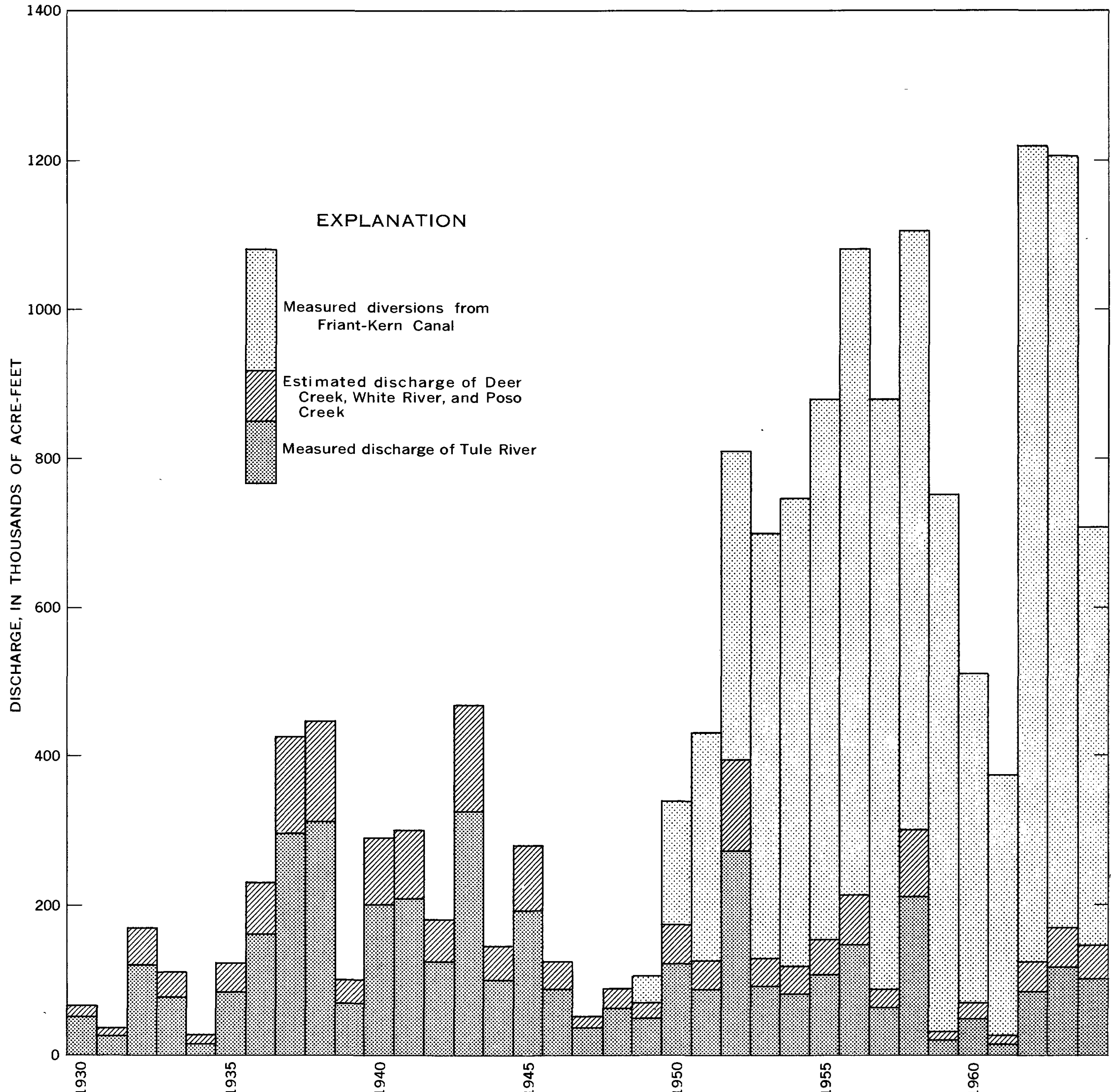


FIGURE 14.—Surface-water supply, 1930–64, exclusive of canal imports from the Kern and Kaweah Rivers (calendar year).

The most striking feature of figure 14 is the effect of deliveries of Friant-Kern Canal water on total surface-water supply. From 1950 through 1964, the annual deliveries from the Friant-Kern Canal ranged from 51 percent (1952) to more than 96 percent (1959) and averaged roughly 80 percent of the surface-water inflow to the area. This influx of a dependable, economical irrigation supply has had a marked effect on ground-water pumpage in the area and indirectly on the magnitude and rate of subsidence that has occurred.

Most of the water diverted from the Friant-Kern Canal is delivered for direct irrigation during the growing season. Some of the water, however, especially during the early years of construction and during years of plentiful runoff, has been deliberately spread as ground-water recharge, but few of the irrigation districts have made measurements of the amount of water diverted for this purpose. The Delano-Earlimart Irrigation District, which since 1955 has received from 15 to 25 percent of the Friant-Kern water delivered in the area (table 3), diverted the following amounts of canal water into spreading areas for ground-water recharge from 1950 through 1964:

Year	Acre-feet	Year	Acre-feet
1950	1,580	1958	4,030
1951	6,280	1959	0
1952	11,430	1960	0
1953	7,690	1961	0
1954	5,200	1962	0
1955	10	1963	5,623
1956	1,860	1964	0
1957	1,920		

GROUND WATER

GENERAL FEATURES

The unconsolidated continental deposits that form the westward-thickening wedge of Sierran detritus constitute the principal source of ground water in the Tulare-Wasco area (figs. 4, 5, 9, 10). These deposits comprise the extensive sand and gravel aquifers and the less extensive fine-grained aquitards of the ground-water reservoir. In the eastern part of the area, the thin sands within the poorly permeable marine siltstones and the underlying permeable sand of the Santa Margarita Formation of Diepenbrock (1933) also supply water to wells.

Recharge to the ground-water reservoir is primarily from precipitation that falls on the tributary watershed east of the Tulare-Wasco area and that enters the ground-water reservoir as deep percolation from the Sierran streams or from the stream diversions and as underflow from the foothill recharge areas. Thus, runoff from Tule River, and to a lesser extent, from Poso Creek, Deer Creek, and White River plays a dominant role in the recharge of the ground-water reservoir. Imports from canals, largely from the Friant-Kern Canal since 1949, also serve as a major source of ground-water recharge. Very little recharge results from precipitation falling within the Tulare-Wasco area proper. Of the 9 inches of precipitation that falls within the Tulare-Wasco area in an average year, less than 1½ inches is "effective" in supplying agricultural requirements (computed by method of Blaney and Criddle, 1950), and probably only a trivial amount percolates down to the water table.

In general, ground water moves westward across the Tulare-Wasco area in much the same direction as the Sierran streams that laid down the sediment now composing the aquifers. In this westward circulation, ground water moves from recharge areas of little confinement through regions of increasing confinement, and in the western part of the area it passes either over or under the lip of the principal confining clay—the Corcoran Clay Member of the Tulare Formation. Under each of these conditions—unconfined, semiconfined, and confined—ground water moves in the direction of maximum hydraulic gradient; that is, from recharge areas of high water level to pumping areas of depressed water level. The direction of movement at any particular time and place can be determined from detailed maps showing the altitude of the water table or of the piezometric surface in confined aquifer systems.

Prior to intensive development, discharge from the ground-water reservoir was by upward percolation from the confined and semi-confined aquifer systems to surface drains or evapotranspiration and by subsurface outflow toward the valley trough. For many years, however, little ground water has discharged naturally, as water levels in all the aquifer systems have been depressed far below the land surface. In spite of the very large surface-water imports from the Friant-Kern and other canals since 1950, pumpage still exceeds replenishment in some years. Pumpage, therefore, represents the principal discharge from the ground-water reservoir under present conditions, but subsurface outflow to the west still occurs in both the semiconfined and the confined aquifer systems.

HISTORY OF DEVELOPMENT

From 1849 to 1870, land in the Tulare-Wasco area was used chiefly for grazing cattle (Small, 1926, p. 310). Hay and other forage crops necessary for the production of livestock were obtained by dry farming until about 1855, at which time the practice of irrigating pasture and cropland with water diverted from streams was initiated.

Following the construction of the Southern Pacific Railroad in 1871–73, a rapid surge in land development occurred. With this new means of transporting farm products to market, there was a transition from the raising of cattle to the growing of cereal grains. By the late 1870's and early 1880's much of the arable land was utilized for growing wheat. Beginning about 1885 there was another transition, from the growing of predominantly grain crops to diversified farming. This change was due largely to the increasing population and to the increased use of surface and ground water for irrigation. By 1886, the total irrigated area was about 40,000 acres.[3] Most of this area was irrigated with water diverted from the Kaweah and Tule Rivers. Smaller acreages were irrigated along Deer Creek and White River. In the southern part of the area about 8,000

[3] W. H. Hall, 1886. Unpublished topographic and hydrologic maps of the San Joaquin Valley, Calif., on file in the archives of the California Department of Water Resources.

acres was irrigated with water imported by canals from the Kern River.

The drilling of a flowing well near Tipton in 1875 by the Southern Pacific Co. stimulated interest in the development of ground water for irrigation purposes. In 1881, a well drilled to a depth of 330 feet on a ranch 4 miles west of Tulare flowed at a rate of about 30 gallons per minutes (Small, 1926, p. 300). Subsequently, many flowing artesian wells were drilled west of the Southern Pacific Railroad. Hall[4] reported 93 flowing wells in the area in 1886. Many of these flowing wells were unregulated, and much of the flow was wasted.

The use of ground water for irrigation rapidly expanded beyond the area of surface-water diversion and outside the area of artesian flow. In 1891, several wells were drilled near Lindsay to provide irrigation water for citrus crops. At the time the wells were drilled, water levels were reported to be about 20 feet below land surface (Menefee and Dodge, 1913, p. 88). The introduction of electrically powered pumping plants about 1900 accelerated the drilling of irrigation wells. By 1905, the number of irrigation wells in the area had increased to about 300 (Mendenhall and others, 1916, p. 252–295).

By 1920–21, an estimated 183,000 acres, 20 percent of the Tulare-Wasco area, was irrigated (fig. 15). Most of this acreage was in the northern part of the area, where surface streams supplied the bulk of the irrigation demands and ground water was used as a supplemental supply during periods of low streamflow. In the southern and western parts of the area, where surface supplies were inadequate or absent, irrigation depended entirely on ground water. Data are not available to differentiate in figure 15 the areas irrigated solely by ground water.

The early exploitation of ground water caused artesian water levels to fall rapidly, and by the late 1920's most of the flowing wells had ceased to flow. The period 1921 to 1939 was a time of accelerated increase in ground-water pumpage. By 1939, water levels had declined 125 feet between Delano and Richgrove (Ingerson, 1941, p. 34–35). Land development and the use of ground water continued to increase from 1939 to 1945.

Immediately following World War II, extensive undeveloped areas were brought into production. The accelerated use of ground water caused another surge of water-level decline, especially in areas of intensive pumpage and restricted recharge. During the 4-year period from 1945 to 1949, water levels declined as much as 25 feet near Lindsay, 30 feet near Pixley, and about 80 feet in the Delano-Richgrove area.

[4] Unpublished reports, field notes, and hydrologic maps of the San Joaquin Valley, Calif., on file in the archives of the California Department of Water Resources.

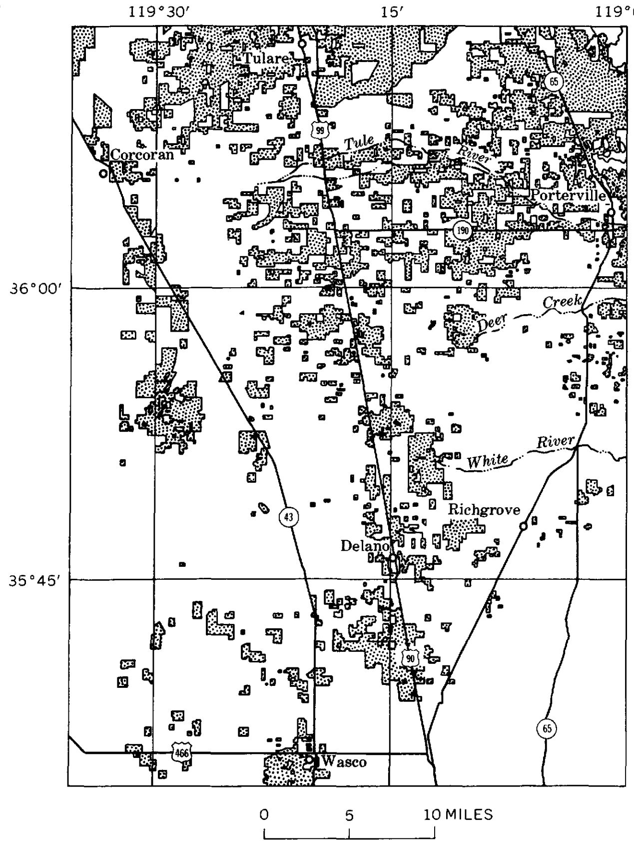


FIGURE 15.—Land irrigated in 1920–21 (shaded). Data from California Department of Engineering (1921) and California Department of Public Works (1922).

Prior to 1949, irrigation in the Tulare-Wasco area depended almost wholly on local supplies. With the importation of surface water from the San Joaquin River via the Friant-Kern Canal beginning in 1949, however, additional acreage was cultivated. Also, much of the ground-water pumping was supplanted by surface diversions from the Friant-Kern Canal. In the area served by the Friant-Kern Canal agricultural expansion continued until about 1958, when roughly half of the Tulare-Wasco area (456,500 acres, based on unpublished crop survey by the California Department of Water Resources, 1958) was under irrigation (fig. 16). As of 1958, most of the unirrigated area was either along the eastern foothills, where irrigation water is presently unavailable from either surface or underground sources, or in a crescentic area delineated roughly by the historic shorelines of Tulare Lake, where ground-water quality and soil conditions are marginal. Information is not available to discriminate in figure 16 the areas irrigated solely or partly by ground water.

During the period from 1949 to 1959, surface-water imports from the Friant-Kern Canal had a marked

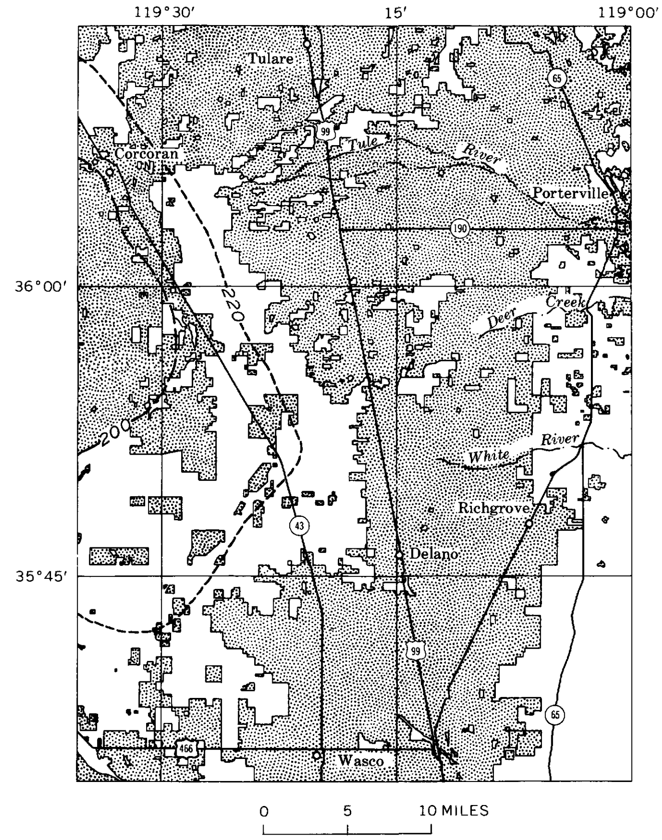


FIGURE 16.—Land irrigated in 1958 (shaded). Dashed contours show the eastern extent of Tulare Lake—220 feet above sea level in 1862, 1868, and 1878 and 200 feet above sea level in 1880. Data from unpublished crop survey of California Department of Water Resources (1958).

effect on ground-water trends within the service area. Water levels rose as much as 150 feet near Lindsay and as much as 40–170 feet in the Delano-Richgrove area. At only a few places within the general service area, particularly between Pixley and Earlimart, did water levels continue to decline. Deficient stream runoff in 1959, 1960, and 1961 (fig. 14) caused a renewed surge of ground-water pumping throughout most of the area. Many irrigation pumps that had been idle for 6–8 years were operated, and water levels temporarily resumed a downward trend.

HYDROLOGIC UNITS

Ground water is generally thought of as occurring under either unconfined (water table) or confined (artesian) conditions. In the Tulare-Wasco area, however, ground water occurs almost wholly under semiconfined or confined conditions. As shown diagrammatically in figure 17, fresh ground water occurs in (1) a semiconfined aquifer system that underlies the entire area, and that extends down to the top of the Corcoran Clay Member in the western part of the area and to the top of the marine strata or to the base of the fresh-water body in the eastern part; (2) a confined aquifer system beneath the confining Corcoran Clay Member in the western part of the area that extends down to the base of the fresh-water body; and (3) a deep confined aquifer tapped only in the Richgrove area, the Santa Margarita Formation as used by Diepenbrock (1933).

SEMICONFINED AQUIFER SYSTEM

The semiconfined aquifer system underlies all the Tulare-Wasco area except where the impermeable Sierran basement complex rises above the water table along the northeast border. In the western part of the area, the semiconfined water body in this aquifer system occupies all but the uppermost part of the deposits extending from the land surface to the top of the Corcoran Clay Member. The thickness of these deposits ranges from about 200 feet at Delano and Pixley to 700 feet northwest of Alpaugh. In 1905, the top of the semiconfined water body overlying the Corcoran was 5–20 feet below the land surface. East of the boundary of the Corcoran Clay Member, the deposits containing the semiconfined water body extend from the land surface down to the top of the marine siltstones of Pliocene age or to the base of the fresh-water body. In most of this eastern area, the thickness of the deposits containing the semiconfined water body ranges from a few hundred to 1,400 feet. The depth to the water table in 1905 was generally less than 100 feet but ranged from 10 to 20 feet at the east boundary of the Corcoran Clay Member to 150 feet or more locally at the east edge of the Tulare-Wasco area. (See 1905 water-table profile, fig. 17.)

In the eastern part of the area, the semiconfined aquifer system can be separated into two units: (1) a shallow, highly permeable zone that underlies much of the area and (2) a deep zone that is hydraulically continuous with the shallow zone but in which confinement increases with depth. The contact between these zones is readily recognized on many of the electric logs and is shown as the contact between the upper slightly weathered alluvium and the lower highly weathered alluvium in figures 4, 5, and 9.

The shallow zone in the semiconfined aquifer system occupies the uppermost part of the unconsolidated continental deposits and ranges in thickness from about 100 to as much as 300 feet. The most permeable deposits in this zone are along the White River, Deer Creek, and the Tule River. During the early years of agricultural development, water for irrigation was pumped almost exclusively from this zone. As water levels declined, deeper wells were drilled and many of the shallow wells were abandoned or restricted to domestic and stock use.

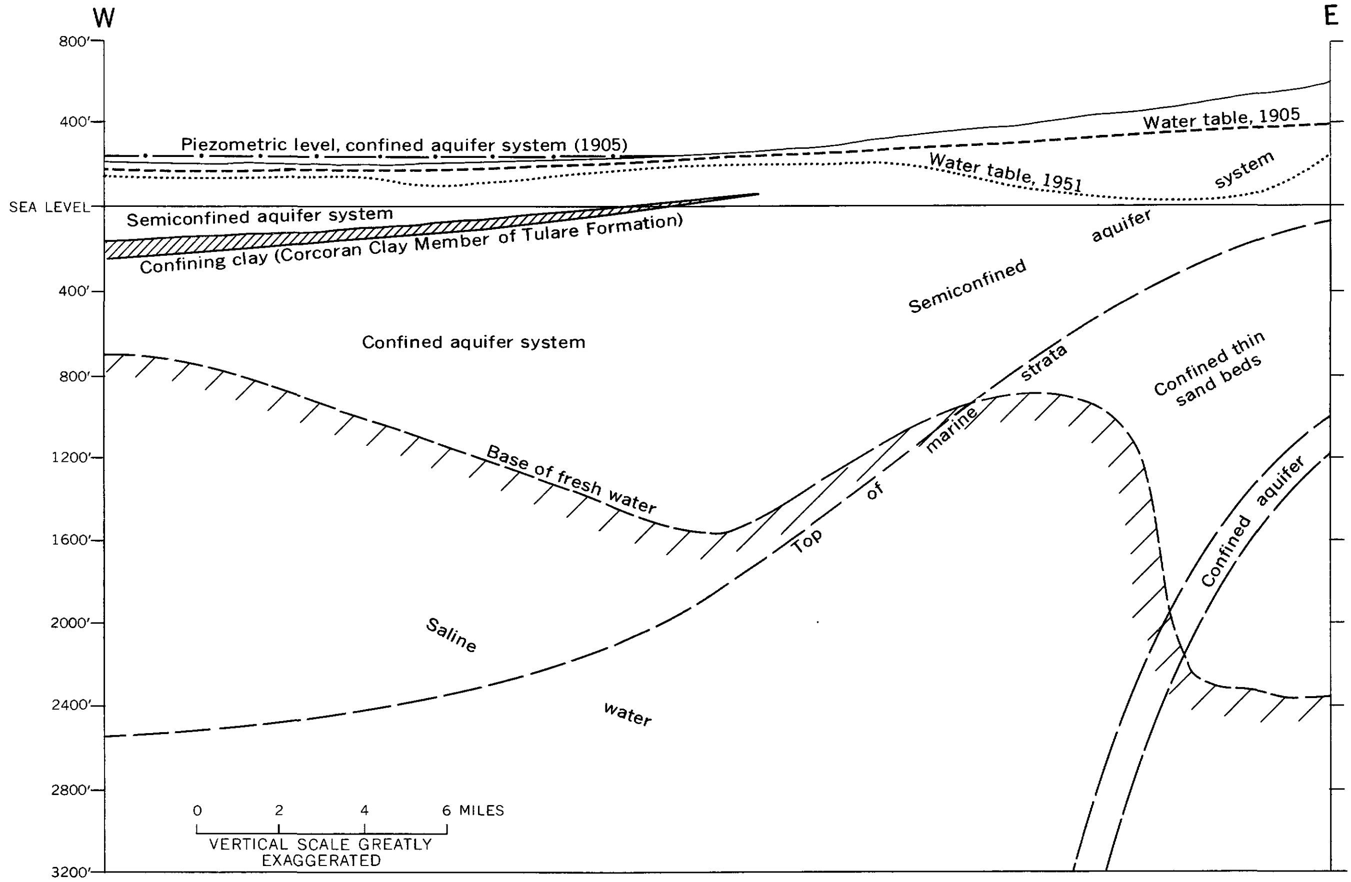


FIGURE 17.—Generalized east-west hydrologic section. Alinement same as for figure 4.

At the present time irrigation wells pump from the shallow zone only along Tule River in the vicinity of Porterville.

The water-table map for 1905 (fig. 22) and the 1905 profile (fig. 17) depict the top of the zone of saturation as determined from measurements of depth to water in wells that were almost all less than 300 feet deep; thus they represent the water table in this shallow zone. By 1951, however, the water table had been drawn down to depths below 200–300 feet in most of the eastern part of the area (see 1951 water-table profile, fig. 17) and hence was below the base of this shallow zone.

The deep zone in the semiconfined aquifer system extends eastward from the east margin of the Corcoran Clay Member and is hydraulically continuous with the confined aquifer system beneath the Corcoran. Wells tapping the deep zone range in depth from about 400 to more than 1,000 feet. Although data are insufficient to determine the actual pumpage from the deep semiconfined zone, probably half the ground water pumped for irrigation in the entire area comes from this sequence of deep continental deposits in the semiconfined aquifer system.

In general, the deeper sand and gravel aquifers show the effects of confinement more than the shallower ones. The degree of confinement also increases from east to west as more and more silt and clay beds interfinger from the west. Before intensive development, water levels in these various discontinuous beds rose to about the same common level, and contour maps could be drawn to represent the composite water surface of this semiconfined aquifer system. Intensive pumping from these beds, however, especially since 1930, has developed differences in head between the various strata of the system. These variations are greatest during the summer months of heaviest pumping, but also persist to a lesser degree through the months of winter recovery.

The perforated interval and variation of water level in water wells of different depths along two east-west lines in the Tulare-Wasco area are shown in hydrologic sections A'–A'' and B–B' (fig. 18). (For location see fig. 6.) As shown, in the eastern half of the area beyond the boundary of the Corcoran Clay Member, most of the wells tap only the semiconfined aquifer system in the continental deposits, and only a few wells extend down into the poorly permeable upper Pliocene marine strata

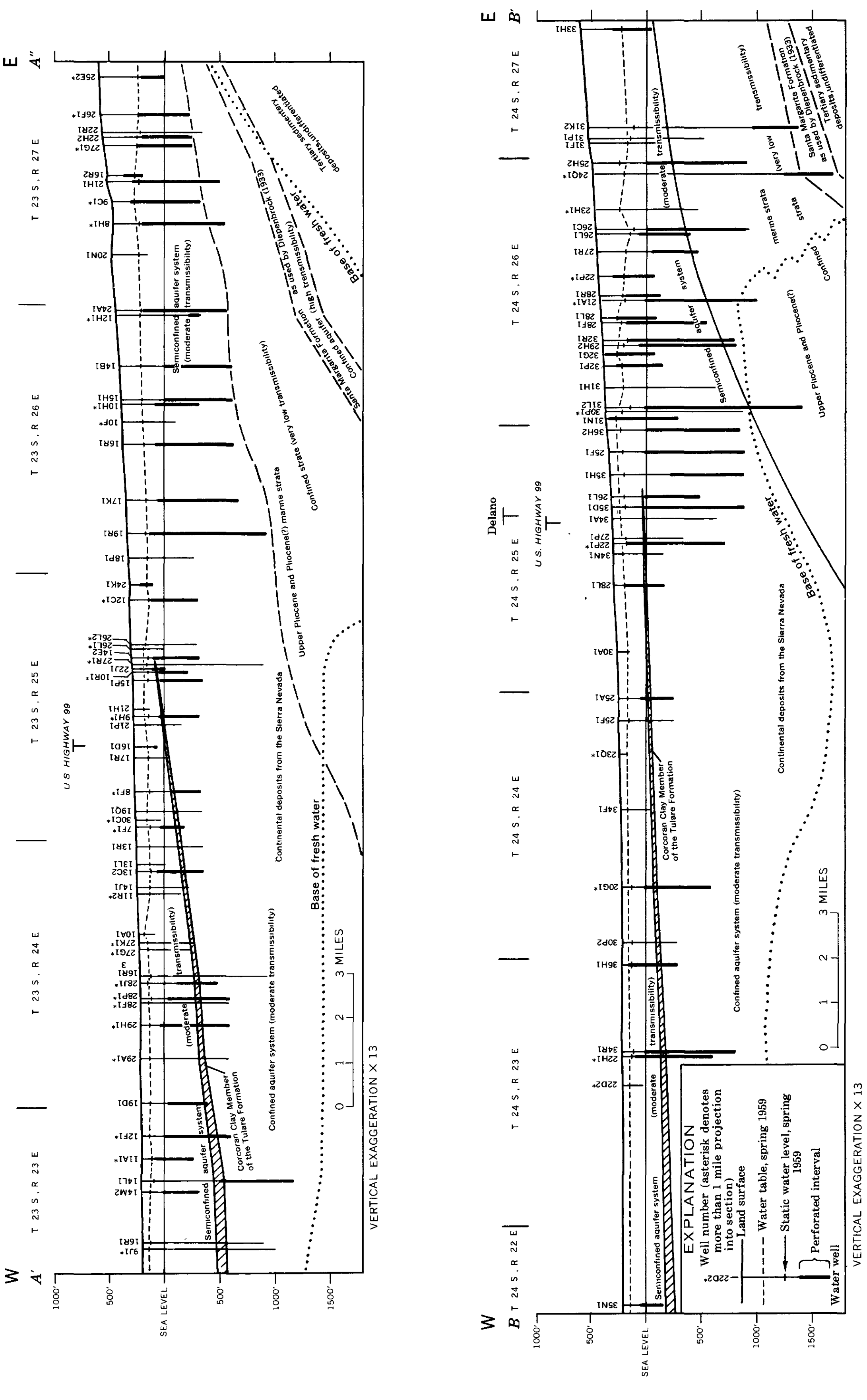


FIGURE 18.—Hydrologic sections A'–A'' and B–B' showing perforated intervals and water levels in wells. Alinement of sections shown in figure 6.

or into the underlying Santa Margarita. Most of the wells tapping the semiconfined aquifer system are perforated continuously from near the water table to the well bottom, and thus the water level in the well is a composite of the head in the various aquifers tapped. In this eastern part of the area, water levels in nearby wells of unequal depth perforated entirely in the continental sands and gravels differ by as much as 40 feet (fig. 18), the deeper wells having the lower water level. Water levels in the deep wells extending downward into the poorly permeable marine strata usually are much lower than those of nearby shallower wells. This head difference indicates that during periods of no pumping, ground water moves downward from the semiconfined continental deposits into the underlying marine strata through wells perforated in both. These consolidated marine strata do not have direct contact with stream recharge and, when drawn down by heavy pumping, may receive most of their recharge by downward movement from the overlying semiconfined beds through well casings.

Because of the wide variation in head in wells of unequal depth in the semiconfined aquifer system east of the Corcoran boundary, water level contour maps for the semiconfined system are difficult to draw. In general, however, in the eastern part of the Tulare-Wasco area, water levels in wells less than 400 feet deep are considered to represent the top of the semiconfined water body, that is, the water table at the top of the zone of saturation. On the other hand, water levels in wells more than 500 feet deep but not extending into the marine deposits beneath are considered to represent a semiconfined piezometric surface that in recent years has stood roughly 20–50 feet below the water table.

In the western half of the area overlying the Corcoran Clay Member confining layer, few wells are perforated solely within the semiconfined aquifer system (fig. 18). These shallow wells are mostly old and of small yield. Most of the larger irrigation wells drilled in recent years extend through the Corcoran and register water levels that are a composite of the semiconfined and confined pressures.

CONFINED AQUIFER SYSTEM

Figure 19 shows the areas in which deep wells tap confined aquifer systems. The principal confined aquifer system is beneath the Corcoran Clay Member. It underlies about 40 percent of the Tulare-Wasco area and extends from the base of the Corcoran down to the base of the fresh-water body (fig. 18). This aquifer system consists of the interfingering lenses and layers of continental gravel and sand, silt, and clay of Tertiary and Quaternary age and merges eastward into the deeper beds of the semiconfined aquifer system. Recharge to this confined aquifer system is almost entirely by subsurface movement under the lip of the Corcoran from the semiconfined aquifer system to the east.

The confined aquifer system is effectively separated from the overlying semiconfined system by the relatively impermeable Corcoran Clay Member of the Tulare Formation and other related clays. As shown in hydrologic sections *A′–A″* and *B–B′* (fig. 18) and geologic section *D–D′* (fig. 10), the depth below the land surface of the Corcoran Clay Member ranges from 200 to 700 feet. Throughout most of the confined aquifer, wells show rapid interference effects of nearby pumping, low storage coefficients, and other characteristic features of an artesian system. At the margin of the Corcoran, however, hydraulic continuity between the shallow and deeper aquifers increases, and the aquifer system displays the characteristics of semiconfinement.

The depths of wells tapping the sub-Corcoran confined aquifer system range from about 400 to 2,000 feet, depending partly on the depth to the top of the confined aquifer system (fig. 11) and depth to the base of fresh water (fig. 10). East of R. 23 E., most of the wells are less than 800 feet deep. In R. 22 and 23 E. in Tulare County, however, about half the wells are on the order of 1,200 feet deep, and a few are in excess of 1,500 feet deep. Beneath the Corcoran Clay Member, the top of the saline water body ranges from 900 to more than 2,000 feet below the land surface. As far as is known, no water is being pumped from this deep confined body of saline water.

Hydrographs of piezometer wells constructed by the Bureau of Reclamation in 1952 (23/23–33A1 and 25/23–29A1, fig. 34) show that near and south of Alpaugh substantial hydraulic separation exists between the upper 350 feet of the confined system and the deposits beneath. This hydraulic separation may be fairly widespread; it was small in 1952 but subsequently increased until in 1964 it was as much as 50 feet (spring high) and 100 feet (summer low). This much head differential within the confined system suggests the possibility of more than one confining layer.

SANTA MARGARITA FORMATION AS USED BY DIEPENBROCK (1933)

During the 1950's, wells drilled to depths of 1,800–2,400 feet in the vicinity of Richgrove first tapped artesian water-bearing sands of the Santa Margarita Formation as used by Diepenbrock (1933); they proved to be a valuable source of ground-water supply. By 1957, about 20 large irrigation wells were taking water

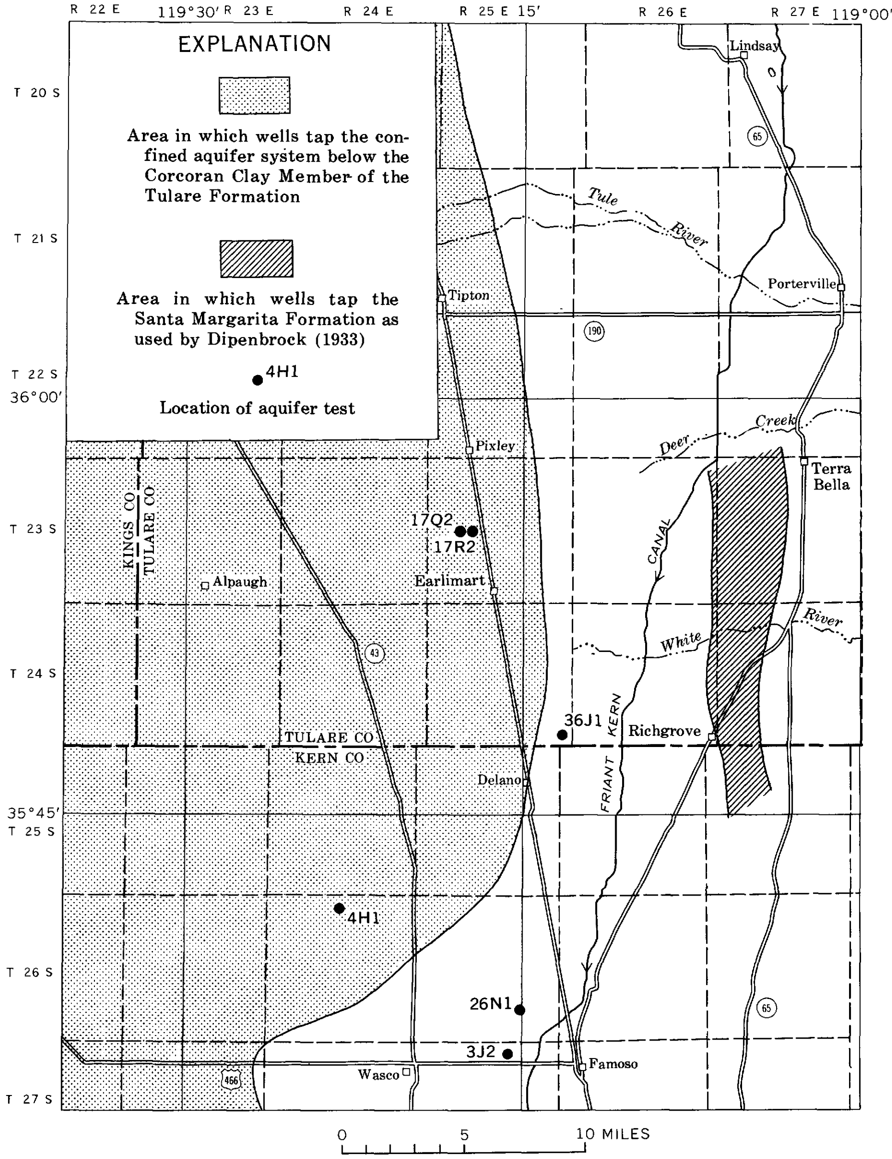


Figure 19.—Areas in which wells tap confined aquifer systems and locations where aquifer tests have been made.

from the Santa Margarita. Most of these wells are perforated in overlying strata as well as in the Santa Margarita; only six are perforated exclusively in the Santa Margarita.

As shown in hydrologic sections *A′–A″* and *B–B′* (fig. 18), the westward dip of the Santa Margarita increases westward from 100 to 250 feet per mile and is much steeper than the land-surface slope; therefore, only in a narrow belt in the eastern part of the area can water be pumped economically from the Santa Margarita. Figure 19 shows the area in which large irrigation wells tap the productive water-bearing sands of the Santa Margarita. The Santa Margarita is overlain by the poorly permeable consolidated upper Pliocene and Pliocene(?) marine siltstone sequence which prevents recharge from above. Because the Santa Margarita does not crop out, recharge to this deep aquifer is probably rather limited. The artesian head in this aquifer was about 100 feet above the water table in 1956 but had been drawn down 110 feet by 1961.

Because the Santa Margarita was deposited in a marine environment, it contained saline water initially. In most of the area where this aquifer is shallow enough to be of economic interest as a source of water supply, the saline water has since been flushed out of the formation by natural ground-water circulation (fig. 18). To the west, it still contains saline water. Where tapped by deep irrigation wells in the Richgrove area, this aquifer yields water that is used extensively to irrigate grapes, citrus fruits, and field crops.

AQUIFER TESTS

Controlled pumping tests have proved to be an effective tool in determining the hydraulic characteristics of an aquifer system. In the usual test, the discharge rate of a pumped well is held constant and measurements are made of the drawdown, which varies with time. The resulting data are analyzed graphically, as outlined by Ferris, Knowles, Brown, and Stallman (1962, p. 91), and the values of T (transmissibility) and S (storage coefficient) (Ferris and others, 1962, p. 72–74) of the aquifer are computed.

Aquifer tests have been made at six sites in the Tulare-Wasco area to determine the aquifer constants, T and S, of the water-bearing deposits. The results of these tests are given in table 4 (written communication, E. J. McClelland, December 1965). The location of the pumped wells at these test locations is shown in figure 19. Four of the tests were made in the semiconfined aquifer system, and two tests, at wells 17Q2 and 17R2, were made in the confined system beneath the Corcoran Clay Member. A seventh test, at well 24/22–28A2, half a mile west of the area boundary, also tested the sub-Corcoran confined aquifer system in an area where it contains thick clayey aquitards. Because of the heterogeneity of the deposits tested and the type of test data obtained, the values of T and S derived from the tests are considered to be only rough approximations of the actual formational constants.

These aquifer tests indicate a wide range in transmissibility and in general suggest that the transmissibility of the deposits in the semiconfined aquifer system is two to three times as great per 100 feet of deposits tapped as that of the sub-Corcoran confined system. The tests for wells 26/24–4H1, 26/25–26N1, and 27/25–3J2, tapping the semiconfined system, were too short, however, for a rigorous interpretation of the data. The coefficient of storage estimated from the tests was on the order of 10^{-5} for the confined aquifer system and 10^{-3}–10^{-4} for the semiconfined system. The tests for the semiconfined system were far too short to develop reliable storage coefficients; nevertheless, their very low value supports the conclusion that at the depths tested the semiconfined system approaches truly confined conditions (Ferris and others, 1962, p. 76).

GROUND-WATER PUMPAGE

Pumping of ground water has been the primary cause of the major changes in water level in the Tulare-Wasco area, and therefore the magnitude of and variation in rate of withdrawals is of basic interest in the study of land subsidence. At least 95 percent of the pumpage is for irrigation use. Estimates of the amount of ground water pumped for irrigation have been made for the years 1950–62 from records of electrical power consumed. In these computations, the pumpage was approximated on the basis of the electrical energy sold on the agricultural power schedule in the various power districts and the average energy required to pump 1 acre-foot of water. Although a small amount of the power sold on the agricultural power schedule was used for purposes other than pumping ground water, a small amount of water was pumped by gas engines or by electricity sold on another power schedule. Data were not available to make estimates of pumpage prior to 1950.

Cities and towns in the Tulare-Wasco area obtain their water supply almost exclusively from wells. Their total use, however, is less than 5 percent of the ground water pumped for irrigation, and therefore estimates

TABLE 4.—*Aquifer-test results*

Pumped well	Date	Test by—	Depth interval tested (ft)	Transmissibility [1] (gpd per ft)	Coefficient of storage [1]	Aquifer system tested	Length of test
Tulare-Wasco area:							
23/25–17Q2	2–15–61	USGS	[2] 300– 600?	15,000	10^{-5}	Confined, sub-Corcoran.	144 hr.
17R2	3–13–63	USGS	280– 603	14,000– 18,000	5×10^{-5}	do	48 hr.
24/25–36J1	2–19–61	USGS	437–1,398	8,000		Semiconfined	144 hr.
26/24–4H1 [3]	3–26–58	KCL [4]	148– 502	150,000–300,000	10^{-3}	do	165 min.
26/25–26N1	3–12–58 and 3–18–58.	KCL and USGS	340– 800	60,000– 70,000	10^{-3}–10^{-4}	do	135 min. 105 min.
27/25–3J2	3–21–58	KCL and USGS	260– 816	25,000– 80,000	10^{-4}	do	120 min.
Just west of area:							
24/22–28A2	4–4–60	USGS	575– 947	20,000	10^{-4}	Confined, sub-Corcoran.	24 hr.

[1] Tentative values, subject to revision.
[2] Perforated interval unknown. Believed to be perforated entirely below the Corcoran Clay Member of the Tulare Formation.
[3] Observation well.
[4] Kern County Land Company.

of ground water used for municipal and domestic purposes were not made for this study.

Two-thirds of the Tulare-Wasco area receives electrical power from the Southern California Edison Co. and comprises all or part of four power districts of its San Joaquin Valley Division (fig. 20). The remaining third of the area receives power from the Pacific Gas and Electric Co. and comprises parts of two large power districts (the Kern and Corcoran districts) of its San Joaquin Division. Because the water-level trends and the type of power data available for computing pumpage in the two power-company service areas differed, the methods used for estimating pumpage in the two areas were different.

In much of the area supplied with power by the Southern California Edison Co., the downward trend of water levels that had persisted through the 1930's and 1940's was generally reversed in the 1950's with the completion of the Friant-Kern Canal. Although the amount of surface water so imported has varied from year to year (fig. 14), the general effect has been to decrease the demand on wells in the service area and to supply a new source of replenishment to the ground-water reservoir. As a result, water levels rose appreciably in much of the

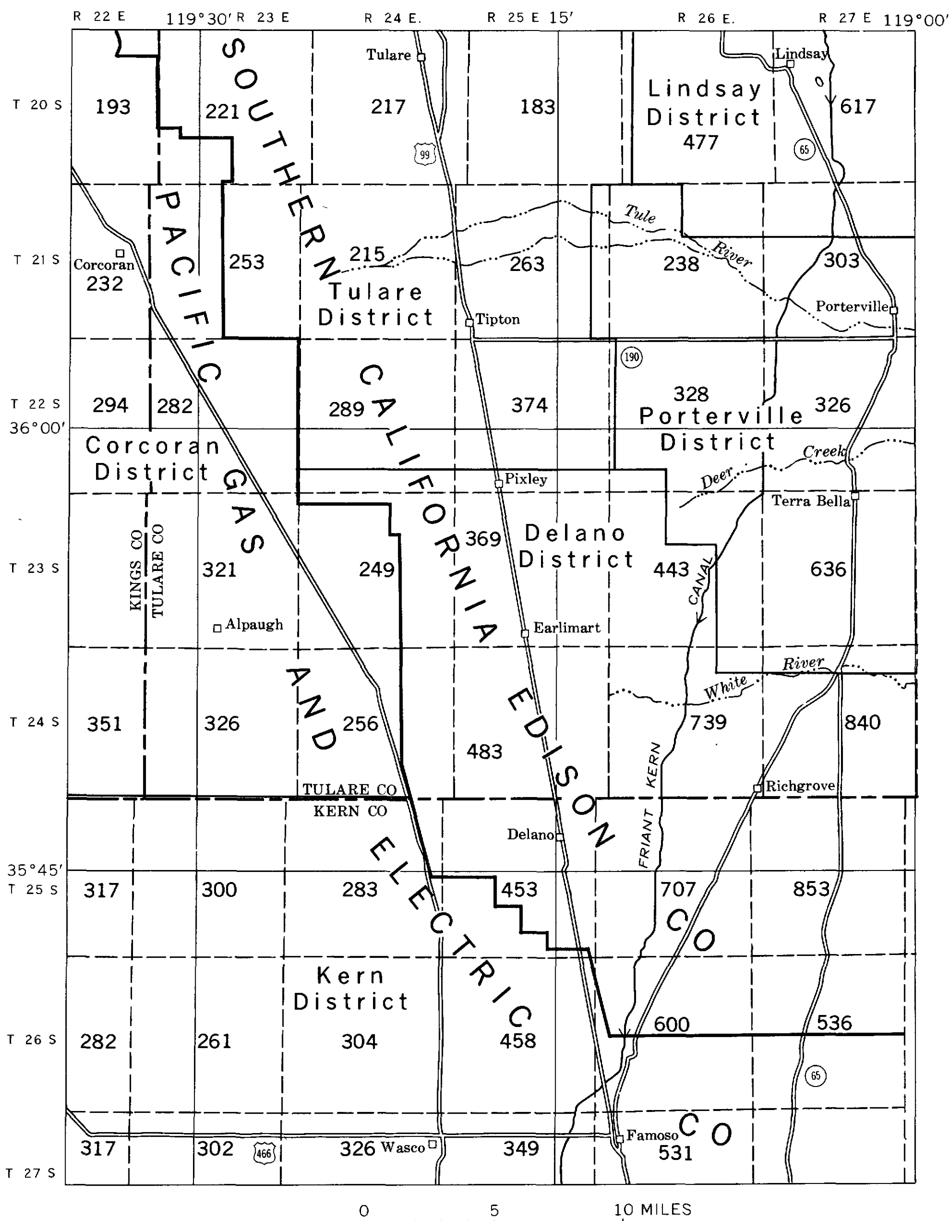


FIGURE 20.—Power districts and rate of power consumption (kwhr per acre-ft, from table 5) by township.

service area from 1951 to 1958; then in years of deficient surface-water supply—1959 through 1961—water levels remained about constant or declined.

Power records made available by the Southern California Edison Co. included (1) total agricultural power consumed in each of its four pertinent power districts for agricultural power years (April 1–March 31) 1956–57, 1959–60, and 1960–61; (2) total agricultural power consumed each year for 1950–62 in its entire San Joaquin Valley Division; and (3) data of several hundred pump-efficiency tests summarized for the pertinent townships in table 5 and in figure 20. During the 3 years for which complete records are available, the agricultural power used in the four pertinent power districts was about 80 percent of the agricultural power consumed in the entire San Joaquin Valley Division of the Southern California Edison Co. The percentage by power districts was Tulare, 23; Lindsay, 8; Porterville, 11; and Delano, 38. It was assumed that the proportionate distribution of power within the four districts for the 3 years of available data was constant for the remainder of the period 1950–62.

The kilowatthours per acre-foot factor given by township in table 5 and shown in figure 20, is considered to represent an average factor for the years 1950–53. To obtain appropriate factors for the years 1954–62, the 1950–53 factor was modified by deriving an average yearly water-level change in each power district from the average water-level graphs for the appropriate ground-water subareas of figure 24. For each foot of rise or

TABLE 5.—*Yield characteristics of irrigation wells in the Tulare-Wasco area, by townships*

[From table 3, Davis, Lofgren, and Mack (1964); data presented as averages for most recent test on each well, 1950-54. Pump test data from Pacific Gas and Electric Co. and Southern California Edison Co.]

Townships (Mount Diablo base line and meridian)	Number of tests (discharge)	Static level (ft.)	Pumping level (ft.)	Drawdown (ft.)	Discharge (gpm)	Specific capacity (gpm per ft)	Kilowatt-hours per acre-foot	Plant efficiency
T. 20 S., R. 22 E	16	74	110	33	1,078	38	193	61
T. 20 S., R. 23 E	186	95	107	13	578	52	221	53
T. 20 S., R. 24 E	223	81	95	13	492	45	217	50
T. 20 S., R. 25 E	160	69	86	18	625	42	183	50
T. 20 S., R. 26 E	344	192	211	23	221	14	477	48
T. 20 S., R. 27 E	111	219	254	35	103	6	617	45
T. 21 S., R. 22 E	25	78	111	33	682	23	232	47
T. 21 S., R. 23 E	58	110	124	24	1,139	58	253	57
T. 21 S., R. 24 E	96	86	108	22	728	50	215	52
T. 21 S., R. 25 E	145	109	131	24	676	35	263	53
T. 21 S., R. 26 E	220	94	110	19	575	43	238	51
T. 21 S., R. 27 E	232	95	121	27	297	20	303	46
T. 22 S., R. 22 E	14	92	158	31	1,036	41	294	56
T. 22 S., R. 23 E	56	107	144	31	1,080	48	282	60
T. 22 S., R. 24 E	109	128	145	21	672	38	289	54
T. 22 S., R. 25 E	153	152	172	20	545	41	374	51
T. 22 S., R. 26 E	190	144	161	15	558	43	328	54
T. 22 S., R. 27 E	61	107	131	30	288	26	326	47
T. 23 S., R. 23 E	9	113	166	50	868	23	321	55
T. 23 S., R. 24 E	40	114	143	----------	871	37	249	58
T. 23 S., R. 25 E	158	144	174	27	514	27	369	51
T. 23 S., R. 26 E	76	195	222	26	773	41	442.5	56
T. 23 S., R. 27 E	21	230	278	29	319	13	636	48
T. 24 S., R. 22 E	4	116	140	24	498	21	351	42
T. 24 S., R. 23 E	10	146	175	18	707	50	326	55
T. 24 S., R. 24 E	8	87	133	43	595	33	256	61
T. 24 S., R. 25 E	147	191	228	38	571	19	483	51
T. 24 S., R. 26 E	94	332	358	39	693	26	739	53
T. 24 S., R. 27 E	21	363	379	36	428	20	840	50
T. 25 S., R. 22 E	7	116	153	37	994	37	317	52
T. 25 S., R. 23 E	58	125	149	24	665	42	300	59
T. 25 S., R. 24 E	50	117	140	25	864	56	283	54
T. 25 S., R. 25 E	140	189	218	31	640	24	453	54
T. 25 S., R. 26 E	125	332	363	37	618	25	707	54
T. 25 S., R. 27 E	12	383	437	54	683	13	853	53
T. 26 S., R. 22 E	10	112	145	28	1,334	39	282	55
T. 26 S., R. 23 E	37	115	131	16	921	65	261	56
T. 26 S., R. 24 E	68	138	160	22	936	58	304	58
T. 26 S., R. 25 E	102	217	240	19	623	59	458	56
T. 26 S., R. 26 E	83	303	323	21	780	47	600	58
T. 26 S., R. 27 E	1	----------	308.2	----------	804	----------	535.7	59.5
T. 27 S., R. 22 E	16	133	161	26	1,012	61	317	49
T. 27 S., R. 23 E	73	143	161	16	1,264	92	302	60
T. 27 S., R. 24 E	198	146	160	14	681	65	326	55
T. 27 S., R. 25 E	84	168	182	14	1,060	102	349	56
T. 27 S., R. 26 E	48	273	295	23	1,092	56	531	60

decline in average water level in the individual power districts, 2 kwhr per acre-ft were subtracted or added, respectively, from the base 1950–53 factor.

After deriving the annual electric power use and kilowatthour per acre-foot factors by these procedures, the agricultural pumpage for the part of the San Joaquin Valley Division within the Tulare-Wasco area and the northern strip of the Tulare and Lindsay power districts outside the area was estimated for each of the years from 1950 through 1962. The pumpage in the part of the Tulare-Wasco area west of the Tulare power district was then assumed to equal the pumpage in the northern strip of the Tulare and Lindsay power districts outside of the project area (fig. 20) in each of these years, as these two areas are approximately equal. Thus, the total pumpage estimated by this means represented that in all of the Southern California Edison Co. service area in the Tulare-Wasco area plus that in the northern part of the Pacific Gas and Electric Co. service area.

In the southwestern part of the Tulare-Wasco area, including the parts of the Corcoran and Kern Districts of the Pacific Gas and Electric Co. lying west and south of the Southern California Edison Co. Delano district (fig. 20), the water-level trend has been generally downward during the fifties and early sixties. Much of this area is supplied solely by ground water, and considerable new land has been brought under cultivation. Water levels in wells declined fairly consistently during the period from 1950 through 1962.

Records available from the Pacific Gas and Electric Co. included (1) the total agricultural power used yearly in its two power districts for the years 1950–62, (2) the amount of power used in the pertinent meter route areas within the two districts for the agricultural power years 1956–57, 1957–58, and 1958–59, and (3) the average rate of power consumption, in kilowatthours per acre-foot, for each pertinent township in their service area for the agricultural power years 1950 through 1957 and for the entire Kern district for the period 1950–62. The proportion of power used in this southwestern area to power used in the entire Kern power district was known for the 3 years from 1956–57 to 1958–59 and was assumed to be constant during the full period 1950–62. The trend of the average kilowatthours per acre-foot for the southwestern area was known for 1950–57 and was extended through 1962 on the basis of the trend in the entire Kern power district. The values of agricultural power and the kilowatthours per acre-feet so obtained were used to compute the ground-water pumpage in this southwestern area west and south of the Southern California Edison Co. Delano power district for the years 1950–62. Table 6 gives the estimated annual ground-water pumpage for the overall Tulare-Wasco area for the period 1950–62. Details of the pumpage calculation are available in the project files of the Geological Survey.

TABLE 6.—*Estimated ground-water pumpage in the Tulare-Wasco area, 1950–62*

[For agricultural power year April 1 to March 31]

Year	*Pumpage (acre-ft)*	*Year*	*Pumpage (acre-ft)*
1950	1, 050, 000	1958	710, 000
1951	1, 110, 000	1959	1, 260, 000
1952	870, 000	1960	1, 370, 000
1953	960, 000	1961	1, 430, 000
1954	960, 000	1962	980, 000
1955	940, 000		
1956	860, 000	Total	13, 470, 000
1957	970, 000		

Figure 21 shows the estimated amount of ground water used for irrigation in the Tulare-Wasco area (table 6) and also the amount of surface water available for irrigation from natural streams and the Friant-Kern Canal (fig 14), for the 13 years 1950 through 1962. The gradual increase in use of combined ground-water and surface-water supply during the period is readily apparent. Ground-water pumpage ranged from 39 percent (1958) to 79 percent (1961) of the total irrigation water used, averaging about 64 percent of annual total

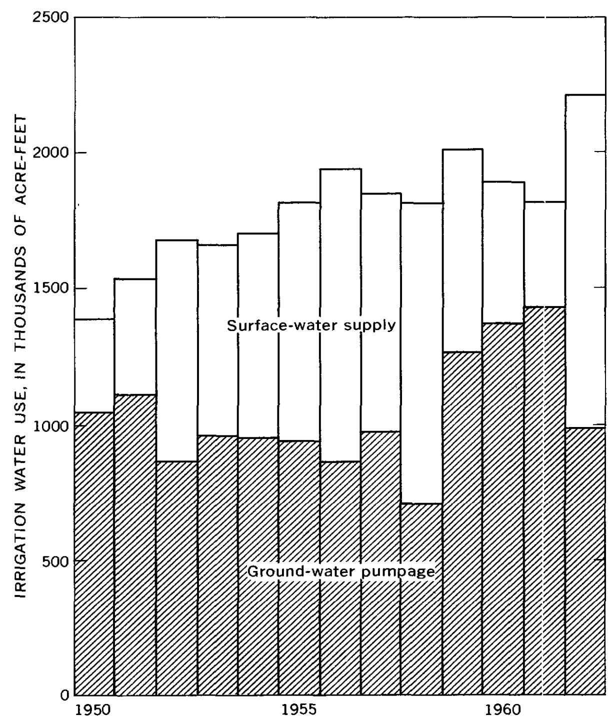


FIGURE 21.—Estimated use of ground water and surface water for irrigation, 1950–62.

supply. There was an irregular but general decrease of ground-water use from 1950 through 1958, followed by a sharp increase in the years of deficient surface supply, 1959–61.

HISTORY OF WATER-LEVEL TRENDS

As discussed later, a decline of the water level generally increases the effective stress on the deposits. In the compactible deposits of the Tulare-Wasco area, the increase in effective stress developed by the historic water-level declines has been sufficient to cause several feet of land subsidence in about half the area and as much as 12 feet near Delano (fig. 50). Therefore, to appraise the relation of subsidence to water-level decline, it is important to document the history of water-level change as specifically as possible. This appraisal is complicated, however, by the distribution and nature of the aquifer systems, the composite nature of the water-level measurements obtained from many of the observation wells, and the fact that periodic measurements were made in very few wells prior to the late forties.

In the western part of the area, a substantial number of the irrigation wells have been drilled into the sub-Corcoran aquifer system. Relatively few of these are known to be perforated only in this confined system, and no periodic measurements are available for such wells prior to 1948. Although the Bureau of Reclamation began a continuing program of water-level measurements in the late forties, periodic measurements have been obtained in very few wells perforated only in the sub-Corcoran aquifer system. At several places, however, the Bureau of Reclamation has installed piezometers that register the head in one or more intervals below the Corcoran Clay Member and has recorded these measurements periodically.

In the eastern part of the area beyond the limits of the Corcoran Clay Member, the degree of hydraulic confinement in the semiconfined aquifer system increases with depth. Intensive pumping has lowered the head in some aquifers much more than in others. Well casings usually are perforated throughout the saturated section penetrated. Water levels in deep wells, therefore, are composite levels influenced to some degree by the head in each aquifer tapped and thus do not define the head in the deeper aquifers. No wells tap only the deeper aquifers, so the change in head with depth has not been recorded directly. This is a severe limitation in the calculation of changes in effective stress that are directly related to subsidence.

Several maps showing the altitude of or the change in water levels in wells are included in this report. The maps that show the altitude of the water surface for the semiconfined aquifer system for 1905 (fig. 22) and for 1920–21 (fig. 23) were based primarily on water levels in relatively shallow wells (less than 500 feet deep) and are considered to depict a level that approximately represents the water table at the top of the semiconfined water body. Since 1948, however, the distribution of measurements in shallow wells has been insufficient to furnish adequate control on the water table. Therefore, the maps showing water-level change in the semiconfined system from 1920–21 to 1948 (fig. 25), from 1948 to 1954 (fig. 26), and from 1954 to 1959 (fig. 27) have been constructed from measurements in wells of various depths, some as deep as 1,000 feet. Accordingly, these change maps are only gross approximations of the changes in water level that have occurred in the semiconfined system. Only in February 1959 were sufficient measurements made in shallow wells (less than 400 feet deep) to construct a map (fig. 28) that is a fair approximation of the water table at the top of the semiconfined water body. This map, therefore, is directly comparable to the water-table maps of 1905 and 1920–21.

Hydrographs have been included in the report to illustrate the water-level trend in various parts of the area. These are of two types: (1) hydrographs showing long-term average levels for eight ground-water subareas (fig. 24) and (2) hydrographs that show the fluctuations of the water level for particular depth intervals at specific locations (figs. 31, 33, 34, and 35). Many of these hydrographs are paired with bench-mark graphs which are considered later in relating subsidence to water-level decline.

GENERAL DECLINE, 1905–51

Before extensive ground-water development, wells tapping the principal confined aquifer system flowed throughout almost all the area underlain by the Corcoran Clay Member. During a well canvass of the area in 1905–6, Mendenhall, Dole, and Stabler (1916) located about 200 flowing wells, mostly with small discharges. Artesian heads for these wells were not measured in 1905–6; thus, a map showing the piezometric surface for the sub-Corcoran confined aquifer system for this early date cannot be drawn. Figure 22 shows the area of flowing wells and the altitude of the water table in the eastern part of the semiconfined aquifer system as of 1905. The east boundary of the area of flowing wells was approximately along the 280-foot topographic contour from Tulare to Delano and generally was about 2 miles west of the east boundary of the Corcoran confining layer. Although Mendenhall did not attempt to extend water-table contours on the semiconfined system westward into the area of flowing wells, measurements of depth to water in shallow wells reported by

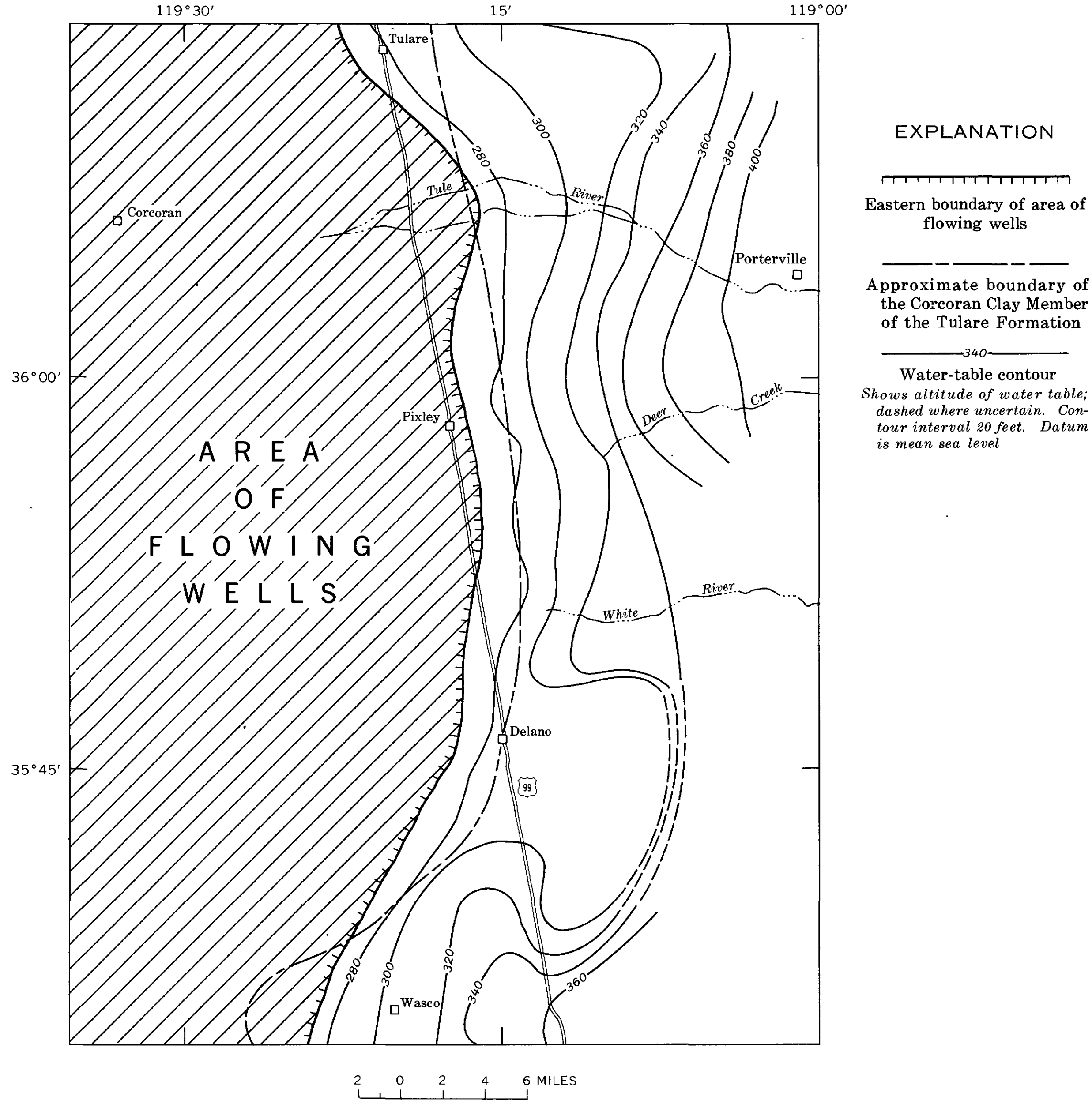


FIGURE 22.—Altitude of the water table and area of flowing wells in 1905. Modified from Mendenhall, Dole, and Stabler (1916, pl. 1).

him show that the depth to water in the semiconfined aquifer system overlying the Corcoran Clay Member ranged from 5 to 15 feet below the land surface at that time.

Increased ground-water development between 1905 and 1921 caused decline of water levels. Figure 23 shows the altitude of water levels in the semiconfined aquifer system in 1920–21. Water levels in this system had been drawn down from 10 to 80 feet since 1905. In the northwest quadrant of the area, the Tule and Kaweah Rivers still furnished most of the irrigation demands. Water-level declines were greatest in an intense cone of pumping drawdown at Lindsay. With the exception of the Lindsay pumping cone, ground water moved generally westward across the area toward the Tulare Lake bed at gradients of about 15 feet per mile on the east to about 3 feet per mile on the west. The marked ground-water mound along the distributaries of the Tule River west of Porterville shows the influence of stream recharge (fig. 23).

In the sub-Corcoran confined aquifer system, artesian wells continued to flow only in a small area northwest

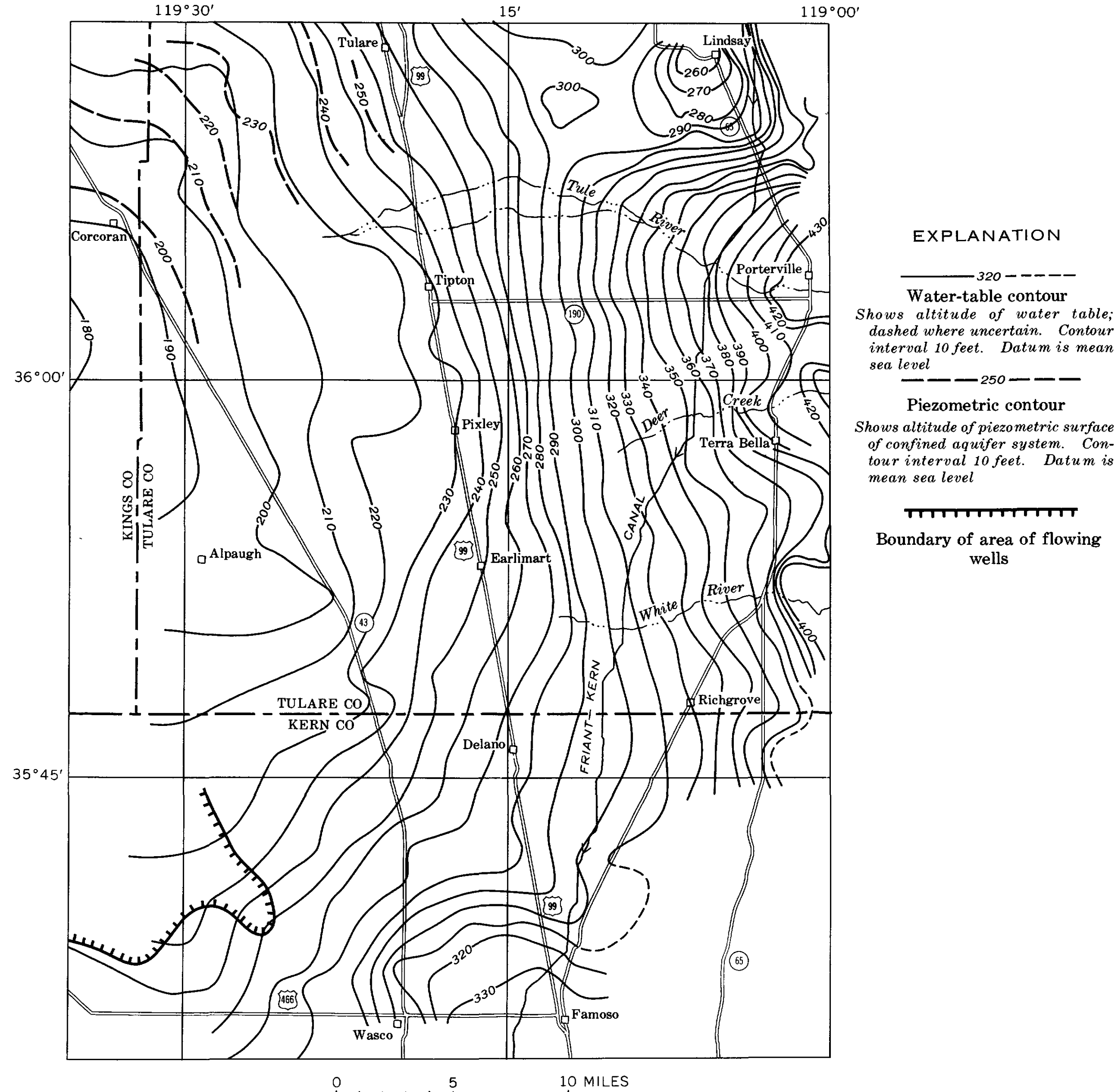


Figure 23.—Generalized water-level contours as of December 1920 (Kern County) and November 1921 (Tulare County). Data from California Department of Engineering (1921, map 2) and California Department of Public Works (1922, map 2).

of Wasco (fig. 23). Southwest of Tulare, the piezometric surface of the confined aquifer system had been drawn down to 5–10 feet above the water table by 1921.

Ground-water levels throughout the Tulare-Wasco area declined from 1921 through 1935, owing to prolonged subnormal stream runoff (fig. 12) and accelerated pumping. As shown in the hydrographs of figure 24, the long-term trends of average ground-water levels in eight subareas wholly or partly in the Tulare-Wasco area (California Department of Water Resources, 1964, pls. 10, 11) indicate a general decline of 2–4 feet per year through 1935 for all parts of the area represented. West of these subareas, ground-water pumpage was considerably less intensive, and water-level declines were less than those shown in figure 24.

From 1936 to 1943, average water levels rose 20–30 feet in areas served by diversions from the Kaweah and Tule Rivers (see hydrographs of subareas 10, 11, 13; fig. 24) in response to increased surface-water supply (fig. 14). Recovery was less and of shorter duration in the Lindsay-Exeter area of intensive ground-water pumping (subarea 12). Water levels in these northern

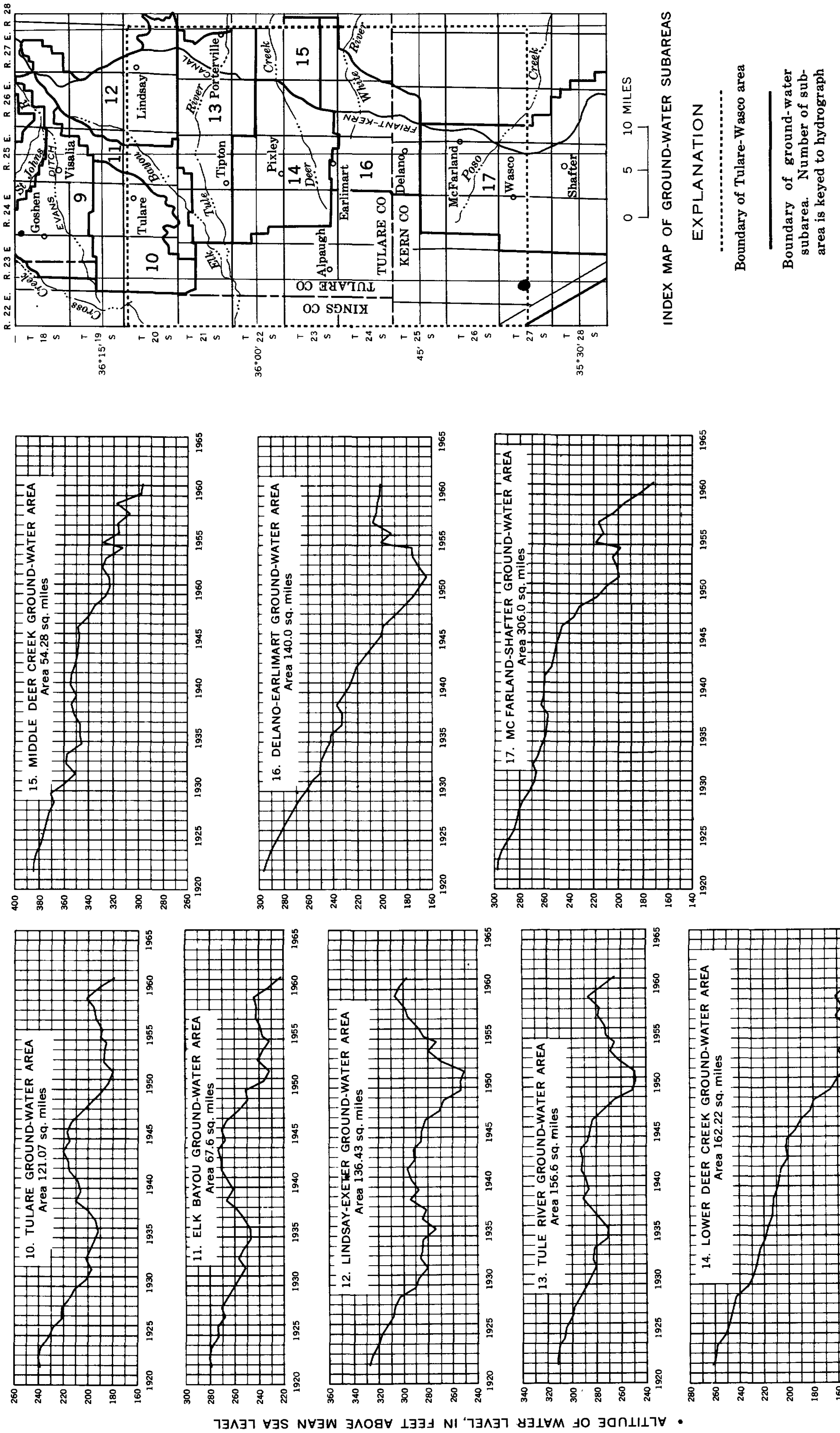


FIGURE 24.—Long-term trends of average water levels, 1921–61, in eight ground-water subareas wholly or partly within the Tulare-Wasco area. (Modified from California Department of Water Resources, 1964, pls. 10, 11).

subareas resumed their downward trend from 1944 to 1951, during a period of deficient stream runoff and increased ground-water pumpage following World War II. In the central and south-central parts of the Tulare-Wasco area (hydrographs of subareas 14, 16, 17; fig. 24), where surface supplies were limited and more large wells were being drilled, average water levels continued to decline throughout the 30-year period from 1921 through 1951.

Figure 25 shows the change in ground-water levels in the semiconfined aquifer system from 1920–21 to 1948. This map is based on the comparison of a water-level contour map for February 1948 (not included in this report) with the water-table contours shown in figure 23. The water level had declined more than 40 feet throughout more than half the Tulare-Wasco area, and in most of the southeastern quadrant, declines ranged from 60 to 220 feet during the 28-year period. In the vicinity of Richgrove, where little recharge occurs, an especially sharp pumping cone had developed around a cluster of highly productive deep wells. Water-level decline was small in the western part of the area, but

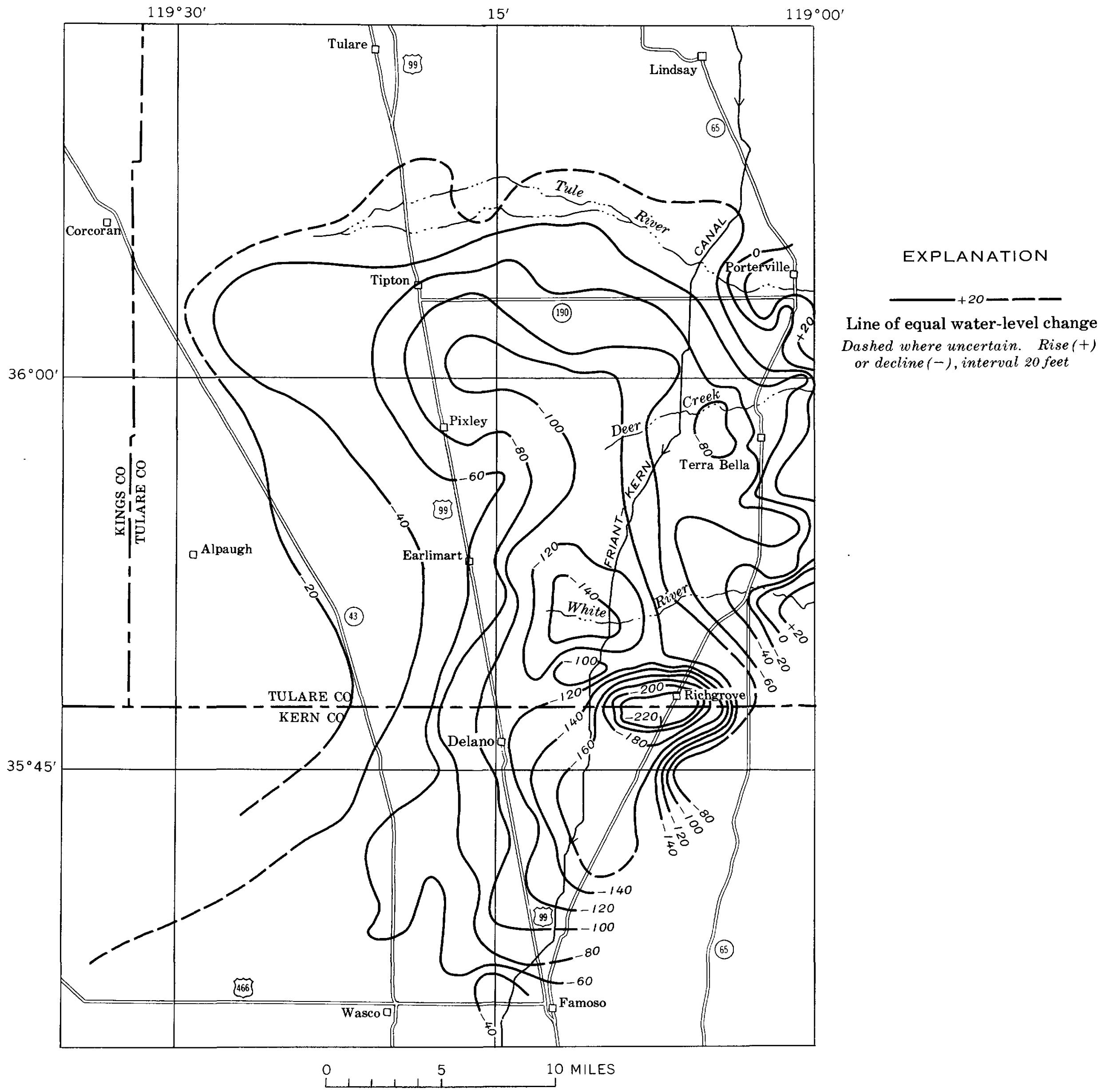


FIGURE 25.—Change in water level in the semiconfined aquifer system, 1920–21 to 1948. Change based on water-level contour maps for 1920–21 (see fig. 23) and 1948. The 1920–21 measurements were made during November and December, and the 1948 measurements were made mostly in February.

measurements in 1948 were not adequate to provide control for extending lines of equal change through that area.

PARTIAL RECOVERY, 1951–59

The importation of water to the Tulare-Wasco area through the Friant-Kern Canal, which began in 1949 (fig. 14), had a marked effect on the ground-water regimen within and adjacent to the canal service areas. The newly imported water replaced much of the ground-water pumpage in these areas and also supplied a new source of replenishment to the ground-water reservoir by downward percolation of irrigation water applied in excess of consumptive-use requirements of the crops. As a result, by 1951, when the canal import had grown to 304 thousand acre-feet (table 3), the water levels beneath and adjacent to the canal service areas began to respond to the decrease in draft and increase in replenishment. The effect of the new imports on the water levels is strikingly illustrated by the rapid recovery of average water levels in ground-water subareas 12, 13, and 16 of figure 24. Average water levels in the other five subareas also showed a general cessation of the downward trend of prior years. This marked change in water level trend had a significant effect on the rate of land subsidence, as is discussed later in this report.

In general, by 1951, water levels in deep wells had been drawn down considerably below the levels of shallower wells. During the 1951–59 recovery period, water levels in both deep and shallow wells rose abruptly; however, in most parts of the area, the water levels in deeper wells rose more than those in shallow wells. In 1959, therefore, the difference in water level between shallow and deep wells at any location was generally less than at any time since the forties.

The effect of the Friant-Kern imports on water levels in the semiconfined aquifer system is shown by two water-level change maps. Figure 26 shows the change from 1948 to 1954, and figure 27 the change from 1954 to 1959. These two periods were selected to evaluate the change in the water level, primarily because of the availability of vertical-control data. A network of bench marks was established in the Tulare-Wasco area in 1948 and was releveled in 1954 to define the magnitude of subsidence in the 6-year period; it was also releveled in 1958–59, at about the time of the greatest recovery of the water levels. Although maps showing change in the piezometric surface of the deeper part of the semiconfined aquifer system and of the piezometric surface of the sub-Corcoran aquifer system would be more directly related to the subsidence of the land surface, data were not available for constructing water-level change maps for those piezometric surfaces.

The change in the position of the water level from 1948 to 1954 in most of the Friant-Kern Canal service area south of Porterville is illustrated areally in figure 26. Water-level recovery occurred in two areas: southwest of Porterville, where it exceeded 20 feet, and northeast of Delano, where it was as much as 40 feet. Water levels continued to decline in a narrow belt 4–6 miles east of the Friant-Kern Canal, in the southern part of the area that had not yet received a large quantity of canal water, and in a small area east of Earlimart. More than 60 feet of decline occurred in a pumping depression southwest of Richgrove.

From 1954 to 1959, the water level in the semiconfined aquifer system rose in most of the east-central part of the Tulare-Wasco area in response to increased surface-water imports from the Friant-Kern Canal (fig. 27). In the 5-year period 1954–58, inclusive, the average yearly delivery of Friant-Kern Canal water to the area was 760 thousand acre-feet (table 3). The water-level rise was greatest east and southeast of Delano, where it ranged from 40 to 100 feet, and west of Porterville, where it exceeded 20 feet. Maximum recovery was about 4 miles northeast of Delano, where water levels had risen 100 feet since 1954 and as much as 130 feet since 1948. Water-level decline continued south of Porterville and in the southwestern part of the area where canal water was not available. The maximum decline of water level during this period occurred in a local cone of pumping drawdown south of Terra Bella.

From 1950 through 1958, more than 5 million acre-feet of Friant-Kern Canal water was supplied to irrigation districts in the Tulare-Wasco area (table 3) to bring about the water-level recovery shown in figures 26 and 27. This rise in water levels had a marked effect in decreasing the rate of land subsidence.

WATER LEVELS IN 1959

Water-level measurements were made by the Geological Survey in about 800 selected observation wells in February 1959 to determine the position of the water level in deep and shallow wells in the semiconfined aquifer system and the piezometric levels of the confined aquifer systems, also to assist in defining the changes that had occurred in more than 60 years of ground-water exploitation. On the basis of these data and some additional measurements by the Bureau of Reclamation, three ground-water contour maps have been prepared. One (based on measurements in wells less than 400 ft deep) depicts the water table in the semiconfined aquifer system; the second (based on

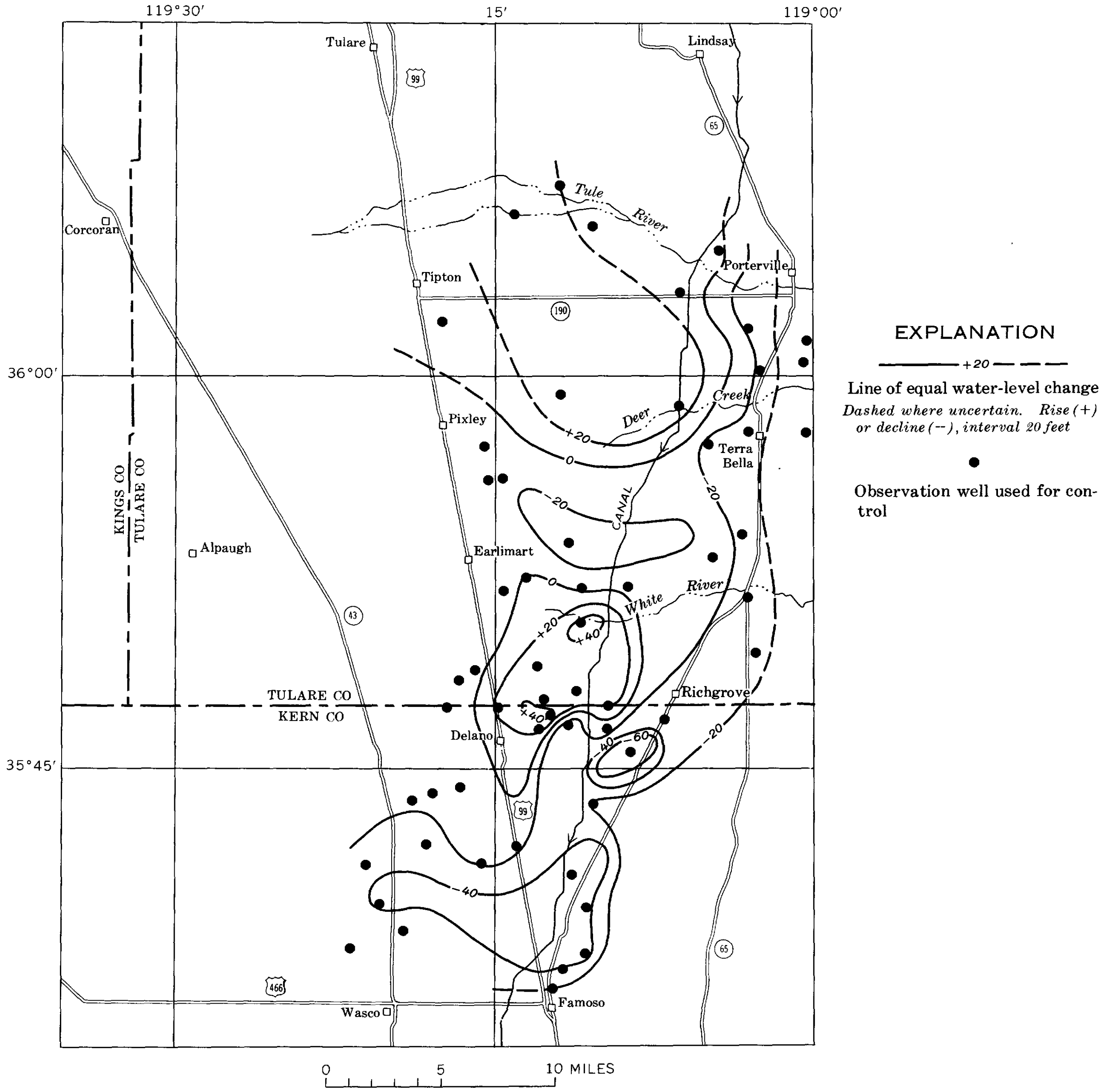


FIGURE 26.—Change in the water level in the semiconfined aquifer system, 1948–54, in the eastern part of the Tulare-Wasco area. Change based on February measurements in 1948 and 1954.

measurements in wells more than 500 ft deep) shows the piezometric surface in the deeper, more confined, beds of the semiconfined aquifer system; the third defines the piezometric surfaces of the sub-Corcoran and the Santa Margarita confined water bodies.

WATER TABLE, SEMICONFINED AQUIFER SYSTEM

Figure 28 shows the altitude of the water table in the semiconfined aquifer system as of February 1959. Only water levels in wells less than 400 feet deep were used in the preparation of this map, and where nearby wells had different water levels, only the shallowest were used. Therefore, the map shows, in effect, the configuration of the water table at the top of the zone of saturation. The water table contours of 1959 are highly irregular, instead of being relatively smooth and denoting a gentle westward-sloping water table as in 1905 (fig. 22) and 1920–21 (fig. 23).

Within much of the eastern part of the area, the water table in February 1959 was the highest it had been since the middle to late forties (fig. 24). This high level was the result of increasing deliveries from the

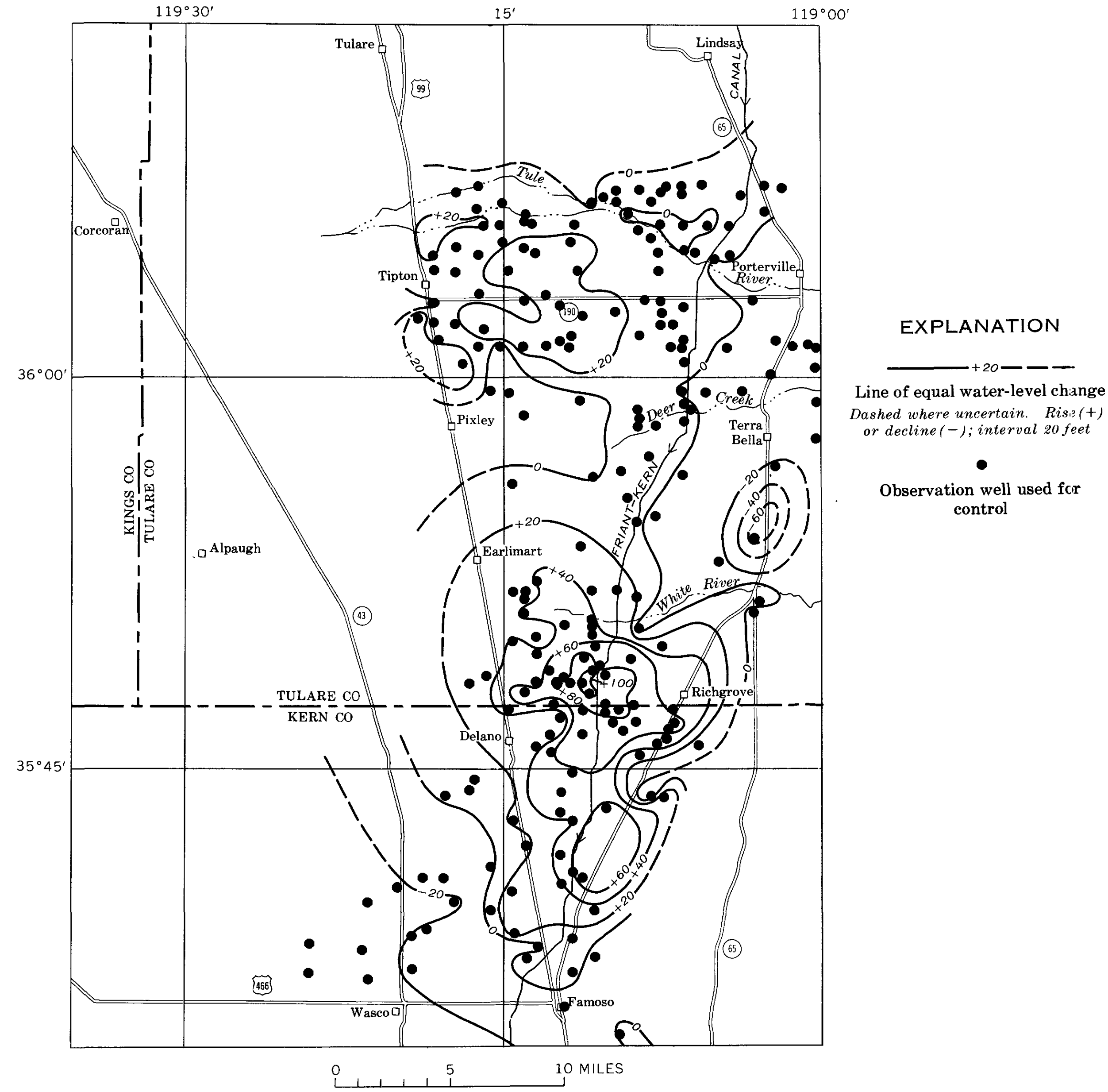


FIGURE 27.—Change in the water level in the semiconfined aquifer system, 1954–59, in the eastern part of the Tulare-Wasco area. Change based on February measurements in 1954 and 1959.

Friant-Kern Canal, decreasing pumping demand in the fifties (figs. 14, 21), and better than average local surface-water diversions in 1958 (fig. 14).

The most prominent replenishment features shown in figure 28 are the recharge mounds along the Tule River, to a lesser extent along Deer Creek, and in the vicinity of Delano along the southern service area of the Friant-Kern Canal. At Lindsay, the water table had recovered to roughly the same level it was at in 1921 (fig. 23); however, the cone of maximum drawdown had shifted about 6 miles to the southwest where the water table was about 75 feet lower than in 1921.

The water table was lowest in the pumping trough extending west from Pixley and Alpaugh and in a small area west of Wasco. In these areas, the water table had declined from a few feet below the land surface (alt 200–260 ft above sea level) in 1905 to an altitude of about 120 feet in 1959. South of Richgrove, pumping from an area of minimal recharge had created a pumping trough along the Richgrove-Famoso highway.

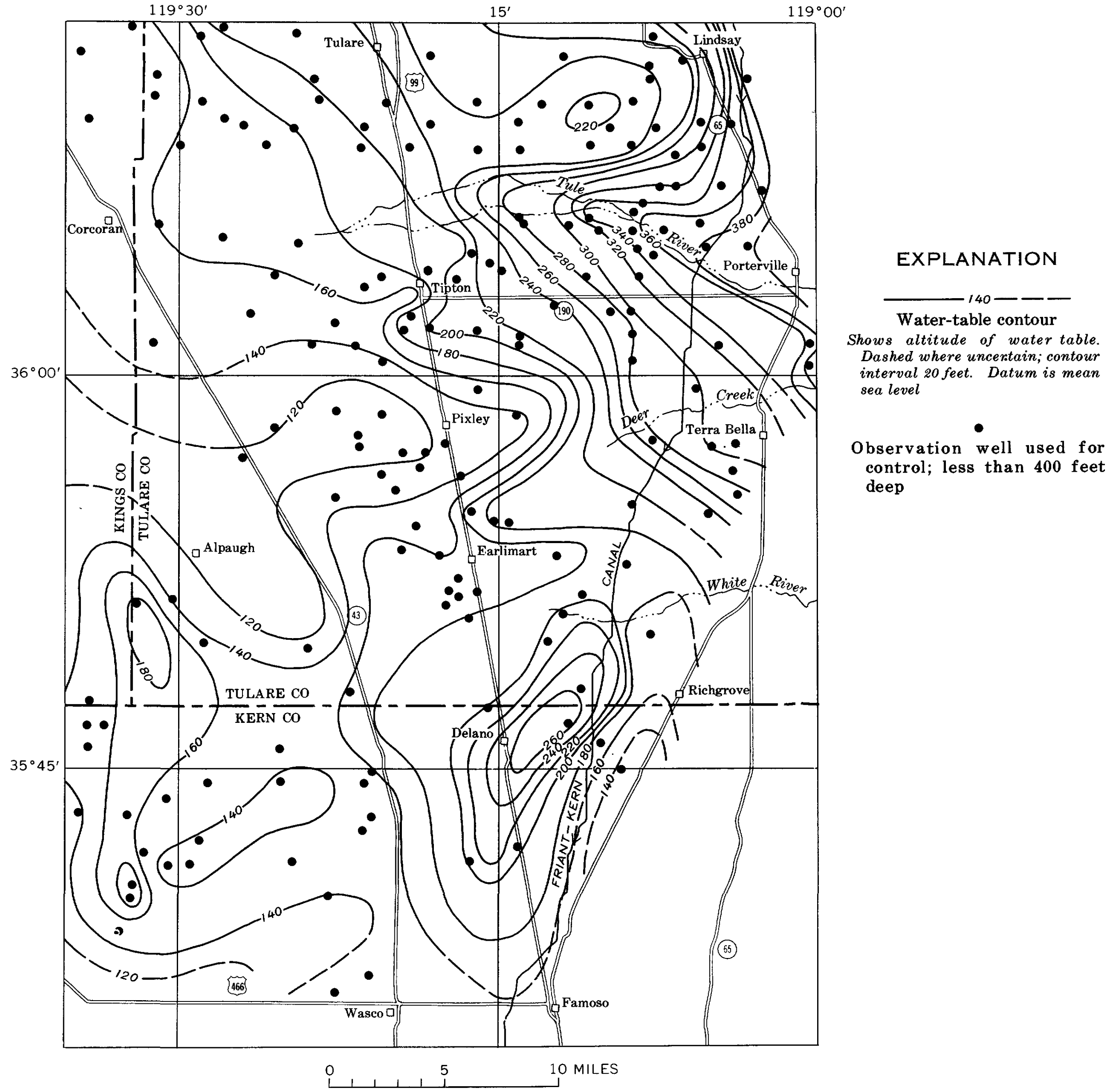


Figure 28.—Altitude of the water table in the semiconfined aquifer system, February 1959.

PIEZOMETRIC SURFACE, SEMICONFINED AQUIFER SYSTEM

Figure 29 shows the configuration of the water surface in February 1959 for deep wells tapping the semiconfined aquifer system. Only the water levels in wells deeper than 500 feet and not tapping the Santa Margarita water body (fig. 18) were used in the preparation of this map. Therefore, this map shows only the piezometric surface in the deeper, more confined, aquifers of the semiconfined system. Compaction of this lower part of the semiconfined system is believed to have caused most of the land subsidence east of U.S. Highway 99.

As shown in figure 29, the contours for this piezometric surface have been terminated at the east edge of the Corcoran confining layer where the deeper sands and gravels of the semiconfined system merge with the confined aquifer system below the Corcoran Clay Member (figs. 4, 5). Also, contours have been omitted in the northern part of the map where insufficient water-level control was available for deep wells. Few of the wells drilled in the Lindsay-Tulare area are deeper than 500 feet, and most of these are perforated throughout the saturated section. Of the water levels measured in that

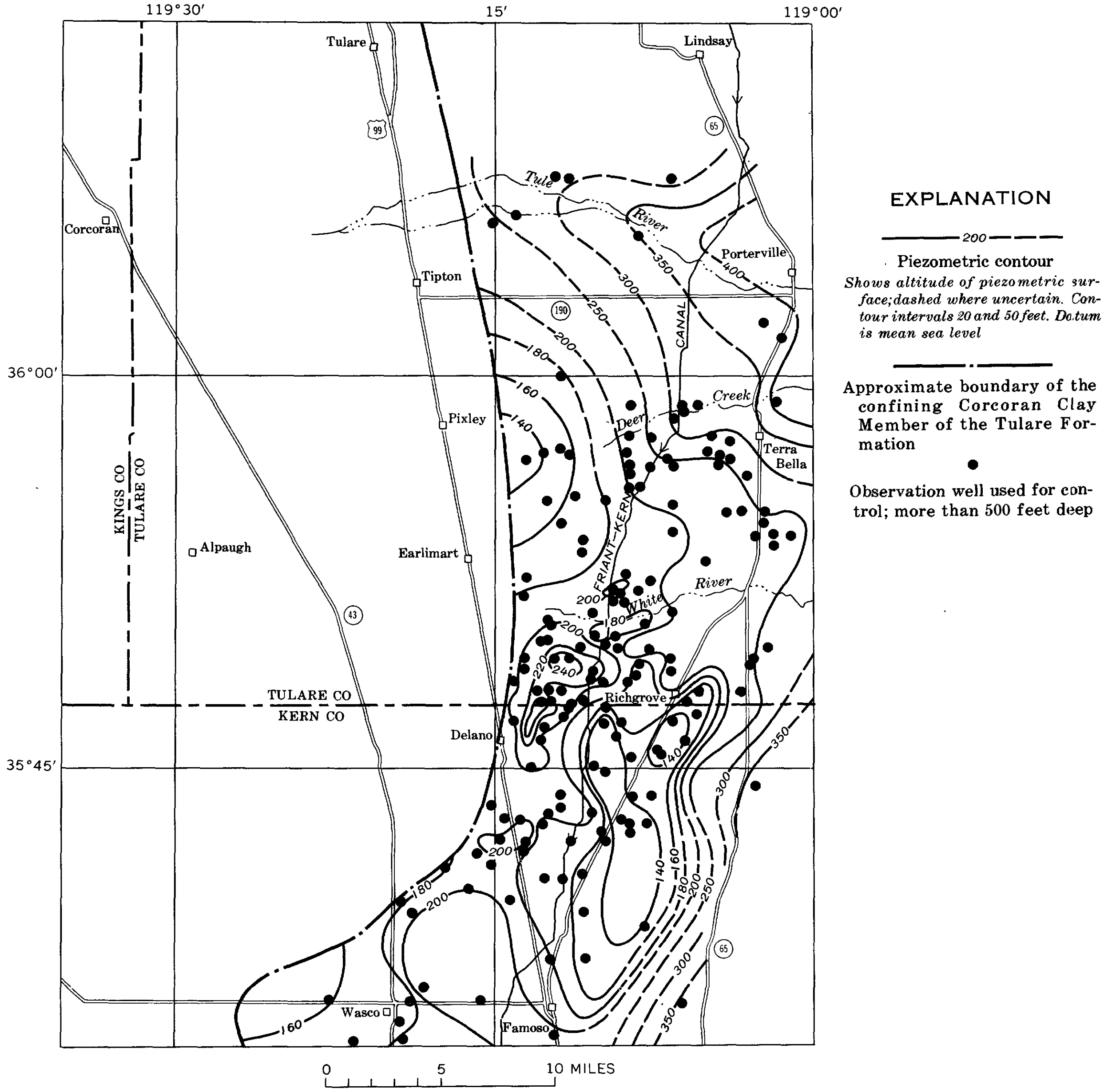


Figure 29.—Piezometric surface of the semiconfined aquifer system, February 1959.

area in the spring of 1959, none was considered representative for the lower part of the semiconfined system.

In February 1959, the water table (fig. 28) was higher than the piezometric surface of the deeper zones of the semiconfined aquifer system (fig. 29) in most of the area where major imports of surface water had been received from the Friant-Kern Canal. This difference was particularly evident in the central area between Delano, Richgrove, Terra Bella, and a point 5 miles northeast of Tipton. In a broad area east of Delano, and also in a small area southeast of Pixley, the water level in shallow wells was as much as 60 feet above the level of deeper wells. In the southern part of the area where much less canal water had been received (table 3; fig. 13), notably northeast and northwest of Famoso, the water table was generally 10–40 feet below the piezometric surface. Between and to the west of Terra Bella and Porterville, the water level in shallow wells stood 10–60 feet below the level of the deeper wells.

WATER LEVEL OF THE CONFINED AQUIFER SYSTEM

Few wells in the western part of the Tulare-Wasco area tap only the confined aquifer system below the Corcoran Clay Member (fig. 18). Many of the deeper wells are perforated both above and below this confining layer, and their water levels are a composite of the upper semiconfined and lower confined pressures. Only 14 of the observation wells measured during the spring of 1959 were considered representative of the sub-Corcoran confined system. The measurements obtained from these wells were the basis of figure 30 which shows the February 1959 piezometric surface for this confined aquifer system. Dashed contours have been extended east to the boundary of the Corcoran Clay Member to join the piezometric contours for water levels in the deep wells in the semiconfined aquifer system (fig. 29) because the two water bodies are continuous. Owing to the wide range of perforated intervals in wells whose water levels were used to construct figure 29, however, the dashed contours of figure 32 immediately west of the Corcoran boundary represent only a rough approximation of the piezometric surface in the confined aquifer system.

Because of the scarcity of observation wells, the contours defining the sub-Corcoran piezometric surface are generalized. These piezometric contours, considered to-

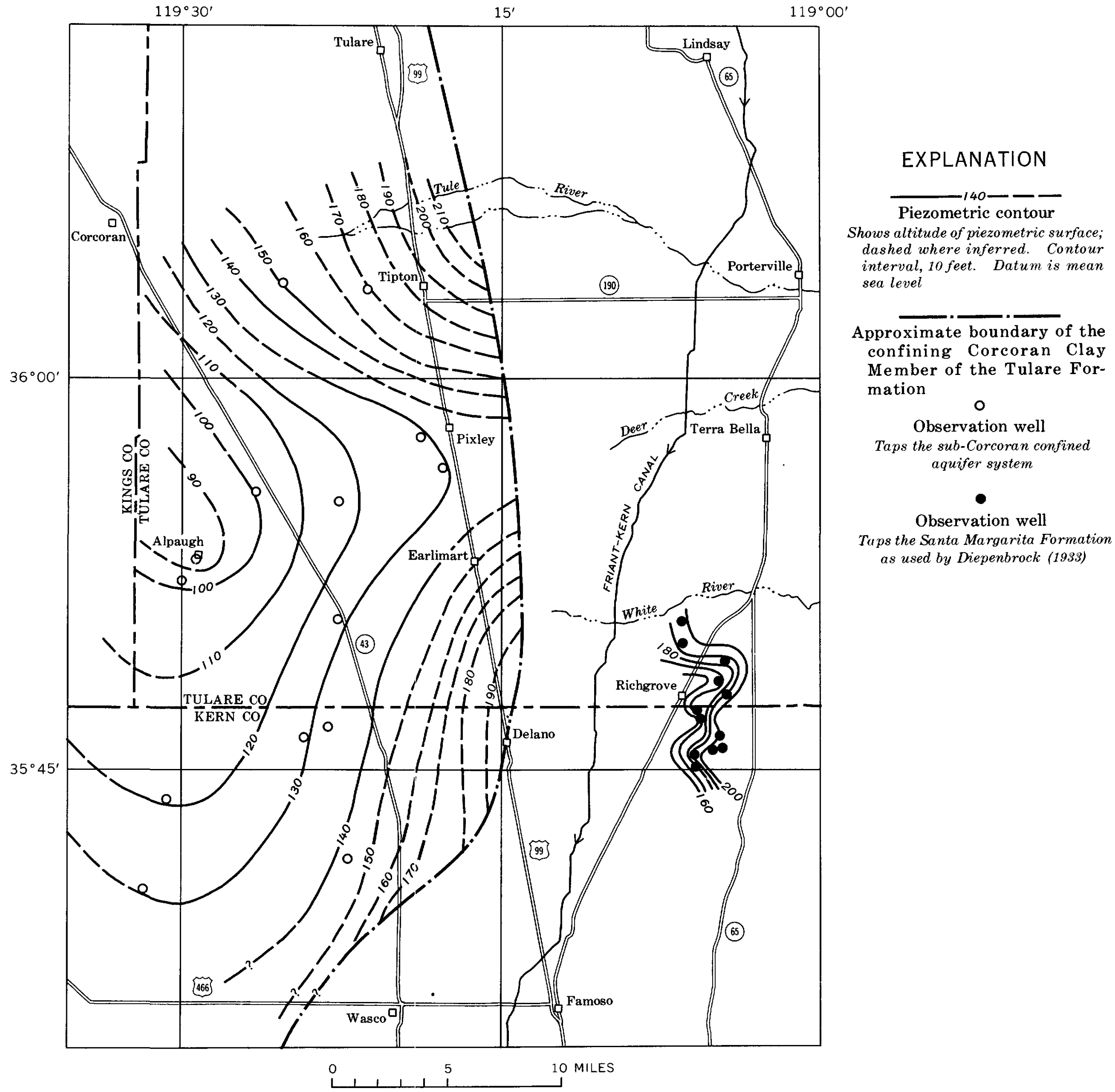


FIGURE 30.—Piezometric surfaces of the confined aquifer systems, February 1959. Dashed contours near boundary of the Corcoran Clay Member are extensions of the piezometric surface in the semiconfined aquifer system (fig. 29).

gether with the piezometric contours in the semiconfined aquifer system to the east (fig. 29), indicate however, that ground-water movement beneath the edge of the confining clay converged toward the west-central part of the area. The artesian head at Alpaugh had been drawn down more than 130 feet since 1905 by heavy pumping.

An upward gradient through the Corcoran confining layer prevailed until about 1920, but subsequent depression of the piezometric head in the underlying confined system reversed the direction of this gradient. As of spring 1959, the piezometric head in the confined aquifer system was as much as 60 feet below the overlying semiconfined water surface. Because of the very low permeability of the clay confining layer, however, the amount of recharge that moves downward through the clay under this downward hydraulic gradient is small. Recharge to the confined aquifer system is thus derived almost exclusively from the deep semiconfined aquifers that project under the confining clay and to an unknown extent through irrigation wells and gravel envelopes from the overlying semiconfined aquifer system.

WATER LEVEL IN THE SANTA MARGARITA FORMATION AS USED BY DIEPENBROCK (1933)

Eighteen large irrigation wells in the vicinity of Richgrove, drilled to depths greater than 1,800 feet, are perforated in the productive Santa Margarita Formation as used by Diepenbrock (1933). Only six of these wells tap exclusively this deep artesian aquifer; however, a half dozen others include in their perforated interval only the lower part of the overlying poorly permeable marine siltstone as shown in hydrologic section *B–B′* (fig. 18) and thus have water levels believed to be representative of the Santa Margarita. Figure 30 shows the configuration of the piezometric surface of the confined water in the Santa Margarita in February 1959; the plotting was controlled by the water levels of the 12 wells that are not perforated in the semiconfined aquifer system.

Ground water has been pumped from the confined Santa Margarita water body since the early 1950's. This withdrawal has had a marked effect on water levels in wells tapping this formation. As indicated by the hydrograph of well 25/27-18A1 (fig. 31). The head in the Santa Margarita declined as much as 156 feet from August 1956 to October 1964, at an average rate of about 20 feet per year.

As of spring 1959, the water level in wells tapping the Santa Margarita (fig. 30) generally stood within 50 feet of the same altitude as the water level of the deep aquifers of the semiconfined aquifer system (fig. 29), but ranged from 20 feet higher to 90 feet lower. Piezometric contours are highly contorted, and probably are influenced by pumping cones around individual wells as well as by the regional drawdown that has developed since this aquifer was first tapped in 1954. Contours indicate a local westward piezometric gradient in the Santa Margarita of about 25 feet per mile.

SUMMARY OF WATER-LEVEL TRENDS

Hydrographs of 15 observation wells or piezometers are included to indicate long-term water-level trends at various locations in each of the aquifer systems. Also included are graphs showing subsidence of bench marks near many of these observation wells; they will be considered later in the discussion "Relation of subsidence to water-level change." Locations of all wells and bench marks for which graphs are included in this report are shown in figure 32.

Because effective stresses are generally greatest and subsidence usually most rapid during periods of maximum water-level decline, changes in seasonal low water

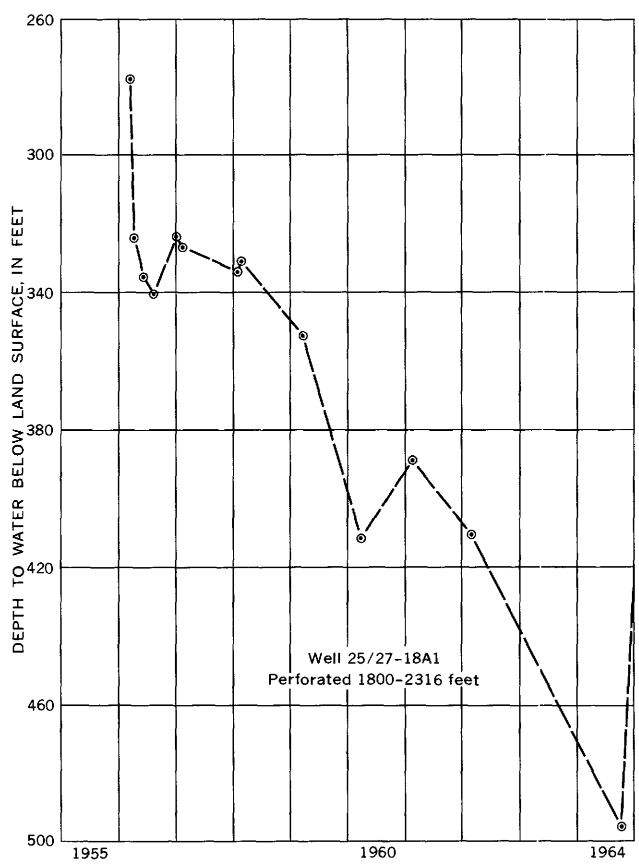


FIGURE 31.—Hydrograph of well 25/27-18A1 tapping the confined Santa Margarita Formation as used by Diepenbrock (1933), 3 miles south of Richgrove. See figure 32 for location of well.

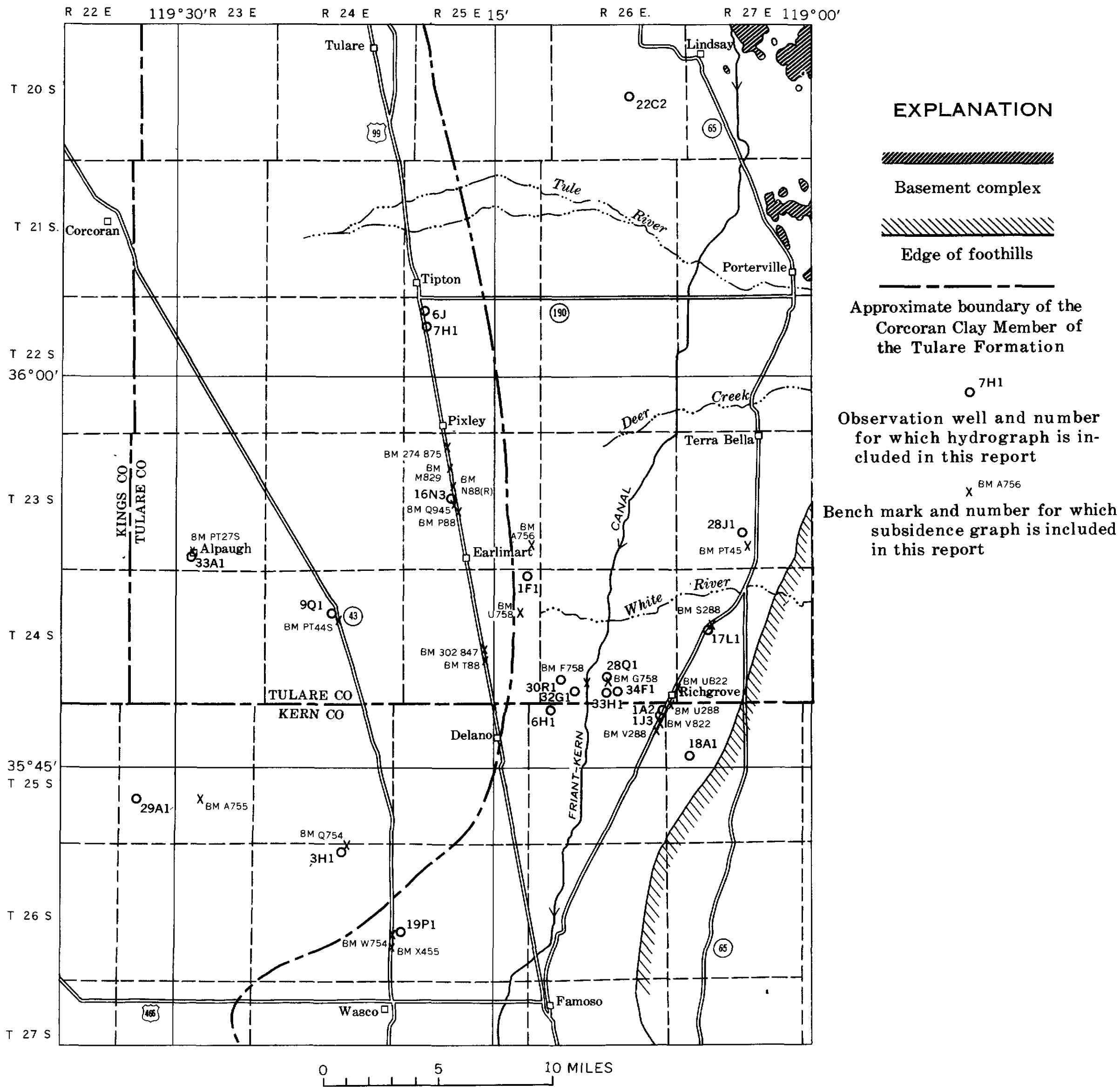


FIGURE 32.—Location of wells and bench marks for which graphs are included in this report.

levels are more significant in relation to compaction and subsidence than are changes in seasonal high levels. The discussion of water-level trends that follows relates to seasonal low levels where possible.

SEMICONFINED AQUIFER SYSTEM

The long-term hydrographs of six wells tapping the semiconfined aquifer system in the eastern part of the area are shown in figure 33. Well 20/26–22C2, drilled to a depth of 247 feet in the northeastern part of the area (fig. 32), shows the water-level trend from 1925 to 1964, 4 miles southwest of Lindsay. Few irrigation wells in this part of the area are more than 600 feet deep, and water levels are relatively shallow. As shown by the hydrograph of well 20/26–22C2, the water level was declining when the record began in 1925, and it declined an additional 135 feet from 1925 to 1951, owing to heavy pumping. From 1951 to 1959, the water level rose about 80 feet in response to surface water imports from the Friant-Kern Canal. Following a 2-year decline, it rose again in 1964 to about the same level as in 1936.

Shallow water levels in the semiconfined aquifer system overlying the outer fringe of the Corcoran Clay Member in the Tipton-Pixley area followed much the same pattern. As shown by hydrographs of wells 22/25–6J and 22/25–7H1 (fig. 33), 2 miles south of

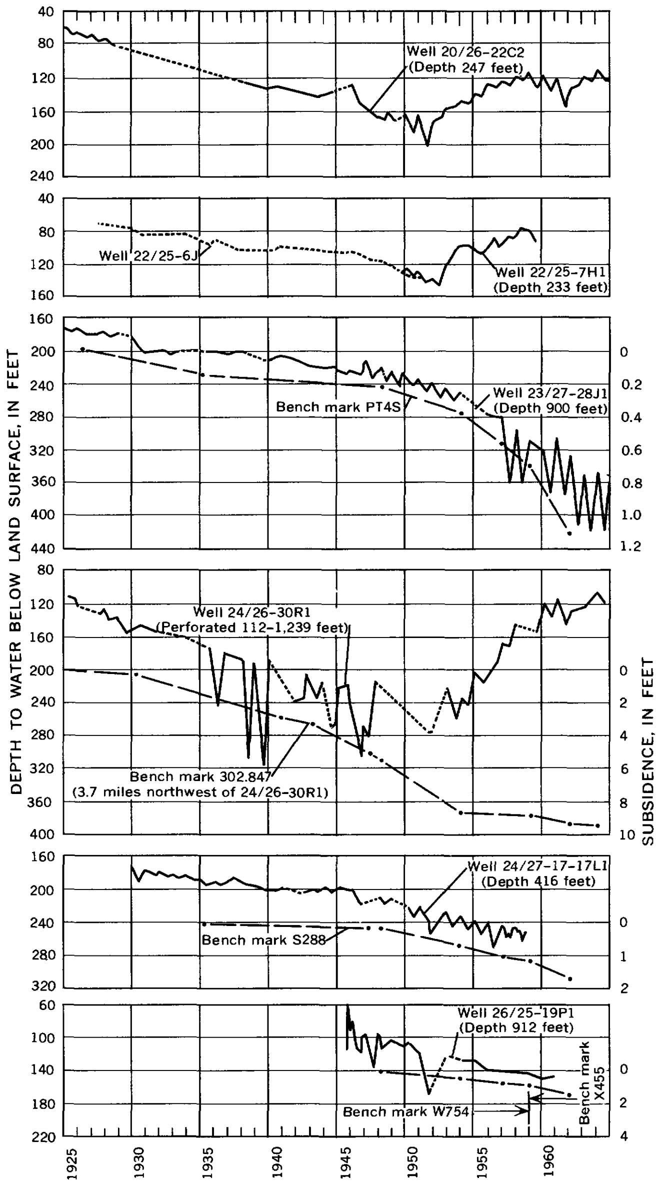


FIGURE 33.—Hydrographs of six wells tapping the semiconfined aquifer system and graphs of subsidence of selected nearby bench marks. See figure 32 for location of wells and bench marks.

Tipton, the water level declined about 75 feet from 1927 to 1952, then rose sharply in response to surface-water imports, and in 1958 stood at about the same height as in 1927.

In the east-central part of the area, intensive pumping has caused water levels to decline almost continuously since records began. Observation well 23/27–28J1, 900 feet deep and about 8 miles northeast of Richgrove, is considerably east of the Friant-Kern service area. The water level in this well (fig. 33) showed a uniform decline of about 85 feet from 1925 to 1953, then an accelerated decline of 160 feet through 1964. Of special significance was the marked increase in the range of seasonal fluctuations, from 4 feet in 1925–26, to about 20 feet in the early fifties, to 70 feet in 1964. This change suggests a marked increase in the rate of seasonal pumping which closely parallels the trend of water-level decline. No evidence of water-level recovery during the fifties was observed in any of the wells of this area.

Observation well 24/26–30R1, drilled to a depth of 1,239 feet in an intensely developed area 4 miles northeast of Delano, is typical of irrigation wells in this vicinity. Because it is perforated throughout most of its depth, this well registers a composite water level of various depth zones. The water level in this well declined about 170 feet from 1925 to 1951, but rose sharply about the same amount during the period of surface-water import, 1951–64. Seasonal fluctuations due to pumping were much less after 1951 than during the forties when ground-water pumpage supplied most of the irrigation requirements.

Hydrographs of wells 24/27–17L1 and 26/25–19P1 (fig. 33), located 3 miles northeast of Richgrove and 4 miles north of Wasco, respectively, each show an uninterrupted downward water-level trend throughout the period of record. Like well 23/27–28J1, well 24/27–17L1 is located in an interfan area of little natural recharge east of the service area of the Friant-Kern Canal. Similarly, much of the area around well 26/25–19P1, is outside of organized irrigation districts that have received surface water deliveries from the Friant-Kern Canal. Though the region has received canal imports from the Kern River for many years, pumpage has exceeded recharge, and water levels in most of the irrigation wells have declined without interruption. The spring high water level in well 26/25–19P1 declined about 85 feet during the period of available record, 1945–61.

In the western part of the area, water levels in the semiconfined aquifer system overlying the Corcoran Clay Member generally declined throughout the period of record, 1952–64. As shown by the hydrograph of piezometer 1, well 23/23–33A1 (fig. 34), completed by the Bureau of Reclamation in 1952 to register water-level changes in the 350–550-foot depth zone of the semiconfined aquifer at Alpaugh, the shallow water level declined about 25 feet from 1952 to 1964. During this 13-year period, the seasonal fluctuation and the long-term downward trend remained relatively constant. Eleven miles to the south-southwest, the hydrograph of piezometer 3, well 25/23–29A1 (fig. 34), completed by the Bureau of Reclamation in 1952 in the 0–280-foot depth zone, shows a general decline of about 17 feet dur-

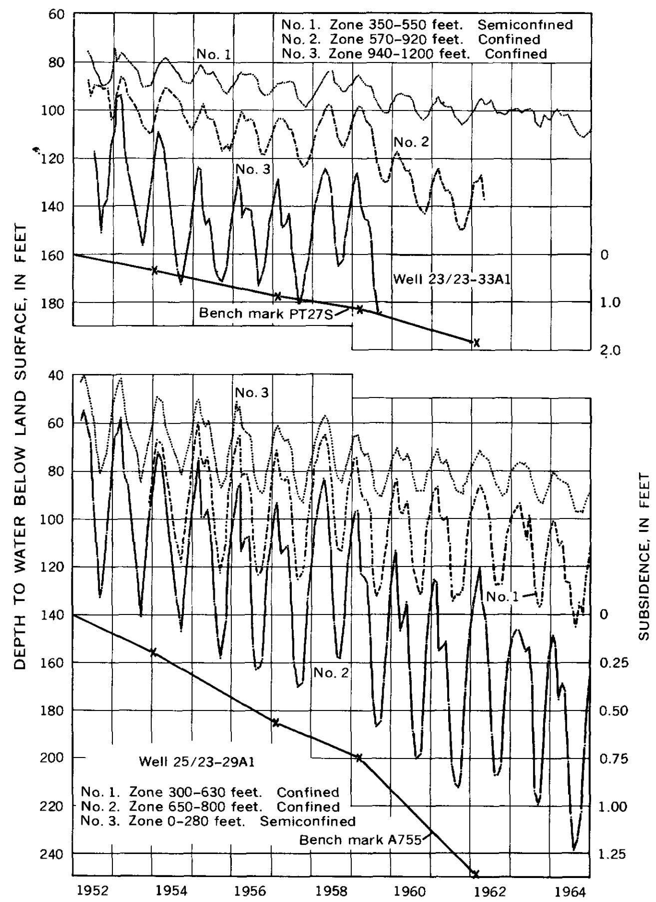


FIGURE 34.—Hydrographs of piezometers tapping the semiconfined and confined aquifer systems at and south of Alpaugh, and graphs of subsidence of nearby bench marks. See figure 32 for location of wells and bench marks.

ing the 13 years of record. The range of seasonal fluctuations decreased from 40 feet in 1952 to about 17 feet in 1964.

CONFINED AQUIFER SYSTEM

In 1905, wells tapping the confined aquifer system flowed throughout most of the area underlain by the Corcoran Clay Member (fig. 22). Field notes of 1906 (in files of the U.S. Geological Survey, Sacramento, Calif.) reported an artesian head 20 feet above land surface in a well in T. 23 S., R. 23 E., sec. 33, which tapped sands 1,200–1,400 feet deep. From 1906 to 1952, when Bureau of Reclamation piezometers were installed, little information is available to indicate the trend of water levels in the sub-Corcoran aquifer system. The 1906 field notes and the hydrograph for piezometer 3 (fig. 34) indicate, however, that the artesian head in the deeper part of the confined system in well 23/23–33 at Alpaugh declined about 114 feet from 1906 to 1953.

The hydrographs of the two deepest piezometers in well 23/23–33A1 (fig. 34), which were completed by the Bureau of Reclamation in 1952, to register head at two different depth intervals, indicate change in piezometric head in the confined aquifer system at Alpaugh. The hydrograph for piezometer 2, registering water-level changes in the 570–920-foot depth zone, shows a continuing seasonal fluctuation of about 20 feet per year and an overall downward trend of about 40 feet during the 10 years of available record. A suggested flattening of the hydrograph from 1955 to spring 1959, however, and a marked increase in rate of decline from 1959 to 1961, are in contrast to the nearly uniform decline of water level in the overlying semiconfined zone (piezometer 1, fig. 34). The water level in the deeper confined zone (piezometer 3, 940–1,200-foot depth zone), on the other hand, fluctuated from 45 to 60 feet each year and declined erratically during the 1952–59 period of available record. Through this period, the downward hydraulic gradient through the confining layer (zone 1 to zone 2) and also within the confined aquifer system (zone 2 to zone 3) increased with time. It is noteworthy that at all times during the period shown, a greater downward head differential existed within the confined aquifer system than across the confining clay.

At the piezometer site 11 miles south-southwest of Alpaugh, hydrographs of two piezometers in Bureau of Reclamation well 25/23–29A1 (fig. 34) indicate the changes in water level in two depth zones in the confined aquifer system. As at Alpaugh, two different water levels are registered in the confined system at this location, with a definite and increasing gradient between the two. Piezometer 1, measuring the 300–630-foot depth zone, showed a continuing seasonal fluctuation of 35–50 feet per year and a general downward trend of seasonal lows of about 3 feet per year. The water level in piezometer 2, measuring the 650–800-foot depth zone fluctuated through a range of 70–80 feet per year and declined about 9 feet per year from 1952 to 1964. Here also, the downward head differential within the confined system (piezometers 1, 2) was much greater than that across the confining layer (piezometers 3, 1). The seasonal and long-term patterns of all three hydrographs are similar, varying mostly in the amount of seasonal fluctuation and long-term decline.

Hydrographs of two other wells tapping the confined aquifer system northwest and southwest of Delano are shown in figure 35. Well 24/24–9Q1, 1,200 feet deep and 9 miles northwest of Delano, reportedly flowed when first drilled (date unknown). Although intermediate records are not available, the spring-high-water level in this well had fallen to 70 feet in 1951 and continued to decline to 110 feet below land surface by the spring of 1961, the last year of available record. Seasonal fluctuations during the 12 years of record varied from 10

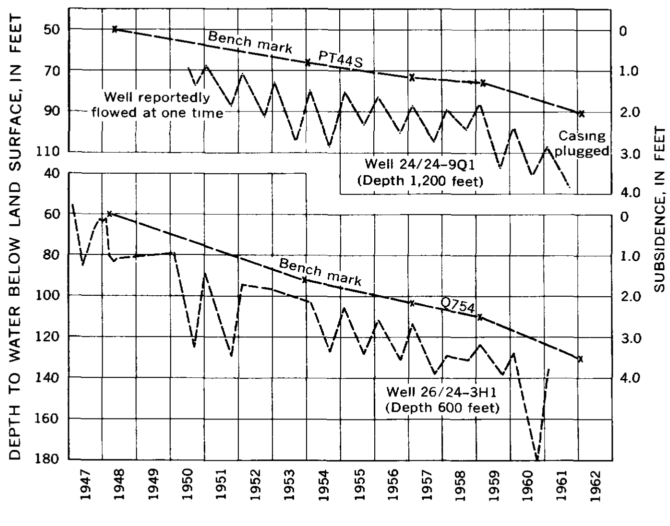


FIGURE 35.—Hydrographs of two wells tapping the confined aquifer system west of Delano and graphs of subsidence of nearby bench marks. See figure 32 for location of wells and bench marks.

to 30 feet. Well 26/24–3H1, drilled to a depth of 600 feet 9 miles southwest of Delano, showed a similar downward trend from 1947 to 1961 (fig. 35). Although a lack of data makes the hydrograph of this well appear more erratic than probably was the actual case, the trend of the annual spring highs declined about 6 feet per year.

As indicated by the hydrographs of figure 34, multiple water levels and large head differentials occur within the confined aquifer system near Alpaugh. A consistent downward head differential that is greater than the differential across the principal confining layer has existed since 1952 within the confined aquifer system. Confined water levels throughout the area have shown a consistent long-term downward trend, with no suggestion of cessation or recovery as was typical of the semiconfined aquifer system in the eastern part of the area during the fifties. No effects of recharge from surface-water deliveries from the Friant-Kern Canal are observed in any of the hydrographs of the confined aquifer system.

SUBSIDENCE OF THE LAND SURFACE

Land subsidence was first recognized in the Tulare-Wasco area in 1935, when consulting engineer I. H. Althouse of Porterville completed a survey which indicated considerable settlement of bench marks in the central part of the area (Ingerson, 1941, p. 40). Certain levels that he ran indicated definite subsidence when compared with altitudes given on topographic maps of the Geological Survey surveyed in 1926. The following was reported in the local Porterville newspaper (July 20, 1939):

Two miles north of Delano the valley floor has sunk five feet below the elevation established in 1927 * * *. At Earlimart the subsidence amounts to about two feet * * *. That the sinking of the earth's surface is probably due to the removal of great amounts of underground water, allowing deep strata to be compressed under the weight of the overlying soil is supported by the fact that the point where the subsidence is the deepest is approximately where the greatest amount of water has been pumped from below and further by the fact that west of Delano where there has been very little pumping, no depressing of the surface is shown.

This evidence of subsidence caused considerable concern, and in 1940, a detailed survey was made of the subsiding area by the California Division of Water Resources. Level circuits were run from stable bench marks in the eastern foothills throughout the subsidence area, and ties were made to more than 100 bench marks of the Geological Survey and the Coast and Geodetic Survey. New altitudes were established at roughly 500 section corners, and these were compared with corresponding altitudes on Geological Survey topographic maps (surveyed in 1925–27, but based largely on 1902 leveling control along U.S. Highway 99). Using these data, Ingerson (1941, fig. 7) prepared the first map delineating subsidence in the Tulare-Wasco area (fig. 36). The map showed that an area extending about 20 miles along the Southern Pacific Railroad from Pixley to McFarland and totaling more than 200 square

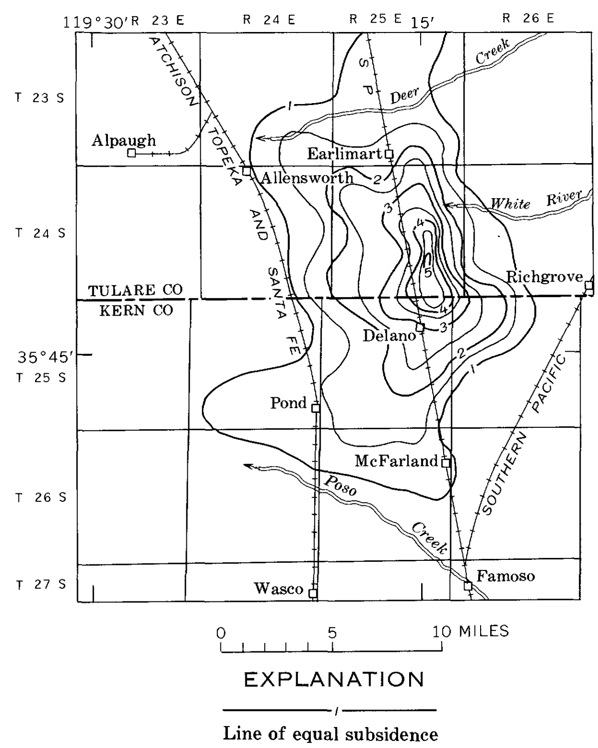


FIGURE 36.—Lines of equal subsidence in the Delano area, 1902–40 (from Ingerson, 1941, fig. 7).

miles subsided more than 1 foot from 1902 to 1940. Ingerson also presented a series of depth-to-water and subsidence profiles along the Southern Pacific Railroad. He attributed the subsidence primarily to water-level decline, which had ranged from 25 to 125 feet in the subsiding area from 1921 to 1939 (Ingerson, 1941, fig. 4).

LEVELING DATA AVAILABLE

The first precise leveling in the Tulare-Wasco area was done by the Geological Survey in 1901–2. Bench marks were established along the main line of the Southern Pacific Railroad as part of a line of levels run from the tidal bench mark at Benicia to Mojave, Calif. Altitudes for this early survey were published in Geological Survey Bulletin 342 and later in Bulletin 766 (U.S. Geological Survey, 1908, 1925). Only eight of these early bench marks were recovered during the 1931 resurvey of this line by the Coast and Geodetic Survey. Altitudes for these eight bench marks, published in Geological Survey Bulletins 342 and 766, were recently revised but not published by the Topographic Division of the Geological Survey. Unpublished readjusted altitudes, based on a recomputation of the 1901–2 levels in areas now known to be subsiding were furnished by the Topographic Division (written commun., Nov. 1961) and were used in preparing figure 39. The Topographic Division also established bench marks along several survey lines in conjunction with their 1926 mapping program.

In 1931, a line of first-order levels was run by the Coast and Geodetic Survey along the Southern Pacific Railroad adjacent to Highway 99. Subsequently, first- and second-order levels were run along various lines in the Tulare-Wasco area in 1935, 1940, 1943, and 1947. In 1948, with the realization of the importance of adequate leveling control in this area of land subsidence, the Coast and Geodetic Survey, in consultation with the Geological Survey and other interested agencies, laid out a detailed network of level lines throughout the subsidence area, and a schedule of periodic releveling was set up.

Figure 37 shows the network of level lines for which comparative leveling by the Coast and Geodetic Survey in 1948 and in subsequent resurveys is available. Lines from this network extend beyond the limits of the map and tie on the north, west, and south with an extensive network of level lines in the San Joaquin Valley. As shown, first-order lines extend to stable bench marks in bedrock east of Porterville and at Woody. Bench marks along these lines furnish control for areal topographic mapping by the Geological Survey, for engineering surveys by public and private agencies, and for the computation of the rate and extent of land subsidence.

PROBLEMS RELATED TO ACCURATE LEVELING IN SUBSIDENCE AREAS

Standard methods of leveling and adjusting errors of closure in a leveling circuit are inadequate in an area of active land subsidence. Concepts of assigning absolute altitude to bench marks and of distributing the error of closure proportionately along the length of the circuit usually cannot be applied. Altitudes assigned to bench marks apply strictly only to the date that the survey was made and then are only as accurate as is the altitude of the reference bench mark. During periods of rapid subsidence, bench marks in centers of the most active areas may subside as much as 0.004 foot per day. From the time a leveling party quits work at a particular bench mark on a Friday evening until the following Monday morning, more than 0.01 foot of subsidence could have occurred, and thus, maintaining an accuracy of even 0.01 foot requires that several special procedures be followed. Because of the unstable conditions, absolute altitudes reported for bench marks in centers of most rapid subsidence should be considered accurate to no more than a tenth of a foot. Relative altitudes between adjacent bench marks, however, are usually much more accurate.

The Tulare-Wasco area falls within four 30-minute quadrangles, as designated by the Coast and Geodetic Survey (fig. 37). Two additional quadrangles include the level lines that tie to bedrock bench marks on the east. Within these quadrangles, the Coast and Geodetic Survey has assigned the individual line numbers (fig. 37), which are used in identifying the individual bench marks. Table 7 gives the years and months in which leveling has been done by the Coast and Geodetic Survey for each of these level lines. In the tabulation, quadrangles and level lines are numbered in accordance with Coast and Geodetic Survey published designations (fig. 37). In addition to the leveling summarized in table 7, leveling control used in the subsidence investigation of the Tulare-Wasco area includes the 1902 leveling of bench marks along line 101 by the Geological Survey and the 1940 leveling of the California Division of Water Resources used by Ingerson (1941) in preparing his figure 7 (reproduced here as figure 36). The amount of subsidence between successive levelings is readily computed as the difference between the respective altitudes shown. Chronologic tabulations of adjusted altitudes of bench marks throughout the Tulare-Wasco area, prepared by the Coast and Geodetic Survey, have served as the basis for preparing the subsidence maps, profiles, and graphs in this report and have proved invaluable in this investigation.

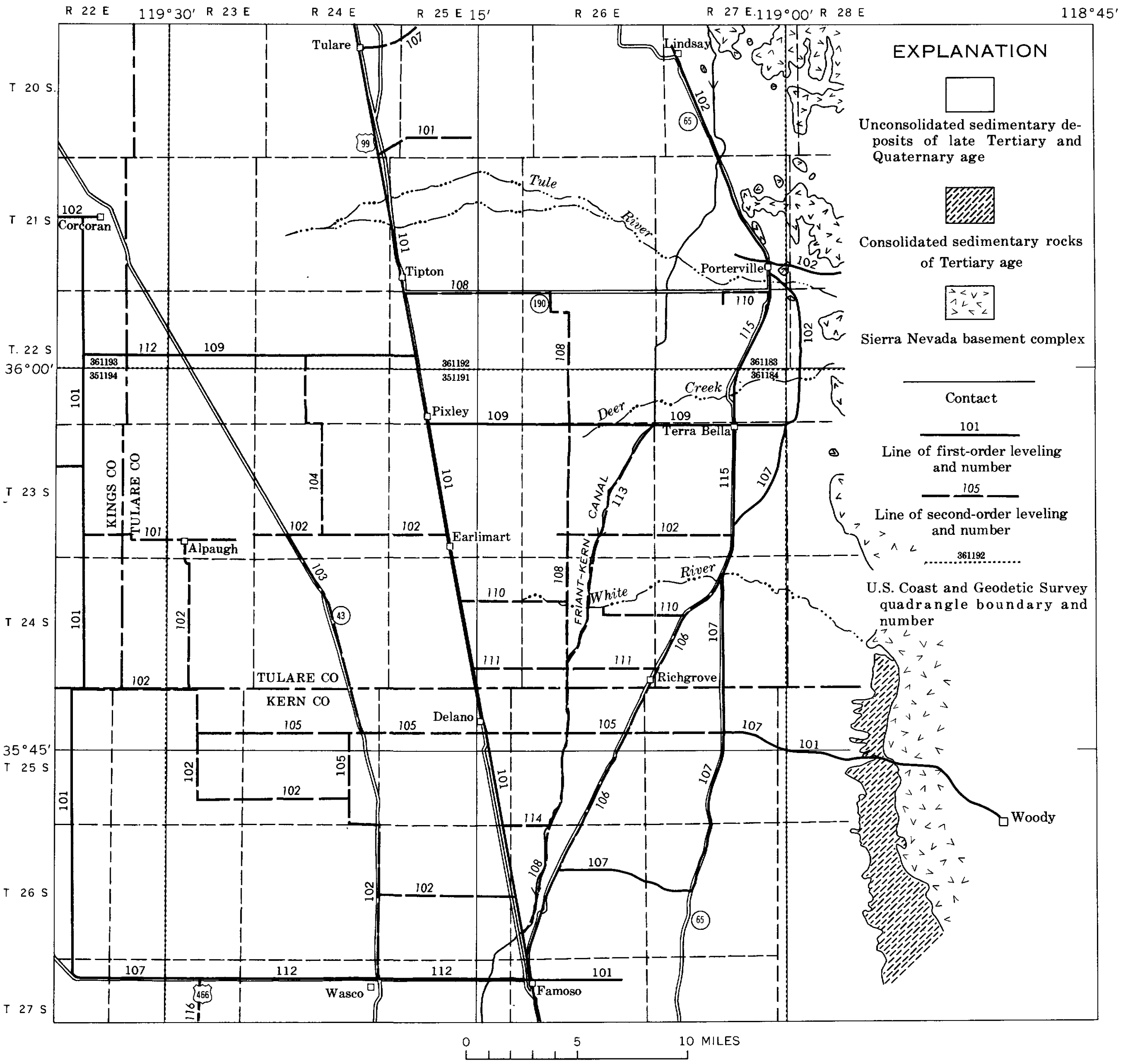


FIGURE 37.—Network of leveling by the U.S. Coast and Geodetic Survey. The level-line numbers in each quadrangle are those published by the Coast and Geodetic Survey.

In order to maintain leveling accuracy in subsidence areas, the following precautions should be considered:

1. Insofar as possible, leveling should be completed during the season of least rapid subsidence. In the Tulare-Wasco area, the rate of subsidence is most rapid during the seasonal water-level decline and is at a minimum during the winter months of December through February, when water levels are high.
2. In areas of major land subsidence, bench marks must be considered as continually changing in altitude. Level circuits should be tied to bench marks outside the centers of most rapid subsidence. If leveling of a line is interrupted for more than a few days, the survey should be rerun from a reference bench mark in a relatively stable area before continuing the circuit. Also, errors in circuit closure should be assigned where subsidence is most rapid.
3. The network should tie at several places, if possible, to bench marks on stable bedrock outside the subsidence area. The part of the leveling network within the subsidence area should be considered as "floating" until a tie to a stable bench mark can be made; then the error of closure should be distributed back into the circuit.

TABLE 7.—*Dates of leveling control by the U.S. Coast and Geodetic Svrvey in the Tulare-Wasco area, 1931-64*

Quadrangle	Line	1931	1933	1935	1940	1942	1943	1947	1948	1953–54	1957	1958–59	1962	1964
351191	101	Feb.			Sept.-Oct.		Mar.	May	Feb.	Nov. 53	Jan.	Feb. 59	Feb.-Mar.	Feb.
	102								Mar.	Dec. 53-Jan. 54	Feb.	Mar. 59	Feb.-Mar.	
	103								May	Jan. 54	Feb.	Mar. 59	Mar.	
	104								May	Feb. 54	Feb.	Mar. 59	Mar.	
	105								Mar.	Dec. 53	Feb.	Feb.-Mar. 59	Jan.-Mar.	Feb.
	106			Mar.				Apr.	Apr.	Nov. 53	Mar.	Feb. 59	Feb.	Feb.
	107			Mar.				May	Apr.	Nov. 53-Mar. 54	Jan.	Feb. 59	Jan.-Feb.	Feb.
	108								Apr.	Nov. 53-Mar. 54	Feb.	Mar. 59	Feb.	
	109					Dec.		June	Apr.	Mar. 54	Feb.	Feb. 59	Feb.	Feb.
	110								Apr.	Mar. 54	Feb.-Mar.	Mar. 59	Feb.	
	111								Apr.	Mar. 54	Feb.-Mar.	Mar. 59	Feb.	
	112			Jan.			Mar.		Feb.	Nov. 53-Jan. 54	Feb.-Mar.	Feb. 59	Mar.	
	113									Nov. 53	Feb.	Mar. 59		
	114									Mar. 54	Feb.	Mar. 59		
	115			Feb.		Dec.		June		Feb. 54	Mar.	Mar. 59	Feb.	Feb.
	116					Dec.				Mar. 54	June	Mar. 59		
351194	101			Feb.		Dec.			May	Jan.-Feb. 54	Feb.-Mar.	Jan.-Feb. 59	Mar.	
	102								May	Jan. 54	Feb.	Mar. 59	Mar.	
	103					Dec.				Feb.-Mar. 54	Mar.-Apr.	Nov.-Dec. 58	Mar.	
	107			Jan.				Apr.		Feb. 54	Mar.	Nov. 58-Mar. 59	Mar.	
361183	102							Apr.		Nov. 53-Mar. 54	Mar.	Feb.-Mar. 59	Feb.	Feb.
361192	101	Jan.		Feb.	Aug.		Feb.	June	Mar.	Feb.-Mar. 54	Feb.-Apr.	Feb. 59	Feb.-Mar.	
	102			Feb.	Aug.			Apr.		Mar. 54	Mar.-May	Jan. 58; Jan.-Mar. 59	Feb.	Feb.
	107			Feb.	Aug.					Feb. 54		Feb. 59	Feb.-Mar.	
	108								Apr.	Mar. 54	Feb.	Mar. 59	Feb.	
	109						Jan.		May	Feb. 54	Feb.	Feb. 59	Mar.	
	110			Feb.				Apr.		Feb. 54	Mar.	Mar. 59	Feb.	Feb.
361193	102			Feb.		Dec.			June	Feb. 54	Mar.	Dec. 58	Mar.	
	112						Jan.		May	Feb. 54	Feb.	Feb. 59	Mar.	

Fortunately, most of the leveling by the Coast and Geodetic Survey in the Tulare-Wasco area has been done during the winter months when water levels in wells are high and the rate of subsidence is minimal. When the level network was established in 1948, many of the problems involved in the leveling of subsiding areas were clearly recognized. Later, bench marks were established on bedrock outcrops east of Porterville and at Woody, east of Delano, and these were used as stable reference ties for each subsequent resurvey. Adjustments that have been made in closing leveling traverses have taken areas of subsidence into account, and floating sections of the network have been tied to the stable bench marks.

Land subsidence also poses serious problems in maintaining topographic-map control as bench marks continue to subside. Eight of the thirty 7½-minute topographic quadrangle maps of the Geological Survey that cover the Tulare-Wasco area had been remapped as of 1954 to correct for the land subsidence since the original surveys. By 1959, however, as much as 2½ feet of additional subsidence had occurred locally in the remapped area, and by 1962, some of the topographic contours were as much as 5 feet in error. For two-thirds of the Tulare-Wasco area, the latest topographic mapping was done in 1926, and much of this apparently was tied to 1901–02 benchmark control.

MAGNITUDE AND AREAL EXTENT OF SUBSIDENCE

The magnitude, extent, and rate of subsidence in the Tulare-Wasco area, as defined primarily by the results of releveling of bench marks but in part by the topographic mapping, are shown by a series of graphs, profiles, and maps (figs. 38–51) in this section. These illustrate the great variation in subsidence, both areally and in time, during the period of leveling control.

Plots of subsidence at bench marks of longest record near the two centers of maximum subsidence in the Tulare-Wasco area illustrate the magnitude and the variation in rate of subsidence at those places from 1901–2 to 1964 (fig. 38). The locations of these bench marks and their relation to the centers of maximum subsidence are shown in figure 50. They also are included in the series of subsidence profiles along U.S. Highway 99 (fig. 38). Bench mark 302.847 is 4 miles

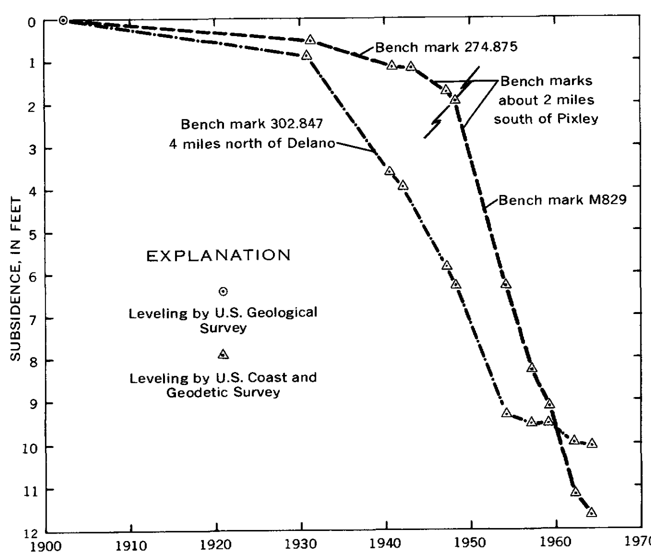


FIGURE 38.—Subsidence of bench marks near centers of maximum subsidence, 1901–2 to 1964. Location of bench marks shown in figure 50.

north of Delano; bench marks 274.875 and M829 are about 2 miles south of Pixley and 0.5 mile apart.

The rate of subsidence of the bench marks at both sites increased almost continuously from 1931 to 1954, although the pattern of increase differed at the two sites, presumably owing to differing rates of water-level decline. After 1954, however, the rate of subsidence at the bench mark north of Delano decreased greatly in response to a rise in water levels attributable to the increased water supply and ground-water recharge from Friant-Kern Canal imports. In contrast, bench mark M829, south of Pixley, continued to subside at approximately the same rate as before 1954, because it is in an area relying almost wholly on ground water for irrigation. The bench mark north of Delano subsided only about 0.7 foot from 1954 to 1964, whereas bench mark M829 south of Pixley subsided 5.3 feet, or about seven times as much. Graphs showing the subsidence of a number of bench marks in other parts of the subsidence area are shown in figures 33–35.

SUBSIDENCE PROFILES

The available leveling data along line 101 (fig. 37) were used to prepare the subsidence profiles of figure 39, which show the magnitude and extent of subsidence from Tulare to Famoso between successive levelings since 1901–2. Each profile is based on the altitude of the individual bench marks for the date indicated. The 1931 altitude of each bench mark, as determined by the first leveling of the Coast and Geodetic Survey, is used as the reference datum. Eight of the Geological Survey bench marks from Tulare to south of Earlimart surveyed in 1902 were recovered in 1931. The subsidence at these bench marks between 1901–2 and 1931 is shown by a dashed line above the 1931 datum. Profiles between Pixley and Delano show the subsidence between successive levelings from 1931 to 1964. North of Pixley and south of Delano, the latest releveling was in 1962.

As shown in figure 39, the entire reach from Tulare on the north to Famoso on the south has been affected by subsidence since 1931. Prior to 1948, the most rapid subsidence was between Earlimart and Delano, in the vicinity of bench mark 302.847 (fig. 38); the location of most rapid subsidence since 1948 has been about 8 miles northward. Between Pixley and Earlimart, the continued decline of water levels in the confined aquifer system due to heavy pumping caused a nearly constant rate of subsidence from 1948 to 1964 (bench mark M829, fig. 38). As of spring 1964, 12.1 feet of subsidence had occurred at bench mark P88, in the center of maximum subsidence between Pixley and Earlimart. Through much of the area, the subsidence rate slowed markedly between the 1953–54 leveling and the 1957 leveling, and in the southern half of the section, between Earlimart and Famoso, subsidence stopped from 1957 to 1959 (fig. 46). This cessation was in direct response to large water-level recoveries brought about by the importation of surface water through the Friant-Kern Canal, beginning in 1950. From 1959 through 1962, which were years of deficient surface supply and increased pumping, water levels in deep wells again began to decline, and subsidence resumed along the entire reach from Tulare to Famoso; maximum rates between Tulare and Tipton and between Pixley and Earlimart were about 0.7 foot per year.

Figure 40 shows the magnitude of subsidence between successive levelings along line X–X', eastward through Pixley (fig. 44), for the period 1942–43 to 1964 (to 1962, west of Pixley). This line of profiles extends from bench mark M662, 6 miles south of Corcoran, eastward to bench mark N288 at Terra Bella. As shown in figure 44, the line is offset 3 miles to the south at Pixley. Because earlier leveling data were not available, the 1942–43 bench-mark altitudes were used as the straightline base for this section. The amount of subsidence since 1942–43 along this line is least near Terra Bella and greatest east of Pixley. The substantial decrease in the rate of subsidence between 1954 and 1959 (5-year period) compared to the rate between 1948 and 1954 (6-year period) reflects the effect of decreased pumping and increased recharge from surface-water imports. The accelerated subsidence in 1959–62 was the result of increased pumping and water-level decline during 3 years of deficient surface supply. In the confined aquifer system west of Pixley, the decline was a continuation of the earlier trend. In the semiconfined system east of Pixley, the decline was primarily in the piezometric surface of the deeper more confined zones; in some of the canal service area, the water table of the semiconfined system actually rose from 1959 to 1962. (For an example, see figure 68, middle graph, hydrograph for 25/26–6H1.)

The amount of subsidence along the Tulare-Kern County line between successive levelings from 1948 to 1962 is shown in figure 41. From bench mark B758 to a point east of Richgrove, the line is offset about 1 mile north of the county line. In general, less subsidence has occurred since 1948 in this part of the area than farther north (line X–X', fig. 40). The longest history of subsidence along this line is at bench mark U88, adjacent to U.S. Highway 99, where 4.36 feet of subsidence occurred from 1931 to 1948. Of particular interest is the belt of decreased subsidence in the vicinity of the Friant-Kern Canal. Water deliveries from the canal began in this area in 1951 and apparently had a direct effect on reducing the rate of subsidence.

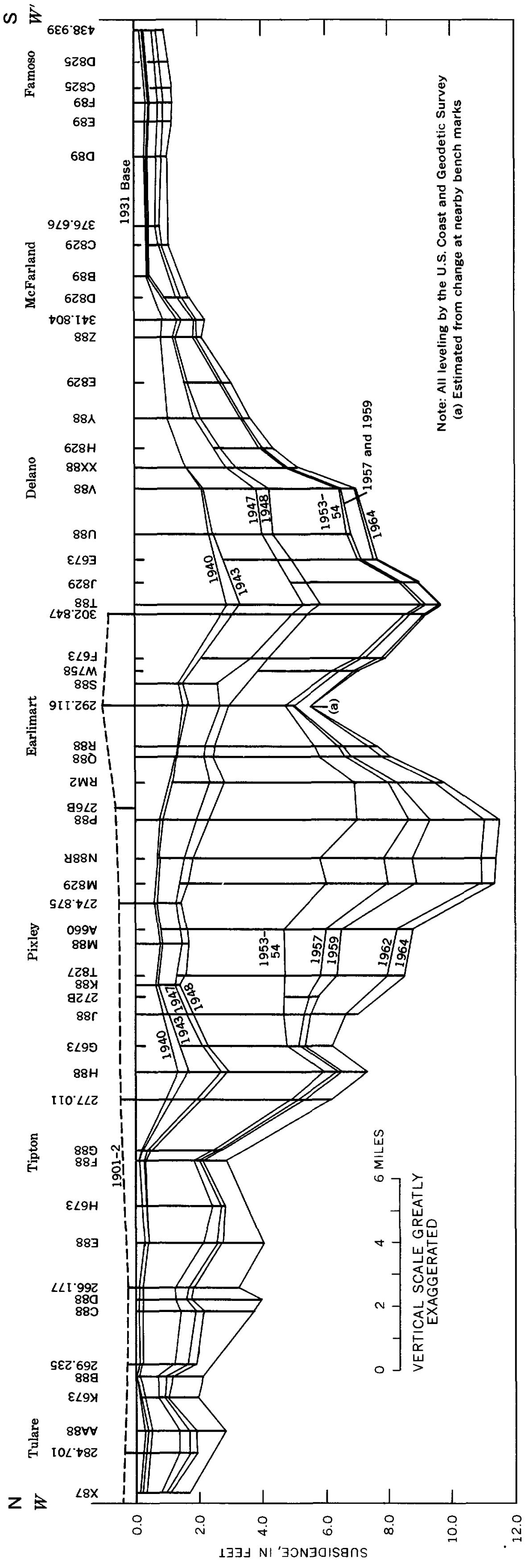


FIGURE 39.—Land-subsidence profiles W–W′, along U.S. Highway 99 from Tulare to Famoso, 1901–2 to 1964. For location see figure 44.

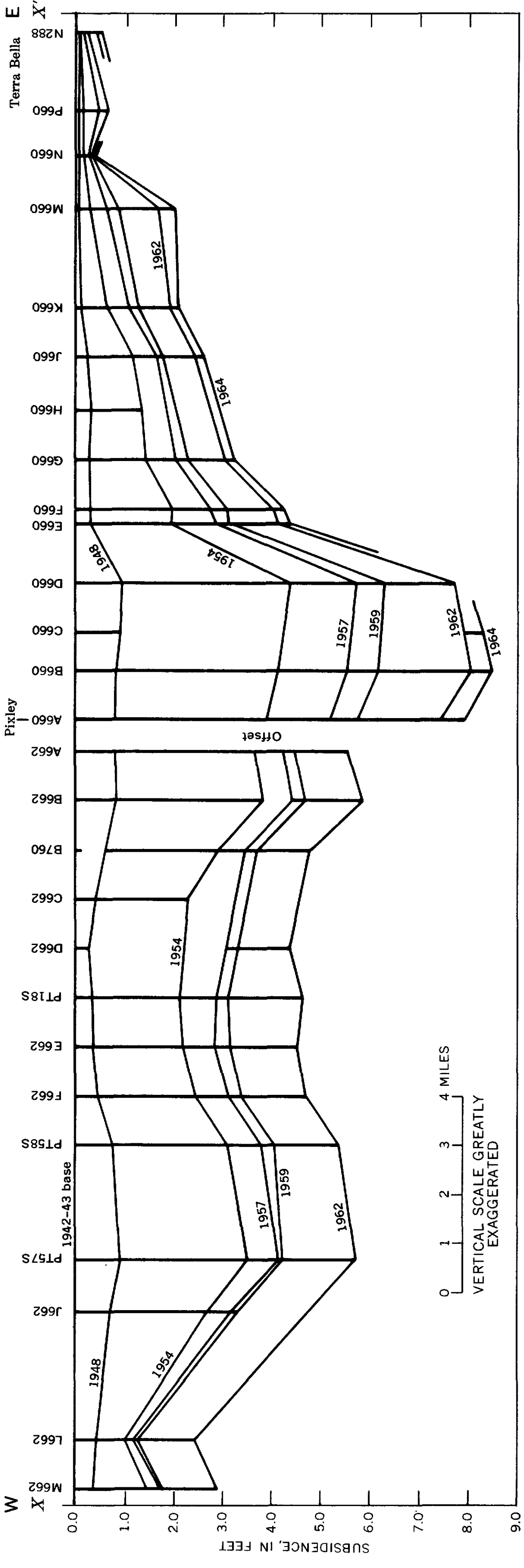


FIGURE 40.—Land-subsidence profiles X–X′, 1942–43 to 1964. For location, see figure 44.

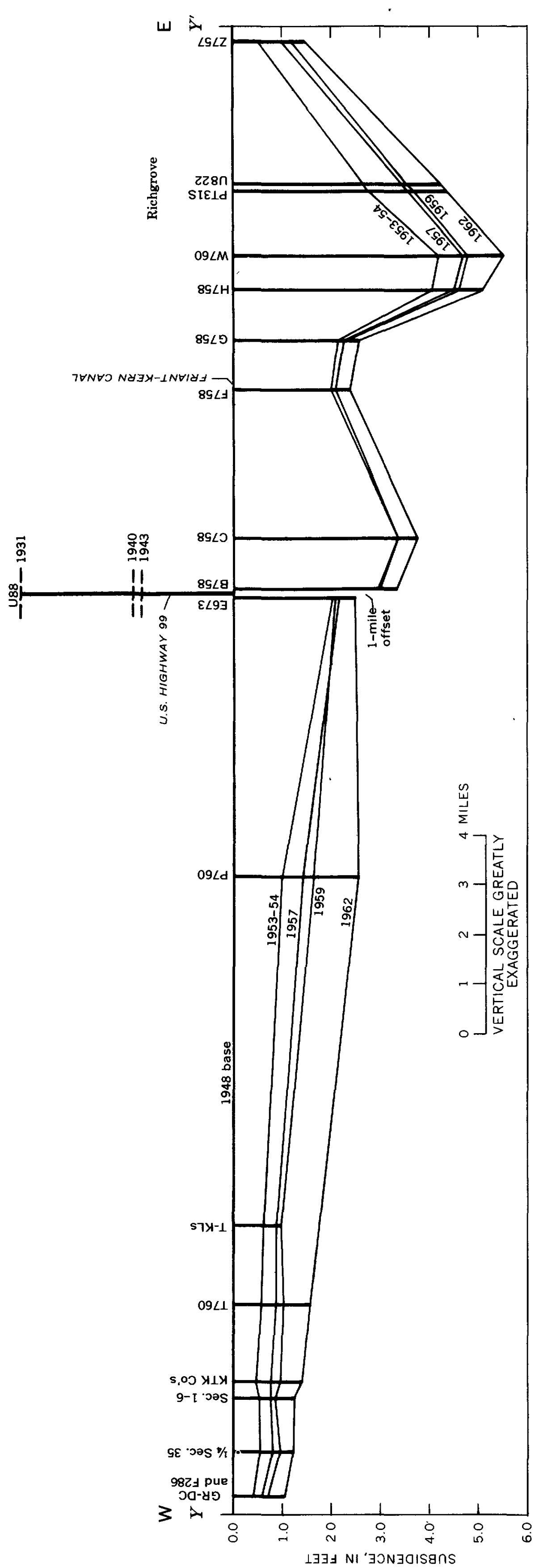


FIGURE 41.—Land-subsidence profiles Y—Y', 1948–62. For location see figure 44.

Subsidence profiles along line *Z–Z′* for the period 1935–64 are shown in figure 42. The southwest half of line *Z–Z′* was not surveyed in 1962 and 1964; therefore, profiles for these years could not be plotted for this part of the line. As shown, nearly 5 feet of subsidence has occurred since 1935 in two centers, one at Richgrove and the other about 4 miles southwest of Richgrove. The rate of subsidence in these areas was much greater from 1948 to 1953 than during subsequent periods. The subsidence depression at Richgrove coincides in general with the area of maximum decline of water level from 1920–21 to 1948 (fig. 25).

SUBSIDENCE MAPS

Two sets of topographic maps of the Tulare-Wasco area have been published by the U.S. Geological Survey: (1) 7½-minute quadrangle maps (scale 1:31,680), prepared from a 1925–26 survey but referenced in part to bench-mark altitudes of the 1901–2 survey and (2) 7½-minute quadrangle maps (scale 1:24,000), eight of which were resurveyed in 1953 and 1954 by using as primary vertical control the Coast and Geodetic Survey's 1953–54 bench-mark altitudes. These eight quadrangles include most of the area of major subsidence. Within the extent of the eight remapped quadrangles, the land-surface contours on the two sets of quadrangles were compared in order to obtain a rough approximation of the magnitude and areal extent of the land subsidence that had occurred as of 1954. Outside the area of the eight remapped quadrangles, subsidence was approximated by comparing the contours on the 1925–26 maps with the altitude of bench marks established by the 1953–54 releveling of the Coast and Geodetic Survey. The subsidence map so obtained (fig. 43) shows the approximate extent and magnitude of land subsidence in the Tulare-Wasco area between 1926 and 1954. Although a small amount of subsidence may have occurred prior to 1926, the magnitude is indeterminate; however, it is known to be negligible compared to subsidence since 1926. Therefore, 1926 is considered to be the beginning date of appreciable subsidence in the Tulare-Wasco area.

As shown in figure 43, subsidence as of 1954 amounted to 12 feet in the principal subsidence depression north of Delano and to more than 6 feet between Pixley and Earlimart. Also, the configuration of the lines of equal subsidence is not far different from the configuration of the lines on Ingerson's map showing subsidence as of 1940 (fig. 36). Planimetering of figure 43 indicates that about 1.16 million acre-feet of subsidence had occurred within the 2-foot subsidence line, and an estimated 180 thousand acre-feet had occurred outside the 2-foot line. Thus, the total volume of subsidence for the 28-year period, 1926–54, was about 1.34 million acre-feet. Roughly this same volume of water was permanently

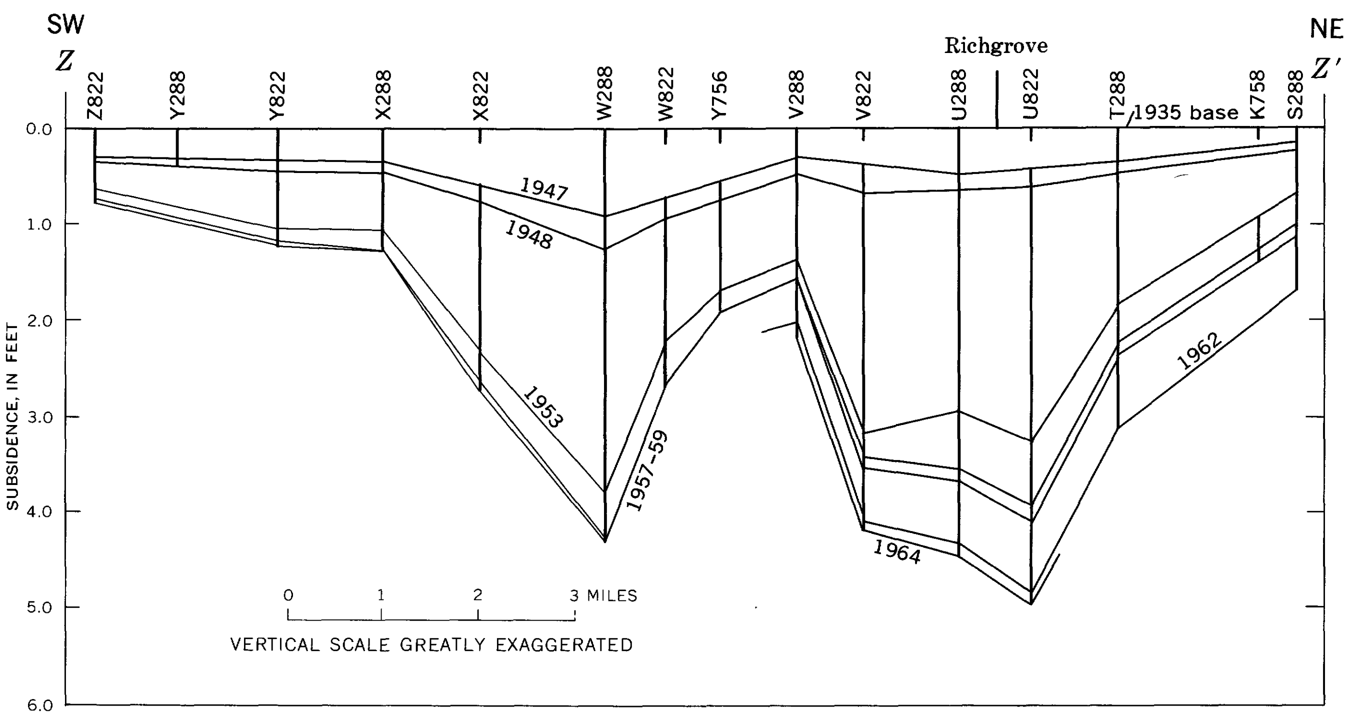


FIGURE 42.—Land-subsidence profiles *Z–Z′*, 1935–64. For location, see figure 44.

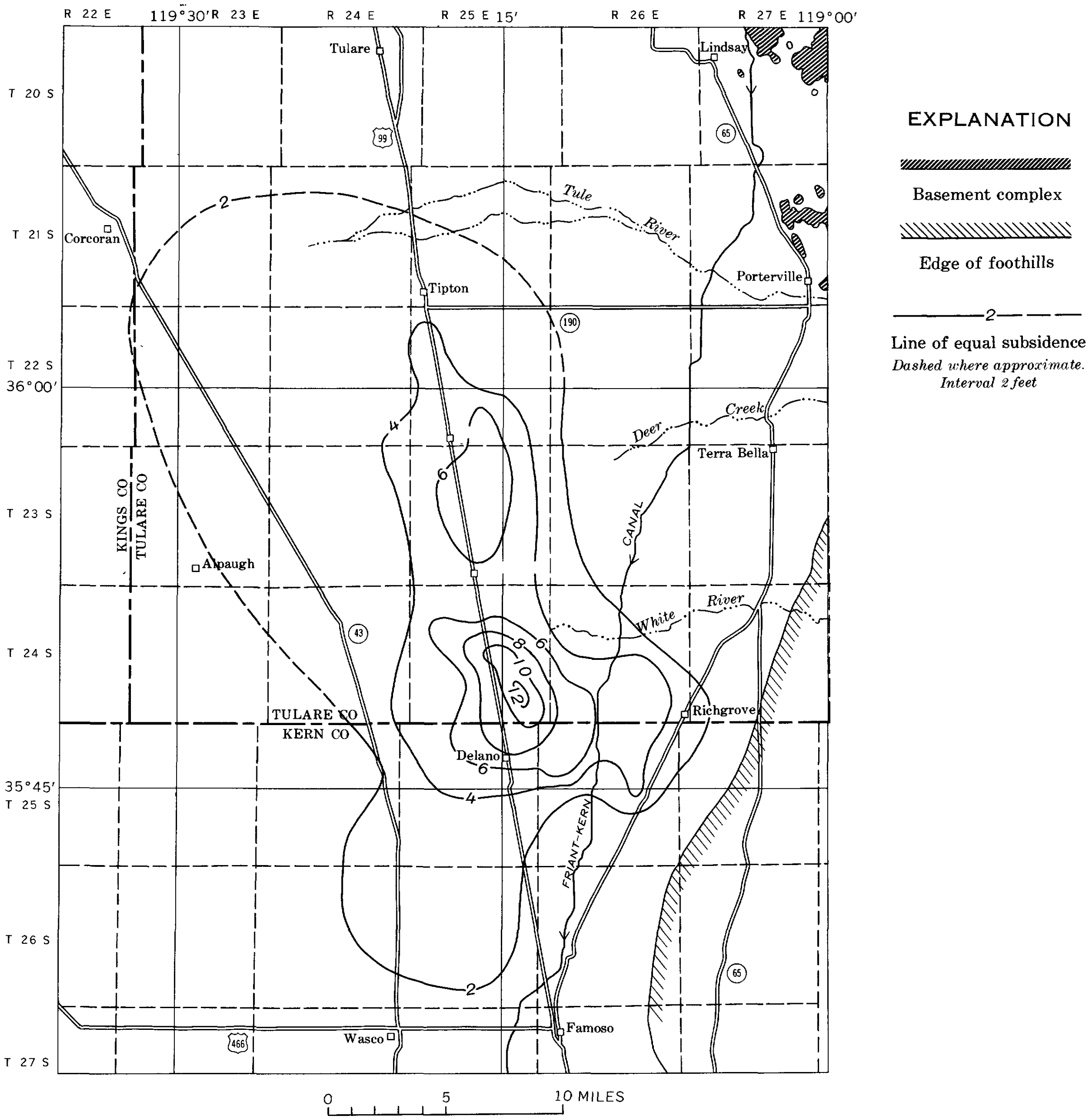


FIGURE 43.—Land subsidence 1926–54. Compiled from topographic maps of the U.S. Geological Survey, surveyed in 1925-26 and in 1953–54, and leveling of the U.S. Coast and Geodetic Survey in 1953–54.

removed from ground-water storage owing to the compaction of the sediments.

Figure 44 shows the magnitude and areal extent of the subsidence between 1948 and 1954. The lines of equal subsidence are based on the change of altitude of about 300 bench marks between the 1948 and 1954 levelings of the Coast and Geodetic Survey. In most of the area between Earlimart and Tulare, more subsidence occurred during this 6-year period than had occurred from 1926 to 1948 (fig. 39). The most rapid subsidence during the 6-year period was west of Richgrove, north of Delano, and between Pixley and Earlimart. Also, an elongate subsidence trough developed along the highway southeast of Corcoran. About 780,000 acre-feet of subsidence (obtained by planimetering fig. 44) occurred in this 6-year period. Even though water levels in part of the Friant-Kern Canal service area started to rise in 1951 (fig. 24), the rate of subsidence was only beginning to decrease by 1954. The 1953–54 leveling, therefore, marks the transition between the accelerating rate of subsidence that preceded this date and the decreasing rate that followed.

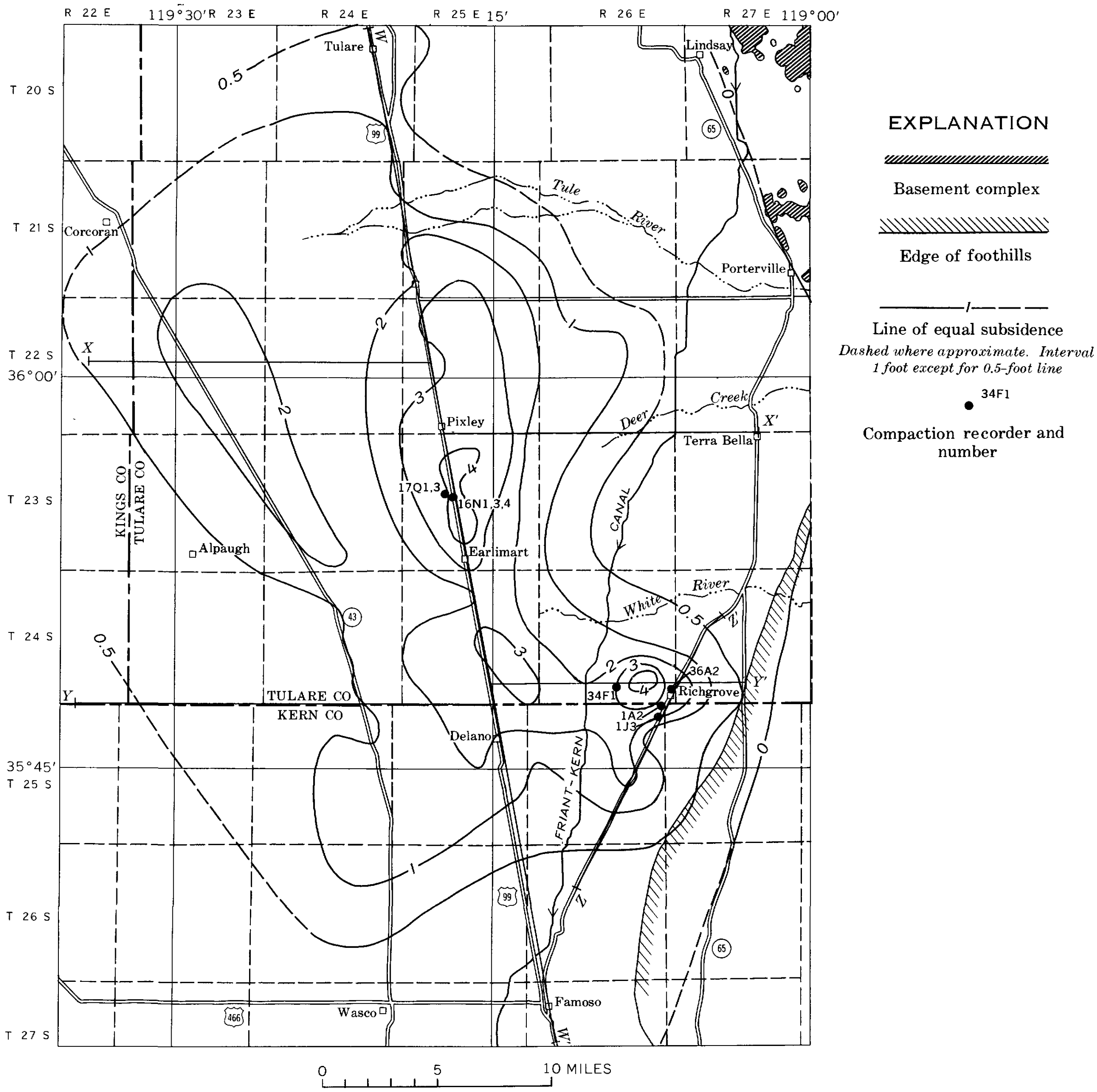


Figure 44.—Land subsidence, 1948–54, and location of subsidence profiles. Compiled from leveling of the U.S. Coast and Geodetic Survey, February to May 1948 and November 1953 to March 1954.

The water-level change map for 1948–54 (fig. 26) does not show centers of water-level decline to be coincident with the areas of subsidence north of Delano and west of Richgrove (fig. 44). In fact, the 3-foot subsidence depression north of Delano is in an area where the water level in relatively shallow wells experienced a net recovery of as much as 40 feet from 1948 to 1954. This discrepancy suggests that compaction continued in the deeper, more confined, beds of the semiconfined system, which may not have recovered appreciable head by 1954. About one-quarter of the wells in this area (SE¼, T. 24 S., R. 25 E.) are more than 1,000 feet deep. West of Richgrove, a number of deep wells drilled between 1948 and 1954 not only greatly increased the rate of pumpage from the deep part of the aquifer system but also tapped the underlying highly compactible marine beds (fig. 5) for the first time.

The effect of the sharp water-level recoveries that followed importation of surface water through the Friant-Kern Canal is shown in figure 45. This map, showing the amount of subsidence in the 3-year period, 1954–57, is based on leveling in the winter months of 1954 and

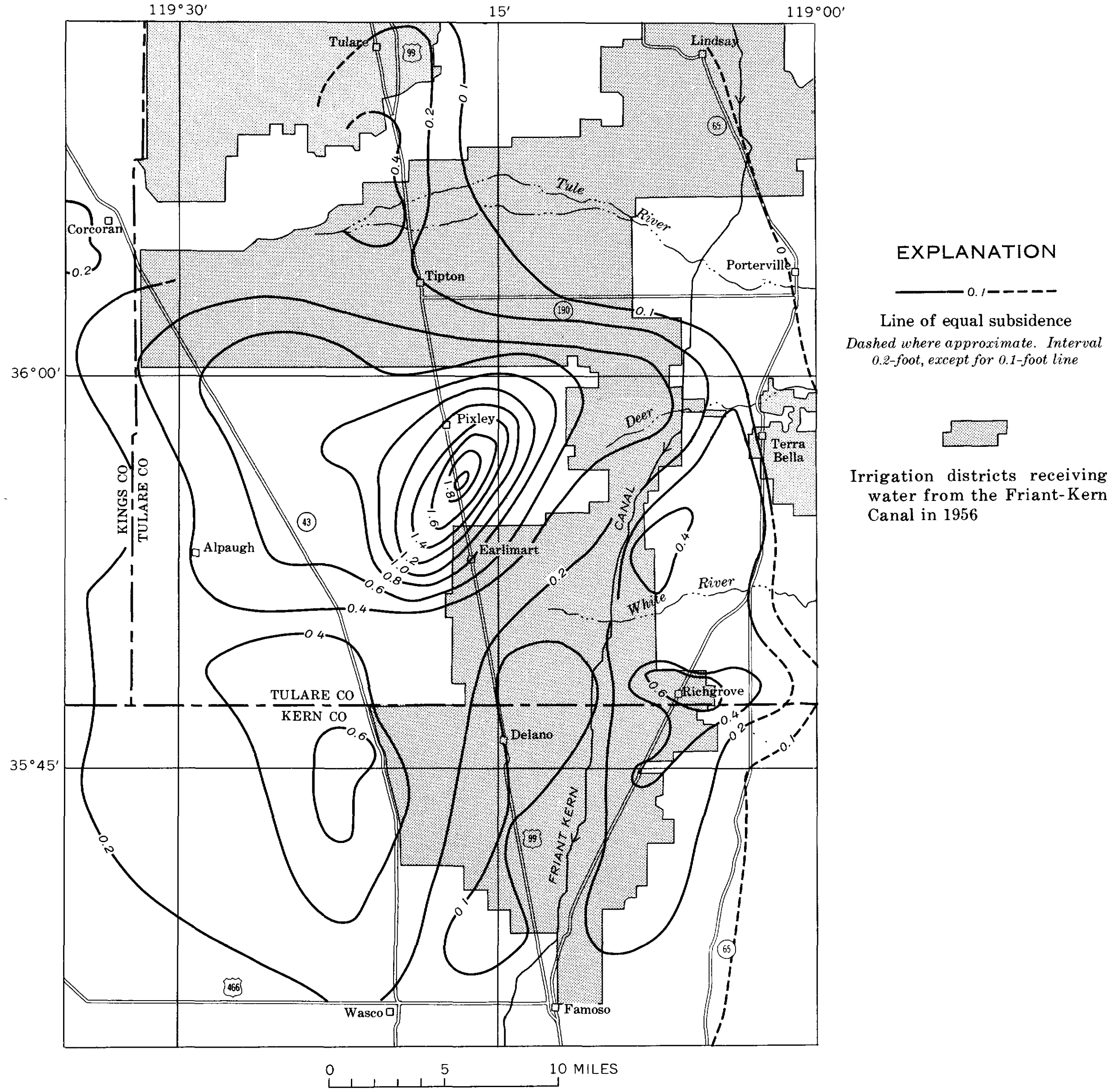


Figure 45.—Land subsidence, 1954–57, and districts receiving irrigation water from the Friant-Kern Canal in 1956. Subsidence lines compiled from leveling of the U.S. Coast and Geodetic Survey, November 1953 to March 1954 and January to March 1957.

1957 (table 7). The shaded pattern in figure 45 shows the areal extent of irrigation districts receiving surface-water diversions from the Friant-Kern Canal in 1956 (table 3; fig. 13). Within these districts, the reduction in the rate of subsidence in the 3-year period 1954–57, compared to the 6-year period 1948–54, is striking. For example, in the area of historic maximum subsidence about 4 miles north of Delano, subsidence decreased from 3 feet in the 6-year period 1948–54 (0.5 ft per yr, fig. 44) to 0.1 foot in the 3-year period 1954–57 (0.03 ft per yr, fig. 45). Subsidence of more than 0.1 foot per year (0.3 ft of subsidence during the 3 years, fig. 45), continued in the Pixley-Earlimart area, in a broad area between Alpaugh and Wasco, in a local area east of the Friant-Kern Canal 6 miles north of Richgrove, and at Richgrove. In the Pixley-Earlimart area and in the area north of Wasco, subsidence continued at a rate about equal to that of 1948–54 presumably because these areas did not receive surface-water imports in 1954–57, but rather were irrigated by ground water pumped from local wells.

Figure 46 shows the amount of subsidence in the Tulare-Wasco area in the 2-year period from winter 1957 to winter 1959. Although subsidence of more than 0.2 foot per year (0.4 ft of subsidence during the 2 years) occurred in the Pixley-Earlimart area and in a small area 9 miles north of Richgrove, the rate in most of the area did not exceed 0.1 foot per year. In the vicinity of Delano and in an area of more than 100 square miles of farm land west of the Friant-Kern Canal, subsidence had ceased by 1957, owing to the appreciable rise in water levels that began in 1954 (fig. 27).

Surface-water supply was deficient in the 3 years from 1959 to 1962 (fig. 14), and withdrawal from wells increased (fig. 21). Water levels in deeper wells within the Friant-Kern Canal service area again began to fall, although the water table in much of the canal service area continued to rise. Figure 47 shows the magnitude and extent of subsidence in this 3-year period between winter 1959 and winter 1962. Maximum subsidence was 2 feet in the Pixley-Earlimart area, and subsidence exceeded 1.4 feet midway between Tulare and Pixley on U.S. Highway 99 and 8 miles northwest

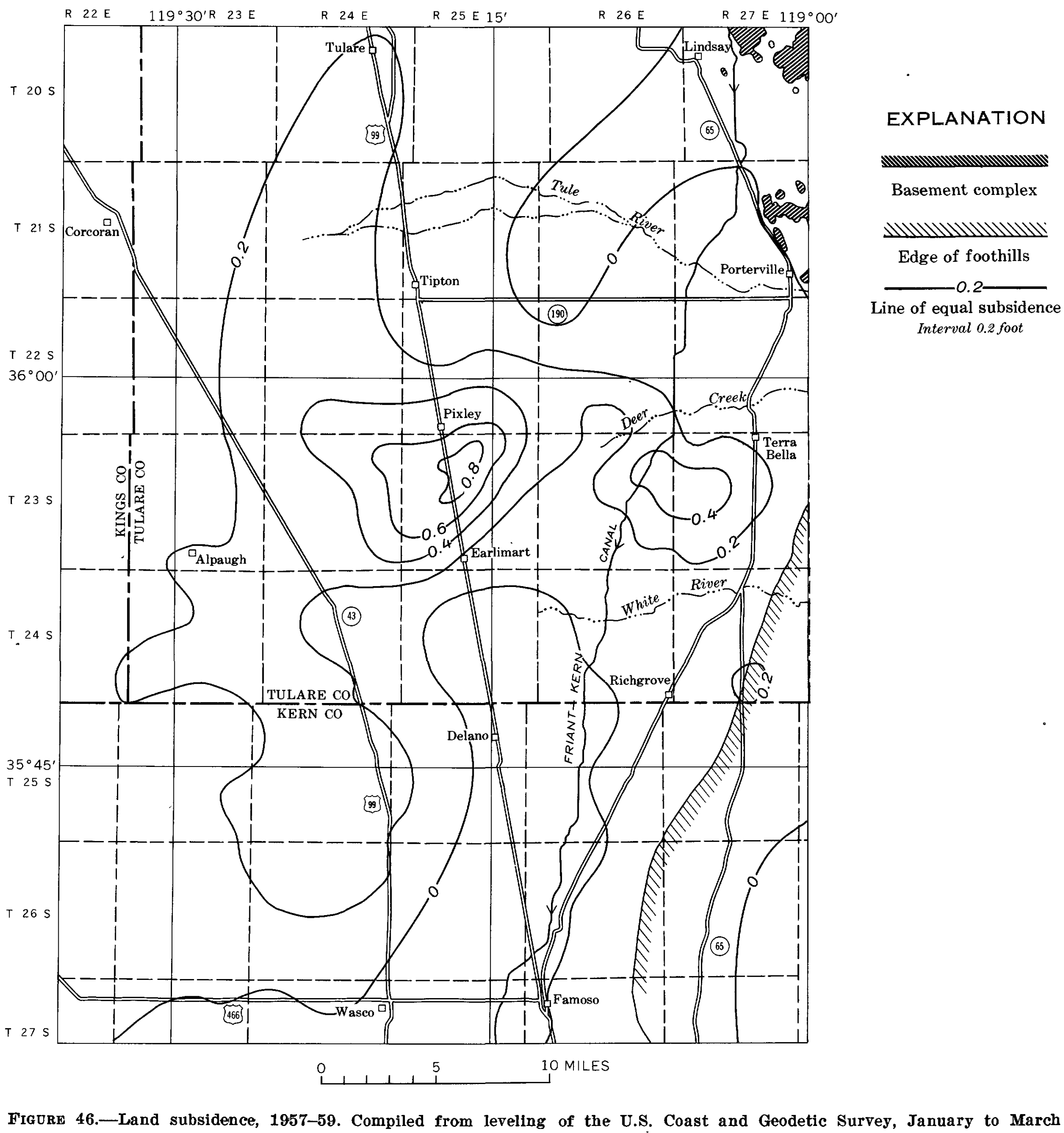


Figure 46.—Land subsidence, 1957–59. Compiled from leveling of the U.S. Coast and Geodetic Survey, January to March 1957 and February to March 1959.

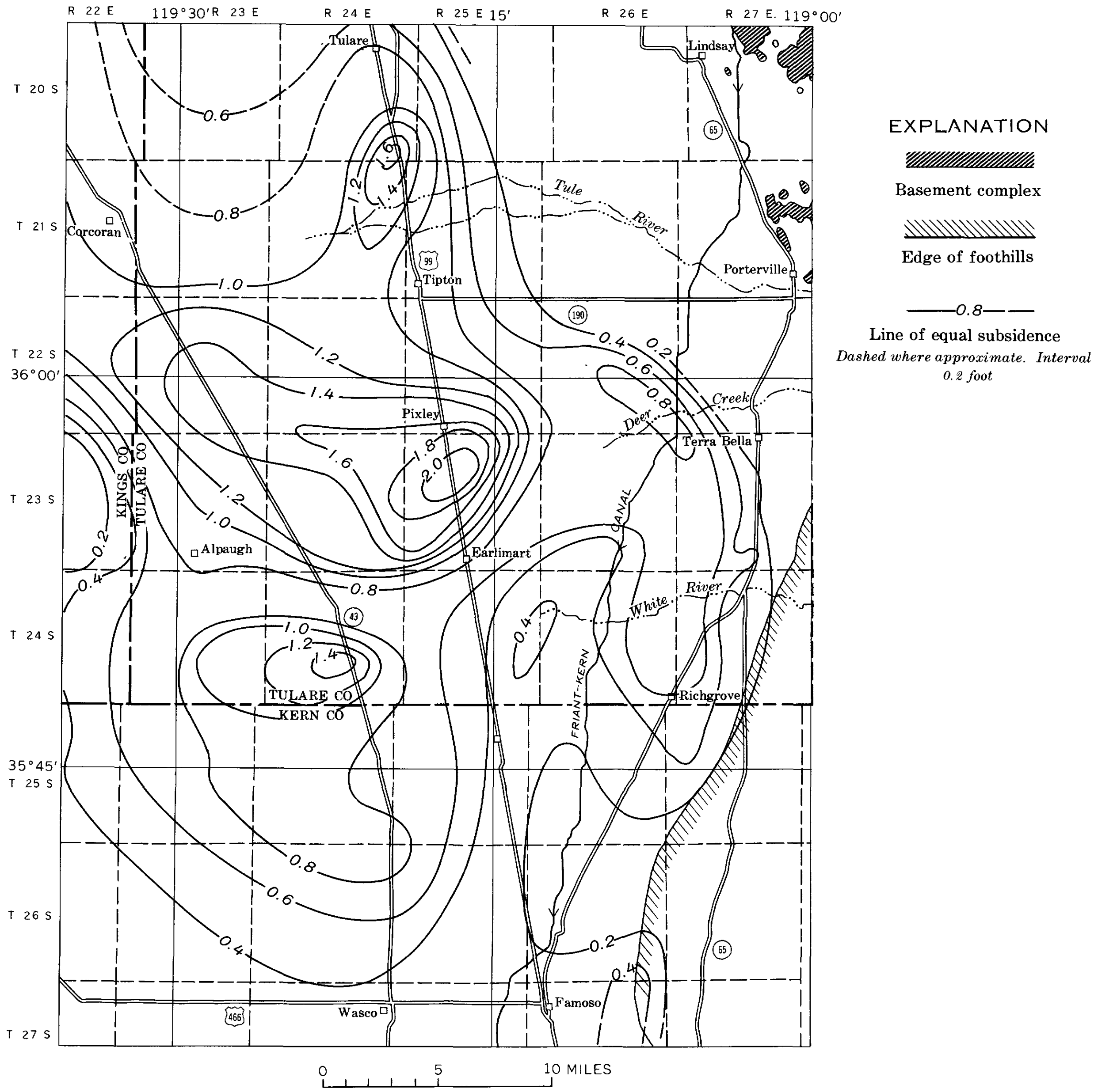


Figure 47.—Land subsidence, 1959–62. Compiled from leveling of the U.S. Coast and Geodetic Survey, February to March 1959 and January to April 1962.

of Delano. Subsidence exceeded 0.2 foot along 18 miles of the Friant-Kern Canal, as water deliveries from the canal decreased to less than half (table 3, 1961) their earlier maximums. More than half the Tulare-Wasco area again subsided at rates greater than 0.1 foot per year. Roughly 480,000 acre-feet of subsidence occurred in the area during the 3-year period 1959–62.

VOLUME OF SUBSIDENCE

The cumulative volume of subsidence in the Tulare-Wasco area from 1926 to winter 1962, based on the subsidence maps of figures 36 and 43–47, was about 2.2 million acre-feet (fig. 48). Plotted points on the graph show the cumulative volume of subsidence as of the dates when control was available, and the connecting line indicates the estimated rate of cumulative increase in subsidence. The volumes of subsidence were obtained by using a planimeter to measure the areas of equal subsidence on the several subsidence maps.

The average rates of subsidence in thousands of acre-feet per year during the six periods of available data from 1926 to 1962 are shown in figure 49. The curved dashed line shows the probable subsidence during this period. The high rate of subsidence from 1948 to 1954

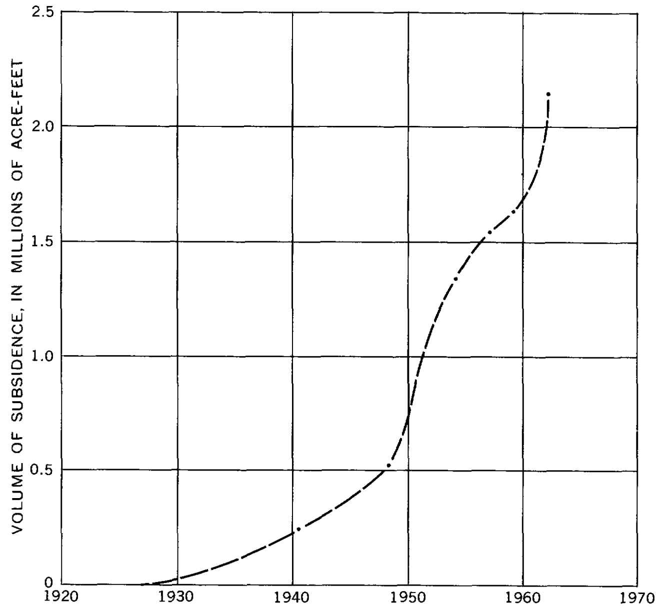


FIGURE 48.—Cumulative volume of subsidence, 1926–62. Points indicate times of leveling control.

and again from 1959 to 1962, with an intervening 5-year period of reduced subsidence, is clearly shown in figure 49 and roughly agrees with the trend of ground-water pumpage shown in figure 21.

Figure 50 shows the total amount of subsidence in the Tulare-Wasco area from 1926 to 1962. The map was compiled from a comparison of topographic maps for the period 1926–54 (fig. 43) and from leveling of the U.S. Coast and Geodetic Survey for the period 1954–62. Subsidence was more than 10 feet in two centers: (1) 3 miles north of Delano and (2) between Pixley and Earlimart. In the southernmost of these centers (north of Delano), subsidence occurred almost entirely before 1954 (figs. 39, 43); from 1954 to 1962,

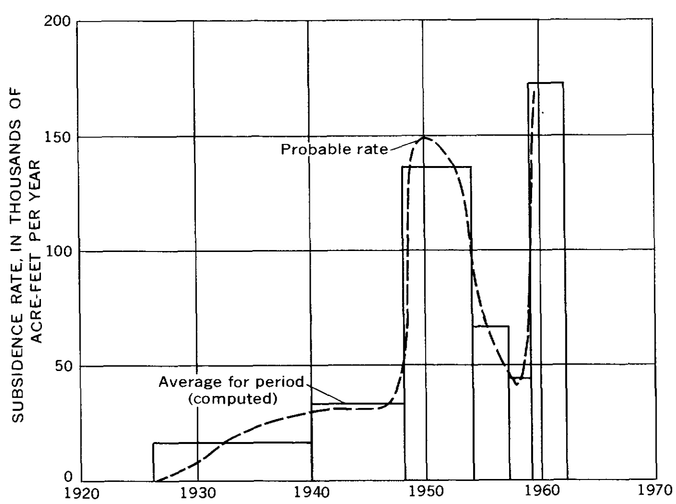


FIGURE 49.—Rate of subsidence, 1926–62.

the maximum subsidence during each period between levelings was between Pixley and Earlimart. As much as 11.5 feet of subsidence occurred in this area of continuous ground-water withdrawal between 1926 and 1962, but most of this subsidence took place after 1948 (fig. 39).

On the basis of planimetered areas of figure 50, the following relationships were obtained. By 1962, approximately 514,000 acres, or about 53 percent of the entire Tulare-Wasco area, had subsided more than 2 feet, and about 110,000 acres, or 11 percent of the area, had subsided more than 5 feet. One small area had subsided a maximum of 12.8 feet. These relationships are demonstrated in figure 51. The area under the curve represents the volume of subsidence, which is 2.2 million acre-feet for the period 1926–62 as measured from this plot. About 10 percent of the total volume of subsidence occurred in areas that subsided less than 2 feet.

POSSIBLE CAUSES OF LAND SUBSIDENCE

Three types of land subsidence due to man's activities have been recognized in or adjacent to the San Joaquin Valley: (1) subsidence due to the compaction of aquifer systems caused by a reduction of fluid pressures (Poland and Davis, 1956, 1969), (2) subsidence due to the hydrocompaction of moisture-deficient surficial deposits caused by wetting (Inter-Agency Committee, 1958; Bull, 1964; Lofgren, 1969), and (3), subsidence due to the oxidation and compaction of peat soils in the Sacramento-San Joaquin Delta areas as a result of drainage and cultivation (Weir, 1950). Of these three types, only the first is known to be occurring in the Tulare-Wasco area.

The removal of fluids from oil and gas fields is a possible cause of local subsidence, but only two fields are of appreciable size in the Tulare-Wasco area—the Trico gas field south of Alpaugh, in T. 24 S., R. 23 E., and the Semitropic oil field west of Wasco, in T. 27 S., R. 23 E. A comparison of leveling across the Trico gas field in 1948 and 1962 and across the Semitropic oil field in 1935 and 1962 indicates that withdrawals from these fields did not contribute appreciably to the areal subsidence.

Tectonic movement is another possible cause contributing to land subsidence in the Tulare-Wasco area. Davis and Green (1962, p. D–90) postulated that post-depositional downwarping was responsible for much of the structural closure of about 300 feet in the Corcoran Clay Member of the Tulare Formation beneath the Tulare Lake bed, which extends east into the western part of the Tulare-Wasco area (fig. 6). However, if structural downwarping has been occurring uniformly since the deposition of the Corcoran Clay Member in

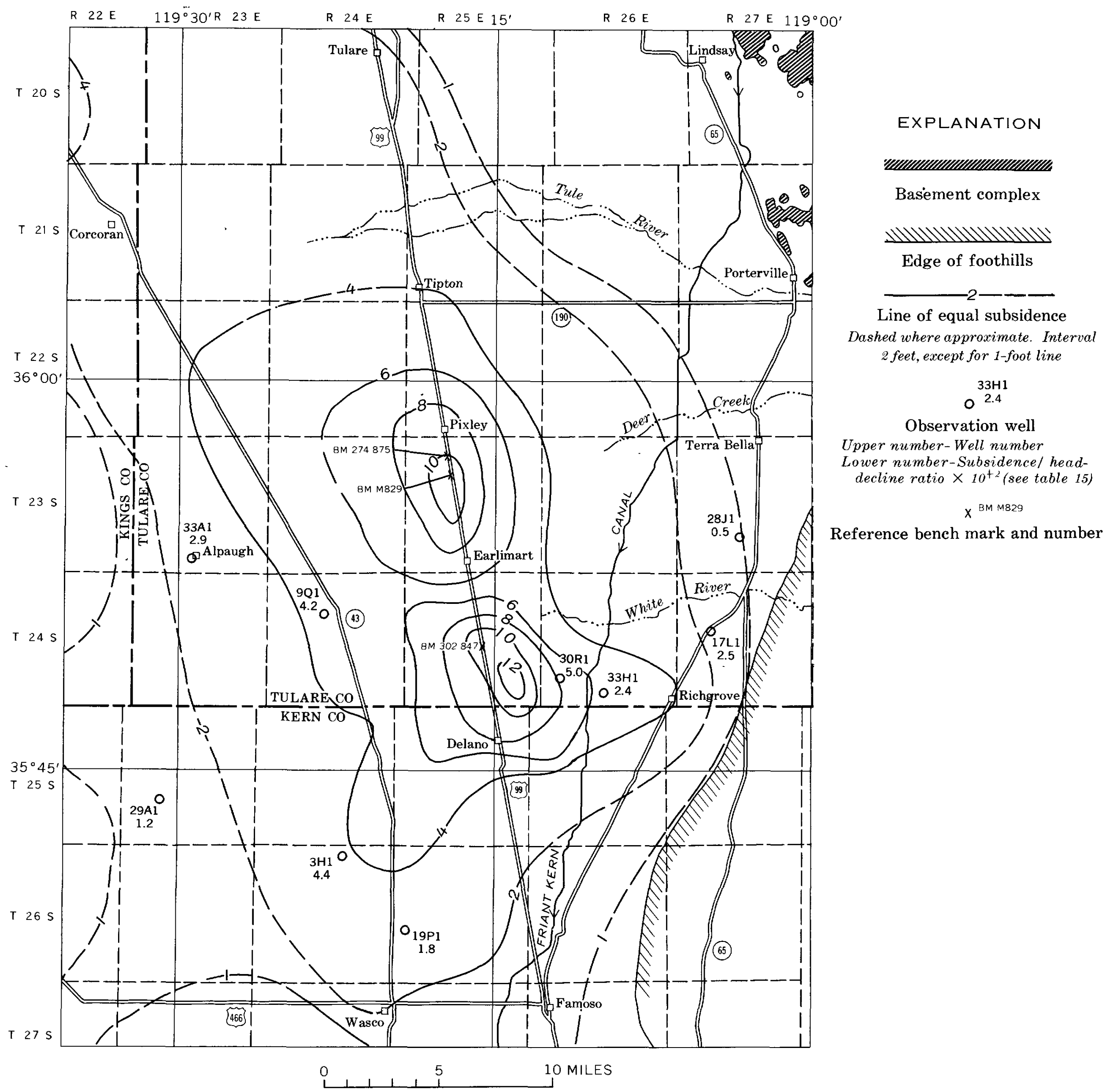


Figure 50.—Land subsidence, 1926–62. Compiled from comparison of topographic maps, 1926–54, and leveling of the U.S. Coast and Geodetic Survey, 1954–62.

Pleistocene time, the rate would have been so slow that it would not have appreciably affected the altitude of bench marks in the western part of the Tulare-Wasco area in the historic span of leveling control. There is no direct evidence of tectonic adjustment in the Tulare-Wasco area since vertical control was first established. It is concluded, therefore, that tectonic movement has not contributed appreciably to the subsidence described in this report.

As stated earlier (B49), the causal relation of water-level decline to the subsidence of the land surface was recognized as early as 1935. Ingerson (1941) also considered the possibility that vibrations of highway and rail traffic and shocks from explosive blasts were factors contributing to land subsidence. There is no evidence, however, that either natural or artificial vibrations have caused a measurable increase in the amount or the rate of subsidence.

The evidence is conclusive in time and place that subsidence is directly related to water-level decline and that it slows down or ceases in response to water-level recovery. This report concludes that water-level change is the cause of all measurable subsidence in the Tulare-Wasco area.

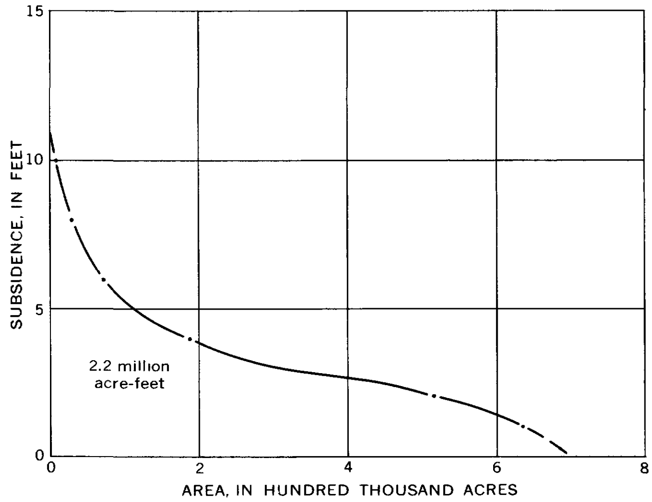


FIGURE 51.—Relation of magnitude to area of subsidence, 1926–62. Area under the curve equals the volume of subsidence.

ANALYSIS OF HYDRAULIC STRESSES CAUSING COMPACTION

Under natural conditions, unconsolidated deposits are generally in equilibrium with their overburden load. An increase in grain-to-grain stress, however, due to either surficial loading or a change in ground-water levels, causes a corresponding strain or compaction of the deposits. The magnitude of the strain is dependent on the compressibility of the deposits, which is related to their physical and chemical properties; the magnitude of the increased stress; possibly the type and rate of stress applied; and the stress history, that is, whether the increased stress is being applied for the first time or has been attained or exceeded previously.

Depending on the nature of the deposits, compaction may be (1) largely elastic, in which case stress and strain are proportional, independent of time, and reversible, or (2) principally nonelastic, in which case the granular structure is rearranged in such a way that the volume is permanently decreased. In general, if the deposits are coarse-grained sand and gravel, the compaction will be small, chiefly elastic, and thus reversible, whereas if they contain fine-grained clayey beds, the compaction will be much greater, chiefly inelastic, and thus permanent. In either type of compaction, subsidence of the land surface is due to a one-directional compression of the deposits.

Three different types of stresses cause compaction of an aquifer system. They are closely interrelated, yet are of such different nature that a clear distinction is of utmost importance. The first of these types is a gravitational stress, caused by the effective weight of overlying deposits and transmitted downward through the grain-to-grain contacts in the deposits. The second type is a hydrostatic stress, caused by the weight of the interstitial water and transmitted downward through the water. The third type is a dynamic seepage stress exerted on the grains by the viscous drag of vertically moving interstitial water. The first and third types are additive in their effect and together compose the grain-to-grain stress which effectively changes the void ratio and mechanical properties of the deposit; this combined stress is commonly known as the "effective stress." The second type of stress, although it tends to compress each individual grain, has virtually no tendency to change the void ratio of the deposit and thus is referred to as a "neutral stress."

Only two of the various methods of analyzing the effect of these stresses in a compacting aquifer system (Taylor, 1948, p. 203) are considered here. They vary in their conceptual approach; however, both give the same mathematical results and can be used to check each other. The classical method, the approach more often used in practical soil mechanics problems, considers the combined total weight of grains and water (geostatic load) in the system and the neutral, hydrostatic stress. The second method considers the static gravitational stress of the grains, which comprises their true weight above the water table and submerged (buoyed) weight below the water table, and the vertical seepage stresses that may exist in the system. Inasmuch as changes in grain-to-grain effective stress, both gravitational stress and stress due to seepage, are directly responsible for the compaction of the deposits and are directly related to changes in head in an aquifer system, the latter method has proved simpler and clearer in analyzing subsidence in this investigation.

The Terzaghi theory of consolidation (Terzaghi and Peck, 1948, p. 233) commonly is used to estimate the magnitude and rate of compaction that will occur in fine-grained clayey deposits under a given change in stress. According to this theory of consolidation, compaction results from the slow escape of pore water from the stressed deposits, accompanied by a gradual transfer of stress from the pore water to the granular structure of the deposits. When an increment of loading stress is applied to a fine-grained interbed (aquitard), the entire stress increase, at first, is borne by the interstitial water; grain-to-grain stress can increase only as the interbed drains. A high hydraulic gradient at the surface of the interbed causes rapid drainage from the pores near the surface. Gradually, the excess pressure decreases, the intergranular stress increases, and the void ratio decreases. This gradual process always is in a more advanced state near the drainage surfaces of the interbed and at a less advanced state near its center. Because of this hydrodynamic lag, strain cannot take place all at once in the interbed, but only as rapidly as drainage can occur. Coarse-grained beds, on the other hand, drain rapidly, and increased effective stresses quickly cause compaction of the beds and an adjustment of these beds to their new stress condition.

Water-level changes in subsidence areas may change effective stresses in two different ways:

1. A change in the position of the water table changes the effective stress, owing to the increase or decrease in buoyant support of grains in the zone of the change; this change in gravitational stress is transmitted downward to all underlying deposits.
2. A change in position of the water table or the piezometric surface (artesian head) or both that induces vertical hydraulic gradients across confining or semiconfining beds produces a seepage stress which is algebraically additive to gravitational forces and thereby changes the effective stress in the deposits. A change in effective stress also results if a natural preexisting seepage stress is altered in direction or magnitude by a change in head.

In the following analysis of stresses, compaction is considered under two different hydraulic regimes: (1) water-table (unconfined) conditions, in which no vertical hydraulic gradients exist, and (2) artesian (confined) conditions, in which vertical gradients exist and result in seepage stresses that usually represent the major part of the change in effective stress. Generally, the analysis of effective stress change involves both changes in buoyant support and changes in seepage forces, both with time and with depth.

Figure 52 shows the components of effective stress at three depths in an assumed hydrologic system involving a confined aquifer system with an interbedded aquitard and an overlying unconfined aquifer. For purposes of demonstration, a porosity, n, of 40 percent and an average specific gravity, G, of 2.7 for the individual mineral grains are assumed. All stresses in the system are expressed in units of feet of water (1 ft. of water equals 0.43 psi) so that they are directly additive and are relatable to changes in hydraulic head. Thus, the unit weight of deposits above the water table (ignoring the contained moisture), γ_d, may be expressed

$$\gamma_d=(1-n)\cdot G\cdot\gamma_w,$$

where

γ_w=unit weight of water.

Correspondingly, the buoyant (submerged) unit weight, γ', of the deposits below the water table equals

$$\gamma'=(1-n)(G-1)\gamma_w.$$

If the numerical values assumed for n and G are used and if γ_w is expressed as 1 foot of water, the effective stress due to the weight of deposits above the water table equals about 1.6 feet of water per foot of thickness, and the effective stress due to the weight of deposits below the water table equals approximately 1.0 foot of water per foot of thickness.

UNCONFINED (WATER-TABLE) CONDITIONS

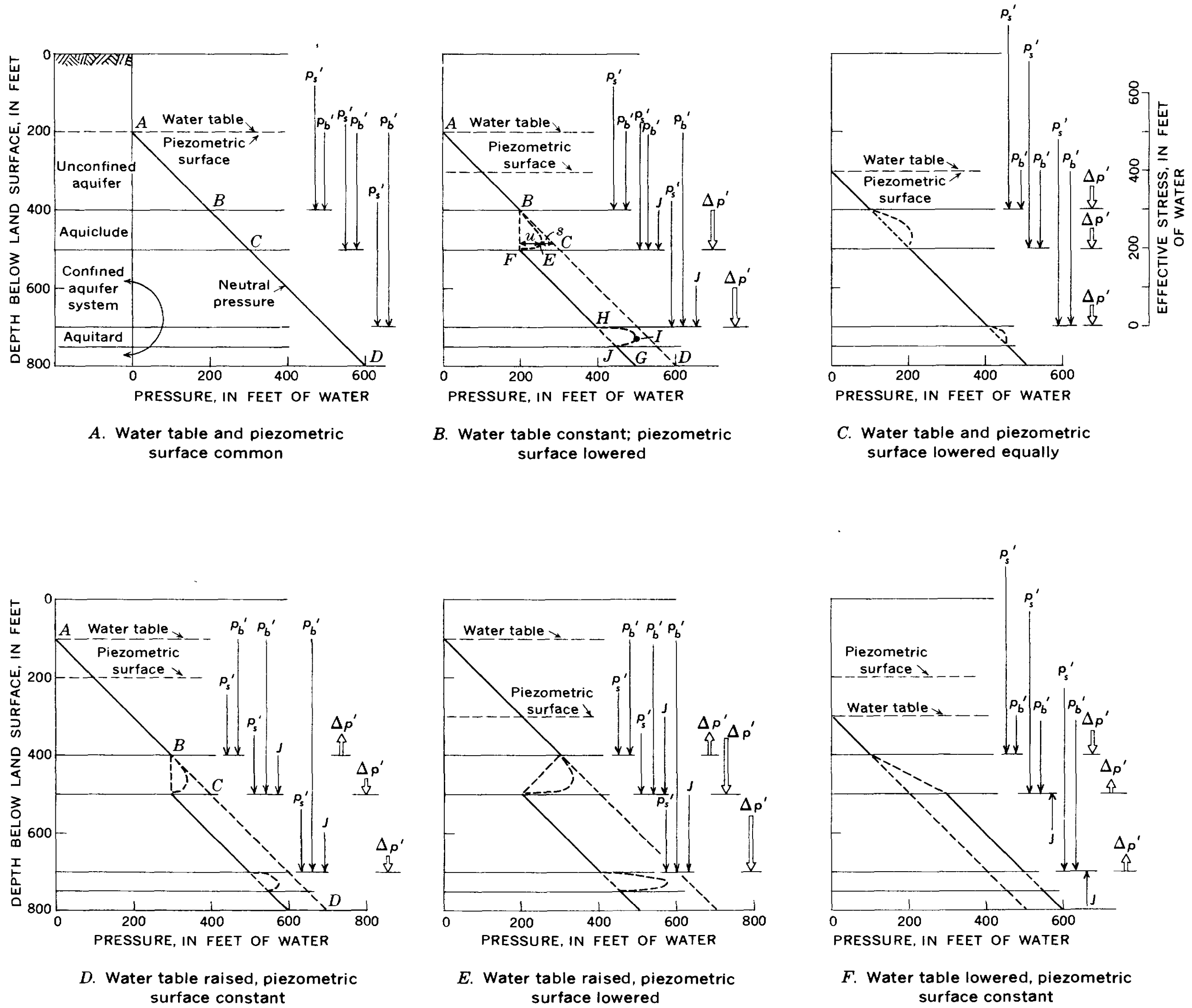
Before pumping lowers the water table in an unconfined aquifer, the deposits are generally in equilibrium with the natural effective stresses. For any element of the deposit, these effective stresses equal the true weight (per unit area) of the unsaturated deposits and the buoyant weight (per unit area) of the saturated deposits that overlie the element. As the water table is lowered, the effective unit weight of the deposits in the dewatered zone increases from the submerged unit weight, γ', (weight of solids minus the weight of the displaced water) to the unit weight, γ_d, of the solids. The effective grain-to-grain stress in the aquifer below the dewatered zone is thus increased by the loss of buoyant support in the dewatered zone. The increase in effective stress at any depth below the lowered water table in an unconfined aquifer is equal to the increase in unit weight of the dewatered deposits multiplied by the dewatered thickness. Using the previously assumed unit weights, the effective stress below the lowered water table is calculated to increase 0.6 foot for each foot of water-table lowering.

CONFINED (ARTESIAN) CONDITIONS

Under simple hydrostatic conditions in a confined aquifer system (fig. 52A), the hydraulic heads above and below the confining layer stand at the same altitude. No hydraulic gradient exists across the confining layer; therefore, no seepage occurs through the confining layer. The effective stresses under these hydrostatic conditions are the same as in the unconfined aquifer; that is, they are equal to the gravitational stress of the overlying deposits.

If both the water table and the piezometric head in the confined aquifer are 200 feet below land surface (fig. 52A), the two components of effective stress exerted downward on the grains, owing to the weight of deposits above the water table (vector p_s') and owing to the buoyant weight of deposits below the water table (vector p_b') are as follows: 320 feet and 200 feet, respectively, on the top of the confining layer; 320 feet and 300 feet, on the top of the confined aquifer system; and 320 feet and 500 feet on the top of the aquitard at a depth of 700 feet.

If from the hydrostatic condition of figure 52A, the artesian pressure in a confined aquifer system is drawn



All stresses in feet of water; based on assumed porosity=0.40 and specific gravity=2.70

p_s' =effective stress due to weight of unsaturated deposits

p_b' =effective stress due to buoyant weight of submerged deposits

J =seepage stress

$\Delta p'$=change in total effective stress from condition A

FIGURE 52.—Effective-stress diagrams for a confined aquifer system overlain by an unconfined aquifer.

down below an unchanging water table by pumping (fig. 52*B*), gravitational stresses remain the same; however, a downward hydraulic gradient which induces downward seepage is developed across the confining layer (aquiclude). The loss of hydraulic head through the aquiclude represents the energy expended in moving the water through the pore passages. As head is dissipated by viscous flow through the confining layer, the energy in the moving water is transferred by viscous drag to the granular skeleton of the deposit. The force corresponding to this energy transfer is exerted in the direction of flow and is algebraically additive with the gravitational stresses that tend to compact the deposits.

As commonly used, the term "seepage force" refers to the energy transfer within the body through which the seepage takes place. As defined by Scott (1963, p. 96, equation 4–20), the seepage force, f, exerted on the grains can be represented by the expression

$$f=h\cdot\gamma_w\cdot A,$$

in which

h=head loss across an incremental thickness and
A=cross sectional area.

Within an aquiclude compacting under the stress of downward seepage (fig. 52*B*), the hydraulic gradient and therefore the seepage force per unit thickness vary from a minimum at the upper surface to a maximum at the lower surface until steady-state conditions are reached. The loading effect of the incremental seepage force developed through each unit volume vertically through the aquiclude is additive downstream. Thus, the net effect of these incremental units of seepage force at any point in the structure of the aquiclude is equal to the summation of the incremental forces upstream from that point. Although the distribution of these forces within the aquiclude may be indeterminate, the total seepage force accumulated through the aquiclude is equal to the total head differential across it. Thus, at the base of the aquiclude, the total seepage force, F, may be expressed as

$$F=H\cdot\gamma_w\cdot A.$$

The total seepage force per unit area, J, hereafter referred to as the seepage stress, is derived by

$$J=\frac{F}{A}=H\cdot\gamma_w$$

This seepage stress is transmitted downward through the intergranular structure of the aquifer system below the aquiclude.

In the assumed ground-water systems of figure 52*B*, straight line ABCD represents the hydrostatic pressure (neutral pressure) gradient that existed before pumping began. The deposits are adjusted to the overburden load, which equals the actual weight of the deposits above the water table plus the buoyant weight of the submerged deposits. After pumping has lowered the head in the permeable members of the confined aquifer system to 300 feet, the effective stresses shown by vectors in figure 52*B* would prevail at the depths represented by the arrow points. The length CF represents the 100 feet of head decline, and FG represents the reduced pressure in the confined aquifer system. With a 100-foot head loss through the confining layer, a 100-foot seeepage stress is immediately developed across the confining layer and transmitted through grain-to-grain contacts to the underlying aquifer system. Even though normal hydrostatic pressure gradients exist both in the unconfined (line AB) and in the confined aquifer systems (line FG), through the confining aquiclude changing hydraulic gradients and transient flow conditions occur until a steady hydrodynamic gradient (line BF) is established between the heads at the upper and lower surfaces of the aquiclude. Initially, the head distribution through the confining clay approximates lines BC and CF. Curved line BEF represents a transient distribution of head in the confining layer at some intermediate time before steady flow is established.

As shown in figure 52*B*, the length s indicates the magnitude of the seepage stress at a particular depth in the aquiclude, and the length u indicates the excess over steady-state head (Taylor, 1948, p. 221, 236) that remains in the interstitial voids at that depth. Also, the area BCFEB is proportional to the part of the ultimate compaction that has occurred, and area BEFB to the part of the ultimate compaction that has not taken place. Domenico and Mifflin (1965, p. 571) referred to the combined area BCFB as the effective-pressure area. As adjustment continues, excess pore pressures are reduced and compaction occurs within the aquiclude. After equilibrium conditions have been established, head distribution through the aquiclude follows straight line BF (assuming uniform permeability), and uniform flow conditions and a constant seepage gradient prevail through the aquiclude. Under these conditions, 1 foot of head is lost (transferred to the grains) through each foot of thickness of the aquiclude. The accumulated downward seepage thrust exerted on the grains by the moving water thus varies linearly from 0 feet at the upper surface of the aquiclude to 100 feet at its lower surface. The total seepage stress, equal to the head differential across the aquiclude, is exerted on the granular structure of all underlying beds in the aquifer system. The time involved in reaching complete adjustment is dependent chiefly on the thickness, compressibility, and permeability of the confining layer.

At all times after the head in the confined aquifer system is lowered to 300 feet, the magnitude of the seepage stress (increased effective stress) exerted downward on all beds within the confined system (below the aquiclude) is 100 feet (distance CF, fig. 52*B*). In the more permeable, less compactible, aquifers of the confined system, the increase in effective stress occurs rapidly. Within the aquitards, however, no change in effective stress can occur until water escapes from the slow-draining, compacting beds. The reduction in head in the permeable aquifers creates a two-directional hydraulic gradient outward from the center of the aquitard which induces seepage from and compaction of the aquitard. Two-directional drainage occurs from the aquitard and excess pore pressures are transient (curved line HIJ, fig. 52*B*) until equilibrium conditions (straight line HJ) are established. Although upward and downward seepage stresses occur within the aquitard during this adjustment, they have no net external effect on the rest of the aquifer system.

The open arrows ($\Delta p'$) at two depths in the hydrologic section of figure 52*B* are vectors indicating the change in effective stress from the hydrostatic conditions of figure 52*A*. Thus, the net effect of lowering the piezometric head in the confined aquifer system 100 feet below the water table is to create a seepage stress through the confining layer and ultimately to increase the effective stress in all beds in the confined aquifer system by 100 feet. No change in effective stress occurs in the unconfined aquifer overlying the confining layer. Although a small part of the resulting deformation of the confined aquifer system is elastic and thus reversible, most represents an irreversible rearrangement of fine particles in the clayey sediments to a more dense state.

Figure 52*C* represents a dual water-level lowering, with both the water table and piezometric surface lowered 100 feet below the level of figure 52*A*. A normal hydrostatic gradient of pressure with depth exists in the aquifers and is ultimately achieved in the aquiclude and aquitard as well. Effective stresses throughout the section, however, are considerably different from conditions of either figure 52*A* or figure 52*B*. Loss of buoyant support in the dewatered zone causes the effective stress changes shown in figure 52*C*. The net change in stress from conditions of figure 52*A* is shown at three depths by the open arrow vectors. Although the effective stress throughout the section is increased from conditions of figure 52*A* by the loss of buoyant support, the stresses in the confined aquifer system are less than those shown in figure 52*B* because there is no seepage stress component. If the head in the confined aquifer system had been drawn down to the condition shown in figure 52*B* before the hydrostatic conditions shown in figure 52*C* were established, rebound would tend to occur throughout the confined aquifer system as the water table was drawn down.

If the piezometric surface remains constant and the water table is raised 100 feet above the conditions of figure 52*A*, the effective stresses shown by the vectors in figure 52*D* are produced. A raised water table reduces the gravitational stress below the raised level by providing buoyant support of the grains in the zone of water-table rise; however, it also creates a downward seepage stress across the confining layer. The net change, therefore, from conditions of figure 52*A* is an increase in effective stress throughout the confined aquifer system. It is noteworthy that in changing from the conditions of figure 52*C* to the conditions of figure 52*D*, rebound would occur in the unconfined aquifer, but no change in stress would occur in the underlying confined system.

If the water table is raised 100 feet above and the piezometric surface is lowered 100 feet below the hydrostatic conditions of figure 52*A*, the effective stresses shown in figure 52*E* will prevail. An increase in buoyant support causes reduced gravitational stress in the unconfined aquifer, as it did under the conditions of figure 52*D*. The 200 feet of head differential across the confining layer represents a seepage stress of 200 feet exerted downward on the deposits in the confined aquifer system. Under these conditions, the change in effective stress in the confined aquifer system, due to the combined changes in gravitational and seepage stress from the hydrostatic condition of figure 52*A*, is 140 feet, a quantity considerably greater than that for conditions illustrated in figures 52*B*–*D*.

Figure 52*F* shows the effective stresses under the sixth general condition, in which the water table is lowered 100 feet below the piezometric surface of figure 52*A*. Here the effective stress in the unconfined aquifer is increased 60 feet, owing to the loss of buoyant support in the zone of the lowered water table. Because of upward seepage stresses that developed through the aquiclude, however, the effective stress throughout the confined aquifer system is reduced by 40 feet from the hydrostatic condition of figure 52*A*.

In summary, the following generalizations can be made with respect to effective stress analysis:

1. For purposes of stress analysis, a ground-water reservoir may act as an aquifer system if no significant vertical head differentials (seepage forces) occur within the reservoir under ordinary pumping stress. It may be considered to include one or more confined (artesian) systems if vertical head differentials within the reservoir are significant.
2. Under the conditions assumed for demonstration on page B68, the effective stress in an unconfined aquifer increases 0.6 foot for each foot of decline of the water table and decreases 0.6 foot for each foot of rise of the water table. These values would change somewhat for different values of porosity. The change in effective stress equals the change in buoyant support of the deposits in the interval of water-table change and is independent of the specific gravity of the grains.

3. The effective stress in a confined aquifer system is affected by changes in both the water table and the piezometric head in the confined system. For the values of porosity and specific gravity assumed in the analysis, a rise in the water table of 1 foot causes about 0.4 foot of increase in effective stress, whereas a decline of 1 foot in the piezometric surface causes 1 foot of increase in effective stress.

COMPACTION OF THE WATER-YIELDING DEPOSITS

The amount of compaction at a given location depends on the thickness and compressibility of the deposits, the magnitude of the increase in effective stress, the time of stress application, and possibly the type of stress applied. The range of stress change, grain size, clay mineralogy, and geochemistry of the pore water all affect the compressibility of the deposits. Also, the effective stresses in a confined aquifer system are affected by (1) water-level changes in an overlying unconfined or semiconfined aquifer system and (2) by seepage stresses that may develop across the confined aquifer system.

This section includes a description of the recording equipment used to measure compaction to depths as great as 2,200 feet, a discussion of the measured compaction at several locations where sufficient data are available, and a computation of compaction at Pixley based on Terzaghi's theory of consolidation and field and laboratory data.

COMPACTION-RECORDER INSTALLATIONS

Subsidence of the land surface is measured by periodic leveling of a network of bench marks, whereas compaction of the deposits is measured by observing the change in thickness of a particular sequence of the deposits. For any given time interval, subsidence of the land surface should equal the sum of the incremental compaction of all strata between the land surface and the bottom of the compacting section. A special type of installation (Lofgren, 1961, p. B49) is being used to measure the rate and magnitude of compaction in the Tulare-Wasco area. As shown in figure 53, the assembly consists of a heavy weight emplaced in the formation below the bottom of a well casing and an attached cable stretched upward in the casing and counterweighted at the land surface to maintain constant tension. A monthly recorder (Stevens, type F, with battery-driven Elix clock) mounted over the open casing is used to measure directly the amount of cable that rises above the casing as compaction occurs. At the land surface during compaction, the bottom-hole weight appears to rise; actually, the vertical distance from the land surface to the bottom-hole weight shortens.

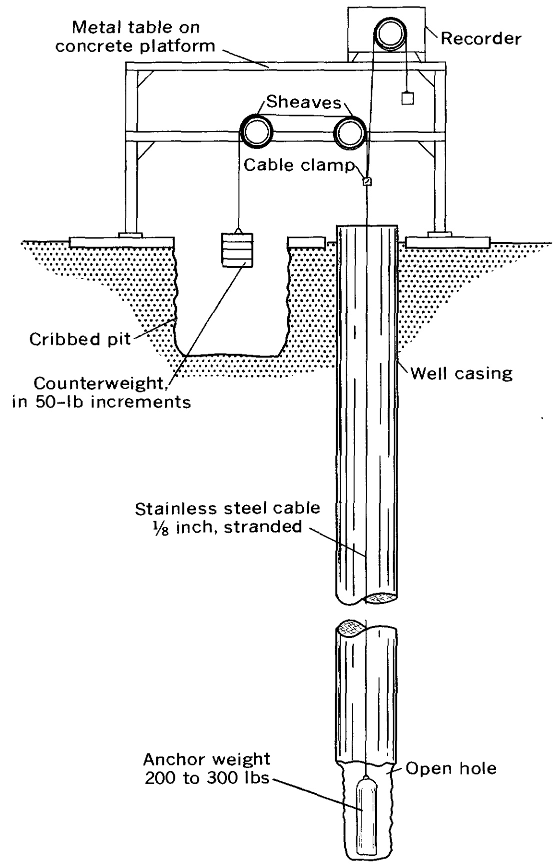


FIGURE 53.—Compaction-recorder installation.

The success of this type of recorder installation depends largely on the durability and stretch characteristics of the down-hole cable and the minimization of down-hole friction between the cable and the well casing. The cable must remain at constant length during the period of record. If the length changes, due to temperature changes, fatigue elongation, or untwisting, this change is measured by the recorder and is indistinguishable from the record of actual compaction. Friction in the system, both down-hole and in the recording mechanism above the land surface, results in a stepped or interrupted record of compaction. This reduces the accuracy and resolution of the recorded data, especially during reversals in trend. Ball-bearing sheaves have been used in the installation to reduce frictional drag.

During the early phases of the investigation, a 1/8-inch, 7 by 7 stranded, preformed, galvanized steel aircraft cable was used. Eight recorder units were installed with this cable and, except for the Pixley recorder, 23/26–16N1, all cables failed in 6–15 months because of corrosion. In general, failure due to corrosion occurred in the interval of water-level fluctuations in the well casing and was most rapid in wells that had excessive falling water. After experimentation with methods to prevent corrosion, a specially manufactured ⅛-inch, stainless steel, 7 by 7 stranded, plastic coated preformed cable was selected, and four of the installations were rebuilt (table 8) with this cable in 1959. Further experimentation with an uncoated ⅛-inch, 7 by 7 stranded, preformed stainless steel cable, and an uncoated ⅛-inch, 1 by 19 stranded, preformed stainless steel cable seemed to reduce the down-hole friction of the system; the 1 by 19 stranded cable had even better performance characteristics than the 7 by 7 cable. Seven compaction-recorder installations in the Tulare-Wasco area were rebuilt in January 1966 with the 1 by 19 stranded cable and improved mechanical equipment to obtain a more precise record of compaction.

Compaction recorders were operated in 11 wells during the investigation, and eight of these were still in operation as of December 31, 1964. Companion water-level recorders were operated in five of these 11 wells and in one other observation well. The period of record of these recorders is given in table 8. The locations of the nine compaction recorders that have operated since 1958 are shown in figure 44. Four of the recorder units were installed in specially drilled cased holes; the others were placed in unused irrigation wells which were cleaned out and deepened about 20 feet to permit setting the anchor weights below the casing bottom. Two of the compaction recorders, 23/25–8J2 and 24/26–30P1, were not reinstalled after the cable failure in 1958, and their record was too short to be of use in computing compaction rates.

As shown in figure 44, the compaction recorders were installed in the two areas that subsided most rapidly from 1948 to 1954. At one site in each of these two subsidence centers, 23/25–16N1 near Pixley and 24/26–36A2 at Richgrove, test holes were cored and logged to obtain a detailed description of the type of deposits penetrated. Selected cored samples from these holes were tested in the laboratory to determine their physical and consolidation characteristics (Johnson and others, 1968).

At most of the sites, the compaction was recorded at a 1:1 scale, that is, 0.1 foot of compaction in the depth interval registered 0.1 foot of displacement on the recorder chart. At the Pixley site (23/25–16N1), however, as described later, the compaction was recorded at a 12:1 or 24:1 vertical amplification. This amplified compaction record and the corresponding water-level record permitted detailed correlation of the compaction with fluctuations in artesian pressure in the confined aquifer system.

TABLE 8.—*Water-level and compaction recorders in the Tulare-Wasco area*

[Records dated 12-31-64 are last records available]

Well (Unused irrigation well unless otherwise marked)	Depth (ft)	Records available (month and year)	
		Water level	Compaction
23/25– 8J2	270	None	9–57 to 4–58.
16N2 [1]	760	do	4–58 to 12–31–64.
16N3 [2]	430	6–59 to 12–31–64	6–59 to 12–31–64.
16N4 [2]	250	do	Do.
17Q1	615	None	9–57 to 12–58.
17Q3	355	9–57 to 12–31–64	9–57 to 1–59; 1–59 to 12–31–64.
24/26–30P1	1,150	None	9–57 to 3–58.
34F1	1,510	1–57 to 12–31–64	9–57 to 12–58; 1–59 to 12–31–64.
36A2 [1]	2,200	None	5–59 to 12–31–64.
25/26–1A2	892	9–57 to 9–58; 1–59 to 12–31–64	9–57 to 6–58; 1–59 to 12–31–64.
1J3	897	None	Do.
1K2	2,200	4–60 to 12–31–64	None.

[1] Cored test well.
[2] Drilled test well.

COMPACTION OF DEPOSITS NEAR PIXLEY

MEAURED COMPACTION

Compaction recorders of the type shown in figure 53 and companion water-level recorders were installed in two unused irrigation wells, 23/25–17Q1 and 17Q3 (table 8), in the center of maximum subsidence near Pixley (fig. 44) in September 1957. A third compaction recorder was installed in a newly drilled nearby test well 23/25–16N1 in April 1958. These recorder units were anchored at three different depths, and each measured the amount of compaction between the land surface and the respective anchor depth. By comparing the compaction records of the three recorders during a common period, the amount of compaction in each of three depth zones has been computed. Two of the three compaction recorders failed, due to cable corrosion in the winter of 1958. Before the failure, however, several months of valuable record was obtained. The recorded compaction from June 1 through August 31, 1958, is summarized in the following table:

Recorder	*Anchor depth (ft)*	*Measured compaction (ft)*	*Compaction in depth interval*	
			Feet	*Percent*
	Surface			
			0.01	3
23/25–17Q3	355	0.01		
			.19	66
17Q1	615	.20		
			.09	31
16N1	760	.29		

Although these results apply to only part of one pumping season, it is concluded that during this period (1) essentially no compaction occurred in the upper 355 feet of deposits, (2) roughly two-thirds of the measured compaction occurred in the most heavily pumped zone between depths of 355 and 615 feet, and (3) about one-third of the measured compaction occurred in the

615–760-foot depth zone. No record is available of the amount of compaction in the deposits below a depth of 760 feet.

Early in 1959 water-level and compaction recorders were reinstalled in unused irrigation well 23/25–17Q3 to record water-level fluctuations in the semiconfined aquifer system and the compaction above 355 feet. Also, recorders were installed in two newly drilled test wells 23/25–16N3 and 16N4 (table 8). Test well 16N3 was bottomed at a depth of 430 feet, and its casing was perforated between depths of 360 and 420 feet to record water-level fluctuations in the most heavily pumped part of the confined aquifer system. Test well 16N4 was drilled to a depth of 250 feet, and its casing was perforated between depths of 200 and 240 feet to record water-level fluctuations in the semiconfined aquifer system. Thus, four compaction recorders, three in a cluster at 16N1, 16N3, and 16N4 and a fourth 1,500 feet west at 17Q3, all in T. 23 S., R. 25 E. (fig. 44), and with anchor depths of 760, 430, 250, and 355 feet, respectively, below the land surface (fig. 56*A*) have been in continuous operation since June 1959. The completion depth of 760 feet for test well 16N1 exceeded the depth of the irrigation wells in the immediate vicinity and thus was inferred to span the depth range of most of the compacting deposits.

Figure 54 is a plot of land subsidence, compaction, water-level fluctuation, and change in effective stress in the subsidence center 3 miles south of Pixley. The graph shows the compaction measured in well 23/25–16N1 from May 1958 through 1964; the fluctuation of water level in the semiconfined aquifer system, as measured in well 23/25–16N4; the fluctuation of artesian head in the confined aquifer system, as measured in well 23/25–16N3; the change in effective stress in the confined aquifer system, as computed from changes in water level in the semiconfined and confined aquifer systems (fig. 52); and the subsidence of bench mark Q945 at recorder site 16N1, determined by leveling of the Coast and Geodetic Survey from distant stable bench marks three times between January 1959 and February 1964.

The leveling of bench mark Q945 in January 1959, January 1962, and February 1964 permitted comparison of compaction to subsidence in the two intervening time periods. From January 1959 to January 1962, bench

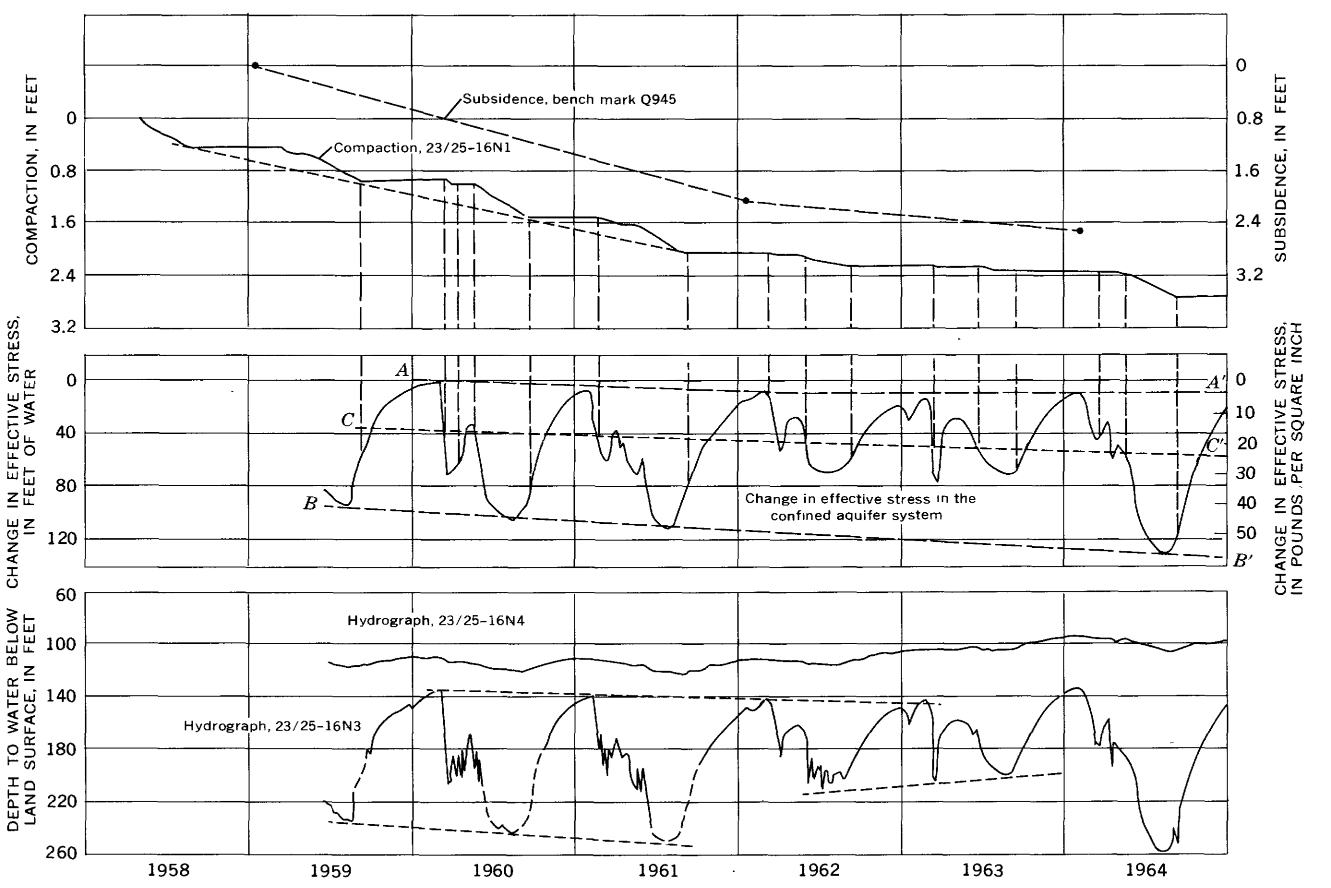


FIGURE 54.—Land subsidence, compaction, water-level fluctuations, and change in effective stress in the subsidence center 3 miles south of Pixley.

mark Q945 subsided 2.08 feet, and measured compaction in well 23/25–16N1 was 1.60 feet. Thus, the measured compaction to a depth of 760 feet in the 3-year period was 77 percent of the total subsidence. From January 1962 to February 1964, bench mark Q945 subsided 0.46 foot, and measured compaction in well 16N1 was 0.30 foot. Compaction thus equaled 65 percent of the total subsidence during this second period. For the 5-year span, the total compaction of 1.90 feet was 75 percent of the total subsidence of 2.54 feet. Thus, 0.64 foot of vertical shortening, or about 25 percent of the subsidence during the 5-year period, was due to compaction of deposits in the confined aquifer system below a depth of 760 feet. This compaction below 760 feet indicates that the drawdown effects of pumping extended to depths considerably below the deepest irrigation wells in the immediate vicinity, but whether the pumping effects were from distant or nearby wells is not known.

Comparison of the compaction rate with fluctuations in water level in the semiconfined and confined aquifer systems indicates that compaction began each year during the period of rapid head decline in the confined aquifer system, continued through the pumping season, and ceased during the early stages of head recovery. Also, the magnitude of compaction each year is related to the magnitude of seasonal head drawdown. This relation is illustrated clearly by the increase in head decline and compaction in 1964 as compared to 1963. Each year from 1959 to 1964, the water level in the semiconfined aquifer system (16N4) registered a seasonal fluctuation less than 10 percent of the artesian-head change in the confined aquifer system (16N3) and, after 1961, it showed a gradual rise. The change in piezometric head in the confined system, therefore, was the dominant component of the change in effective stress that caused compaction in the confined zone.

The center graph of figure 54 shows the change in effective stress in the permeable aquifers of the confined aquifer system for the period 1959–64, as computed from the hydrographs of wells 23/25–16N3 and 16N4 (fig. 52). The changes in effective stress in the compactible fine-grained beds of low permeability are less, but the magnitudes are not known. During this period, the effective-stress change fluctuated annually through a range of 60 feet to more than 100 feet, and being dominated by the changes in piezometric head in the confined aquifer system, was nearly parallel to the hydrograph of well 23/25–16N3. Dashed line *A–A′*, with a slight change in slope in 1962, approximates the trend of winter crests (low effective stress) of the effective-stress graph and indicates a winter-minimum stress increase of about 4 feet of water (1.7 psi) per year from 1960 to 1962. Although the 1963 crest failed to reach line *A–A′*, the 1964 crest was about equal to that of 1962. Dashed straight line *B–B′* approximates the declining trend of summer troughs (high stress) of the effective-stress graph for all years except 1962 and 1963. The summer-maximum stress increased at an average rate of about 7 feet of water (3.0 psi) per year.

Of special interest in relating compaction to changes in effective stress is the position of straight line *C–C′* (fig. 54). Vertical dashed lines have been drawn downward to the effective-stress graph from points marking the beginning and end of most rapid compaction in well 23/25–16N1. Straight line *C–C′* is drawn as near as possible through the points on the effective-stress curve where compaction began each season. Most of the compaction occurred when the effective stress was below (higher stress) line *C–C′*; little or no compaction occurred when the effective stress was above (lower stress) line *C–C′*. Compaction continued for several weeks after the maximum effective stress was attained but always terminated before line *C–C′* was reached on the recovery limb of the stress curve. In general, the amount of compaction in any year was related to the area below line *C–C′* bounded by the effective-stress curve.

Figure 55 shows the record of four compaction recorders and subsidence of nearby bench mark Q945, 3 miles south of Pixley, for the period 1960–64. These recorders were anchored at different depths (table 8; fig. 56*A*), and the installations had stabilized during several months of operation prior to January 1960. The

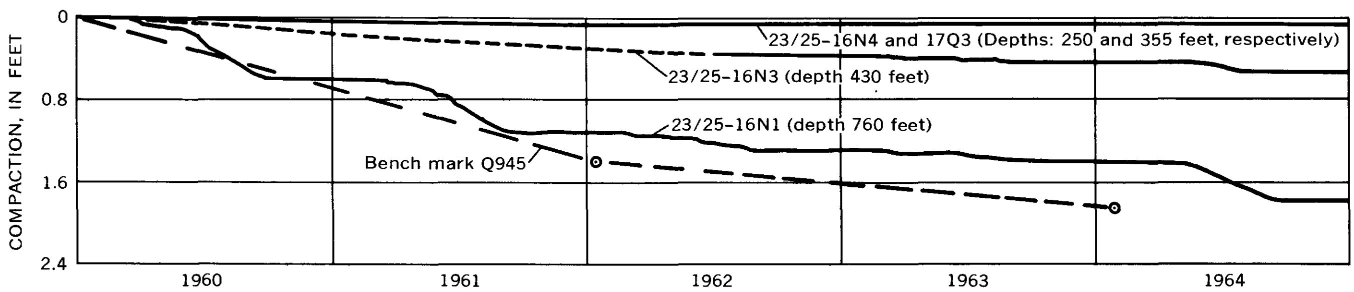


FIGURE 55.—Record of four compaction recorders and subsidence of a nearby bench mark, 3 miles south of Pixley, 1960–64.

observed subsidence of bench mark Q945 is a measure of the total compaction of deposits at the site as of January 1962 and January 1964 (this bench mark was also leveled in January 1959; see fig. 54). By computing the difference in amount of compaction measured by the various recorders, the compaction in each of the three depth zones was obtained; these results are summarized in table 9.

The water level in the semiconfined aquifer system (fig. 54, hydrograph 16N4) rose from 1961 through 1964; so, effective stresses did not increase in the deposits above the confining clay layers. Compaction recorders 16N4 (250 feet) and 17Q3 (355 feet) registered only a few hundredths of a foot of compaction during this period. However, compaction recorders 16N1 and 16N3, with anchor depths of 760 and 430 feet, respectively, recorded significant compaction (table 9). Unit compaction in the 355–430-foot zone was greater than in the 430–760-foot zone in each of the 5 years; it ranged from 1.2 times the unit rate of the lower zone in 1960, when compaction in the aquifer system was the greatest, to 2.5 times that

TABLE 9.—*Compaction rate of unconsolidated deposits in the Pixley area in four depth zones during 5 years of record*

[Symbols used: VS, very small]

Depth zone (ft)	Measured compaction (ft)					Unit compaction ($\times10^{-3}$ ft per ft)					Specific unit compaction (seasonal) [1] ($\times10^{-5}$ ft per ft ^{2})				
	1960	1961	1962	1963	1964	1960	1961	1962	1963	1964	1960	1961	1962	1963	1964
0–355	0.02	0.01	0.03	0	0.02	VS	VS	VS	VS	VS	VS	VS	VS	VS	VS
355–430	.13	.13	.05	0.04	.08	1.7	1.7	0.7	0.5	1.1	2.5	2.4	2.5	1.9	1.3
430–760	.45	.37	.10	.07	.26	1.4	1.1	.3	.2	0.8	2.1	1.6	1.1	0.7	0.9
0–760	.60	.51	.18	.11	.36										

[1] Based on only the change in effective stress during the period of compaction, that is, below line *C–C′*, fig. 54.

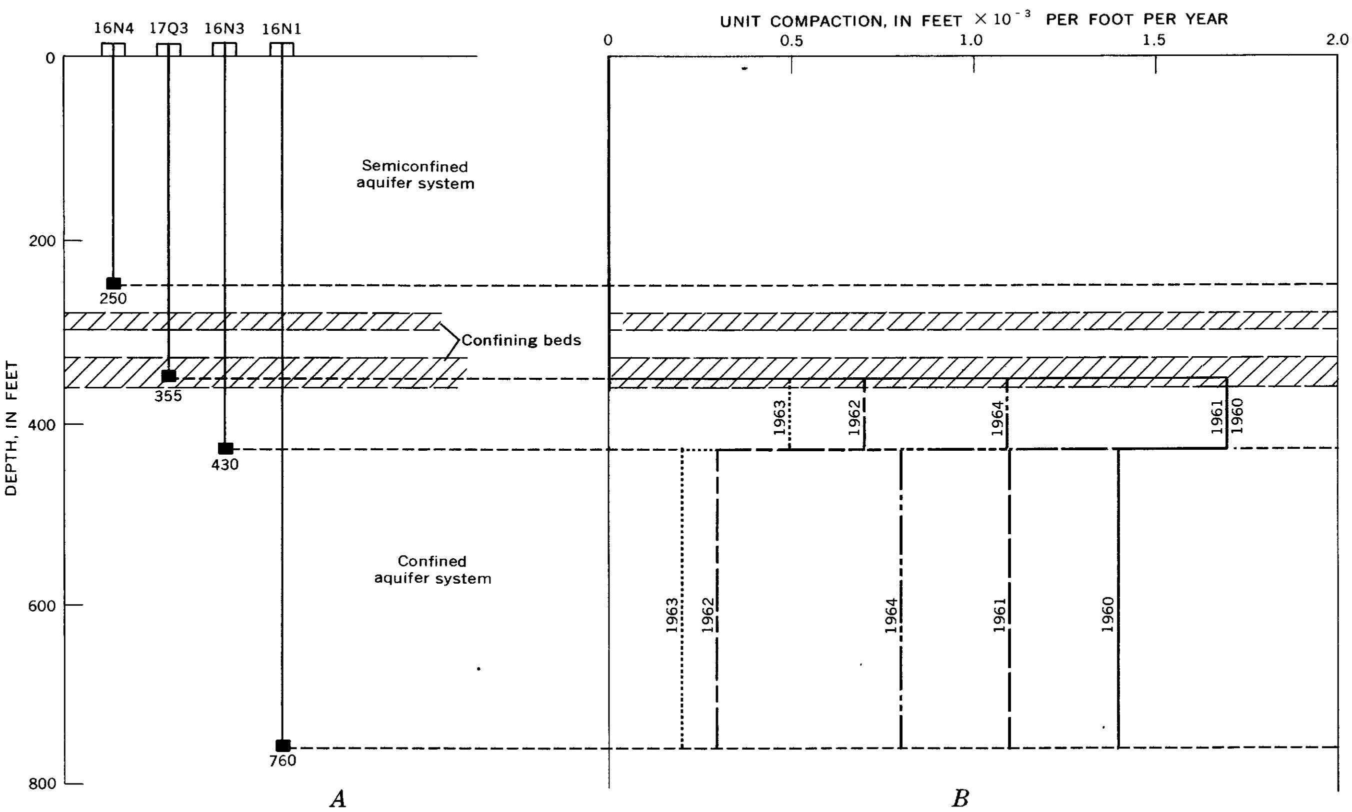


FIGURE 56.—Annual rate of compaction of deposits in four depth zones, 3 miles south of Pixley, 1960–64. *A*, Relation of recorders to the hydrologic units. *B*, Measured compaction rate in four depth zones for 5 years of record.

of the lower zone in 1963, when compaction was the least. Specific unit compaction (seasonal),[5] which is the unit compaction per foot of seasonal change in effective stress (fig. 54), ranged during these 5 years from 2.5 to 1.3×10^{-5} foot per foot^2 in the 355–430-foot zone and from 2.1 to 0.7×10^{-5} foot per foot^2 in the 430–760-foot zone.

Figure 56 shows the relation of the four compaction recorders to the confining clay layers and the unit compaction in each of the depth intervals for the period 1960–64. Inasmuch as most of the nearby pumping was from wells tapping only the confined aquifer system, it is not surprising that virtually all the measured compaction was below 355 feet and that 75 percent of the observed subsidence (1960–64) was caused by compaction in the 355–760-foot zone. It is also noteworthy that the highest unit compaction was in the micaceous silty sands containing clayey interbeds in the 355–430-foot depth zone (fig. 7).

The relationship between seasonal unit compaction in two depth zones near Pixley (table 9) and the change in stress during the period of compaction which produced the vertical shortening is shown graphically in figure 57 for 5 years, 1960–64. Thus, the upper left end of each stress-strain line of figure 57 represents the stress at which seasonal compaction was first recognized, and the coordinates of the lower right end represent the maximum compaction and stress that was attained that year. Stress changes are based on the arbitrary scale of figure 54, where zero change in stress was assumed for the high point of the stress curve during the first year of continuous record. The slope of each year-line of figure 57, representing the stress-strain relationship for a particular depth zone, is inversely proportional to corresponding values of specific unit compaction (table 9).

The effect of slow drainage from the fine-grained beds on the rate of compaction of the two depth zones is illustrated by the progressive increase in slope of the stress-strain lines of figure 57. During the 4½-year period from January 1960 to June 1964, the effective stresses in the confined aquifer system exceeded the July 1960 stress for only 5 weeks in 1961 (center graph, fig. 54). Slow drainage and associated compaction continued at a diminishing rate (steeper slope, fig. 57) throughout the part of the period that stresses were below line C–C' (fig. 54). When previous maximum stresses were exceeded in June 1964, renewed compaction occurred throughout the aquifer system. The increased compaction rate during 1964 for the 430–760-foot depth zone is particularly noticeable in figure 57*B*, where the 1964 stress-strain line falls above the 1963 line.

To obtain a detailed correlation between the measured compaction and the related fluctuations of the piezometric surface of the confined aquifer system, an amplifying compaction recorder was installed at well 23/25–16N1 in May 1961. This recorder was geared to the direct-reading recorder to give a 12:1 or 24:1 vertical amplification of the compaction record as compaction ocurred. The center graph of figure 58 shows the direct 1:1 record of compaction measured by recorder 23/25–16N1 during 12 months of 1962 and 1963. The lower graph, which is the 12:1 amplified compaction record, shows an excellent correlation with the water-level fluctuations in well 23/25–16N3 (top graph). During this 12-month period, the water level in the semiconfined aquifer system rose slightly; thus head changes in the confined aquifer system approximately equaled the changes in effective stress in the compacting deposits. The continuous rise in water level in well 16N3 from late July 1962 (fig. 54) to January 2, 1963, caused a slight expansion of the aquifer system (fig. 58*C*). About 0.0022 foot of expansion was measured during October, November, and December of 1962 during a water-level recovery. Pumping during March caused the water level to fall again, and after it had declined about 5 feet below its March high, measurable compaction was observed in the amplified record. Rapid compaction occurred for 10 days (March 10 to March 20), during which the water level in well 16N3 dropped 48 feet.

Compaction during this 10-day period amounted to 0.031 foot, at a rate of 0.65×10^{-3} foot per foot of water-level decline. During the straight-line part of the declining record, March 12–17, a water-level decline of 7.3 feet per day caused compaction of 5.5×10^{-3} foot per day, at a rate of about 0.76×10^{-3} foot per foot of water-level decline. For 9 days of water-level recovery after reaching the spring low of March 21, compaction continued at a diminishing rate. It was not until the water level had recovered 35 feet from the March 21 low that compaction stopped. Through April, May, and early June, the water level remained above the March 29 level, at which compaction stopped, and water-level fluctuations resulted in little or no observed compaction. Soon after the water level had fallen below the March 29 level, however, rapid compaction resumed, and thereafter, each minor fluctuation of the water level in the

[5] The values of effective-stress change used in deriving numerical values of specific unit compaction are those measured in the permeable beds during the period of compaction. The effective-stress change in the fine-grained compactible beds is less by the amount of the residual excess pore pressure, which is not known. Stress change in the permeable beds is the best evidence available of changes in the less permeable, compactible beds. After all excess pore pressures are dissipated, the effective stress in the permeable and less permeable beds is the same.

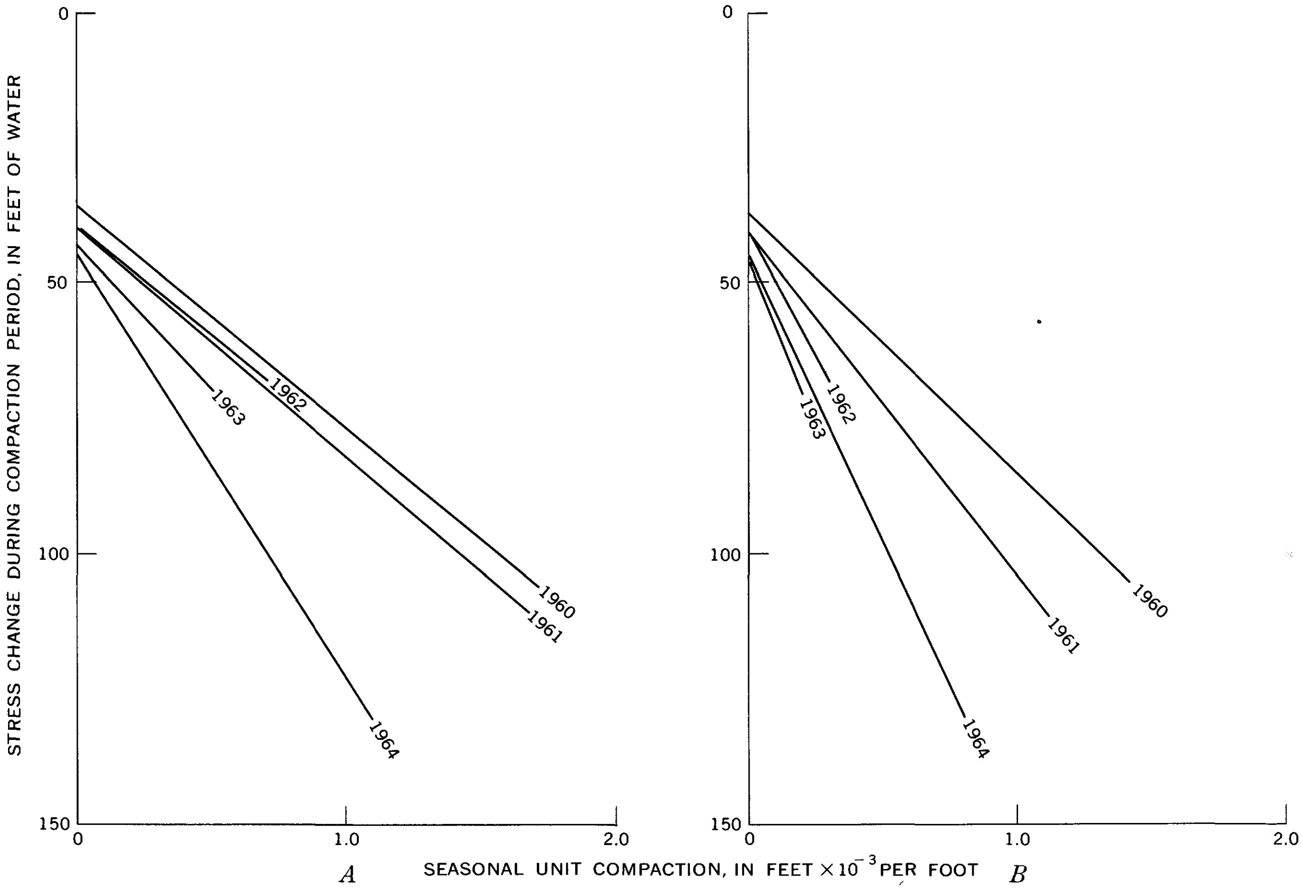


FIGURE 57.—Relation of seasonal unit compaction to stress change during the compaction period in two depth zones of the confined aquifer system near Pixley, 1960–64. *A*, 355–430-foot depth zone. *B*, 430–760-foot depth zone.

confirmed aquifer system had an observable effect on the rate of compaction (fig. 58*B*, *C*). From June 24 to August 31, 28 feet of water-level decline caused 0.068 foot of compaction, at a rate of 2.4×10^{-3} foot per foot of water-level decline. Mechanical difficulties during August and September 1963 resulted in a broken record in both the hydrograph of well 23/25–16N3 and the amplified compaction record of well 23/25–16N1 (fig. 58).

The delicate sensitivity of the aquifer system to changes in effective stress is readily apparent in the graphs of figure 58. Under certain conditions, compaction of the deposits may begin within minutes after pumping affects the pressure in the confined aquifer system. Compaction continues as long as excess pore pressures remain in the aquitards and thus may continue at a diminishing rate even during the early stages of water-level recovery. A very small part of the compaction is elastic in nature, and rebound may occur when the stress is decreased (Oct.–Dec. 1962, fig. 58). Most of the compaction, however, is nonelastic in nature and represents a permanent decrease in the volume of the stressed deposits.

As shown in figure 59, rebound occurred in the compaction record of well 23/25–16N1 during periods of water-level recovery that preceded and followed a major water-level decline in March 1963. The water-level in the confined aquifer system rose continuously from mid-January to the end of February (hydrograph 23/25–16N3, fig. 54). During February, the water level rise of 11 feet (fig. 59) resulted in a measured rebound of about 8×10^{-4} foot, or a rebound of 7.5×10^{-5} foot per foot of water-level rise. From March 9 to March 21, a water-level decline of roughly 50 feet produced an abrupt compaction of 0.034 foot, or 0.68×10^{-3} foot of compaction per foot of water-level decline. Water-level recovery of 26 feet from March 23 to March 30 resulted in cessation of compaction, which was followed by more than a month of continued water-level recovery and rebound. From March 30 to April 24, water levels in the confined aquifer system rose 16 feet, and about 9.4×10^{-4} foot of rebound, for a rebound of 5.9×10^{-5} foot per foot of water-level rise, occurred. During the 3-month period from February to April (1963), the water level in the overlying semiconfined aquifer system rose slightly, and no measurable compaction was

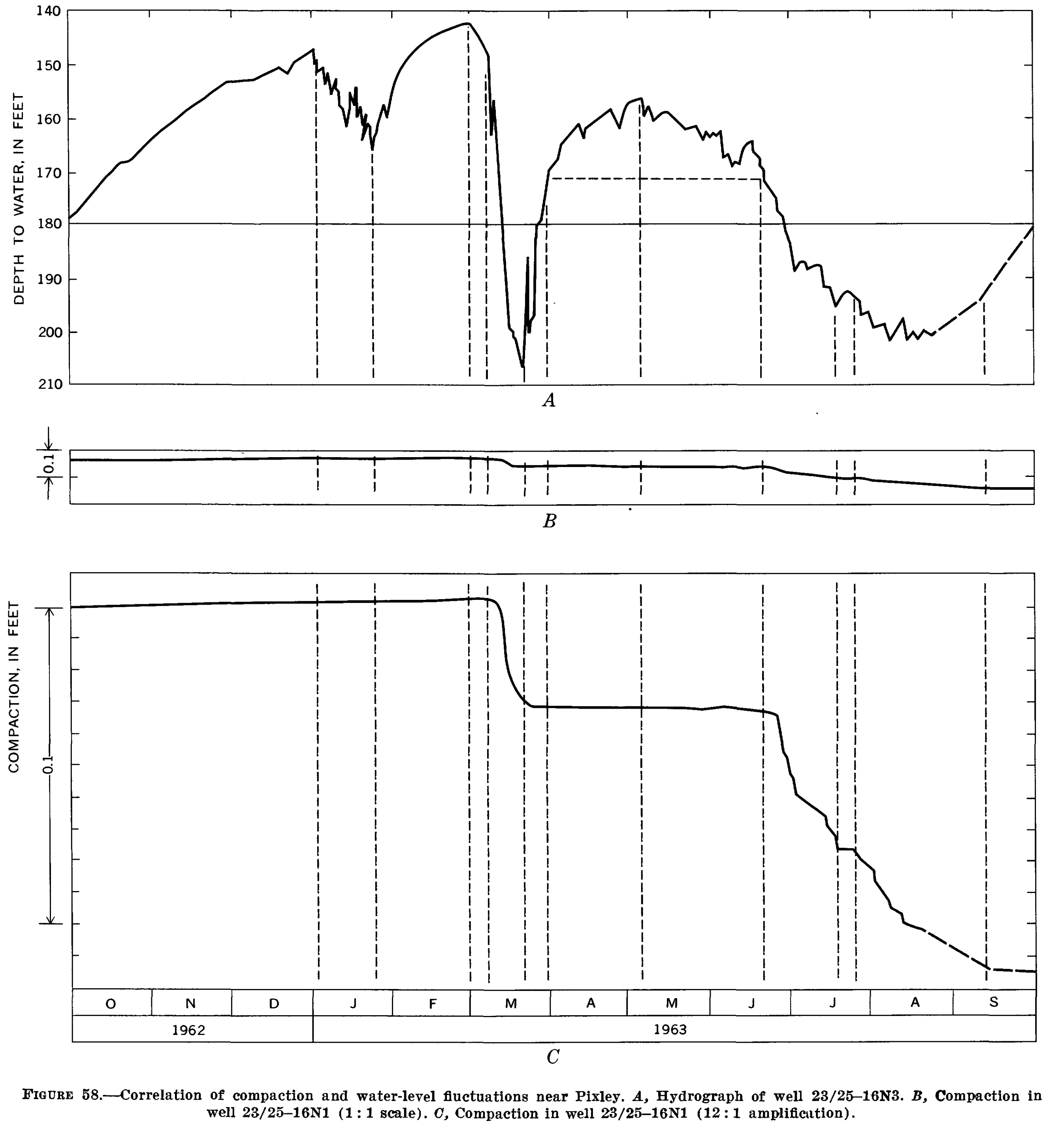


FIGURE 58.—Correlation of compaction and water-level fluctuations near Pixley. *A*, Hydrograph of well 23/25–16N3. *B*, Compaction in well 23/25–16N1 (1 : 1 scale). *C*, Compaction in well 23/25–16N1 (12 : 1 amplification).

recorded by either the 250-foot or the 355-foot compaction recorders.

Assuming that all the measured rebound and compaction of the 760-foot recorder occurred in the 355–760-foot depth zone, the February 1–March 9 rebound represented 1.8×10^{-7} foot of rebound per foot of water-level rise per foot of aquifer thickness, the March 9–March 21 compaction represented 1.7×10^{-6} foot of compaction per foot of water-level decline per foot of thickness, and the March 30–April 24 rebound represented 1.5×10^{-7} foot of expansion per foot of water-level rise per foot of thickness. Table 10 summarizes the computed compaction and rebound of figures 58 and 59. It is noteworthy that the specific unit rebound is at least an order of magnitude smaller than the specific unit compaction. Rebound and compaction are largely elas-

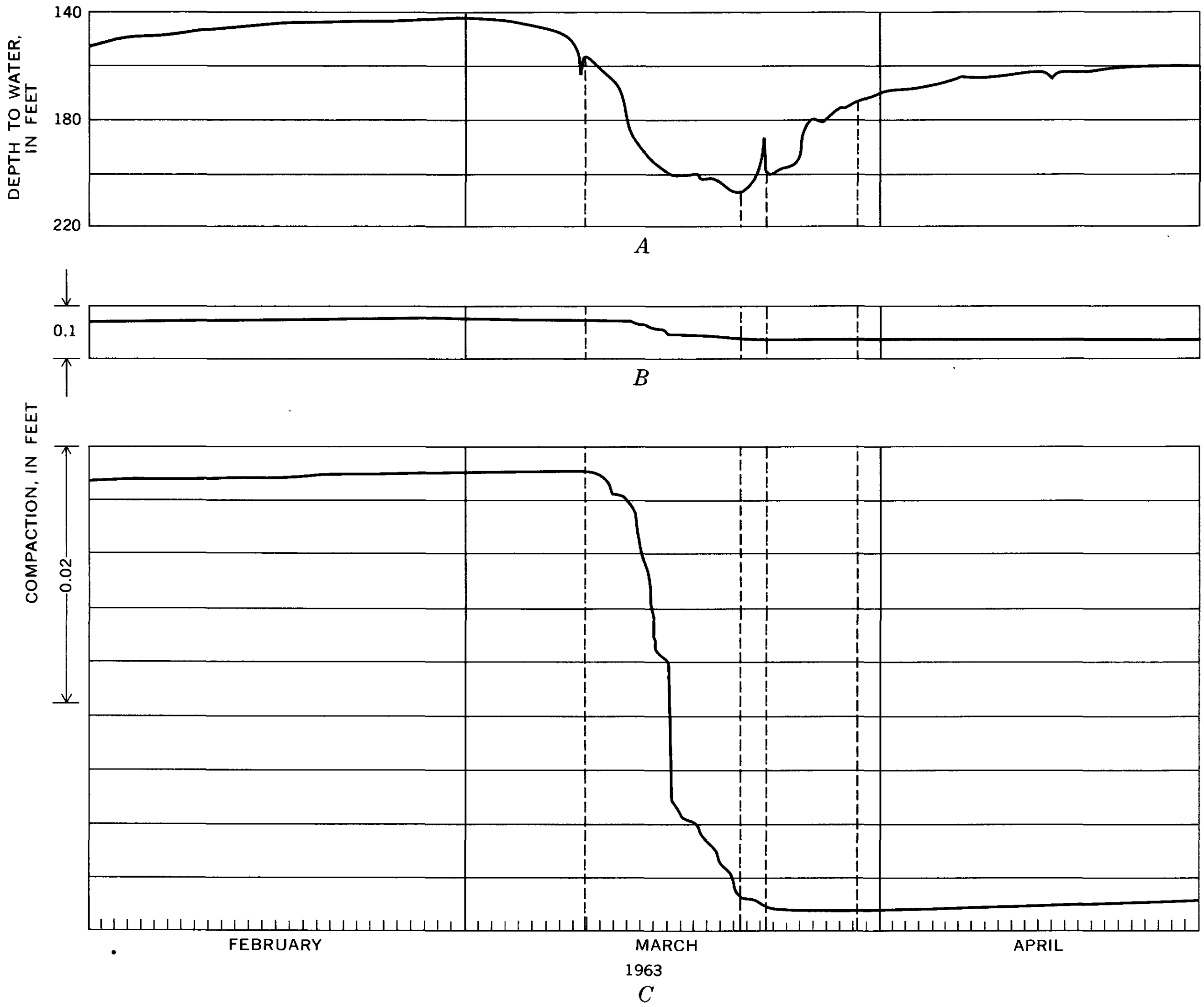


FIGURE 59.—Observed rebound and compaction near Pixley. *A*, Water-level fluctuations—well 23/25–16N3. *B*, Compaction record—well 23/25–16N1. *C*, Compaction record—well 23/25–16N1 (24 : 1 vertical amplification).

tic through this range of water-level fluctuation, and the specific unit values are one to two orders of magnitude smaller than the value of specific unit compaction shown in table 9.

Summary of measured compaction

Results obtained at the Pixley recorder site in relating compaction and subsidence to changes in effective stress and water-level fluctuations are of significance not only for Pixley and the Tulare-Wasco area but also for other subsidence areas where similar stress-strain relationships apply. Multiple-compaction and water-level recorders at this site, through 5 years (1959–64) of continuous operation, have supplied the most detailed record of compaction and water-level change in the San Joaquin Valley.

The seasonal fluctuations of the piezometric head in the confined aquifer system, between winter highs of about 140 feet below land surface and summer lows of 200–260 feet, depended on the amount of pumpage required to augment the limited and variable supply of surface water. Except in 1962 and 1963, the summer lows tended to deepen several feet each successive year. Annual fluctuations in the semiconfined system were about 10 percent as great as those in the confined system, and from 1961 to 1964 the water level gradually rose. Only minor increases in effective stress occurred in the semiconfined aquifer system from 1959 through 1961, and little or no compaction was measured in the upper 355 feet of deposits. Because changes in the semiconfined water level were small, piezometric fluctuations in the confined system were the dominant factor in computing

TABLE 10.—*Compaction and rebound characteristics of the confined aquifer system near Pixley*

Date	Figure reference	Compaction		Rebound	
		Specific compaction [1]	Specific unit compaction [2]	Specific rebound [3]	Specific unit rebound [4]
10- 1-62 to 12-31-62	57			6.9×10^{-5}	1.7×10^{-7}
3- 7-63 to 3-12-63	57	0.67×10^{-3}	1.7×10^{-6}		
6-24-63 to 8-12-63	57	2.4×10^{-3}	5.9×10^{-6}		
6- 5-62 to 6-11-62	58	$.83\times10^{-3}$	2.0×10^{-6}		
6-22-62 to 6-24-62	58	$.42\times10^{-3}$	1.0×10^{-6}		
7- 5-62 to 7-10-62	58	$.62\times10^{-3}$	1.5×10^{-6}		
2- 1-63 to 2-28-63	59			7.5×10^{-5}	1.8×10^{-7}
3- 9-63 to 3-21-63	59	$.68\times10^{-3}$	1.7×10^{-6}		
3-30-63 to 4-24-63	59			5.9×10^{-5}	1.5×10^{-7}

[1] Feet of compaction per foot of increase in effective stress.
[2] Feet of compaction per foot of compacting deposits per foot of increase in effective stress.
[3] Fect of expansion per foot of decrease in effective stress.
[4] Fect of expansion per foot of expanding deposits per foot of decrease in effective stress.

changes in effective stress in the confined aquifer system. The graph of effective-stress change, therefore, resembles closely the hydrograph of well 23/25–16N3 (fig. 54), both in magnitude and configuration.

The average rate of subsidence at the Pixley site (bench mark Q945) diminished from 0.69 foot per year (1959–62) to 0.23 foot per year (1962–64) in response to a marked, though temporary, change in the pumping pattern. Significant compaction in the confined aquifer system occurred only when the effective stress was in the lower (greater stress) two-thirds of its annual cycle. The amount of compaction each year was roughly proportional to the area bounded by the effective-stress curve under the *C–C′* line (fig. 54). Of the 2.54 feet of subsidence from January 1959 to February 1964, little or none represented compaction in the 0–355-foot depth zone of the semiconfined system; 1.90 feet of compaction, or 75 percent of the subsidence, was above 760 feet.

Because of differences in drainage characteristics, the individual fine-grained beds in the confined aquifer system are at different stages of compaction at each level of effective stress below line *C–C′* (fig. 54). The rate of compaction of each bed and of the depth interval as a whole varies as the effective stress changes. An empirical correlation can be made, however, between the rate of change in effective stress and the rate of compaction or subsidence after a sufficiently long period of comparable record is available to establish a long-term trend for these interrelated variables. From 1959 to 1961, for example, the trend of water levels and subsidence continued roughly downward as it had for several years. During this period, the effective stress increased at a rate of about 9 feet per year (trend of summer troughs, fig. 54), while bench mark Q945 subsided at a 3-year average rate of 0.69 foot per year, a ratio of 0.077 foot of subsidence per foot of effective stress increase. Reduced pumping during 1962 and 1963 caused a marked reduction in the rate of subsidence during these years, and even though heavy pumping in 1964 caused the effective stress in the confined aquifer system to decline to the projected trend line *B–B′*, the subsidence rate from 1962 to 1964, as inferred from the compaction graph of well 23/25–16N1 (fig. 54), was much less than during the 1959–61 period.

The thickness and compressibility of the compacting deposits vary greatly, both areally and with depth, throughout the Tulare-Wasco area. Also, the seasonal fluctuations and trend of water levels in the confined and semiconfined aquifer system vary from place to place. The measured rates of compaction and subsidence at the Pixley site, therefore, do not apply to other parts of the area. The general stress-strain relationships, however, do apply. Compaction is directly related to change in effective stress, which in turn is computed from changes in hydraulic head in the confined and the semiconfined aquifer systems. To establish a relationship between compaction, subsidence, and water-level change at any location, one or both of the following two types of data can be used:

1. Field measurements of compaction, subsidence, and water-level change in the principal hydrologic units, from which the overall transient response of the sequence of deposits to changes in effective stress can be analyzed for several years of record.
2. Detailed records of thickness and character of beds in the compacting zone, as obtained from electric logs, and a measure of the compressibility of the individual beds, as obtained from consolidation tests on selected cored samples, from which a rough estimate of the ultimate compaction of the system can be made for a given change in effective stress.

The application of the first type of data at one location has been presented in preceding pages. The application of the second type of data for the same Pixley site is considered in the following pages. In few locations in the Tulare-Wasco area are sufficient data available to apply either of the two procedures.

COMPUTED COMPACTION

On the basis of Terzaghi's theory of consolidation (Taylor, 1948, p. 208), the amount of compaction that would occur at a particular site in a subsidence area resulting from a given water-level decline, can be computed from laboratory test data taken at that site. By using a procedure outlined by Gibbs (1960) and applied in another subsidence area by Miller (1961), the amount of compaction that could be expected at the Pixley core hole (23/25–16N1) under the historic changes in water levels was computed. Water-level declines approximating the actual changes at the Pixley site from 1905 to 1964 were used in these computations. This method of computation requires that the lithology and hydraulic history of the aquifer system be known. Also, laboratory test data must be available for sufficient core samples to give a representative measure of the compressibility of the individual lithologic zones under a given change in loading stress.

As shown in figure 60, the 760 feet of unconsolidated deposits penetrated by the Pixley core hole, 23/25–16N1, was subdivided into 10 zones, on the basis of a study of the electric log and the core samples. The individual depth zones were selected to include deposits of similar lithology and physical character, insofar as possible. Laboratory consolidation tests were available for six cored samples from this sequence (table 11); the test results of four of these samples were used to represent the compressibility of the deposits in the 10 depth zones (fig. 60). Thus, the consolidation data for a sample considered most representative of the deposits of that zone were used in the following computations, even though the sample may not have come from that zone.

TABLE 11.—*Results of consolidation tests on samples from the Pixley core hole, 23/25–16N1*

[Data from Earth Laboratory, U.S. Bur. Reclamation, Denver, Colo.]

Sample	Depth (ft)	Description	Grain size (percent) Sand	Grain size (percent) Silt and clay	Load range (psi)	Compression index C_c	Coefficient consolidation c_v (ft² per yr)
23L–226	261.7–261.9	Sand, with clay; brown	55	45	200–400	0.17	311.0
227	283.5–283.9	Clay, with fine sand; gray	10	90	200–400	.62	9.9
228 [1]	292.0–292.4	Clay, with fine sand; gray to brown.	20	80	200–400	.53	192.7
229	450.1–450.5	Clay, silty; brown	5	95	300–600	.40	4.8
232 [1]	630.3–630.7	Sand, silty; brown	55	45		.25	
234	723.5–723.8	Silt, sandy; brown	40	60		.35	

[1] Not used in computations.

The laboratory data from 47 core samples tested by the Geological Survey (Johnson and others, 1968, table 4) were used to compute the average specific gravity, G, and the average porosity, n, for deposits in each of the 10 depth zones. Table 12 gives the depths to water in the confined and semiconfined aquifer systems and the seepage stresses used in computing compaction at the Pixley core hole. From these data, the dry unit weight (lb per cu ft) or the buoyant unit weight (lb per cu ft) was computed for each zone (dry unit weight for deposits above the water table and buoyant unit weight for deposits below the water table). These unit weights were used to compute the total effective overburden load (in psi) for the midpoint of each of the 10 zones for each of 5 years. Even though the weight of the deposits above the water table exceeds the dry unit weight by the amount of retained moisture, the moisture retention of the deposits was not known, and thus the dry weight was used as an approximation of the actual weight of the deposits. The increase in effective stress due to seepage stress exerted through the confining clay of zone 4 (equal to the head differential, in psi) was added to the computed effective overburden load. Thus, the total effective stress tending to compact the deposits was obtained for the midpoint of each zone for each of the 5 years (table 13).

TABLE 12.—*Depths to water in the confined and semiconfined aquifer systems and seepage stresses used in computing compaction at the Pixley core hole, 1905–64*

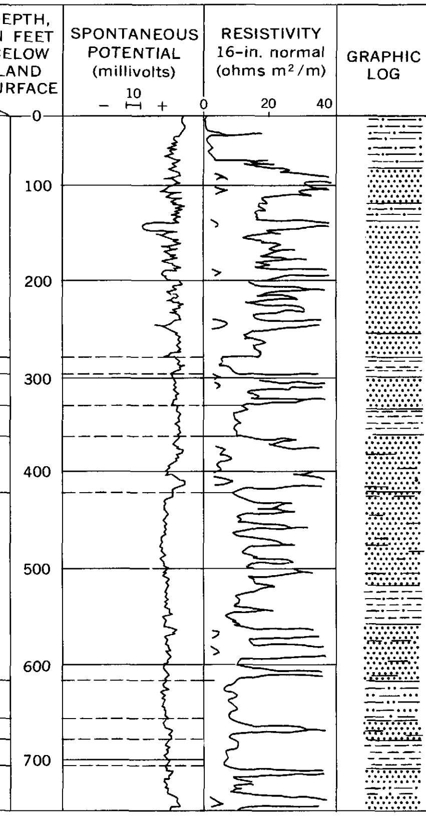
Year	Depth to water below land surface, in feet: Semiconfined	Depth to water below land surface, in feet: Confined	Seepage stress: Feet	Seepage stress: Pounds per square inch
1905	10	−5	−15	−6.5
1931	59	64	5	2.2
1948	91	125	34	14.7
1959	110	232	122	52.9
1964	95	260	165	71.5

TABLE 13.—*Effective stress, void ratio, and computed compaction for each of the lithologic zones at the Pixley core hole, 1905–64*

Zone	Depth (ft)	Thickness (ft)	Compacting thickness [1] (ft)	Average specific gravity (G)	Average porosity (n)	1905 Effective stress [2] (psi)	1905 Void ratio [3] (e)	1931 Effective stress (psi)	1931 Void ratio (e)	1948 Effective stress (psi)	1948 Void ratio (e)	1959 Effective stress (psi)	1959 Void ratio (e)	1964 Effective stress (psi)	1964 Void ratio (e)	Ultimate compaction [4] (feet) 1905–31	1931–48	1948–59	1959–64	1905–64
1	0–280	280	80	2.68	0.36	68.6	0.498	81.7	0.481	90.3	0.470	95.5	0.469	91.4	[5] 0.469	0.91	0.59	0.05	0	1.55
2	280–296	16	16	2.68	.56	136.9	1.112	150.0	1.085	158.6	1.072	163.8	1.063	159.7	[5] 1.063	.20	.10	.07	0	.37
3	296–330	34	34	2.69	.40	146.9	.745	160.0	.732	168.6	.724	173.8	.719	169.7	[5] .719	.25	.16	.10	0	.51
4	330–360	30	30	2.70	.38	154.8	.769	176.9	.744	197.7	.727	241.1	.696	255.6	.687	.42	.29	.54	.16	1.41
5	360–420	60	0	2.72	.42			Assumed no compaction								0	0	0	0	0
6	420–620	200	160	2.70	.42	230.5	.677	252.6	.665	273.4	.651	316.8	.629	331.3	.620	1.15	1.34	2.13	.88	5.50
7	620–660	40	40	2.68	.41	282.1	.670	304.2	.658	325.0	.645	368.4	.619	382.9	.611	.29	.31	.63	.20	1.43
8	660–680	20	10	2.73	.37	295.4	.640	317.5	.628	338.3	.617	381.7	.596	396.2	.590	.07	.07	.13	.04	.31
9	680–710	30	30	2.69	.40	306.7	.656	328.8	.641	349.6	.629	400.0	.602	407.5	.599	.27	.22	.50	.06	1.05
10	710–760	50	30	2.68	.43	324.5	.624	345.6	.613	366.4	.603	409.8	.584	424.3	.578	.20	.19	.36	.11	.86
Total																3.76	3.27	4.51	1.45	12.99

[1] Estimated from electric log; fig. 60.
[2] Computed for midpoint of zone.
[3] From consolidation curve of representative sample.
[4] Compaction estimated to occur ultimately as a result of effective stress change for the time period indicated.
[5] Assumed no rebound.

ZONE	DEPTH (feet)	CONSOLIDATION TEST USED	C_c	c_v
1	0-280	23L-226	0.17	311.0
2	280-296	23L-227	0.62	9.9
3	296-330	23L-234	0.35	-
4	330-360	23L-229	0.40	4.8
5	360-420	-	-	-
6	420-620	23L-234	0.35	-
7	620-660	23L-229	0.40	4.8
8	660-680	23L-234	0.35	-
9	680-710	23L-229	0.40	4.8
10	710-760	23L-234	0.35	-



GENERALIZED LITHOLOGIC DESCRIPTION (from core descriptions and electric log)

30-80 Silt, sandy, loose to plastic, micaceous, yellowish-brown.

80-115 Sand, silty, loose to plastic, fine to coarse, yellowish brown.

115-138 Silt, sandy, loose to plastic, gravelly, calcareous, micaceous, yellowish-brown.

138-258 Sand, silty, loose to plastic, fine to coarse, micaceous, yellowish-brown.

258-280 Sand, silty, clayey, fine, some coarse, calcareous near bottom, micaceous,yellowish -brown.

280-296 Clay, plastic, silty, micaceous, pale brown to bluish-gray diatoms[1].

296-330 Sand, silty, loose to plastic, fine to coarse, micaceous pale olive to yellowish-brown.

330-360 Clay, sandy, silty, plastic, micaceous,calcareous streaks, yellowish-brown; thin sand interbeds[2].

360-420 Sand, silty, fine to coarse, gravelly, micaceous, yellowish-brown; thin clay interbeds.

420-520 Sand, silty, clayey, fine to coarse, some gravel, calcareous streaks, micaceous, yellowish-brown; clay, silt interbeds.

520-560 Clay, sandy, silty, plastic, gravelly, calcareous streaks, carbonaceous material, micaceous, yellowish-brown; thin sand interbeds.

560-620 Sand, silty, loose to friable, fine to coarse, gravelly some biotite, yellowish-brown; clay interbeds.

620-660 Silt, sandy, loose to plastic, some carbonaceous material calcareous nodules, micaceous, yellowish-brown; thin sand and clay interbeds.

660-680 Sand, silty, clayey, loose, fine to coarse, carbonaceous material brown to olive.

680-710 Clay, plastic, massive, calcareous nodules, micaceous,yellowish-brown.

710-752 Sand,loose, friable, massive, fine to coarse, micaceous.

[1]Corcoran Clay Member of Tulare Formation.
[2]Principal confining layer.

FIGURE 60.—Lithologic subdivision of the Pixley core hole, 23/25–16N1, for application of consolidation test data. C_c, **compression index;** c_v, **consolidation coefficient, in square feet per year.**

As shown in figure 22, artesian wells still flowed in the vicinity of the Pixley core hole in 1905 (Mendenhall and others, 1916). By 1929, however, the shallow water level was 56 feet below the land surface, and in 1931, the confined water level was 64 feet below the land surface in a deep Pixley municipal well. Continued pumping caused continued decline, but the artesian head declined more rapidly than the semiconfined water level.

Figure 61 shows the generalized trend of water levels in the shallow semiconfined aquifer system and in the underlying confined aquifer system in the vicinity of the Pixley core hole. These plots, in general, represent the spring high-water level, except for the confined system in which the seasonal pumping drawdown is assumed to have increased consistently from about 1945 to 1960, as shown. Although some summer-pumping drawdown must have occurred in the confined aquifer system prior to 1944, it is assumed to have been small compared to the summer drawdown in later years of more intensive pumping; it was roughly equivalent to the summer drawdown in the semiconfined system prior to 1944. Prior to 1944, the seepage force was computed as the difference between the spring high-water levels in the two systems, which was, in turn, assumed to be about equal to the difference between the summer low-water levels. After 1944, accelerated pumping caused rapidly increasing summer drawdowns in the confined aquifer system, and the seepage force was computed as the maximum head differential during the pumping season. Although these maximum stresses were directly applicable only during a short summer period, they did apply during the part of the year when subsidence was most rapid (fig. 57).

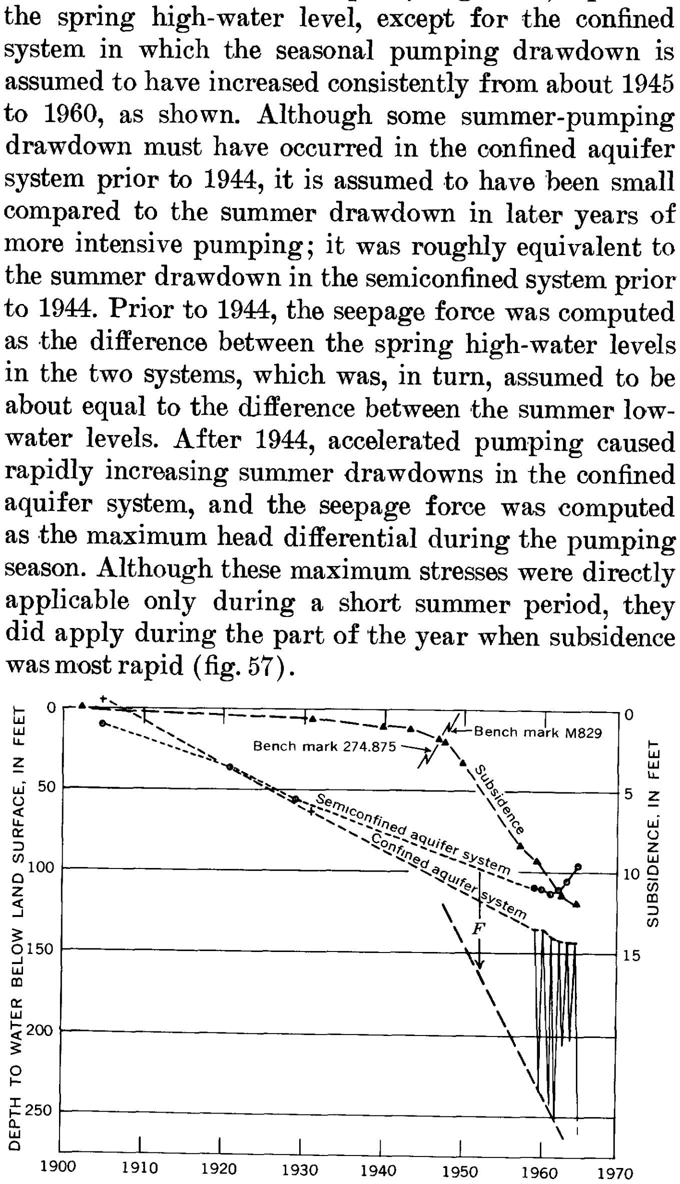


FIGURE 61.—Trend of water levels in the semiconfined and confined aquifer systems at the Pixley core hole, 23/25–16N1, and observed subsidence of nearby bench marks. The vector F, which changes with time, indicates the magnitude of the seepage force that was used in computing the increases in effective stress due to pumping.

As of 1943 (fig. 61), 82 feet of water-level decline in the semiconfined aquifer system and a corresponding 95 feet of decline in the deeper confined-aquifer system had caused roughly 1.2 feet of subsidence at bench mark 274.875. With continued water-level decline, subsidence at this location in 1947 was about 2.0 feet (bench mark M829 replaced bench mark 274.875 after 1947). As a result of accelerated seasonal drawdown in the confined aquifer system, however, the subsidence rate increased sharply after 1948. Under the new pumping regimen (1948–62), water levels in the semiconfined and confined aquifers fell roughly 1.3 and 9.0 (summer low level) feet per year, respectively. The subsidence rate during this period increased to 0.67 foot per year—more than 20 times the 1905–43 rate. Since 1948, the accelerated downward trend of artesian head during each successive summer pumping season seems to be the determining factor in the increased rate of subsidence.

By using the computed effective stress for each zone (table 13), and the one-dimensional consolidation curve of the sample considered representative of the zone (fig. 60), the theoretical void ratio of each zone was determined for each year being considered. Figure 62 is a plot of the consolidation data for core sample 23L–229, used for estimating void ratios in zones 4, 7, and 9. The left graph (fig. 62*A*) is a semilogarithmic plot of the data, as determined by the Bureau of Reclamation; the right graph, figure 62*B*, is an arithmetic replot of part of the same data, prepared to facilitate interpolating intermediate points on the graph. Figure 62 *B* indicates the effective stress (load, in psi) in 1905 and 1931 for zone 4 and the corresponding void ratios for these two years. In a similar way, the void ratios for each of the lithologic zones for each of the 5 years (table 13) were computed from the consolidation curve selected as representative for that zone. Because of its coarse sandy texture (fig. 60), zone 5 was assumed to have undergone no appreciable compaction, even though some compaction was measured between 1959 and 1964 for a somewhat thicker interval (table 9).

The amount of compaction in a particular zone that results from the computed change in void ratio is expressed by the following equation:

$$\Delta h = \frac{e_1 - e_2}{1 + e_1} h,$$

in which

Δh = vertical shortening or compaction of the zone in feet,
e_1 = initial void ratio,
e_2 = void ratio after loading, and
h = thickness of the compacting zone, in feet.

Values of e_1 and e_2 were obtained for each zone from the particular e-log curve as just described. On this basis, the

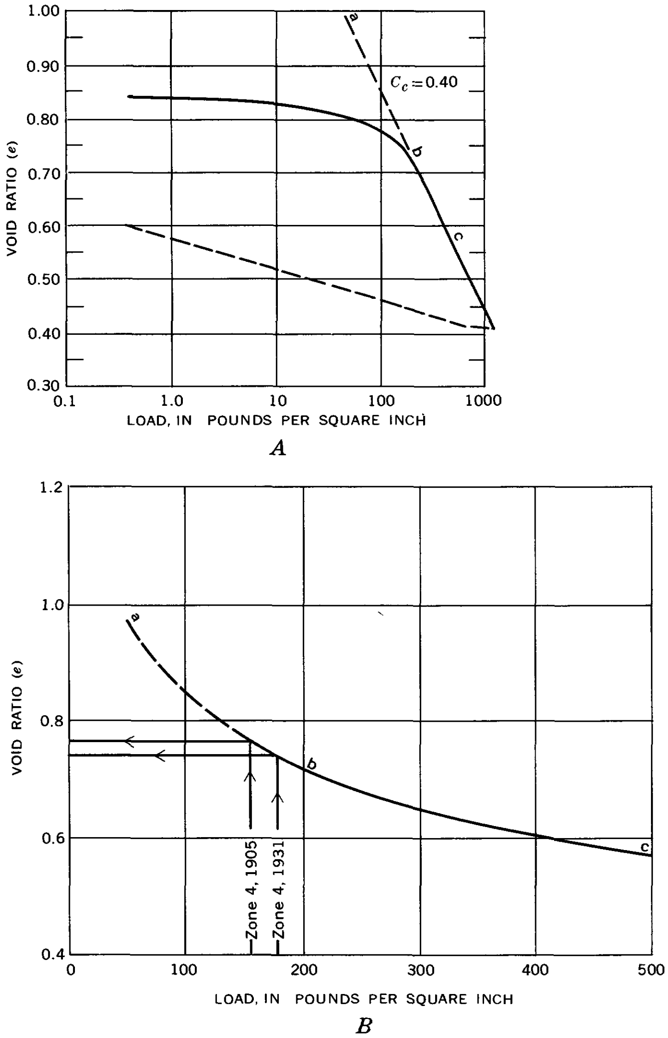


FIGURE 62.—One-dimensional consolidation data for core sample 23L–229, Pixley core hole. *A*, Semilogarithmic plot. *B*, Arithmetic plot. Test by Earth Laboratory, U.S. Bureau of Reclamation, Denver, Colo.

ultimate compaction that would occur in each of the 10 depth zones under the effective stress conditions of 1931, 1948, 1959, and 1964 was estimated (table 13). In these computations, the thickness used for each of the zones was reduced to include only that part of the zone considered to be compactible, as estimated from the electric log (fig. 60). The values of computed compaction indicate the ultimate compaction that would occur under the hydrologic conditions of the given time periods, even though come of the compaction would be delayed many years because of slow drainage.

The estimated ultimate compaction that would occur as a result of the effective stress changes from 1905 to 1964 is 12.99 feet (table 13). Of this amount, 1.45 feet of compaction would be due to stress increases incurred from 1959 to 1964. Although no information is available as to the amount of compaction that actually occurred from 1905 to 1959, 1.90 feet of compaction was measured at the Pixley core hole from spring 1959 to spring 1964. Thus, for the 5-year period 1959–64, compaction measured by the 760-foot recorder exceeded the computed ultimate compaction for the same period by 0.45 foot, or about 24 percent.

From the data of table 13, a rough measure of the compressibility of the confined aquifer systems can be obtained for use in predicting future subsidence at the Pixley recorder site. Considering zones 4 through 10 (table 13) as a single hydrologic unit, the ultimate specific unit compaction for the measured part of the confined aquifer system was obtained for four periods of record from the following values of stress change and compaction:

Period	Compaction (ft)	Stress change (psi)	Stress change (ft of water)	Ultimate specific unit compaction ($\times 10^{-4}$ ft per ft^2)
1905–31	2.40	22.1	50.8	1.1
1931–48	2.42	20.8	47.8	1.1
1948–59	4.29	43.4	99.9	1.0
1959–64	1.45	14.5	33.4	1.0
1905–64	10.56	100.8	231.8	1.1

Change in effective stress at the time of ultimate compaction for each period was assumed to be common for all beds of zones 4 through 10 and was converted to "feet of water" units for the computation. It is significant that ultimate specific unit compaction as here computed is the same parameter as Terzaghi's (Terzaghi and Peck, 1948, p. 64) coefficient of volume compressibility (m_v).

As noted in the table, the computed value of specific unit compaction for the overall confined aquifer system was about 1.1×10^{-4} foot per foot^2 for the four periods of water-level decline. This value suggests that if unconfined water levels remain nearly unchanged in the future and confined water levels follow the same declining trend, roughly 1.1×10^{-4} foot of compaction will occur in each foot of aquifer-system thickness for each foot of increase in effective stress beyond the 1964 value.

TIME LAG OF COMPACTION

One complicating condition that must be considered when comparing computed ultimate compaction with actual measured compaction is the time delay for compaction to occur, referred to here as time lag of compaction. Because of the slow rate of drainage from fine-grained deposits, particularly those that are thick and of very low permeability, years or even centuries may be required for ultimate compaction to be completed for a given change in effective stress; this period, based on the Terzaghi theory of consolidation (Terzaghi and Peck, 1948, p. 241), can be computed from the consolidation test data by the equation

$$t=\frac{Th^2}{c_v},$$

in which

t = time since application of increased stress, in years,
T = time factor that varies with the percentage of ultimate compaction completed,
h = thickness of the compacting layer, in feet, and
c_v = coefficient of consolidation, in square feet per year.

If the stress is assumed to have been instantaneously and fully applied at $t=0$, $T=0.0076$ for 10 percent compaction, about 0.2 for 50 percent compaction, and 1.0 for about 93 percent compaction. If a compacting layer is free to drain through both its upper and lower surfaces, as is a clay interbed within an aquifer system, the thickness used in the preceding equation is $h/2$. If a compacting layer drains through only one surface, as does a confining layer over a drawdown aquifer system, the full thickness of the confining layer, h, is used.

Values of the coefficient of consolidation were determined for only four samples from the Pixley core hole (table 11). From these determinations, however, an estimation was made of the length of time required for compaction to occur in the Pixley area after an assumed water-level lowering. The preceding equation states that the time required for excess pore water to drain from a compacting layer varies as the square of the thickness. Also, the time varies inversely as the coefficient of consolidation, which, at the Pixley site, ranged from 4.8 to 9.9 for the silty clay aquitards to 311 for a clayey sand (sample 23L–226, table 11). Undoubtedly, untested beds in the deposits at the Pixley core hole have coefficients of consolidation both larger and smaller than these values. The coefficients for the tested samples, however, give some indication of the range of time required for compaction to occur in the slow-draining beds.

The substitution of the parameters of the Pixley deposits in the time equation shows that only the thickest finest-grained layers have compaction times of more than a few weeks or months. In the sandy sequence of zone 1 (fig. 60), few of the finer silt beds are more than 10 feet thick, and only two are 23 feet thick or more. Even these thicker beds probably include thin sandy stringers which reduce greatly the time required for drainage. Considering, for example, the silt bed from 115 to 138 feet below land surface and assuming $c_v=311$ feet^2 per year and two-directional drainage ($h/2=11.5$ ft), the time required for 10 percent compaction under any given effective-stress increase is roughly 3.2×10^{-3} years, or about 1 day. About 1 month of drainage would be required to complete 50 percent of the compaction and roughly 5 months to complete 93 percent.

By similar computations, the compaction time for the 16-foot thick Corcoran Clay Member (depth 280–296 ft; assume $c_v=9.9$ ft^2 per yr for the entire thickness and two-directional drainage) would range from 0.05 year for 10 percent compaction, to 1.3 years for 50 percent compaction, to about 6.5 years for 93 percent compaction. Correspondingly slow drainage would occur in the other fine-grained beds, particularly those that are more than 10 feet thick. The computed compaction time for the four slowest draining beds, assuming one-directional drainage for zone 4, the principal confining bed at this site, and two-directional drainage for zones 2, 7, and 9, follows:

Zone	Depth (ft)	Thickness (ft)	Coefficient of consolidation c_v (ft^2 per yr)	Time, in years, for percentage of compaction to occur		
				10 percent	50 percent	93 percent
2	280–296	16	9.9	0.05	1.3	6.5
4	330–360	30	4.8	1.4	38	187
7	620–660	40	4.8	.6	17	83
9	680–710	30	4.8	.3	9	46

From table 13 and figure 60, it is noted that about 60 percent of the ultimate compaction occurs in relatively permeable zones, which drain probably within a few days or weeks. This rapid response undoubtedly represents the "short term" compaction observed at the Pixley recorder site (figs. 54, 59), but probably 40 percent of the compaction occurs in beds with compaction lags comparable to those summarized in the preceding table. Figure 63 shows the estimated time delay, or lag

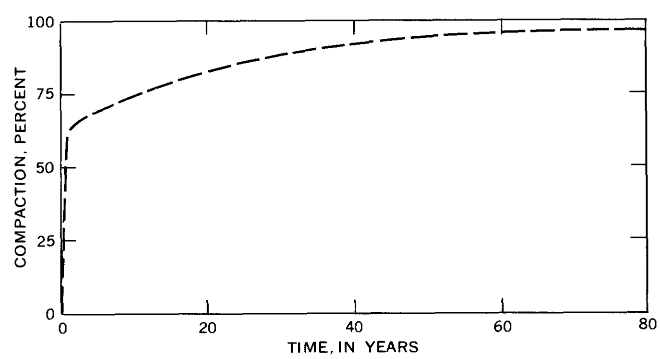


FIGURE 63.—Estimated time required for compaction of deposits to 760-foot depth at Pixley following an increase in effective stress.

effect, for compaction of the 760 feet of unconsolidated deposits penetrated by the Pixley core hole after an increase in effective press is applied. The figure suggests that as much as 60 percent of the ultimate compaction under a given stress increase might occur within the first several months but that 75 percent of the ultimate compaction would require 10 years. During periods of sustained water-level decline, the delayed residual, or lag, compaction from previous stress increases is cumulative; thus, the percentage of the actual measured compaction that is residual compaction changes with time and with changes in effective stress.

CORRELATION OF SUBSIDENCE, COMPACTION, AND WATER-LEVEL CHANGE

Measured compaction of the upper 760 feet of deposits at the Pixley core hole, as mentioned previously, composed 75 percent of the subsidence for the 5-year period from 1959 to 1964; therefore, 25 percent of the total compaction in the 5 years probably occurred at depths below 760 feet. Also, as suggested by figure 63, about 75 percent of the ultimate compaction due to effective stress increase to 1964 had occurred by 1964. These results suggest three limitations in relating water-level fluctuations to measured and computed compaction and to observed subsidence at this site:

1. Compaction and subsidence are directly related to changes in effective stress, which in turn are caused by water-level changes. Water-level changes must be converted to effective-stress changes in each of the compacting beds before a direct correlation can be made. The effective-stress changes are known only for the aquifers, not for the aquitards.
2. The compaction characteristics of the deposits below the 760-foot depth and also the changes in effective stress in this deep zone may be considerably different from conditions above the 760-foot depth. Therefore, the compaction below 760 feet may not always parallel the compaction above 760 feet.
3. Because of the slow drainage of fine-grained beds and the associated delay in the compaction of these deposits, subsidence at a particular time may be more closely related to past water-level changes than to current changes. Certainly, after a given change in effective stress has occurred in the coarse-grained beds and these beds have fully adjusted to the new stress, any further vertical shortening of the aquifer system would result from delayed compaction of the fine-grained beds. The ratio of subsidence to head decline, therefore, is meaningful in anticipating future subsidence only when residual compaction represents only a small part of the total subsidence or the ratio is related to a sufficiently long period of uniform water-level decline that the component of residual compaction is nearly constant.

Figure 64 shows the relationship between observed subsidence at the Pixley site and the computed ultimate compaction of the deposits to a depth of 760 feet for the estimated stress changes from 1905 to 1964, as given in table 13. Also shown is the measured compaction of the upper 760 feet of deposits from 1958 to 1964. Since 25 percent of the ultimate compaction represents residual compaction as of 1964 which had not yet resulted in subsidence, and since about 25 percent of the measured subsidence is due to compaction below 760 feet, the amount of computed ultimate compaction and the measured subsidence should be about equal for any stress change, as long as this approximate relationship is maintained. Even though the total amount of computed compaction during the 59-year period roughly approximates the observed subsidence, the two curves do not look alike. The hydrograph for the confined system from which compaction was computed (fig. 61) had only one control point between 1905 and 1958. If the confined head at this site had actually declined slower before 1944 and faster after 1944 than figure 61 indicates, the computed compaction and subsidence graphs would be more parallel.

On the other hand, if the hydrograph for the confined system (fig. 61) is accepted as approximately correct, the small amount of observed subsidence prior to 1944 in response to water-table and artesian-head declines of nearly 100 feet suggests that the deposits may have been consolidated at some prehistoric time under a greater effective stress than that which existed in 1905. The deficient record for the artesian head precludes a conclusion as to which interpretation is the more likely one.

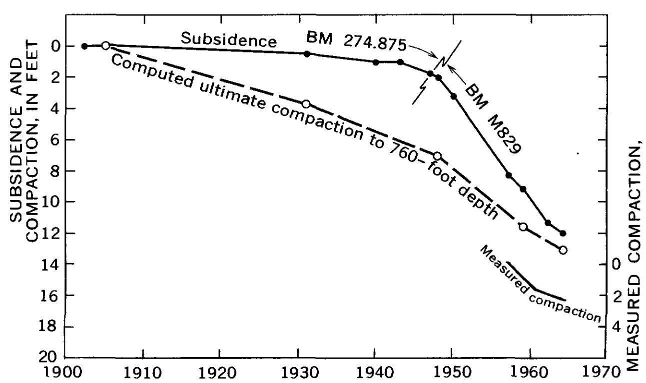


FIGURE 64.—Computed ultimate compaction, measured compaction, and observed subsidence at the Pixley core hole, 1902–64. About 25 percent of subsidence is due to compaction below 760 feet. About 25 percent of computed ultimate compaction represents residual lag.

COMPACTION IN THE VICINITY OF RICHGROVE

Prior to 1945 most of the irrigation wells in the vicinity of Richgrove were less than 1,000 feet deep. Pumping of these early wells had lowered water levels as much as 40 feet below the virgin condition by 1930 (fig. 65), and increased pumping during the 1930's steepened the downward trend of water levels. Following World War II, increased ground-water development, including the drilling of deeper wells, caused water levels in the Richgrove area to fall even more rapidly. This long-term decline of water levels, notably accelerated since about 1946, resulted in extensive land subsidence in the Richgrove area. Subsidence was most rapid between 1948 and 1954 (figs. 44, 65).

Beginning in 1952, imports of surface water from the Bureau of Reclamation's Friant-Kern Canal caused a marked reversal in water-level trend. By spring 1959, water levels in the deeper part of the semiconfined aquifer system had recovered as much as 100 feet from their 1951 low levels (fig. 65). During this recovery period, many of the larger irrigation wells were idle, and seasonal water-level fluctuations were less than half as large as during the late forties.

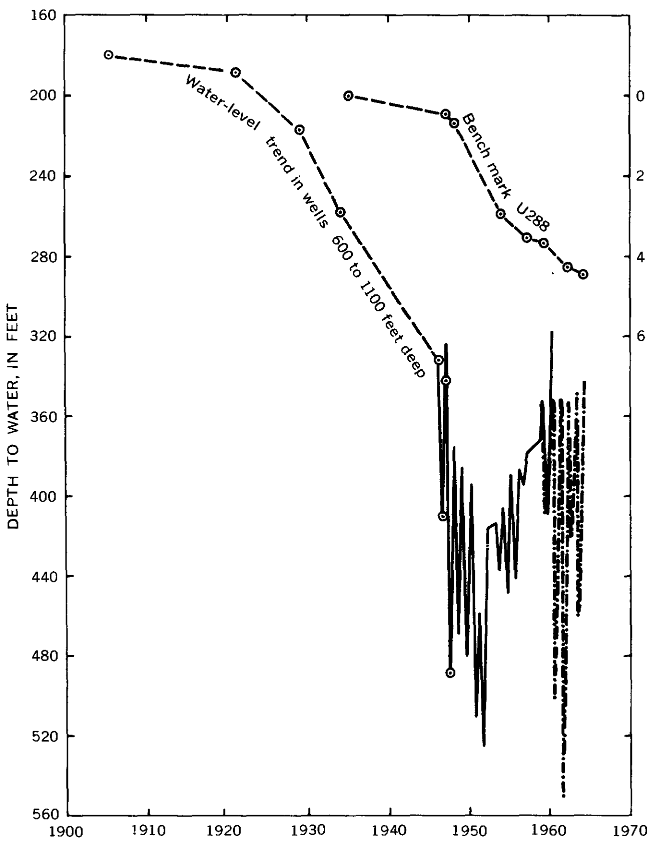


FIGURE 65.—Relation of subsidence to water-level decline at Richgrove, 1905–64. Source of water-level data: 1905, water-level map of Mendenhall (1916, pl. 1); 1920, water-level map of California Division of Engineering and Irrigation (California Department of Public Works, 1922); 1929, water-level map of California Division of Water Resources (Department of Public Works, 1934); 1934, measurement, well 25/26–1J3; 1946–60, hydrograph, well 25/26–1J3; 1959–64, hydrograph, well 25/26–1A2.

Surface-water supply was deficient in 1959–61 (fig. 21), and most of the idle pumps were again turned on to supply irrigation needs. Although water levels rose to about the same level during the early spring of each year, the amplitude of the seasonal fluctuation (fig. 65) increased. These 3 years of deficient runoff were followed by 2 years of above normal surface-water supply (fig. 14), resulting in a marked recovery of the seasonal low.

The upper right plot of figure 65 shows the subsidence at bench mark U288 (for location, see figure 66) in response to the long-term water-level decline in the Richgrove area. Little subsidence apparently occurred prior to 1940 (fig. 42), by which time water levels in wells 600–1,100 feet deep had fallen more than 100 feet. The rate of water-level decline had greatly increased by 1946, when the earliest continuing records were available. Leveling control was not available in 1951 when the water level was lowest; however, the water-level trend suggests that the subsidence rate was probably even higher than the dashed line indicates for the period 1947–51 and lower than the dashed line indicates for the succeeding 3 years. From 1954 to 1959, the subsidence rate decreased markedly in response to the rising water level. The effect of the intensified pumping of 1959–61 followed by reduced pumping in 1962 and 1963 is clearly reflected in the subsidence trend of bench mark U288. (See also, lower graph, fig. 68.)

The hydrograph in figure 66 shows in detail the water-level fluctuations in observation well 25/26–1A2, 892 feet deep and perforated below 200 feet. During the spring of each year from 1959 through 1963, the water level returned to about the same high level, even though yearly pumpage varied greatly. The amplitude of the seasonal fluctuations, however, increased from 96 feet in 1959 to 148 feet in 1960 and to 198 feet in 1961. During this 3-year span, bench marks U822, U288, V822, and V288 subsided 0.72, 0.62, 0.59, and 0.44 foot, respectively. During the succeeding 2 years of reduced pumping and relatively high water levels, 1962 and 1963, summer drawdown was more irregular and varied from 75 feet in 1962 to about 115 feet for a month in the spring of 1963. Subsidence of bench marks U822, U288, V822, and V288 for the 2 years was 0.15, 0.13, 0.10, and 0.15 foot, respectively.

Heavy pumping during the summer of 1964 caused a water-level drawdown of about 200 feet. Bench-mark control during this last year, however, was not available to determine the rate of subsidence that accompanied this renewed seasonal water-level decline.

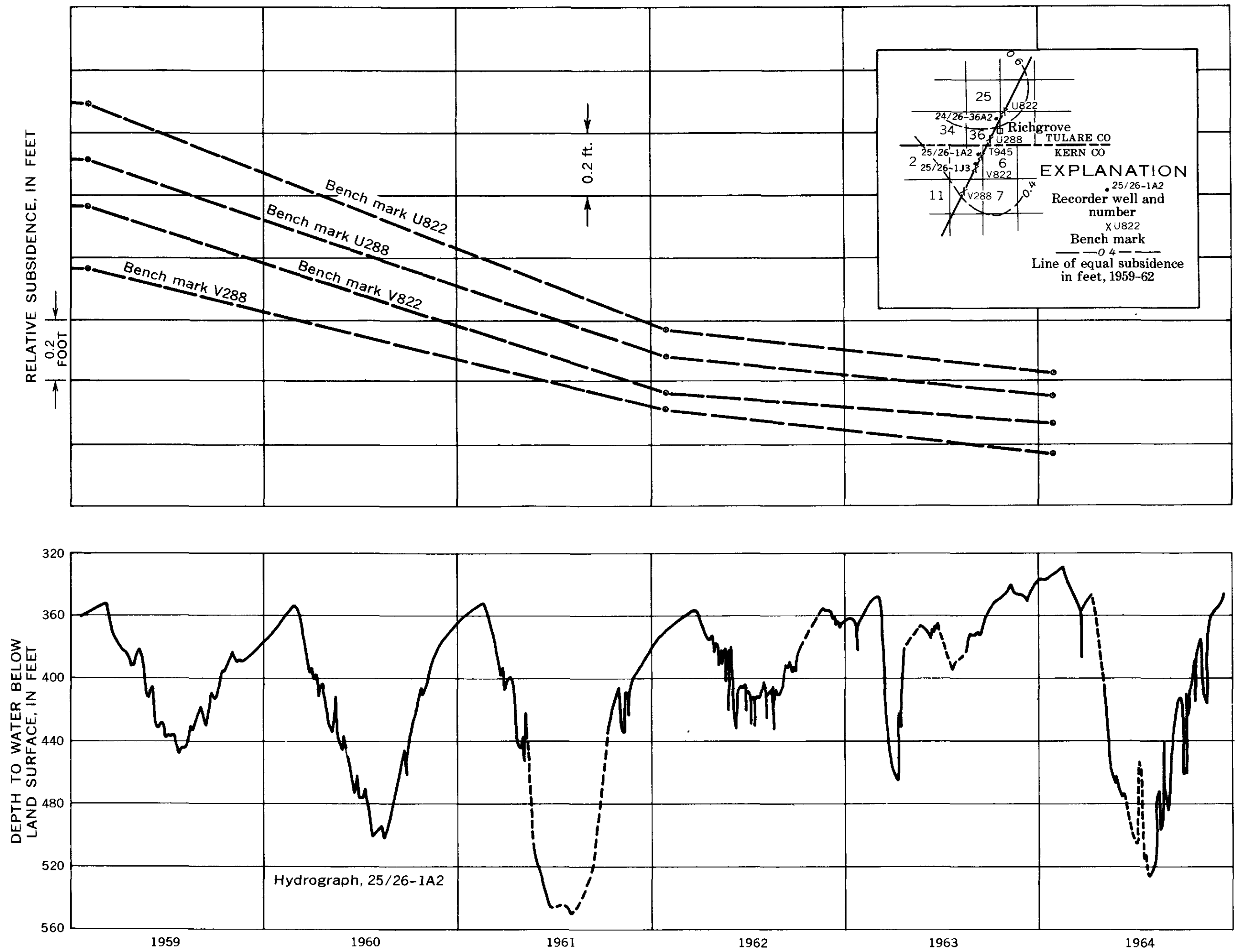


FIGURE 66.—Correlation of water-level fluctuations in an 892-foot well with subsidence of four bench marks near Richgrove, 1959–64.

Three compaction recorders were maintained in the Richgrove area from 1959 through 1964 (table 8)—two in unused irrigation wells about 900 feet deep and the third in the 2,200-foot Richgrove core hole—in an area that had been actively subsiding (fig. 44). The recorders were similar to those operating near Pixley (fig. 53) and were installed to measure the magnitude and rate of compaction within two depth zones. The two 900-foot wells (25/26–1A2 and 1J3) span the continental deposits from the Sierra Nevada and about 150 feet of the underlying marine siltstone. The deep recorder (24/26-36A2) spans the continental deposits, the entire marine siltstone sequence (744–1,900 feet below the land surface), and the underlying sand aquifer of the Santa Margarita Formation as used by Diepenbrock (1933). Thus, it spans all the deposits tapped by water wells in the Richgrove area. Because of mechanical complications, the record obtained from each of the three installations is only an approximation of the actual compaction at the site and thus cannot be analyzed in detail. For this reason, the compaction graphs have not been included in this report.

MEASURED COMPACTION AT 24/26–36A2

Compaction recorder 24/26–36A2 (for location, see fig. 66, insert) was installed in the Richgrove core hole in May 1959 (table 8), with the bottom-hole anchor set at a depth of 2,200 feet. Because of excessive friction between the compaction cable and the 4-inch casing, however, the recorder registered compaction only when the cable was oscillated manually, and therefore the record is not amenable to detailed quantitative analysis.

The following qualitative conclusions, however, were obtained from the continuous record of compaction at 36 A2 and water-level change in well 25/26–1A2:

1. After adjustment for mechanical problems, the compaction measured by recorder 24/26–36A2, spanning 2,200 feet of unconsolidated and semiconsolidated deposits, roughly equaled the total subsidence of 0.87 foot (bench mark U822) during the period of leveling control, February 1959–February 1964. This agreement indicates that compaction due to change in effective stress in the deposits tapped by water wells has been the principal and probably the sole cause of subsidence near Richgrove since February 1959.
2. A definite correlation exists between the measured compaction in well 24/26–36A2 and the water-level trend in observation well 25/26–1A2 (fig. 66). The rate of compaction was greatest during March through June each year when the water level in well 1A2 was falling most rapidly. The compaction curve flattened abruptly during periods of water-level rise. Little or no compaction occurred during 5 to 7 months each year when the water-level was relatively high.
3. Water-level fluctuations in well 25/26–1A2 are not representative of the entire thickness of compacting deposits at the Richgrove core hole. Not only is the observation well more than a mile from the core hole where subsidence rates are much less (fig. 66, inset), but also it penetrates only the upper 892 feet of the 2,200-foot sequence of deposits spanned by recorder 24/26–36A2. Furthermore, the marine siltstone unit that extends from a depth of 744–1,900 feet at the Richgrove core hole has permeability and compressibility characteristics that are markedly different from the deposits above 744 feet. When tested in the consolidometer, samples of this marine siltstone were consistently highly compressible. No well casings are perforated solely in the siltstone, and thus little information is available regarding changes in effective stress that have occurred in the siltstone beds.

MEASURED COMPACTION AT 25/26–1A2 AND 1J3

In September 1957, compaction recorders were installed in two unused irrigation wells, 25/26–1A2 and 1J3, 892 and 897 feet deep, respectively. These wells are 0.3 mile apart and about 1.5 miles southwest of the Richgrove core hole (fig. 66, inset). A water-level recorder also was placed on well 1A2, which is perforated from 200 feet to bottom. Because of installation complications, the recorders were placed on wooden platforms, which swelled in the wet winter months causing an inaccuracy of as much as 0.05 foot in the record. This seasonal deflection due to wetting and drying has somewhat masked the true compaction record at both sites, especially during years of little subsidence.

Measured compaction at these sites from 1959 to 1964 (February) was equal to about half the total subsidence of 0.69 foot (bench mark V822, fig. 66) as determined by leveling. Inasmuch as compaction occurred only in the deposits below the water table (depth about 250 ft), the compacting interval measured in these wells included about 500 feet of continental deposits and 150 feet of the underlying marine siltstone. It is concluded that compaction occurred also in the thick and highly compressible marine siltstone deposits below 900 feet (tapped by a few deeper wells), where it is thought about half the subsidence occurred from 1959 to 1964.

The magnitude and rate of measured compaction at both sites correlate with water-level fluctuations in well 25/26–1A2 (fig. 66), which is perforated through the same depth interval as the compacting deposits spanned by these two recorders. Compaction occurred in the 5 months from March through July when the water level in well 1A2 was declining rapidly, but was negligible the rest of the year. There was little time delay in the compaction response to water-level decline or for a water-level rise to stop compaction.

LABORATORY CONSOLIDATION TESTS

The composite logs for the Richgrove core hole are shown in figure 8, and the depths from which selected samples were tested in the laboratory for consolidation characteristics are given in table 14. The subsidence at the Richgrove site was due to compaction of the water-bearing deposits as the pore pressures were reduced by pumping. No compaction was expected within the upper 200 feet of deposits, which has been above the water table in recent years. Also, little compaction was expected within the Santa Margarita below 1,900 feet, because pumping from these sands did not commence until 1954; furthermore, clean sands generally do not compact appreciably under increased effective stress. Most of the subsidence at Richgrove, therefore, has resulted from the compaction of the deposits between depths of 200 and 1,900 feet, which include the interbedded sand, silt, and clay of the continental deposits above 744 feet and the underlying marine siltstone with thin interbedded sands (fig. 8). Table 14 gives a brief description of the consolidation test data for samples from the Richgrove core hole.

The compression index, C_c, is the numerical value of the slope of the straight-line segment of the void ratio-logarithm of load curve obtained from a consolidation test (fig. 62). Because a straight-line segment of the curve was not attained in eight of the 15 samples tested (table 14) values of C_c are available for only seven samples between depths of 840 and 1,450 feet, in the marine siltstone. Within this depth range, however, the average value of C_c for plastic clay samples (claystone in the lithologic description of fig. 8) is about 2½ times higher than for samples from the Pixley core hole (table 11). The C_c values in the sandy deposits above 744 feet would be considerably less than those for the plastic clays. Without more detailed laboratory consolidation data, however, and specific information on the head decline that has occurred in the marine siltstone sequence, the amount of compaction in each depth zone during the successive periods of subsidence cannot be calculated.

TABLE 14.—*Description of consolidation test data for samples from the Richgrove core hole*

[Data from Earth Laboratory, U.S. Bur. Reclamation, Denver, Colo.]

Sample	Description	Depth (ft)	Compression index, C_c	Consolidation coefficient, c_v (ft² per yr)
23L-237	Sand	157.1	(1)	55.9
239	Sand	443.0	(1)	120.7
240	Silty clay	516.0	(1)	24.5
241	Silt	607.2	(1)	120.7
242	Silty clay	725.6	(1)	71.2
243	Clay, plastic	843.0	0.76	6.6
244	Clay, plastic	916.1	.63	4.8
246	Clay, plastic	1,115.7	1.18	6.4
247	Clay, plastic	1,155.1	.86	12.5
248	Clay, plastic	1,241.0	1.53	7.2
249	Clay, plastic	1,362.7	.97	5.6
250	Clay, plastic	1,447.4	1.24	4.5
251	Clay, plastic	1,526.2	(1)	1.5
252	Clay, plastic	1,687.0	(1)	18.1
253	Clay, plastic	1,826.2	(1)	2.5

[1] Not calculated because of pronounced curvature and insufficient straight-line segment of void ratio-logarithm of load curve from consolidation test.

MEASURED COMPACTION AT 24/26-34F1

Compaction and water-level recorders were installed in 1957 in reconditioned unused irrigation well 24/26-34F1, located 2½ miles west of Richgrove (fig. 44). The anchor weight (fig. 53) was set at a depth of 1,510 feet, about 550 feet below the top of the upper Pliocene marine siltstone (fig. 5). About half the active irrigation wells in sections 25-27 and 34-36 of T. 24 S., R. 26 E., have been drilled to the depth range of 1,300-1,600 feet and thus tap the deposits spanned by this compaction recorder. Nearly all the other active wells in these sections are less than 1,000 feet deep.

The hydrograph and compaction record of well 24/26-34F1 and the subsidence trend of two nearby bench marks (for location, see figure 32) are shown in figure 67 for the 8-year period 1957-64. The compaction record was interrupted twice due to equipment failure in December 1958 and again in July 1964.

During the 3 years 1959-61, for which comparable records are available, a correlation existed between compaction, subsidence, and the downward trend of water levels in the heavily pumped aquifer system. During this period of deficient surface-water supply, the summer low level in well 34F1 fell about 18 feet per year. The decline caused subsidence of 0.33 foot from March 1959 to February 1962 at bench mark G758, about half a mile northwest of the recorder well, as determined by leveling. The measured compaction in well 34F1 (1,510 ft. deep) in this same period was approximately equal to the measured subsidence at bench mark G758. The subsidence rate at bench mark U822, about 2½ miles to the east of recorder

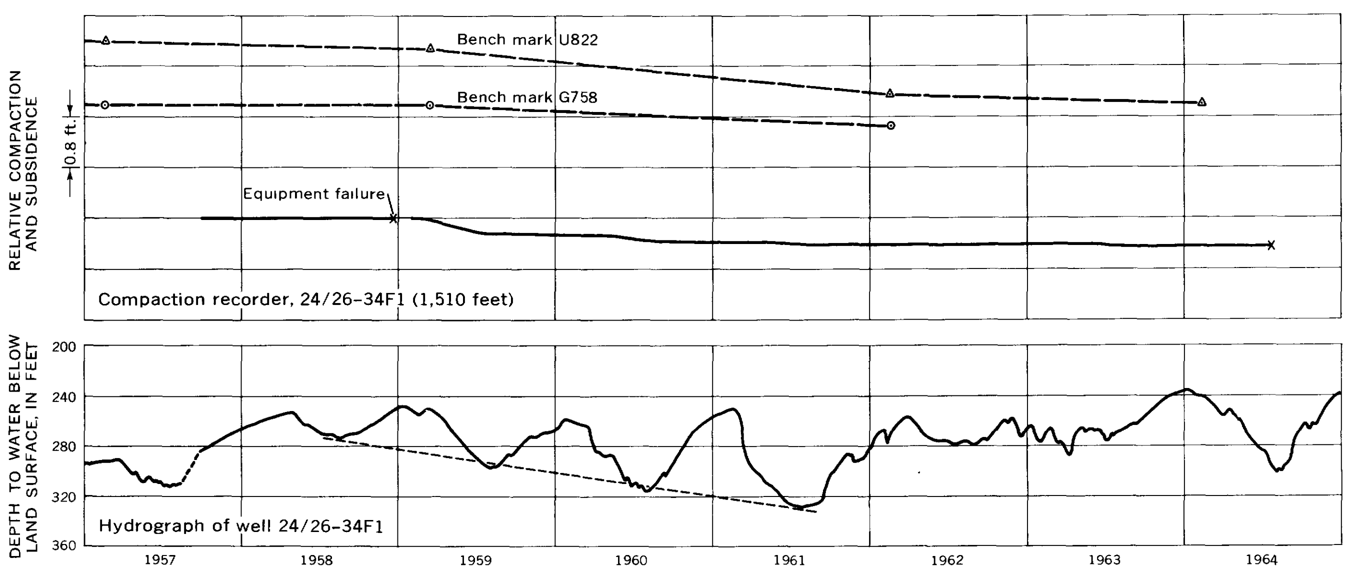


FIGURE 67.—Correlation of subsidence and compaction with water-level fluctuations, 2½ miles west of Richgrove, 1957-64.

24/26-34F1, was about twice the rate at bench mark G758 from March 1959 to February 1962.

From 1962 through 1964, water levels remained relatively high in well 24/26-34F1, and little compaction was recorded. No leveling was done in this vicinity during the 1964 resurvey of a few level lines in the Tulare-Wasco area (table 7, line 108), but the compaction record indicates that subsidence was very small.

The long-term trend of water levels in the vicinity of well 24/26-34F1 is shown in the upper graph of figure 68. Here, the hydrographs of wells 24/26-33H1 (1930-54) and 24/26-28Q1 (1952-57) extend the water-level record back to 1930 and show the marked effect that imports of surface water from the Friant-Kern Canal during the fifties had on ground-water levels in the area. This same general pattern of long-term water-

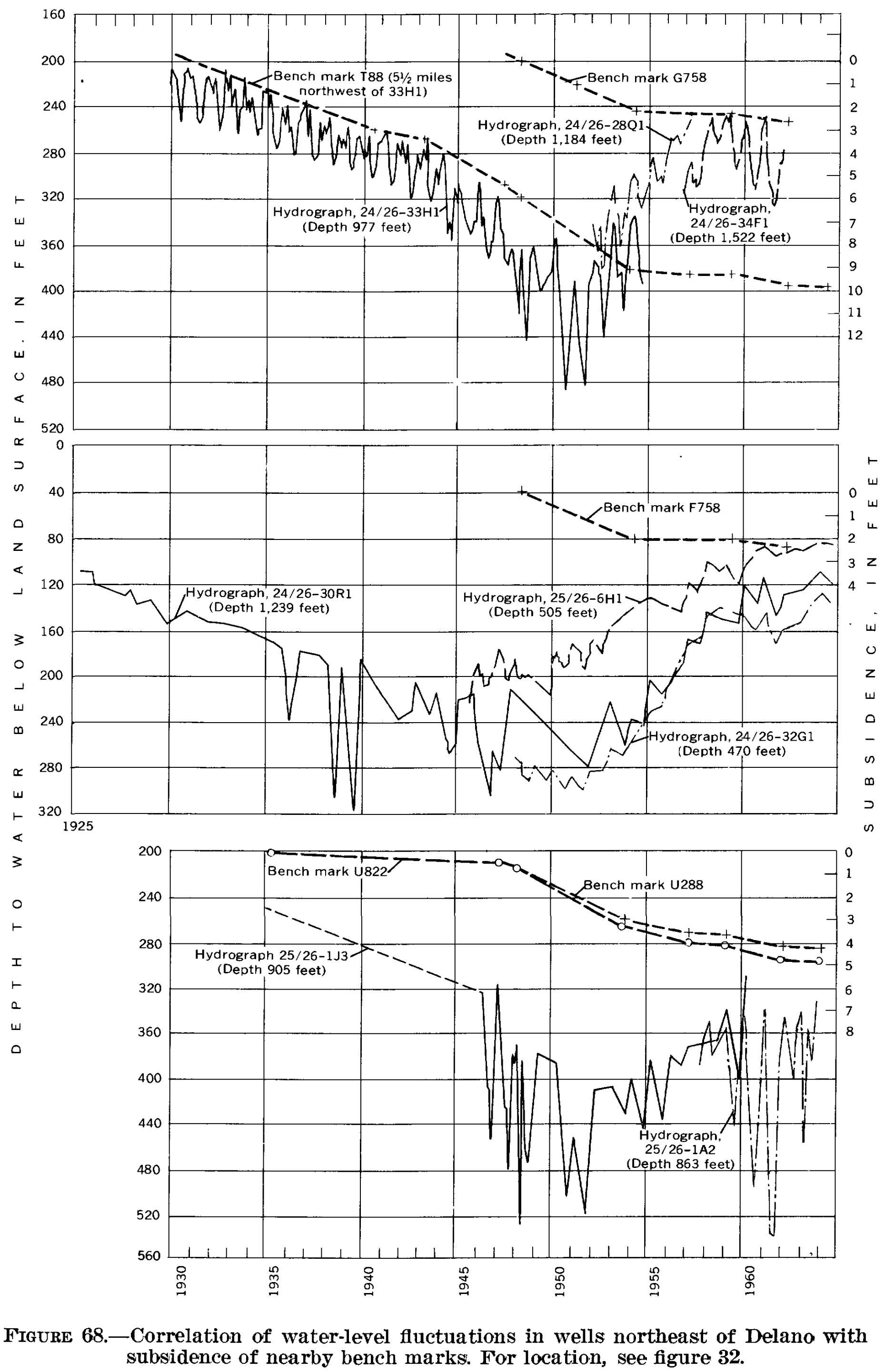


FIGURE 68.—Correlation of water-level fluctuations in wells northeast of Delano with subsidence of nearby bench marks. For location, see figure 32.

level decline to about 1950, followed by a recovery to about their earlier levels during the fifties, is indicated by the hydrographs of three observation wells about 3 miles west of 24/26–34F1 (center graphs, fig. 68).

RELATION OF SUBSIDENCE TO WATER-LEVEL CHANGE

Subsidence in the study area is due to compaction of the desposits that is caused by changes in effective stress resulting from water-level changes. For a given water-level change in the coarse-grained beds of a complex aquifer system, some beds may compact, other beds may expand, and still other beds may remain virtually unchanged in thickness. Compaction of an individual bed occurs only as rapidly as pore water can escape from the deposits. Coarse-grained beds yield water rapidly and may adjust to an increased effective stress within minutes, whereas a thick fine-grained slow-draining bed might take tens of years or centuries to reach hydraulic adjustment, that is, for all excess pore pressures to dissipate. Subsidence of the land surface, therefore, is the net change in thickness of all the individual beds.

According to the estimate represented by figure 63, about 60 percent of the ultimate compaction at the Pixley recorder site that would result from the change in water levels from 1959 to 1964 occurred in the same months as the responsible water-level decline. About 25 percent of the computed ultimate compaction would occur more than 10 years after the water-level change. Time delay occurs to some degree in all compacting aquifer systems and seriously complicates the direct relationship between subsidence and water-level change.

During periods when water-level declines produce new maximum effective stresses in the aquifer system, all beds tend to compact. Each bed responds to the increased stress at a rate determined by its permeability, compressibility, and thickness, but probably no two beds respond in exactly the same manner. Some beds reach adjustment quickly; others drain slowly and will have compacted only slightly when the next seasonal water-level recovery occurs. As water levels rise from the seasonal lows and the effective stress in the individual beds is reduced, again each bed responds independently. Some beds may have attained ultimate compaction under the maximum stress and may tend to expand elastically under the reduced stress. Other slow-draining beds may have compacted only slightly and might continue to compact through much of the recovery period. The change at the land surface is the composite change of all the individual beds. The response of the overall aquifer system can be estimated either by assuming an average response for all the beds combined or by considering each bed separately under the change in effective stress.

The actual change in head in each of the beds of the semiconfined and confined aquifer systems since groundwater development began in the Tulare-Wasco area is not clearly defined. Water levels in both the semiconfined and confined aquifer systems generally declined throughout the area from 1905 to about 1950. Since 1950, however, water levels in the eastern part of the area served by the Friant-Kern Canal have generally risen, whereas water levels in the western part have continued their downward trend. For the western part of the area, water-level data are restricted to the hydrographs of a few wells which indicate the change in head in the principal aquifer system during only a few years of record. For most of the area, the change in water level, shown by the hydrographs, depends on the well depth.

Because of inadequate water-level control, computation of long-term changes in effective stress was possible at only a few localities. For most of the area, only gross changes in water levels for the principal water-producing zone are available, and little information is available to indicate long-term changes in the water table or in the piezometric head in the less productive zones. Inasmuch as the changes in head in the principal aquifers are the best data available and as they are related to changes in effective stress at a given location, they have been used to derive ratios between subsidence and head decline at nine locations. These ratios are a rough approximation of the response of the aquifer system under a given change in stress.

Table 15 gives the rate of subsidence, the rate of head decline, and the corresponding subsidence to head-decline ratio for eight wells of figures 33, 34, and 35, and also for one nearby well of figure 68. The locations of the nine sites involved and the respective subsidence to head-decline ratios are shown in figure 50.

In computing the subsidence to head-decline ratios of table 15, only the long-term trend of declining water levels in deep wells tapping the principal aquifer system was considered. The ratios at the nine locations ranged from 0.5×10^{-2} to 5.0×10^{-2}. As shown in figure 50, the subsidence to head-decline ratio is smallest in areas of least subsidence and is greatest where subsidence has continued for many years and where the amount of subsidence is the greatest. In general, this ratio is a rough measure of the response of the aquifer system to changes in stress, but it may also be used to approximate future subsidence, provided the ratio is applied only to water-level declines in excess of prior historic low levels.

TABLE 15.—*Relationship between subsidence and head decline at nine locations*

Well (for location see fig. 32)	Reference figure	Period	Nearby bench mark	Average rate of head decline (ft per yr)	Average rate of subsidence (ft per yr)	Subsidence to head-decline ratio ($\times 10^{-2}$)
23/23-33A1 (No. 3)	34	1952–59	2PT27S	5.9	0.17	2.9
23/27-28J1	33	1926–62	PT4S	(1)	(1)	.5
24/24-9Q1	35	1950–59	PT44S	3.1	.13	4.2
	35	1959–62	PT44S	5.3	.25	4.7
24/26-30R1	33	1930–46	302.847	(1)	(1)	5.0
24/26-33H1	68	1943–51	G758	16.0	.38	2.4
24/27-17L1	33	1935–57	S288	(1)	(1)	2.5
25/23-29A1	34	1952–59	A755	8.0	.10	1.2
	34	1959–62	A755	12.0	.21	1.8
26/24-3H1	35	1948–62	Q754	5.7	.25	4.4
26/25-19P1	33	1948–59	W754	4.4	.08	1.8

[1] Changing rate; parallelism of graphs indicates constant ratio.

In an attempt to relate subsidence to water-level decline on an areal basis, a rough approximation of long-term water-level change and subsidence was made for that part of the Tulare-Wasco area where these data were available. From these rough data, the lines of equal subsidence to head-decline ratio of figure 69 were obtained. For the part of the area east of the boundary of the confining Corcoran Clay Member, the head decline in deep wells from 1928 to 1948 (fig. 25) and the subsidence as of 1954 (fig. 43) were used to compute the long-term subsidence to head-decline ratio. For the area west of the Corcoran Clay Member boundary, the change in head in the confined aquifer system from about 1905 to 1959 was related to the subsidence that had occurred to 1962 (fig. 50). Little information is available as to water-level conditions in the western part of the area in 1905 other than that artesian wells flowed throughout much of the area (fig. 22). For this computation, the 1905 piezometric head was assumed to be at land surface; thus the 1905–59 change in head was computed as the difference between the topographic map contours and the 1959 piezometric contours of figure 30. The water-level changes used in the computations are, of course, only a rough approximation of the actual head changes in the aquifer system; also, these computations do not take into account the changes in effective stress that resulted from fluctuations in the water table. The gross effect of these discrepancies, however, is probably within 30 percent of the actual, but indeterminate, values, and the subsidence to head-decline ratios thus obtained are as good a measure of the response of the aquifer system to changes in stress as is available.

Figure 69 shows on an areal basis the subsidence to head-decline ratios for that part of the area where long-term water-level change and subsidence could be approximated. Also shown are the point values of subsidence to head-decline ratio of table 15 (see also fig. 50). It is significant that five of the point values are in reasonable agreement with the areal lines of equal subsidence to head-decline ratio, even though two of the point values are considerably high and two are considerably low. These subsidence to head-decline ratios, rough as they are, are probably the best parameter available for estimating future subsidence for water-level declines below historic low levels.

PARAMETERS FOR ESTIMATING SUBSIDENCE UNDER ASSUMED HYDROLOGIC CHANGE

Three parameters are of prime significance in estimating the amount of subsidence that will occur under assumed hydrologic change: (1) the change in effective stress, (2) the compressibility of the deposits, and (3) the thickness of the compacting beds. The time rate of compaction, or coefficient of compaction (c_v, fig. 60), of the slow-draining beds must also be known if the rate of subsidence is of concern. If these parameters are known, estimates of future subsidence can be made.

The following general criteria can be applied in relating subsidence to head decline:

1. Where little or no increase in effective stress has occurred, no compaction is expected.
2. Where increased effective stress has caused measurable subsidence, further increases in effective stress will cause continued subsidence.
3. Delayed, or "lag," compaction of slow-draining beds may represent a major part of the ultimate subsidence at a location. Such compaction, and related subsidence, may continue for many months or years after water levels become stabilized at a lower level.
4. In areas where both subsidence and water-level decline have been observed for a sufficiently long period to establish a long-term relationship, the ratio between these two parameters can be pro-

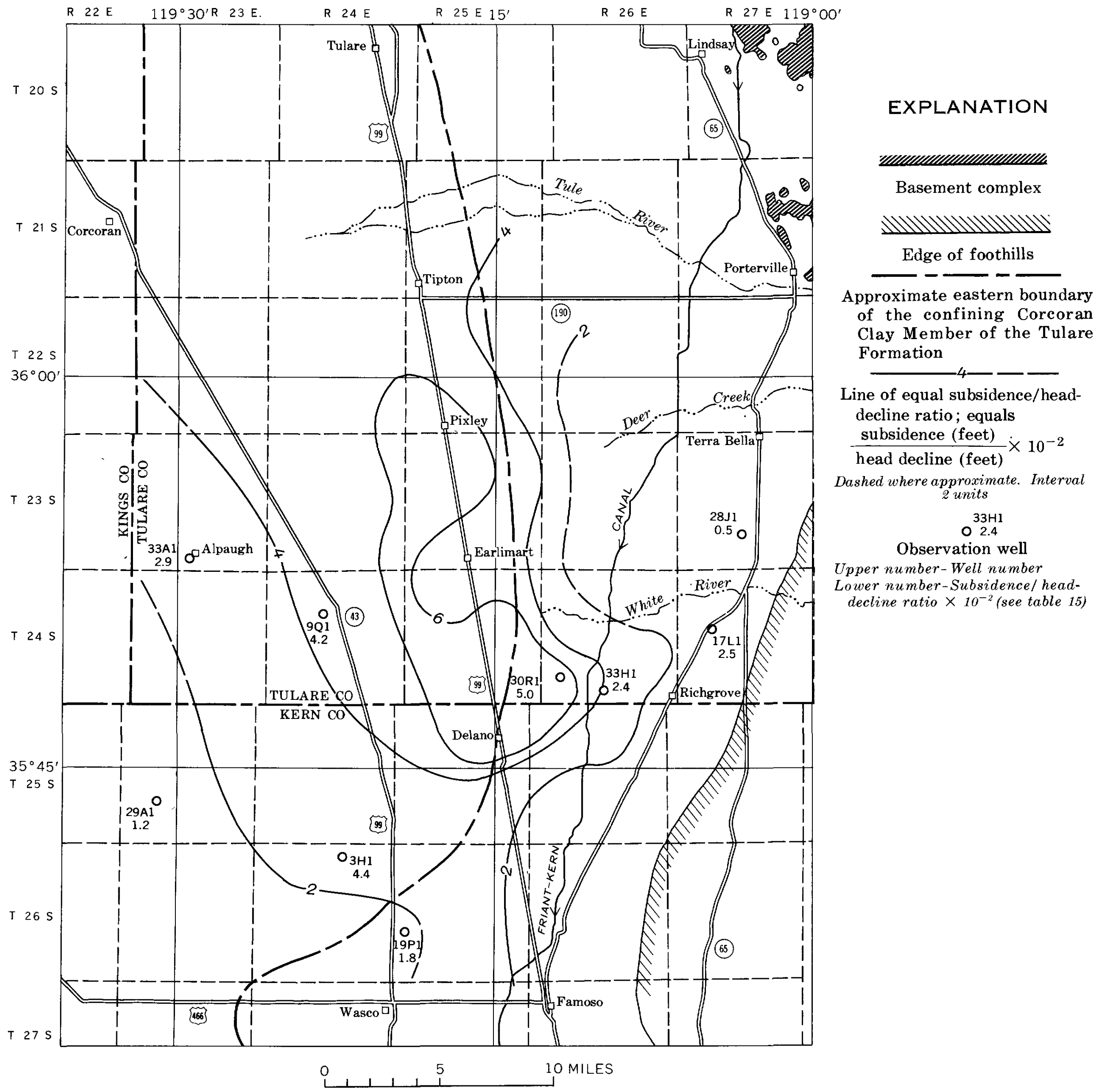


FIGURE 69.—Subsidence to head-decline ratios for that part of the Tulare-Wasco area where data on long-term water-level change and subsidence were available. For area west of Corcoran Clay Member boundary, based on head change in confined aquifer system, 1905–59, and subsidence in 1962. For area east of Corcoran Clay Member boundary, based on head change in deeper wells tapping the semiconfined aquifer system, 1928–48, and subsidence to 1954.

jected into the future as far as the projected water-level trend justifies. This relationship does not take into account residual "lag" effects; thus minimum values of subsidence are determined by this means. Where water levels have declined and then partially recovered, the subsidence to head-decline ratio has little significance until water levels return to their former low levels.

As in most ground-water reservoirs, neither the semiconfined nor the confined aquifer systems of the Tulare-Wasco area are simple hydrologic units. Intercalated silt and clay lenses within these aquifer systems create a diverse range of pore pressures in the various beds. An analysis of effective stresses and compaction rates at any location, therefore, is not a simple relationship. Effective-stress computations generally must be made for each of the subunits of the aquifer system, using either known or assumed hydrologic data. Also, the only places in the Tulare-Wasco area where the compressibility of some of the compacting beds has been measured directly are at Pixley and at Richgrove where cored samples have been tested in the laboratory. Because of the rapid areal change in lithology, it is impractical to consider obtaining the hydrologic and compressibility field data on a regional basis that would be necessary to compute subsidence using the conventional soil-mechanics approach.

The practical method of estimating future subsidence areally is to utilize an approximate parameter based on the historic response of the sediments to increase in stress (water-level change). The approximate parameter most effective in this study is the ratio of subsidence to head decline that can be derived from subsidence and water-level change maps, together with graphs showing subsidence and water-level change at specific locations (fig. 69). To derive meaningful ratios of subsidence to head decline, great care is needed in selecting water-level declines representative of the stress change in the principal compacting zone. This ratio is most meaningful for long periods of continuous water-level decline and has little significance unless water levels at the end of the period are at their lowest level.

EXAMPLES OF APPLICATION OF PARAMETERS AT FOUR SITES

The following four examples of the application of available parameters, rough as they are, to estimate future subsidence under assumed water-level decline not only give projected values at these sites, but outline the method of predicting subsidence for other parts of the area. Since no attempt has been made to forecast future water-level trends, subsidence is herein estimated in terms of head decline in the principal aquifer system, as measured by water levels in selected observation wells.

At Pixley, a compressibility parameter for the confined aquifer system, derived from laboratory consolidation tests and computations made earlier in this report (p. B83), is applied directly to obtain an estimate of ultimate subsidence. At the other three sites, subsidence to head-decline ratios are applied to derive rough estimates of subsidence that would be expected from additional long-term head decline below historic low levels at these sites. For other parts of the area, the best available data for deriving crude estimates of the subsidence that would occur if water levels in the principal aquifer system were lowered below historic minimum levels are values of subsidence to head-decline ratios from figure 69, applied as for the three sites.

AT THE PIXLEY CORE HOLE, 23/25-16N1

From the data of table 13, a rough measure of the compressibility of the confined aquifer system was obtained which is here used to estimate future subsidence at the Pixley core hole for assumed head decline. Thus, as tabulated on page B83, the ultimate specific unit compaction (compressibility) for the 60 years from 1905 to 1964 was 1.1×10^{-4} foot of compaction per foot of aquifer-system thickness for each foot of increase in effective stress. If the water level in the semiconfined aquifer system is assumed to remain nearly constant in the future, as it has since 1962, then the water-level trend of wells tapping the confined system will approximate the effective-stress trend for the compacting system.

By using 1.1×10^{-4} foot per foot^2 as the measure of compressibility and an estimated compacting thickness of 600 feet, the following amounts of ultimate subsidence (compaction) are estimated for various assumed head declines in the confined aquifer system at Pixley:

Piezometric head decline below 1964 levels (ft)	*Estimated ultimate subsidence* [1] *(ft)*	*Estimated short-term subsidence* [1] *(ft)*
10	0. 7	0. 5
50	3. 3	2. 5
100	6. 6	5. 0
200	13. 2	9. 9

[1] Assuming a constant water table at 100 feet below the land surface.

Inasmuch as short-term subsidence (less than 10 years) represents about three-quarters of the ultimate subsidence, these estimates are also tabulated. It is significant that if the piezometric level at Pixley is drawn down 100 feet below the 1964 level, it will be below the base of the confining layer for a short period each year, and if it is drawn down 200 feet below the 1964 level, it will be below the confining layer continuously. Under the unconfined condition thus developed in the compacting aquifer system, the amount of subsidence per foot of water-level decline would be only about two-thirds as great as under confined conditions.

These values apply specifically to the Pixley site and to the conditions of 1964 as a reference base. If deeper wells are drilled in the area and thereby compaction occurs at greater depths, or if the shallow water level changes appreciably from the 1964 level, the estimated amounts of subsidence would be changed accordingly. No attempt is made to anticipate the rate at which water levels may decline in the future. If confined water levels should decline significantly below the 1964 level, however, the amount of subsidence would probably be approximately that which is indicated in the table. It is noteworthy that when similar computations are applied to the stress changes that occurred from 1948 to 1964, confirmatory results of subsidence are obtained. For example, a 1948–64 piezometric lowering of about 130 feet resulted in 9.5 feet of subsidence (bench mark N88 reset), as compared to 8.6 feet computed from the value of 1.1×10^{-4} foot^{-1} for ultimate specific unit compaction. (See p. B94.)

Relating 9.5 feet of subsidence to 130 feet of head decline for the 1948–64 period gives a subsidence to head-decline ratio of 7.3×10^{-2}. This value is in close agreement with the value obtained from figure 69. This ratio, if multiplied by an assumed 100 feet of future head decline, would indicate about 7.3 feet of ultimate subsidence, which also is in reasonable agreement with the 6.6 feet of subsidence of the preceding tabulation.

AT ALPAUGH, 23/23–33A1

As shown in the upper graphs of figure 34, the water level in the semiconfined aquifer system (well 23/23–33A1, piezometer 1) at Alpaugh declined about 2 feet per year (average decline of seasonal low levels) from 1952 through 1964. Also, the piezometric head in both the upper and lower zones of the confined aquifer system (piezometers 2, 3, respectively), although much more irregular and unmeasured during the last part of the period, declined roughly 5 feet per year. This decline suggests an average increase in effective stress in the confined aquifer system (fig. 52) equivalent to about 4 feet of water per year. Subsidence for the period averaged about 0.18 foot per year. Assuming that all the subsidence at this location is due to compaction of the confined aquifer system, a reasonable approximation, considering the depth of the producing wells and the depth of the confining clay layer, the ratio of subsidence to effective-stress increase roughly equals 4.5×10^{-2}. This ratio suggests that as long as present trends continue, 1 foot of subsidence will occur for each 22 feet of increased effective stress.

For the following tabulation this ratio was used to estimate the subsidence that would occur at Alpaugh if the 1952–62 water-level trends continued:

Water-level decline		*Increase in effective stress (ft of water)*	*Estimated subsidence (feet)*
Confined system (ft)	*Semiconfined system (ft)*		
10	4	8	0.4
50	20	40	1.8
100	40	80	3.6
150	60	120	5.5
200	80	160	7.3
300	120	240	10.9

The estimates represent only a minimum value for ultimate subsidence resulting from the specified change in effective stress because the amount of time lag and residual compaction (subsidence) as of 1962 is unknown. On the basis of theoretical considerations of figure 52, if shallow water levels remained constant, while confined water levels continued downward, the subsidence would be about 25 percent greater than that shown in the preceding table.

AT WELL 25/23–29A1, 11 MILES SOUTHWEST OF ALPAUGH

As at Alpaugh, water levels in both the semiconfined and confined aquifer systems at well 25/23–29A1, 11 miles southwest of Alpaugh, maintained a downward trend during the 1952–64 period of record (fig. 34). The shallow, semiconfined water level declined an average of 1.5 feet per year (trend of summer low levels) during this period, the upper confined level declined about 2.5 feet per year, and the lower confined level declined roughly 9 feet per year. Nearby subsidence (bench mark A755) averaged about 0.13 foot per year from 1952 to 1962. If these generalized downward water-level trends were to continue at the same proportional rates, 0.1 foot of subsidence would occur for each 7 feet of head decline in the deep confined zone. The following tabulation indicates the estimated subsidence at this location if the 1952–64 water-level trends continue:

Water-level decline, confined system, deep zone (ft)	*Estimated subsidence (ft)*
7	0.1
50	.7
100	1.4
200	2.9
300	4.3

Because of the complexity of the hydraulic conditions in the compacting confined-aquifer system and the scant amount of water-level data (p. B48), the change in effective stress at the site can only be approximated. There is little basis for estimating subsidence during periods when water levels are significantly above the 1964 conditions.

FIVE MILES NORTHEAST OF DELANO

As shown by the upper and center graphs of figure 68, water levels in the semiconfined aquifer system 5 miles northeast of Delano generally declined until about 1951, and then recovered during the following 9 years. Water levels in deep wells (24/26–33H1, 28Q1, 34F1, and 30R1), intermediate wells, e.g. 24/26–32G1 (470 ft deep), and shallow wells, e.g. 25/26–6H1 (297 ft deep) followed the same general pattern, except that the shallow water level was 20–100 feet higher than the deeper water levels.

Subsidence in this area, as indicated by the graphs of bench marks G758 and F758 (for location, see fig. 32), continued at a rate of from 0.3 to 0.5 foot per year for 2–3 years after deep water levels began to recover and then abruptly abated. During the late fifties, when water levels were considerably above their earlier lows, and thereby effective stresses in the semiconfined aquifer system were less than their previous maxima, little or no subsidence occurred. During the dry years of 1959–61 (fig. 14), when water levels in deep wells again declined, subsidence recommenced (bench mark F758) or the rate increased (bench mark G758), even though effective stresses were much lower than 10 years earlier.

The progressive compaction of the various beds of the semiconfined aquifer system was interrupted by the water-level recovery of the fifties, but more subsidence will probably occur if water levels again fall through the range of previous decline. No method is known, however, for estimating the amount of subsidence that will occur at this location until effective stresses are again as great as they were in 1950. It is reasonable to conclude that during the second cycle of effective-stress increase the subsidence would be considerably less than during the first cycle, but how much less is not known. If effective stresses should exceed their 1950 maximum values, it is anticipated that subsidence would continue at about its pre-1950 rate, that is, about 1 foot of subsidence for each 30 feet of water-level decline.

As shown in figure 69, the subsidence to head-decline ratios at wells 24/26–30R1 and 33H1 are considerably lower when derived from the hydrographs of figure 68 than from the water-level change map (fig. 26). Apparently, water levels in these wells have been drawn down deeper than the regional water-level contours indicate. By using a subsidence to head-decline ratio of 3.8×10^{-2} (fig. 69), the following amounts of subsidence at well 24/26–33H1 were calculated for the listed drawdowns below historic low levels:

Water-level decline, principal aquifer system (ft)	*Estimated subsidence (ft)*
10	0. 4
50	1. 9
100	3. 8
200	7. 6

METHODS OF DECREASING OR STOPPING SUBSIDENCE

Theoretically, subsidence will continue at a given location as long as excess pore pressures exist within the underlying deposits, but will stop as soon as excess pore pressures are dissipated. Thus, as long as declining water levels continue to produce increasing effective stresses, subsidence will continue. When the rate of effective-stress increase is reduced, or the effective stresses in the system are significantly reduced by water-level recovery, subsidence will slow down or eventually stop. Inasmuch as a small part of the compaction in a subsiding area is elastic in nature and will be recovered when the applied stress is removed, slight rebound of the land surface should occur when water levels recover. Slight rebound has been measured at several locations in the Tulare-Wasco area during periods of water-level recovery.

SEASONAL CHANGES IN WATER LEVELS

As shown by the stepped record of compaction recorder 23/25–16N1 (fig. 54, upper), little or no compaction occurs at this location during about one-third of each year when water levels are high. In fact, slight rebound has been measured during periods of seasonal high water levels (fig. 59). This rebound indicates that the process of aquifer-system compaction is effectively stopped by raising the water levels in the confined aquifer system enough to bring effective stresses above the *C–C′* line.

The magnitude of the seepage stress in an aquifer system (difference in head between the confined and overlying semiconfined aquifer systems) plays a dominant role in producing subsidence (fig. 52). As shown in figure 54, the rate of subsidence at Pixley is greatly increased during periods of increased seasonal drawdown. Inasmuch as the seepage stress is the principal component of effective stress in much of the Tulare-Wasco area, the rate of subsidence can be reduced by decreasing the seasonal range of water-level fluctuations in the confined aquifer system. It is significant that changes in effective stress are only about half as great in the confined aquifer system when water levels in the confined and semiconfined aquifer systems are lowered together, as when the semiconfined water level is held constant and the confined water level is drawn down seasonally by pumping. Therefore, additional compaction of the confined aquifer system could be reduced by planned lowering of the water level in the overlying semiconfined system to conform with head decline in the confined system.

LONG-TERM WATER-LEVEL CHANGES

The long-term graphs of figures 33, 34, 35, and 68 show the correlation between water-level trend and subsidence in various parts of the area. Of particular interest is the marked change in the rate of subsidence north and east of Delano (fig. 68) during periods of water-level recovery. Thus, from 1954 to 1957 little subsidence occurred in the area of imported surface water (fig. 45) where water levels recovered as much as 150 feet. Also, in the Delano-Famoso-Wasco area, where 1948–54 subsidence rates were as much as 0.5 foot per year, no subsidence occurred from 1957 to 1959 (fig. 46) in response to continued water-level recovery.

As shown in figure 49, the subsidence rate in the Tulare-Wasco area decreased from about 150,000 acre-feet per year (1950) during a period of maximum water-level decline to about 40,000 acre-feet per year during maximum water-level recovery. This decrease is shown graphically in figure 48, where the slope of the curve denoting the volumetric rate of subsidence was about the same in the late fifties as it was in about 1946.

To sum up, any method that could be employed to reduce the ground-water pumpage of an area would tend to reduce the subsidence. Also, centers of intense subsidence could be eliminated by distributing the withdrawal wells more uniformly.

CONCLUSIONS AS TO METHODS OF DECREASING OR STOPPING SUBSIDENCE

1. Inasmuch as the thickness and compressibility of deposits in a subsiding area change only slightly as subsidence increases, the rate of subsidence at any location is directly related to the change in effective stress that results during ground-water development. Continued increase in effective stress will cause continued subsidence. Subsidence can be slowed, however, by reducing the rate of increase in effective stress or by permitting water levels to stabilize and thereby stopping further increase in effective stress. Subsidence can be stopped altogether by raising water levels sufficiently to eliminate all residual excess pore pressures in the aquitards.
2. In the western part of the Tulare-Wasco area, the subsidence rate under continued pumping can be reduced by increasing withdrawal from the semiconfined aquifer system, so that water levels in the confined and semiconfined systems are drawn down at about the same rate. This method would reduce the seepage stresses in the confined system and thereby reduce the rate of compaction of that system.
3. Also, throughout the study area the subsidence rate can be markedly decreased by reducing the seasonal head decline in the confined aquifer system. This method might be accomplished by wider spacing of pumping wells, by moving some of the large pumping wells outside of areas of maximum summer drawdown, or by holding canal deliveries during years of deficient surface supply until midseason.
4. The mining of ground water in subsiding (as well as nonsubsiding) areas is ultimately limited by economic considerations. When the practical range of water-level fluctuations in the ground-water basin is established for optimum cyclic storage, the basin can be precompacted by creating maximum effective stresses in the basin by pumping, and then permitting water levels to recover to their predetermined operating range.
5. Slight rebound of the land surface was observed in several areas of large water-level recovery. Measured rebound at Pixley during recovery represented 1 or 2 percent of the earlier compaction during a corresponding period of drawdown. Northeast of Delano, as much as 0.05 foot of rebound was observed at several bench marks from 1957 to 1959; the rebound resulted from widespread water-level recovery.

SUMMARY AND CONCLUSIONS

Intensive pumping of ground water in the Tulare-Wasco area since 1905 has resulted in extensive land subsidence. As of 1962, 800 square miles of irrigable land had undergone more than 1 foot of subsidence, and as much as 12 feet of subsidence had occurred locally. Although subsidence has continued for more than 40 years, it has occurred so gradually and over such a broad area that it has gone unnoticed to most local residents. Many well casings have been severely damaged by the subsidence, however, and its detrimental and costly effects have been of serious concern to surveyors, design and construction engineers, irrigation districts, and some landowners for more than 20 years.

The deposits penetrated by wells in the Tulare-Wasco area and the underlying sediments and bedrock, include the following, in descending order of occurrence: (1) A thick sequence of unconsolidated continental deposits of late Tertiary and Quaternary age derived from the Sierra Nevada, that constitute the principal ground-water reservoir, (2) semiconsolidated and consolidated upper Pliocene and Pliocene(?) marine strata, tapped by water wells in the eastern part of the area, (3) the Santa Margarita Formation as used by Diepenbrock (1933), a thin marine sand, tapped by water wells near Richgrove, (4) an undifferentiated sequence of lower Tertiary sand and siltstone, not tapped by water wells, and (5) the crystalline basement complex. A well-sorted diatomaceous lake clay—the Corcoran Clay Member of the Tulare Formation—within the continental deposits in the western half of the area forms an effective ground-water confining bed.

The unconsolidated continental deposits, derived almost wholly from the Sierra Nevada, dip gently westward, and the underlying marine deposits dip more steeply westward beneath the study area. Most of the ground water is pumped from the unconsolidated continental deposits, which for the most part are moderately permeable.

Usable ground water occurs in two principal aquifer systems: (1) a semiconfined system that underlies the entire area and that extends downward from the water table to the top of the Corcoran Clay Member in the western part of the area and to the top of the marine strata or to the base of the fresh-water body in the eastern part and (2) a confined aquifer system beneath the confining Corcoran Clay Member in the western part of the area that extends down to the base of the fresh-water body. In addition, a deep confined aquifer—the Santa Margarita Formation as used by Diepenbrock (1933)—is tapped only in the vicinity of Richgrove.

Four natural streams enter the Tulare-Wasco area from the Sierra Nevada on the east. Tule River has long been an important source of irrigation supply, whereas Deer Creek, Poso Creek, and White River flow only intermittently and in most years supply only small quantities of water to the area. Also, canal diversions from the Kern and Kaweah Rivers and, since 1950, from the Friant-Kern Canal have been an important source of irrigation supply. Imports from the Friant-Kern Canal since 1953 have far exceeded all other surface-water sources and have greatly reduced the ground-water pumpage in the canal service area. Recharge to the ground-water reservoir is principally from deep percolation from the Sierran streams and canal diversions, but also comes from underflow in the foothill recharge area.

Little ground water was used in the Tulare-Wasco area prior to the introduction of electrically powered pumping plants in about the year 1900. Since the early twenties, however, the use of ground water has accelerated and has resulted in severe water-level declines in much of the area. By 1940, water levels had declined 125 feet between Delano and Richgrove, and extensive subsidence was recognized. Water levels continued to decline throughout the area until the early 1950's, when surface-water imports via the Friant-Kern Canal reversed the downward trend of water levels in the canal service area. Since the early 1950's, therefore, two different trends have prevailed: (1) in the western half of the area, water levels both above and below the confining layer have continued to decline, the shallow levels trending downward at a slower rate than the deeper levels, and (2) in the eastern half of the area, shallow water levels have generally remained constant or risen slightly; while the levels in deeper wells rose during the fifties and leveled off or declined during the early sixties.

Estimated ground-water pumpage for agricultural use from 1950 through 1962 ranged from 0.7 million acre-feet in 1958 to 1.4 million acre-feet in 1961.

Subsidence was first recognized in the Tulare-Wasco area in 1935, when leveling showed definite changes in altitude of the land surface from 1926 topographic maps. In 1940, surveys indicated that an area of more than 200 square miles had experienced more than 1 foot of subsidence since 1902. Repeated leveling of a network of bench marks throughout the subsidence area in 1947–1948, 1953–54, 1957, 1959, 1962, and partial releveling in 1964, have provided the data for a series of subsidence maps and profiles that define the extent and magnitude of the subsidence. The annual volumetric rate of subsidence, which is directly related to seasonal pumping, varied from a 1948–54 average of about 136,000 acre-feet to 45,000 acre-feet in 1957–59 and a maximum of 173,000 acre-feet in 1959-62. As of 1962, at least 600.-000 acres had subsided more than 1 foot, and 10,000 acres had subsided more than 10 feet. The cumulative volume of subsidence from 1926 to winter 1962 was about 2.2 million acre-feet. Subsidence will continue as long as ground-water levels are drawn down below prior low levels.

During the 13 years from 1950 to 1962, 1.4 million acre-feet of subsidence occurred as a result of pumping 13.5 million acre-feet of ground water. The volume of subsidence, therefore, represented about 10 percent of the total ground-water pumpage.

Subsidence is due to the compaction of the water-yielding deposits as intergranular effective stresses are increased by lowered ground-water levels. The amount of compaction at a given locality depends on the thickness and compressibility of the deposits and the magnitude of the effective stress change.

Specially designed compaction recorders, measuring the vertical shortening of the stratigraphic section to depths as great as 2,200 feet, were operated in 11 wells during the investigation. Of these recorders, eight were still in operation as of December 31, 1964. Companion water-level recorders were operated in five of these wells and also in one other observation well. At Pixley, where the most detailed measurements of compaction are available, little or no compaction occurred in the 0–355-foot depth zone from January 1959 to February 1964, whereas 1.90 feet of compaction, or 75 percent of the total subsidence, occurred in the 355–760-foot zone; about 0.64 foot of vertical shortening, or 25 percent of the subsidence, occurred in the confined deposits below 760 feet. The rate of subsidence at this site varied from 0.69 foot per year (1959–62) to 0.23 foot per year (1962–64), in response to a marked, though temporary, change in the pumping pattern. The computed compaction at this site, based on laboratory consolidation tests of representative core samples and Terzaghi's theory of consolidation, agreed reasonably well with the measured compaction for the given change in effective stress.

It is concluded that water-level change is the cause of the subsidence in the Tulare-Wasco area and that neither tectonic movement nor hydrocompaction have been contributing factors to the land subsidence. Also, there is no evidence that either natural or artificial vibrations have caused a measurable increase in either the amount or the rate of subsidence.

The direct cause of the subsidence is the change in effective stress in the deposits due to a change in ground-water levels. Water-level changes in subsidence areas may change effective stresses in two different ways: (1) a change in the position of the water table changes the effective stress because of the change in buoyant support of grains in the zone of the change or (2) a change in position of the water table or the piezometric surface (artesian head) or both that induces hydraulic gradients across confining or semiconfining beds produces a seepage stress which is algebraically additive to gravitational stresses.

If the artesian head remains unchanged, a rise in the water table reduces effective stresses in the unconfined parts of the aquifer system but increases the effective stress in the confined parts, due to the increased downward seepage stress. A decline in the water table, on the other hand, increases the effective stresses in the saturated part of the unconfined aquifer system, but decreases the effective stress in the confined beds. A decline in piezometric head in a confined aquifer system, however, has no effect on stresses in an overlying unconfined system, but increases the stress in the confined beds. The magnitude of the change in effective stress is nearly twice as great for a given head change in a confined system as for the same head change in an unconfined system.

Based on the findings of this investigation, the following criteria may be applied to anticipate the amount of subsidence that will occur under assumed hydrologic change:

1. Inasmuch as changes in ground-water levels are responsible for subsidence, little subsidence would be expected if little change in ground-water level had occurred.
2. If subsidence is known to have occurred in response to a given increase in effective stress (water-level change), future increases in effective stress will cause roughly proportional subsidence provided the time intervals are comparable.
3. For this hydrologically complex area, the subsidence to head-decline ratios established during periods of continuing subsidence and water-level decline are the best means for deriving crude estimates of the subsidence that would occur if water levels in the principal aquifer system were lowered below historic minimum levels. Subsidence to head-decline ratios range from about 0.5×10^{-2} foot of subsidence per foot of head decline in areas where little subsidence has occurred to more than 6.0×10^{-2} feet of subsidence per foot of head decline where subsidence has been the greatest. Where the water-level trend has been reversed, however, and effective stresses have been decreased sufficiently to stop subsidence, little future subsidence would be anticipated unless prior maximum effective stresses were exceeded.
4. Because of the slow drainage from the thicker less permeable beds in an aquifer system, subsidence may continue long after maximum effective stresses have been imposed on the permeable beds (aquifers).

It has been clearly demonstrated in the service area of the Friant-Kern Canal that subsidence can be effectively stopped by raising ground-water levels sufficiently high to eliminate all excess pore pressures in the aquitards. Also, it is concluded that if water levels are held at a constant low level, subsidence will stop after all lag, or residual, compaction has been accomplished. As long as excess pore pressures exist in any of the compactible beds, drainage from these beds will occur and subsidence will continue.

No method is known for stopping subsidence other than that of raising the head in the aquifers sufficiently to eliminate the excess pore pressures in the aquitards. This method can be effected either by decreasing pumpage, increasing recharge, or both. If neither is practicable, however, under favorable circumstances subsidence rates may be substantially reduced by redistributing the total pumpage in time and in space so as to reduce local seasonal head declines and minimize the development of seepage stresses (hydraulic gradients) across confining beds within the ground-water reservoir.

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INDEX

[Italic page numbers indicate major references]

U. S. GOVERNMENT PRINTING OFFICE : 1969 O 332-133