Land Subsidence Due To Ground-Water Withdrawal in the Los Banos–Kettleman City Area, California, Part 3. Interrelations of Water-Level Change, Change in Aquifer-System Thickness, and Subsidence

GEOLOGICAL SURVEY PROFESSIONAL PAPER 437-G

Prepared in cooperation with the
California Department of Water Resources

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By WILLIAM B. BULL *and* JOSEPH F. POLAND

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data

Bull, William B. 1930–

Land subsidence due to ground-water withdrawal in the Los Banos–Kettleman City area, California.

(Studies of land subsidence) (Geological Survey Professional Paper 437–E–G)

Pt. 2 by W. B. Bull; pt. 3 by W. B. Bull and J. F. Poland.

Includes bibliographies and indexes.

CONTENTS: pt. 1. Changes in the hydrologic environment conducive to subsidence.—pt. 2. Subsidence and compaction of deposits. [etc.]

Supt. of Docs. No.: I 19.16:437–G

1. Subsidences (Earth movements)—California—San Joaquin Valley. 2. Aquifers—California—San Joaquin Valley. 3. Water, Underground—California—San Joaquin Valley. I. Miller, Raymond E. II. Poland, Joseph Fairfield, 1908– III. California. Dept. of Water Resources. IV. Title. V. Series. VI. Series: United States. Geological Survey. Professional Paper 437–E–G.

QE75.P9 No. 437–E–G [GB485.C2] 557.3'08s [551.3'5] 74–28239

For sale by the Superintendent of Documents, U.S. Government Printing Office

Washington, D.C. 20402

Stock Number 024-001-02611

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By WILLIAM B. BULL and JOSEPH F. POLAND

ABSTRACT

By increasing the stresses tending to compact the deposits by as much as 50 percent, man has created the world's largest area of intense land subsidence in the west-central San Joaquin Valley, Calif. As of 1966, more than 2,000 square miles had subsided more than 1 foot, and the area that had subsided more than 10 feet was 70 miles long. Maximum subsidence was 26 feet.

The increase in stress caused by pumping of ground water can be expressed in feet of water. A seepage stress of 1 foot of water occurs for each foot of head differential resulting from either artesian-head change or change in water-table position. Stress increase resulting directly from artesian-head decline has caused most of the compaction and subsidence. Each foot of water-table change also causes a 0.6-foot stress change because of removal or addition of buoyant support of the deposits within the interval of water-table change and a 0.2-foot stress change because of part of the pore water being changed from a neutral-stress condition to an effective-stress condition, or vice versa. The effect of water-table change is to alter the grain-to-grain stress in the unconfined aquifer by ± 0.8 foot of water per foot of water-table change. The effect of water-table change on stress in the deeper confined zones is to alter the stress by only ± 0.2 foot of water because the seepage-stress change more than offsets the sum of the two other stress changes.

Changes in aquifer-system thickness may be both elastic (are reversible and occur with minor time delay) and inelastic (are irreversible and occur with large time delay). As of 1966 excess pore pressures existed in many of the aquitards and net aquifer-system expansion occurred briefly or not at all, but elastic changes did affect the monthly amounts of measured compaction. Compaction rates were maximal during times of head decline because elastic compaction is additive with virgin compaction, and compaction rates were minimal during times of head rise because expansion is subtractive from virgin compaction. In the study area, the elastic component of seasonal compaction varies from less than 5 to about 90 percent. The percentage depends not only on the lithology and permeability of the deposits, but also on the magnitude and rate of increase of present applied stress as compared with past effective stress maximums and durations.

Three concurrent processes are tending to change aquifer-system thickness during times of applied-stress decrease—elastic expansion with no measurable time delay (presumably chiefly of the aquifers), delayed elastic expansion (presumably chiefly of the thin aquitards and the outer parts of the thick aquitards), and virgin compaction (presumably of the thick aquitards and aquicludes). Compaction due to decay of excess pore pressures may still occur in thick clay beds after 60 feet of head recovery in adjacent aquifers, but only 1 foot of head recovery may be needed to reverse the trend from recorded compaction to recorded net expansion, even when water levels are near historic lows. The approximate modulus of expansion (net specific unit expansion) of the upper-zone aquifer system at the Lemoore and Yearout sites is about $3.5 \times 10^{-6}\text{ft}^{-1}$ (foot per foot of aquifer-system thickness per foot of decrease in applied stress). During a period of seasonal head recovery at the Lemoore site, the net specific unit expansion varied from 0.6 to $3.6 \times 10^{-6}\text{ft}^{-1}$ as the rates of residual compaction and nondelayed and delayed expansion varied concurrently with changes in the magnitude and rate of applied-stress decrease.

Little time is needed to raise pore pressures in many of the aquitards. Compaction ceases when aquifer pore pressures rise to equilibrium with the maximum pore pressure in a contiguous aquitard, thus preventing further expulsion of water. Further pore-pressure increases in the aquifers are transmitted fairly rapidly into the aquitards because their specific storage in the elastic range is small.

The prediction of subsidence is largely empirical, and reasonable predictions can be made only if the rates and magnitudes of future applied-stress changes can be predicted accurately. The time-dependent nature of the pore-pressure decay in the aquitards and aquicludes greatly complicates estimates of compaction for heterogeneous aquifer systems.

Most of the subsidence since 1960 has been the result of prior applied-stress increases. In many of the thick beds of low permeability, the applied stress has not yet become effective because of insufficient time for pore pressures in the aquicludes and aquitards to reach equilibrium with the head in the aquifers. Determination of the rates and changes of rates of residual compaction is important in the prediction of subsidence.

The rate of decrease of aquitard-aquifer pore-pressure differentials can be evaluated at some sites through study of change of mean daily compaction rates for selected applied stress levels. In the 703–2,000-foot depth interval at the Cantua site, the relation between mean daily compaction rate (y) and time (x) for the 1961–67 period is

$$y=0.0028e^{-0.096x}.$$

Because increase in applied stress was negligible from 1961 to 1967, the decrease in the post-1961 rate of daily compaction can be used to estimate future residual compaction. A 10-percent decrease in residual compaction rate had occurred as of mid-1962 and 45 percent as of 1968, and a 90-percent decrease is predicted by about 1986, assuming a hydrologic environment similar to that of the 1961–67 period. Exponents of similar equations for other compaction-recorder sites indicate that the rate of pore-pressure decay is twice as rapid in the northern as in the southern part of the study area.

Importation of surface water has resulted in alleviation of subsidence in the Delta-Mendota Canal service area and in the vicinity of Stratford and Lemoore. Deliveries of water from the San Luis Canal section of the California Aqueduct should result in widespread alleviation of subsidence.

INTRODUCTION

By increasing the stress tending to compact the unconsolidated deposits by as much as 50 percent, man has created the world's largest area of intense land subsidence in the west-central San Joaquin Valley. Withdrawal of ground water for agriculture has caused more than 2,000 square miles to subside more than 1 foot. As of 1966, the area that had subsided more than 10 feet was 70 miles long and included 500 square miles; maximum subsidence was 26 feet.

Water-level changes in the aquifer systems have increased the applied stresses and have caused accelerated compaction of the deposits. Detailed knowledge of the interrelations of water-level change, change in aquifer-system thickness, and the concurrent changes in the altitude of the land surface is necessary for a better understanding of the mechanics of aquifer systems and the compaction of sediments, as well as for the development of criteria in predicting future land subsidence.

This paper is the third of three reports discussing land subsidence due to ground-water withdrawal in the Los Banos–Kettleman City area, California. Part 1 (Bull and Miller, 1974) is a factual presentation of the hydrologic factors conducive to land subsidence in the study area. Part 2 (Bull, 1974) contains basic data and interpretation about the land subsidence and compaction that have been measured in the area and discusses geologic factors influencing the amounts, rates, and distribution of compaction.

The introduction to all three parts, in Part 1 (Bull and Miller, 1974), includes descriptions of the geographic setting of the study area, the formation and objectives of the Inter-Agency Committee on Land Subsidence, the scope of the field and laboratory work for the cooperative and federal subsidence programs, and brief summaries about land subsidence and compaction. For a summary of the hydrologic environment, and the man-induced changes in the hydrologic environment, the reader is referred to the summary and conclusions of Part 1 (Bull and Miller, 1974). The principal areas of land subsidence due to ground-water withdrawal in California and the topographic and cultural features of the Los Banos–Kettleman City subsidence area are shown in figures 1 and 2 of Part 1 (Bull and Miller, 1974).

The boundaries of the Los Banos–Kettleman City study area, bench marks, observation wells, compaction recorders, core holes, and lines of section referred to in this report are shown in figure 1. The northeastern boundary as shown in figure 1 is along the valley trough, but as of 1966, as much as 8 feet of subsidence had occurred east of the valley trough. Therefore, in much of the study, the 1-foot subsidence line of 1920–28 to 1966 (Pt. 2, Bull, 1974, fig. 9) was used as the east boundary of the subsidence area.

PURPOSES OF REPORT

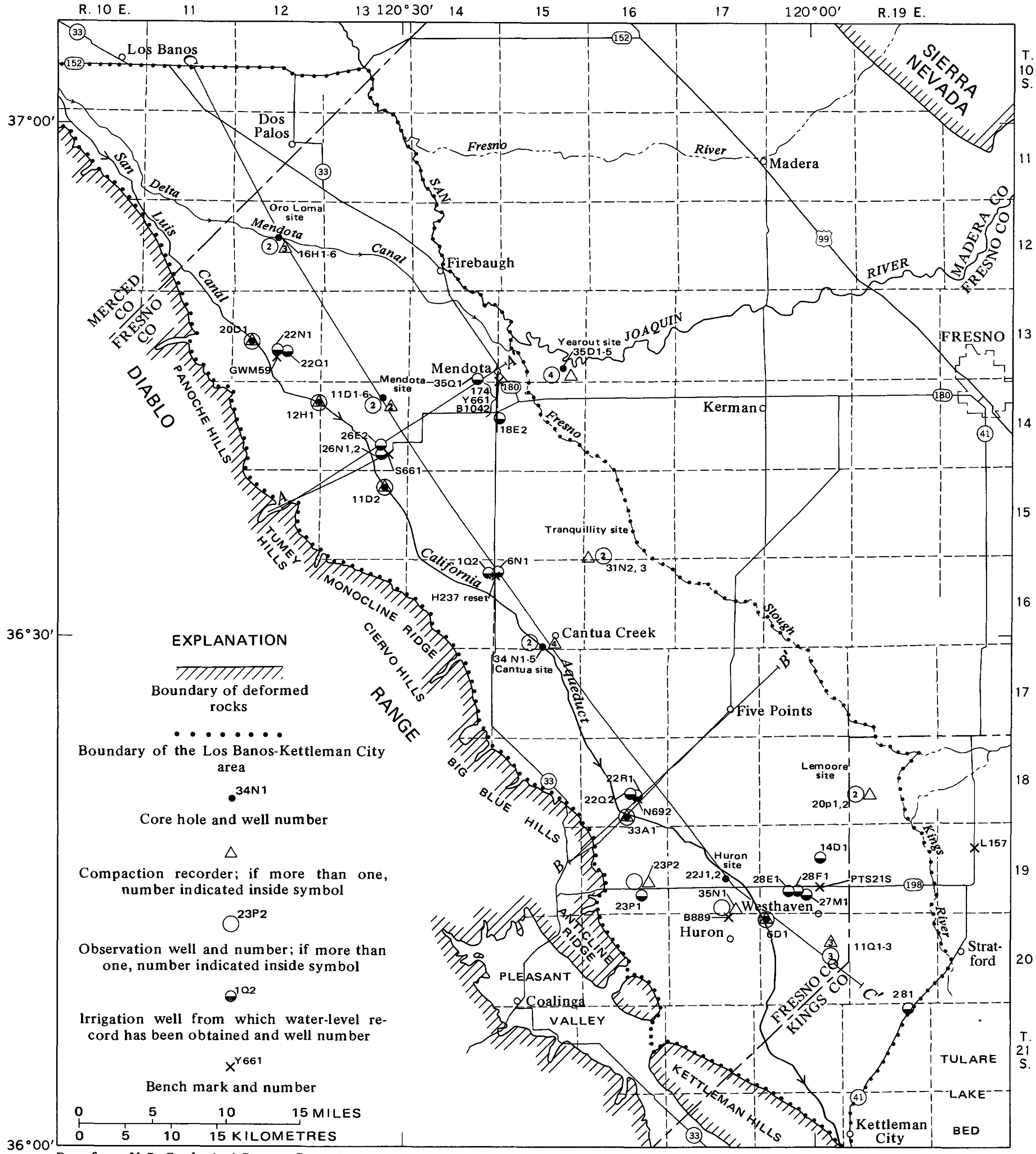
The overall purpose of Part 3 is to relate water-level changes to changes in thickness of the aquifer-system skeleton in the west-central San Joaquin Valley. This goal consists of three purposes. The first is to review how grain-to-grain stresses are changed by water-level changes. The analysis of stresses has been discussed by Lofgren (1968), but a modified method of applied-stress computation is used in this study. The second purpose is to show the effects of change in applied stress on aquifer-system thickness. Three components of change in aquifer-system thickness are discussed. The third purpose is to provide criteria for predicting future subsidence in the study area and to assess the reliability of the possible ways of predicting future subsidence.

The bulk of the information presented in this paper concerns events that occurred before April 1966, which was the time of a complete survey of the bench-mark network by the U.S. Coast and Geodetic Survey (now National Geodetic Survey of the National Ocean Survey, National Oceanic and Atmospheric Administration). Post-March 1966 data are presented and discussed only to present facts or concepts that cannot be demonstrated with the earlier data.

DEFINITION OF TERMS

The geologic and engineering literature contains a variety of terms that have been used to describe the processes and environmental conditions involved in the mechanics of stressed aquifer systems and of land subsidence due to withdrawal of subsurface fluids. The usage of certain of these terms in reports by the U.S. Geological Survey research staff investigating mechanics of aquifer systems and land subsidence is defined and explained in a glossary published separately (Poland and others, 1972). Several terms that have developed as a result of the Survey's investigations are also defined in that glossary.

The aquifer systems that have compacted sufficiently to produce significant subsidence in California and elsewhere are composed of unconsolidated to semiconsolidated clastic sediments. The definitions given in the published glossary are directed toward this type of sed-



Base from U.S. Geological Survey Central Valley map, 1:250,000, 1958

FIGURE 1.—Bench marks, observation wells, compaction recorders, core holes, and lines of section referred to in this report.

iments; they do not attempt to span the full range of rock types that contain and yield ground water. In defining the components of the compacting stresses, the contribution of membrane effects due to salinity or electrical gradients has been discounted as relatively insignificant in the areas studied.

In our research reports, pressures or stresses causing compaction are usually expressed in equivalent "feet of water head" (1 ft of water = 0.433 lb in^{-2} (pounds per square inch)).

A committee on redefinition of ground-water terms, composed of members of the Geological Survey, recently issued a report entitled "Definitions of Selected Ground-Water Terms" (Lohman and others, 1972). The reader is referred to that report for definitions of many ground-water terms.

ACKNOWLEDGMENTS

The cooperation of numerous ranchers, landowners, and companies is acknowledged for supplying essential information to the subsidence project and for giving permission to install and maintain wells and equipment for obtaining water-level and compaction information. Particular assistance was given by the Pacific Gas and Electric Co., Westlands Water District, and Russell Giffen, Inc.

The financial cooperation of the California Department of Water Resources made this study possible, and information provided by the U.S. Bureau of Reclamation from core holes and observation wells contributed significantly to the essential data.

This work could not have been completed without the discussions, interest, and assistance of the many people who have been associated with the land-subsidence studies since 1956. We appreciate particularly the helpful discussions and review of the manuscript by our colleagues B. E. Lofgren, F. S. Riley, D. C. Helm, and G. H. Davis. Mr. Bull enjoyed working together with R. L. Ireland and R. G. Pugh on a variety of jobs in the field, and the authors appreciate their extensive help in collection and assembling of field data. Special credit is due Mr. Ireland for his meticulous care and thoughtful foresight in the installation and operation of the equipment for recording compaction and water-level changes during the entire period of record.

ANALYSIS OF STRESS CHANGES TENDING TO CAUSE COMPACTION

Compaction is caused by the grain-to-grain load which results from all the stress-producing factors in the overlying stratigraphic section. In the Los Banos–Kettleman City area, and elsewhere, stress changes caused by man's changes of the hydrologic environment are superimposed on the prior natural stresses tending to compact the deposits. The ratio of manmade to natural applied stress varies considerably with geographic area and with depth, but can be large. For example, the applied stress at the 600-foot depth at the Cantua recorder site was increased from about 330 to about 500 lb in^{-2} as the result of 400 feet of artesian-head decline. About 52 percent increase in applied stress has occurred as a result of man's change in the hydrologic environment at the 600-foot depth. However, at the 200-foot depth at the same site, no change in applied stress has occurred. The 200-foot depth is about 10 feet below the water table, which has not changed position substantially at the site during the past 60 years.

Water-level changes in both the confined and unconfined parts of the aquifer systems cause changes in applied stress and thereby alter the preexisting stress distribution within each sedimentary bed. Applied stresses become effective stresses only as rapidly as water can be expelled from a given bed.

A stress that does not tend to cause compaction is the hydrostatic (neutral) stress, which is equal to the depth below the water surface times the unit weight of water, and is transmitted downward through the water between the grains. The hydrostatic stress is considered neutral because, although it tends to compress each grain, it does not tend to change the grain-to-grain relationships significantly.

The basic theory used by the Geological Survey regarding the stresses produced by water-level change within an aquifer system has been discussed by Lofgren (1968, 1969) and Poland (Poland and Davis, 1969). The theory is summarized briefly in this paper, first, to provide the reader necessary background before applying the theoretical concepts to the actual mechanics of aquifer systems, and second, because a different approach from that described by Lofgren will be used in computing the changes in stress that result from water-table change.

STRESS CHANGE DUE TO CHANGE IN SEEPAGE FORCES

A major contribution to the theory of mechanics of aquifers was made by Lofgren by the application of the seepage-stress concept (Taylor, 1948; Scott, 1963) to the distribution of stresses in a compacting aquifer system (Lofgren, 1968; Lofgren and Klausing, 1969). Although several methods can be used to obtain the same results (Taylor, 1948, p. 203; Poland and Davis, 1969), the seepage-force concept provides the most logical dynamic explanation of how changes in confined and unconfined water levels affect stress relations in porous media.

Seepage forces are developed by the establishment of a hydraulic gradient across an aquiclude or aquitard. The hydraulic gradient may be caused by either water-table or artesian-head change and may induce flow either upward or downward across the bed responsible for the head differential. Flow through the bed is accompanied by dissipation of the hydraulic head. The seepage force corresponding to this loss of hydraulic head is transferred to the granular skeleton and is exerted in the direction of the overall route of flow. Lofgren and Klausing (1969, p. B67) stated,

> Within an aquiclude compacting under the stress of downward seepage, 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. ***. 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.

The large artesian-head decline that has occurred in the Los Banos–Kettleman City area has produced seepage forces within the upper confining bed that have tended to cause changes in effective stress in all underlying beds within the depth interval of artesian-head decline. Because seepage stresses are equal (assuming no water-table change) to the changes in artesian head, it is convenient to express the seepage stresses in units of feet of water (1 ft of water equals 0.433 lb in^{-2}). If the other factors tending to change the applied stress in the aquifer system also are expressed in feet of water, then the various components tending to change the stress condition at a given point in the aquifer system can be added algebraically to obtain the net change in applied stress.

STRESS CHANGE DUE TO FLUCTUATION OF THE WATER TABLE

Water-table fluctuations will be discussed mainly as an influence on stress changes within the lower zone (confined aquifer system)—the zone in which most of the manmade compaction in the study area has occurred. Changes in the position of the water table affect the applied stress on the lower zone in three ways: by changing the head differential and therefore the seepage stresses across the confining clays; by removing or supplying buoyant support of the grains within the depth interval affected by water-table change, depending on whether the water table declines or rises; and by eliminating or developing water of specific retention as the deposits become saturated or unsaturated.

Water-table rise tends to increase the seepage stress on the lower-zone deposits, each foot of water-table rise being equivalent to 1 foot of (water) increase in applied stress on the lower zone. Thus, water-table rise has the same effect on the seepage stress as an equivalent decline in lower-zone artesian head. However, as will be shown later, the tendency toward increase of seepage stress as a result of water-table rise is largely offset by the two other components of stress resulting from water-table rise is largely offset by the two other components of stress resulting from water-table rise.

Conversely, water-table decline tends to decrease the seepage stress on the lower zone, with each foot of water-table decline tending to decrease the applied stress on the lower zone by 1 foot of water.

BUOYANCY EFFECTS

The effect of change in buoyant support of the granular skeleton of the deposits within the depth interval of water-table change has been described by Lofgren (1968). The dry unit weight, γ_d, of deposits above a water table can be expressed as

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

where n is the mean porosity, G is the mean specific gravity of the mineral grains, and γ_W is the unit weight of water. The submerged unit weight of the deposits, γ', below the water table is expressed as

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

Physical tests of cores from the Los Banos–Kettleman City area indicate that a mean porosity of 0.40 and a mean specific gravity of the grains of 2.70 is appropriate for the deposits in the zone of water-table change (Johnson and others, 1968). Substituting in the preceding equations, the applied stress due to weight of deposits above the water table equals about 1.6 feet of water per foot of thickness, and the applied stress due to the weight of deposits submerged below the water table is about 1.0 foot of water per foot of thickness. Thus, the change in applied stress on all underlying deposits resulting from the buoyancy component is +0.6 foot of water for each foot of water-table decline and −0.6 foot of water for each foot of water-table rise. This type of water-level change results in large changes in stress, per foot of water-table change, above the first aquiclude. However, the effect of this buoyancy component of water-table change on stress in the lower zone is to cancel much of the change in seepage stress induced by the water-table change.

EFFECT OF SPECIFIC RETENTION IN THE UNSATURATED ZONE

The effects of the two results of water-table change discussed earlier pertain to seepage and buoyancy processes. A stress component caused by a third process also is used in this paper for computations of applied stress in areas of water-table change.

The weight of the water contained in the deposits above the water table is part of the applied stress tending to compact the underlying saturated deposits. If the additional weight of this water is not considered, the net computed stress change on the lower zone due to water-table change will be twice as large as it should be. The effect of specific retention on applied stress is discussed in detail because it pertains to a process of stress change that is different from those of the other two stress components.

Change from a saturated to an unsaturated condition causes the stress condition of the retained water to be changed from a neutral to an applied stress. Where the contained water is supported by underlying pore water, it represents a neutral stress. If the water table should decline, not all the water will drain from the deposits. The weight of the water retained represents a change from a neutral stress to a stress that is applied to all the underlying deposits. Conversely, under conditions of water-table rise, the weight of water that was part of the applied stress becomes a neutral stress.

The amount of water retained in the deposits above the water table varies with clay content. Nearly all the water-table deposits are Diablo[1] alluvial fans. Large differences in clay content commonly occur in adjacent beds. Clay content (Johnson and others, 1968) in most sand beds ranges from 5 to 20 percent, but the finer grained beds usually contain 30–50 percent clay. Data on specific yield and specific retention for various materials (Johnson, 1967) suggest that a mean specific retention of 20 percent (by volume) is a reasonable approximation for the alluvial-fan deposits.

Therefore, for purposes of computing the change in applied stress resulting from the water of specific retention, a value of 0.2 of the volume is used. (This represents a moisture content of 12.4 percent of the weight of the solids in deposits assigned a porosity of 0.40 and a specific gravity of 2.70.) The amount of retained water will be more than the value used in this report where the clay content of the deposits exceeds roughly 20 percent and where the moisture content of the deposits above the water table exceeds specific retention but is less than saturation.

Use of the assigned value of 0.2 of the volume of the deposit for the water of specific retention has the following effect on the computed applied stress resulting from water-table change. During a water-table decline, as each foot of deposits becomes unsaturated, an increase in applied stress equivalent to 0.2 foot of water will be applied to all the underlying deposits as half of the water in material assumed to have a porosity of 0.40 is transferred from a neutral to an applied-stress condition. The effect of a water-table rise will be to decrease the applied stress on the underlying deposits as a result of this component. As in the case of buoyancy of the granular skeleton, the water of the specific retention component will tend to offset the seepage-stress change applied to the lower zone as a result of change in the position of the water table.

[1]Principal source of deposits, where identified, is indicated as Diablo (derived from the Diablo Range) or Sierra (derived from the Sierra Nevada).

EQUATION SUMMING CHANGE IN APPLIED STRESS

The change in applied stress within a confined aquifer system due to changes in the potentiometric surfaces may be summarized as

$$\Delta p_a = -(\Delta h_c - \Delta h_u Y_s),$$

where p_a is the applied stress expressed in feet of water, h_c is the head (assumed uniform) in the confined aquifer system, h_u is the head in the overlying unconfined aquifer, and Y_s is the average specific yield (expressed as a decimal fraction) in the interval of water-table fluctuation (Poland and others, 1972, p. 6). Change in stress applied to a fine-grained bed becomes effective in changing the thickness of the bed only as rapidly as the diffusivity of the medium permits decay of excess pore pressures and thus allows the internal grain-to-grain stress (effective stress) to change.

COMBINED EFFECT OF MAN-INDUCED STRESS CHANGES TENDING TO CAUSE ADDITIONAL COMPACTION OF THE LOWER ZONE

Compaction of the lower-zone aquifer system accounts for at least 55–95 percent of the subsidence in different parts of the study area (Pt. 2, Bull, 1974, fig. 45). Therefore, the following computation of stresses will use the lower zone as an appropriate example.

Changes in lower-zone artesian head cause changes in applied stress on the lower-zone deposits that are equal to 1 foot of water for each foot of head change. Because of the convenient way in which the stresses have been expressed, changes in lower-zone water levels are numerically equal to changes in applied stress where no water-table change has occurred during a given period. The position of the water table has not changed more than 50 feet since 1951 in most of the study area; therefore, the recorded head changes in the confined aquifer systems approximate the applied-stress changes.

Locally, the water table has risen more than 100 feet and in another part of the area has declined more than 350 feet. In all areas of significant water-table change, the resulting change in applied stress on the lower zone has been computed as discussed subsequently and added algebraically to the change in applied stress indicated by lower-zone water-level change.

The applied stress diagrams in figure 2 show the effect of the three components of change in applied stress on the lower zone that are concurrent with water-table change. Derivation of the assigned values was discussed in the previous section. Head changes affect the seepage processes by 1 foot of water per foot of head change. The absence or presence of buoyant support for the granular skeleton results in an applied stress due to the dry weight of deposits above the water table of 1.6 feet of water per foot of thickness and an applied stress due to the weight of the deposits below the water table of 1.0 foot of water per foot of thickness. The applied stress due to contained water in deposits above the water table is equal to 0.2 foot of water per foot of thickness.

The conditions shown in figure 2*A* represent the initial conditions in a diagrammatic aquifer system. Unsaturated deposits extend to a depth of 200 feet, which is the initial position of both the water table and the potentiometric surface of the confined aquifer system. An unconfined aquifer occurs between 200 and 340 feet, and a 50-foot aquiclude occurs between 340 and 390 feet. A confined aquifer system occurs below a depth of 390 feet, and the top of an aquitard at a depth of 500 feet has been selected as the reference plane for which to compute applied stresses and changes in applied stresses. Because the water table and the potentiometric surface occur at the same level, a head differential does not exist across the aquiclude and no seepage stress is present. The distribution of neutral pressures is hydrostatic, the same as if no confining bed were present. The vectors P_s, P_w, and P_b represent the three components of stress applied to the top of the aquitard at a depth of 500 feet. The initial total applied stress is 660 feet of water. The applied stress due to the dry weight of the unsaturated deposits is the largest component even though it is derived from a thickness of deposits that is only two-thirds as thick as the saturated section above the aquitard.

Conditions after a water-table decline of 100 feet are depicted in figure 2*B*. The vector of applied stress due to the weight of the dry deposits above the water table is greater than the sum of the other two vectors, and the total gravitational stress applied to the top of the aquitard at a depth of 500 feet is 740 feet of water. The gravitational components tending to increase applied stress as a result of the water-table decline total 80 feet of water ($\Delta P_b + \Delta P_s + \Delta P_w$). Sixty feet of the increase is the result of loss of buoyancy of the grains in the dewatered section, and 20 feet of the increase is the result of transfer of the retained pore water from a neutral to an applied-stress condition. The 100 feet of water-table decline also caused a head differential across the aquiclude that has resulted in an upward seepage stress of 100 feet. The net effect of the three water-table components of stresses tending to change the stress applied to the top of the lower-zone aquitard is to decrease the applied stress by 20 feet of water.

Conditions after a water-table rise of 100 feet are depicted in figure 2*C*. The component of applied stress due to the weight of the submerged deposits is the dominant source of stress applied to the top of the lower-zone aquitard, and the total gravitational stress applied to the top of the aquitard is 580 feet of water. The gravitational components tending to decrease the applied stress (from the initial condition shown in fig. 2*A*) as a result of the water-table rise total 80 feet of water. Sixty feet of the decrease in applied stress is the result of

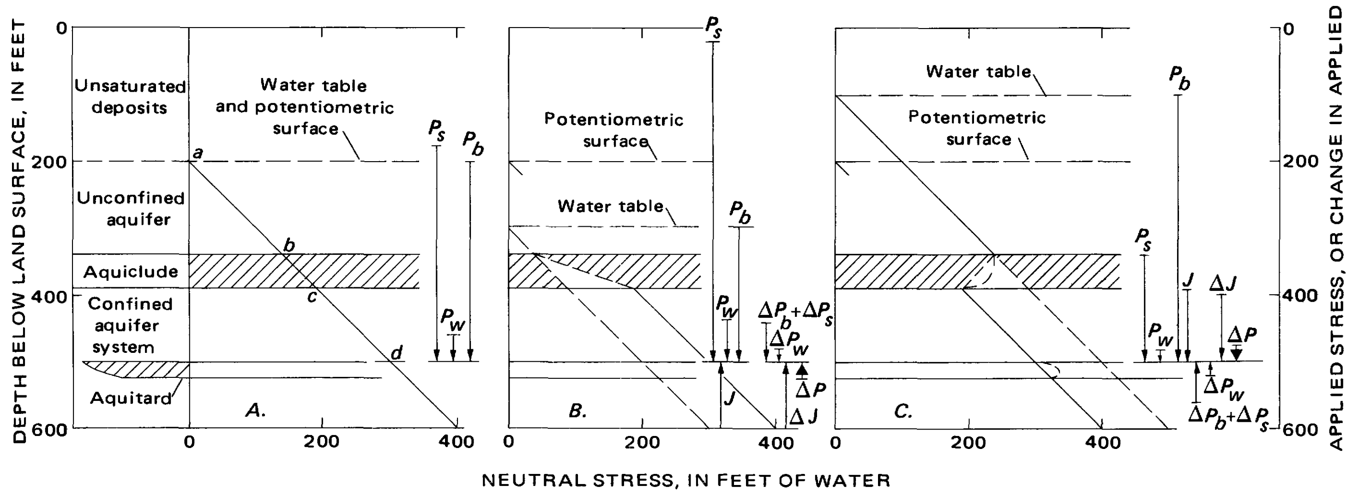


FIGURE 2.—Effect of water-table change on lower-zone applied stress. *A*, Water table and lower-zone potentiometric surface at same level. *B*, Water table lowered, potentiometric surface constant. *C*, Water table raised, potentiometric surface constant. All stresses in feet of water; based on assumed porosity of 0.40, specific gravity of 2.70, and specific retention of 0.20 by volume. P_s = applied stress due to dry weight of unsaturated deposits; P_b = applied stress due to buoyant weight of submerged deposits; P_w = applied stress due to weight of contained water in unsaturated deposits; J = seepage stress; ΔP = change in total applied stress from condition *A*.

buoyancy effects tending to lift the grains in the section that has been submerged, and 20 feet of the decrease is the result of transfer of the pore water from an applied-stress to a neutral-stress condition. The 100 feet of water-table rise also caused a head differential across the aquiclude that has resulted in a downward seepage stress of 100 feet. The net effect of the three water-table components of stress change applied to the top of the lower-zone aquitard is to increase the applied stress by 20 feet of water.

The net effect of stress change on the lower-zone deposits per unit change in the position of the water table will be minor. Changes in stress resulting from buoyancy changes and changes in the stress condition of the contained water are more than offset by the change in seepage stress that also results from change in the position of the water table. A net change of applied stress on the lower zone of 0.2 foot of water per foot of water-table change is the resultant of the three components tending to change the applied stress. If the contained water above the water table is not taken into account, the net change in applied stress would be 0.4 foot of water—twice as large as it should be.

During 1951–65, local water-table declines caused as much as 40–70 feet of water applied-stress decrease on the lower zone. Locally, change from a confined to a water-table condition below the Corcoran Clay Member of the Tulare Formation has decreased the rate of applied-stress increase from 1.0 to 0.8 foot of water per additional foot of lower-zone water-level decline.

INTERRELATIONS OF WATER-LEVEL CHANGE, CHANGE IN AQUIFER-SYSTEM THICKNESS, AND SUBSIDENCE

Part 1 (Bull and Miller, 1974), Part 2 (Bull, 1974), and the preceding section of this paper have discussed the hydrologic environment, the stress changes caused by changes in the hydrologic environment, and the compaction of the ground-water reservoir and resulting land subsidence. The purpose of this section is to show the interrelations of change in applied stress caused by changes in the positions of the potentiometric surfaces including the water table, decrease or increase in aquifer-system thickness, and land subsidence.

In most of the area the decline in artesian head approximates the increase in stress, expressed in feet of water, tending to compact the lower-zone deposits. Changes in the position of the water table have been minor at most observation-well sites during the periods of record. Also, about 5 feet of water-table change causes a net change in applied stress on the confined zones that is equivalent to only 1 foot of change in artesian head. Therefore, the plots of change in artesian head shown in figures 3–23 are representative of the general changes in applied stress (in feet of water) that have occurred in the deposits in which the wells are perforated.

First, the records from two lines of section and specific sites throughout the area are interpreted. Then, the regional change in applied stress on the lower-zone deposits that has resulted from changes in the positions of the potentiometric surfaces of the lower zone and the water table is analyzed for a 17-year period as the basis for a specific compaction map of the lower zone.

RELATION OF SUBSIDENCE TO ARTESIAN-HEAD DECLINE

A comparison of the regional declines in land-surface altitudes and the artesian head of the lower zone between 1943 and 1966 is shown in figures 3 and 4. The plots showing change in head do not extend as far southwest as the plots showing change in the land-surface altitude, because the area near the foothills of the Diablo Range had not been developed agriculturally in 1943 and hence no head measurements were made west of those shown.

Profiles of subsidence and artesian-head decline between Tumey Hills and Mendota are shown in figure 3. The subsidence profiles reveal a slightly asymmetrical change in the altitude of the land surface. The profiles of artesian-head decline roughly parallel each other, but do not have the same overall configuration as the subsidence profiles. The profiles of head decline show progressively larger amounts of decline to the west, whereas the subsidence profiles have a pronounced reversal about midway along the line of section. By 1966 a maximum of 24 feet of subsidence had occurred since 1943 where the head had declined only 190 feet; farther to the southwest, only 14 feet of subsidence had occurred where the head had declined 350 feet.

The profiles of subsidence and artesian-head decline between Anticline Ridge and Fresno Slough in figure 4 reveal a history that is roughly similar to that shown in figure 3. The subsidence profiles show a markedly asymmetrical change in land-surface altitude. The profiles of head decline parallel each other in the east half of the line of profile, but show a marked divergence in the west half. The 1955 head-decline profile is similar to the subsidence profile in that it reverses its trend and is asymmetrical. The trough of the head-decline profile is 1–2 miles southwest of the trough of the subsidence profile. By 1966, the head-decline profile did not show a reversal, but instead had an overall trend of increasing depth to the west. The subsidence maximum of 18 feet occurred where the head had declined 200 feet, but 5 miles to the southwest only 3 feet of subsidence had occurred where the head had declined 275 feet.

It is readily apparent from figures 3 and 4 that al-

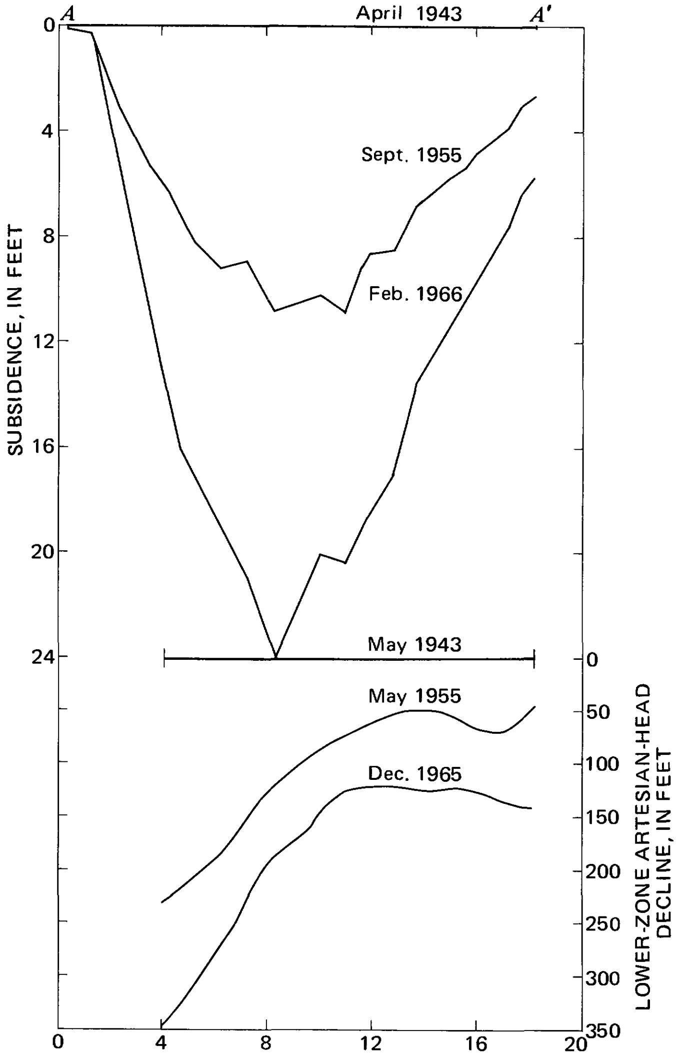


FIGURE 3.—Profiles of subsidence and artesian-head decline, 1943–66, Tumey Hills to Mendota.

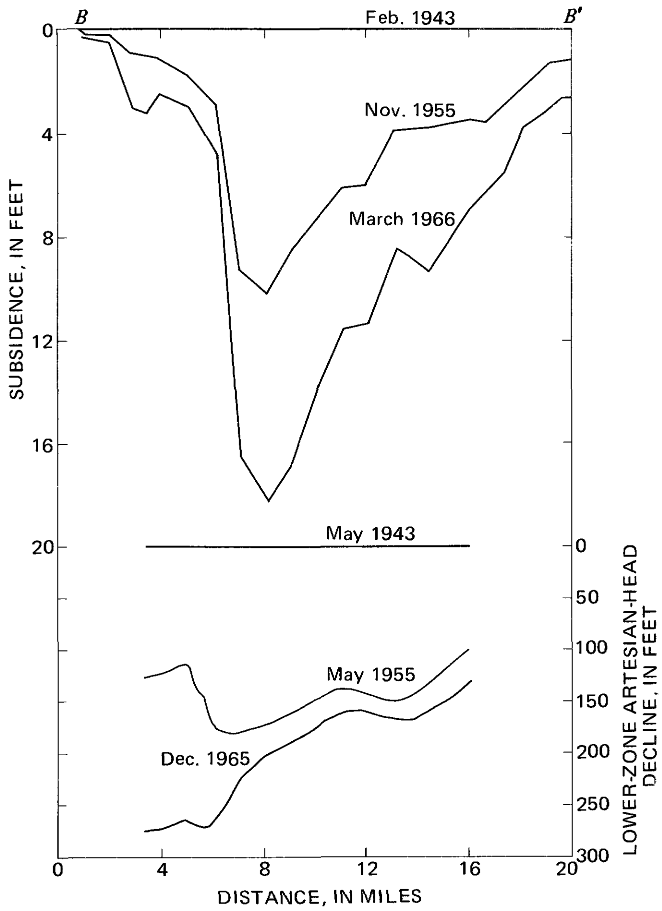


FIGURE 4.—Profiles of subsidence and artesian-head decline, 1943–66, Anticline Ridge to Fresno Slough.

though subsidence is associated with head decline, the quantitative relation between cause and effect varies within the study area. For example, the subsidence/head-decline ratio varies along the line of profile 3 from 0.12 to 0.04, and the ratio varies along the line of profile for figure 4 from 0.09 to 0.01. Geologic reasons for the variability of the subsidence/head decline ratio are discussed in Part 2 (Bull, 1974).

Comparisons of subsidence and change in artesian head are shown for selected bench marks and nearby wells in figures 5–10. The ratio of the water level to the subsidence scales is 20:1. The hydrographs consist of selected measurements that represent times of maximal applied stress during the intensive pumping periods of late winter and summer. Description of the six sites is from north to south, and the locations of the bench marks and wells are shown in figure 1.

Subsidence and artesian-head decline near bench mark GWM59, 15 miles west of Mendota, are shown in figure 5. Subsidence rates increased between 1940 and 1955, and since then have undergone a slight, but con-

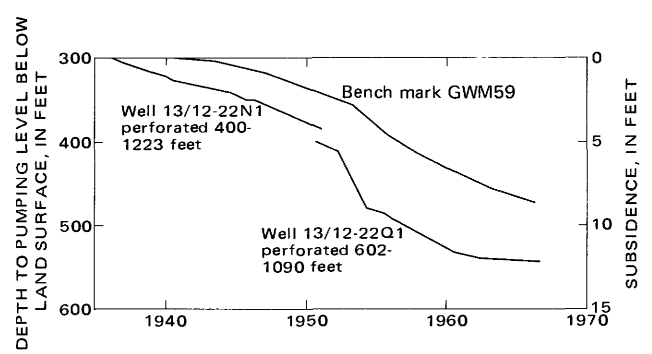


FIGURE 5.—Subsidence and artesian-head decline near bench mark GWM59.

tinuing, decrease. The water-level record reveals a parallel history of accelerating, then decelerating, rate of decline. Since 1960, summer low water levels have undergone little decline, while the subsidence has continued at a moderately rapid rate.

Subsidence and artesian-head decline near Mendota are shown in figure 6. This site provides the longest bench-mark record of subsidence in the Los Banos–Kettleman City area. The overall trends of both the subsidence and water-level plots have been toward gradually increasing rates of subsidence and head decline.

Subsidence and artesian-head decline 10 miles southwest of Mendota are shown in figure 7. Bench mark S661 has subsided more than any other bench mark in the San Joaquin Valley, even though the period of record extends only as far back as 1943. Rapid compaction has destroyed well casings within a few years. Thus, the records from several wells are necessary to show the trend in water levels. Both the rates of subsidence and head decline have decreased since the mid-1950's.

Subsidence and artesian-head decline near bench mark H237 (reset), 6 miles northwest of Cantua Creek, are shown in figure 8. Well 16/15–6N1 was one of the first wells drilled in the vicinity of the bench mark, and the water-level record during the early 1940's indicates that little head decline occurred during initial agricultural development. Between 1944 and 1961, the artesian head declined rapidly, and since 1961 the head has continued to decline but at slower rates than previously. The rate of subsidence increased until about 1960 and has been roughly constant since then.

Subsidence and artesian-head decline southwest of Five Points are shown in figure 9. The head-decline

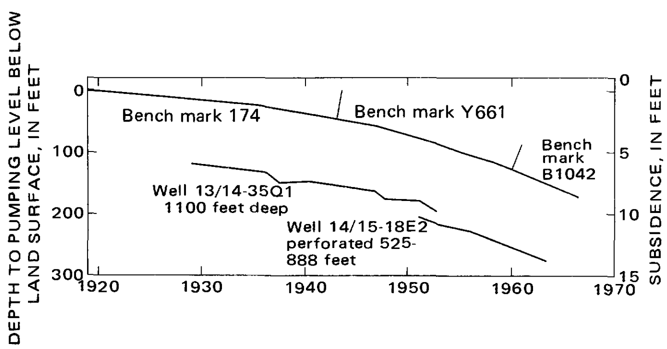


FIGURE 6.—Subsidence and artesian-head decline near bench mark B1042.

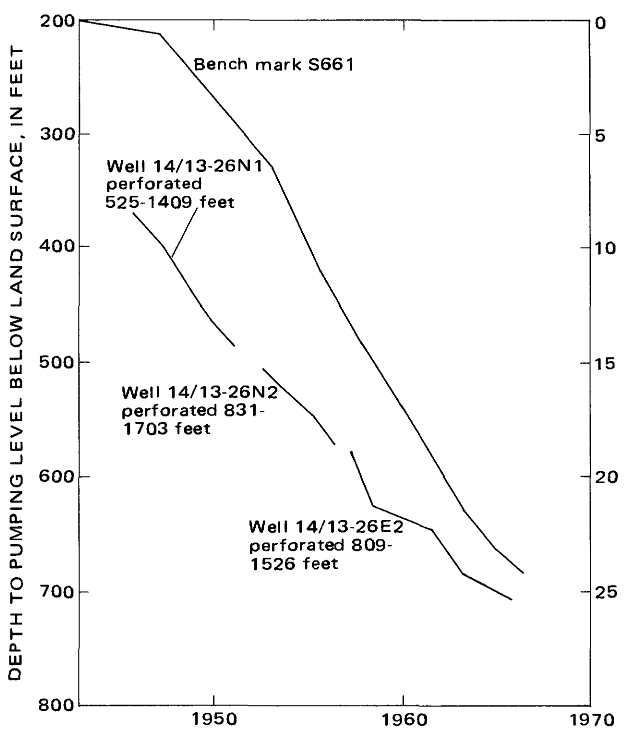


FIGURE 7.—Subsidence and artesian-head decline near bench mark S661.

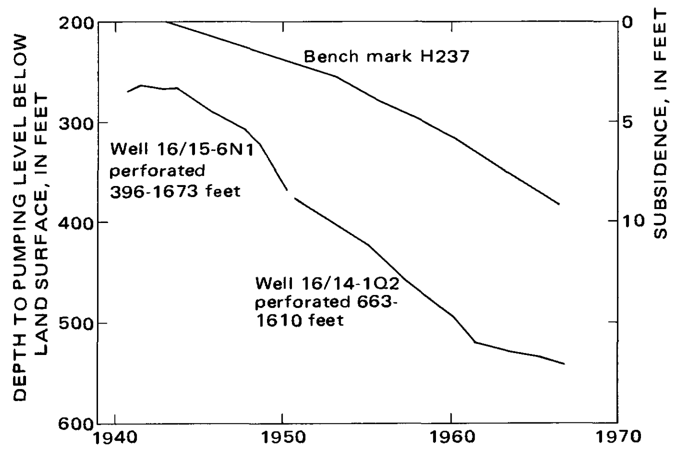


FIGURE 8.—Subsidence and artesian-head decline near bench mark H237 (reset).

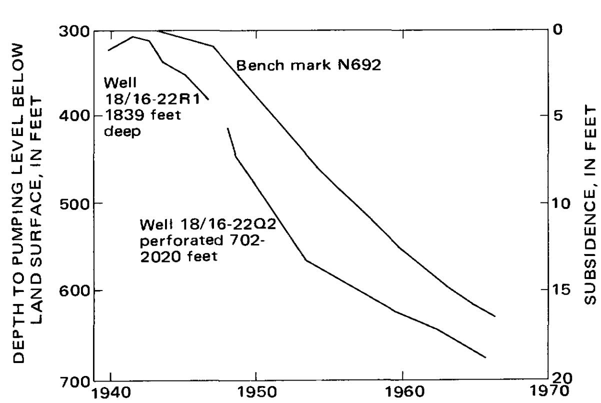


FIGURE 9.—Subsidence and artesian-head decline near bench mark N692.

trend is similar to that shown in figure 8, although the head decline since 1940 has been about 90 feet greater near bench mark N692 than near bench mark H237. The subsidence histories of the two bench marks are similar until 1960, but since 1960 the rate of subsidence at bench mark N692 has decreased slightly, while that at bench mark H237 has been constant.

Subsidence and artesian-head decline near Westhaven are shown in figure 10. Wells in the vicinity of this bench mark provide the longest record of head decline in the Los Banos-Kettleman City area. The water-level record begins in 1918, and the bench-mark record begins in 1923. The rapid decline in artesian head between 1947 and 1953 coincided with a period of marked agricultural expansion after World War II. The subsidence rate increase after 1947 coincided with the increased rate of head decline.

The relation between subsidence and the change in applied stress on the lower-zone deposits is discussed for three of the preceding sites with reference to figures 33-35.

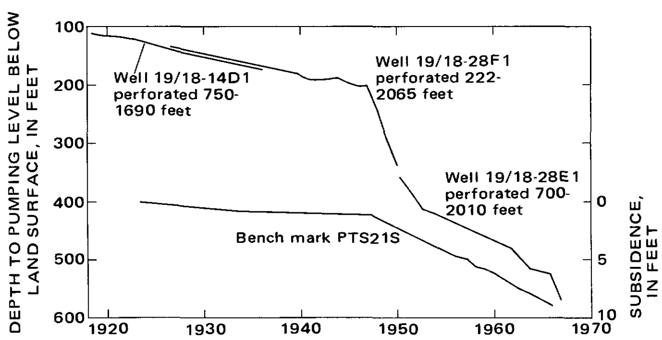


FIGURE 10.—Subsidence and artesian-head decline near bench mark PTS21S.

RELATION OF CHANGES IN AQUIFER-SYSTEM THICKNESS TO CHANGE IN ARTESIAN HEAD

The history of subsidence, compaction, and changes in artesian head near Huron from 1954 to 1960 is shown in figure 11 by means of graphs of subsidence of the land surface at B889, compaction in a well 2,030 feet deep as recorded by shortening of a cable anchored at the bottom of the well (Lofgren, 1961), and change in head as recorded by a float-type water-level recorder on well 19/18-27M1. The compaction record was the result of the first attempt to measure compaction in the study area. A good record was obtained from mid-1955 until the fall of 1960, when the cable of the compaction recorder failed because of corrosion. Attempts to install new equipment were unsuccessful. Bench mark B889 and well 19/17-35N1 are close together about 1½ miles north of Huron, but well 19/18-27M1 is about 5 miles east of the compaction-recorder site. Wells suitable for water-level recorders were not available nearer the compaction recorder.

The plots of subsidence and compaction in figure 11 are about parallel, indicating that most of the compaction causing the subsidence occurred above the depth of the compaction anchor at 2,030 feet. From October 1955 to January 1960, measured compaction was 85 percent of the total subsidence as observed by releveling of the nearby benchmark. The hydrograph for well 19/18-27M1 reveals an overall rate of head decline of about 8 ft yr^{-1} (feet per year). Superimposed on the long-term trend are seasonal fluctuations of 40-70 feet. Comparison of the compaction and water-level plots shows that maximum compaction rates occur during seasons of declining head. Compaction rates are small or net compaction ceases during seasons of rising artesian head.

The trends of annual compaction rates and lower-zone artesian-head decline at the Oro Loma site near the Delta-Mendota Canal are shown in figure 12. The amounts of annual compaction measured by a cable-type recorder anchored at 1,000 feet in well 12/12-16H2 decreased from 0.44 ft yr^{-1} in 1959 to 0.08 ft yr^{-1} in 1965. The water level in well 12/12-16H6 indicates that the summer low water levels have been almost the same since 1960 but that the recovery of the water levels during the winters has become progressively less. Hence, the seasonal fluctuations decreased from 23 feet in 1960 to 9 feet in 1965.

The compaction shown in figure 12 is virgin compaction occurring in the thicker more clayey aquitards and aquicludes that still are characterized by residual excess pore pressures. The decrease in annual compaction rates reflects a progressive decrease in pore-pressure differences between aquifers and aquitards in the aquifer system as water drains to the more permeable strata.

ELASTIC AND INELASTIC CHANGES IN AQUIFER-SYSTEM THICKNESS

Not all virgin compaction is inelastic. A small part of the virgin decrease in aquifer-system thickness is elastic. The next two sections will describe some aspects of elastic compaction and expansion of the aquifer system, as well as virgin compaction, in response to change in applied stress as indicated by change in artesian head.

The following modification of Jacob's (1940) equation for the coefficient of storage provides a convenient way to visualize the relative importance of the elastic and inelastic components of compaction due to artesian-head decline:

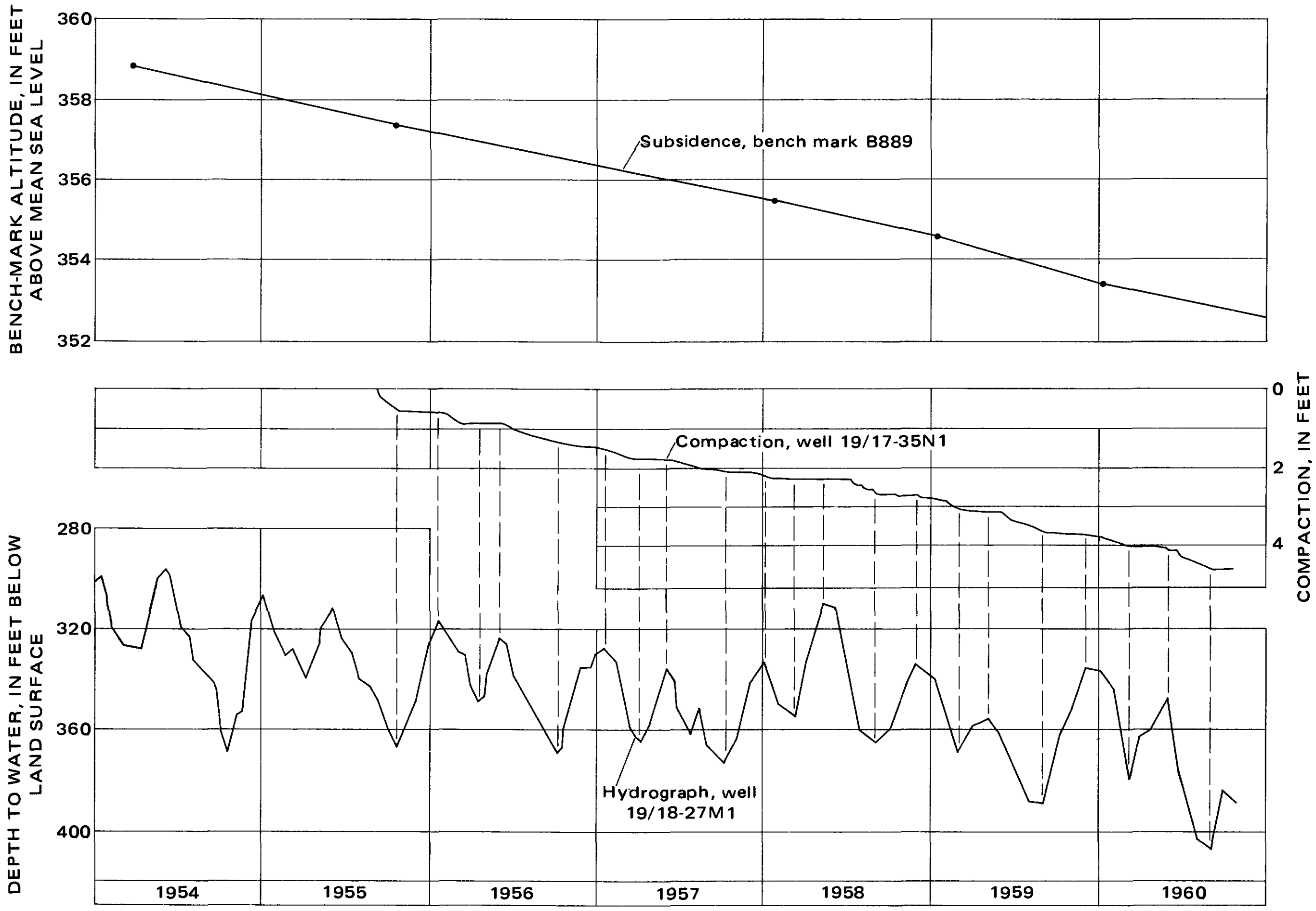


FIGURE 11.—Subsidence, compaction, and artesian-head decline near Huron.

		Elastic components						*Inelastic component*
Total water from storage per unit decline in head	=	Expansion of water	+	Compression of aquifers	+	Compression of aquitards	+	Compaction of aquitards
S_t	=	$\gamma mn/E_w$	+	$\gamma m_1/E_s$	+	$\gamma m_2/E_c$	+	$\gamma m_2\beta_c$.

γ is the specific weight of water, n is the mean porosity of the aquifer system, m_1 is the thickness of the aquifers, m_2 is the thickness of the aquitards, m is the thickness of the aquifer system, E_w is the bulk modulus of elasticity of water, E_s and E_c are the moduli of elasticity of the aquifers and aquitards respectively, and β_c is the modulus of compressibility for the inelastic compaction of the aquitards. Assumptions for this equation are that the aquifer system consists of uncemented granular material and that the release of water from all parts of the aquifer system is instantaneous. These assumptions are met for the first three terms of the equation. Because a timelag exists for the compaction of aquitards, the field determination of the fourth term is only an approximate minimum value.

The water that is obtained from storage as a result of head decline is obtained from the elastic expansion of the water contained in the pore spaces and the compression of the aquifer-system skeleton containing the water.

The following example compares the general magnitude of the storage components yielded as a result of artesian-head decline for well 19/16–23P2:

$$S_t = mn/E_w + \gamma m_1/E_s + \gamma m_2/E_c + \gamma m_2 \beta_c$$

$$36 \times 10^{-3} = (1.0 \quad + \quad 2.5 \quad + \quad 32) \times 10^{-3}\,.$$

The component of 1.0×10^{-3} is the amount of water released from storage per unit head decline as a result of expansion of water, assuming a porosity of 0.4, a thick-

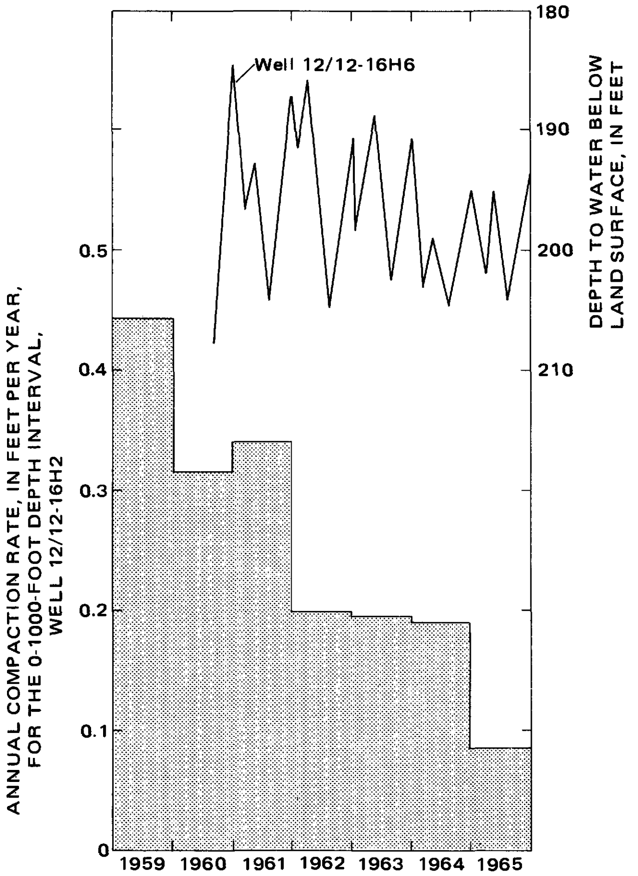


FIGURE 12.—Relation of annual compaction rates to change in artesian head at the Oro Loma site.

ness of 1,800 feet, and 3×10^5 lb in^{-2} for the modulus of elasticity for water.

The component of 2.5×10^{-3} is an estimate of the minimum amount of water released from storage per unit head decline as a result of elastic compression of the aquifers and aquitards within the 1,800-foot thickness and thus combines the second and third terms of the original equation. The estimate is based on the mean recorded net expansion measured during 18 periods of head recovery in which recorded expansion exceeded 0.01 foot. It is assumed that elastic compression is equal to elastic expansion and that change in thickness in the elastic range of deformation is linear with change in effective stress. As will be discussed later, amounts of recorded expansion generally are less than amounts of actual expansion because of concurrent delayed compaction in beds with residual excess pore pressure. Thus, the value of 2.5×10^{-3} should be regarded as a minimum.

The inelastic component of 32×10^{-3} (the fourth term of the equation) is an estimate of the minimum amount of inelastic compaction of the aquifer system per unit head decline. The amount is based on the total subsidence that has occurred at well 19/16-23P2 as of 1966 minus the estimated elastic compaction that has occurred for the historic increase in applied stress. About 8 feet of inelastic subsidence has occurred as a result of 250 feet of increase in applied stress. Continued recording of compaction during times of nonrising water levels, when potentiometric levels are above the historic low levels at well 19/16-23P2, indicates that the applied stress has not become fully effective in the finer grained parts of the aquifer system and that ultimate amounts of compaction have not occurred yet. Thus, the value of 32×10^{-3} should be regarded as a minimum.

The thickness of the deposits affected by changes in applied stress was estimated on the basis of the following information. The compaction anchor is set at a depth of 2,200 feet in well 19/16-23P2. Pumping of well 19/16-23P1, about 500 feet from the recorder well, controls to a large extent changes in applied stress at the compaction-recorder site. The casing of the gravel-packed irrigation well is perforated from 660 to 2,155 feet below land surface. It is assumed that the drawdown in the irrigation well affects the artesian head for aquifers below a depth of about 400 feet. Hence, the storage components are based on an estimated thickness of 1,800 feet.

For the example at well 23P2, most of the water derived from storage is yielded by inelastic compaction of the aquifer system. The amount of water yielded by elastic compression of the aquifer system is at least two or three times that yielded by elastic expansion of the water. Inelastic aquifer-system compaction has provided at least 32 times the amount of water of expansion.

The estimates of the components of the storage coefficient in those parts of the study area where large amounts of land subsidence have occurred indicate that less than one-tenth of the long-term compaction of the aquifer system is the result of elastic compression. A similar conclusion was reached by Poland (1961). It will be shown later, however, that in one area of minor subsidence, the elastic component of compaction accounted for most of the compaction during a 6-month period. (See end of section "The Yearout Site.")

RELATION OF MONTHLY COMPACTION TO WATER-LEVEL CHANGE

The monthly compaction that has been recorded at four sites is compared with the record of change in lower-zone water level in figures 13–17. The times of the measurement of the compaction usually are 28 days apart, but range from 26 to 32 days.

The amount of compaction measured since the previous visit to the recorder site is dependent on several factors other than the change in aquifer-system thickness. Casing-cable friction at most sites makes it necessary to stress the cable manually during each visit. Manual stressing of the cable overcomes the friction that may prevent recording of compaction. The cable is stretched more than the amount of compaction that occurred during the month, but if friction characteristics remain the same from month to month, cable stresses between and below the points of contact between the casing and the cable should return to approximately the same tensions after each manual stressing. Examination of many records indicates that the friction characteristics of a given recorder system do not change noticeably with time. A more important source of error for a given measurement is the variation in the individual mode of manual movement of the counterweights. However, little variation is apparent between the results obtained from a single operator from month to month.

Errors introduced into measurements of compaction by individual differences in stressing are not cumulative and are compensated for in succeeding measurements. As the total amount of measured compaction accumulates during a period of several months, the ratio of error to total compaction decreases.

No attempt has been made to compensate for possible errors introduced into the measurements of a single month. Where the measurement of a given month appears to be in error, the amount of measured compaction is simply added to the compaction of an adjacent month and a mean value is shown for the combined periods. In addition, all records of apparent expansion of the aquifer system have been removed by averaging the measured expansion with the measured compaction of an adjacent month, or months. Recorded expansion was removed because it was not possible at some sites to separate objectively the records of net expansion that result from head recovery from the records of apparent expansion that are the result of operator error.

At some sites, such as the Oro Loma site, friction was large and the operator error was large compared to the small amount of monthly compaction. For this reason, the evaluation of the monthly compaction record for the Oro Loma site is not included; instead, annual compaction rates and water-level changes at Oro Loma are shown in figure 12.

At the four other sites (see figs. 13–17), friction was small or the amount of operator error was small compared with the large amounts of monthly compaction being measured. The records from these sites provide useful information about the changes in compaction rates as related to the changes in applied stress, as indicated by changes in water level.

The relation of monthly and bimonthly compaction to lower-zone water-level change for 1961–66 at the Mendota site is shown in figure 13. The water-level record is continuous, and the time of measurement of the compaction is at the end of each period shown. Casing-cable friction is moderate in well 14/13–11D6. Most of the compaction is recorded when the cable is stressed. The total recorded compaction is the sum of the relative cable movement during the period and the relative cable movement resulting from cable stressing at the end of the period.

The general relation at the Mendota and other sites is that the maximum amounts of monthly compaction are recorded during times of declining head. During times of rising head, the amounts of monthly compaction commonly are less than half the maximum values, even when water levels are within 20 feet of historic low levels. As a result, the inverted bar graph in figure 13 gives the general impression that most of the compaction occurs before seasonal low water levels have occurred.

The pattern just described is interpreted as being the result of elastic compaction and expansion of the aqui-

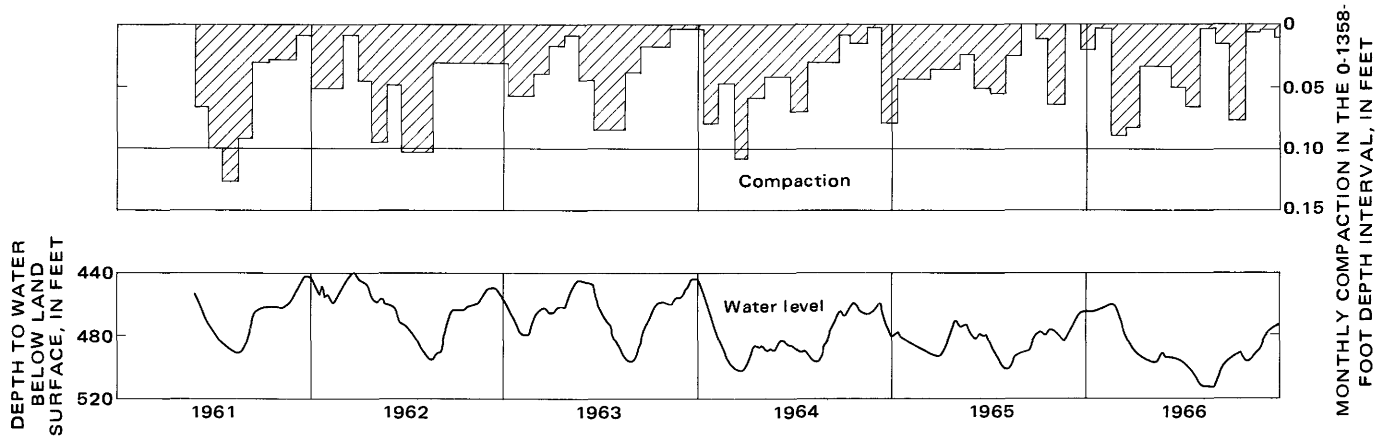


FIGURE 13.—Relation of monthly compaction to lower-zone water-level change at the Mendota site, well 14/13–11D6.

fers and thin aquitards that is superimposed on continuing virgin compaction of the thicker aquitards and aquicludes. Most elastic changes in thickness of the aquifer system are assumed to be rapid and linear in response to change in applied stress. Virgin compaction rates should be more rapid at times of low water levels than at times of high water levels because the applied stress is greater. During times of applied-stress increase, elastic compaction is added to virgin compaction, but during times of applied-stress decrease, elastic expansion is subtracted from virgin compaction.

An estimated elastic component was removed from the recorded compaction values of the 1963 record for well 14/13–11D6 at the Mendota site to evaluate the validity of the foregoing interpretation.[2] The elastic changes were estimated for those deposits assumed to be sufficiently permeable to have little or no time delay for thickness changes during times of applied-stress change. Cores from the Mendota site suggest that the sandy deposits undergoing elastic changes consist chiefly of sands, silts, and thin-bedded clayey sands. A total of 118 feet of clayey deposits was not included in the computation of elastic change in thickness because of the time needed to expel water from aquitards upon increase in applied stress. Also, those aquitards within which virgin compaction was continuing would continue to expel water during times of decrease in applied stress. The core record indicates that 540 feet of sandy deposits occur in the 658-foot interval between the base of the Corcoran Clay Member at a depth of 700 feet and the anchor depth of 1,358 feet. An additional 60 feet of sand is in that part of the upper zone that is assumed to be compacting to cause about 19 percent of the subsidence during 1963–66.

The pattern of computed monthly virgin compaction for the 1963 data varies, depending on the values assigned to specific unit expansion for the 600 feet of sandy deposits within the compacting interval. Low values, such as $1.6\times10^{-6}\text{ft}^{-1}$, reduce the variation in compaction between the periods, but tend to retain the general pattern of figure 13, where maximum compaction values occur before the times of maximum applied stress. A specific unit expansion of $5.0\times10^{-6}\text{ft}^{-1}$ was tried, but resulted in 3 of the 6 months of water-level decline being associated with assigned amounts of elastic compaction that exceeded measured compaction for those months. Thus, a specific unit expansion of $5.0\times10^{-6}\text{ft}^{-1}$ is above an upper limit for assigning a reasonable value of specific unit expansion.

An intermediate value between the extremes of 1.6 and $5.0\times10^{-6}\text{ft}^{-1}$ appears to be reasonable for the purpose of evaluating gross changes in the pattern of monthly and bimonthly compaction. Accordingly, a value of $3.3\times10^{-6}\text{ft}^{-1}$ for elastic specific unit compaction (or expansion) was assigned as a reasonable compromise. The computed elastic specific compaction or expansion of the aquifers, using this assumption, would be $3.3\times10^{-6}\times600=2\times10^{-3}$ feet per foot of water-level change. The assigned value of specific unit expansion appears to be a reasonable approximation when compared with a mean upper-zone value of $3.5\times10^{-6}\text{ft}^{-1}$ measured at the Lemoore site.

The elastic change in gross aquifer thickness at the Mendota site that occurred as a result of net water-level rise or decline was computed for each month. When this change was added to the measured compaction during times of rising water level and subtracted during times of declining water level, computed values of estimated virgin compaction were obtained. The cumulative computed monthly virgin compaction for the period January 2, 1963, to January 7, 1964, was 0.49 foot. The cumulative measured compaction during the same time interval was 0.48 foot. Water levels at the end of this period were only 4 feet higher than at the beginning, and so it is assumed that net elastic change in aquifer-system thickness was negligible during 1963.

The monthly plot of the computed virgin compaction is shown in figure 14. The amounts of computed monthly virgin compaction seem to bear a closer relation to change in applied stress, as indicated by the water-level plot, than does the plot of total monthly compaction in figure 13. Computed virgin compaction is distributed more uniformly throughout the year, and the rate of computed virgin compaction is less during the seasons of high water level. Distortions due to fric-

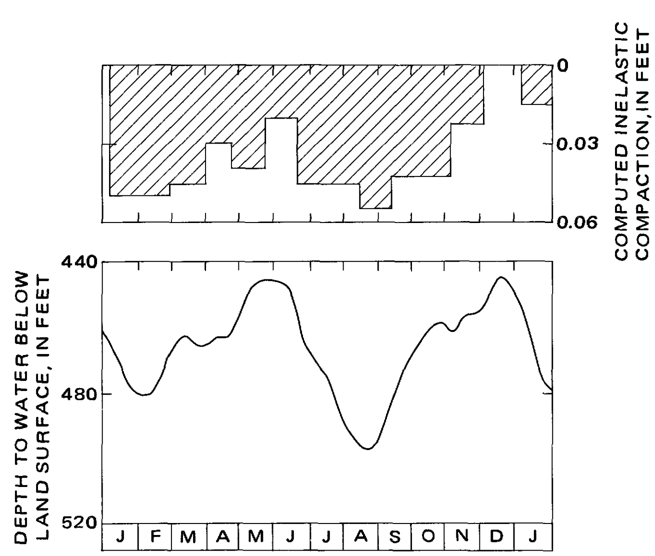


FIGURE 14.—Relation of computed virgin compaction to lower-zone water-level change at well 14/13–11D6.

[2]It should be recognized that during the seasonal rise and fall of artesian head for the aquifers, the boundaries within the aquitards between expanding and compacting thicknesses are constantly changing.

tion within the recorder system and the grossness of the method of removing the elastic component preclude more detailed interpretations of figure 14.

The relation of the recorded compaction to lower-zone water-level change at the Cantua site is shown in figure 15. The compaction-recorder system in well 16/15–34N1 probably has more casing-cable friction than any other compaction-recorder system in the San Joaquin Valley. The friction caused by contact of the vinyl-coated cable and the 4-inch casing in this 2,000-foot well is such that compaction rarely is recorded if the cable is not stressed during each visit.

Well 16/15–34N4 provided a good water-level record for the lower zone from 1960 to April 1963 when the effects of 2 feet of casing shortening caused the casing to rupture in two places. The ruptures allowed upper-zone water to enter the well, causing anomalously high water levels. The well was repaired in December 1964 and a good water-level record has been obtained since.

The casing in the compaction-recorder well apparently has not ruptured, despite the 9 feet of casing shortening that occurred between mid-1960 and 1967. There are two reasons why the compaction-recorder casing has not ruptured: The compaction-recorder well has a 4-inch casing, which is stronger than the 8-inch casing in the water well (Pt. 2, Bull, 1974, fig. **39**), and also has three slip joints which appear to have been effective in relieving much of the stress placed on the casing as a result of compaction.

Despite the large amount of casing-cable friction in well 16/15–34N1, a consistent record of monthly and bimonthly compaction has been obtained. The times of rising water levels are the times of minimum compaction, and the times of declining water levels are the times of maximum compaction. Those months of rapid decline in water level commonly are the months of maximum measured compaction—a situation suggestive of elastic compaction superimposed on virgin compaction of the aquifer system, such as was decribed for the Mendota site.

The relation of recorded monthly compaction to lower-zone water-level changes at well 19/16–23P2, about 8 miles northwest of Huron, is shown in figure 16. Well 19/16–23P2 was an unsuccessful oil test drilled in

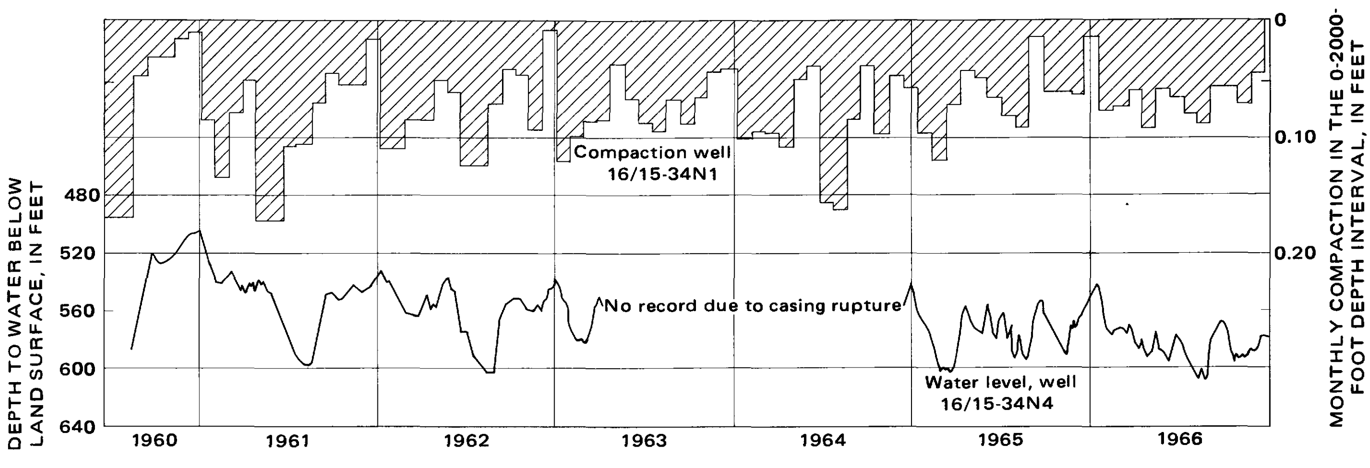


FIGURE 15.—Relation of monthly compaction to lower-zone water-level change at the Cantua site.

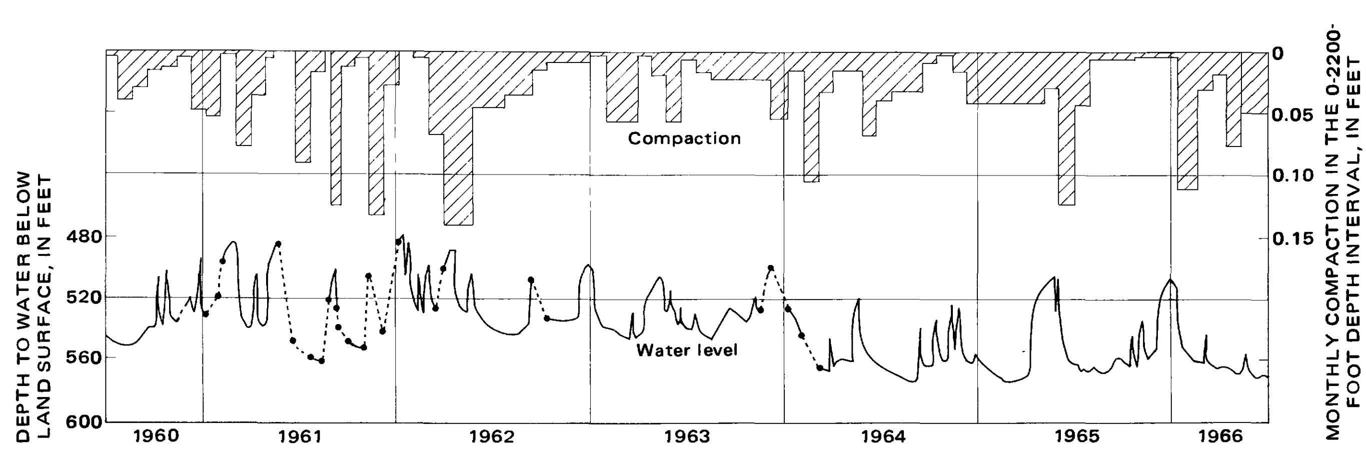


FIGURE 16.—Relation of monthly compaction to lower-zone water-level change at 19/16–23P2.

1950. Subsequently, the surface string of 13 ⅜-inch casing was plugged with cement below 2,200 feet, and the upper part was gun perforated. The well was used as an irrigation well for several years.

The mode of operation of the compaction recorder at this site has not been as consistent as at the other sites. Problems with the cable have been frequent, and the cable had to be replaced five times during the period of record shown in figure 16. The well-casing diameter is 13 inches, which results in less casing-cable friction than if the casing diameter was smaller. However, except for the period since August 1966, friction has been sufficient to require cable stressing at each visit. Prior to August 1966, monthly amounts of compaction tended to be erratic during those periods when the cable was not stressed during each servicing of the installation.

Apparent expansion of the aquifer system has occurred at well 19/16–23P2, but has been removed from the record shown in figure 16 in order to be consistent with the type of presentation shown in figures 13–17.

A float-operated water-level recorder has been used in the same well to obtain a record of the artesian head. Parts of the record, particularly in 1961, are missing because of a tendency of the float to be caught between the compaction cable and the casing. The sharp fluctuations in water level result from the intermittent pumping of irrigation well 19/16–23P1 about 500 feet southwest of the observation well.

Several general features of the records shown in figure 16 are apparent. The times of minimum measured monthly compaction occur mostly during times of rising water levels. Monthly compaction in excess of 0.1 foot occurs during times of rapid artesian-head decline, which suggests that most of these large monthly amounts of compaction are the result of elastic compaction of large thicknesses of deposits. Comparison of the compaction and water-level records is better during those times when the cable was stressed at each visit, such as during 1965 and 1966, than during periods in which the cable was rarely stressed, such as during 1963 and 1964.

No attempt has been made to separate the elastic and virgin components of compaction in the 19/16–23P2 record because of the frequent equipment changes and the inconsistent stressing of the cable.

The relation of compaction to lower-zone water-level changes at the Westhaven site is shown in figure 17. Both the water-level and compaction records are based on monthly measurements. The compaction recorder is described by Poland and Ireland (1965).

The amounts of monthly compaction were small. Most of the compaction occurred during times of declining water levels, and little net compaction was measured during times of rising water levels.

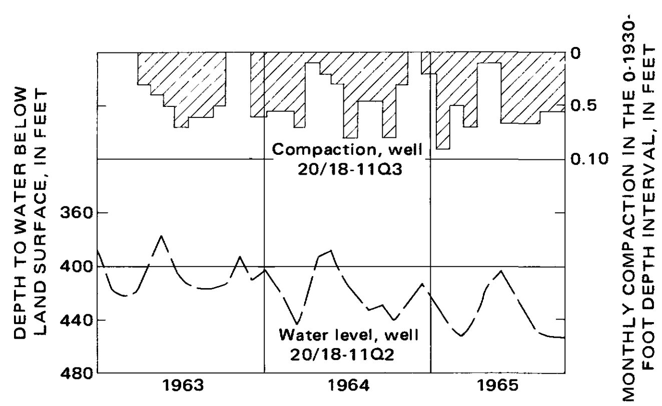


FIGURE 17.—Relation of monthly compaction to lower-zone water-level change at the Westhaven site, 20/18–11Q2, 11Q3.

RELATION OF COMPACTION AND EXPANSION TO CHANGE IN ARTESIAN HEAD

The records of monthly compaction in the preceding section indicated that thickness changes within the elastic range greatly affect the pattern of short-term recorded compaction of the aquifer system. However, the excessive friction at most sites and the low sensitivity of the graphical analysis of figures 13–17 permit only general interpretations. Three sites within the study area have sufficiently low friction that the records can be used to obtain quantitative estimates about the mechanics of the aquifer systems. The net expansion characteristics of the aquifer-system skeleton can be approximated in some cases, and the types of inelastic processes can be identified.

The reader is cautioned to regard the quantitative estimates as being only general approximations. Even at sites where changes in aquifer-system thickness are being measured accurately, two types of questions arise regarding the water-level data. First, in a heterogeneous aquifer system, "What is the interval that is being affected by the head changes indicated by the water-level record?" Where additional data are available, the water-level records of nearby irrigation wells are compared with the observation-well record to see if they are similar and if the times of water-level change coincide with the times of aquifer-system compaction or expansion. In the absence of these cross-checks, it is assumed that the water-level record is representative of the aquifer system. The second question is, "What are the variations in pore pressure in the aquifers and aquitards within the thickness of deposits opposite the perforated casing?" This question cannot be resolved unless piezometers are installed in many aquifers and aquitards. It is assumed that the water-level record represents an integrated pore-pressure distribution for the aquifers and that the pore pressures in the aquitards not only lag behind the pore-pressure changes in the aquifers but also have less seasonal fluctuation than pore pressures in the aquifers. Excess pore pressures in the central parts of the thicker aquitards may have no seasonal fluctuation, only a variable rate of decay, depending on the magnitude of the hydraulic gradient to contiguous aquifers.

Therefore, the general purposes of this section are to provide some gross approximations of the physical constants of the aquifer systems, to illustrate techniques of relating water-level change to change in aquifer-system thickness, and to provide tentative interpretations of the figures and tables of this section.

Most of the following interpretations are based on the classical hydrodynamic theory of soil consolidation (Terzaghi and Peck, 1948, p. 233–242). Field compaction and water-level records help verify parts of the theory of consolidation of clays that has been developed through laboratory investigations. Also, field studies can add to those aspects of the theory that cannot be tested in the laboratory.

Eleven compaction recorders in the study area have recorded net expansion during water-level rise. The records of net expansion from three of the sites are presented in this section. Water-table changes are negligible at all three sites during the periods of record, and so the artesian-head changes are the only causes of the applied-stress changes.

The Lemoore Site

Excellent records of aquifer-system compaction and expansion and the associated water-level changes have been obtained from well 18/19–20P2, about 10 miles northeast of Westhaven. This upper-zone well taps the confined aquifer system above the Corcoran. A float-operated recorder monitors water-level changes through a perforated interval 497–537 feet below the land surface. The well is 577 feet deep, has a 6⅝-inch casing, and has a reverse-lay stainless steel cable that does not require stressing when the charts are changed on the 1:1 and 24:1 recorders.

The depth range of deposits affected by the change in recorded artesian head has been estimated from an electric log of well 18/19–20P1 (Pt. 2, Bull, 1974, fig. 47) and from the water-level record in a nearby well 260 feet deep. The electric log indicates that a continuous sand occurs between depths of 294 and 565 feet, which is confined by lacustrine (Croft, 1972) clay beds at depths of 277–294 and 565–577 feet. The lower clay is the upper part of the Corcoran. Nearby well 18/19–21R3 is perforated in the depth interval 220–260 feet and has a water level that is 40–50 feet higher than the level in well 18/19–20P2 but fluctuates annually about 45 feet. Thus, substantial long-term artesian-head decline has occurred to at least as shallow a depth as the base of a clay bed between depths of 230 and 245 feet, and seasonal fluctuations are sufficiently large to cause elastic compaction and expansion in the sand interval between 245 and 277 feet. For purposes of this discussion, the section penetrated by well 18/19–20P2 that is compacting and expanding is estimated to be between 230 and 577 feet—a thickness of 347 feet. The total thickness of the three clay beds affected by head decline is 44 feet.

The water-level record of well 18/19–20P2 represents the applied-stress changes at the site. Good hydraulic continuity exists in the thick sand sequence between the depths of 294 and 565 feet, which constitutes 89 percent of the aquifer material within the 347-foot thickness. The aquifer between depths of 245 and 277 feet is only 32 feet thick. The rate and amount of head changes differ moderately from that of the aquifer below the 294-foot depth, and it is known that both aquifers undergo head declines during the late winter and summer and have rising heads during the autumn.

Changes in aquifer-system thickness during regional water-level recovery are shown in figure 18, which includes the summer low water level of 214 feet and the winter high water level of 157 feet. The water-level recovery needed to record net expansion generally is only 1–2 feet. The fact that only 1 foot of applied-stress decrease was needed to initiate net aquifer-system expansion when the depth to water was 214, 201, and 169 feet shows that the aggregate virgin compaction of the beds was small. Virgin compaction may continue at a slow rate in a few tens of feet of clay beds during times of water-level rise, when most of the deposits are expanding. The net result is recorded expansion almost as soon as applied stress starts to decrease. Furthermore, the 1-foot rise in water level needed to reverse the trend from compaction to net expansion indicates that the amounts of casing-cable friction and lag in the recorder system are minimal.

In a major contribution, Riley (1969) developed a graphical method for plotting field measurements of water-level change and compaction as stress-strain curves. Under favorable circumstances, these can be used to obtain quantitative values for gross elastic storage and compressibility parameters and other characteristics of compacting aquifer systems. A stress-strain plot for well 18/19–20P2 is shown in figure 19. Consecutive periods of repeated applied-stress increase and decrease produce a series of loops, or nearly parallel segments, that are displaced with increasing time toward the right side of the plot as a result of cumulative inelastic compaction. Cumulative compaction between two dates can be determined along any line of equal applied stress.

The descending segments of the stress-strain plot are of particular interest because they represent the times

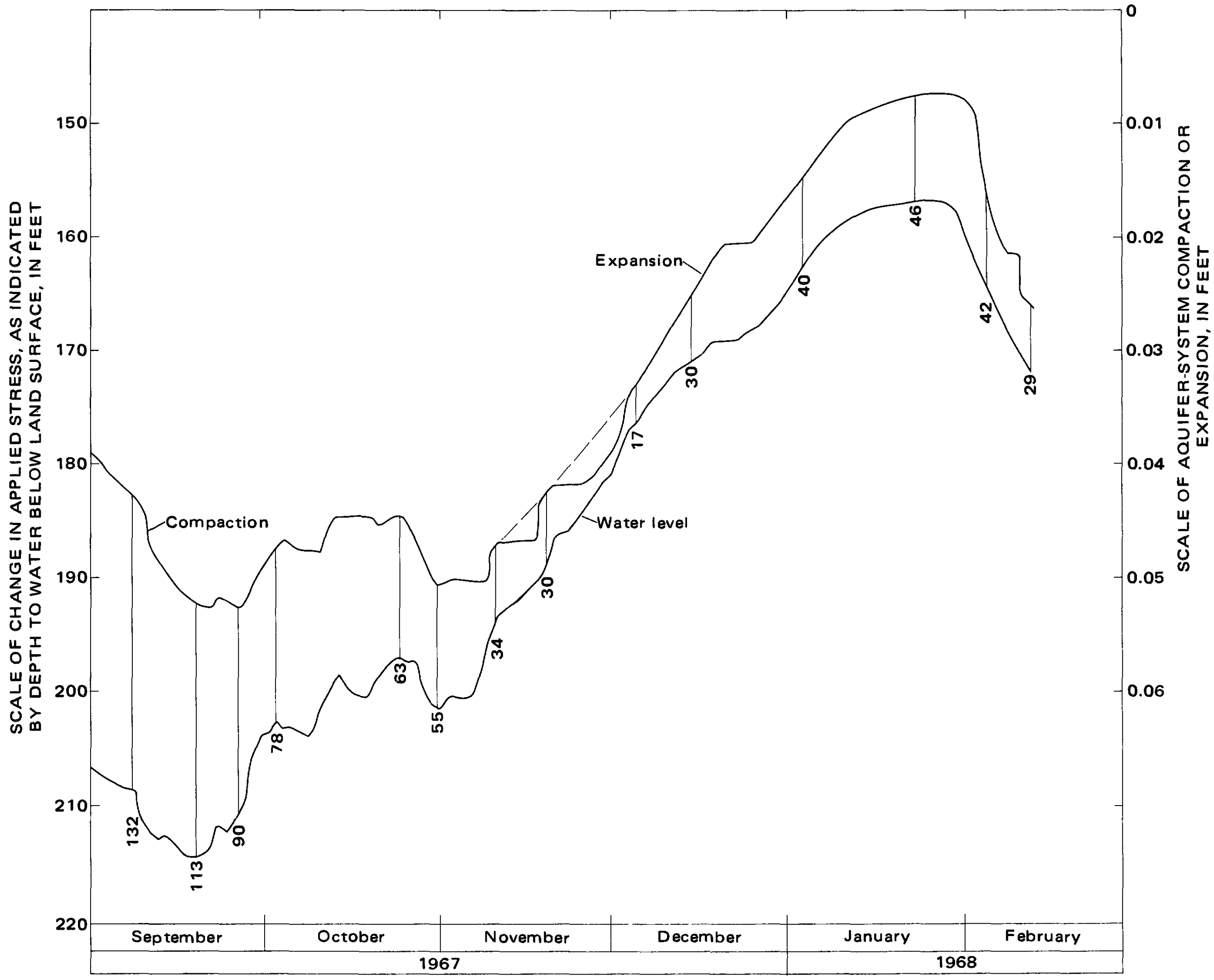


FIGURE 18.—Relation of aquifer-system compaction or expansion to water-level change, well 18/19–20P2.

of net aquifer-system expansion. The mean slope of the lower parts of the descending limbs provide a means of approximating the modulus of expansion of the aquifer system—the specific expansion. The net specific expansion indicated by the mean slope shown in figure 19 is 1.2×10^{-3}. This is the component of the storage coefficient attributable to elastic response of the confined aquifer system skeleton. The net specific unit expansion is

$$\frac{1.2\times10^{-3}}{347 \text{ feet}}=3.5\times10^{-6}\text{ft}^{-1};$$

this is the component of specific storage attributable to elastic response of the confined system skeleton.

The descending and rising limbs of the plot are not congruent. At times of equal applied stress, the rising limb may be to the left of the descending limb (5/8/67 and 4/19/67) or to the right of the descending limb (2/10/68 and 12/20/67). These variations can be explained by differences in the rates of delayed changes that are occurring in the aquifer system. The greatest sensitivity of the stress-strain plot is in determining the approximate elastic properties of the aquifer systems. A graphical procedure that is sensitive in determining virgin changes (fig. 18) will be used to describe the hydrodynamic processes and to explain the variations in the stress-strain plot.

Figure 18 shows the effects of variation in the rates and types of time-delayed changes on aquifer-system thickness. The previous discussion about the relation of monthly compaction to water-level changes showed the importance of elastic changes on recorded compaction during times of changing applied stress, and so it can be assumed that much of the thickness change in figure 18 is elastic. If all the thickness changes were elastic and

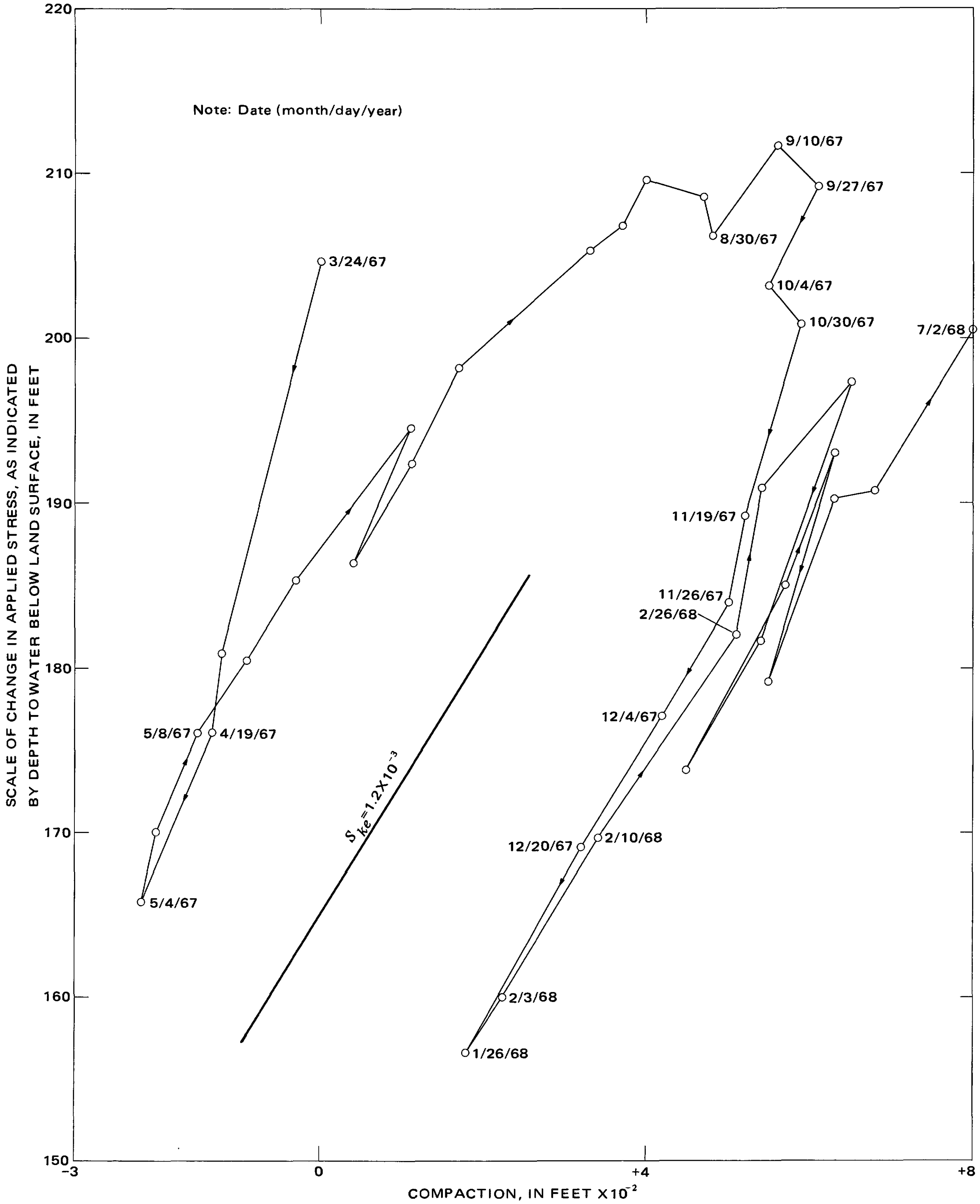


FIGURE 19.—Stress-strain plot for well 18/19-20P2. (Modified from Poland, 1969a, p. 19.)

occurred without time delay, the expansion and compaction plot would parallel the plot of applied-stress change represented by the water-level record. Only a small part of the two plots is parallel—near the 175-foot depth-to-water part of the record. At deeper water levels, convergence of the plots from September into December is interpreted as being the result of continuing virgin compaction that is concurrent with elastic expansion. The result is that net expansion is less than if virgin compaction were not continuing. At rising water levels above 175 feet, the divergence of the plots is interpreted as being the result of delayed expansion. Delayed expansion may have been occurring at deeper water levels also, but was masked by large rates of virgin compaction.

The relative magnitudes of convergence and divergence at selected times are shown by the dimensionless numbers in figure 18. The rate of convergence is more rapid during times of deep than shallow water levels, indicating that virgin compaction rates are larger during times of larger applied stress.

The large rate of convergence during the period of declining water levels early in February as compared with the divergence rates preceding the start of head decline indicates that time-delayed compaction was occurring at water levels of less than 170 feet. It cannot be determined if part of the delayed compaction is inelastic, because either elastic or inelastic compaction would cause the convergence patterns in figure 18. Three thick clay beds are influenced by water-level changes in well 18/19–20P2. Apparently, one or more of the beds is sufficiently thick and of sufficiently low diffusivity to retain excess pore pressures after 57 feet of head recovery from the summer low water level of 214 feet. These excess pore pressures have resulted from years of cumulative head decline. The linear plot for the same time period in figure 19 suggests that most of the change in aquifer-system thickness at water levels above 170 feet is elastic. It should be kept in mind, however, that concurrent delayed compaction and delayed expansion tend to offset each other to an unknown degree that varies with applied-stress level.

The presence of delayed expansion shows that three concurrent processes are tending to change aquifer-system thickness during times of applied-stress decrease—elastic expansion with no measurable time delay (presumably chiefly of the aquifers), delayed elastic expansion (presumably of the thin aquitards and outer parts of the thick aquitards), and virgin compaction (presumably of the thick aquitards and aquicludes). It is assumed that the rates of elastic change in the aquifers occur linearly and that inelastic compaction rates decrease and delayed expansion rates increase with decreasing applied stress. The amounts of delayed expansion at the Lemoore site cannot be estimated, because virgin compaction was occurring at the same time. However, it appears that during times of high water levels the rates of delayed expansion exceed the rates of virgin compaction, for a given rate of applied-stress decrease.

Variations in net specific unit expansion during the seasonal decrease in applied stress are shown in table 1.

TABLE 1.—*Variation in net specific unit expansion during a period of seasonal head recovery at well 18/19–20P2*

Date	Depth to water (ft)	Water-level rise (ft)	Mean rate of water-level rise (ft per day)	Recorded net expansion (ft)	Specific unit expansion ($\times 10^{-6}ft^{-1}$)
1967					
Sept. 20	214.0				
Sept. 22	211.5	2.5	1.2	0.0005	0.6
Sept. 24	212.0				
Oct. 2	202.5	9.5	1.1	.006	1.8
Oct. 8	204.0				
Oct. 13	198.0	4.0	.8	.003	2.2
Oct. 31	201.5				
Nov. 10	195.0	6.5	.6	.004	1.8
Do	195.0				
Nov. 18	190.0	5.0	.6	.004	2.3
Do	190.0				
Dec. 4	177.0	13.0	.8	.013	2.9
Do	177.0				
Dec. 18	169.7	7.3	.5	.009	3.5
Do	169.7				
1968					
Jan. 10	159.0	10.7	.5	.012	3.2
Do	159.0				
Jan. 21	157.0	2.0	.2	.0025	3.6

The mean rates of water-level rise were 1.2 feet per day immediately after the summer low water level, but decreased to 0.2 foot per day for an 11-day period preceding the winter high water level. Most of the periods had mean rates of water-level rise of 0.6–0.8 foot per day.

The values of net specific unit expansion for the nine intervals of head recovery at well 18/19–20P2 given in table 1 form a logical sequence when considered in a context of the combined effects of decreasing rates of water-level rise (decrease in applied stress), concurrent decrease in virgin compaction rates, and increase in delayed expansion rates. Table 1 shows that net specific unit expansion reaches a value of 3.5×10^{-6} more than 1 month before the winter high water level. Low values of net specific unit expansion occur during the three periods after the summer low water level, even though the rates of head recovery are the most rapid during these periods. The low values of net specific unit expansion are interpreted as being the result of rapid rates of virgin compaction. Between October 8 and December 18, the rates of water-level rise are roughly constant, but the values of net specific unit compaction increased from 2.2×10^{-6} to $3.5\times10^{-6}ft^{-1}$. This increase can be attributed largely to a decrease in the rate of virgin compaction with decrease in applied stress and to an increasing rate of delayed expansion.

THE YEAROUT SITE

Monthly compaction and expansion and water levels have been measured in upper-zone well 13/15–35D5, about 4 miles east of Mendota. The 4-inch well casing is perforated opposite Sierra micaceous sands and silts at depths of 373–433 feet. The bottom of a pipe-type compaction gage is set in the upper part of the Corcoran at a depth of 440 feet (Pt. 2, Bull, 1974, table 1).

The depth range of deposits affected by change in recorded artesian head was estimated from an electric log of well 13/15–35D1 (200 ft west of well 35D5) and water-level data from observation well 35D5 and irrigation well 13/15–34A1 (325 ft west of well 35D5 and perforated at depths of 100–276 ft). Comparison of the compaction and water-level records indicates that the water levels of the two wells are about the same during times of no pumping. However, head decline is larger in well 13/15–34A1 because pumping is more intense in the 100–200 -foot-deep sand section than in the 280–430-foot-deep sand and silt section. Comparison of a 10:1 expanded-scale compaction record and the two water-level records shows that the detailed variations of the compaction record coincide with short-term water-level fluctuations in well 13/15–34A1. For purposes of this discussion, the section penetrated by well 13/15–35D5 that is compacting and expanding is estimated to be between depths of 100 and 440 feet—a thickness of 340 feet.

The monthly water-level measurements for well 13/15–35D5 represent the approximate trend in applied-stress change at the site. Because larger seasonal fluctuations occur in the upper part of the aquifer system, the seasonal changes indicated by the water-level record for well 13/15–35D5 should be regarded as minimal mean changes in head. Monthly instead of continuous water-level measurements also result in minimal seasonal recorded head changes.

The relation of water-level and aquifer-system-thickness changes in well 13/15–35D5 are shown in figure 20. The general trends of the plots are parallel, but short-term departures from parallelism are apparent for some months.

Maximum values of net specific unit expansion can be computed for the fall and winter of 1966–67 and 1967–68. For 1966–67, the specific unit expansion was

$$\frac{\text{0.051-ft increase in thickness}}{\text{(340-ft thickness)} \times \begin{array}{l}\text{(38-ft decrease}\\ \text{in applied stress}\\ \text{as indicated by}\\ \text{water-level rise)}\end{array}} = 4.0\times10^{-6}\text{ft}^{-1}.$$

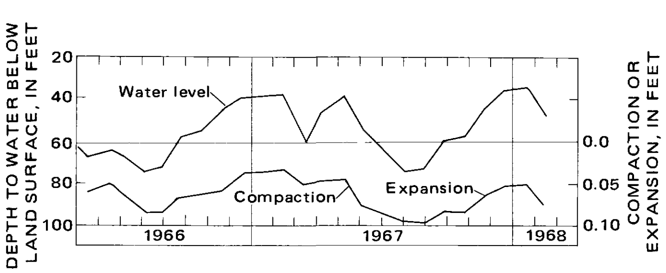


FIGURE 20.—Relation of aquifer-system compaction or expansion to water-level change, well 13/15–35D5.

The specific unit expansion for the 0.045 foot of expansion and 39 feet of head recovery in 1967–68 was $3.4\times10^{-6}\text{ft}^{-1}$. These values are regarded as maximal because the upper part of the aquifer system probably had larger seasonal water-level changes than the lower part represented by the record from well 13/15–35D5. It is concluded that the specific unit expansion at the Yearout site is not greatly different from that at the Lemoore site ($3.5\times10^{-6}\text{ft}^{-1}$, from fig. 19).

Most of the upper-zone thickness changes at well 13/15–35D5 are elastic. Between August 2, 1966, and August 1, 1967, the net cumulative compaction at the site was only 0.013 foot, during which time a net water-level rise of 1 foot occurred. Between August 2, 1966, and February 14, 1967, a seasonal water-level recovery was accompanied by a net expansion of the aquifer system of 0.051 foot. Assuming that half of the delayed compaction occurred during each of the two halves of the year, 0.058 foot (0.051 ft+0.0065 ft=0.058 ft) of expansion occurred during the 6½-month period of head rise, and 0.058 foot (0.064 ft−0.0065 ft=0.058 ft) of elastic compaction occurred during the 5½ months of head decline. The elastic component of seasonal compaction (0.58 ft/0.064 ft) is estimated to be about 90 percent. Thus, as at most of the other sites, elastic changes greatly affect short-term recorded compaction during times of head change.

WELL 19/16–23P2

In August 1966, the compaction recorder in well 19/16–23P2 was rebuilt to obtain a better record of aquifer-system compaction and expansion. The recorder system is described in Part 2 (Bull, 1974). The 24:1 expanded-scale record assists in evaluating small amounts of compaction and net expansion and in determining the times of change from recorded compaction to recorded expansion. A discussion of the thickness of Diablo alluvial-fan deposits affected by the applied stress changes was presented on page G13 of the present report.

The record from well 19/16–23P2 can be used to determine long-term cumulative compaction to illustrate the importance of the relative magnitudes of rates of head recovery and delayed compaction in determining whether net expansion or compaction occurs to demonstrate the large mechanical lag in this compaction recorder 2,200 feet deep, and to evaluate the relative friction and stretch characteristics of the different types of cables that have been used in the well.

In addition to casing-cable friction, the type of well construction also requires scrutiny. The casing is plugged with cement below the compaction anchor and is encased to the land surface in a cement jacket, a system which poses the question of whether the casing-cement construction seriously distorts the response of the aquifer system to changes in effective stress.

The casing has been telescoped by vertical shortening of the adjacent deposits. About 97 percent of the compaction measured at the site results in casing shortening, and only 3 percent results in increased protrusion of the casing above the land surface. Although it cannot be proved that casing shortening is distributed identically to formation shortening, the assumption is made that casing deformation conforms with aquifer-system deformation. Poland and Ireland (1965, p. B182) also made this assumption at the Westhaven site on the basis of casing shortening being equal to 95 percent of the compaction.

Compaction and water-level records for February–July 1967 are shown in figure 21. The effects of intermittent pumping of nearby irrigation well 23P1 are superimposed on a regional water-level rise. Net aquifer-system expansion was recorded during times of rapid decrease in applied stress as indicated by water-level rise, and aquifer-system compaction occurred during times of increase in applied stress as indicated by water-level decline. A brief 10-foot recovery in potentiometric level in early June was sufficient to cause a reversal from recorded compaction to recorded expansion.

The fact that compaction exceeded expansion in figure 21 during a net rise in potentiometric level is attributed to delayed compaction as water was expelled gradually from aquitards that had residual excess pore pressures. In March, water levels were deeper than 580 feet. In June, water levels declined to only 575 feet, but 0.08 foot of delayed compaction had occurred since March.

Detailed compaction and water-level changes for a 1-month period, March 14 to April 13, 1967, are shown in figure 22. The 1:1 and 24:1 records of compaction and expansion have been traced directly from the field charts, and the water-level record has been replotted and positioned vertically so that the April 3 compaction and water-level plots coincide. The stepped compaction record is the result of casing-cable friction.

The water level in observation well 23P2 rose 19 feet between March 18 and 22, while the nearby irrigation well pump was turned off, and declined 17 feet when the well was pumped again. The water level rose about 2 feet between March 29 and April 3, as a result of regional head rise (fig. 21). After the irrigation well pump was turned off on April 3, the water level rose 31 feet in 10 days.

The water level had been drawn down below the 570-foot depth six times in the preceding years, but had been drawn down below the 580-foot depth only once (during February and March 1967, fig. 21). About 0.006 foot of compaction was recorded during the March 13–18 head-decline period. The shortening probably was largely delayed virgin compaction from prior head declines.

The recorded net aquifer-system expansion of 0.015 foot between March 18 and March 22 resulted from a 19-foot rise in potentiometric level. The first measured expansion was about 19 hours after the irrigation well pump had stopped and after about 10 feet of water-level recovery had occurred. After expansion was first recorded, about 5 feet of water-level recovery occurred for each 0.01 foot of recorded net expansion.

When the irrigation well pump started again on March 22, a new period of compaction began. By the time the applied stress had increased 17 feet, 0.01 foot of compaction had been recorded. Then, while the applied stress decreased 2 feet between March 29 and April 3, an additional 0.015 foot of net virgin compaction was recorded. This delayed compaction is interpreted as being the result of continuing slow explusion of water from aquitards whose pore pressures greatly exceeded the pore pressures in the adjacent aquifers.

A second period of aquifer-system expansion began April 3 when the irrigation-well pump was turned off After 14 hours, and 10 feet of water-level rise, expansion was recorded again. By April 13, 31 feet of water-level recovery and 0.025 foot of net aquifer-system expansion had been recorded. After expansion was first recorded, about 9 feet of water-level recovery occurred for each 0.01 foot of expansion. The high points on the 24:1 record of aquifer-system expansion from April 4 to 13 form a curve similar to the curve of applied-stress reduction.

The similarity of the expansion and decrease-in-applied-stress curves is interpreted as suggesting that little time is needed to raise pore pressures in many of the aquitards. Compaction ceases when the pore pressures in the aquifers rise to the maximum pore pressure in a contiguous aquitard, thus preventing further expulsion of water. Further increases in pressure are transmitted fairly rapidly, even in aquitards, because in the elastic range their specific storage is very small.

The mechanics of elastic aquifer-system compaction is in distinct contrast to inelastic compaction, in regard to the volumes of water involved. During periods of decreasing aquifer pressures (water-level decline), elastic expansion of the water and elastic decrease in pore volume occur, and these volumes are small. When the effective stresses in the aquifers exceed prior effective stresses in adjacent aquitards, virgin compaction occurs. The volume of water moving out of the aquitards at such times generally is many times larger than the volume of water moving into the aquitards to establish pressure equilibrium during periods of rising water

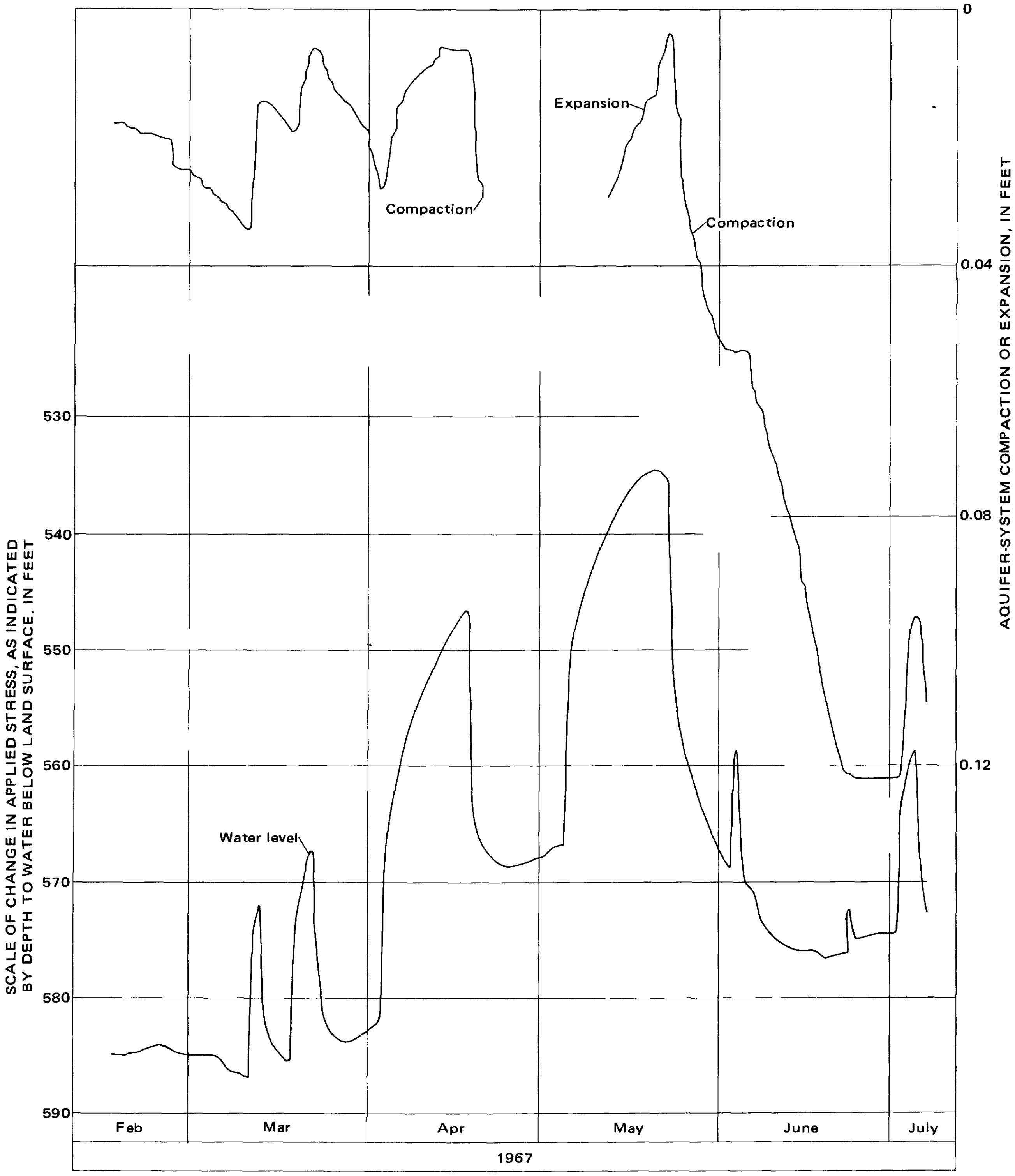


FIGURE 21.—Relation of aquifer-system compaction and expansion to water-level change in well 19/16–23P2, February-July 1967.

levels and elastic expansion of the aquitards.

The time lag at the reversals from compaction to recorded expansion is due to the mechanics of the aquifer system and to the mechanics of the recorder. Elastic expansion is concurrent with decrease of grain-to-grain stress, even when net compaction is continuing within some aquitards. When the aggregate expansion of the aquifers and thinner aquitards exceeds aggregate shortening of the thicker aquitards still compacting, net expansion of the aquifer system will occur.

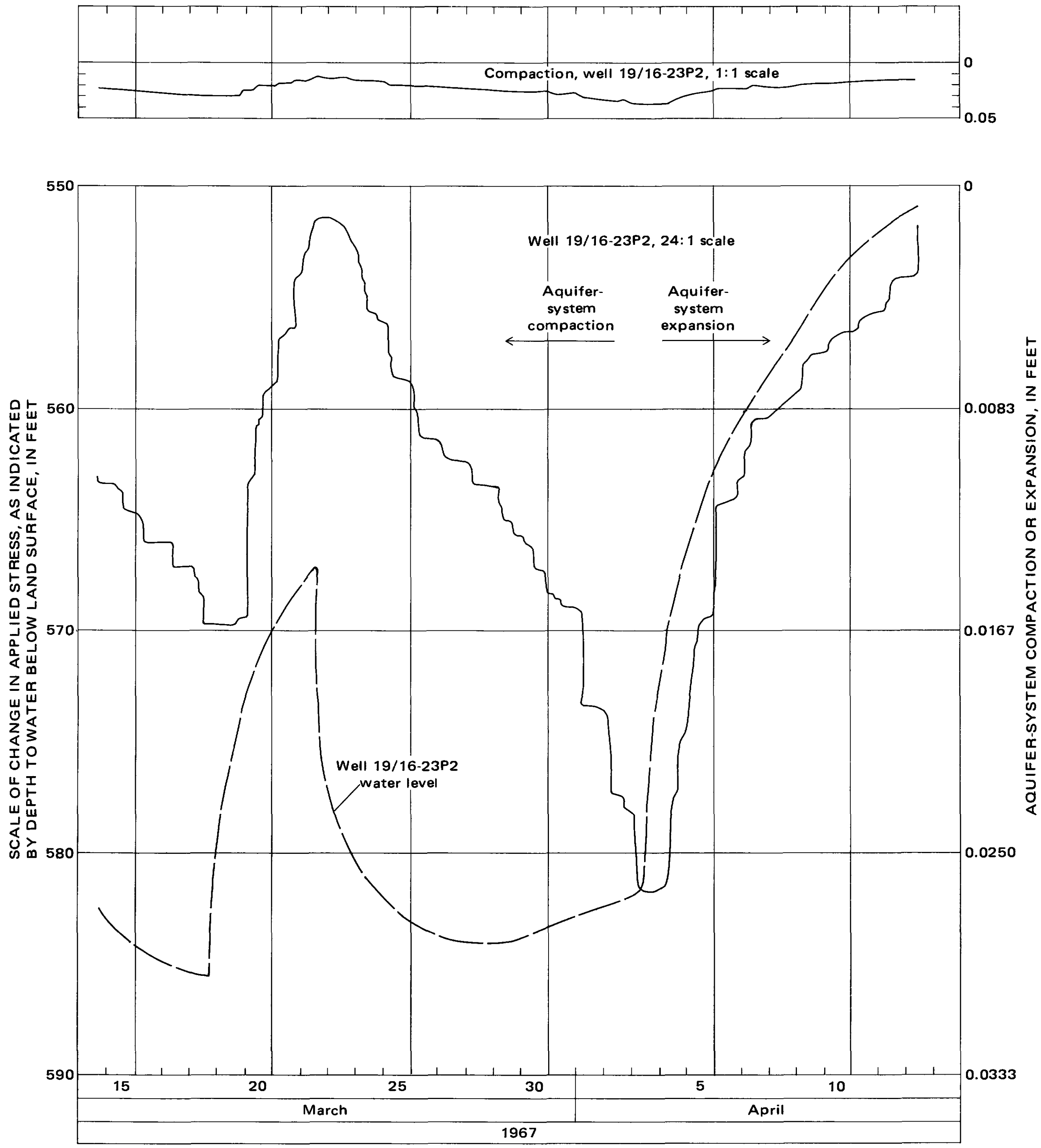


FIGURE 22.—Relation of aquifer-system compaction and expansion to water-level change in well 19/16-23P2, March 14–April 13, 1967.

Expansion will not be recorded, however, until the direction of movement of the recording equipment has been reversed. When a system that has casing-cable friction is recording compaction below the uppermost point of contact between the casing and the cable, cable tension is reduced below that point. The counterweights move down relative to the concrete pad, when the cable tension is reduced by an amount that exceeds friction in the system. On the other hand, expansion is recorded after cable tension has increased to the point where friction is overcome and the counterweights begin to rise. The amount of movement needed to reverse the loaded gear train in the recording equipment is negligible compared with the amount of movement necessary to change cable stresses in a system where casing-cable friction is significant.

Because of the mechanical lag in the recorder system, the water levels at which net expansion is first recorded are higher than when the net expansion first occurred. For the periods of aquifer-system expansion shown in figure 21, net expansion was first recorded when the water level had risen about 10 feet, but net expansion probably had begun earlier.

The proportions of elastic and virgin compaction probably changed during periods of declining potentiometric levels. For the period of record shown in figure 21, the proportion of elastic to virgin compaction, per unit decline in head, probably was largest when water levels were higher than 550 feet and probably was smallest when water levels were lower than 580 feet. The initial stages of rapid compaction that coincided with the rapid declines in water level that occurred from the 547-foot depth to water in April and the 535-foot depth to water in May probably are largely elastic. As water levels continued to decline, a progressively larger number of beds within the aquifer system began to contribute to the virgin component of compaction.

The relation of aquifer-system compaction and expansion to water-level change at well 19/16–23P2 during a typical summer pumping season is shown in figure 23. The nearby irrigation well was pumping during the entire summer, except for a 12-day period in May and a 4-day period in September. Again, the times of recorded compaction coincided with times of increasing applied stress, and the times of recorded expansion coincided with times of decrease in applied stress. However, the

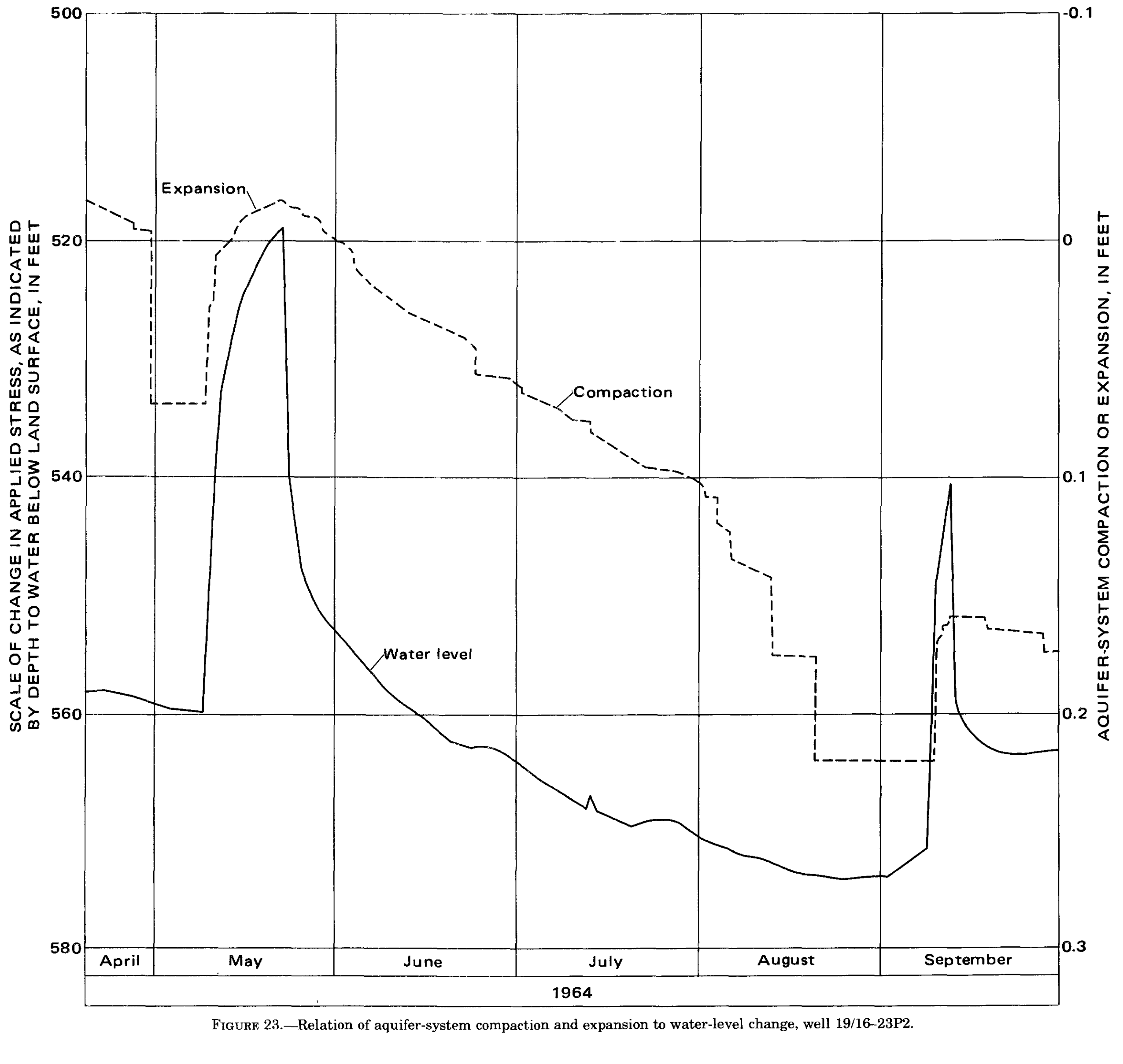


FIGURE 23.—Relation of aquifer-system compaction and expansion to water-level change, well 19/16–23P2.

curves of change in applied stress and change in aquifer-system thickness do not show the parallelism of the plots in figure 22. The plots in figure 23 suggest that much more friction was present in the recorder system in 1964 than during the period shown in figure 22.

Many of the apparent differences between figures 22 and 23 can be explained by comparing the differences in the equipment used to measure changes in aquifer-system thickness for the two time periods. Such a comparison also illustrates the need to manually stress the compaction cable at each monthly visit at some recorder sites. A ⅛-inch stainless steel 7×7 stranded uncoated cable was used during the period of record shown in figure 23. The cable had twice the stretch characteristics (B.E. Lofgren, April 22, 1968, written commun.) of the reverse-lay cable used during the period of record shown in figure 22. Therefore, before installation of the reverse-lay cable, larger changes in aquifer-system thickness were necessary during expansion to increase cable tension below the uppermost friction point sufficiently to overcome the casing-cable friction.

Although expansion was recorded many times at the site, net recorded expansion exceeded 0.01 foot only 18 times during the 1962–67 period. Maximum recorded expansion was 0.094 foot. The following data and interpretations pertain to the above 18 times of expansion.

The delay between the start of water-level recovery and the start of recorded expansion is a function of the rate of applied-stress decrease, the difference in cable stress above and below the uppermost casing-cable friction point at the start of applied stress decrease, the magnitude of cable-casing friction, and the stretch characteristics of the cable. The delay ranged from 38 hours for vinyl-coated cable (large stretch and friction properties) to 6 hours for the reverse-lay cable (low stretch and friction properties). The associated water-level recoveries were 21 and 6 feet, respectively.

The number of hours between the start of water-level recovery and the start of recorded expansion does not seem to be related to the depth to water at the beginning of water-level recovery. For example, the six times in which 7–10 hours of water-level recovery occurred before recorded expansion started were associated with initial water levels ranging from 545 to 587 feet below the land surface.

The specific unit expansion of the 18 times when recorded expansion exceeded 0.01 foot ranged from 0.6 to $3.1\times10^{-6}\text{ft}^{-1}$. The presence of delayed compaction indicates that minimum values of net specific unit expansion are being obtained for the amounts of expansion and applied-stress decrease that occurred after expansion was first recorded. It is concluded that the mean value of $1.4\times10^{-6}\text{ft}^{-1}$ for the 18 times is a minimum value for the net specific unit expansion and that a representative value for the 1962–67 period may be larger than $2.0\times10^{-6}\text{ft}^{-1}$.

RELATION OF LOWER-ZONE COMPACTION TO CHANGE IN APPLIED STRESS

Regional applied-stress increases have resulted from the changes in the positions of the lower-zone potentiometric surface and the water table. The algebraic sum of stresses caused by these two types of regional water-level change provides information regarding the increase in lower-zone applied stress during a selected 17-year period. Then, by estimating the lower-zone compaction, the specific compaction (compaction per unit applied-stress increase) can be derived. The specific compaction map relates the estimated compaction to the observed change in applied stress on a regional basis, thus permitting examination of the effect of hydrologic (other than long-term water-level change) and geologic factors on compaction.

The period between 1943 and 1960 was selected as the interval to appraise the specific compaction. The period is sufficiently long to eliminate some short-term factors that might affect the results of a 3- to 6-year appraisal. The 1943–December 1959 subsidence map (Pt. 2, Bull, 1974, fig. 10) shows only the subsidence that has resulted from artesian-head decline. The earliest widespread water-level control within the study area is based largely on measurements made by the Pacific Gas and Electric Co. in 1943. Most of these measurements were made during the summer pumping season. The 1960 water-level map (Pt. 1, Bull and Miller, 1974, fig. 33) also is based on measurements made largely during the summer pumping season. Some recent maps have many control points, but are based on water-level measurements made at the time of winter high water levels. Thus, the 1943–60 period fills the requirements of being long and having good control regarding changes in the position of the potentiometric surface and altitude of the land surface.

The regional change in total applied stress on the lower zone was determined as a result of the seepage-stress change, the gravitational change resulting from the gain or loss in buoyancy of the grains caused by water-table change, and the gravitational change resulting from the change of pore water from a saturated to an unsaturated condition, or vice versa.

The change in applied stress on the lower zone resulting from change in the position of the water table between 1943 and 1960 is shown in figure 24. For those areas that were developed agriculturally by 1960 but not in 1943, the water table was assumed to have remained constant until irrigation began. Electric logs of the first water wells drilled within a given part of the

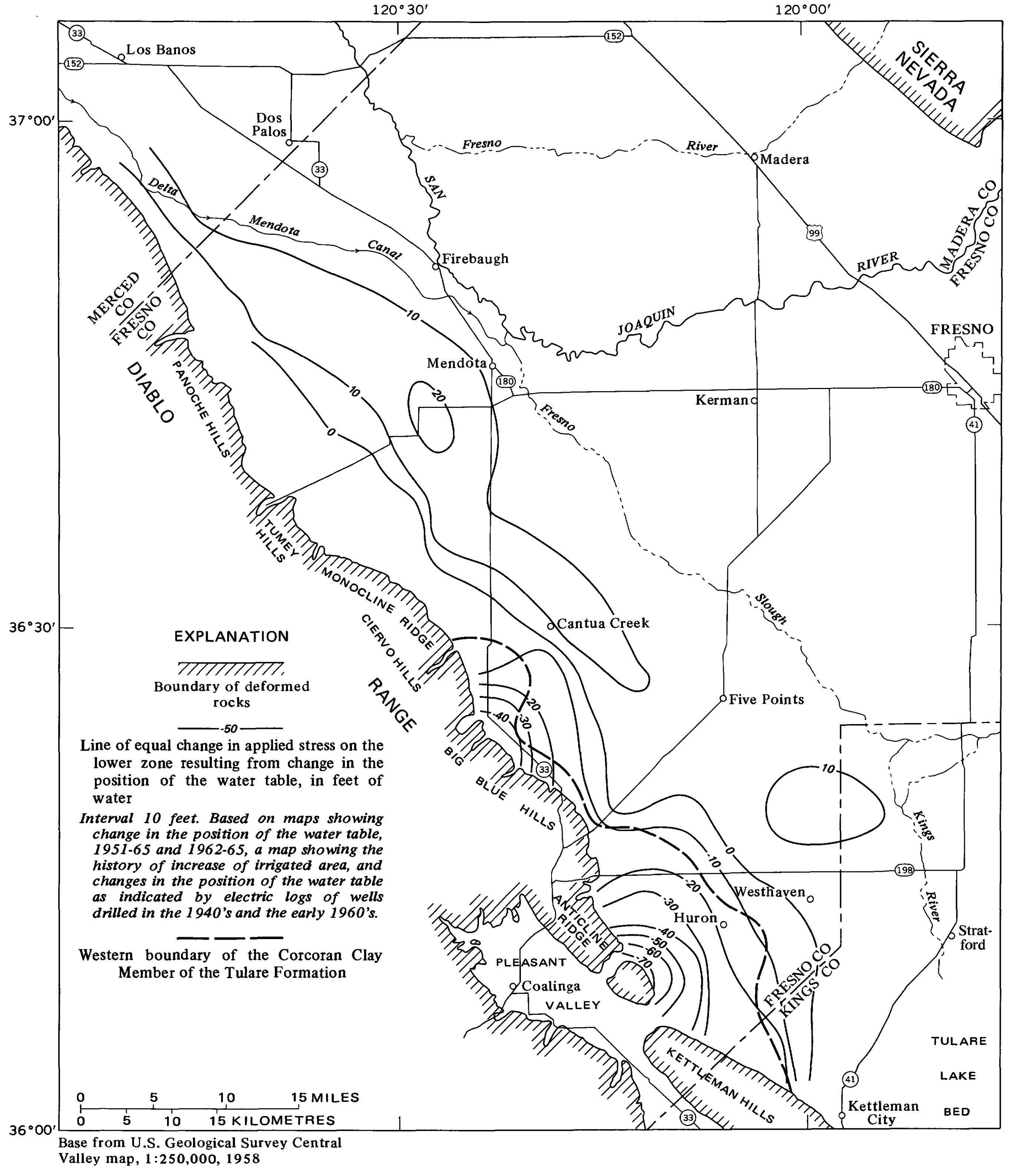


FIGURE 24.—Change in applied stress on the lower zone resulting from change in the position of the water table, 1943–60.

area provided valuable information about the position of the water table at the onset of irrigation. The rates of water-table change were derived largely from hydrographs from shallow wells and from maps showing the position and change of the water table during much of the 17-year period.

Within the areas of near-surface subsidence (Pt. 2, Bull, 1974, fig. 10), little change in the position of the water table has been noted. Within these areas, the moisture-deficient deposits apparently absorbed most of the moisture that percolated below the root zone during the 1943–60 period. This moisture added above the water table increased the applied stress on the lower zone. However, because the quantity is small and is unknown, this increment of stress increase was not included.

The change in applied stress on the lower zone that has resulted from change in the position of the water table between 1943 and 1960 is small. The total range in applied-stress change is 100 feet, from about +25 feet to −75 feet, but the stress change for more than 90 percent of the area is within ±20 feet of water.

Water-table rise is characteristic of most of the area east of the west boundary of the Corcoran Clay Member of the Tulare Formation. In much of the area, water-table rise has caused less than 10 feet of increase in applied stress on the lower-zone deposits. In the small area southwest of Mendota, about 20 feet of increase in applied stress has occurred as the result of 100 feet of water-table rise.

Large water-table declines occurred in all the area west of the Corcoran because of pumping of wells perforated 400–1,900 feet below the water table. Water-table decline extended as much as 5 miles east of the west boundary of the Corcoran aquiclude and may have influenced the rates of water-table rise for even greater distances to the east. The areas of maximum water-table decline coincide with the areas in which vertical permeability in the upper zone is greatest. The maximum decrease in applied stress on the lower zone was 70 feet, southwest of Huron, and was the result of 350 feet of water-table decline. The good vertical permeability of the deposits southwest of Huron has permitted recharge from streamflow with a high concentration of dissolved solids to move down into the main ground-water body (Davis and Poland, 1957, p. 459).

The change in applied stress on the lower zone that has resulted from lower-zone artesian-head decline is equal to the head decline in feet of water. The decline of the lower-zone potentiometric surface from 1943 to 1960 (fig. 25) represents the increase in applied stress as a result of the component, which is large compared with the stress increase resulting from water-table change. Areas of applied-stress increase of 300 feet are widespread, and locally the applied stress increased as much as 400 feet.

The change in total applied stress on the lower zone is the algebraic sum of the data shown in figures 24 and 25. Artesian-head decline has occurred throughout the area during the 1943–60 period. The net water-table component has been added to the head-decline component in areas of water-table rise and has been subtracted in areas of water-table decline. Figure 26 shows the 1943–60 total applied-stress increase, which ranges from 75 feet in the northern part of the area to a maximum of 350–400 feet near the Big Blue Hills. The general pattern of the map conforms to the change in artesian head because change in head is the dominant component. Except for the area between Huron and Westhaven, the maximum increase in applied stress is near the west boundary of the study area, which is the side of least ground-water recharge to the lower zone.

Not all the land subsidence, however, is the result of compaction of the lower-zone deposits. Information from 12 compaction-recorder sites in different parts of the area provides estimates of the amounts and proportions of compaction occurring above and below the principal confining bed—the Corcoran. The minimum proportion of compaction occurring in the lower zone ranges from about 95 percent at the Oro Loma site in the northern part of the area to about 58 percent at the Westhaven site in the southern part of the area. North of the road between Five Points and Anticline Ridge, more than 80 percent of the compaction occurs in the lower zone, except within a small area near Fresno Slough where most of the pumpage is from the upper zone.

The proportions of compaction in the two zones (Pt. 2, Bull, 1974, fig. 45) are based on post-1958 information, which is considered applicable for the 1943–59 period because the proportions of water pumped from the two zones (based on well-perforation data) apparently have not changed materially since 1943.

The compaction isopleths for the lower zone (fig. 27) for the 1943–59 period were derived from the 1943–December 1959 subsidence map, using the information noted. The values of lower-zone compaction for most of the area are nearly as large as the amounts of land subsidence due to artesian-head decline during the period (Pt. 2, Bull, 1974, fig. 10). However, the amounts of lower-zone compaction are considerably less than subsidence along most of Fresno Slough and south of the Five Points–Anticline Ridge road. The overall trend of maximum amounts of lower-zone compaction increases northward from the vicinity of Huron to the area southwest of Mendota.

The ratio of the lower-zone compaction (fig. 27) to the lower-zone increase in applied stress (fig. 26)—specific compaction—is shown in figure 28. In a general sense, compaction of unconsolidated deposits increases with increasing applied stress. One purpose of computing the compaction per unit change in applied stress is to gain an insight into factors, other than long-term change in applied stress, that may affect the amounts of compac-

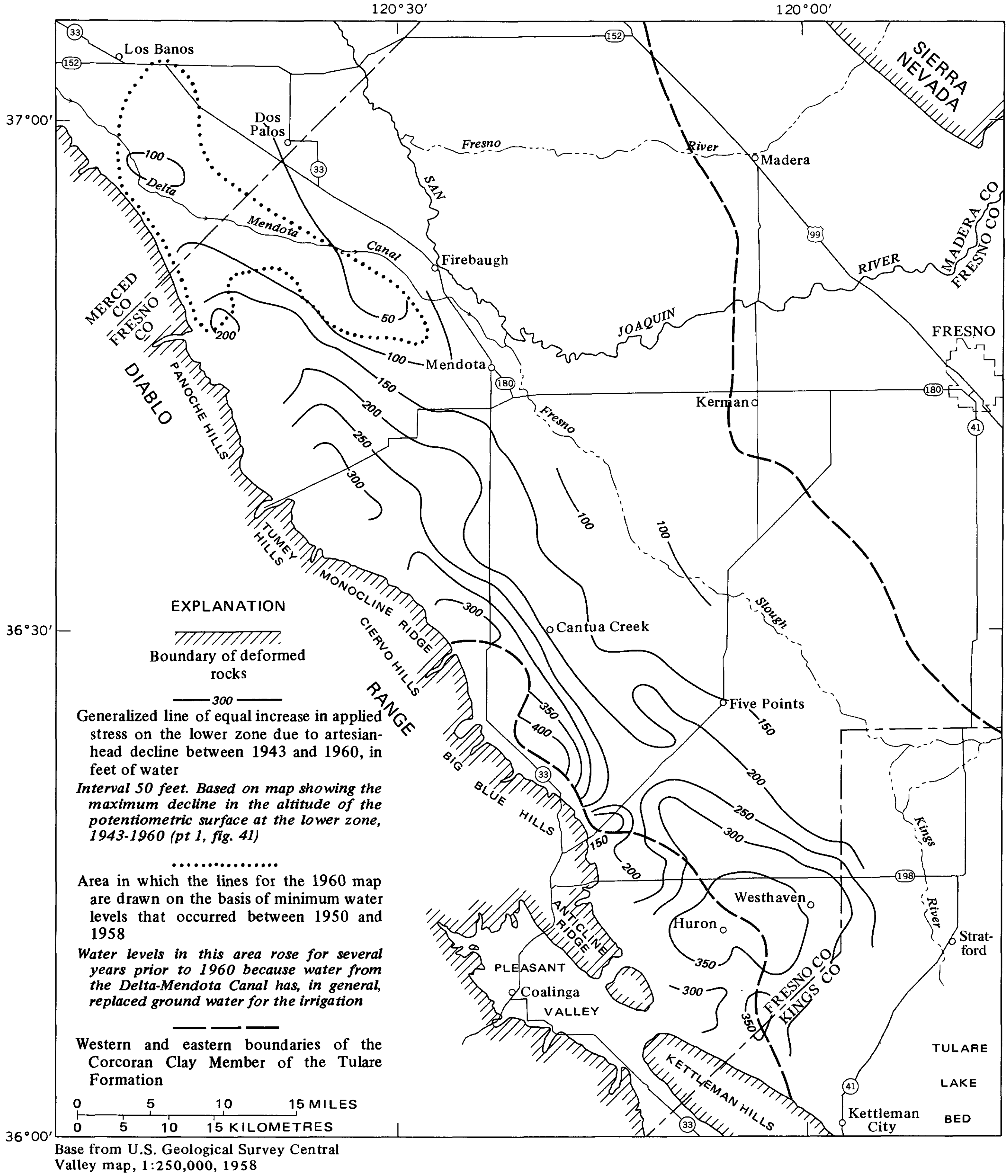


FIGURE 25.—Increase in applied stress on the lower zone resulting from artesian-head decline between 1943 and 1960.

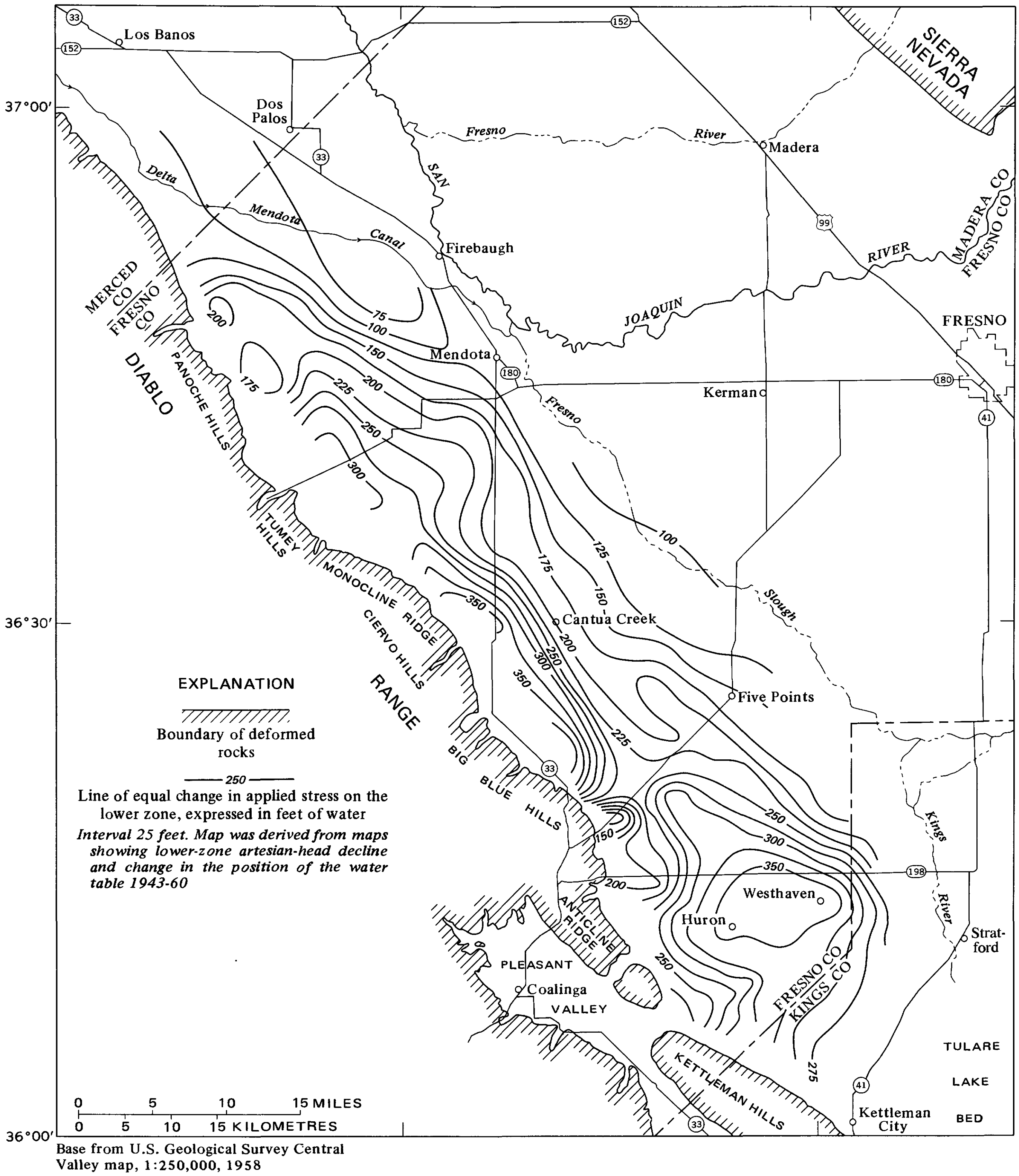


FIGURE 26.—Increase in total applied stress on the lower zone, 1943–60.

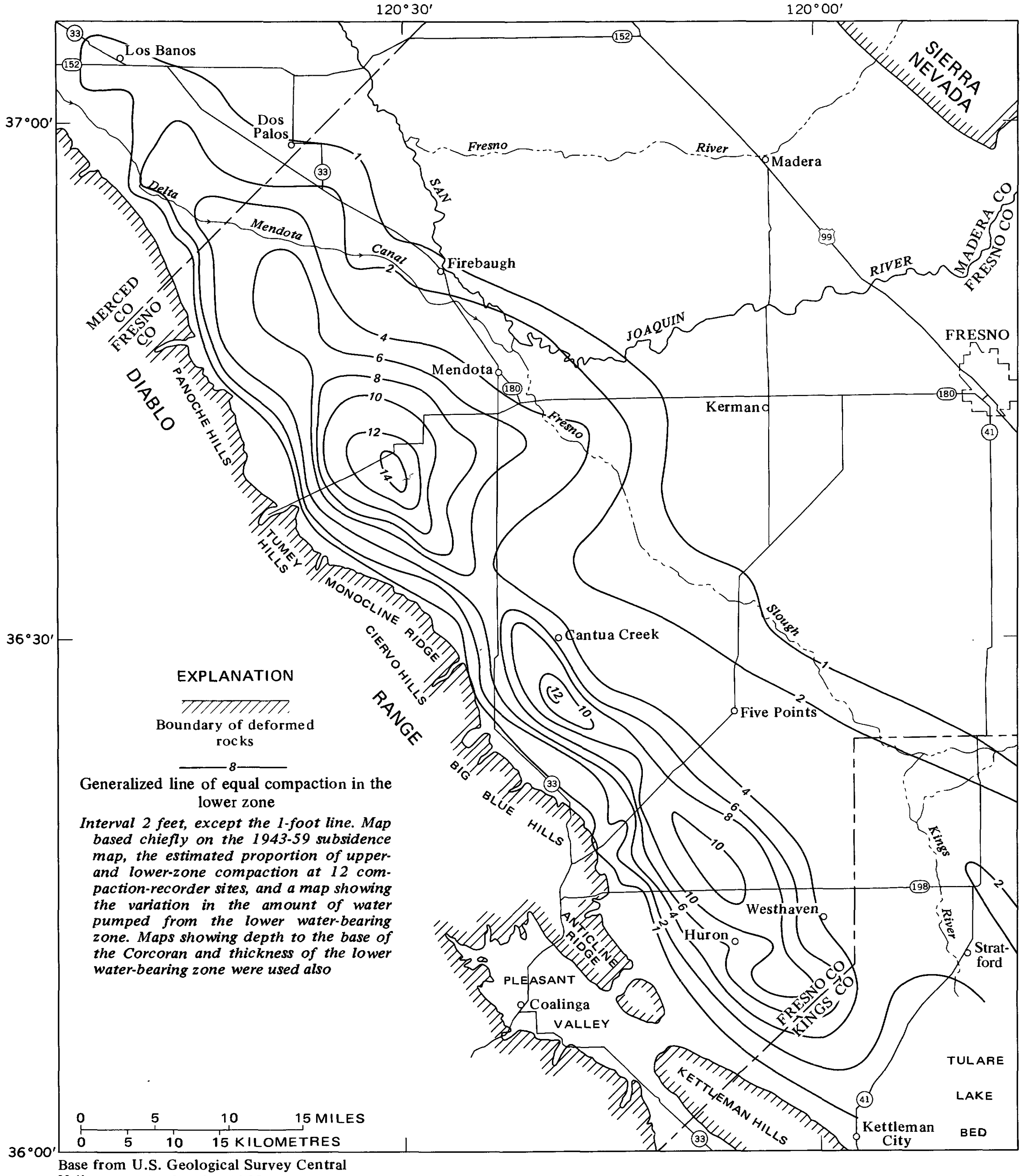


FIGURE 27.—Estimated compaction of the lower zone, 1943–59.

tion. If there were no variation in the other factors affecting lower-zone compaction and the history of applied-stress increase was similar regionally, uniform values of specific compaction would be characteristic of the entire area. However, a pronounced anomaly is readily apparent in figure 28. The specific compaction of

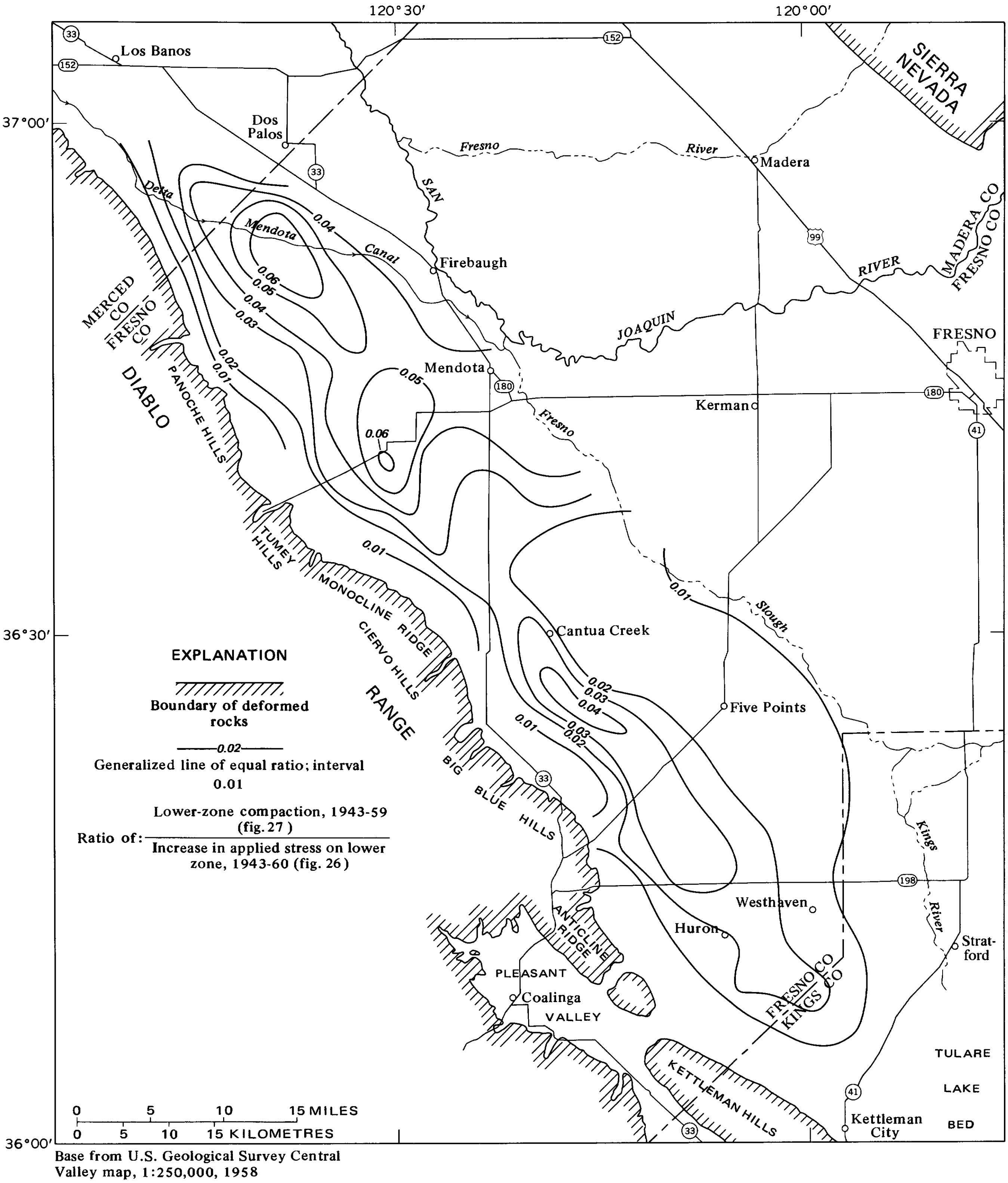


FIGURE 28.—Specific compaction of the lower zone, 1943–60.

much of the northern third of the area is twice that of the southern two-thirds of the area. The variations in specific compaction demonstrate that other factors —hydrologic and geologic—affect compaction and subsidence within the Los Banos–Kettleman City area. The geologic and hydrologic factors affecting specific compaction and specific unit compaction are discussed in detail in Part 2 (Bull, 1974).

A map showing estimated specific unit compaction of the lower water-bearing zone, 1943–60, was introduced in Part 2 (Bull, 1974, fig. 54). That map was obtained by dividing the specific compaction of figure 28 by the thickness of the lower zone to derive values of compaction per foot of applied stress increase per foot of aquifer-system thickness. The resulting specific unit compaction was about four times as great in the northern part of the area as in the south. The geologic factors evaluated in part 2 are prior total applied stress, mean lithology, and the source and mode of deposition of the different genetic types of deposits.

Based on the detailed analysis of the specific unit compaction map in Part 2 (Bull, 1974), it is concluded that the higher specific compaction in the northern area (fig. 28) is due principally to the following factors:

1. The prior total applied stress as of 1943 was less in the northern part of the area than in the southern part, and thus the compressibility of deposits of a given lithology is higher. In general, values of compressibility decrease as effective stress increases.
2. Genetic differences of the deposits are conducive to more rapid expulsion of water from the deposits in the northern area. The aquitards of the flood-plain deposits in the northern subarea are thinner than the aquitards of the alluvial-fan and lacustrine deposits in the southern subarea. Also the flood-plain aquitards may be twice as permeable as the alluvial-fan and lacustrine aquitards (Pt. 2, Bull, 1974, table 6). More rapid expulsion from the thinner more permeable beds should produce values of specific compaction for the 1943–60 period that are closer to ultimate values than those to the south. These geologic factors contribute toward the higher specific compaction in the northern part of figure 28.

Another hydrologic parameter that shows the concentric, or enclosed, pattern of isopleths that is similar to the pattern of specific compaction within the study area is the overall pattern of seasonal head decline. The seasonal head decline shown in Part 1 (Bull and Miller, 1974, fig. 43) is for the period between December 1965 and August 1966. However, the pattern probably is representative of the latter part of the 1943–60 period because the area irrigated with ground water was about the same as in 1966. Seasonal variations in head during the early part of 1943–60 period probably were less along the west and south sides of the study area and probably were greater in the northern part. The small amount of seasonal head decline in the northern part of the area in 1966 (Pt. 1, Bull and Miller, 1974, fig. 43) is due chiefly to the small number of wells taking water from the lower zone. Formerly, large amounts of water were pumped from the lower zone in the north end of the area, prior to delivery of water from the Delta-Mendota Canal in 1954.

Geologic factors likewise affect the pattern of seasonal head decline. The seasonal head decline in 1966 was extreme near Kettleman City because of the barriers to recharge provided by the Kettleman Hills and the clay plug beneath Tulare Lake bed. Opposite the Big Blue Hills, seasonal head decline is largely influenced by wells tapping the Pliocene marine and estuarine sequence of the Etchegoin Formation (Miller and others, 1971, p. E16–E17) that receives negligible recharge.

The seasonal variations in head in the study area do not consist of a simple winter high and a summer low. The most common pattern, reflecting the irrigation schedule, is for the winter recovery high to be followed by a water-level decline in February and March that approaches the depth to water during the summer. During April and May, water levels recover almost to the winter high before declining to the summer lows. Thus it is common in areas of large specific compaction for the lower-zone head to undergo two fluctuations each year that exceed 60 feet. Examples of hydrographs with large seasonal fluctuations in areas of large specific compaction are shown in figures 13 and 15–17.

One possible explanation for the relation between the magnitudes of seasonal fluctuations in head and specific compaction is that hysteresis may be important in areas of large seasonal fluctuations in head. On the basis of laboratory tests, Terzaghi and Peck (1948, p. 107) stated, "If the load is removed at the same rate at which it was previously applied, the elastic recovery is smaller than the preceding compression. If the load is again applied, the recompression curve joins the main branch without any break, and the decompression and recompression curves enclose a hysteresis loop." The rejoining of the recompression curve with the main branch of the curve of a stress-strain plot indicates that in situations of recurrent application of stress on either sands or clays in laboratory consolidation tests (1) short-term decreases in applied stress do not appreciably change the amount of ultimate consolidation from what it would have been if periodic decreases in stress had not occurred and (2) the maximum applied stress is the dominant control in consolidation tests where stress is periodically decreased and reapplied gradually.

The results of laboratory testing as just described suggest that the dominant controlling stress in areas of recurrent application of stress to unconsolidated deposits as a result of artesian-head decline may be the summer pumping lows. Little is known about the effect of periodic loading on the compaction characteristics of different types of naturally occurring materials, but the preceding discussion suggests that detailed studies of the relation between seasonal fluctuation in artesian head and specific compaction might be productive.

CRITERIA FOR THE PREDICTION OF FUTURE SUBSIDENCE

Estimates of the amounts, rates, and distribution of future subsidence are important in the planning, construction, and maintenance of large engineering structures. The economic aspects of subsidence are particularly important for large water-distribution systems. The cost of the San Luis Canal section of the California Aqueduct was increased substantially because of the additional freeboard that had to be included for the estimated subsidence that would occur between the time the canal was constructed and the time when delivery of imported water would raise ground-water levels sufficiently so that subsidence would cease. The canal passes through the areas of most intense subsidence caused by change in water levels. A master drain will be built low on the west slope near the valley trough to alleviate the problems associated with locally high water tables and to remove waste irrigation waters. This drain will be within the subsidence area.

Another major expense caused by land subsidence is damage to well casings. Damage to the casings of wells pumped to supplement the surface-water imports will continue as long as compaction of the deposits adjacent to the casings continues.

The prediction of subsidence is largely empirical. Although data about many of the factors affecting compaction have been obtained, the interrelations of these factors are so complex that it is difficult to predict future amounts of subsidence with confidence. Prior attempts to predict subsidence by the use of laboratory data will be discussed, but the main purpose of this section will be to describe empirical techniques and criteria for estimating future subsidence—criteria that are based on the past history of relations between change in applied stress and compaction within the study area.

Compaction of the deposits in the Los Banos–Kettleman City area has occurred because large increases in effective stress have occurred, highly compressible deposits are present, and the compressible deposits are thick. These are the fundamental factors that determine the magnitude of ultimate compaction and subsidence. In those parts of the area where the deposits are generally of low compressibility or highly compressible deposits are thin, the magnitude of future subsidence would be small, even if future increases in effective stress were large. For example, 600 feet of applied-stress increase has resulted in only 1 foot of subsidence in the area adjacent to the Big Blue Hills where wells tap the thick Etchegoin Formation. Conversely, in those parts of the area where thick compressible deposits occur (southwest of Mendota and near Huron), large amounts of ultimate compaction and subsidence would occur even if future increases in effective stress should be moderate. However, the rate of future subsidence in some areas of thick compressible deposits may not be large because of the time required for the applied stresses to become effective in thick beds of low permeability.

The factor subject to future variation is the change in applied stresses resulting from water-level changes. Because future rates of water-level change cannot be predicted with precision, the following discussion will be limited mainly to criteria for prediction, rather than the actual prediction of land-surface altitudes at specific future times. Sufficient information is available to estimate the subsidence rates that will prevail after 60 feet of water-level recovery in the study area.

TIMELAG OF COMPACTION

Compaction of fine-grained beds (aquitards) and resulting land subsidence are time-dependent processes because water cannot be expelled rapidly from beds of low permeability when applied stress is increased. For this reason and because the compressibility of water is much less than the structural compressibility of fine-grained beds, the additional load applied to aquitards and aquicludes is initially borne almost entirely by the pore water. If stress is applied to the aquifer system by loading at the land surface, the immediate result is an absolute increase in pore pressure within the fine-grained beds. If the stress is applied by lowering head in confined aquifers, the immediate result in the adjacent aquitards is an unchanged absolute pore pressure, which represents an increased pore pressure relative to the newly reduced head in adjacent aquifers.

The increased pore pressures in the aquitards, whether absolute or relative, induce flow of water from these aquitards to adjacent aquifers and concurrent reduction in pore volume of the aquitards. The rate of flow, and hence the rate of compaction, is, at any time, a function of the magnitude of the pore-pressure differences between the aquitards and the aquifers. During a specified interval, the volume of water expelled, decrease in pore volume, and volume of compaction are equivalent.

Flow from aquitards to aquifers continues until the compaction of the aquitards produces a structure strong enough to withstand the increased applied stress. When the required compressive strength is attained, the pore water in the aquitards no longer bears a portion of the applied stress, and pore pressures thereafter are controlled by the heads in the adjacent aquifers. Within the aquitards, as long as effective stresses do not exceed preconsolidation stresses, changes in pore pressures are characterized by steady-state vertical flow and negligible changes in storage.

During the period of nonsteady-state outward flow from the aquitards and gradual progression toward steady-state flow conditions, the difference between the pore pressure at a point in a fine-grained bed and the pore pressure that would exist at that point if steady-state flow conditions prevailed is termed "excess pore pressure." At any time during the compaction of a clay bed, the average excess pore pressure within the bed is a measure of additional compaction that will occur ultimately if the increase in applied stress is maintained until all excess pore pressures have decayed.

The time required to dissipate excess pore pressures in a clay stratum is determined by the volume of water (per unit area) that must be expelled to attain the required reduction in pore volume and by the average rate (per unit area) of outward flow. The volume of water to be expelled varies directly with the magnitude of the increase in applied stress, Δp_a, the compressibility of clay, m_v, and the thickness, b', of the bed. The average flow rate varies directly with the increased stress and the vertical permeability of the clay, K', and inversely with the bed thickness. Thus, the time required for the decay of excess pore pressures in a clay bed is a nonlinear function of a time constant for the bed defined by $(m_v\gamma_w b'\Delta p_a)/(\Delta p_a K'/b')$, in which γ_w is the unit weight of water. Multiplying m_v by γ_w converts the stress term in compressibility from units of force per unit area to units of equivalent head. In the latter form, it is dimensionally compatible with the conventional units for permeability (vertical hydraulic conductivity, K') in which the hydraulic gradient is defined in units of head. Thus, the time constant, $m_v\gamma_w b'^2/K'$, is seen to be the ratio of the square of the bed thickness to the hydraulic diffusivity, K'/S_s', and to have the dimension of time. In the case of a clay losing water to both upper and lower sands, the half thickness, $b'/2$, rather than b' determines the time constant. For a given sustained increase in applied stress on an individual clay bed, an interval of one time constant is required to permit dissipation of 93 percent of the resulting excess pore pressures in that bed. An interval corresponding to half the value of the time constant will permit 76 percent of the ultimate compaction to occur, but twice the time constant is required to achieve 99 percent of ultimate compaction.

In the study area, the diffusivities (equivalent to c_v, the coefficient of consolidation) of the aquitards in the lower zone are low, typically 1–100 square feet per year (Johnson and others, 1968, table 9), and the aquitard thicknesses, though widely variable, may be substantial. At the Cantua site, for example, 22 of the 138 aquitards in the lower zone range in thickness from 15 to 50 feet (Pt. 2, Bull, 1974, table 8). Thus, even if heads in the aquifer system are stabilized, many years may be required to approach steady-state pore pressures in adjacent aquifers and aquitards.

The time-dependent nature of the pore-pressure decay in the aquitards and aquicludes is an important factor that complicates the problem of developing criteria for estimating or predicting compaction of heterogeneous aquifer systems, even when a substantial history of change in applied stress and correlative land subsidence is known, as in the Los Banos –Kettleman City area.

If applied stress has increased during some time period and then has stabilized and the subsidence rate is observed for a number of years thereafter, methods are available for estimating the future subsidence by use of exponential decay curves (Prokopovich and Hebert, 1968).

If, following a period of known applied-stress increase and observed subsidence, applied stress decreases sufficiently to stop subsidence, approximate values for the average compressibility of the compacting deposits can be computed. These computed compressibilities can be utilized to estimate the magnitude of ultimate compaction (or subsidence) that would occur as a result of any future increase in applied stress beyond the preconsolidation stress (Poland, 1969b).

The applied stress has continued to increase with time and in an irregular pattern in much of the study area, making it difficult to establish criteria for estimating future subsidence under an assumed future change in applied stress. One of the principal reasons for this difficulty is that there is no economically practical way to measure vertical distribution of excess pore pressures in numerous aquitards at several sites.

Some appreciation of the difficulty of developing criteria for estimating future subsidence under an assumed hydrologic change in the study area can be obtained at sites where long-term information about subsidence and applied-stress increase is available. The variation in the ratios of subsidence to increase in lower-zone applied stress and head decline to subsidence is instructive in illustrating the problem. If it were not for the time lag inherent in the compaction of the fine-grained sediments, the ratio of subsidence to increase in applied stress would represent the product of the compressibility and thickness of the aquifer system. At a given site, this product would be a constant that could be used to calculate the subsidence that would result from any specified future stress increase. It will be seen, however, that this ratio is far from constant and is, in fact, a complex function of stress history.

CONDITIONS BEFORE DELIVERY OF CANAL WATER

Maximum canal deliveries are not scheduled until the mid-1970's, and widespread compaction and subsidence will continue until the distribution systems to deliver the canal water are completed. Additional compaction is anticipated in some of the thicker clays after maximum deliveries of imported water are attained because the rise in potentiometric levels in the aquifers probably will not be sufficient to eliminate all excess pore pressures in these clays. Wells will still supply nearly one-third of the irrigation water used in the Los Banos–Kettleman City area.

The economics of pumping ground water will determine, in part, the rates and amounts of subsidence before canal water is available. Because the amounts of water pumped exceed recharge in the area, water levels have declined as much as 500 feet in the last 20 years. By 1966, the cost of pumping ground water had increased to more than $15 per acre-foot in large parts of the area. Equipment needed to pump the water has become progressively more expensive as pump bowls have been lowered to maintain submergence. Larger pump motors and additional electricity have been needed to raise the water to the land surface. The result has been one of the greatest concentrations of electric power use for agriculture in the world.

The depths from which lower-zone water had to be pumped in the summer of 1965 are shown in figure 29. The depth to pumping level ranged from less than 200 feet to more than 1,000 feet, and in most of the area, water had to be pumped from depths of more than 400 feet. The increased costs of pumping water have reduced profit margins. In those areas where the depth to pumping level was 700–1,000 feet in 1965, the land is not farmed as intensively as it was when water levels were as much as 300 feet higher.

The past rate of subsidence can be used to predict future subsidence if it is appropriate to assume that the past trend in subsidence rate will be maintained into the future. Two types of subsidence plots at a given bench mark are shown in figure 30. The plot of cumulative subsidence provides information about the total amount of subsidence that has occurred at any particular time, and changes in the slope of the cumulative subsidence plot are indicative of the general changes in rate of subsidence that have occurred.

A plot of subsidence rate is much more instructive than a cumulative plot for predicting future amounts of settlement. The plot of subsidence rate in figure 30 is a generalized curve derived from a graphical integration of a rate bar graph. For examples of rate bar graphs and curves, see Part 2 (Bull, 1974, fig. 22).

Unforeseeable changes in rate make extrapolations of either cumulative subsidence or subsidence rate curves of limited value. For example, the changes in subsidence rate at bench mark S661 in 1954, 1957, and 1962 shown in figure 30 would have been most difficult to predict in advance and actually were not noticed until several years after they occurred. In those parts of the study area where surface water has been available in some years but not in others, the trend in subsidence rates has changed more frequently and abruptly than in the example shown in figure 30. (See fig. 42.)

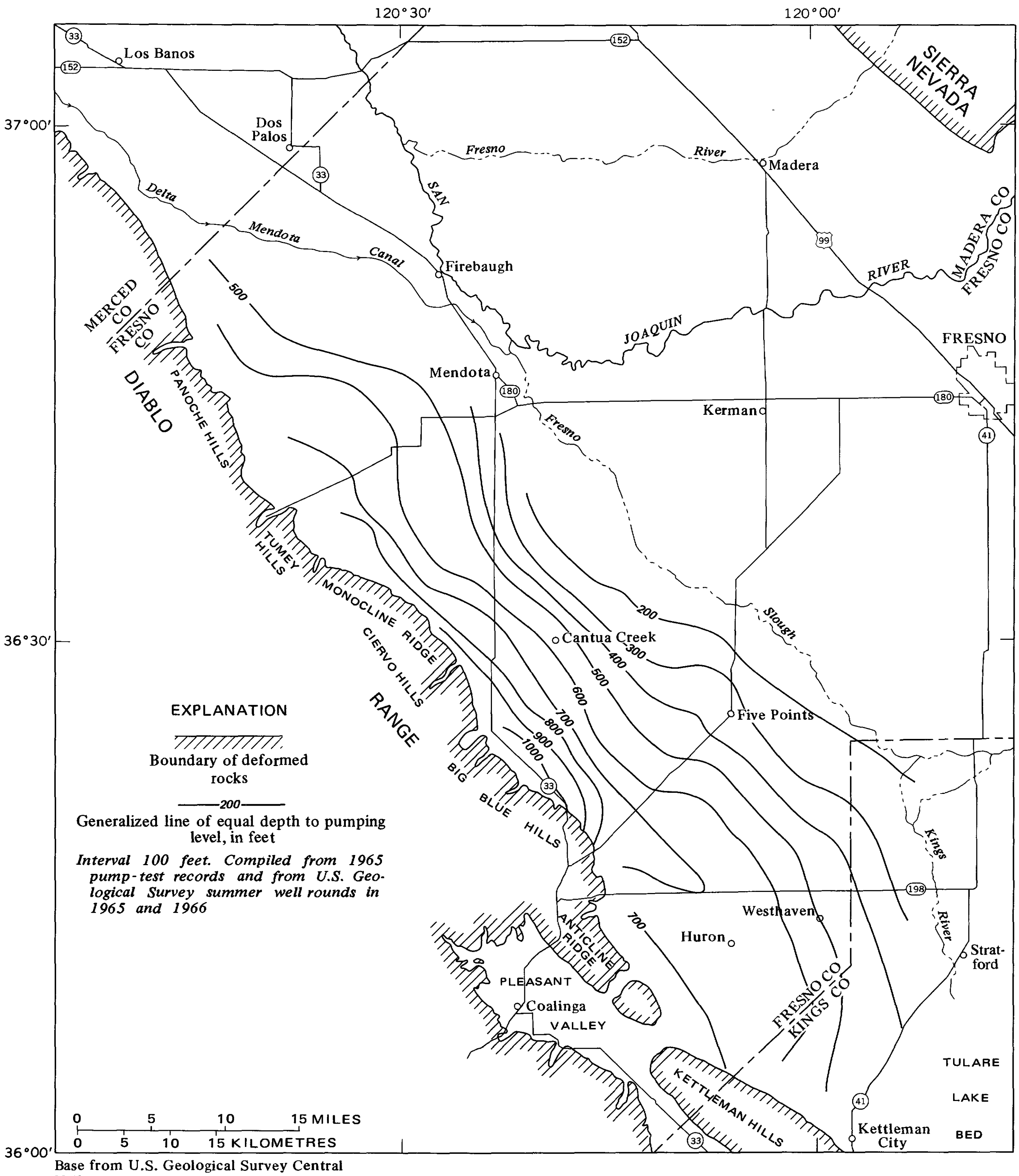
Another approach is to estimate the amount of applied-stress increase per foot of subsidence. The amount of potentiometric level decline per foot of subsidence during a 10–20-year period can form the basis for predicting minimum amounts of future subsidence, should the rate of increase in applied stress, as indicated by water levels, continue to be the same.

The number of feet of lower-zone head decline associated with each foot of subsidence during the 1943–60 period is shown in figure 31. The change in the lower-zone potentiometric surface was chosen because three-fourths of the water pumped to cause the increase in applied stress and subsidence has been withdrawn from the lower zone, and at least three-quarters of the compaction has occurred there (Pt. 2, Bull, 1974, fig. 45). The near-surface subsidence component has been removed from the total subsidence measured by bench-mark surveys for this period. The change in head is based on the maximum head decline during the period; therefore, in the northern part of the area where water levels were recovering in 1960, water levels of the mid-1950's were used.

The number of feet of lower-zone head decline associated with each foot of subsidence during the 1943–60 period generally ranged from 15 feet to 400 feet. For large parts of the area, less than 25 feet of head decline were associated with each foot of subsidence for the 1943–60 period.

The use of this map to make empirical predictions of the minimum amounts of subsidence that would occur in the future as a result of an assumed head decline would be dependent on the following assumptions.

1. It is recognized that substantial draft is from the upper zone in parts of the area where wells are perforated in both the upper and lower zones. It is assumed that the proportion of perforated interval in the upper and lower zones and the lateral recharge characteristics of the two zones will not change. If this assumption is true, then a given amount of head decline in the lower zone will be associated with a proportionately similar head decline in confined aquifers in the upper zone. In effect, the technique described here would utilize



Base from U.S. Geological Survey Central Valley map, 1:250,000, 1958

FIGURE 29.—Depth to lower-zone pumping level, summer 1965.

estimated future head declines in the lower zone as indicators of the change in applied stress in all the confined and semiconfined zones, using the assumption that future patterns of water-level change will be proportionately the same as the past history of water-level change in the different parts

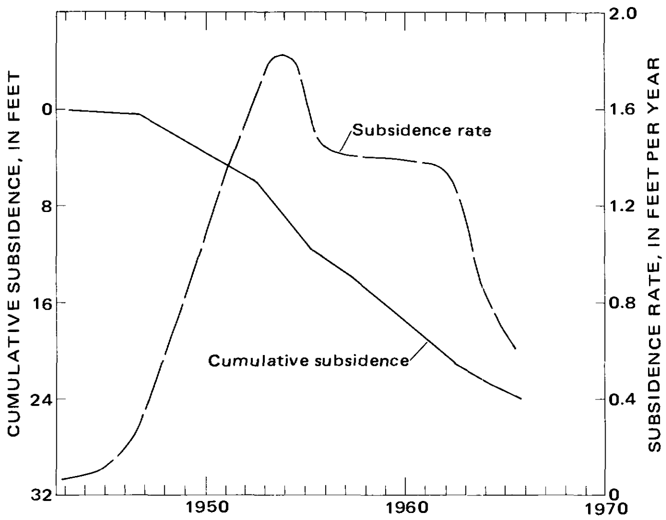


FIGURE 30.—Cumulative subsidence and subsidence rate for bench mark S661.

of the aquifer systems.

2. The water table has risen in some parts and has declined in other parts of the area. If the head decline/subsidence technique were to be used, it would be assumed that the trend of water-table change in the future would be the same as in the past.

The values shown in figure 31 are maximum values of the ratio because the head decline/subsidence ratio so derived does not take into account the time lag of compaction.

Although figure 31 may be of use to administrators and planners, the reciprocal of the head decline/subsidence ratio may be of more interest to hydrologists. The specific subsidence—the ratio of subsidence to head decline—is shown in figure 32 and approximates a minimum value of the storage coefficient component for virgin compaction of the aquifer-system skeleton. If the 1943–59 subsidence values were the ultimate compaction amounts that would result from the applied-stress increase for the same period, then figure 32 would represent the sum of two components of storage per unit head decline—the inelastic compaction and the elastic compaction. The component of storage due to elastic compression of the aquifer system probably accounts for less than 5 percent of the storage values approximated in figure 32. The biggest unknowns in the use of specific subsidence as an approximation of the storage coefficient of the aquifer-system skeleton are the magnitudes and areal variations of excess pore pressures in 1943 and 1960. If the mean aquifer-aquitard pore-pressure differentials were roughly the same at the two times, then the values of figure 32 would be a fair approximation of the sum of the two storage components for virgin compaction. They would also be a reliable tool for predicting ultimate subsidence from a postulated additional head decline.

Long-term changes in the importance of delayed compaction as related to the rate of applied-stress increase are shown in figures 33 through 35 for points in the northern, central, and southern parts of the study area.

Applied-stress increase and subsidence relations for a site in the northern part of the study area are shown in figure 33. Bench mark GWM59 is about 8 miles south of the Oro Loma compaction-recorder site. About 90 percent of the subsidence of this bench mark can be attributed to lower-zone compaction. Cumulative plots of subsidence and head decline for the site are shown in figure 5.

The history of increase in applied stress in the vicinity of bench mark GWM59 is shown in figure 33*A*. The amount of water-table rise is estimated to be 31 feet since 1940, as compared with 200 feet of head decline during the same period. The overall rise in the water table accounts for only about 3 percent of the stress increase on the lower zone. However, the proportion of applied-stress increase resulting from water-table rise is important for some periods. For example, during the 1963–66 period, water-table rise accounted for one-fourth of the increase in stress applied to the lower zone.

The history of applied-stress increase in the vicinity of bench mark GWM59 reveals an increasing rate of applied-stress increase until 1956 and a decreasing rate since then. A maximum rate of increase in applied stress of 17.8 ft yr^{-1} occurred during the 1953–55 period, but the rate of increase in applied stress had decreased to only 1.7 ft yr^{-1} during the 1963–66 period.

In figure 33*B*, each bar in the graph portrays the relation between the lower-zone applied-stress increase and the concurrent subsidence for the time period between two bench-mark surveys. The subsidence/increase-in-lower-zone-applied-stress ratio is shown on the right side of the graph and the equivalent head decline/subsidence ratio is shown on the left side. If water-table rise had not affected the increase in lower-zone applied stress, the numbers along the left side of the graph would represent the number of feet of head decline associated with each foot of subsidence. Because water-table rise has increased the stresses applied to the lower zone, the left sides of the graphs in figures 33–35 treat the stress increases as equivalent lower-zone head declines.

The subsidence/increase-in-lower-zone-applied-stress ratio at bench mark GWM59 has increased exponentially during the period of record, and the head decline/subsidence ratio has decreased from 50 to 6.

The changes in the ratios shown in figure 33*B* are interpreted as the result of a progressive increase in

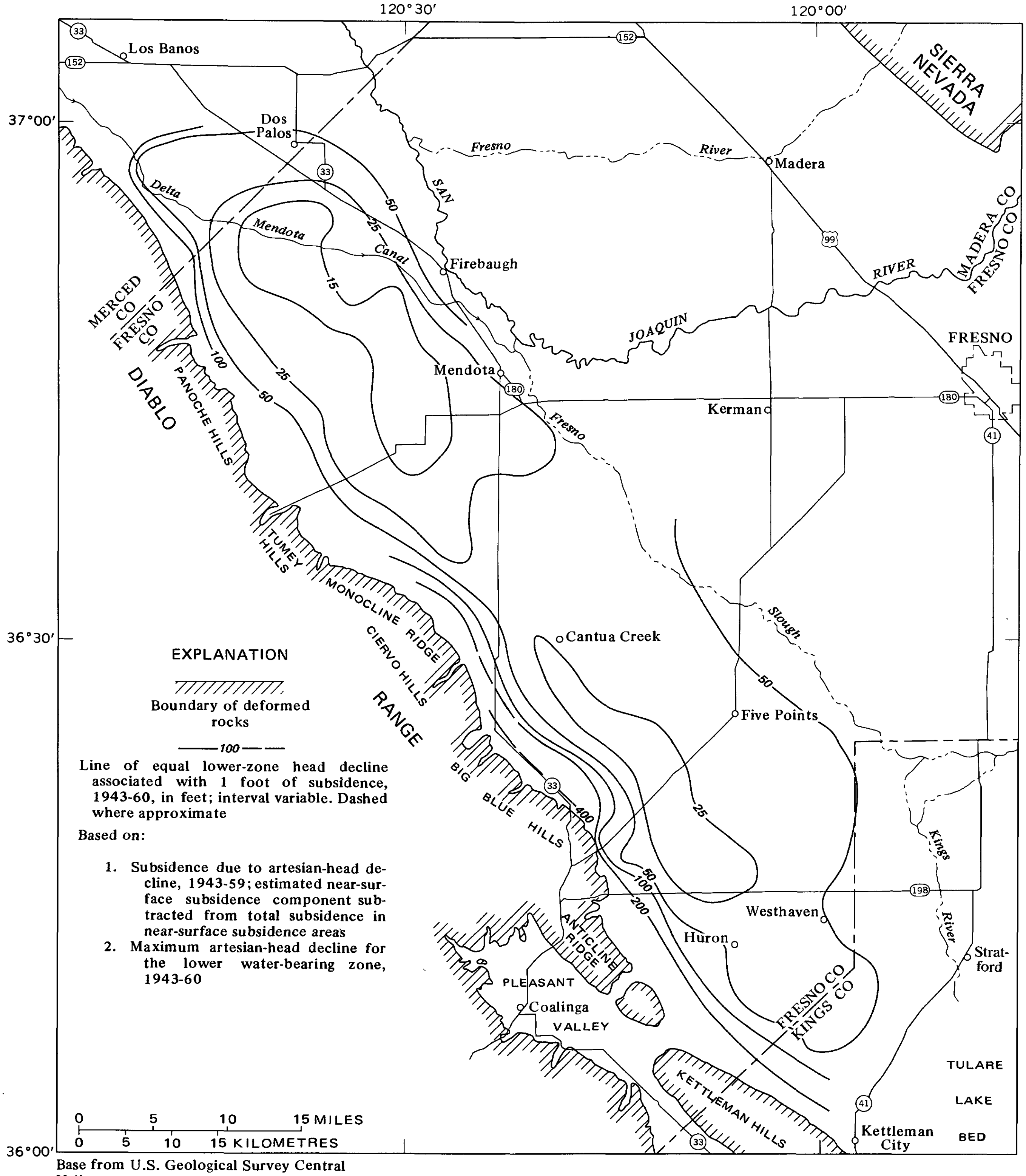


FIGURE 31.—Number of feet of lower-zone head decline associated with each foot of subsidence, 1943–60.

excess pore pressure in the aquitards during the consecutive time periods. If the time delay associated with much of the compaction were not present, the bars of the graph of figure 33B would have a uniform height that would be a function of the compressibility and thickness of the deposits at the site. The changes in the ratios

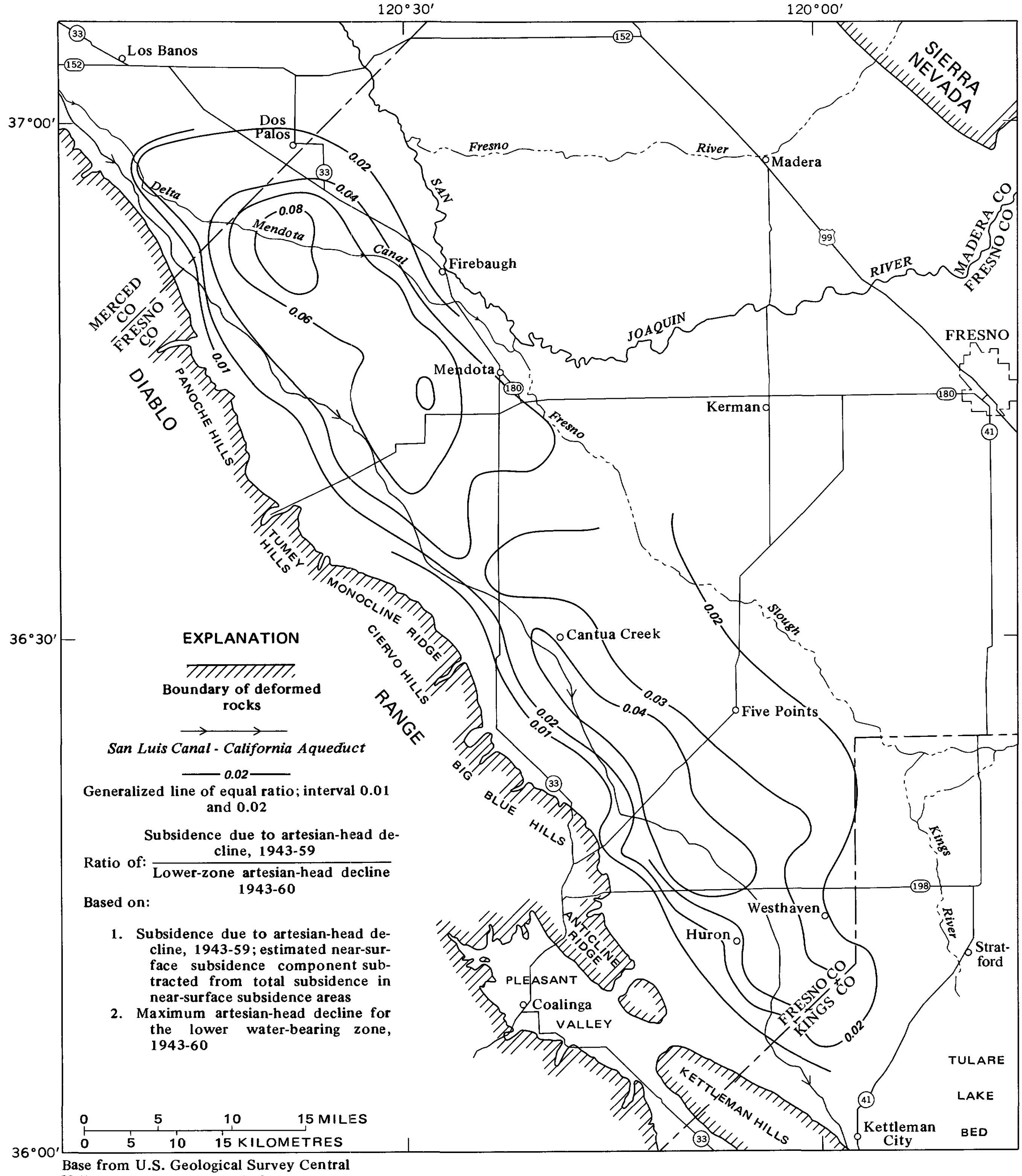


FIGURE 32.—Specific subsidence, 1943-59.

between 1940 and 1956 indicate that average excess pore pressures doubled during this period of accelerating increase of applied stress. Delayed compaction has become even more important since 1956 because the rate of applied-stress increase has declined progressively. Nearly all the 2 feet of subsidence that occurred

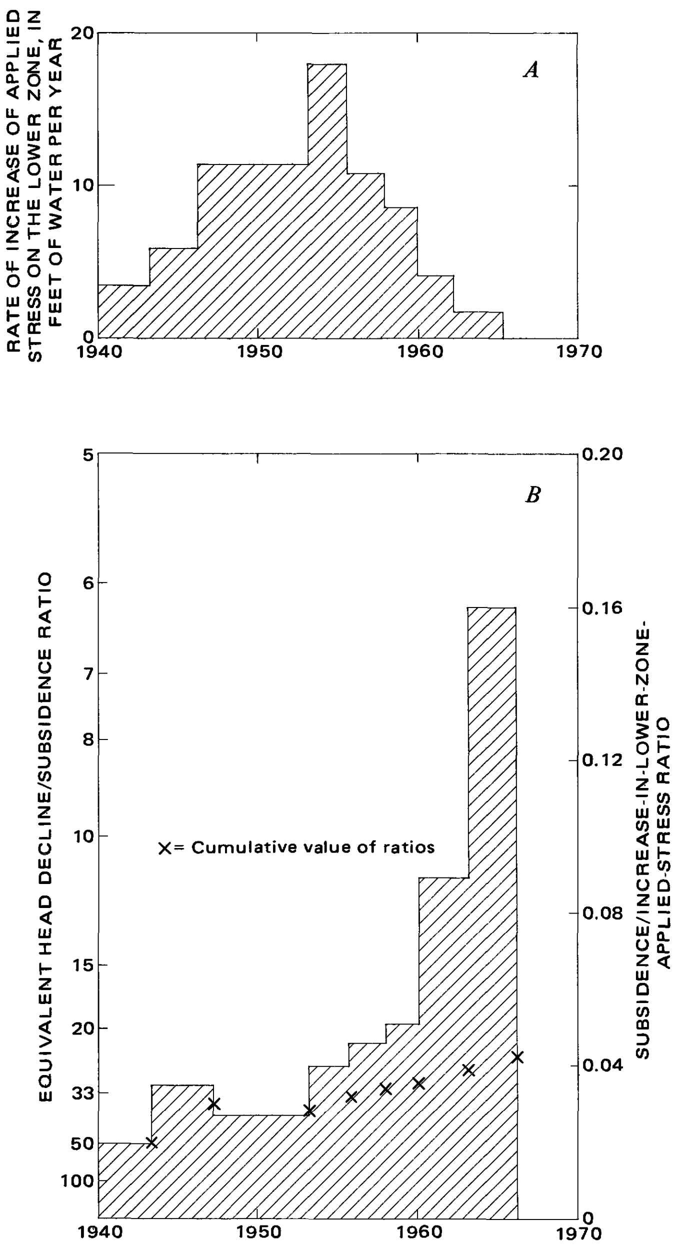


FIGURE 33.—Applied-stress increase and subsidence relations at bench mark GWM59. *A*, Change in rate of increase of applied stress on the lower zone. *B*, Change in the ratio of subsidence to increase in lower-zone applied stress.

from 1959 to 1966 is interpreted as being the result of stresses initially applied before 1959.

The history of increase in applied stress in the vicinity of bench mark H237 (reset) is shown in figure 34. The bench mark is in the central part of the study area about 6 miles northwest of the town of Cantua Creek. About 85–90 percent of the subsidence of this bench mark is the result of lower-zone compaction. The estimated amount of water-table rise during the period of record is about 56 feet as compared to 270 feet of head decline. Thus, the change in the position of the water table

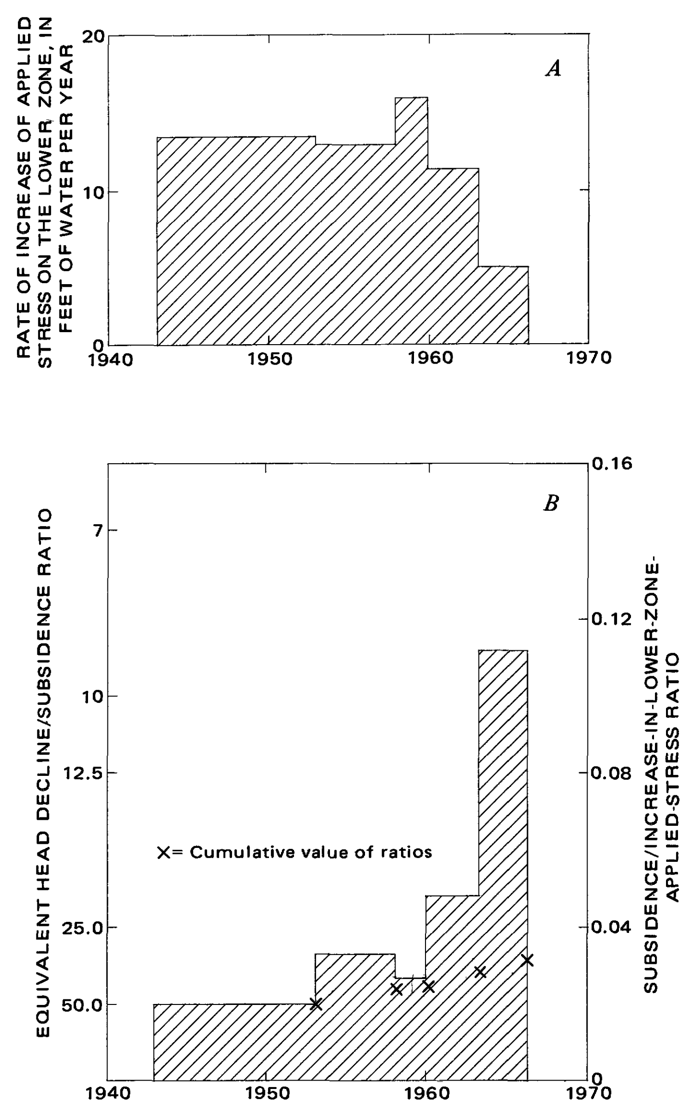


FIGURE 34.—Applied-stress increase and subsidence relations at bench mark H237 (reset). *A*, Change in rate of increase of applied stress on the lower zone. *B*, Change in the ratio of subsidence to increase in lower-zone applied stress.

accounts for about 4 percent of the change in stress applied to the lower zone.

The rate of increase in applied stress on the lower zone has been moderately high for most of the period of record. Between 1943 and 1959 little change in rate occurred, the rate fluctuating about a mean increase of about 14 ft yr^{-1} for the three periods shown. Since 1959 the rate of applied-stress increase has decreased steadily. During the 1957–59 period, the applied stress was increasing at a rate of 16 ft yr^{-1}, but during the 1963–66 period, the rate of increase had declined to only 5 ft yr^{-1}.

Figure 34*B* shows that the subsidence/increase-in-lower-zone-applied-stress ratio for bench mark H237 (reset) did not increase greatly until after 1959. Between 1943 and 1959, the ratio ranged from 0.020 to 0.033. After 1959, the ratio increased greatly. Between

1959 and 1963 the ratio was 0.048, and between 1963 and 1966 the ratio increased to 0.114. The equivalent head decline/subsidence ratio decreased from 50 during the 1943–53 period to about 9 during the 1963–66 period.

Comparison of figures 34*A* and *B* shows that between 1943 and 1963, when the rate of applied-stress increase ranged from 11.4 to 16.0 ft yr^{-1}, the ratio of subsidence to stress increase more than doubled from 0.020 to 0.048. This change in the ratio is interpreted as representing a substantial increase in the magnitude of excess pore pressures during a 20-year period of steady head decline with no intervening periods of stable head to provide sufficient time for the aquifer system to approach a steady-state pore-pressure distribution. The 1963–66 period was characterized by slightly lower compaction rates and a decrease in the rate of applied-stress increase to only 5 ft yr^{-1}. Most of the compaction that occurred during the 1963–66 period is interpreted as being delayed virgin compaction resulting from prior periods of head decline.

The variations of increase in applied stress in the vicinity of bench mark PTS21S are shown in figure 35. The bench mark is in the southern part of the study area about 2 miles north of Westhaven. About 60 percent of the subsidence of this bench mark has been the result of lower-zone compaction. Change in applied stress that can be attributed to change in the position of the water table is minor in the vicinity of the bench mark. The estimated water-table rise has been only 15 feet as compared with 422 feet of lower-zone head decline (fig. 10). Water-table rise accounts for less than 1 percent of the applied-stress increase at the site.

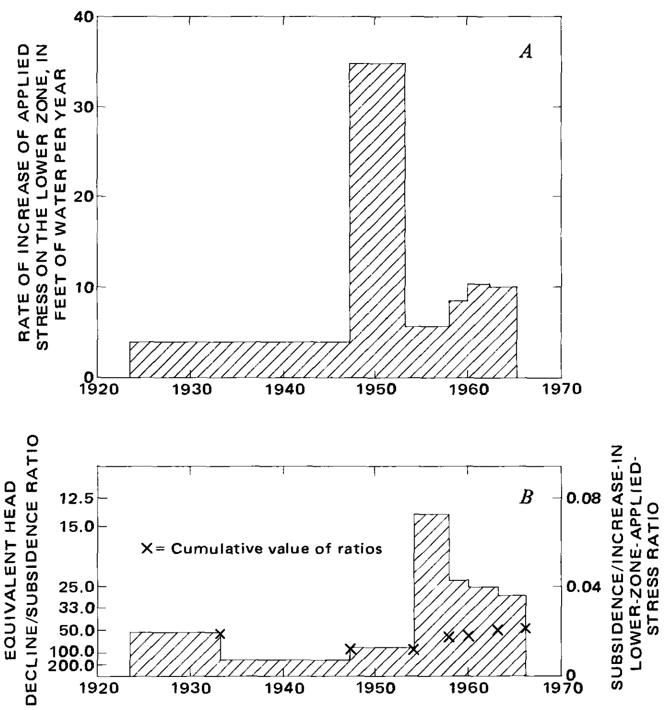


FIGURE 35.—Applied-stress increase and subsidence relations at bench mark PTS21S. *A*, Change in rate of increase of applied stress on the lower zone. *B*, Change in the ratio of subsidence to increase in lower-zone applied stress.

Because about 40 percent of the compaction at bench mark PTS21S has occurred in the upper zone, the ratios of subsidence to increase in lower-zone applied stress are apt to be misleading, unless head changes have been similar in the upper and lower zones. Similar head changes have occurred in the two zones at the Westhaven compaction-recorder site 5 miles to the south of bench mark PTS21S (Pt. 1, Bull and Miller, 1974, fig. 14). It is tentatively assumed that the heads above and below the Corcoran also are similar in the area near bench mark PTS21S, but such an assumption is tenuous in an area of highly lensing alluvial-fan deposits.

The history of applied-stress increase in the vicinity of bench mark PTS21S does not have a consistent trend and is dominated by a period of 35 ft yr^{-1} applied-stress increase between 1947 and 1954.

The ratio of subsidence to increase in lower-zone applied stress at bench mark PTS21S decreased between 1923 and 1954, the ratio being only 0.007 during the 1937–47 period as compared with 0.019 during the 1923–33 period. The overall trend since the mid-1940's appears to have been one of overall increase of the ratio, which may be the result of the increasing importance of delayed compaction. The head decline/subsidence ratio ranges from about 140 feet during the 1933–47 period to 14 feet during the 1954–57 period. The apparent lesser proportion of delayed compaction occurring at PTS21S as compared with that at bench marks GWM59 and H237 (reset) may be because the post-1960 head declines have been roughly twice as large at PTS21S or perhaps because relatively thick-bedded alluvial-fan deposits of low permeability at bench mark PTS21S do not permit delayed compaction to occur as rapidly as at the other two bench-mark sites.

Figures 33 and 34 demonstrate the importance of time-delayed virgin compaction for those attempting to predict future subsidence, and figure 35 shows the extreme variations that can occur in cause-effect type ratios. The lack of consistent ratios at all three sites demonstrates the hazard of attempting to predict future subsidence by an extrapolation of such ratios when based on short time intervals.

However, cumulative ratios derived for periods ranging from 2 to more than 4 decades can be used to furnish minimum estimates of the subsidence that would occur ultimately from a given additional increase in applied stress—that is, subsidence in response to a given increase in effective stress. The cumulative ratios are computed from the total subsidence and applied-stress increase for the period of record before a given date.

Such minimal values would serve as a floor for estimates of subsidence obtained by other methods. The cumulative values of the ratios for figures 33–35 are shown by the ×'s. As with other cumulative graphical techniques, the effect is to smooth out the short-term variations. The cumulative values of these ratios as plotted for 1966 agree with the ratios in figure 32.

Another factor that should be considered in areas of intense land subsidence is the permeability decrease caused by compaction. Compaction of the aquitards has reduced their vertical permeability, thereby tending to increase the time required for excess pore pressures in the aquitards to reach equilibrium with those in adjacent aquifers. Locally, the overall water-bearing section has been decreased in thickness by 2 percent or more. The actual decrease in thickness of some of the compressible and rapidly compacting beds may be more than 4 percent. Under conditions of uniform increase in applied stress, decreasing permeability of the compressible beds that occurs as a consequence of compaction results in a decrease in the rate of pore-pressure decay and compaction of the aquitards.

COMPUTATION OF AQUIFER-SYSTEM PORE-PRESSURE DECAY

The compaction during a time period is a function of the rate of flow of water from the aquitards and aquicludes, which in turn is a function of aquitard-aquifer pore-pressure differentials. Thus, prediction of the rate of pore-pressure decay and delayed compaction at a site provides estimates of future subsidence, assuming that the applied stress will remain relatively constant.

Two methods of predicting aquifer-system pore-pressure decay can be illustrated by field data from the Los Banos–Kettleman City area. In much of the northern part of the study area, an equilibrium has been approached between ground-water inflow and outflow. Although the applied stress has been increased greatly from the preagricultural development conditions, little seasonal or long-term change in applied stress has occurred during the 1960–67 period. Thus, bench-mark surveys in these areas provide information about decrease in the rate of aquifer-system compaction under a constant stress. Future compaction can then be estimated by graphical projection or through the use of power-function equations of the type described by Prokopovich and Hebert (1968, p. 920).

The preceding technique cannot be used in most of the study area because the artesian head has not been stabilized and hence applied stress has not been constant during 2–3 bench-mark surveys, as in the northern area. However, at some sites the rate of applied-stress increase has decreased greatly since 1960, and the total post-1960 applied-stress increase is only 2–6 percent of the pre-1960 stress increase. Thus, when compared with the prior periods of stress increase, the load on the aquifer system may be considered roughly constant since about 1960. The lack of sufficient bench-mark surveys can be circumvented at some sites by using compaction-recorder data. The problem of large seasonal variations in applied stress can be largely eliminated by using recorded compaction amounts for selected ranges of applied stress. This technique works best at those sites where large amounts of compaction are being measured and where seasonal and longer term applied-stress changes are minimal.

The minimum rate of decrease of delayed compaction after a given date at the four multiple compaction-recorder sites can be determined by computing the changes in the mean daily compaction rates of lower-zone deposits for selected applied stresses. The selected applied stresses for the four sets of graphs in figure 36 are ranges of applied stress. The minimum applied stress was placed at a lower-zone potentiometric level below which compaction was generally recorded each month. The maximum applied stress was the maximum depth to water for a given year. At all four sites, the maximum summer depths to water (minimum lower-zone potentiometric levels) during the last half of the period of record shown in figure 36 were deeper than the maximum summer depths to water during the first half of the period of record; however, the change was not large, and at three of the sites the summer low-water level increased 4–20 feet. The maximum depth to water had the following ranges: the Oro Loma site, 202–206 feet; the Mendota site, 496–516 feet; the Cantua site, 600–618 feet; and the Westhaven site, 419–458 feet. The component of change in applied stress that can be attributed to water-table change at the four sites is negligible; hence, it is not portrayed in figure 36.

Decrease in the mean compaction rate at the Oro Loma site for those days when the depth to water in well 16H6 exceeded 190 feet is shown in figure 36*A*. The compaction was measured in the depth interval extending from 35 to 535 feet below the Corcoran. During the 1963–66 period, 55 percent of the subsidence was the result of compaction in the upper 1,000 feet of deposits, and 45 percent of the subsidence was the result of compaction occurring below 1,000 feet. For most of the period of record, the depth to water exceeded 190 feet for 365 days a year. The curve showing the trend of the mean daily compaction rate shows a progressive decrease in slope with time. In 1961 the mean daily compaction rate was 0.0009 foot per day, but by 1967 the rate had decreased to 0.0003 foot per day.

Decrease in the mean compaction rate at the Mendota site for those days when the depth to water exceeded 470 feet is shown in figure 36*B*. The compaction was meas-

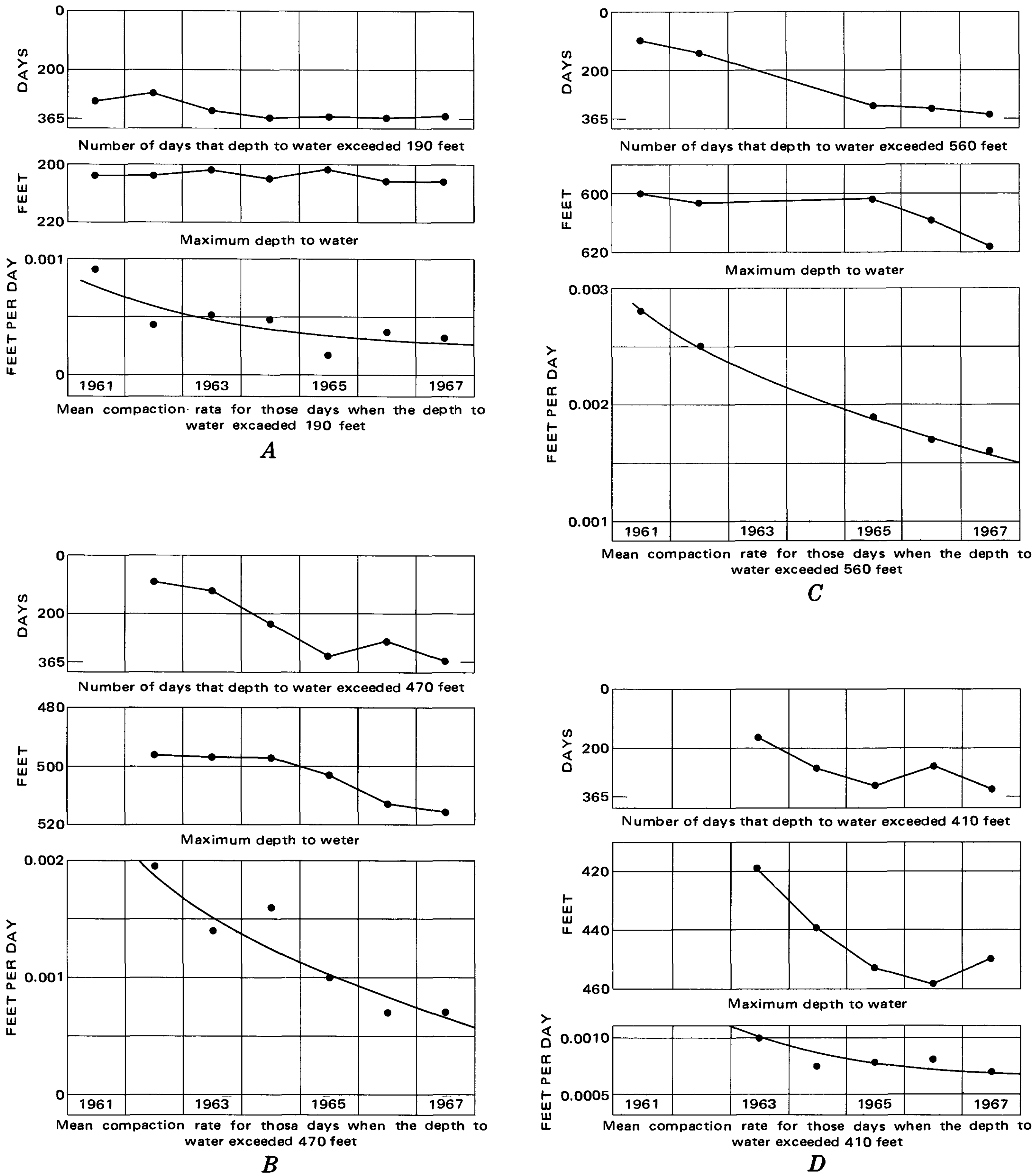


FIGURE 36.—Changes in the mean daily compaction rate of deposits for selected applied stresses. *A*, Oro Loma site; depth interval 500–1,000 feet. *B*, Mendota site; depth interval 780–1,358 feet. *C*, Cantua site; depth interval 703–2,000 feet. *D*, Westhaven site; depth interval 830–1,930 feet.

ured in the depth interval extending from 80 feet to 658 feet below the Corcoran. During the 1963–66 period, 31 percent of the compaction that was causing the subsidence occurred below the 1,358-foot depth. During the period of record, the number of days that the depth to water exceeded 470 feet increased from 91 to 365 days.

The curve shows an overall decrease in the mean daily compaction rate with time. In 1962 the mean daily compaction rate was 0.002 foot per day, but by 1967 the rate had decreased to 0.0007 foot per day.

Decrease in the mean daily compaction rate at the Cantua site for those days when the depth to water exceeded 560 feet is shown in figure 36*C*. The compaction was measured in the depth interval extending from 128 feet to 1,425 feet below the Corcoran. During the 1963–66 period, 12 percent of the compaction causing subsidence at the site was the result of compaction below 2,000 feet. The number of days that the depth to water exceeded 560 feet increased from 98 to 359 days during the period of record. The curve showing the trend of decrease in daily compaction rate is close to all the points. Data are not available for 1963 and 1964 because of a casing failure in the well used to observe changes in water level. In 1961 the mean daily compaction rate was 0.0028 foot per day, but by 1967 the rate had decreased to 0.0016 foot per day.

Decrease in the mean daily compaction rate at the Westhaven site for those days when the depth to water exceeded 410 feet is shown in figure 36*D*. The compaction was measured in the depth interval extending from 100 feet to 1,185 feet below the Corcoran. About 95 percent of the compaction is estimated to occur above the 1,930-foot depth. During the period of record, the number of days that the depth to water exceeded 410 feet increased from 161 to 335 days. The curve at this site also is suggestive of a decrease in the rate of daily compaction. In 1963 the mean daily compaction rate was 0.0010 foot per day, but by 1967 the rate had decreased to 0.0007 foot per day.

The rate at which applied stress becomes effective in the fine-grained, poorly permeable parts of the aquifer system decreases progressively with time in an exponential manner. All four mean-daily-compaction-rate plots in figure 36 are best fitted with exponential curves. The mean daily compaction rates in 1967 are only one-third to two-thirds the rates at the beginning of the 5–7-year periods.

The mean-daily-compaction-rate plots may be represented by a general exponential equation of the type

$$y = ce^{mx},$$

in which c and m are determined by the data for each site. A semilogarithmic plot of the decrease in the mean daily compaction rate of the Cantua site data (fig. 37) shows that the points have virtually no scatter about the regression line. The daily compaction rate is decreasing exponentially in the 703–2,000-foot-depth zone for those days in which the depth to water exceeds 560 feet. The equation for the linear plot of mean daily compaction rate (y) and the time since mid-1961 in years (x) is

$$y = 0.0028\, e^{-0.096x}.$$

The intercept that controls the coefficient was selected arbitrarily as mid-1961, but the exponent includes m—the rate of change of y with respect to x (-0.096) of the plot in figure 37. Comparison of values of m for similar plots in other depth zones, or areas, should provide some general useful information regarding the rate of completion of pore-pressure decay in the aquifer systems.

The curve in figure 37 may be extrapolated as an example of predictive technique if it is assumed that the maximum depth to water will continue to fluctuate between 610 and 620 feet and that the water level will be deeper than 560 feet for 365 days each year. Despite the continued decrease in compaction rate, 0.4 foot of compaction would still be occurring in the 703–2,000-foot-depth interval during the year 1971. During the period between the 1963–66 bench-mark

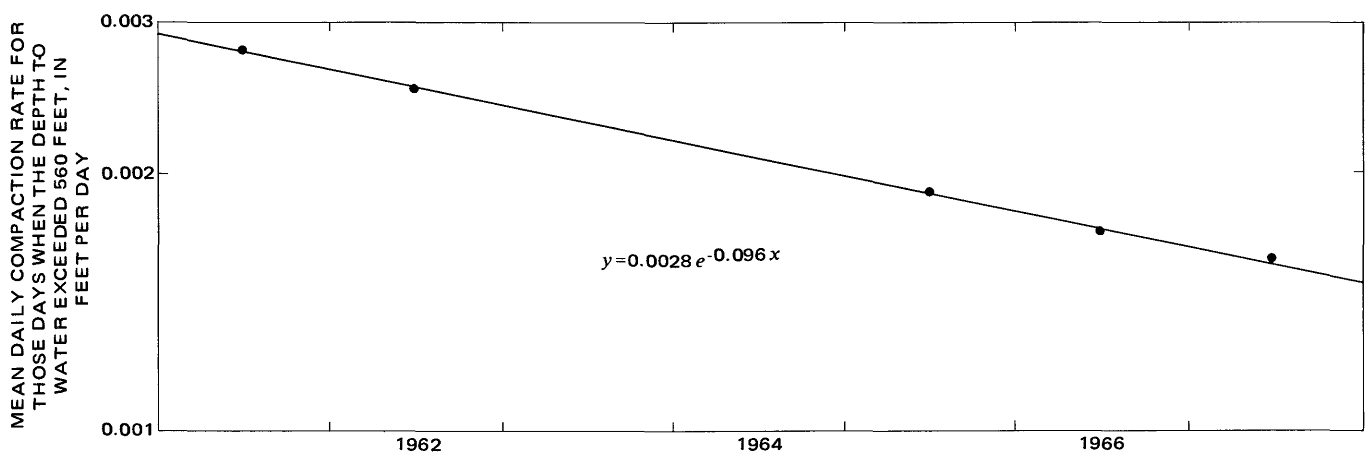


FIGURE 37.—Decrease in the mean daily compaction rate in the 703–2,000-foot-depth interval at the Cantua site.

surveys, 18 percent of the compaction measured in the upper 2,000 feet of deposits occurred above 703 feet, and 12 percent of the subsidence was the result of compaction below 2,000 feet. If these proportions were the same in 1971, the amount of subsidence during the year would be about 0.56 foot (0.09 ft would be occurring in the 0–703-ft-depth interval, 0.40 ft would be occurring in the 703–2,000-ft-depth interval, and 0.07 ft would be occurring below a depth of 2,000 ft). Thus, the minimum amounts of future compaction and subsidence at the Cantua site would be large even if the water levels never exceed historic low levels.

Importation of surface water in the next decade probably will invalidate the assumption made for the purposes of the preceding discussion that the water level would be deeper than 560 feet at all times of the year. An estimate of the rate of subsidence after an assumed water-level rise will be presented in the next section.

The time needed to approach steady-state pore pressures in the 703–2,000-foot-depth interval at the Cantua site can be estimated on the basis of figure 37. The total head decline at the site of roughly 400 feet is large compared with the 18-foot head decline of 1961–67. Therefore, for purposes of the projection shown in figure 38, it is assumed that mid-1961 is the time of an unknown mean aquitard-aquifer pore-pressure differential and that the mean head in the aquifers remains constant thereafter. The rate at which the 1961 excess pore pressures would be dissipated can be expressed as a function of the change in mean daily compaction rate, using 1961 as the initial time. The curve in figure 38 describes the same equation as shown in figure 37. The solid line represents the controlled time period shown in figure 37, and the dashed part of the curve, the post-1967 extrapolation of the curve, which after six decades, is essentially asymptotic to a zero-compaction rate line. Figure 38 shows a decreasing rate of completion of post-1961 residual compaction. By mid-1962, 10 percent of the residual compaction had occurred, and by 1968, 45 percent had occurred. The estimate of the future percent completion of post-1967 compaction indicates that it would be 1975 and 1991 before 50 and 90 percent, respectively, of the residual compaction had occurred. By the year 2033, the yearly compaction would have decreased to only 0.001 foot.

The decrease in the mean daily compaction rate of the lower zone at all four multiple compaction-recorder sites (derived from figure 36) is shown in figure 39. The plot for the Cantua site has little scatter, but the plots for the other sites have large amounts of scatter. The scatter is larger at those sites with low compaction rates, thus reflecting the problems in measuring small amounts of compaction with the equipment presently in use. The degree of scatter is so large for the Oro Loma site data that the points for 1962 and 1965 were rejected as being unreasonable. Computation of m values for the four lines shown in figure 39 gave the following results: Cantua site, −0.096; Mendota site, −0.21; Westhaven site, −0.091; and the Oro Loma site, −0.18 (a minimum value). The m values are indicative of only the general rates of decrease of compaction rates at the sites because the applied stresses were not constant during the periods of record.

The implication in figure 39 is that the rate of decrease in the mean daily compaction rate for the two southern sites is only about half that for the two northern sites. The mean daily compaction rate at the Westhaven site has been decreasing less than at the Cantua site, but would have decreased more rapidly if there had not been an overall head decline of 39 feet from 1963 to 1966.

The overall lithology of the lower zone (Pt. 2, Bull, 1974, fig. 61) is more clayey at the Oro Loma and Westhaven sites than at the Mendota and Cantua sites. Therefore, the overall amounts of clay in the lower zone at the sites does not appear to explain the more rapid

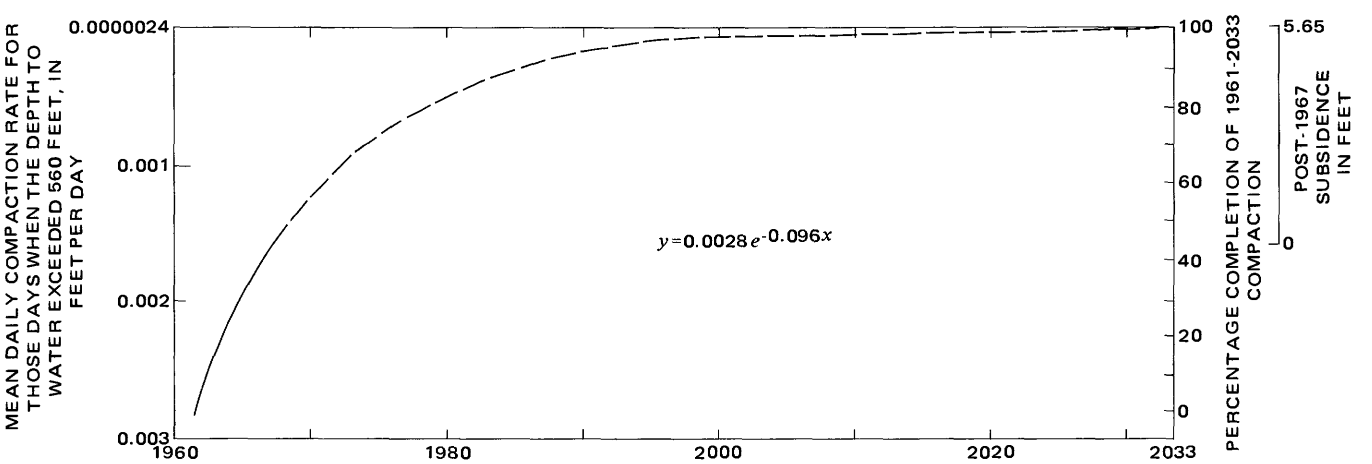


FIGURE 38.—Estimated time needed for residual compaction to occur after mid-1961, 703–2,000-foot-depth interval, Cantua site.

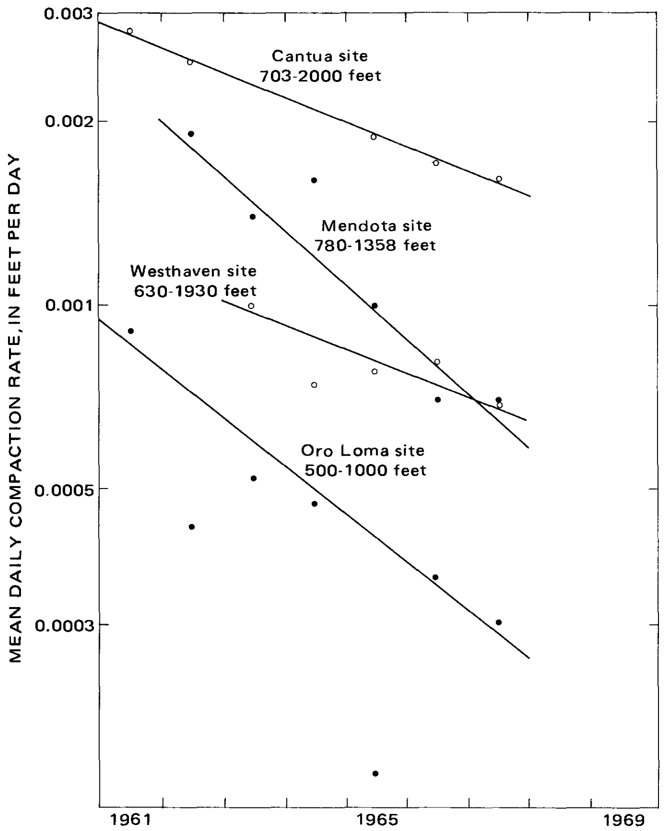


FIGURE 39.—Decrease in the mean daily compaction rate of the lower-zone deposits at the multiple compaction-recorder sites. (Derived from fig. 36.)

compaction rates at the Oro Loma and Mendota sites. The bedding of the lower-zone deposits is different in the northern and southern parts of the area and is described in detail in Part 2 (Bull, 1974). Flood-plain deposits predominate in the northern part of the area, clayey alluvial-fan deposits predominate in the southern part, and a mixture of alluvial-fan, lacustrine, and flood-plain deposits occurs in the lower zone of the central part (Miller and others, 1971).

Because the time needed to dissipate excess pore pressures is a function of the square of aquitard thickness, a bed thickness factor can be substituted for the time needed to dissipate a given excess pore pressure from an aquitard of a given lithology. If aquitard thickness is expressed as (aquitard thickness/2)^2 and weighted mean aquitard-thickness factors are derived from the micrologs of the core holes, comparisons of the relative ease of pore-pressure dissipation can be made. Micrologs are not available for the Westhaven site. The Oro Loma, Mendota, and Cantua sites have weighted mean aquitard-thickness factors of 16, 11, and 34, respectively (Pt. 2, Bull, 1974, table 7). Thus, the sites with the most rapid decrease of mean daily compaction rates (fig. 39) have thinner lower-zone aquitards than does the Cantua site. Therefore, the rates of decrease of mean daily compaction indicated by the regression plots in figure 39 may be in large part a function of areal variations in aquitard thickness.

The difference in the rates of decrease of mean daily compaction rates in the northern and southern parts of the study area implies that for a given head decline, greater excess pore pressures exist, as of 1967, in the lower-zone deposits in the southern part of the area than in the northern part. The situation may simply be that response to a given increase in applied stress has caused more rapid compaction in the northern than in the southern part of the area.

The preceding discussion concerned prediction of compaction based on empirical compaction relations of large thicknesses of deposits at multiple compaction-recorder sites. The time delay involved in the compaction of saturated fine-grained deposits can also be computed from consolidation tests of core-hole samples from subsidence areas.

Direct computations of ultimate compaction for a given increase in applied stress, based on laboratory consolidation tests, have been made by Miller (1961). The method is a refinement of a technique outlined by Gibbs (1959, p. 4, 5) based on Terzaghi's consolidation theory (1948). The chief merit of the approach is that the time delay associated with virgin compaction is considered. A chief problem is that because of the high cost of consolidation tests, generally relatively few test results have been available from a given core hole. For the four Inter-Agency core holes in the Los Banos–Kettleman City area, consolidation tests were made on 60 cores, an average of 15 per hole. The average depth of the core holes was 1,700 feet, and so the mean spacing of consolidation-test cores was 110 feet. As a result of the paucity of tests, hundreds of feet of deposits may be assigned consolidation characteristics on a subjective basis. The results of Miller's computations of future compaction at the Oro Loma site have been published (1961). Because of the limited number of consolidation tests, it was decided not to include updated computations in this paper. However, the computations of ultimate compaction made for the Oro Loma site in 1960 on the basis of consolidation tests should be reviewed as of 7 years later, in order to compare earlier predictions with actual subsidence.

The basic procedure used by Miller (1961) is as follows: (1) The fine-grained part of the aquifer system is divided into thickness segments and each segment is assigned consolidation-test results considered to be typical of the deposits of that segment. The results of one consolidation test may be used for many segments. (2) The change in applied stress for a given time period is determined. (3) Estimates of compaction are computed on the basis of the void-ratio change determined graphically from the straight-line part of the one-dimensional consolidation curves. (4) The effect of thick clay beds on rates of pore-pressure decay is taken into account using the Terzaghi equation. (5) A sum of the computed compaction for all the segments is determined for one or more time periods.

The attempt to compute residual compaction on the basis of consolidation tests resulted in estimates of compaction and subsidence that are too low. Miller (1961, p. 57, 58) estimated that 0.8 foot of residual compaction would occur at Oro Loma after 1959 in the depth interval 465–1,000 feet, as a result of prior decline in artesian pressure that occurred between 1937 and 1959. The maximum summer depths to water at the Oro Loma site have remained about the same in each year since 1959 (fig. 36*A*). However, as of 1968, the amount of residual compaction measured since 1959 within the depth interval was already twice the amount computed on the basis of laboratory consolidation tests.

The chief problem of using consolidation-test results to estimate subsidence in the San Joaquin Valley has been an insufficient number of consolidation tests to define variations in compressibility due to the wide range in character of aquitard materials. In addition to the limited number of tests, the subjective decision as to what constitutes the "fine grained" deposits within the aquifer system may lead to underestimations of future subsidence.

The use of consolidation tests to estimate compaction or subsidence for a given change in applied stress appears to have much greater potential in the Santa Clara Valley, Calif. (Poland, 1969b, p. 288–290). The fine-grained beds in the Sunnyvale and San Jose core holes that were sampled for consolidation tests have compressibilities or compression indices that group rather closely. Poland suggested that the well section be divided into zones not more than 200 feet thick, a suggestion that would reduce the effects of nonlinear compressibility decrease with increasing effective stress. He concluded that approximate ultimate compaction for a zone can be computed using the equation

$$\Delta z = m_v m \Delta p',$$

where

Δz is the computed ultimate subsidence or compaction,

m_v is the mean compressibility of the compacting beds,

m is the aggregate thickness of the compacting beds, and

$\Delta p'$ is the change in effective stress.

Better estimates should be obtained for the Santa Clara Valley than for the San Joaquin Valley because of the lesser variation in the compressibility of the deposits. The most subjective element in the equation is m, the aggregate thickness of the compacting beds.

Computation of future subsidence that would result from the compaction of a given bed also can be made. For example, useful computations of the compaction rate of the Corcoran Clay Member of the Tulare Formation at the Oro Loma site have been made by Miller (1961, p. 57, 58), using the Terzaghi equation. He used the entire thickness of the Corcoran because compaction of the clay occurs by drainage into the underlying aquifer as a result of the downward head differential. A value of the consolidation coefficient of 0.92 square foot per year obtained for the load (effective stress) range 200–400 lb in $^{-2}$ was used by Miller, who assumed that this coefficient applied to the entire thickness of the Corcoran at the site—that is, that the Corcoran had uniform vertical permeability throughout its 86-foot thickness. Under these assumptions, Miller found that 8,000 years would be required for about 93 percent of the compaction to occur in response to a given applied stress, that 1,600 years would be required for 50 percent of the compaction to occur, and that 60 years would be necessary for only 10 percent of the compaction to occur. He also concluded that the Corcoran is compacting very slowly at the Oro Loma site at a rate of roughly 0.01 ft yr^{-1}.

The consolidation characteristics of the fine-grained materials in the various types of deposits are given in Part 2 (Bull, 1974, table 9). Many of the fine-grained beds from which cores were obtained for consolidation tests are not thick nor do they have a large areal extent. Except for the lacustrine clays, the beds within the study area characteristically are intertonguing lenses.

CONDITIONS AFTER DELIVERY OF CANAL WATER

Importation of surface water into the study area by the San Luis Canal section of the California Aqueduct should eliminate much of the ground-water overdraft that has caused large artesian-head decline and subsidence since 1920. Canal water will not be delivered to all areas at the same time, and even after maximum deliveries can be made through the completed distribution system, ranchers will continue to pump 400,000–500,000 acre-feet of ground water per year after full development of the project area.

The San Luis Canal section of the California Aqueduct is a federal-state joint-use facility.[3] It is part of the major canal under construction for transporting

[3]The authors are indebted to many Bureau of Reclamation employees for furnishing statistics and general information about the San Luis project. Most of the following information was obtained from Richard Bateman, Ralph Cole, William Cooke, Alfred Harvey, and David Magleby.

water from areas of abundant water in northern California to areas needing water in central and southern California. At the north boundary of the San Luis service area, the canal has a bottom height of 85 feet, and the width at the top of the lining is 217 feet. The depth from the canal floor to the top of the lining is 35 feet, and the design capacity of the canal is 13,100 cubic feet per second. Water will be withdrawn for irrigation at many points along the canal, and at Kettleman City, on the south edge of the study area, its design capacity is 8,100 cubic feet per second. The gradient of the canal is only 4×10^{-5} (2½ in./mi).

The canal was completed in 1968 at an estimated cost of $548 million for the canal and storage features. At least an additional $284 million is expected to be spent in the construction of distribution systems both upslope and downslope from the canal. Upon completion of the distribution systems, a maximum of 1,200,000 acre-feet of water can be delivered to the San Luis service area each year. The ultimate demand of the service area is estimated to be 1,600,000 acre-feet per year, which means that about 400,000–500,000 acre-feet of ground water will have to be pumped in order to satisfy the demand. The location of the canal, service area, and proposed master drain are shown in figure 40.

One reason for continued pumping of ground water will be to provide a mix of irrigation water that will percolate into the surface soils more readily than the sodium chloride water of 200–300 milligrams per liter total dissolved solids that will be delivered from the Sacramento River system to the San Luis service area.

The schedule of delivery of water to the San Luis service area is the determining factor in how rapidly the pumping rate will decrease and the artesian head will rise, resulting in the alleviation of subsidence in parts of the area and elimination of subsidence in other parts of the area. The delivery of water is based to such a large extent on political and economic factors that as of mid-1968 it is not possible to estimate the schedule of water delivery. Some of the problems that have to be solved before delivery of water include these: the 160-acre limitation landowners have to agree to before they are eligible to receive canal water; funds for the construction of distribution systems are becoming increasingly difficult to obtain during a period of war-time economy; and appropriate means of removing waste irrigation water have to be made from those parts of the area where the water table is close to the root zone. Furthermore, farmers may prefer to continue to use some of the wells drilled shortly before imported surface water becomes available.

Delivery of water is expected to occur in three stages. The first area to receive large amounts of canal water is downslope from the canal in the northern part of the area. The next area will be downslope from the canal in the southern part of the area. The area upslope from the canal will receive canal water last because the time needed to construct facilities to move water upslope is greater than that for the gravity-flow structures to be used downslope from the canal.

One method of evaluating the influence of importation of canal water is to study the effect of past imports of water. The following discussion will make such an evaluation in the northern and southern parts of the area. Then a prediction of future subsidence rates will be made under assumed conditions.

In the Los Banos–Kettleman City area as a whole, the subsidence rates were accelerating during the 1943–53 period. In most of the area, subsidence rates increased until 1955–60, but have decreased since 1960. Despite the reversal in subsidence rate in the middle and late 1950's, rates in 1959–63 were more than twice those in 1943–53 in much of the area.

A pronounced exception to the general increase in subsidence rates was the northern part of the Los Banos–Kettleman City area, the area that had been receiving Delta-Mendota Canal water since 1953. The effect of delivery of Delta-Mendota Canal water on subsidence rates in this northern area is shown in figure 41. Large-scale deliveries of water from the Delta-Mendota Canal began in 1954. Parts of the area within, and the area to the north of, the Delta-Mendota Canal service area shown in figure 41 were receiving surface-water imports from other smaller canals prior to delivery of Delta-Mendota Canal water. In 1960, a local water company completed the construction of a lift system upslope from the Delta-Mendota Canal and began to irrigate a large area near the foothills with imported surface water.

The subsidence rate in the northern part of the Los Banos–Kettleman City area during the period 1943–53 is shown in figure 41*A*. Rates in part of the area that later received canal water exceeded 0.4 ft yr^{-1}, as compared with maximum subsidence rates farther south of slightly more than 0.6 ft yr^{-1} during the same period. The pattern of rate isopleths for the 1943–53 period continues from the southeast directly into the middle of the area later to receive water imports from the Delta-Mendota Canal.

Figure 41*B* shows the change in mean subsidence rates from 1943–53 to 1959–63. The most apparent change between the patterns of isopleths of figures 41*A* and *B* is that the trough defined by the isopleths that extended to the Merced County line in the 1943–53 period stops abruptly at the south edge of the service area of the Delta-Mendota Canal. The maximum subsidence rate within the service area during the 1959–63 period was 0.5 ft yr^{-1} at the south edge. Water levels in

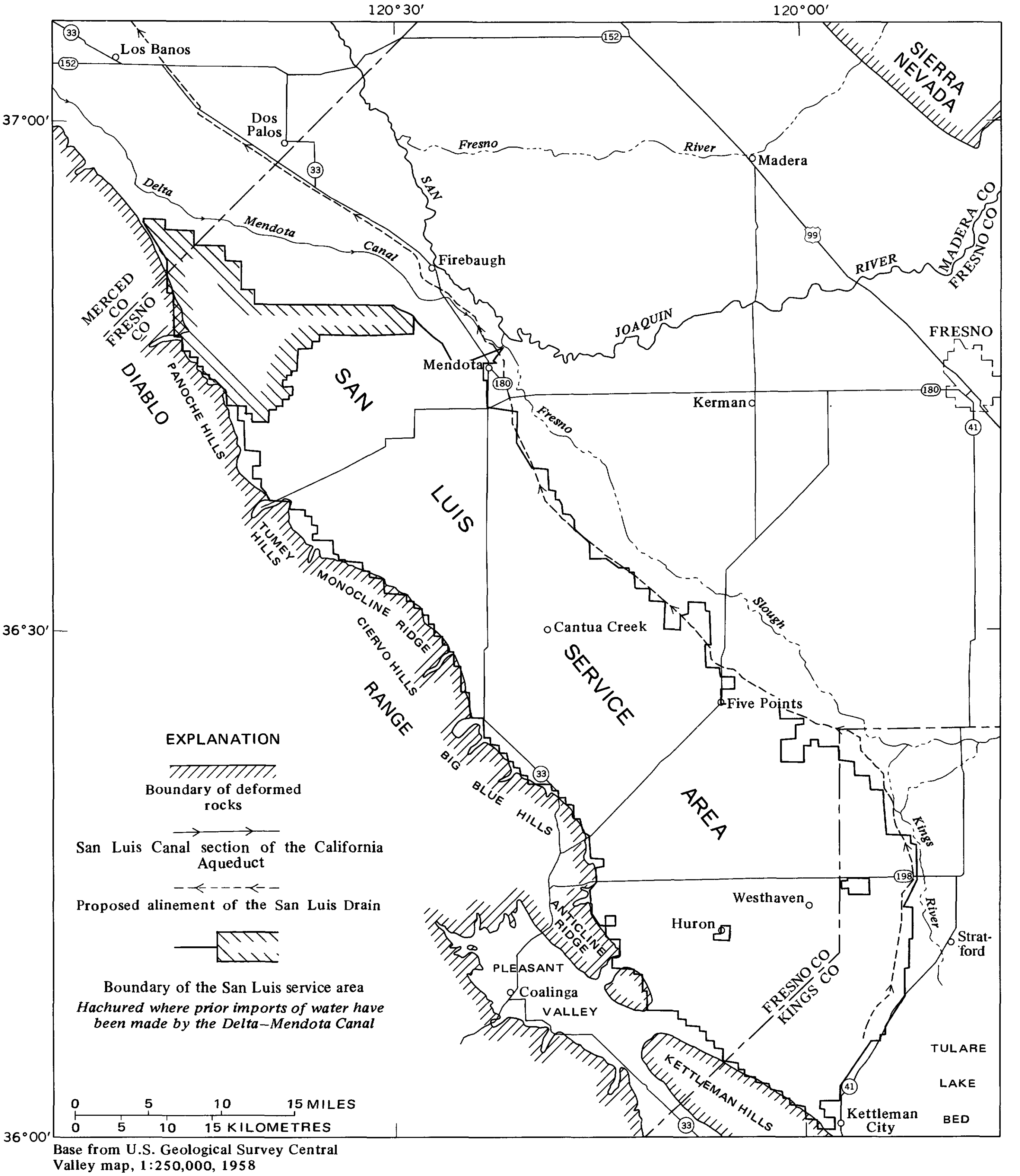


FIGURE 40.—Areas to receive water from the San Luis Canal section of the California Aqueduct.

the southern part of the service area were maintained at the previously low levels or were still declining at slow rates because of the large overdraft caused by lower-zone pumping in the area immediately to the south.

Within a 100-square-mile area of figure 41*B*, which includes most of the area that has received large

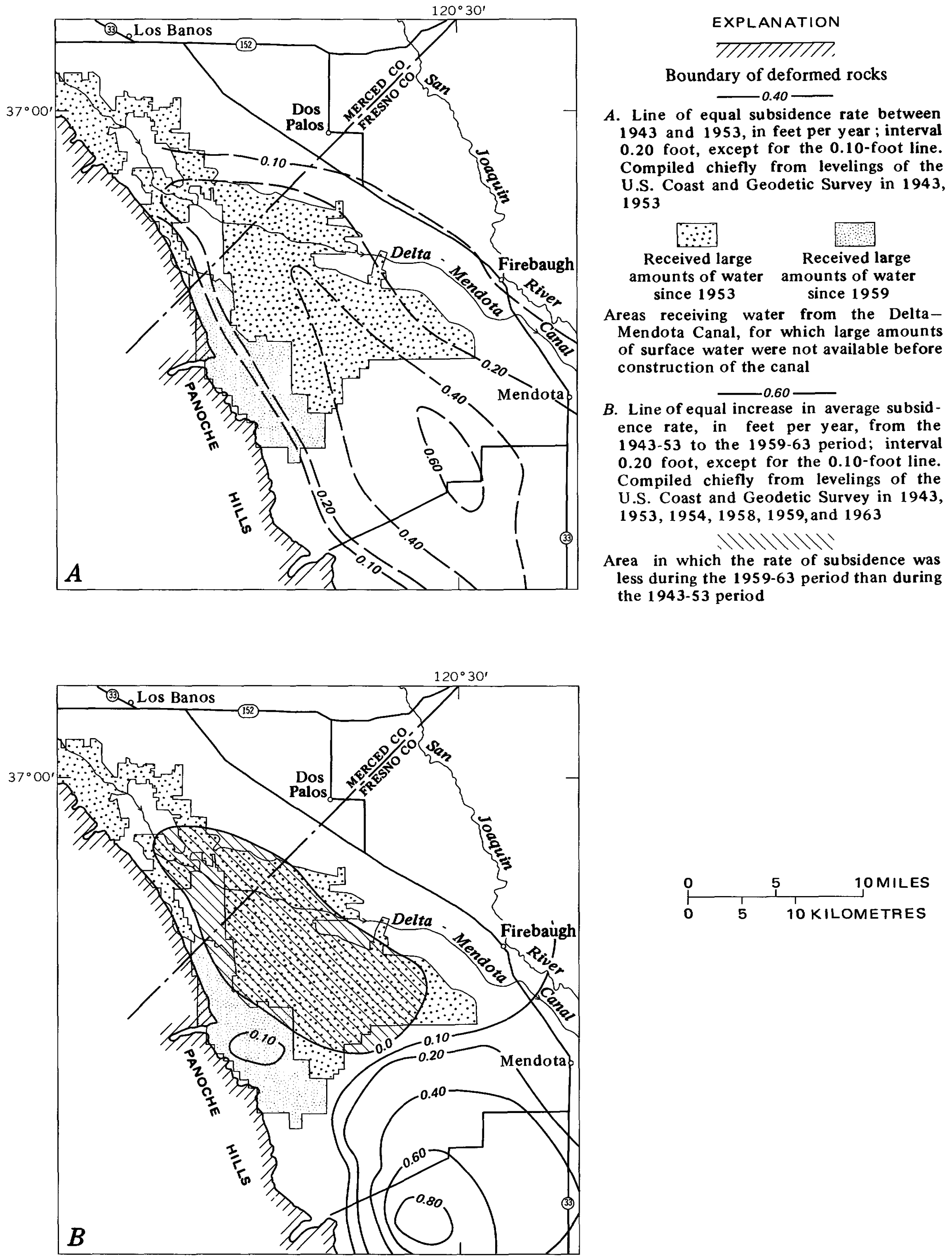


FIGURE 41.—Effect of delivery of Delta-Mendota Canal water on subsidence rates in the northern part of the Los Banos-Kettleman City area.

amounts of surface water since 1953, the subsidence rate was less during the 1959–63 period than during the 1943–53 period. Subsidence was alleviated in varying degrees within this 100-square-mile area, despite the continued acceleration of subsidence rates and overdraft south of the service area. Within the service area, local pumping of lower-zone water continued, but lower-zone water levels rose more than 40 feet between 1955 and 1966 in some wells.

The area near the foothills that has received large amounts of canal water since 1959 has undergone only a slight increase in subsidence rate since the 1943–53 period. Much of this area was not farmed until after 1947. The area immediately to the south also shows negligible increase in subsidence rate, but was yet to be farmed as of 1968.

Subsidence alleviation in the Delta-Mendota Canal service area was the result of sustained importation of surface water. The effect of intermittent importation of surface water in part of the southern part of the Los Banos–Kettleman City area is shown in figure 42.

The interrelations of subsidence rates, artesian-head decline, and surface-water imports near Stratford and Lemoore show that even occasional surface-water imports influence the subsidence rate. Before construction of Pine Flat Dam on the Kings River in the Sierra Nevada, the rate of subsidence of bench mark L157 increased as follows: 1933 to December 1942, 0.0 ft yr^{-1}; 1942 to May 1947, 0.06 ft yr^{-1}; and May 1947 to March 1954, 0.37 ft yr^{-1}. Since completion of Pine Flat Dam in 1954, subsidence rates have varied markedly, ranging from 0.3 ft yr^{-1} between January 1958 and January 1959 to 0.44 ft yr^{-1} between January 1960 and March 1963.

The inverted bar graph of annual discharge downstream from the Lemoore weir indicates the trends in availability of surface water for agriculture in the Stratford-Lemoore area that resulted from the construction of Pine Flat Dam. Discharge downstream from the Lemoore weir has ranged from 0 acre-feet in 1961 to more than 500,000 acre-feet in 1958. The 2 years when annual discharge exceeded 200,000 acre-feet were times of greatly reduced subsidence rate at bench mark L157. Periods of marked reduction of surface water imports, such as in 1957 and 1960 to early 1963, were associated with an eightfold increase in subsidence

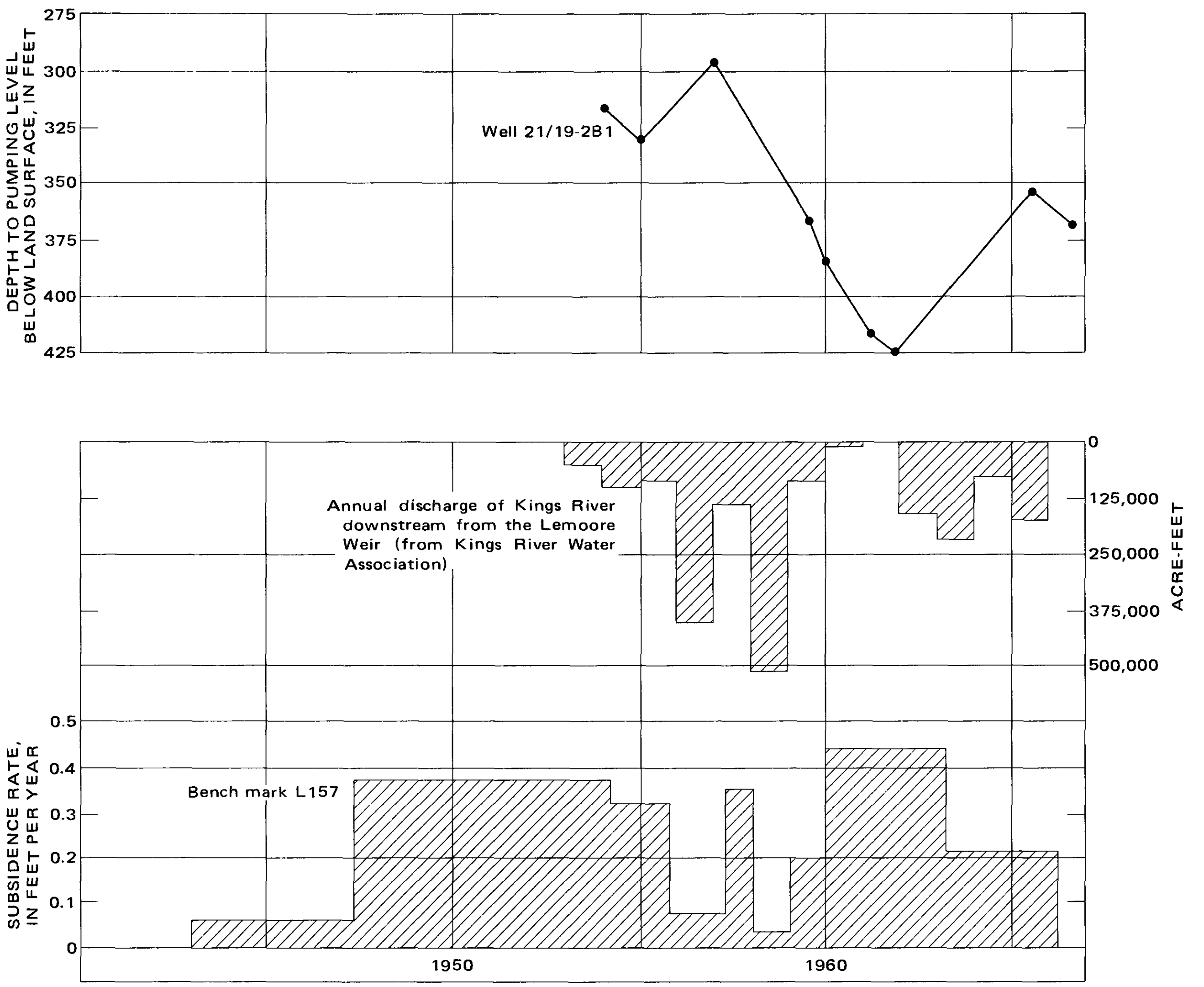


FIGURE 42.—Interrelations of subsidence rates, artesian-head decline, and surface-water imports near Stratford and Lemoore.

rate, when compared with the mean subsidence rate in 2 years of abundant surface water.

Measurements of the pumping level in well 21/19–2B1, although infrequent, show general trends that agree with the records of subsidence rates and surface-water imports. This well is 1,990 feet deep and taps only the lower zone. The time of maximum recorded depth to pumping level late in 1961 coincides with the year of minimum availability of surface water and occurs in the period of maximum subsidence rate. The time of minimum recorded depth to pumping level late in 1956 is associated with a year of large surface-water import and with a period when the subsidence rate was only 0.07 ft yr^{-1}.

The interrelations shown in figure 42 indicate that little residual compaction would occur if water levels were raised more than 50 feet.

Accurate prediction of subsidence rates for an entire region at a specified future date may not be possible because of the many highly variable factors that influence change in applied stress. However, it can be assumed that importation of canal water will decrease pumping and will cause artesian heads to rise, and thereby alleviate subsidence to varying degrees in all areas of decrease in applied stress and possibly eliminate subsidence in parts of the area. The following discussion, although made in the form of a prediction, is intended as an example of the application of criteria for the prediction of future subsidence after a postulated decrease in applied stress.

Estimated subsidence rates based upon a postulated increase in lower-zone artesian head are made in table 2 and in figure 43. The estimates were made on data available as of December 1967. The year 1970 is used as the time of the hypothetical head rise. It is necessary to specify a date for the estimated rates because of the continuing decay of excess pore pressures that have resulted from previous head declines. The year 1970 may or may not be the time of major recovery of lower-zone artesian head. It can be stated with certainty, however, that increase in head as the result of canal-water imports will not be uniform, nor will it occur at the same time in all parts of the area.

TABLE 2.—*Estimated annual subsidence rates in the Los Banos-Kettleman City area if summer lower-zone water levels rose 60 feet and the seasonal fluctuation were reduced to 10–20 feet*

Subarea	Estimated rate if water levels rose 60 feet in 1968[1] (ft/yr)	Estimated rate if water levels rose 60 feet in 1970[2] (ft/yr)
1A	0	0
1B	0 –0.2	0 –0.1
2	0 –0.2	0 –0.1
3	0.1–0.3	0.1–0.2
4	0.3–0.5	0.2–0.3
5	0.1–0.3	0.1–0.2
6	0.1–0.2	0 –0.2
7	0 –0.2	0 –0.1
8	0.2–0.4	0.2–0.3
9	0.4–0.6	0.3–0.4
10	0 –0.2	0 –0.1
11	0.2–0.4	0.2–0.3
12	0.1–0.2	0 –0.2
13	0 –0.2	0 –0.1

[1]Based on 1963–66 subsidence rate map, compaction rate after 60 ft of water-level rise at compaction-recorder sites, lithofacies maps, and lower-zone seasonal fluctuation map.
[2]Correction of estimated 1968 rates based on residual compaction graphs (figs. 38, 39).

A 60-foot increase in head was selected for several reasons. It is a reasonable minimum amount of rise in the summer potentiometric level that will occur after large-scale deliveries are underway, but probably is less than the ultimate amount of head recovery that will occur in much of the area after the maximum delivery of surface water. It is possible that the lower-zone artesian head will rise more than 200 feet in parts of the study area, despite the estimate that total ground-water pumpage under full import conditions will still be about half a million acre-feet.

About 60 feet of seasonal water-level recovery has occurred at many of the compaction-recorder sites. If a larger value of postulated head rise had been selected—100 feet, for example—then the compaction records would be of little use in determining the rate of compaction after given amounts of head recovery.

The estimates of future subsidence rates after a postulated head recovery represent an integration of knowledge regarding many aspects of the hydrology and geology of the Los Banos–Kettleman City area. Because many different types of knowledge and experience are involved, the results should be considered in part to be subjective. However, the large amount of factual data that is available makes the estimates more objective than the reader might first suspect. The general pattern of subsidence rates is well established from the 1963–66 subsidence rate map (Pt. 2, Bull, 1974, fig. 19).

The compaction rate after 60 feet of seasonal lower-zone head recovery is available from most of the compaction-recorder sites. In evaluating the compaction records, it is important to remember that the amounts of recorded compaction during a period of water-level rise are the net result of two components tending to change aquifer-system thickness: Delayed compaction of the aquicludes and many of the aquitards will tend to cause compaction to be recorded; elastic expansion of the aquifers and some of the aquitards also will tend to cause expansion to be recorded. The net result of these two components is dependent on the rates of delayed compaction and water-level rise. If the rates of water-level rise are sufficiently rapid, net expansion may be recorded, even though delayed compaction is continuing in parts of the aquifer system. In this case, recorded compaction may resume after a period of water-level rise, assuming that water levels are constant after the head recovery. Rates of delayed compaction that are recorded while water levels are rising are minimum rates.

Two lithofacies maps (Pt. 2, Bull, 1974, figs. 63, 66)

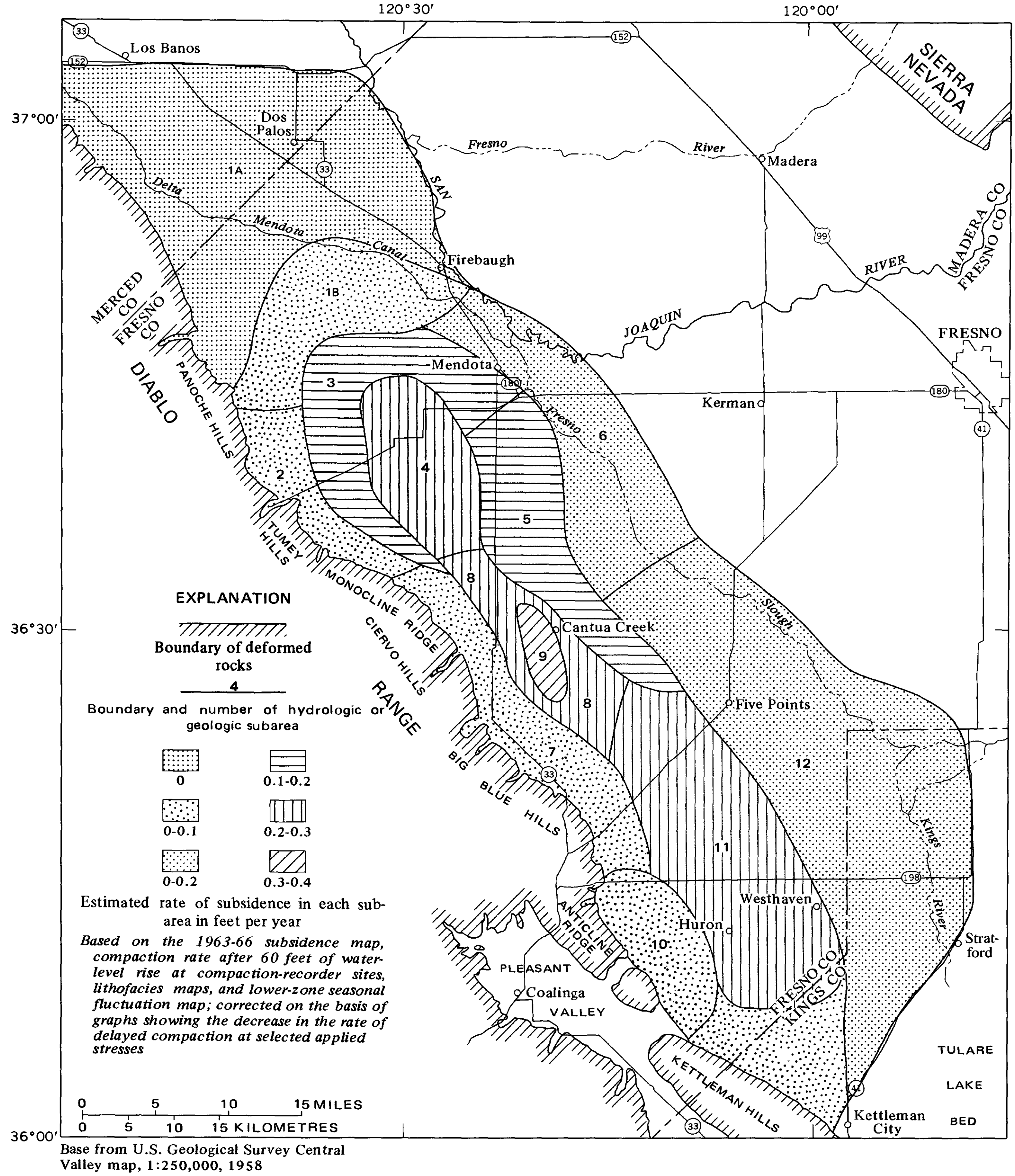


FIGURE 43.—Estimated annual subsidence rates in the Los Banos–Kettleman City area in 1970 if summer lower-zone water levels rose 60 feet and the seasonal fluctuation were reduced to 10–20 feet.

were used in the evaluation. One map shows the general patterns of the mean lithology of the lower zone, and the other map shows the distribution of genetic classes of deposits with different types of bedding, which have an important influence on the rate at which water can be expelled from the compressible deposits and hence on the rate of compaction. Most of the subarea boundaries that trend generally east-west in figure 43 were selected on a hydrogeologic basis. Subarea boundaries that parallel the length of the area also parallel the lines of equal subsidence rate, or boundaries of Sierra and Diablo deposits.

The lower-zone seasonal fluctuation had to be considered also. A 60-foot head rise for summer levels would raise the minimum seasonal water level 50 feet above the 1967 winter high water levels in parts of the area. In other parts of the area, 60 feet is only half the seasonal fluctuation that was occurring in 1967. It is assumed that seasonal fluctuation of artesian head will decrease as the ground-water pumpage decreases. A range of 10–20 feet of seasonal fluctuation was selected for the purposes of table 2 and figure 43. The amount of seasonal fluctuation that is postulated is about the same as has been occurring in that part of the area that already has received large-scale surface-water imports—the service area of the Delta-Mendota Canal. In 1966 and 1967, seasonal fluctuations in most of the Delta-Mendota Canal service area were 5–20 feet.

The factors just described were the principal sources of information used to estimate the subsidence rates if summer water levels had risen 60 feet in 1968 (table 2). Maximum estimated subsidence rates after a postulated water-level rise in 1968 exceed half a foot per year in subarea 9, but in most of the area would be 0.1–0.3 ft yr^{-1}.

The estimates of 1968 subsidence rates if the postulated water-level rise had occurred were made only to form a basis for predicting future rates within small areas, or at given points, after a summer head recovery has actually occurred. The potentiometric levels during the summer of 1968 actually reached historic lows in most of the area.

To estimate subsidence for some future year, the decrease in the rates of delayed compaction has to be estimated and applied as a correction to the 1968 estimates. The selected year of 1970 for a postulated 60 feet of summer head rise is 2½ years after the December 1967 base date. The plots of decrease in the rate of delayed compaction in figures 38 and 39 indicate that after a 2½-year period, residual compaction in the northern part of the area would be roughly 35 percent complete and would be roughly 15–20 percent complete in the southern part of the area. The larger correction factor was applied in subareas 1 through 4, and the smaller correction factor was applied in subareas 5 through 13.

The end result of the foregoing computations and corrections is the set of estimated subsidence rates in 1970 if the summer water levels in that year should be 60 feet above the 1967 summer levels. These estimates do not take into account the elastic expansion, principally of the aquifers, that will occur as a result of the postulated 60 feet of head rise. The only data available at the time of the writing of this paper are the amounts of net specific unit expansion at three sites. The net values are considered as minimum values of specific unit expansion, but at least 0.1 foot of expansion should occur in most of the area as a result of 60 feet of lower-zone head recovery. Change in altitude of bench marks surveyed before and after an actual 60-foot head recovery would include the effects of the elastic expansion of the more permeable beds within the aquifer system and thus may result in lower observed subsidence rates than shown in figure 43. The rates given in table 2 and figure 43 are based on the premise that summer water levels will not change significantly after the 60-foot water-level recovery.

Over long time periods, elastic expansion of the lower zone in response to substantial recovery of artesian head may be offset by compaction resulting from increase in stress that will be applied to the lower zone as a result of water-table rise. The water table is rising at the present time in most of the study area. Importation of additional supplies of water for agriculture probably will result in an acceleration of water-table rise. Every 5 feet of water-table rise will tend to offset 1 foot of lower-zone head recovery. For example, 50 feet of water-table rise in an area where the lower zone is confined and the lower-zone head remains constant will result in an increase in applied stress on the lower zone of 10 feet of water.

Surface-water deliveries have been made in subarea 1A for a long time, and the head decline that has caused subsidence began in this area before 1920 (Pt. 1, Bull and Miller, 1974, fig. 21). Sixty feet of head rise should cause compaction to cease, except in the Corcoran, and probably will result in minor net expansion in much of the subarea.

Subarea 1B is that part of the Delta-Mendota Canal service area adjacent to the area of excessive ground-water pumping to the south. Much of the delayed compaction may have already occurred in the Diablo flood-plain deposits that underlie this subarea, and so it is anticipated that subsidence rates would be low should water levels rise.

Most of subarea 2 bordering the foothills of the Diablo Range has never been irrigated, but the proportion of irrigated land increases to the northeast. Much of the head decline and associated subsidence that has occurred in the past has been the result of ground-water movement to the areas of intense pumping to the northeast of subarea 2.

The lower-zone deposits underlying subarea 3 consist chiefly of Diablo flood-plain deposits. The thin aquitards typical of this class of deposits have contributed to rapid expulsion of water during past periods of applied stress.

Subarea 4 also is underlain principally by Diablo flood-plain deposits. Although this has been the area of maximum subsidence rate in the past (Pt. 2, Bull, 1974, fig. 18), the potential for future delayed compaction is considered to be about the same as subarea 11, where lower subsidence rates have occurred in the past.

Subarea 5 is underlain chiefly by Sierra flood-plain deposits, but these deposits are finer grained than the Sierra flood-plain deposits to the east in subarea 6. Future subsidence is expected to occur within this subarea, but the amounts should be small.

Nearly all the head decline that has occurred in subarea 6 has been the result of excessive lower-zone overdraft to the west. Thus, 60 feet of head rise would consist mainly of a decrease in the gradient of the potentiometric surface to the west. Subsidence rates may decrease to nearly 0 in parts of the area where the lower-zone deposits consist mainly of sand that has few interbeds of fine-grained material. However, expansion of agricultural development and additional pumping of lower-zone water in those parts of the subarea outside of the San Luis Canal service area may result in subsidence rates of as much as 0.2 ft yr^{-1}.

Most of the wells in subarea 7 tap sands and thick clays of the Etchegoin Formation. Subsidence rates were low during the 1963–66 period, but probably will not decrease markedly because of the large excess pore pressures that probably exist in very thick clay beds. Also, 60 feet of head rise is minor when compared with the 400–500 feet of head decline that has occurred in the subarea.

Subareas 8 and 9 have lower-zone deposits that are similar to those of subarea 4, except that the Diablo deposits consist of alluvial-fan instead of flood-plain deposits. Sierra and lacustrine deposits make up a large portion of the section.

Records from the Cantua recorder site indicate that maximum delayed compaction may occur within subarea 9. At least 100 feet and possibly more than 200 feet of head recovery may be necessary to eliminate excess pore pressures at this site. The area is underlain by several types of deposits.

The water-table rise that should occur in the coarse-grained deposits of subarea 10 southwest of the confining influence of the Corcoran should cause a steady and rapid decline in applied stress on the aquifer system which approaches a water-table type of aquifer next to the foothills. The lensing clay beds in the fan deposits of the subarea generally are not thick, and periods of rapid water-level rise at one site (19/16–23P2) are accompanied by recorded net aquifer expansion.

The amount of subsidence after delivery of canal water may be greater in subarea 11 than elsewhere in the study area because of the thick section of interbedded fine-grained deposits from both Diablo and Sierra sources that constitute the lower zone in this subarea. Head declines have been large, but the rates of compaction have not been as rapid as in subarea 4, where much less head decline has occurred. These facts are interpreted to mean that excess pore pressures are large in subarea 11, thus favoring large amounts of delayed compaction. Net expansion is recorded in the subarea, but only because of the rapid rate of head recovery that occurs after extremely large seasonal water-level declines (Pt. 1, Bull and Miller, 1974, fig. 43).

Subarea 12 is much the same as subarea 6, except that heavy pumping has occurred in the upper as well as in the lower zone. The estimates of future subsidence are based on the premise of 60 feet of head rise in the upper as well as in the lower zone in subarea 12 and in the southeastern part of subarea 11.

In many respects, the situation in subarea 13 is similar to that in subarea 7, except that the deposits from which the water is being pumped are the lower part of the continental Tulare Formation.

SUMMARY

Water-level changes resulting from pumping of ground water and irrigation have changed the stresses tending to compress the alluvium of the Los Banos–Kettleman City area. Change in stress applied on the confined lower zone, in which three-fourths of the compaction is occurring, is the algebraic sum of the following components of stress change:

1. A seepage stress equal to the lower-zone artesian-head change.
2. A seepage stress equal to the head differential caused by change in water-table position.
3. A stress caused by change in buoyancy of the deposits within the depth interval that is being dewatered, or saturated, as a result of water-table change.
4. A stress caused by part of the pore water being changed from a condition of neutral to applied stress, or vice versa, that occurs within the depth interval being affected by water-table change.

The magnitudes of the various stresses on the confined zones (expressed in feet of water) is as follows, assuming a porosity of 0.4, a specific gravity of 2.7, and a moisture content (specific retention) of the dewatered deposits of 0.2 the volume: Seepage stresses resulting from either artesian-head change or change in water-table position cause 1 foot of change in applied stress per foot of change in head differential. Each foot of water-table change also causes a 0.6-foot stress change because of removal or addition of buoyant support of the deposits within the interval of water-table change and a 0.2-foot stress change because of part of the pore water

being changed from a neutral-stress condition to an effective-stress condition, or vice versa. The effect of water-table change is to change the effective stress in the unconfined aquifer by ±0.8 foot of water per foot of water-table change. The effect of water-table change on stress changes in the deeper confined zones is to change the stress by only ±0.2 foot of water because the seepage-stress change more than offsets the sum of the two other stress changes.

Applied-stress increase on the lower-zone deposits has been as much as 500 feet of water as a result of artesian-head decline, and water-table change has caused as much as 25 feet of stress increase in the northern part of the area and as much as 75 feet of stress decrease in the southern part.

Over long time spans, the rates of compaction (and subsidence) per unit applied-stress increase accelerate with additional applied-stress increase, but vary widely because of geologic and hydrologic factors. For example, in some areas applied-stress increases of less than 200 feet have resulted in 20 feet of compaction, but locally along the west margin of the area, increase in applied stress of 400 feet has caused only 1 foot of compaction.

Changes in aquifer-system thickness are elastic (are reversible and occur with minor time delay) and inelastic (are irreversible and occur with large time delay). Under the pore-pressure conditions of the sixties, in much of the area net aquifer-system expansion occurred briefly or not at all, but elastic changes affected the monthly amounts of measured compaction. Maximum compaction rates occur during times of head decline because elastic compaction is additive with virgin compaction; minimum compaction rates occur during times of head rise because expansion is subtracted from virgin compaction. Removal of the estimated component of elastic change of aquifer-system thickness shows that virgin compaction is distributed more uniformly throughout the year than is the observed net monthly compaction and decreases during times of applied-stress decrease.

The elastic component of seasonal compaction varies from less than 5 to about 90 percent, depending on the lithology and permeability of the deposits and on the magnitude and rate of applied-stress increase as compared with previous effective stress maximums and durations.

Good records of net aquifer-system expansion have been obtained at three sites. Amounts of net expansion of almost 0.1 foot have been recorded during times of decrease in applied stress indicated by rise in artesian head. Under the conditions of excess pore pressures existing in aquitards in the sixties, three concurrent processes were tending to change aquifer-system thickness during times of applied-stress decrease—elastic expansion with no measurable time delay (presumably chiefly of the aquifers), delayed elastic expansion (presumably chiefly of the thin aquitards and the outer parts of the thick aquitards), and virgin compaction (presumably of the aquicludes and thick aquitards). Delayed compaction due to continuing decay of excess pore pressures may still occur in thick clay beds after 60 feet or more of head recovery in contiguous aquifers.

The net change in aquifer-system thickness that results from these three concurrent processes is chiefly a function of the rate of change of applied stress and the hydraulic conductivities of the different materials constituting the aquifer system. During rapid applied-stress decrease, net expansion may be recorded while some aquitards are still undergoing virgin compaction. Delayed expansion rates increase with decreasing applied stress and may exceed the decreasing virgin compaction rates for short time periods of rapid applied-stress decrease. During periods of slow applied-stress decrease, virgin compaction rates may continue to exceed delayed expansion rates and net compaction results.

The approximate modulus of expansion (net specific unit expansion) of the upper-zone aquifer system at the Lemoore and Yearout sites is about $3.5\times10^{-6}\text{ft}^{-1}$. During a period of seasonal head recovery at the Lemoore site, the net specific unit expansion varied from 0.6 to $3.6\times10^{-6}\text{ft}^{-1}$, as the rates of virgin compaction and of nondelayed and delayed elastic expansion varied concurrently with changes in the magnitude and rate of applied-stress decrease.

Little time is needed to raise pore pressures in many of the aquitards. Compaction ceases when aquifer pore pressures rise to equilibrium with the maximum pore pressure in contiguous aquitards, thus preventing further expulsion of water. Additional pore-pressure increases in the aquifers are transmitted fairly rapidly into the aquitards because their specific storage in the elastic range is small.

The time lag between the start of head recovery and the start of recorded expansion depends on the mechanics of the aquifer and recorder systems. Net aquifer-system expansion will not occur until the expansion rate exceeds the compaction rate. Net expansion will not be recorded until cable tension below the uppermost friction point between the casing and the cable is increased to the point where it overcomes the friction, reverses the sense of movement in the recorder system, and raises the counterweights. The minimum amounts of head recovery that occurred before net expansion was first recorded were 6 feet at well 19/16–23P2 and 1 foot at well 18/19–20P2.

Prediction of the amounts, rates, and distribution of subsidence during future time periods in the Los

Banos–Kettleman City area is not meaningful unless the magnitude and time distribution of change in applied stress can be predicted with reasonable accuracy. The time-dependent nature of the pore-pressure decay in the aquitards and aquicludes also complicates estimates of compaction of heterogeneous aquifer systems. Therefore, the most practical approach is to provide criteria for the prediction of subsidence rate, assess the critical factors affecting compaction rates, and make predictions of future subsidence rates on the basis of postulated hydrologic changes.

Prediction of trends of future subsidence based on historic subsidence graphs is most likely to be useful when based on subsidence-rate plots, rather than cumulative subsidence plots.

Head decline/subsidence or subsidence/head decline ratios determined for long time periods on an areal basis are a useful tool for predicting minimum ultimate subsidence from a postulated additional head decline. These ratios also are useful for predicting the *rate* of future subsidence if the future rate of applied-stress increase is the same as the rate of applied-stress increase during the period for which the head decline/subsidence ratios were determined. If the rate of applied-stress increase accelerates in the future, estimates of subsidence based on past ratios will most likely be less than the amounts of subsidence occurring in the future. If the rate of applied-stress increase decelerates in the future, estimates of subsidence based on past head decline/subsidence ratios will probably also be low compared with actual amounts of subsidence, because of the large amounts of residual compaction that will continue even during times of little or no increase in applied stress.

Most of the subsidence since 1960 has been the result of increase in applied stress prior to 1960 that did not have sufficient time to become fully effective in many of the thicker aquitards because of their low vertical permeabilities. The occurrence of residual compaction is particularly apparent in areas of large head decline and subsidence that continue to have seasonal fluctuations in artesian head of more than 40 feet. In much of the area, the rate of increase in applied stress has been decreasing since the mid-1950's because the rate of lower-zone head decline has decreased from more than 10–15 ft yr^{-1} to only 1–5 ft yr^{-1}. The rates of compaction and subsidence have not undergone a proportionate decrease. Instead, the rate of compaction has continued to be ⅓–⅔ of the earlier rates as a result of a large component of residual virgin compaction that is occurring in thick beds with low permeabilities. The increase in the delayed compaction component occurring during the past few decades is readily apparent in plots of the ratio of subsidence to lower-zone increase in applied stress.

The rate of decrease of aquitard-aquifer pore-pressure differentials can be evaluated at some sites through study of change of mean daily compaction rates for selected applied stress levels. In the 703–2,000-foot-depth interval at the Cantua site, the relation between mean daily compaction rate (y) and time (x) for the 1961–67 period is

$$y=0.0028e^{-0.096x}.$$

A 10-percent decrease in residual compaction rate had occurred as of mid-1962 and 45 percent by 1968, and a 90-percent decrease is predicted to have occurred by about 1986, assuming a hydrologic environment similar to that of the 1961–67 period. Exponents of similar equations for other compaction-recorder sites indicate that the rate of pore-pressure decay is twice as rapid in the northern as in the southern part of the study area. Weighted mean aquitard thickness factors (aquitard thickness/2)^2 derived from micrologs of core holes show that the sites of most rapid decrease of mean daily compaction rates have thinner aquitards than does the Cantua site in the southern part of the area.

Laboratory consolidation test results are useful in predicting the rates and amounts of compaction of the clay beds from which the samples were cored, but estimates of future amounts of compaction of entire aquifer systems may be of doubtful value if based on only a few consolidation tests. Prior attempts to estimate future subsidence on the basis of consolidation-test results from the study area have resulted in underestimation of future subsidence because of an insufficient number of consolidation tests to define variations in compressibility due to different types of aquitard materials.

Importation of surface water in the past has resulted in marked reductions in subsidence rate. In the service area of the Delta-Mendota Canal, the subsidence rate during the 1959–63 period was less than that during the 1943–53 period, but in the area south of the service area, the rate of subsidence had doubled between the same time periods. Intermittent delivery of water from the Kings River in the vicinity of Stratford and Lemoore, after construction of the Pine Flat Dam, has caused temporary rise in artesian head and decrease in subsidence to rates that were as low as 0.03 ft yr^{-1} during years of abundant surface water. During years when surface water was not available, the artesian head declined, and subsidence rates increased to more than 0.44 ft yr^{-1}. Delivery of water from the San Luis Canal section of the California Aqueduct should result in widespread alleviation of subsidence, even before maximum deliveries are obtained.

Assuming that as of 1970 lower-zone summer water levels throughout the study area will be raised 60 feet and seasonal fluctuation will be reduced to 10–20 feet, the rate of subsidence should be reduced substantially for two reasons. First, the rate of subsidence would be less even if water were not imported, because the rate of applied-stress increase has been decreasing and the delayed compaction rate has been decreasing exponentially. Secondly, a 60-foot water-level rise would eliminate excess pore pressures in some beds and would decrease the applied stress on those beds still having excess pore pressures. On the basis of many types of information available in December 1967, a postulated 60-foot water-level rise by 1970 would result in maximum subsidence rates of only 0.3–0.4 ft yr^{-1}, and large areas that were subsiding 0.2–0.4 ft yr^{-1} between 1963 and 1966 would be subsiding less than 0.2 ft yr^{-1}.

Water-level rises of 100–200 feet should eliminate or reduce subsidence rates to negligible amounts throughout the Los Banos–Kettleman City area.

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U. S. GOVERNMENT PRINTING OFFICE: 1975-O-689-905/13