LAND SUBSIDENCE IN THE SAN JOAQUIN VALLEY, CALIFORNIA, AS OF 1983

By R. L. Ireland

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CONVERSION FACTORS

The inch-pound system of units is used in this report. For readers who prefer metric (SI) units, the conversion factors for the terms used are listed below:

Multiply	By	To obtain
ft (foot)	0.3048	m (meter)
ft/yr (foot per year)	.3048	m/a (meter per year)
inch	25.4	mm (millimeter)
mi (mile)	1.609	km (kilometer)
mi^2 (square mile)	2.590	km^2 (square kilometer)

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ABSTRACT

Land subsidence due to ground-water withdrawal in the San Joaquin Valley that began in the mid-1920's and reached a maximum of 29.7 feet in 1981 has been halted by the importation of surface water through major canals and the California Aqueduct in the 1950's through 1970's.

Water levels throughout most of the San Joaquin Valley have recovered to 1940-50 levels. Extensometer, water-level, and subsidence data from this long-term subsidence study can be utilized to manage the ground-water basin so as to prevent serious future subsidence.

Leveling by the California Department of Water Resources in 1981-82 showed a maximum land-surface rebound of about 0.5 foot along the California Aqueduct from 1977-78 to 1981-82. This land-surface rebound is directly related to the 1976-77 drought. Measured subsidence during the drought was mostly in the elastic range; only a small part was inelastic (permanent subsidence). Field extensometers confirm expansion of the aquifer system but the expansion was less than land-surface rebound observed by the spirit leveling of bench marks.

The computer program and extensometer and water-level data collected on this long-term cooperative study on land subsidence are stored on computer tape No. 220691, type 6250BPI, at the U.S. Geological Survey Information Services Division, Reston, Virginia.

INTRODUCTION

General Statement

The San Joaquin Valley (fig. 1), a broad alluviated structural trough constituting the southern two-thirds of the Central Valley of California, is 250 mi long, averages 40 mi in width, and encompasses 10,000 mi^2 excluding the rolling foothills that skirt the valley on three sides. The pertinent geographic features of the area discussed in this report--the southern four-fifths of the San Joaquin Valley--are shown in figure 1.

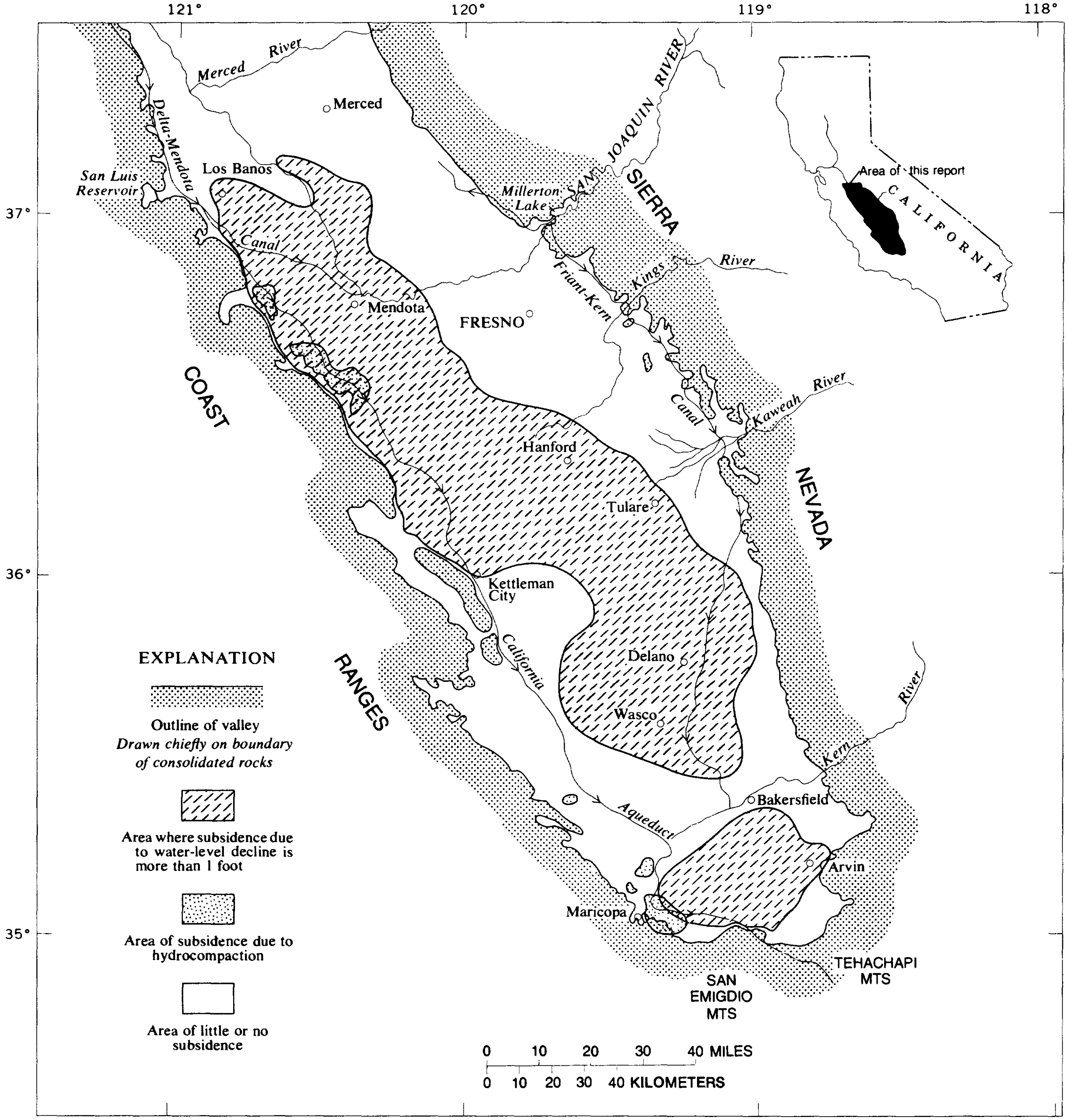
Land subsidence due to ground-water withdrawal began in the San Joaquin Valley in the mid-1920's. In western Fresno County, the maximum exceeded 28 ft by 1970 (Poland and others, 1975) and reached 29.7 ft in 1981. More than 5,200 mi^2 of irrigable land, one-half of the entire valley, has subsided at least 1 ft.

Subsidence has caused serious and costly problems for the farmer in recurrent land leveling and repair or replacement of deep-water wells due to ruptured casings and has changed the gradient and course of valley creeks and streams, causing unexpected flooding. Subsidence also has caused serious problems in the construction and maintenance of highways and water-transport structures. However, throughout most of the valley, subsidence has occurred so slowly and over such a broad area that its effects have gone largely unnoticed by most residents.

Importation of surface water to areas of serious ground-water withdrawal began in 1950 when water from the San Joaquin River was brought south through the Friant-Kern Canal, which extends to the Kern River (fig. 1). Importation from the Friant-Kern Canal to the east-side area south of the Kern River began in 1966. Surface-water imports to the northwestern part of the area via the Delta-Mendota Canal began in the early 1950's. Surface-water imports from the Sacramento-San Joaquin Delta to water-deficient areas on the west side and to the south end of the valley via the California Aqueduct began in 1968 in the northwestern part of the area and in 1970 in the south end of the valley.

As a result of the importation of surface water via the canals and the California Aqueduct to subsiding areas, pumping of ground water in these areas was greatly reduced and the rapid decline of artesian head was reversed, starting in the late 1960's and early 1970's. In 1983, after three decades of withdrawal and one decade of water-level recovery, ground-water levels in most actively subsiding areas of the San Joaquin Valley ground-water basin had returned to or recovered above their 1940-50 levels and subsidence had slowed considerably or stopped.

Not all the effects of the subsidence due to ground-water withdrawal have been bad. The deposits of the ground-water basin are now largely "preconsolidated" to their historic low water levels. The basin can now be managed for cyclic ground-water storage nearly to the historic low water levels without serious additional land subsidence.



Base from U.S. Geological Survey
1:1,000,000, State base map, 1940

FIGURE 1. — Geographic features of central and southern San Joaquin Valley and areas affected by subsidence (Modified from Ireland and others, 1984, fig.1).

Causes of Subsidence

Four types of subsidence occur in the San Joaquin Valley. In order of decreasing magnitude, they are (1) subsidence caused by water-level decline (ground-water withdrawal) and consequent compaction of aquifer systems, (2) subsidence related to the hydrocompaction[1] of moisture-deficient deposits above the water table, (3) subsidence related to fluid withdrawal from oil and gas fields, and (4) subsidence caused by deep-seated tectonic movements. A fifth type, subsidence caused by the oxidation and compaction of peat soils, occurs in the Sacramento-San Joaquin Delta area.

The primary causes of subsidence in the San Joaquin Valley are aquifer-system compaction due to water-level decline and near-surface hydrocompaction. The data presented in this report are primarily related to these two types of subsidence; the principal areas affected are shown in figure 1. These areas are mostly in the western and southern parts of the valley where runoff from surface streams is minimal.

Most of the subsiding area in the San Joaquin Valley is underlain by a continuous and extensive confining bed; and most of the pumping withdrawal and compaction due to head decline occurs in the confined aquifer system beneath this bed. The approximate boundary of the confining bed, where known, is shown in figure 1 (Lofgren and Klausing, 1969; Miller and others, 1971; Croft, 1972). North of Wasco, the confining bed is the Pleistocene Corcoran Clay Member of the Tulare Formation, which also has been called the E-clay by Croft (1972). The boundary of the confining bed (fig. 1) conforms fairly closely with the area affected by subsidence, except in the semiconfined system east of Delano (Lofgren and Klausing, 1969). For convenience, the unconfined to semiconfined water-bearing deposits above the confining bed are referred to as the upper water-bearing zone and the confined system beneath the confining bed as the lower water-bearing zone.

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[1] Hydrocompaction is the process of volume decrease and density increase that occurs when moisture-deficient deposits compact as they are wetted for the first time since burial (Prokopovich, 1963; Lofgren, 1969, p. 273). The vertical downward movement of the land surface that results from this process has been called "shallow subsidence" (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958, p. 22) and "near-surface subsidence" (Lofgren, 1960; Bull, 1964a).

Purpose and Scope

This is the final report of a study of land subsidence in California made in cooperation with the California Department of Water Resources. The study has been closely interrelated with a Federal research investigation of the mechanics of aquifer systems. Subsidence in the San Joaquin Valley has been studied in this cooperative program since 1956. Poland and others (1975) summarized land subsidence in the San Joaquin Valley through 1972 and included an annotated bibliography of the principal published reports resulting from the two research studies. The reader interested in learning more about the scope and findings of those reports is referred to Poland's annotated bibliography. Ireland and others (1984) updated land subsidence in the San Joaquin Valley through the 1970's.

The purposes of this report are to (1) review the status of water-level trends and of subsidence in the San Joaquin Valley from 1980 through 1982 and (2) present updated water-level, compaction, and subsidence data. The third purpose is to present updated profiles of land subsidence along the California Aqueduct based on the California Department of Water Resources 1981-82 releveling of the aqueduct in order to define the extent and magnitude of subsidence or rebound that has occurred along the aqueduct, and to identify probable causes where practicable. This report includes field data through December 1982.

Acknowledgments

The writer acknowledges the cooperation of Federal, State, and local agencies, irrigation districts, private companies, and individuals. Leveling data used in the preparation of the subsidence maps, graphs, and profiles were by the National Geodetic Survey, a component of the National Ocean Survey (formerly the U.S. Coast and Geodetic Survey) and by the California Department of Water Resources.

Water-level data utilized in this report were chiefly from field measurements by the U.S. Geological Survey, but some records were from the U.S. Bureau of Reclamation, the California Department of Water Resources, the Pacific Gas & Electric Co., and irrigation districts.

Well-Numbering System

The well-numbering system used in California by the U.S. Geological Survey and the State of California indicates the location of wells according to the rectangular system for the subdivision of public lands. For example, in the number 12/12-16H2, the part of the number preceding the slash indicates the township (T. 12 S.), the part between the slash and the hyphen shows the range (R. 12 E.), the number between the hyphen and the letter indicates the section (sec. 16), and the letter following the section number indicates the 40-acre subdivision of the section as shown below. Within each 40-acre tract, wells are numbered serially as indicated by the final digit of the well number. Thus, well 12/12-16H2 is the second well listed in the SE¼ of the NE¼ of sec. 16, T. 12 S., R. 12 E. Except for the extreme south end of the valley, which is referenced to the San Bernadino base and meridian, all wells are referenced to the Mount Diablo base and meridian.

In this report wells referenced to the Mount Diablo base and meridian are all located south and east of the base and meridian, making all township numbers South and all range numbers East. Therefore, as in the example, the abbreviations S and E are omitted from the well number for brevity. Wells referenced to the San Bernadino base and meridian are all north and west of the base and meridian and are identified by inclusion of the abbreviations N and W in the township-and-range part of the number.

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

STATUS OF SUBSIDENCE, LEVELING, AND WATER LEVELS

The historic subsidence in the San Joaquin Valley from 1926 to 1970 is shown in figure 2. The measured subsidence at bench mark S661 and artesian-head change in nearby wells, 10 mi southwest of Mendota, from 1943 to 1981 is shown in figure 3 (for location see fig. 17); the subsidence of 27.2 ft from 1943 to 1981 plus 2.5 ft of topographic change from the 1920's to 1943 makes this the locus of maximum known subsidence in the San Joaquin Valley. The 1981 leveling data shows subsidence of 0.09 ft from 1977 to 1981, about 0.02 ft/yr. The water level of 321 ft in December 1982 is the highest since records began in the 1940's.

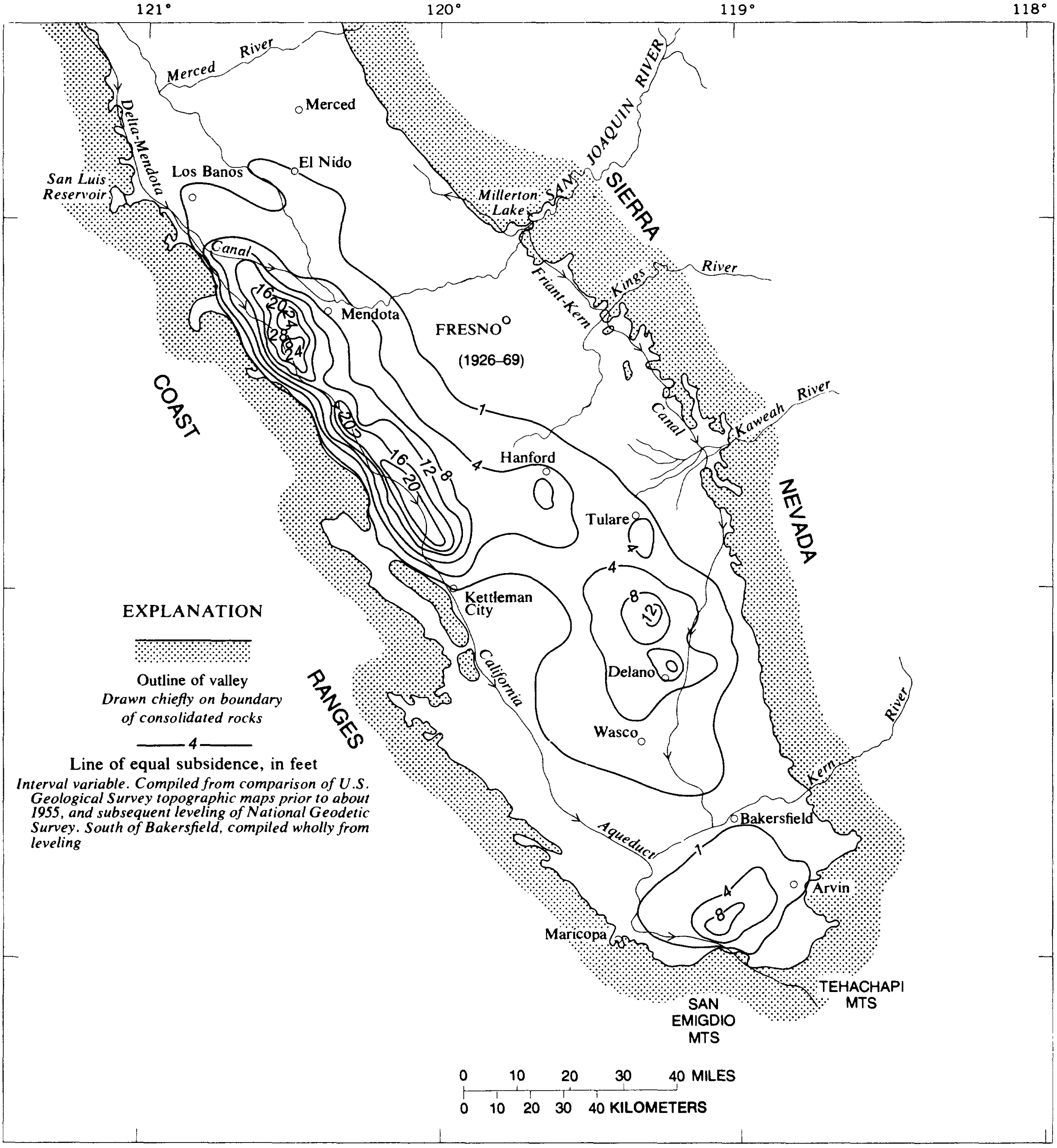


FIGURE 2. — Land subsidence in the San Joaquin Valley, California, 1926–70.

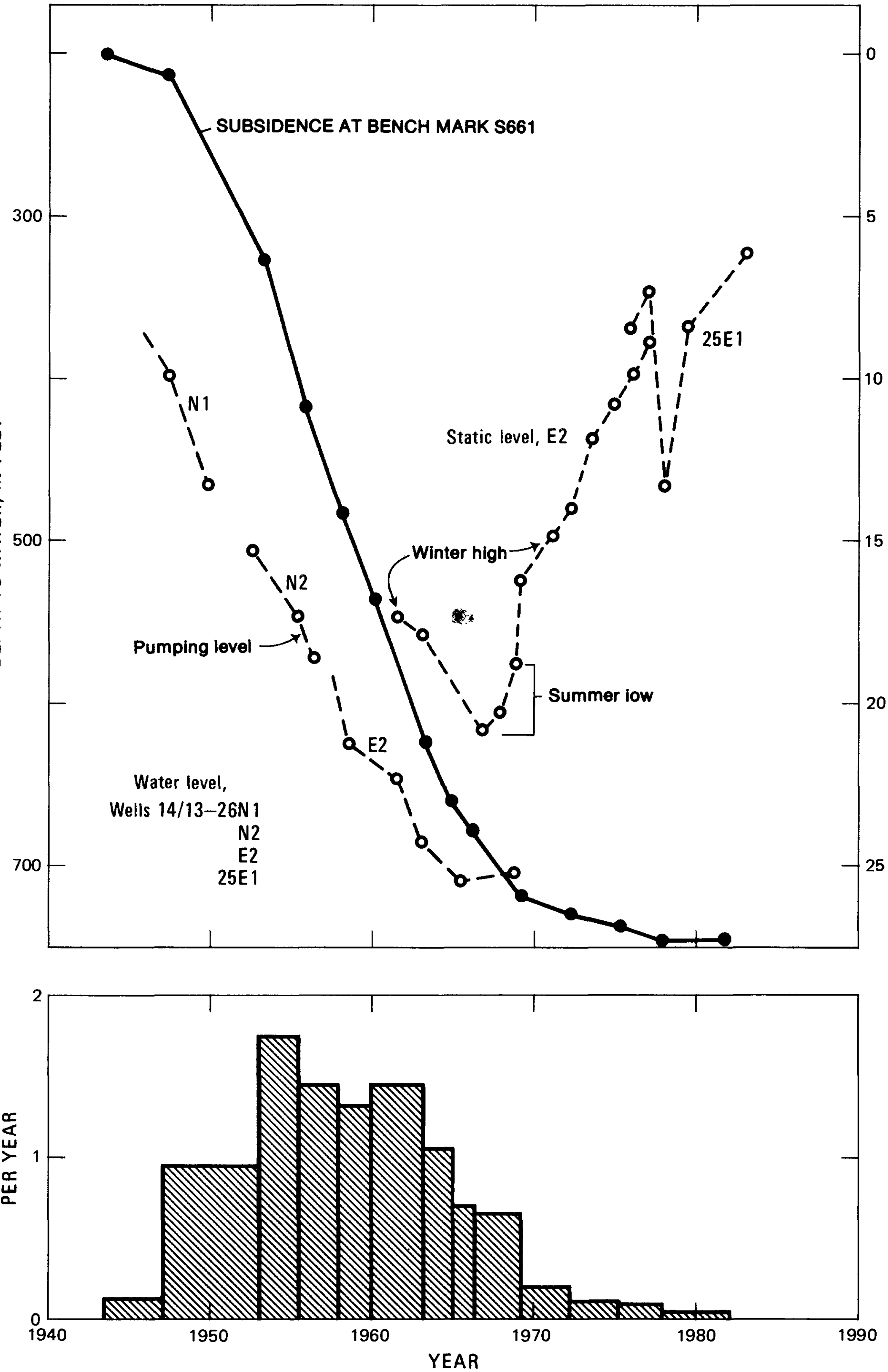


FIGURE 3. — Subsidence and artesian-head change, 10 miles southwest of Mendota (Modified from Ireland and others, 1984,fig. 16).

The network of leveling control periodically resurveyed by the National Geodetic Survey and three areas of detailed studies of land subsidence in the San Joaquin Valley are shown in figure 4. The latest releveling in the Los Banos-Kettleman City area (area A) was in 1971-72. The Tulare-Wasco and Arvin-Maricopa areas (areas B and C) were releveled in 1970 (Ireland and others, 1984). The 1981-82 releveling of the California Aqueduct by the California Department of Water Resources with ties to "stable bedrock reference bench marks" is shown in this figure. The reader interested in the history of leveling in the San Joaquin Valley is referred to Ireland and others (1984, figs. 33 through 35).

Hydrographs in this report show continuing water-level recovery from 1980 through 1982. Annual water-level maps of the California Department of Water Resources (not shown in this report) also show continued recovery in most of the subsiding areas of the valley, indicating that subsidence due to ground-water withdrawal has slowed considerably or stopped.

MONITORING LAND-SURFACE CHANGE ALONG THE CALIFORNIA AQUEDUCT

The reach of the California Aqueduct in the San Joaquin Valley was completed in 1970. Prior to 1970 only completed segments of the aqueduct were leveled (figs. 5 and 6).

The National Geodetic Survey leveled the California Aqueduct in February 1967, November-December 1967, December 1968, January 1969, October-November 1969, November 1970-January 1971, November 1971-March 1972, and January-May 1975. The California Department of Water Resources leveled the California Aqueduct in November 1977-April 1978 and November 1981-March 1982.

This report includes profiles of land-surface change along segments A-B, B-C, C-D, and D-E of the California Aqueduct (figs. 5 through 8, in pocket; for location see fig. 4). The northern segment, A-B (fig. 5), extending from aqueduct mile 92 at the Fresno-Merced County line to aqueduct mile 174 near Kettleman City, is based on eight periods of releveling from November-December 1967 to December 1981-March 1982. The leveling of November-December 1967 was used as the base instead of the February 1967 leveling because the coverage was more complete in December and allowed for settlement and stabilization after construction of the aqueduct was completed during 1967-68.

The second segment, B-C (fig. 6), extending from aqueduct mile 174 near Kettleman City southward past Lost Hills to aqueduct mile 218, is based on five periods of releveling from October 1967-January 1968 to November 1981-March 1982. Segment C-D (fig. 7) extends from aqueduct mile 218 to aqueduct mile 238 and is based on four periods of releveling from 1970 to 1982. The fourth and southernmost segment, D-C (fig. 8), extending from aqueduct mile 238 to aqueduct mile 287 southwest of Wind Gap Pumping Plant, is based on four periods of releveling from 1970 to 1982.

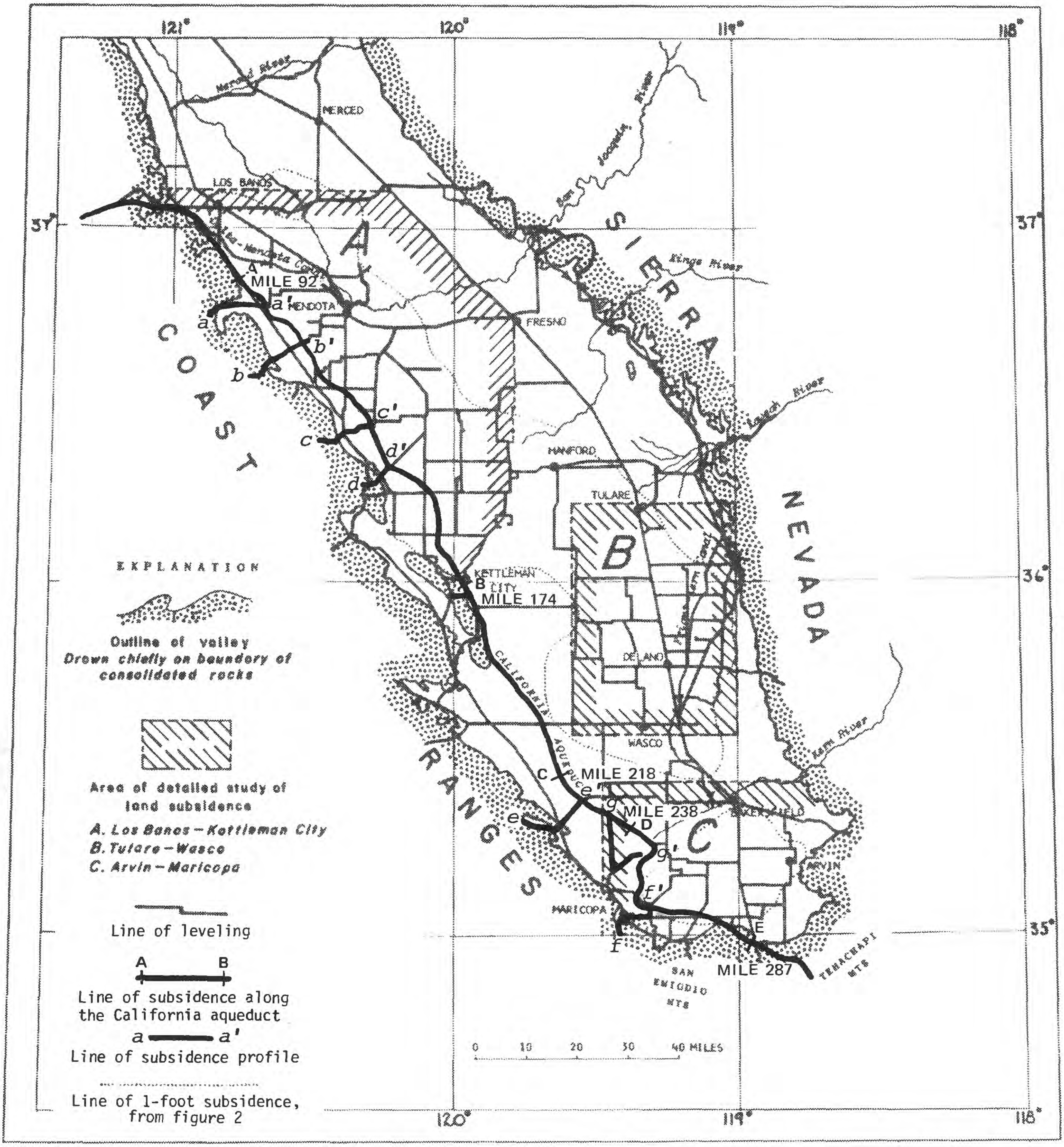


FIGURE 4. — Network of leveling by the U.S. Coast and Geodetic Survey and three areas of detailed studies of land subsidence (Modified from Ireland and others, 1984, fig.32).

Profiles A-B, B-C, and D-E showing land-surface change through 1977-78 were published previously (Ireland and others, 1984). Profile C-D (fig. 7), included in this report, has not been published previously, and completes land-surface change profiles along the entire length of the aqueduct in the subsiding area of the San Joaquin Valley. The 1981-82 leveling along the California Aqueduct is shown on all four profiles.

Note that the subsidence profiles along the aqueduct are drawn with a vertical scale of 1 inch = 1 ft, whereas the horizontal scale is 1 inch = 2 mi (10,560 ft). Thus, the vertical scale is 10,560 times as great as the horizontal scale. This scale difference serves to magnify greatly even very small lateral differentials in the magnitude of subsidence.

In preparing these aqueduct profiles, three types of bench marks are used: bench marks set in the aqueduct lining, bench marks on aqueduct structures, and bench marks adjacent to the aqueduct. Bench marks on aqueduct structures (such as bridges, pumping plants, turnout structures, and checks) show more settlement, especially differential settlement (structure settlement is greater on one side than the other), than bench marks in the aqueduct lining or bench marks adjacent to the aqueduct. Examples of differential structure settlement are shown on each segment. Bench marks in the aqueduct lining are used for these profiles where possible, because they are more representative of the aqueduct subsidence.

The aqueduct traverses areas of subsidence due to water-level decline, hydrocompaction, and oilfield subsidence and may be affected by tectonic subsidence. Areas of known hydrocompaction, shown in figure 1, were prewetted along the aqueduct alinement prior to construction.

Results of the latest leveling change from 1977-78 to 1981-82 are discussed in the following paragraphs. The reader is referred to Ireland and others (1984) for analysis of the aqueduct subsidence from 1967-70 through 1977-78.

Profiles of land subsidence along seven lines to stable bench marks ("bedrock" ties) also are included (figs. 9-15; for location see fig. 4). They extend from bench marks on or near the California Aqueduct to stable bench marks in the hills. The base (beginning year) of these profiles is at or near the year of aqueduct construction.

The aqueduct profiles (figs. 5-8) are discussed from north to south utilizing all available leveling data to determine the magnitude, extent, and probable causes of subsidence or rebound along and near the aqueduct.

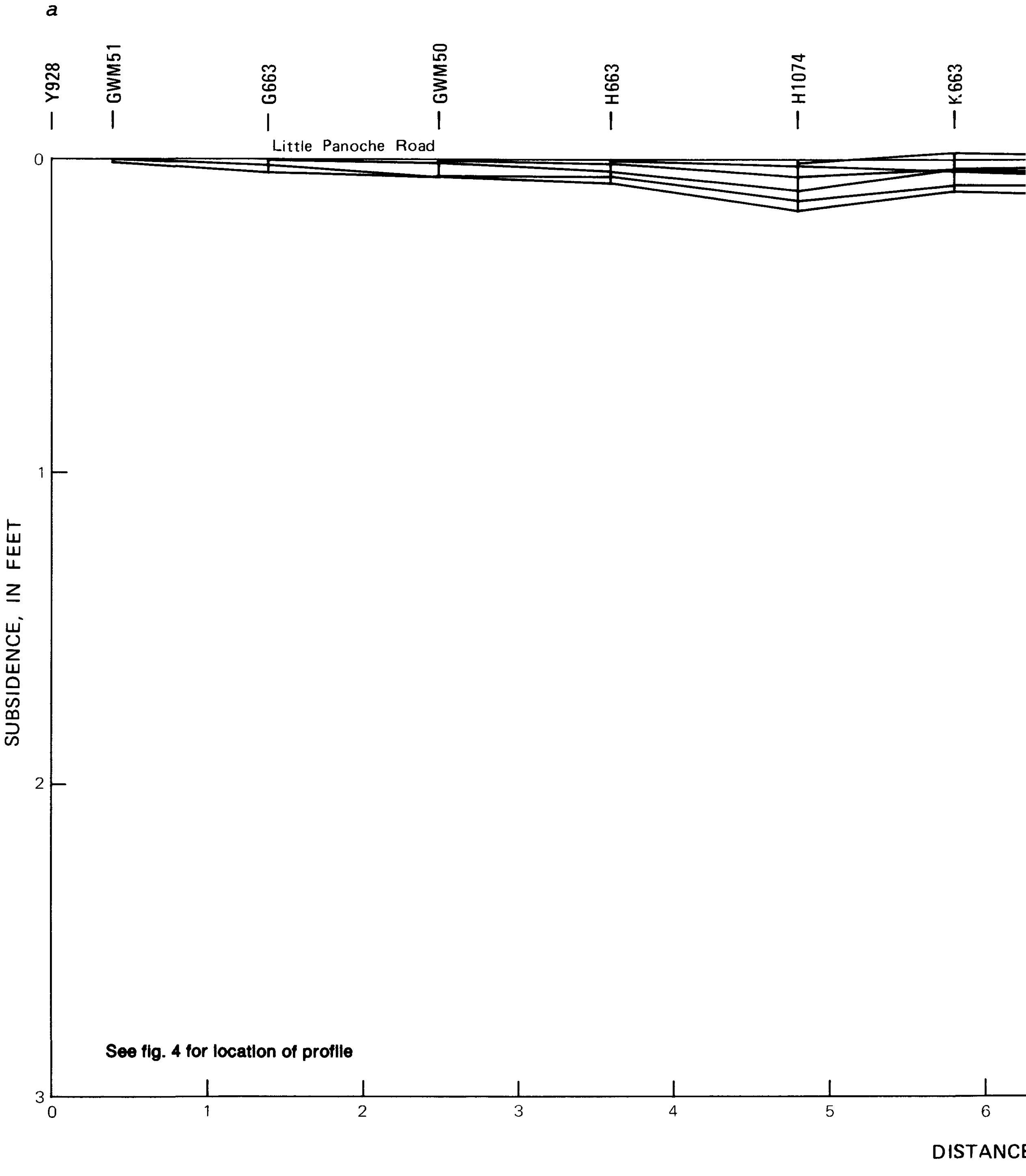
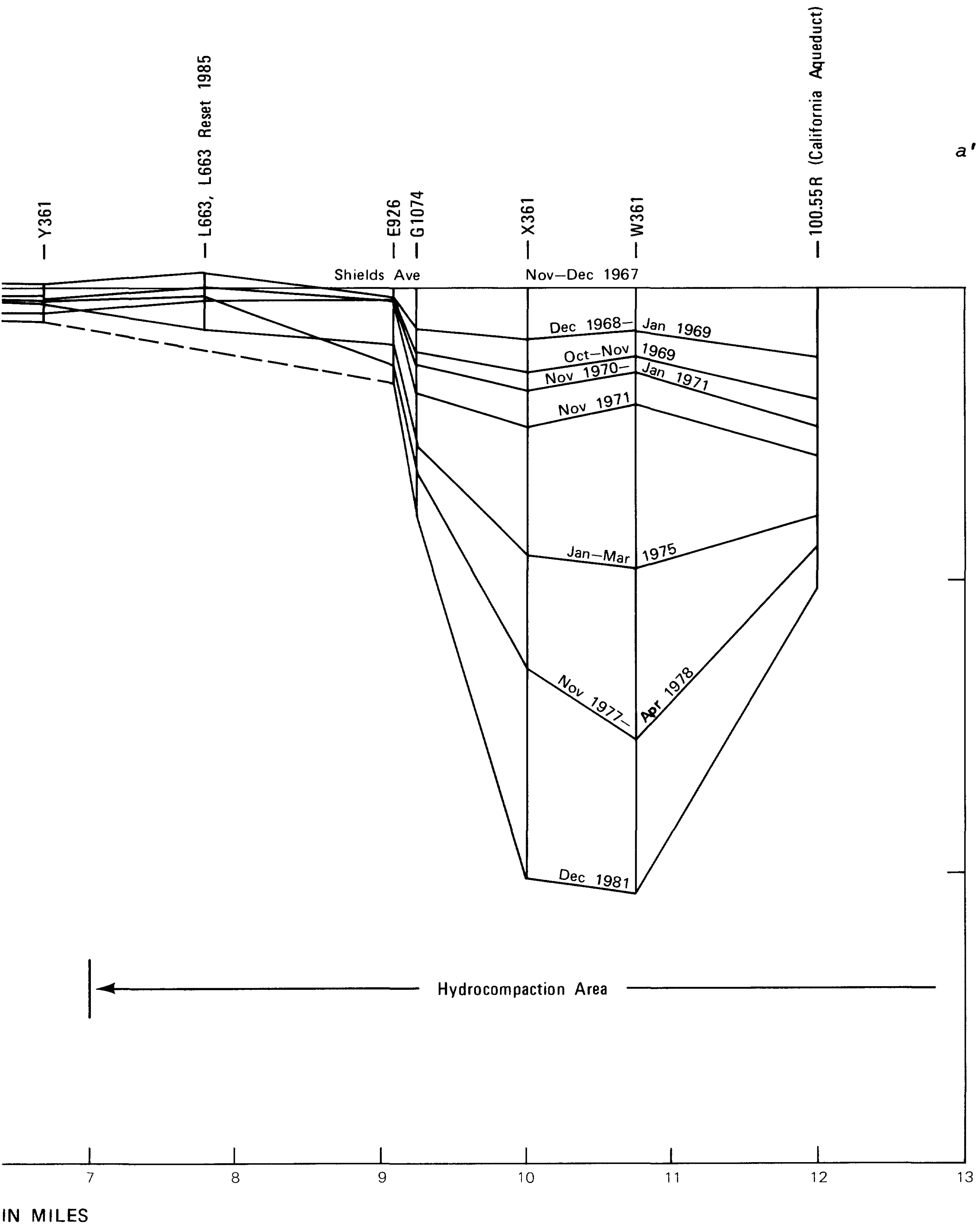
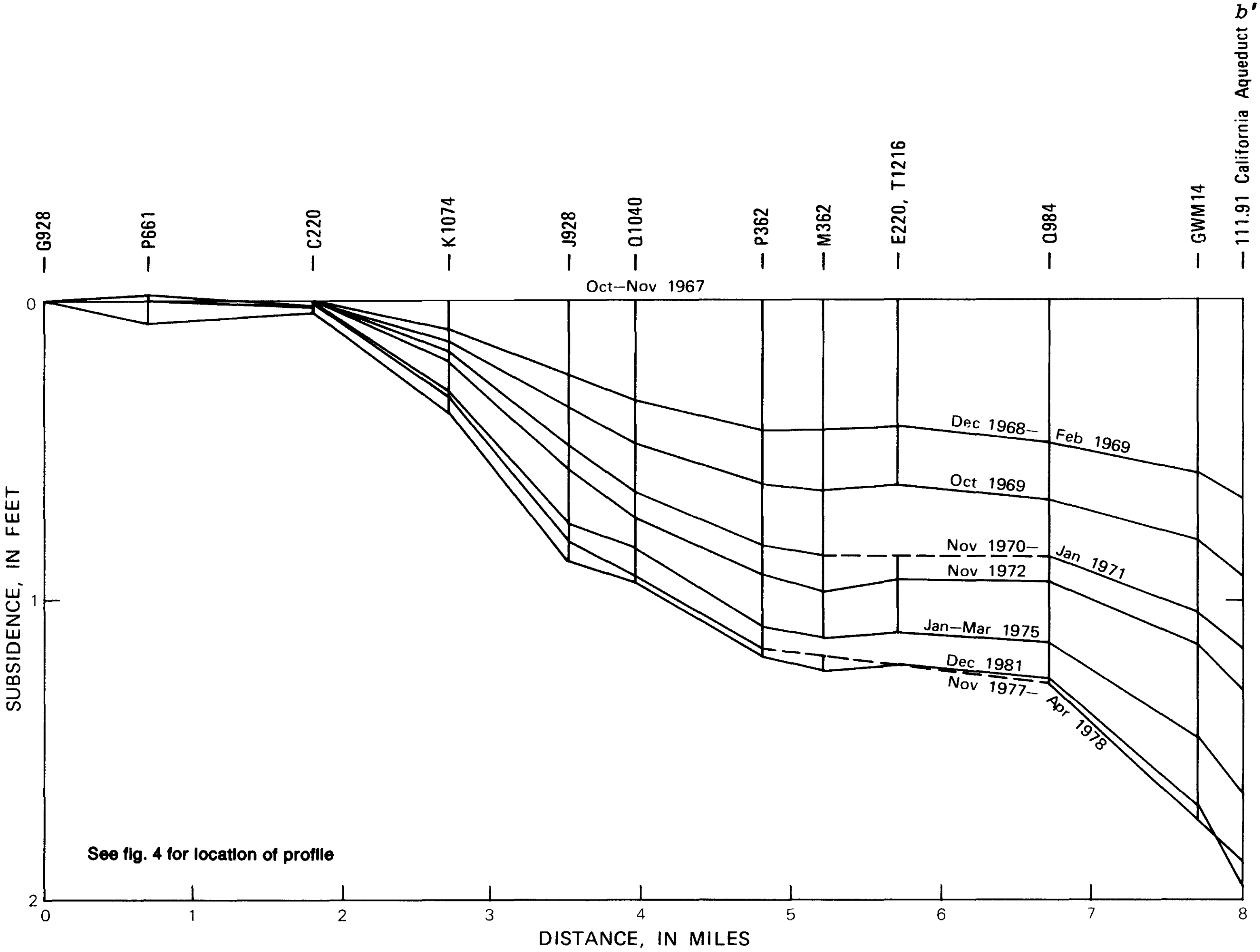


FIGURE 9. — Profiles of land subsidence, a—a′, from

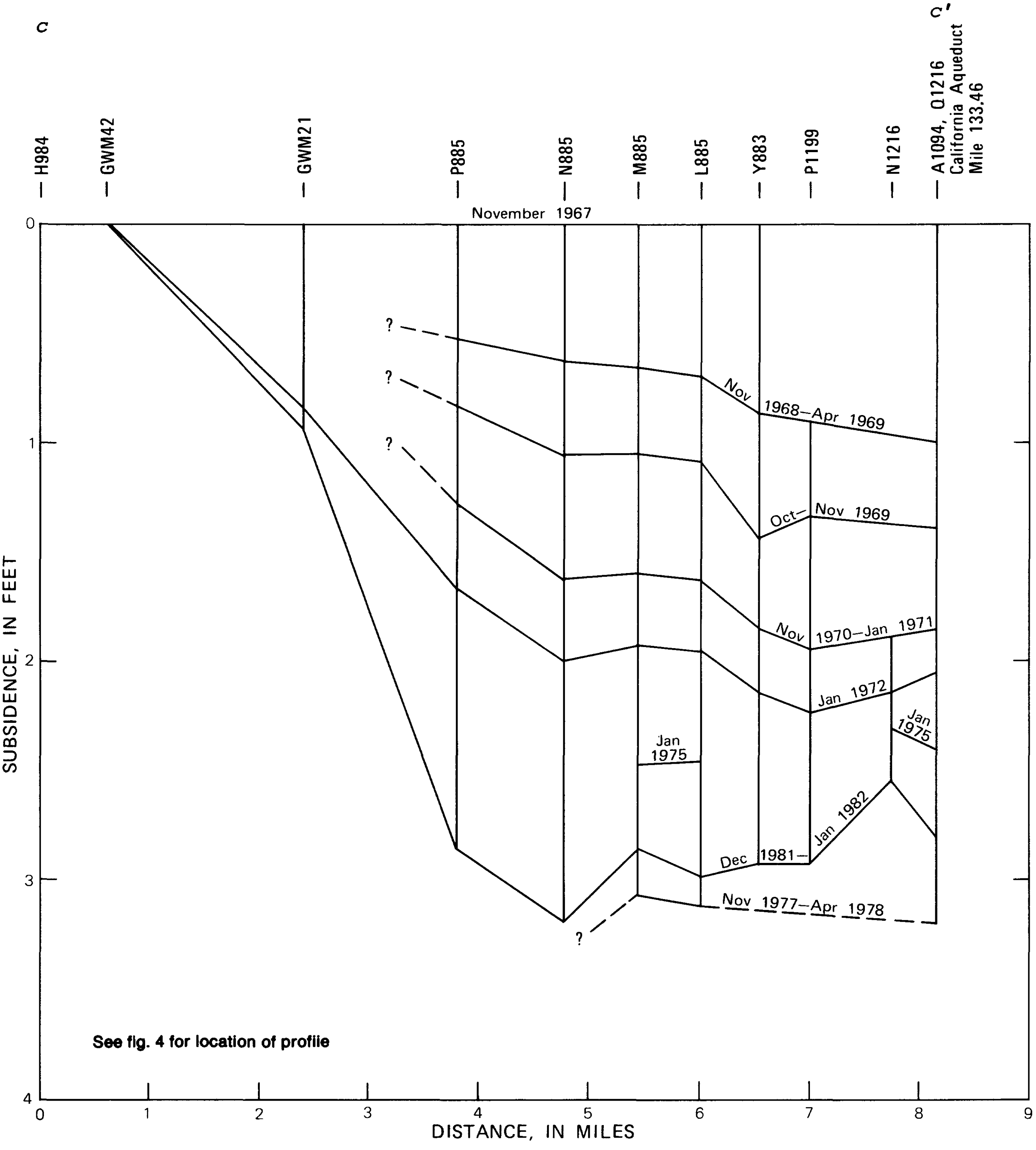


Panoche Hills to the California Aqueduct, 1967 to 1981.



See fig. 4 for location of profile

FIGURE 10. – Profiles of land subsidence, b–b', Tumey Hills to the California Aqueduct, 1967 to 1981.



See fig. 4 for location of profile

FIGURE 11. — Profiles of land subsidence, c—c', along Cantua Creek northeast to the California Aqueduct, 1967 to 1981—82.

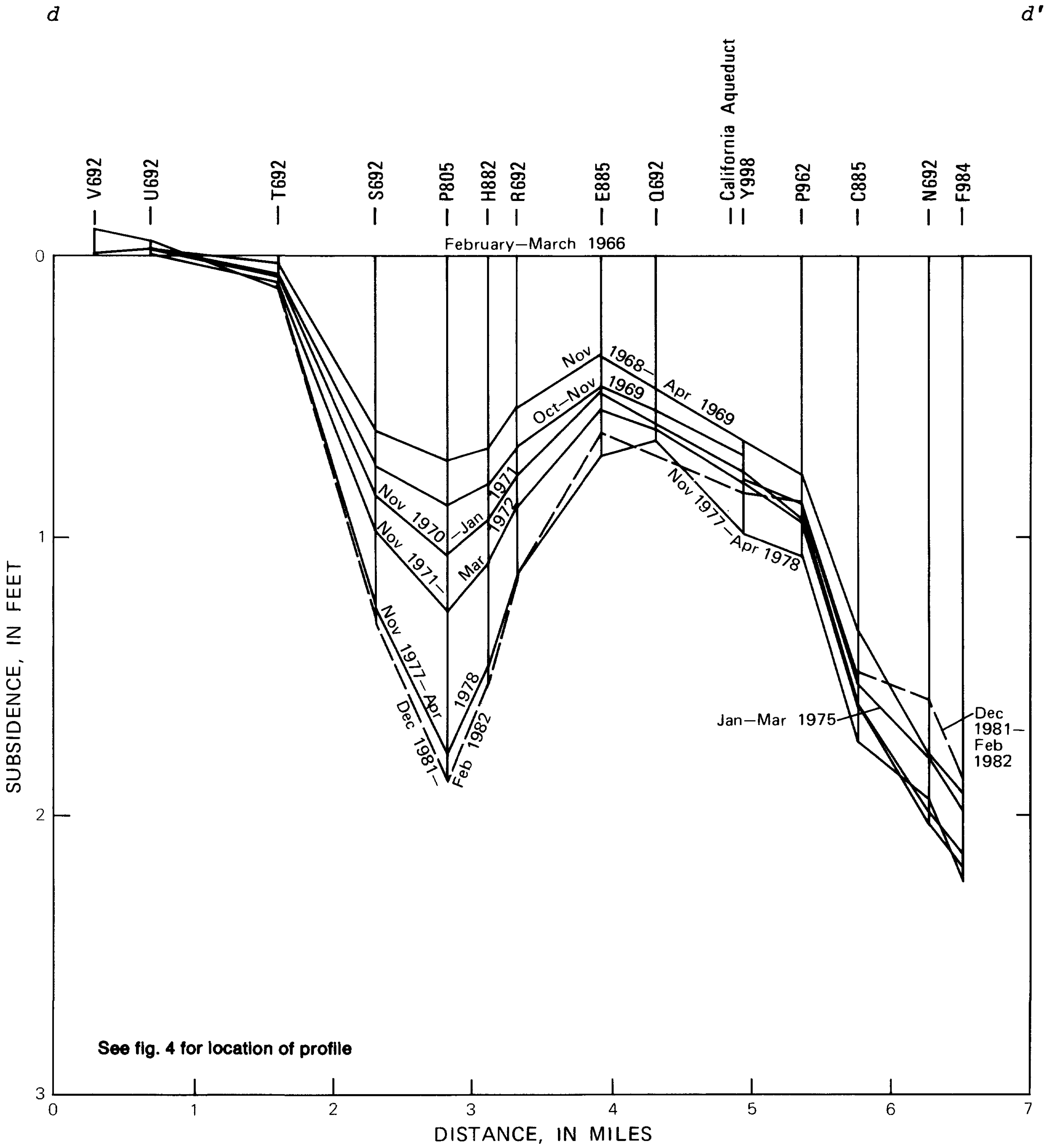


FIGURE 12. — Profiles of land subsidence, d—d', Anticline Ridge northeast across the California Aqueduct, 1966 to 1981—82.

Bedrock tie lines shown and profiles drawn are:

(1) Profile a-a' (fig. 9), Little Panoche Hills tie from "stable" bench mark Y928 east along Panoche Road and Shields Avenue to bench mark 100.55R on the California Aqueduct at aqueduct mile 100.55, is based on seven periods of releveling from November-December 1967 to December 1981;

(2) Profile b-b' (fig. 10), Tumey Hills tie from "stable" bench mark G928 northeast along Panoche Road to bench mark 111.91L on the California Aqueduct at aqueduct mile 111.91, is based on seven periods of releveling from October-November 1967 to December 1981;

(3) Profile c-c' (fig. 11), Cantua Creek tie from "stable" bench mark H984 east along Cantua Creek to bench mark Q1216 on the California Aqueduct at aqueduct mile 133.46, is based on seven periods of releveling from November 1967 to December 1981-January 1982;

(4) Profile d-d' (fig. 12), Anticline Ridge Hill tie from bench mark V692 on Anticline Ridge northeast along the Fresno-Coalinga Road to bench mark Y998 near the California Aqueduct at aqueduct mile 143.12 and northeast to bench mark F984 about 1.7 mi northeast of the California Aqueduct, is based on six periods of releveling from February-March 1966 to December 1981-February 1982;

(5) Profile e-e' (fig. 13), McKittrick Hill tie from "stable" bench mark P991 east to bench mark F67 at McKittrick, is based on two periods of releveling from 1970 to 1982 and northeast from bench mark F67 to bench mark 224.05B on the California Aqueduct at aqueduct mile 224.05 is based on three periods of releveling from 1970 to 1982;

(6) Profile f-f' (fig. 14), Maricopa Hill tie from bench mark Q326 about 2 mi southwest of Maricopa northeast to bench mark R326 at Maricopa, then east along State Highway 166 to bench mark K608 and north along Pentland Road to bench mark 257.48B on the California Aqueduct at aqueduct mile 257.48, is based on three periods of releveling from 1970 to 1982;

(7) Profile g-g' (fig. 15), Elk Hills line from bench mark EH1, about 0.5 mi south of the California Aqueduct at aqueduct mile 229.7, south on Elk Hills Road to bench mark Y548, about 2 mi north of Ford City, and northeast from bench mark Y548 along State Highway 119 to bench mark R548 adjacent to the California Aqueduct at aqueduct mile 245, is based on three periods of releveling from 1964 to 1982.

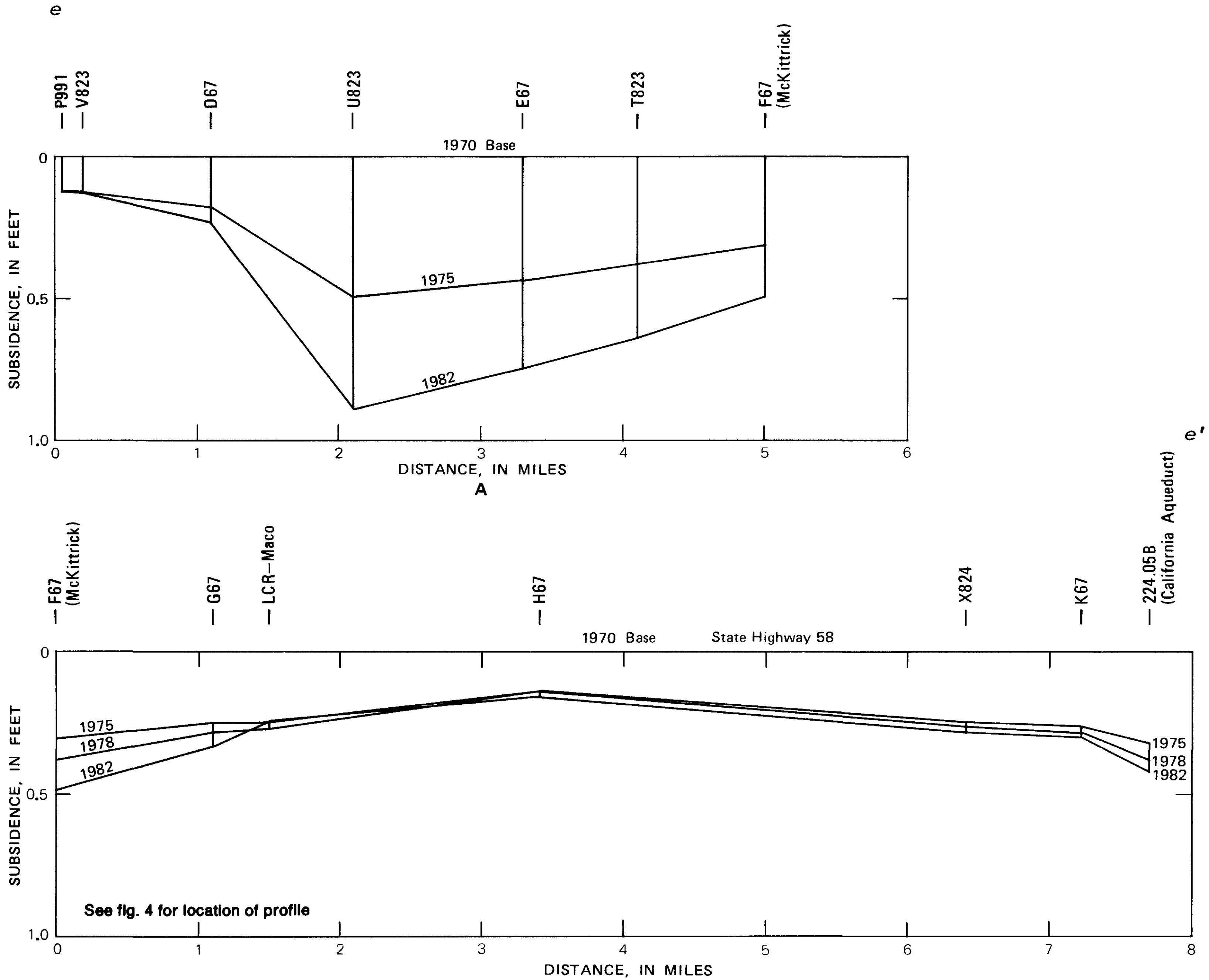


FIGURE 13. – Profiles of land subsidence, e–e′: A, from bench mark P991 southeast to McKittrick; and B, northeast along State Highway 58 to the California Aqueduct, 1970 to 1982.

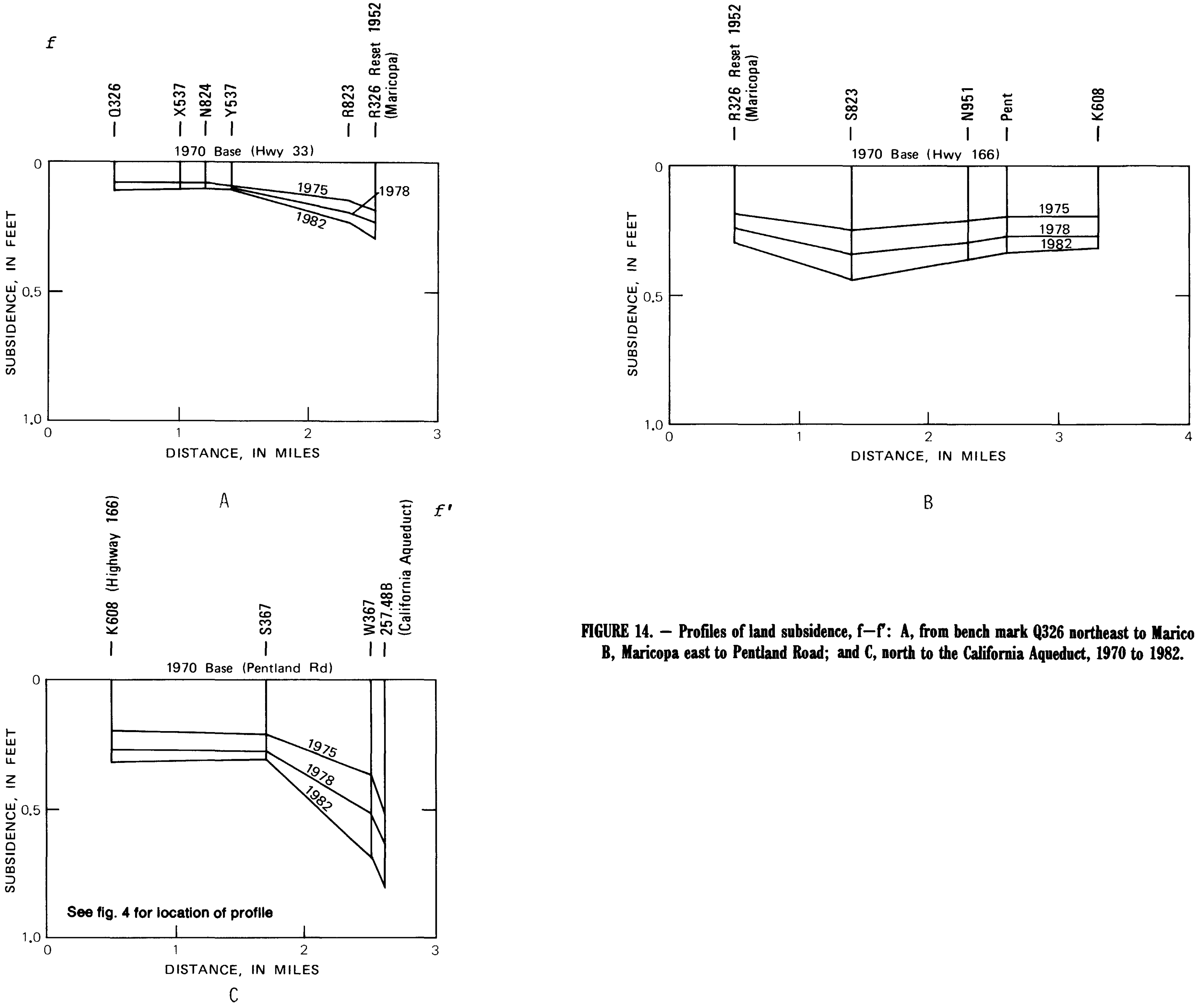


FIGURE 14. — Profiles of land subsidence, f—f': A, from bench mark Q326 northeast to Maricopa; B, Maricopa east to Pentland Road; and C, north to the California Aqueduct, 1970 to 1982.

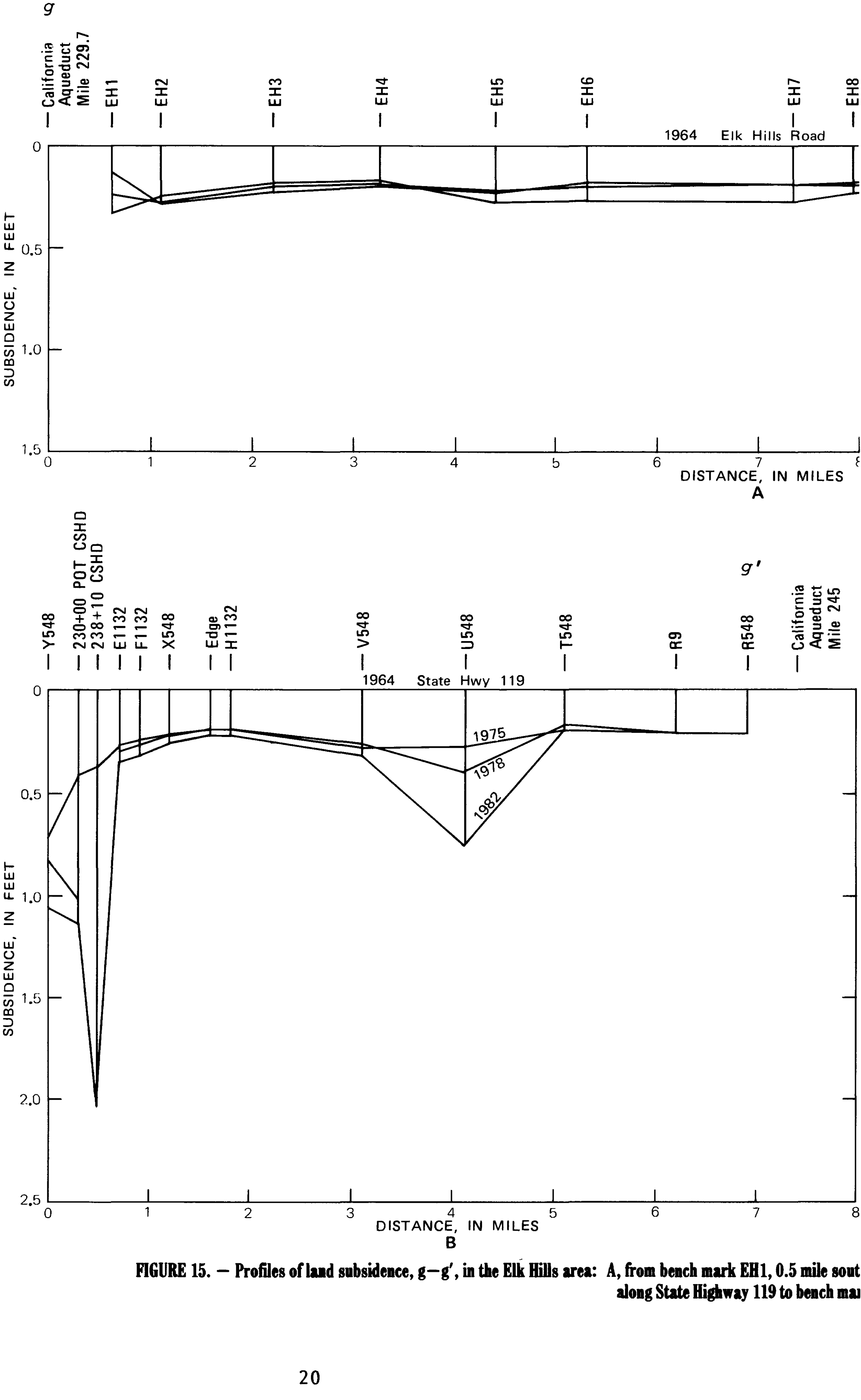
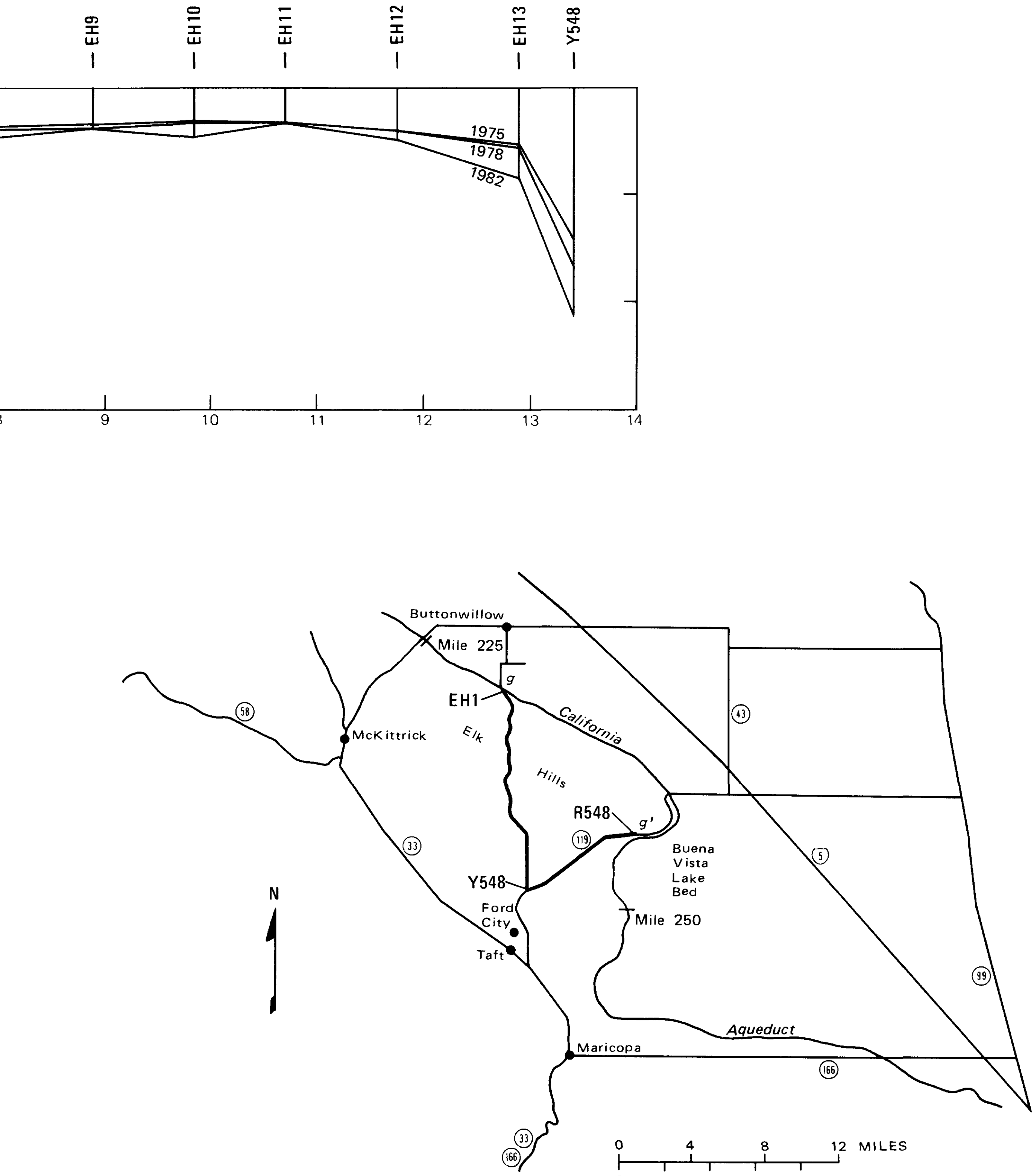


FIGURE 15. — Profiles of land subsidence, g—g', in the Elk Hills area: A, from bench mark EH1, 0.5 mile sout along State Highway 119 to bench mar



h of the California Aqueduct, south to bench mark Y548, about 2 miles north of Ford City; and B, from bench mark Y548 northeast k R548 adjacent to the California Aqueduct, 1964 to 1982.

Aqueduct Subsidence, Mile 92 to Mile 174

Profiles of land subsidence A-B along the California Aqueduct from aqueduct mile 92 to aqueduct mile 174 from 1967 to 1981 are shown in figure 5 (in pocket; for location see fig. 4). Subsidence from aqueduct mile 97 to aqueduct mile 121 ranges from a few hundredths of a foot at mile 98 to a maximum of 0.28 ft at bench mark 102.20R at aqueduct mile 102.20 from 1977-78 to 1981-82. Bench mark 100.55L located on an aqueduct structure on the left side of the aqueduct shown on aqueduct profile A-B subsided 0.23 ft and bench mark 100.55R on the same structure on the right side of the aqueduct shown on profile a-a' (fig. 9; for location see fig. 4) subsided 0.15 ft from 1977-78 to 1981-82, demonstrating the differential subsidence from one side of the aqueduct to the other.

The hydrocompaction area, mile 98 to mile 103 along the aqueduct alinement (fig. 5), was preconsolidated before aqueduct construction. This hydrocompaction area extends about 5 mi west of the aqueduct to the valley boundary. The subsidence from aqueduct mile 98 to mile 103 is mostly residual hydrocompaction. From aqueduct mile 103 to mile 118 the subsidence is minimal, generally less than 0.1 ft. Bench mark W361, 1.5 mi west and bench mark X361, 2 mi west of bench mark 100.55R on subsidence profile a-a' (fig. 9) show 0.53 and 0.73 ft, respectively, of subsidence from 1977-78 to 1981-82. The subsidence at bench marks W361 and X361 is attributed to hydrocompaction. The subsidence decreases to 0.14 ft at bench mark G1074 2.75 mi west of the aqueduct for the same period. The change, subsidence or rebound, from bench mark G1074 to bench mark Y928 is minor, probably within the leveling error.

Bench mark 111.91L at aqueduct mile 111.91 on subsidence profile b-b' (fig. 10) subsided 0.05 ft from 1977-78 to 1981-82. Other bench marks on this profile show only minor change, subsidence or rebound, for this same period.

Three bench marks, X1092, Y1092, and Z1092, at aqueduct miles 118.1, 118.9, and 119.3, respectively, show a few hundredths of a foot rebound, and bench mark A1093 at aqueduct mile 120 shows about 0.2-ft subsidence from 1977-78 to 1981-82 (fig. 5). This reach, mile 114 to mile 129, is a hydrocompaction area which was preconsolidated before the aqueduct was constructed. The subsidence at bench mark A1093 is attributed to residual hydrocompaction.

From bench mark B1093 at aqueduct mile 120.3 to bench mark 173.56B at aqueduct mile 173.56 (fig. 5), the data show significant rebound, ranging from a few hundredths of a foot to about 0.5 ft since the 1977-78 leveling.

Three bench marks, Q1216, L885, and M885 on the transverse profile c-c' (fig. 11) starting at aqueduct mile 133.46, were leveled in 1977-78 and 1981-82. All show rebound for the 1977-78 to 1981-82 period.

Bench mark Y998 on subsidence profile d-d' (fig. 12), located at extensometer well 18/16-33A1 (fig. 26) at aqueduct mile 143.12, shows 0.16-ft rebound from 1977-78 to 1981-82. One bench mark, E885, about 1 mi west of the aqueduct, shows minor rebound. All bench marks east of the aqueduct show rebound with a maximum of 0.37 ft at bench mark F984. This bench mark is about 1.7 mi northeast of the aqueduct, suggesting that the rebound is increasing to the east toward the larger historic subsidence depressions.

This amount of apparent land-surface rebound from aqueduct mile 121 to aqueduct mile 174, indicated by the leveling from 1977-78 to 1981-82, was not expected, especially over such a large area.

In 1977, at the height of the drought, the artesian head in the permeable coarse-grained deposits in the aquifer system was drawn down to levels of the early 1970's by the heavy demand on the ground-water reservoir, causing apparent renewed subsidence of more than 0.5 ft in parts of this area. Extensometers of sufficient depth measured nearly the same amount of aquifer compaction as was indicated by the leveling during 1975 to 1977-78 (Ireland and others, 1984, figs. 44-59).

The rapid recovery of head following the heavy ground-water pumping during the drought began in late 1977, continued through 1978, slowed in 1979, and reached predrought levels in late 1979 and early 1980. With the recovery of head from late 1977 to 1983, pore pressures in the aquifers gradually increased toward equilibrium with residual excess pore pressures in the fine-grained compressible aquitards.

Part of the subsidence, observed or measured, that occurred during the 1976-77 drought was not permanent subsidence. The leveling suggests that the subsidence caused by the ground-water decline during the drought was partly elastic. In figure 5, the 1981-82 profile is above the 1977-78 profile from aqueduct mile 121 to mile 174.

Aqueduct Subsidence, Mile 174 to Mile 218

Profiles of land subsidence B-C along the California Aqueduct from aqueduct mile 174 to aqueduct mile 218 from 1967-68 to 1981-82 are shown in figure 6 (in pocket; for location see fig. 4).

The leveling data from 1977-78 to 1981-82 show minor rebound of a few hundredths of a foot to about 0.16 ft maximum at bench mark 189.33B from aqueduct mile 176 to aqueduct mile 195. At aqueduct mile 195 the rebound stops, and subsidence continues to aqueduct mile 203. The data show subsidence of a few hundredths of a foot to 0.25 ft at bench mark 199.55B in this reach. Subsidence stops at about aqueduct mile 203.2, and bench mark 203.92B shows a minor rebound of about 0.06 ft. Subsidence starts again at about aqueduct mile 204.7, about 0.7 mi north of the town of Lost Hills, and continues to aqueduct mile 217.4. The subsidence in this reach ranges from a few hundredths of a foot to about 0.30 ft at bench mark 213.93B. Bench mark 217.78B at aqueduct mile 217.78 shows a rebound of about 0.11 ft.

Subsidence of the aqueduct from 1977-78 to 1981-82 parallel with the axis of the Lost Hills oil field (aqueduct mile 198 to mile 207, fig. 6) ranged from a few hundredths of a foot to about 0.25 ft. As stated earlier, the profiles show minor rebound just north of the town of Lost Hills; then subsidence increases to nearly the same rates as those north of the town of Lost Hills.

The subsidence within the limits of the Lost Hills oil field is probably due in part to continued removal of fluids and compaction of the shallow oil zones. The reason for the subsidence from aqueduct mile 195-198 and 207-217 is not known. No further research into the causes of continued subsidence has been undertaken in this area. A detailed investigation may be needed to assess the causes of subsidence in the Lost Hills area.

Bench mark X1097 at aqueduct mile 196.75, located on a turnout structure, is another example of structure settlement. This structure was subsiding at a much faster rate from 1967-68 to 1977-78 than surrounding bench marks but now appears to be subsiding at nearly the same rate as nearby bench marks (fig. 6). Bench mark X1097 subsided 0.24 ft from 1977-78 to 1981-82; bench mark 196.57B, located in the aqueduct lining 0.2 mi north, subsided 0.20 ft; and bench mark 197.05B, located 0.3 mi south in the aqueduct lining, subsided 0.24 ft during the same period.

Aqueduct Subsidence, Mile 218 to Mile 238

Profiles of land subsidence C-D along the California Aqueduct from aqueduct mile 218 to aqueduct mile 238 are shown in figure 7 (in pocket; for location see fig. 4). This 20-mi reach has not been included in previous subsidence reports of the San Joaquin Valley because subsidence values were small, generally not exceeding 0.2 to 0.5 ft from 1970 to 1978. One bench mark, 222.89B, shows about 0.75-ft subsidence from 1970 to 1982. All other bench marks show subsidence of less than 0.5 ft from 1970 to 1982. Most subsidence in this reach occurred from 1970 to 1975 and averages 0.2 to 0.4 ft. The subsidence decreases uniformly from north to south.

This 20-mi reach is in a known hydrocompaction area which was preconsolidated before construction. Four bench marks on this profile, 222.89B, 224.05B, 229.71B, and 234.71B, appear to show localized residual hydrocompaction. The 0.2- to 0.4-ft change from 1970 to 1975 may be related to fluid withdrawal or may be residual hydrocompaction or settlement related to aqueduct construction.

The cause of the subsidence shown on subsidence profile e-e' (fig. 13) from bench mark P991 to bench mark F67 at McKittrick is not known, but is probably related to fluid withdrawal (water or oil). The change, subsidence or rebound, from bench mark F67 at McKittrick to the aqueduct at mile 224.05, is minor from 1978 to 1982 and probably is within the limits of leveling error.

Aqueduct Subsidence, Mile 238 to Mile 287

Profiles of land subsidence D-E along the California Aqueduct from aqueduct mile 238 to mile 287 southwest of Wind Gap Pumping Plant are shown in figure 8 (in pocket; for location see fig. 4). The change, subsidence or rebound, is small along this reach from 1978 to 1982. In general, subsidence appears to be related to hydrocompaction and rebound to recovery of water levels.

Leveling data from aqueduct mile 238.50 to mile 245.50 shows land-surface rebound of a few hundredths of a foot to a maximum of 0.1 to 0.2 ft at a few bench marks in this 7-mi reach from 1978 to 1982. Most of this area is not susceptible to hydrocompaction, so the rebound is attributed to water-level recovery. From aqueduct mile 245.50 to mile 262, subsidence ranges from a few hundredths of a foot to generally less than 0.1 to 0.2 ft for the same period. Bench mark 254.50B at mile 254.50 shows about 0.35-ft subsidence. This bench mark is in a known hydrocompaction area that was not preconsolidated before construction. The subsidence at this bench mark is attributed to local hydrocompaction. The erratic undulating subsidence from aqueduct mile 255.36 to mile 261 is attributed to residual hydrocompaction. From aqueduct mile 261 to mile 274 the data show land-surface rebound ranging from a few hundredths of a foot to a maximum of about 0.15 ft at mile 270. This 13-mi reach was preconsolidated before construction, although it was not identified as a known hydrocompaction area. This reach is in the area of subsidence due to water-level decline; therefore, the apparent land-surface rebound is attributed to water-level recovery.

Mile 274 to mile 280.5 is another known hydrocompaction area preconsolidated before construction. Subsidence, ranging from a few hundredths of a foot to about 0.1 ft, starts at mile 274 and continues to mile 276. From mile 276 to mile 280 at the end of the known hydrocompaction area, rebound is generally less than 0.1 ft. From mile 280.5 to mile 287 at the end of this profile, the leveling shows minor rebound of the land surface of a few hundredths of a foot.

Erratic subsidence is illustrated on this profile at bench marks 255.77B and K1210 at aqueduct mile 255.77 and bench mark 273.48A at aqueduct mile 273.48. Bench mark 255.77B subsided 0.57 ft and bench mark K1210 subsided 0.55 ft from 1978 to 1982. These two marks are located on aqueduct structures and are subsiding at a much faster rate than nearby bench marks to the north and south. The change at these two marks at mile 255.77 is related to residual hydrocompaction and continued structure settlement. The subsidence at mile 273.48, bench mark 273.48B, is only 0.04 ft from 1978 to 1982, a much reduced rate over previous years and more in line with the change at nearby bench marks.

Bench marks along subsidence profile f-f' (fig. 14) show subsidence of a few hundredths of a foot to near 0.1 ft from 1978 to 1982. The maximum subsiding bench mark is bench mark 257.48B at mile 257.48 on the aqueduct, 0.24 ft from 1978 to 1982.

Elk Hills Leveling

On subsidence profile g-g' (fig. 15), subsidence at bench marks Y548 and 230+00 POT CSHD was 0.22 and 0.12 ft, respectively, from 1978 to 1982. Bench mark 238+10 CSHD, the maximum subsiding bench mark on this profile, has subsided 2.07 ft from 1964 to 1982 and shows 1.71 ft of subsidence from 1975 to 1982. Bench mark 230+00 POT CSHD, about 0.25 mi west, and bench mark E1122, about 0.25 mi east of bench mark 238+10 CSHD, near the Buena Vista oilfield, show 0.72- and 0.09-ft subsidence, respectively, from 1975 to 1982. The change at these nearby bench marks, east and west, and the fact that bench mark 238+10 CSHD was not leveled in 1978 suggests the large change at this mark may be questionable. One other bench mark on this profile, U548, about 3.25 mi west of the California Aqueduct on State Highway 119, shows 0.37 ft of subsidence from 1978 to 1982. Other bench marks show minor change, subsidence or rebound, for this time period probably within leveling limits.

MONITORING COMPACTION AND CHANGE IN HEAD

The Geological Survey has monitored aquifer-system compaction by means of borehole extensometers and monitored water levels in wells in the San Joaquin Valley during this cooperative study on land subsidence with the California Department of Water Resources since about 1955. Two principal objectives of the study were to determine the depth interval(s) in which compaction was occurring and to measure the magnitude and time distribution of the compaction where possible. These data, together with periodic measurement of land subsidence as determined by spirit-level surveys to surface bench marks, are essential for determining the causes of subsidence and for monitoring the magnitude and the rates of subsidence.

Ireland and others (1984) suggested continued monitoring of subsidence using deep-well extensometers and water-level observation wells as the least costly method of surveillance between relevelings. They also suggested releveling the valleywide subsidence networks. Without releveling the network of bench marks, the amount of regional subsidence or rebound since 1970 is not known in the Tulare-Wasco and Arvin-Maricopa areas and since 1972 in the Los Banos-Kettleman City area.

The cable and free-standing pipe extensometers used throughout this study to measure compaction or expansion of the aquifer system are shown in figure 16. The reader is referred to Ireland and others (1984) for a more detailed explanation of extensometers for monitoring compaction or expansion of the aquifer system and for monitoring water levels to define the cause-and-effect relation of the subsidence process.

Since the start of this study, compaction and water levels have been monitored in many wells. Some wells were drilled and completed specifically for the monitoring program, some were former irrigation wells, and three were deep oil test holes. After many years, well casings have been subjected to many feet of compaction, and some wells have been lost to the monitoring program. The location of 24 sites in the valley where water levels and compaction of the aquifer system have been measured is shown in figure 17. Six of these sites were abandoned during the 1970's.

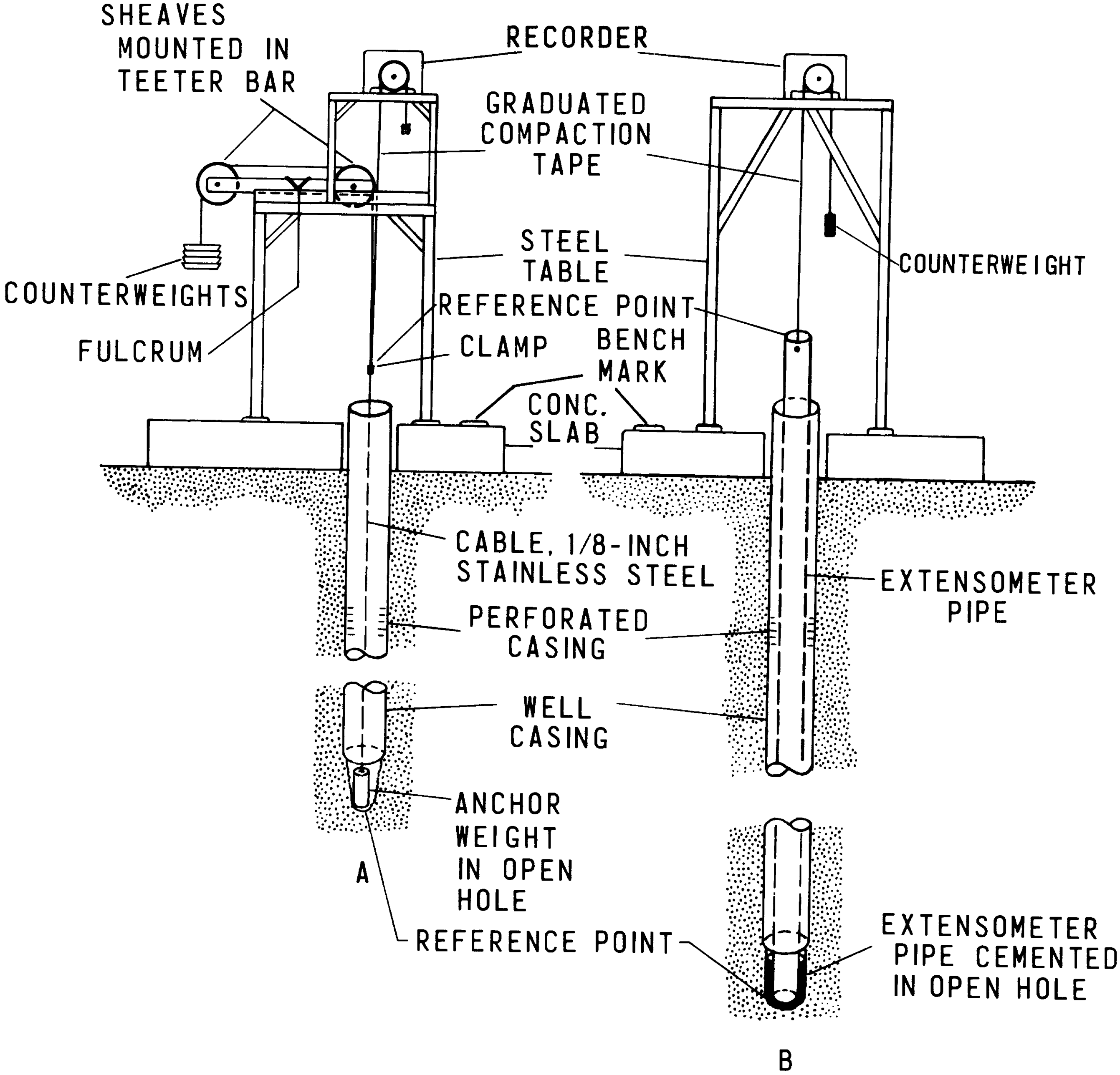


FIGURE 16. — **Recording extensometer installations: A, Cable assembly; and B, pipe assembly. (Modified from Ireland and others, 1984, fig.39)**

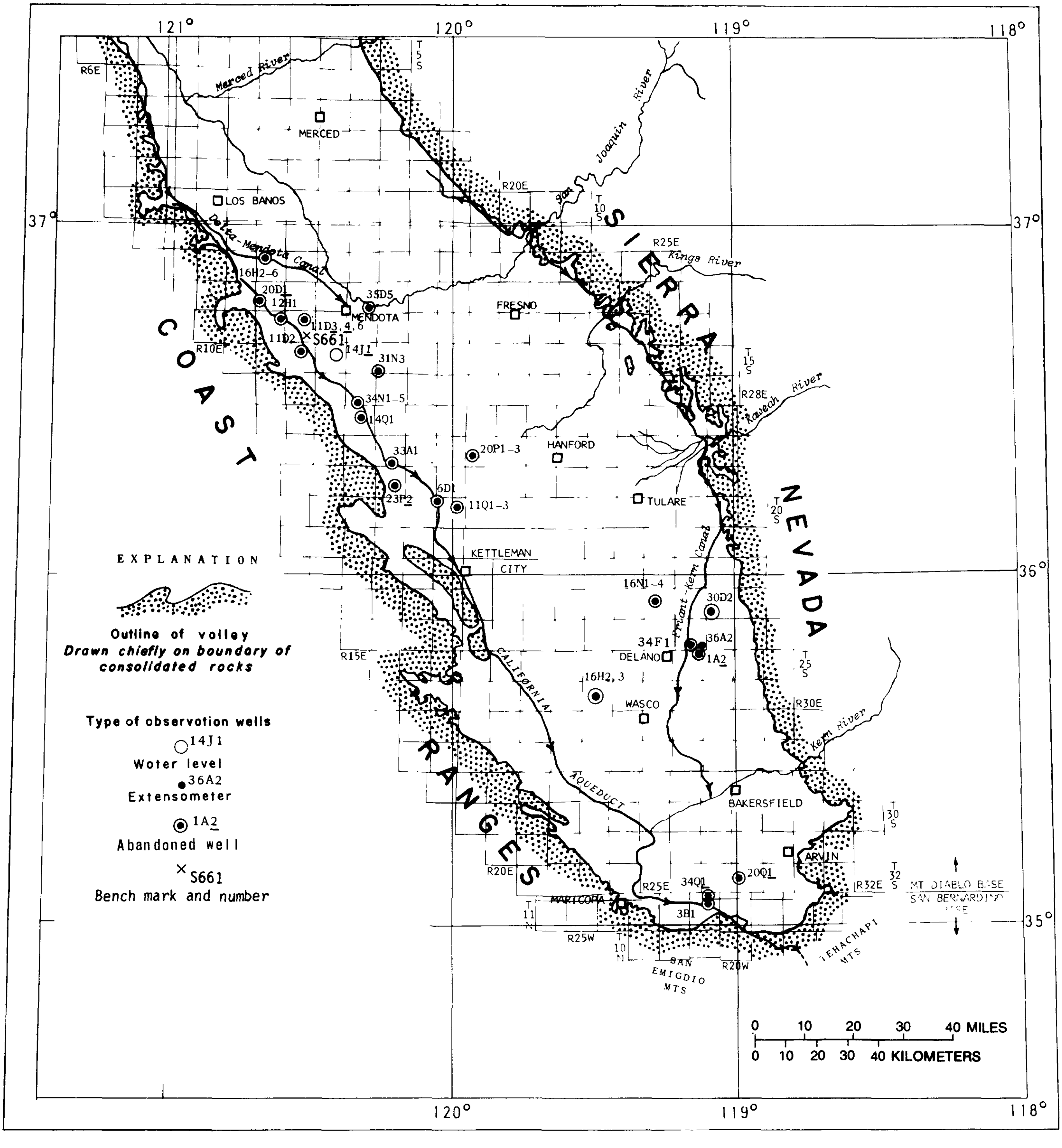


FIGURE 17. — Location of water-level and compaction-measuring sites and bench mark S661 (Modified from Ireland and others, 1984, fig. 40).

The net annual compaction or expansion (negative compaction) at each site through 1982 is summarized in table 1, which also gives compaction or expansion in six additional depth intervals defined by multiple-depth installations.

The Geological Survey terminated field monitoring of compaction and water levels for this study in January 1983. Eight of the monitored sites, consisting of 10 wells along and near the California Aqueduct, will continue to be monitored for compaction of the aquifer system and water levels by the California Department of Water Resources. Five sites, consisting of nine wells, will be monitored by the U.S. Bureau of Reclamation. These include three wells at one site along the Delta-Mendota Canal at Ora Loma in western Fresno County and six wells at four sites--one well along the Friant-Kern Canal near Terra Bella in Tulare County, one well at each of two sites near Richgrove in Tulare County in the Friant-Kern Service Area, and three wells at one site near Pixley in the Pixley Irrigation District in Tulare County.

Five wells at three sites, drilled along the proposed San Joaquin Valley Drain, will be capped for future water-level measurements. The remainder of the wells on this monitoring program have either been abandoned and destroyed or will be in the near future. These are chiefly wells that have developed downhole casing problems, wells of insufficient depth to measure a large percentage of the aquifer compaction, and wells with difficult access.

Records of Compaction and Ground-Water Levels

The records of compaction and depth to water in extensometer wells or in nearby observation wells have been computed on a daily basis; computer plots of these records from 1979 through 1982 are shown in figures 18 through 39. Plots of subsidence of a surface bench mark located at or near the measuring site, determined by precise leveling to a stable bench mark, are shown for four sites which were leveled in 1978 and 1981-82.

The primary purpose of including these records is to show graphically the measured compaction or expansion of the aquifer system and subsidence or rebound of the land surface at specific sites. The change in effective stress in the pertinent aquifers at those sites is indicated by the hydrographs.

The reader interested in the complete set of data which includes graphs of water levels, change in applied stress, compaction and differential compaction, bench-mark subsidence, and stress strain or stress compaction from the start of record is referred to Poland and others (1975) for earlier data and Ireland and others (1984) for later data.

The computer program and extensometer and water-level data collected during this long-term cooperative study on land subsidence with the California Department of Water Resources and the associated Federal study on the mechanics of aquifers are stored on computer tape No. 220691, type 6250BPI, at the U.S. Geological Survey Information Services Division, Reston, Virginia.

Computer plots in this report are shown at larger scale than in earlier reports because of the reduced magnitude of water-level change and the small amounts of compaction, expansion, and rebound that occurred from 1979 to 1983. Note that the compaction graphs show the accumulated compaction for the entire period of record as shown in table 1.

TABLE 1.--Annual compaction at compaction-

[In order to arrive at consistent sums, the amount of annual compaction is
are not accurate to less than a few hundredths

Well number	Anchor depth when installed (feet)	Depth interval (feet)	Start of record[1]	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Los Banos-													
12/12-16H3----	350	0- 350	5/19/58	0.052	0.053	-0.004	0.013	0.036	0.005	0.008	0.007	0.002	0.004
16H4----	500	350- 500	5/19/58	.032	.087	.019	.002	.008	.003	.011	.013	.011	.013
16H2----	1,000	500-1,000	5/19/58	.211	.302	.293	.325	.158	.187	.173	.066	.125	.105
16H2----	1,000	0-1,000	5/19/58	.295	.442	.308	.340	.202	.195	.192	.086	.138	.122
13/12-20D1----	681	0- 681	10/10/61	----	----	----	.077	.340	.215	.119	.182	.120	.094
13/15-35D5----	440	0- 440	5/13/66	----	----	----	----	----	----	----	----	-.022	.014
14/12-12H1----	913	0- 913	1/10/65	----	----	----	----	----	----	----	.414	.336	.239
14/13-11D4----	780	0- 780	1/1/61	----	----	----	.310	.196	.222	.199	.108	.194	.160
11D6----	1,358	780-1,358	5/25/61	----	----	----	.354	.462	.259	.400	.322	.279	.326
11D6----	1,358	0-1,358	5/25/61	----	----	----	.480	.658	.481	.599	.430	.473	.486
15/13-11D2----	958	0- 958	1/11/65	----	----	----	----	----	----	----	.204	.154	.126
15/16-31N3----	596	0- 596	3/23/67	----	----	----	----	----	----	----	----	----	.088
16/15-34N3----	503	0- 503	9/25/58	.010	.118	.093	.087	.138	.082	.096	.082	.085	.090
34N2----	703	503- 703	9/25/58	.094	.232	.123	.191	.167	.172	.174	.104	.104	.122
34N1----	2,000	703-2,000	9/25/58	.286	.857	.717	.867	.697	.710	.829	.634	.614	.604
34N1----	2,000	0-2,000	9/25/58	.390	1.207	.933	1.145	1.002	.964	1.099	.820	.803	.816
34N4----	1,096	0-1,096	8/16/60	----	----	.232	.661	.648	[4].416	----	----	----	----
34N4[5]---	900	0- 900	9/15/64	----	----	----	----	----	----	----	.358	.320	.340
17/15-14Q1----	2,315	0-2,315	11/4/69	----	----	----	----	----	----	----	----	----	----
18/16-33A1----	1,029	0-1,029	3/10/65	----	----	----	----	----	----	----	.128	.210	.186
18/19-20P2----	578	0- 578	3/24/67	----	----	----	----	----	----	----	----	----	.026
19/16-23P2----	2,200	0-2,200	1/2/60	----	----	.508	.660	.553	.378	.424	.259	.552	.355
20/18-6D1-----	867	0- 867	1/11/65	----	----	----	----	----	----	----	.273	.267	.280
6D1-----	867	0- 867	9/23/80										
11Q1----	710	0- 710	7/24/64	----	----	----	----	----	----	.115	.259	.240	.225
11Q2[5]---	845	0- 845	2/27/63	----	----	----	----	----	.230	.330	.300	.330	.290
11Q2----	845	710- 845	7/24/64	----	----	----	----	----	----	.025	.041	.090	.065
11Q3----	1,930	845-1,930	2/27/63	----	----	----	----	----	.261	.212	.357	.240	.199
11Q3----	1,930	0-1,930	1/1/63	----	----	----	----	----	.611	.542	[11].657	[11].570	.489
Tulare-													
22/27-30D2----	1,246	0-1,246	8/13/70	----	----	----	----	----	----	----	----	----	----
23/25-16N4----	250	0- 250	6/24/59	----	0.005	0.024	0.024	0.008	0.007	0.022	0.009	0.001	0
16N3----	430	250- 430	6/24/59	----	.055	.100	.062	.120	.042	.080	.048	.085	.003
16N1----	760	430- 760	6/24/59	----	.184	.433	.473	.051	.056	.253	.131	.225	.063
16N1----	760	0- 760	4/18/58	0.454	.482	.557	.559	.179	.105	.355	.188	.311	.066
24/26-34F1----	1,510	0-1,510	1/21/59	----	.242	.100	.111	-.051	.018	.063	-.025	.068	-.031
36A2----	2,200	0-2,200	5/12/59	----	.059	.342	[11].333	[11].059	.096	.329	.062	[11].145	-.045
25/26-1A2-----	892	0- 892	4/6/59	----	.058	.061	.059	-.013	-.004	.050	-.003	.096	-.012
26/23-16H3----	355	0- 355	8/17/78	----	----	----	----	----	----	----	----	----	----
16H2----	1,002	355-1,002	8/17/78	----	----	----	----	----	----	----	----	----	----
16H2----	1,002	0-1,002	8/17/78	----	----	----	----	----	----	----	----	----	----
Arvin-													
32/28-20Q1----	970	0- 970	4/11/63	----	----	----	----	----	0.192	0.365	0.178	0.255	0.219
12N/21W-34Q1--	810	0- 810	6/2/60	----	----	0.207	0.326	0.271	.209	.186	.266	.197	.130
11N/21W-3B1---	---	810-1,480	4/12/63	----	----	----	----	----	.188	.261	.135	.229	.184
11N/21W-3B1---	1,480	0-1,480	4/12/63	----	----	----	----	----	.326	.447	.401	.426	.314

[1] Date when stabilized installation began giving acceptable record.

[2] Site discontinued October 5, 1976.

[3] Site discontinued October 24, 1974.

[4] Compaction to June 11, 1963.

[5] Compaction based on protrusion of 4-inch casing.

[6] Site discontinued September 24, 1974.

[7] Flooded in 1978.

measuring sites, San Joaquin Valley

shown to a thousandth of a foot; however, many of the measured yearly values of a foot. Minus (-) indicates expansion]

1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	Total measured compaction (feet)
Kettleman City area															
0.002	0	0.002	0	0	-0.001	0	-0.001	0.004	0.013	0	0	0.004	0.001	0.004	0.204
.015	.008	.007	.013	.007	.016	.001	.002	[2].005	----	----	----	----	----	----	.273
.075	.060	.060	.050	.039	.020	.034	.026	----	----	----	----	----	----	----	2.289
.092	.068	.069	.063	.046	.035	.035	.027	.045	.096	.032	.027	.029	.018	.017	3.019
.074	.056	.032	.038	.070	.024	[3].030	----	----	----	----	----	----	----	----	1.471
.022	.006	.034	.050	.015	.025	.029	.024	.025	.024	.001	.008	-.006	.020	-.004	.265
.139	.097	.164	.100	.083	.085	.099	.067	.058	.132	.019	.015	.035	.042	.003	2.127
.071	.001	.013	.013	.007	.014	[3].032	----	----	----	----	----	----	----	----	1.540
.157	.073	.078	.057	.036	.016	.020	----	----	----	----	----	----	----	----	2.839
.228	.074	.091	.070	.043	.030	.052	.017	.039	.180	-.074	-.010	-.010	.023	-.010	4.350
.099	.060	.047	.022	.024	.006	0	.002	-.009	.069	-.012	-.022	-.009	-.029	-.016	.716
.120	.092	.032	.055	.001	.045	.097	-.006	.001	.082	-.038	-.017	-.030	.013	-.007	.528
.101	.130	.112	.104	.051	.061	.040	.058	.023	.051	.013	0	.015	.029	.010	1.679
.118	.046	.077	.040	.031	-.010	-.004	-.037	-.004	.073	-.020	.018	-.018	-.030	-.013	1.750
.573	.312	.202	.108	.001	-.006	-.003	-.029	-.011	.298	[3]-.051	-.010	-.066	-.037	-.039	8.057
.792	.488	.391	.252	.083	.045	.033	-.008	.008	.422	-.058	.008	-.069	-.038	-.042	11.486
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1.957
.334	.233	.210	.231	.075	.017	[6].027	----	----	----	----	----	----	----	----	2.145
----	.079	.478	.225	.088	.013	-.032	-.054	-.009	.542	[7]-.199	0	-.083	-.025	-.045	.978
.124	.034	.094	.060	.073	.023	.036	.009	.004	.099	-.004	-.013	.026	-.021	.012	1.080
.070	.036	.065	.082	.065	.014	-.019	.026	.018	.121	-.035	.014	.009	0	-.024	.468
.328	.201	.192	.143	.198	.029	[8].097	----	----	----	----	----	----	----	----	4.877
.179	.090	.121	.074	.044	.030	-.019	.018	-.006	.189	-.093	[9].022	----	----	----	1.469
												[9]-.020	.014	-.009	-.015
.224	.149	.145	.117	.093	.034	-.016	.012	-.016	.179	-.025	-.019	-.017	0	-.006	1.693
.280	.220	.190	.147	.090	.019	-.023	-.004	-.019	.247	-.053	-.021	-.037	0	-.025	2.491
.056	.071	.045	.030	-.003	-.015	-.007	-.016	-.003	.068	-.028	-.002	-.020	0	-.019	.378
.259	.207	.160	[10].133	.026	-.006	-.092	-.039	.007	.308	-.105	-.083	-.077	-.260	.037	1.744
.539	.427	.350	[10].280	.116	.013	[11]-.115	-.043	-.012	.555	-.158	-.104	-.114	-.260	.012	4.355
Wasco area															
----	----	0.034	0.124	0.316	0.075	0.093	0.086	0.219	0.248	0.028	0.046	0.028	0.074	-0.002	1.301
0.003	-0.002	0	.007	.004	-.002	-.002	.001	.003	.010	-.003	0	-.001	.001	-.003	.116
.057	.005	.033	.022	.058	.005	.016	.019	.039	.053	-.014	.014	-.005	.042	.002	.941
.160	.036	.100	.075	.143	.037	.041	.055	.111	.146	.019	.023	.031	.074	-.025	2.895
.220	.039	.133	.104	.205	.040	.055	.075	.153	.209	.002	.037	.026	.116	-.023	4.647
.038	-.057	.038	-.009	.023	-.028	-.013	.002	.068	.111	-.098	-.034	-.029	.023	-.045	.485
.168	-.060	.143	.012	.118	-.016	.089	.017	.196	.339	-.175	-.002	-.008	.050	-.060	2.013
.018	-.001	.014	-.005	.011	-.010	-.001	-.016	.017	[12].011	----	----	----	----	----	.330
----	----	----	----	----	----	----	----	----	----	-.021	.002	-.007	.019	-.012	-.019
----	----	----	----	----	----	----	----	----	----	-.066	.038	.022	.048	-.009	.033
----	----	----	----	----	----	----	----	----	----	-.087	.040	.015	.067	-.021	.014
Maricopa area															
0.124	0.124	0.095	0.091	0.096	0.060	0.104	0.066	0.040	[12]0.068	----	----	----	----	----	2.047
.014	.186	.153	.060	.070	.062	[13].065	----	----	----	----	----	----	----	----	2.402
.344	.152	.149	-.001	.011	.016	.065	----	----	----	----	----	----	----	----	1.733
.358	.338	.302	.059	.081	.078	.130	.086	.154	.225	[11]-.016	0.024	0.052	0.019	0.011	3.815

[8] Site discontinued September 25, 1974.

[9] Site temporarily out, November 11, 1979, to September 23, 1980.

[10] Data adjustment, 1971 annual compaction estimated due to downhole casing problems.

[11] Mechanical problems at site.

[12] Site discontinued 1978.

[13] Site discontinued September 19, 1974.

The 1977-78 to 1981-82 leveling change shown at extensometer sites 16/15-34N (fig. 24), 18/16-33A1 (fig. 26), and 11N/21W-3B1 (fig. 39) presents an interesting problem. Ireland and others (1984, table 6) computed ratios of compaction versus subsidence for all periods of available leveling and compaction data. Ratios from the period 1975 to 1977-78 were lower than previous ratios; this discrepancy was attributed to field measurement problems with the leveling to the extensometers.

Leveling change from 1977-78 to 1981-82 shows significant rebound and has partly resolved this problem. The water-level drawdowns during the 1976-77 drought caused compaction of 0.4 to 0.5 ft at extensometer well 16/15-34N1. Water-level recovery started in late 1977. The 1981-82 leveling data indicate land-surface rebound of about 0.5 ft. The subsidence observed from 1975 to 1977-78 was partly in the elastic range in some areas and almost wholly in the elastic range in other areas. Ratios computed for the 1977-78 to 1981-82 period were also lower than previous ratios. It became apparent the data were time dependent. Computed compaction/subsidence ratios are affected when the aquifer system changes from a compaction phase to an expansion phase.

Compaction/subsidence ratios can be misleading. Three critical factors affect this ratio: (1) The well should be of sufficient depth to measure all or nearly all of the change (compaction or expansion); (2) the extensometer should be relatively friction free for a continuous record of compaction; and (3) the time of leveling. Most of the extensometer wells on this monitoring program are cable type. Because the aquifer system is thick, the wells are deep, and most have sufficient downhole cable-to-casing friction to preclude continuous monitoring of aquifer-system compaction. Because the extensometer wells require periodic stressing to relieve the downhole friction, they are operated as compaction observation extensometers, and observations are made monthly or bimonthly.

Compaction/subsidence ratios from an extensometer well that has developed sufficient downhole friction to bind the extensometer cable at some nominal depth are probably not meaningful. The extensometer data from such an installation would be only a partial measurement of the total compaction. This problem may occur at extensometer wells that have been subjected to many feet of casing compression resulting from aquifer-system compaction.

Time-of-compaction and time-of-leveling observations are critical when computing compaction/subsidence ratios in a compaction and expansion sequence. If the data are one-directional, water-level decline with associated compaction of the aquifer system, time of observations would not be critical. With the reversal from compaction to expansion of the aquifer system, time becomes critical. If the leveling and compaction observations are not at the time of maximum water-level decline and maximum compaction, the maximum subsidence or compaction amounts are not known. Also if the extensometer is not of sufficient depth to measure all or most of the aquifer-system compaction, the ratios can be misleading. When water levels stop declining and start recovering, expansion of the aquifer system starts immediately when water levels are in the elastic range of stress. Without continuous extensometer and leveling data at the time of change from aquifer-system compaction (subsidence) to aquifer-system expansion (rebound), the compaction/subsidence ratios may not be meaningful.

When compaction/subsidence ratios were computed for the net change from 1975 to 1981-82, omitting the 1977-78 leveling data, ratios were comparable with pre-1975 ratios.

The author cautions the reader that the compaction or expansion values measured at these sites from 1979 to 1983 are small and that the ability of cable-type extensometers to measure reliable change in this range is probably ±0.01 to 0.02 ft/yr. Because of the downhole cable-to-casing friction and other operational problems, values in this range should be treated with caution when reviewing the compaction or expansion and the subsidence shown in figures 18-39.

At extensometer and water-level site 12/12-16H (fig. 18), hydrographs of wells 12/12-16H5 and 16H6, both lower-zone wells, show a continuing rise of water level averaging about 3.5 ft/yr in 16H5 and 6 ft/yr in 16H6 for the 3-year period 1980 through 1982. No significant compaction was measured in extensometer well 16H3 (350-ft extensometer well). Measured compaction averaged about 0.02 ft/yr in 16H2 (1,000-ft extensometer well) from 1980 to 1983 (table 1). Water levels recovered about 11 ft for the same period. The compaction measured in extensometer well 16H2 may be residual compaction or may be partly related to leveling or extensometer measurement problems. The last leveling to this extensometer site was in January 1972; the extensometer measured an average of 62 percent of the subsidence from November 1959 to January 1972 (Ireland and others, 1984, table 6).

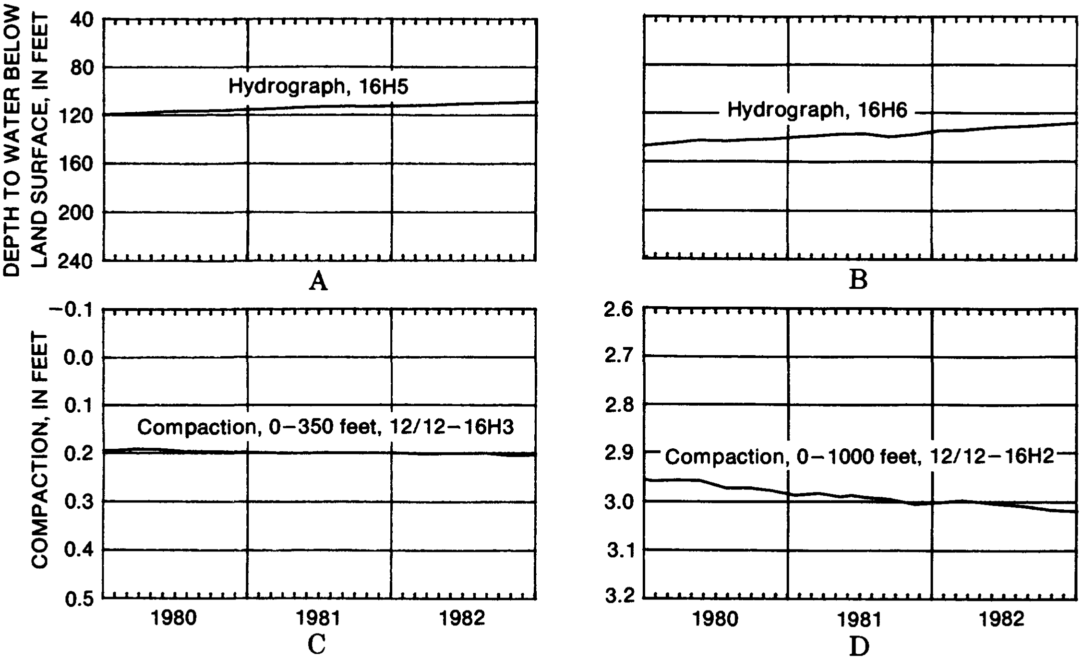


FIGURE 18. — Hydrographs and compaction, 12/12—16H. A, Hydrograph of well 12/12—16H5, perforated 670—712 feet. B, Hydrograph of well 12/12—16H6, perforated 770—990 feet. C, Compaction to 350—foot depth in well 12/12—16H3. D, Compaction to 1000—foot depth in well 12/12—16H2.

Extensometer site 13/15-35D5 (fig. 19) is a free-standing pipe-type extensometer 440 ft deep and an upper-zone water-level well. The hydrograph shows annual fluctuation of 40 to 50 ft/yr from 1980 to 1983. Net compaction was 0.01 ft from 1980 to 1983, indicating water levels are in the elastic range of stress and no significant compaction is occurring in the 440-ft depth interval. The last leveling to this extensometer site was in November 1971; the extensometer measured 33 percent of the subsidence from January 1966 to November 1971 (Ireland and others, 1984, table 6).

Extensometer site 14/12-12H1 (fig. 20) is a cable-type extensometer 913 ft deep and a lower-zone water-level-observation well. The hydrograph shows a continuing rise from 397 ft in January 1980 to 371 ft in January 1983, averaging about 9 ft/yr. Measured compaction was 0.035 ft in 1980, 0.042 ft in 1981, and 0.003 ft in 1982. Bench mark 12H1 (fig. 20) was releveled in December 1977 and December 1981. The subsidence was 0.12 ft, and the extensometer measured 0.12-ft compaction for this same period, indicating all the subsidence is occurring within the 913-ft depth interval. This extensometer measured an average of 62 percent of the subsidence from January 1966 to December 1977 (Ireland and others, 1984, table 6).

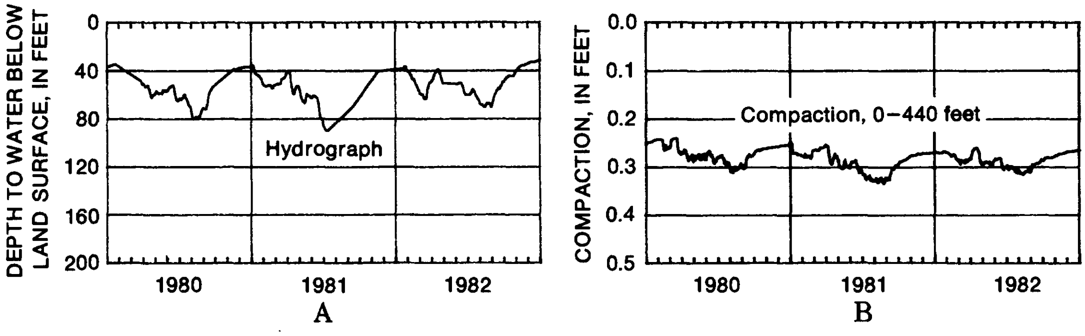


FIGURE 19. – Hydrograph and compaction, 13/15–35D5. A, Hydrograph, perforated 373–433 feet. B, Compaction to 913–foot depth.

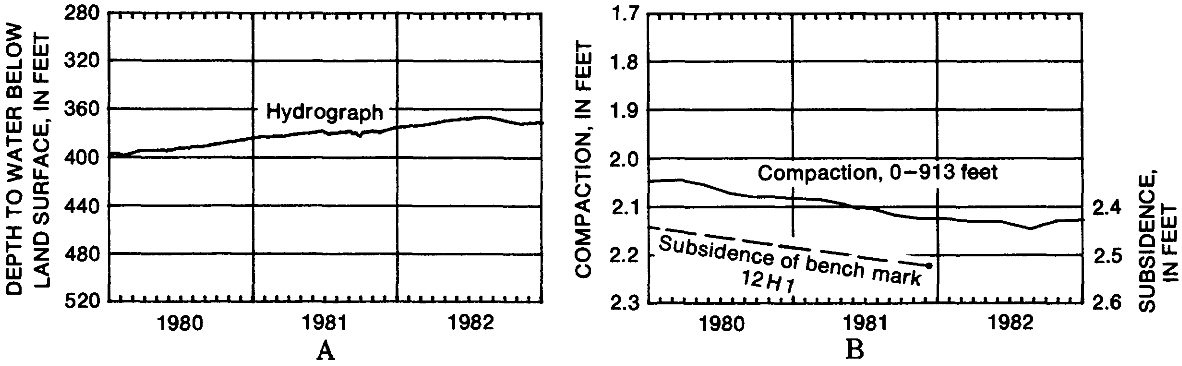


FIGURE 20. – Hydrograph, compaction, and subsidence, 14/12–12H1. A, Hydrograph, perforated 740–936 feet. B, Compaction to 913–foot depth and subsidence of bench mark 12H1.

Extensometer site 14/13-11D6 (fig. 21) is a cable-type extensometer 1,358 ft deep and a lower-zone water-level-observation well. The hydrograph shows a continuing rise from 324 ft in January 1980 to 291 ft in January 1983, averaging 11 ft/yr. The extensometer measured 0.010-ft expansion in 1980, 0.023 ft of compaction in 1981, 0.010-ft expansion in 1982, and has a measured net expansion of about 0.08 ft since 1977. The last leveling at this extensometer site was in February 1975; the extensometer measured an average of 69 percent of the subsidence from February 1963 to February 1975 (Ireland and others, 1984, table 6).

Extensometer site 15/13-11D2 (fig. 22) is a cable-type extensometer 958 ft deep and a lower-zone water-level-observation well. The hydrograph shows a continuing rise from 397 ft in January 1980 to 351 ft in January 1983, averaging 15 ft/yr. The extensometer measured expansion of 0.009 ft in 1980, 0.029 ft in 1981, and 0.016 ft in 1982 and has measured a net expansion of 0.09 ft since 1977. The last leveling to this extensometer site was in February 1975; the extensometer measured an average of 21 percent of the subsidence from January 1966 to February 1975 (Ireland and others, 1984, table 6).

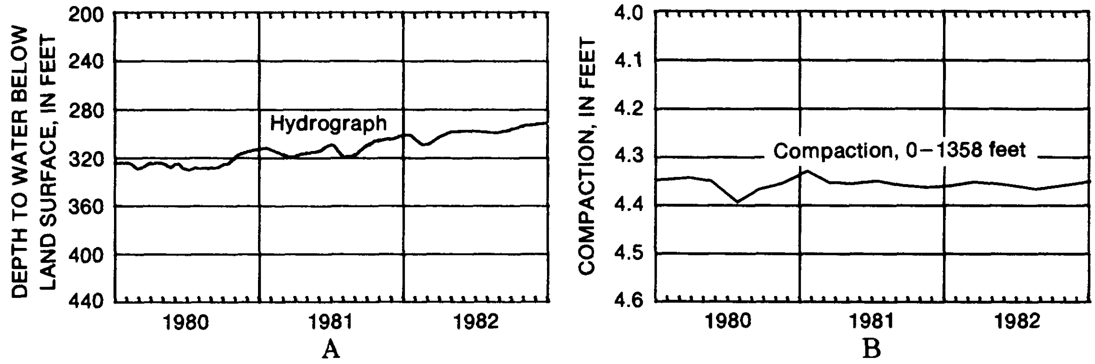


FIGURE 21. — Hydrograph and compaction, 14/13—11D6. A, Hydrograph, perforated 1,133—1,196 feet. B, Compaction to 1,358—foot depth.

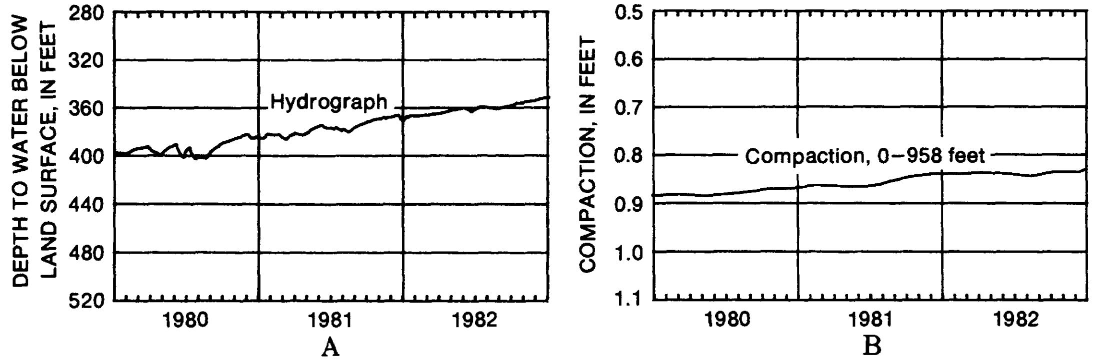


FIGURE 22. — Hydrograph and compaction, 15/13—11D2. A, Hydrograph, perforated 900—960 feet. B, Compaction to 958—foot depth.

Extensometer site 15/16-31N3 (fig. 23) is a cable-type extensometer 596 ft deep and an upper-zone water-level-observation well. The hydrograph shows a continuing rise from 89 ft in January 1980 to 78 ft in January 1983, averaging nearly 4 ft/yr. The extensometer measured 0.030-ft expansion in 1980, 0.013-ft compaction in 1981, and 0.007-ft expansion in 1982, and has measured a net expansion of 0.08 ft since 1977. The last leveling to this extensometer site was in February 1975; the extensometer measured an average of 43 percent of the subsidence from April 1969 to February 1975 (Ireland and others, 1984, table 6).

Extensometer site 16/15-34N (fig. 24) consists of three cable-type extensometers, 34N1, 2,000 ft deep; 34N2, 703 ft deep; and 34N3, 503 ft deep, and two water-level observation wells, 34N4 (lower zone) and 34N5 (upper-zone water-table well). The hydrographs show a continuing rise: the water table in 34N5 rose from 169 ft in January 1980 to 160 ft in January 1983, averaging 3 ft/yr, and water levels in the lower-zone (34N4) rose from 357 ft in January 1980 to 298 ft in January 1983, averaging nearly 20 ft/yr.

Extensometer well 34N1 (2,000 ft) measured expansion of 0.069 ft in 1980, 0.038 ft in 1981, and 0.042 ft in 1982 and has measured a net expansion of nearly 0.21 ft since the 1977 drought. Extensometer well 34N3 (503 ft) measured compaction of 0.015 ft in 1980, 0.029 ft in 1981, and 0.010 ft in 1983. Extensometer well 34N2 (703 ft) measured expansion of 0.003 ft in 1980, 0.001 ft in 1981, and 0.003 ft in 1982. The data suggest continued residual compaction in the 503-ft depth interval, slight expansion in the 503- to 703-ft depth interval, and significant expansion in the lower zone (703- to 2,000-ft depth interval).

The rebound determined by the leveling versus the measured expansion at extensometer 16/15-34N1 presents an interesting problem. During the water-level recovery after the importation of surface water into the area starting in 1968, the extensometer measured continued compaction to 1975. The annual compaction values decreased each year through this recovery period from 0.79 ft in 1968 to 0.03 ft in 1974 with no change in 1975. This compaction was residual compaction of the aquifer system. During the 1976-77 drought the extensometer measured near-zero change in 1976 and 0.42-ft compaction in 1977. Ireland and others (1984, table 6) show this extensometer measuring 97 percent of the subsidence from 1972 to 1975 and only 72 percent of the subsidence from 1975 to 1977-78.

The leveling data, subsidence and rebound, at bench mark G1046 and the measured aquifer-system compaction and expansion at this extensometer site for the years 1975, 1977-78, and 1981-82 are shown in figure 40 (at end of report). The subsidence was 0.600 ft versus aquifer-system compaction of 0.437 ft (73 percent) from February 15, 1975, to January 11, 1978; the rebound was 0.282 ft versus 0.157 ft (56 percent) of aquifer-system expansion from January 11, 1978, to December 15, 1981.

Disregarding the 1977-78 leveling, the net compaction is 88 percent (fig. 40, at end of report) of the net subsidence from 1975 to 1981-82, demonstrating the need of continuous extensometer data and leveling at the time of reversal from aquifer-system compaction to aquifer-system expansion. This extensometer measured an average of 90 percent of the subsidence from 1960 to 1975 (Ireland and others, 1984, table 6).

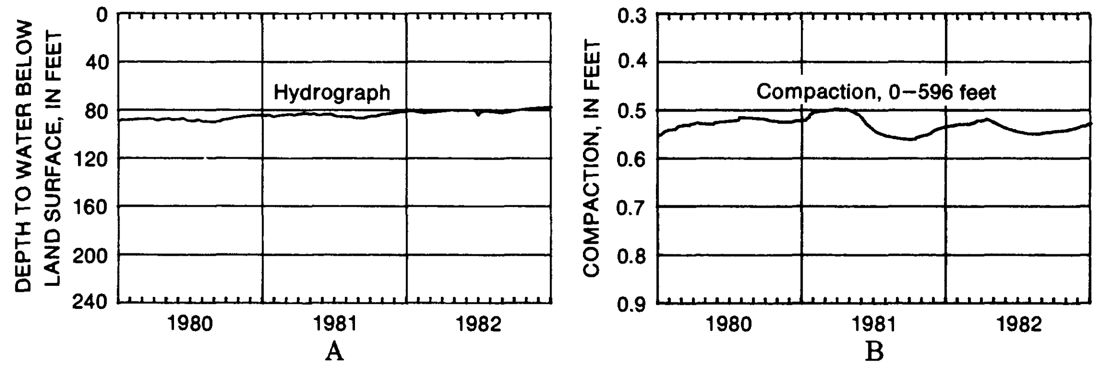


FIGURE 23. — Hydrograph and compaction, 15/16—31N3. A, Hydrograph, perforated 497—537 feet. B, Compaction to 596—foot depth.

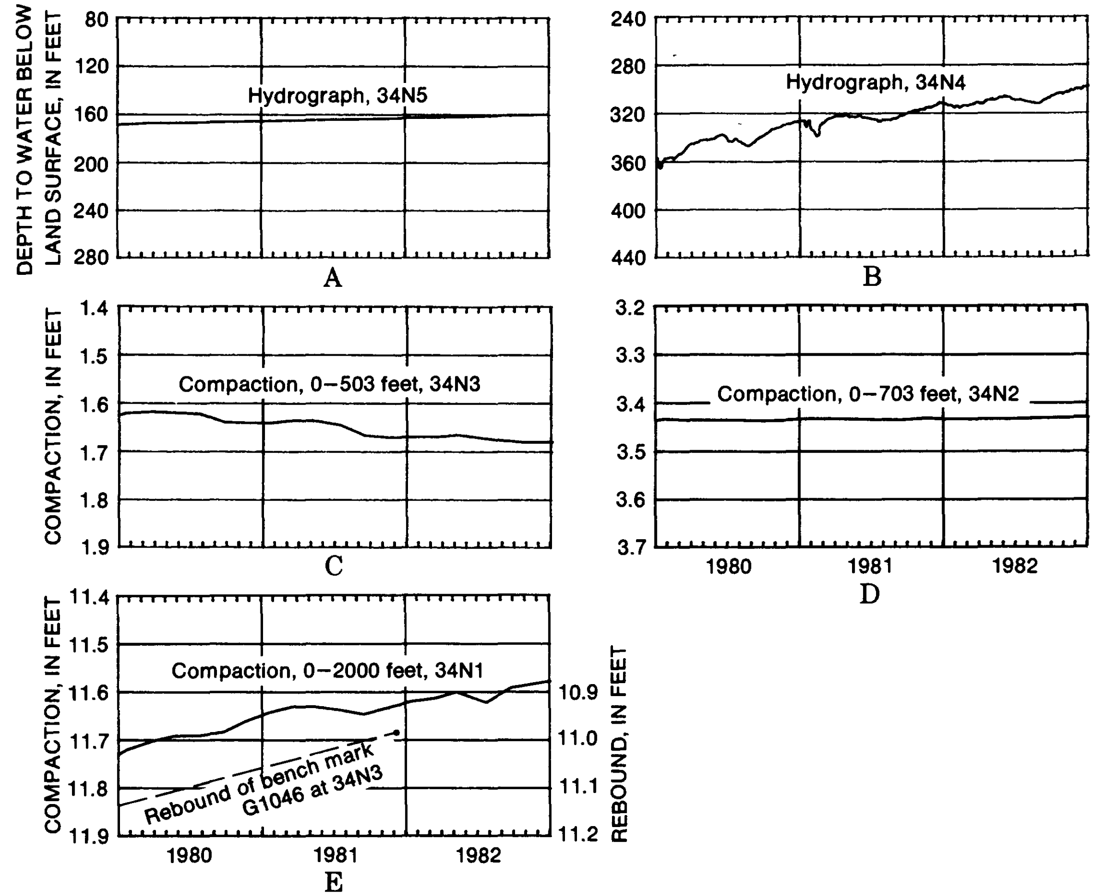


FIGURE 24. — Hydrographs, compaction, and rebound, 16/15—34N. A, Hydrograph of well 16/15—34N5, perforated 240—300 feet. B, Hydrograph of well 16/15—34N4, perforated 1,112 feet. C, Compaction to 503—foot depth in well 16/15—34N3. D, Compaction to 703—foot depth in well 16/15—34N2. E, Compaction to 2,000—foot depth in well 16/15—34N1 and rebound of bench mark G1046 at well 16/15—34N3.

Factors affecting this compaction/subsidence ratio are the depth of the extensometer (this well is 2,000 ft deep; nearby irrigation wells are as much as 2,800 ft deep), time of leveling, and time of compaction observations. This well casing has been subject to more than 11 ft of compaction and may have developed problems at depth; therefore data from this well may only be a partial measurement of the total change in the aquifer system.

Extensometer site 17/15-14Q1 (fig. 25) is a cable-type extensometer 2,315 ft deep and a lower-zone water-level observation well. This is a former oil test well converted to an extensometer that measures casing deformation due to aquifer-system compaction. The hydrograph shows a continuing rise of water level from 366 ft in January 1980 to 306 ft in January 1983, averaging 20 ft/yr. The extensometer measured expansion of 0.083 ft in 1980, 0.025 ft in 1981, 0.045 ft in 1982, and a net expansion of 0.36 ft since 1977.

Bench mark N1216 at this extensometer site was leveled in 1975 and 1982. The data show net subsidence of 0.23 ft from February 1975 to January 1982. The extensometer measured net compaction (casing deformation) of 0.17 ft or 74 percent of the subsidence for the same period. This extensometer measured 75 percent of the subsidence from January 1971 to February 1975.

Extensometer site 18/16-33A1 (fig. 26) is a cable-type extensometer 1,029 ft deep and a lower-zone water-level-observation well. The hydrograph shows a continuing rise of water level from 351 ft in January 1980 to 303 ft in January 1983, averaging 16 ft/yr. The extensometer measured compaction of 0.026 ft in 1980, expansion of 0.021 ft in 1981, and compaction of 0.012 ft in 1982. The extensometer has measured zero net change since 1977.

Bench mark Y998, shown in figure 26, was leveled in January 1978 and in January 1981. The leveling shows a land-surface rebound of 0.16 ft versus 0.01-ft expansion at the extensometer for this period. Expansion of the aquifer system appears to be occurring below 1,029 ft. This extensometer measured 68 percent of the subsidence from February 1966 to October 1969 and from February 1975 to January 1978 (Ireland and others, 1984, table 6).

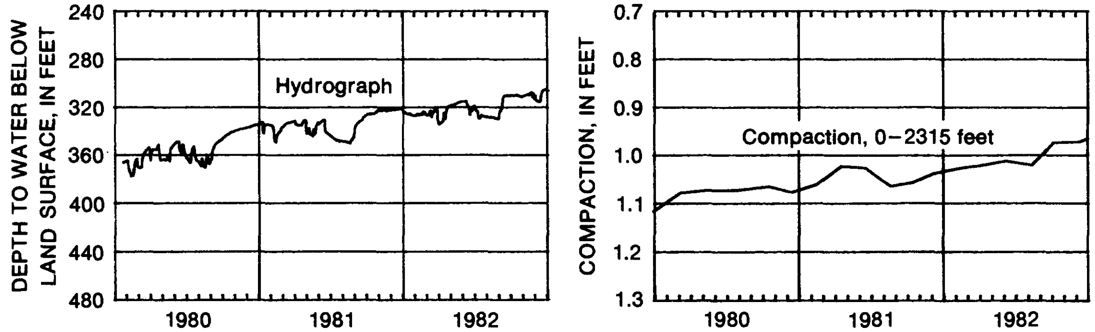


FIGURE 25. — Hydrograph and compaction, 17/15–14Q1. A, Hydrograph, perforated 1,064–1,094 feet. B, Compaction to 2,315–foot depth.

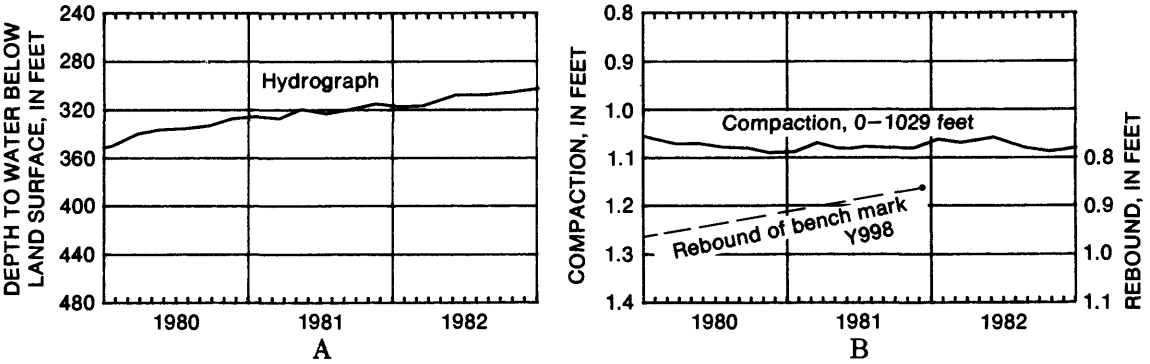


FIGURE 26. – Hydrograph, compaction, and rebound, 18/16–33A1. A, Hydrograph, perforated 858–1,070 feet. B, Compaction to 1,029–foot depth and rebound of bench mark Y998.

Extensometer site 18/19-20P (fig. 27) consists of one cable-type extensometer 20P2, 578 ft deep, and four water-level-observation wells--20P1 (lower zone) and 20P2, 20P3, and 20P4 (upper zone). All hydrographs show rising water levels; 20P4 (123 ft deep) from 121 ft in May 1979 to 105 ft in January 1983; 20P3 (222 ft deep) from 122 ft in January 1980 to 107 ft in January 1983, 20P2 (578 ft deep) from 138 ft in January 1980 to 112 ft in January 1983; and 20P1 (695 ft deep) from 139 ft in January 1980 to 115 ft in January 1983. Heads in all four zones are within 7 ft as of January 1983.

The extensometer, 20P2, measured a net expansion of 0.016 ft from January 1980 to January 1983. The last leveling to this extensometer site was in February 1975. The extensometer measured 33 percent of the land subsidence from April 1969 to February 1975.

Extensometer site 20/18-6D1 (fig. 28) is a cable-type extensometer 867 ft deep and a lower-zone water-level-observation well. The hydrograph shows a rise from the water-level high in December 1980 of 308 ft to the high in December 1982 of 288 ft, averaging 10 ft of recovery per year. The extensometer shows an expansion of 0.015 ft from September 1980 to January 1983.

Bench mark F999 at this extensometer was leveled in January 1978 and December 1981. This site was damaged in late 1979 and was rebuilt in September 1980. The bench-mark change is not shown in figure 28 because an elevation was not established on the reset bench mark in 1980. This extensometer measured 42 percent of the subsidence from February 1966 to January 1978 (Ireland and others, 1984, table 6).

Extensometer site 20/18-11Q1 (fig. 29) is a cable-type extensometer 710 ft deep and an upper-zone water-level-observation well. The hydrograph shows a continuing rise of water level from 257 ft in January 1980 to 204 ft in January 1983, averaging about 18 ft/yr. The extensometer measured expansion of 0.017 ft in 1980, no change in 1981, and expansion of 0.006 ft in 1982, and has measured 0.067 ft of expansion since 1977.

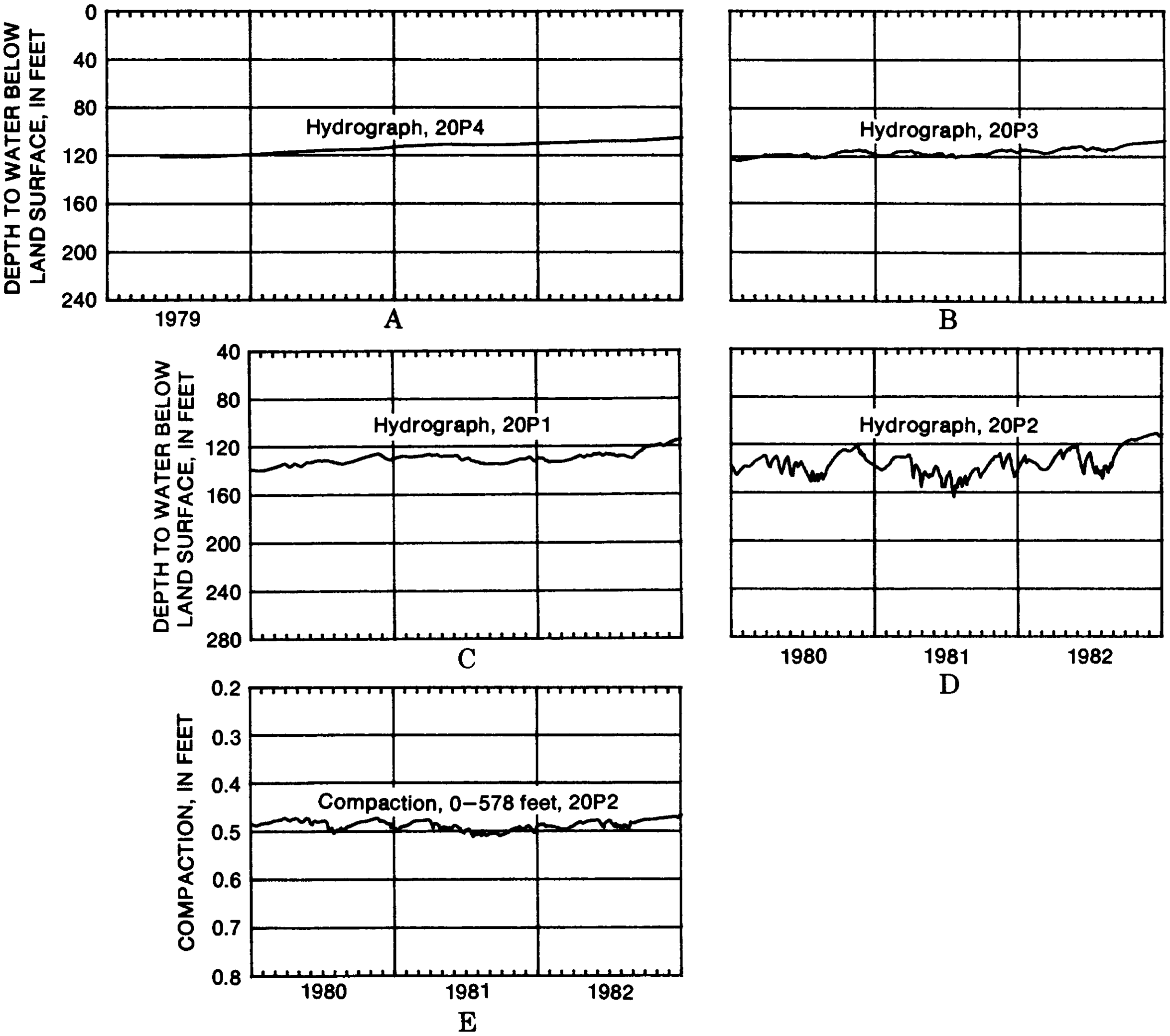


FIGURE 27. — Hydrographs and compaction, 18/19—20P. A, Hydrograph of well 18/19—20P4 (upper water-bearing zone), perforated 120—123 feet. B, Hydrograph of well 18/19—20P3 (upper water-bearing zone), perforated 200—222 feet. C, Hydrograph of well 18/19—P1 (lower water-bearing zone), perforated 647—687 feet. D, Hydrograph of well 18/19—20P2 (upper water-bearing zone), perforated 497—537 feet. E, Compaction to 578—foot depth in well 18/19—20P2.

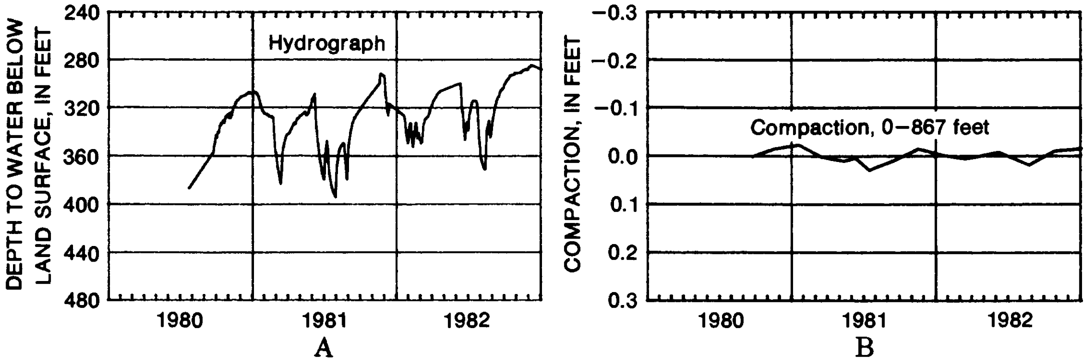


FIGURE 28. — Hydrograph and compaction, 20/18—6D1. A, Hydrograph, perforated 716—736, 706—835, and 851 to 872 feet. B, Compaction to 867—foot depth.

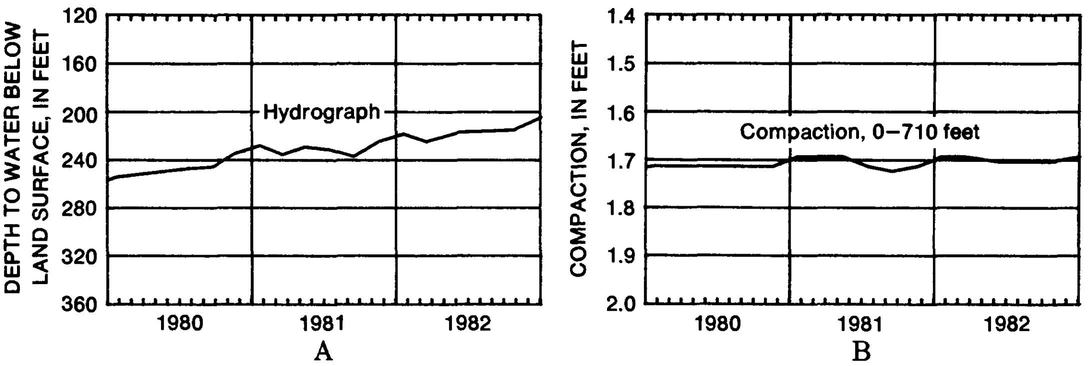


FIGURE 29. — Hydrograph and compaction, 20/18—11Q1. A, Hydrograph, perforated 650—710 feet. B, Compaction to 710—foot depth.

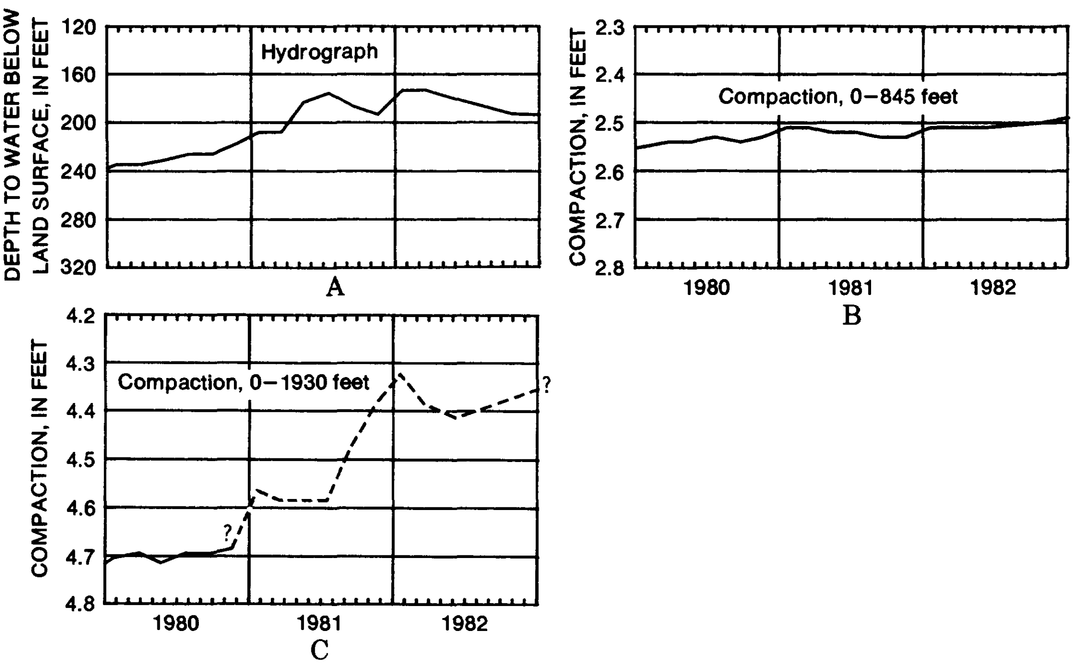


FIGURE 30. — Hydrograph and compaction, 20/18—11Q3. A, Hydrograph, perforated 1,885—1,925 feet. B, Compaction to 845—foot depth (protrusion of 4-inch casing). C, Compaction to 1,930—foot depth.

Extensometer site 20/18-11Q3 (fig. 30) is a former deep-oil test well converted to a multiple-use extensometer and lower-zone water-level-observation well. The well has two casings, the 11.75-inch oil-well casing and an inner 4-inch casing. Extensometer 11Q3 is a cable type 1,930 ft deep that measures casing deformation. Change in the upper 845 ft is measured by the protrusion of the 4-inch casing (Poland and Ireland, 1965). The hydrograph shows a water-level rise from 238 ft in January 1980 to 179 ft in January 1982, averaging about 29 ft/yr, followed by a decline of 15 ft to 194 ft in January 1983.

The 1,930-ft extensometer measured expansion of 0.114 ft in 1980, 0.260 ft in 1981, and compaction of 0.012 ft in 1982, and has measured a net expansion of 0.62 ft since 1977. The large amount of expansion in the 1,930-ft-depth interval shown for 1981 and 1982 is questionable; therefore, the record is questioned after 1980. The measured change in the 845-ft depth interval is 0.037-ft expansion in 1980, no change in 1981, expansion of 0.025 ft in 1982, and a net expansion of 0.14 ft since 1977.

The last leveling to this extensometer was in February 1975. The extensometer, with some adjustments in the data, measured 100 percent of the subsidence from February 1966 to February 1975 (Ireland and others, 1984, table 6).

Extensometer site 22/27-30D2 (fig. 31) is a free-standing pipe-type extensometer 1,246 ft deep and a water-level-observation well. The hydrograph shows an annual fluctuation of about 96 ft in 1980, 111 ft in 1981, 101 ft in 1982, and has recovered annually to near the 220-ft level. During the years 1980 and 1981 (fig. 31), some of the compaction was inelastic. If it had been elastic the amount of compaction would be the same as the amount of expansion during the successive drawdown and recovery periods. The net measured compaction was 0.028 ft in 1980, 0.074 ft in 1981, and a net expansion of 0.002 ft in 1982. As shown on the hydrograph, the large drawdown in 1981 caused a larger amount of compaction.

This extensometer and water-level site is on the Friant-Kern Canal in a critical subsidence area. Additional freeboard was added to the canal in this subsiding area in the 1970's. No leveling is available to this site. This well is located in the Tulare-Wasco subsidence study area (fig. 4), which was last leveled in 1969-70.

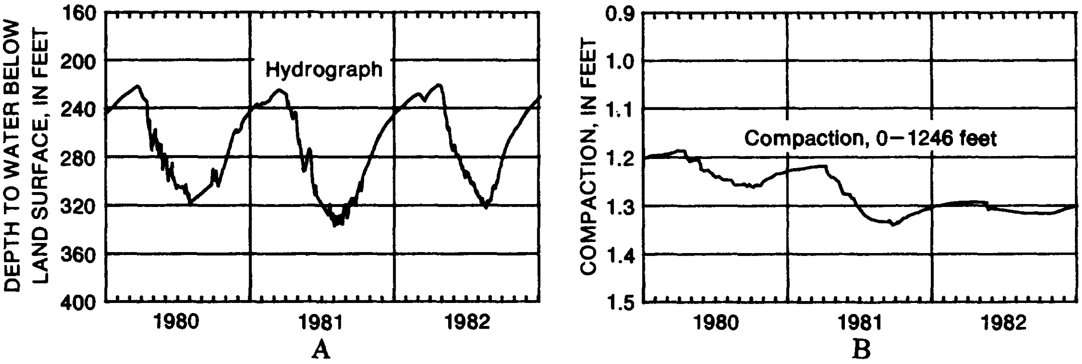


FIGURE 31. — Hydrograph and compaction, 22/27—30D2. A, Hydrograph, perforated 1,083—1,207 feet. B, Compaction to 1,246—foot depth.

Extensometer site 23/25-16N (fig. 32) consists of 16N1, a cable-type extensometer 760 ft deep, and 16N3, a lower-zone water-level-observation well. The hydrograph shows an annual fluctuation of 73 ft in 1980, 149 ft in 1981, 48 ft in 1982, and has recovered annually to the 120- to 130-ft level since 1980. This extensometer also shows that compaction was inelastic during periods of drawdown in 1980 and especially in 1981 but was elastic in 1982. The net measured compaction was 0.026 ft in 1980 and 0.116 ft in 1981; a net expansion of 0.023 ft was measured in 1982. The large drawdown of 150 ft in 1981 due to nearby pumping caused the large amount of compaction. The last leveling to this extensometer site was in January 1970; the extensometer measured 67 percent of the subsidence from February 1959 to January 1970 (Ireland and others, 1984, table 6).

Extensometer site 23/25-16N3 (fig. 33) is a cable-type extensometer 430 ft deep and a lower-zone water-level-observation well. Again, the hydrograph shows an annual fluctuation of about 73 ft in 1980, 149 ft in 1981, 48 ft in 1982, and has recovered annually to near the 120- to 130-ft level (fig. 33). The measured change at this extensometer was expansion of 0.006 ft in 1980, compaction of 0.043 ft in 1981, and compaction of 0.002 ft in 1982. The large water-level drawdown in 1981 caused the large compaction in this 430-ft depth interval. The measured compaction in 16N1 in 1981 (fig. 32B) was 0.116 ft, 0.073 ft more than in 16N3.

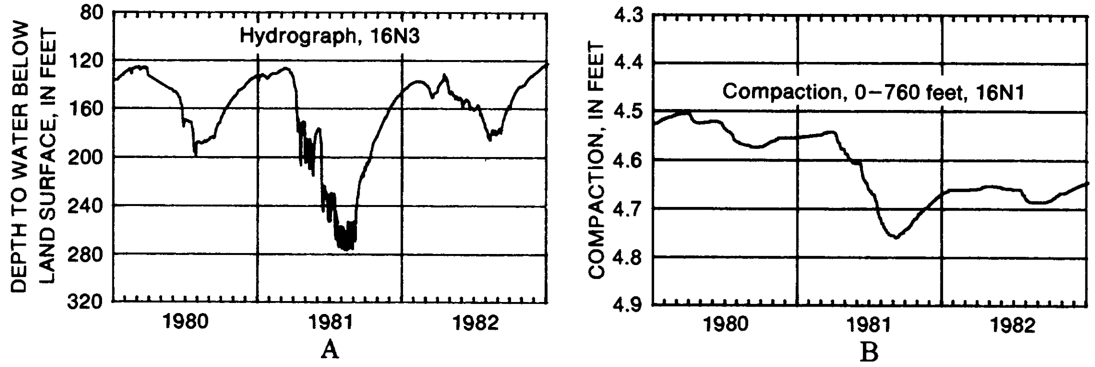


FIGURE 32. — Hydrograph and compaction, 23/25—16N. A, Hydrograph of well 23/25—16N3, perforated 360—420 feet. B, Compaction in 760—foot depth in well 23/25—16N1.

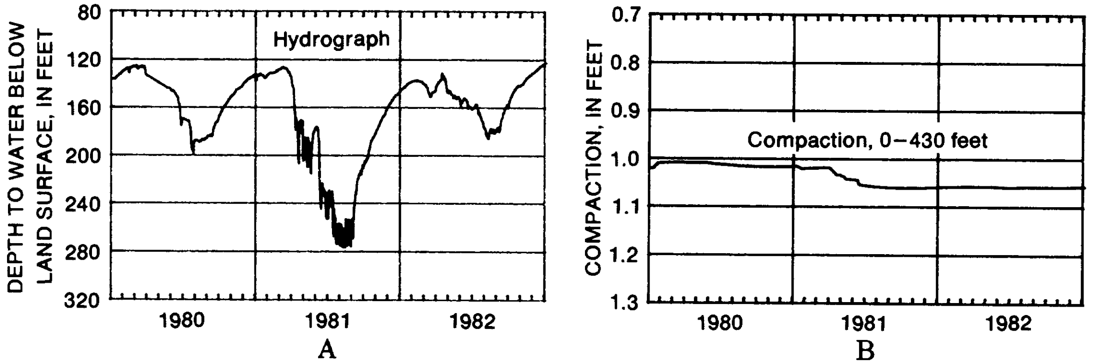


FIGURE 33. — Hydrograph and compaction, 23/25—16N3. A, Hydrograph, perforated 360—420 feet. B, Compaction to 430—foot depth.

Extensometer site 23/25-16N4 (fig. 34) is a cable-type extensometer 250 ft deep and an upper-zone water-level-observation well. The hydrograph shows a rise of 5 ft in 1980, a decline of 9 ft in 1981 (the year of intensive withdrawal), and a rise of 8 ft in 1982. The extensometer measured a net expansion of 0.004 ft from 1979 to 1983. This amount of expansion is questionable because of the error in measuring small amounts of compaction or expansion with a cable-type extensometer. Nevertheless, little (if any) compaction occurred in the upper zone of the aquifer system since 1979 at this site (fig. 34).

Extensometer site 24/26-34F1 (fig. 35) is a cable-type extensometer 1,510 ft deep and a water-level-observation well. The hydrograph shows 9 ft of recovery with very little nearby pumping in 1980, 12 ft of decline with a drawdown of 52 ft during the pumping season in 1981, and a recovery of 19 ft in 1982 with little nearby pumping. The extensometer measured expansion of 0.029 ft in 1980, compaction of 0.023 ft in 1981, expansion of 0.045 ft in 1982, and a net expansion of 0.05 ft from 1979 to 1983. This extensometer measured a net expansion of 0.18 ft since 1977. The data at this site show a very good relation between observed compaction and water levels. Observed compaction and expansion of the aquifer system is elastic and is caused by changes in head in the aquifer system. The last leveling to this extensometer site was in January 1970. The extensometer measured 71 percent of the subsidence from February 1959 to January 1970.

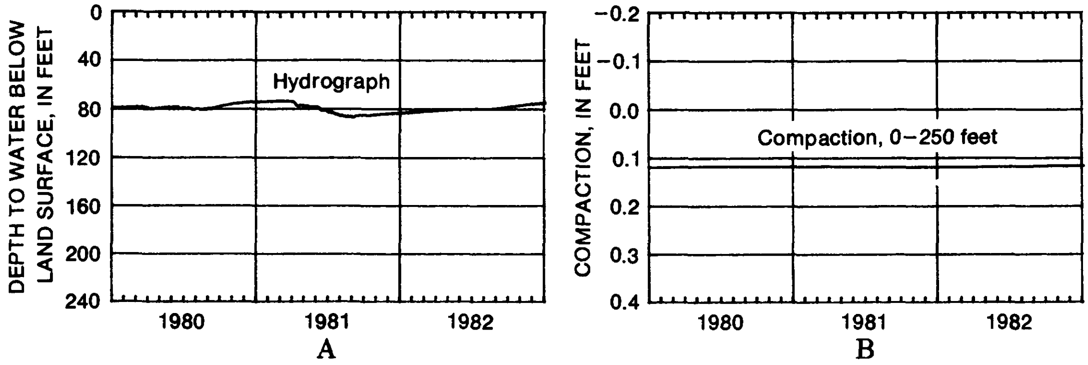


FIGURE 34. — Hydrograph and compaction, 23/25—16N4. A, Hydrograph, perforated 200—240 feet. B, Compaction to 250—foot depth.

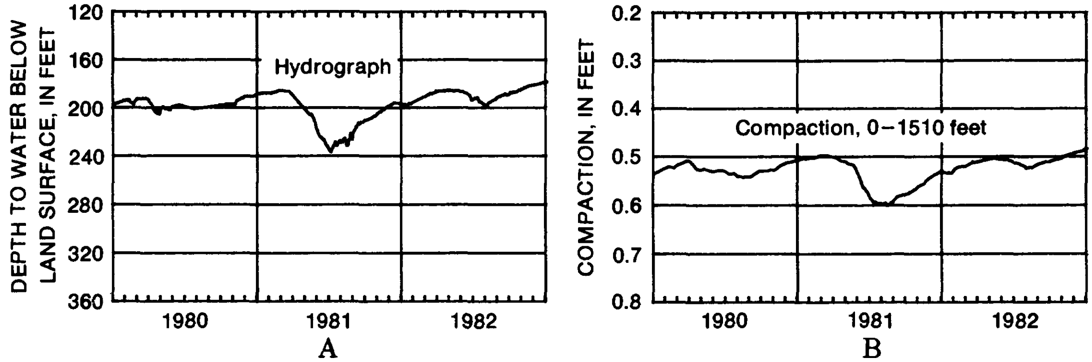
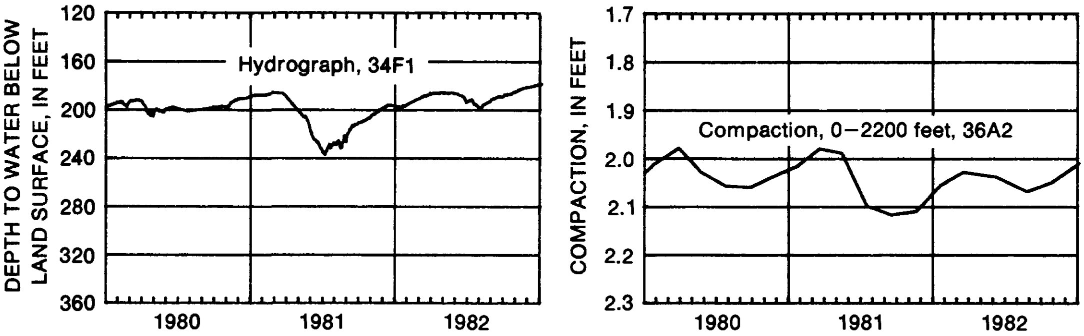
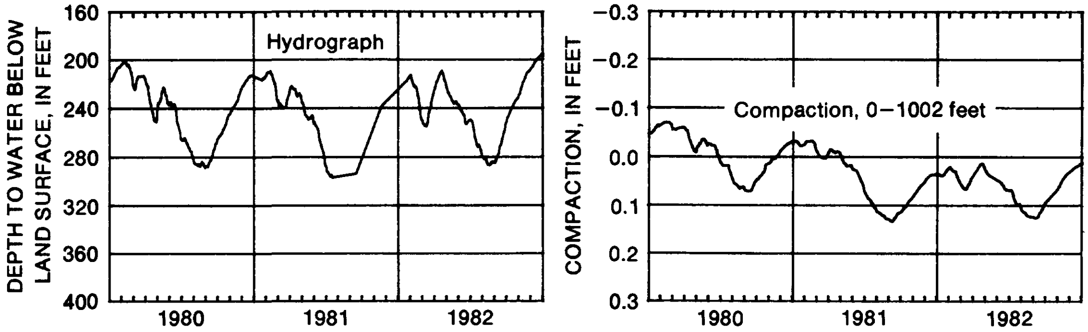


FIGURE 35. — Hydrograph and compaction, 24/26—34F1. A, Hydrograph, perforated 400—1522 feet. B, Compaction to 1,510—foot depth.



A B

FIGURE 36. — Hydrograph of well 24/26–34F1 and compaction in well 24/26–36A2. A, Hydrograph, perforated 400 – 1,522 feet. B, Compaction to 2,200–foot depth.



A B

FIGURE 37. — Hydrograph and compaction, 26/23–16H2. A, Hydrograph, perforated 355–1,002 feet. B, Compaction to 1,002–foot depth.

Extensometer site 24/26-36A2, a cable-type extensometer 2,200 ft deep, and the hydrograph of observation well 24/26-34F1, located about 2.5 mi west, are shown in figure 36. The extensometer measured net expansion of 0.008 ft in 1980, net compaction of 0.050 ft in 1981, net expansion of 0.060 ft in 1982, and net expansion of 0.018 ft from 1979 to 1983. The hydrograph of well 34F1, although the well is quite distant, shows the water-level fluctuation in the area and helps to relate compaction or expansion to water-level changes. This extensometer site was leveled to in 1962 and 1970. Ireland and others (1984, table 6) stated that due to mechanical and(or) data problems, percentage of compaction versus subsidence is not included.

Extensometer site 26/23-16H2 (fig. 37) is a free-standing pipe-type extensometer 1,002 ft deep and a lower-zone water-level-observation well. The hydrograph shows annual water-level fluctuations of 87 ft in 1980, 88 ft in 1981, 78 ft in 1982, and a recovery of 21 ft from 1980 to 1983. The extensometer measured 0.015-ft compaction in 1980, 0.067-ft compaction in 1981, and 0.021-ft expansion in 1982 for a net compaction of 0.06 ft during the 3-year period. Note that some of the compaction in 1980 and 1981 is inelastic because more compaction occurs during the water-level drawdown periods than subsequent expansion during the water-level recovery periods. This extensometer site has not been leveled since the Geological Survey acquired the site in 1978.

Extensometer site 26/23-16H3 (fig. 38) is a free-standing pipe-type extensometer 355 ft deep and a lower-zone (upper part of the lower zone) water-level-observation well; the hydrograph shows fluctuations in water level similar to the hydrograph for well 16H2. Annual fluctuation ranged from 100 ft in 1980, 112 ft in 1981, and 82 ft in 1982 and shows a net recovery of 18 ft for the 3-year period. Measured change in the extensometer was 0.007-ft expansion in 1980, 0.019-ft compaction in 1981, 0.012-ft expansion in 1982, and no net change for the 3-year period in the 355-ft depth interval.

The amount of compaction or expansion is small in extensometer well 16H3 compared to 16H2 because well 16H3 measures changes over a much smaller interval of the aquifer system. Permanent subsidence (inelastic compaction) does not seem to be occurring in the upper part of the lower zone because the amount of compaction during periods of water-level drawdown is about the same as the expansion of the aquifer system during periods of water-level recoveries.

Extensometer site 11N/21W-3B1 (fig. 39) is a cable-type extensometer 1,480 ft deep and a lower-zone water-level-observation well. The hydrograph shows a continuing water-level rise from 364 ft in January 1980 to 346 ft in January 1983, averaging about 9 ft/yr. The extensometer measured compaction of 0.052 ft in 1980, 0.019 ft in 1981, and 0.011 ft in 1982.

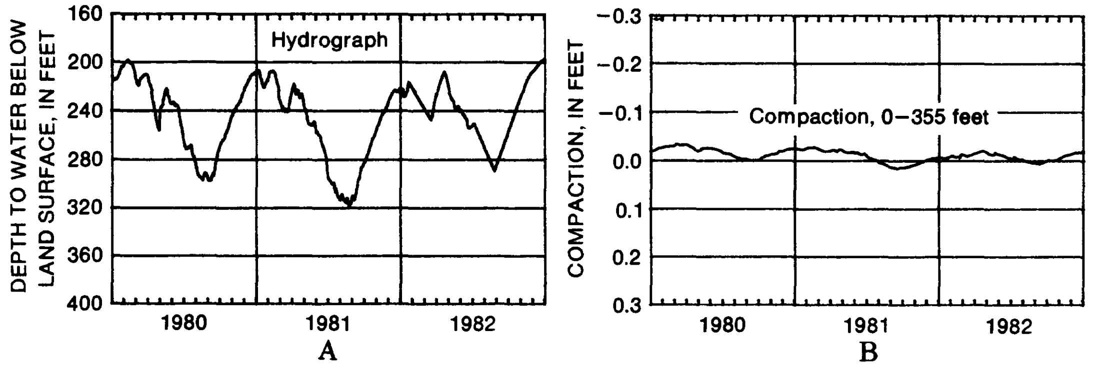


FIGURE 38. – Hydrograph and compaction, 26/23–16H3. A, Hydrograph, perforated 315–335 feet. B, Compaction to 355–foot depth.

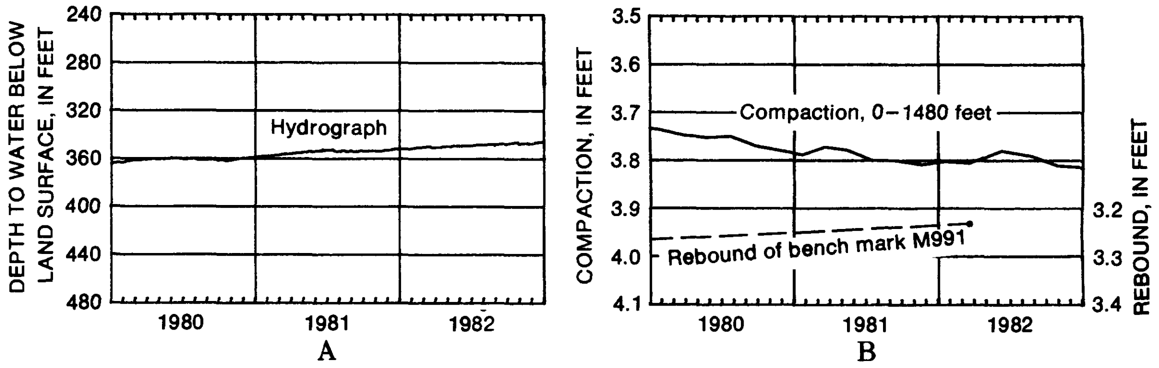


FIGURE 39. – Hydrograph, compaction, and rebound, 11N/21W–3B1. A, Hydrograph, perforated 1,037–1,237 feet. B, Compaction to 1,480–foot depth and rebound of bench mark M991.

The bench mark M991 at this extensometer site was leveled in February 1965, March 1970, May 1975, March 1978, and March 1982. The extensometer measured 90 percent of the subsidence from February 1965 to March 1970, 93 percent from March 1970 to May 1975, and only 73 percent from May 1975 to March 1978 (Ireland and others, 1984, table 6). The 1978 to 1982 leveling shows 0.05-ft rebound while the extensometer measured 0.09-ft compaction for the same period. This site was disturbed when the concrete base was undermined by flood water in early 1978 at about the time of the 1978 leveling. The level data suggest a problem in the 1978 elevation of bench mark M991 at this site. Subsidence from May 1975 to March 1982 was 0.56 ft and measured compaction was 0.53 ft or 95 percent, which is in line with percentages for previous periods.

SUMMARY

Land subsidence in most of the San Joaquin Valley due to ground-water withdrawals seems to have slowed considerably or stopped. The leveling of the California Aqueduct shows minor subsidence, believed to be mostly residual subsidence and residual hydrocompaction along some reaches of the aqueduct. One reach of the aqueduct in western Fresno and Kings Counties shows significant land-surface rebound from 1977-78 to 1981-82, indicating that most of the subsidence that occurred during the 1976-77 drought was elastic and was not permanent.

Records from field extensometers confirm that subsidence due to ground-water-level decline in the valley has been greatly reduced or stopped with the importation of surface water through major canals and the California Aqueduct. Many of the extensometers measured expansion of the aquifer system but generally measured less than the amount indicated by the spirit leveling.

Extensometers in the northern part of the Los Banos-Kettleman City area measured some residual aquifer compaction (subsidence), generally less than 0.1 ft. In the southern part of the area, extensometers measured expansion of the aquifer system from 1979 to 1983.

Extensometers in the Tulare-Wasco and Arvin-Maricopa areas measured subsidence of a few hundredths to about 0.1 ft in 1981, but net change from 1979 to 1983 was generally less than 0.1 ft.

Continued monitoring of subsidence using deep-well extensometers and water-level observation wells is the least costly method of surveillance between relevelings. The amount of regional subsidence or rebound in the San Joaquin Valley since the early 1970's is unknown because releveling of the network of bench marks in each of the major subsiding areas has not been done since 1970 and 1972.

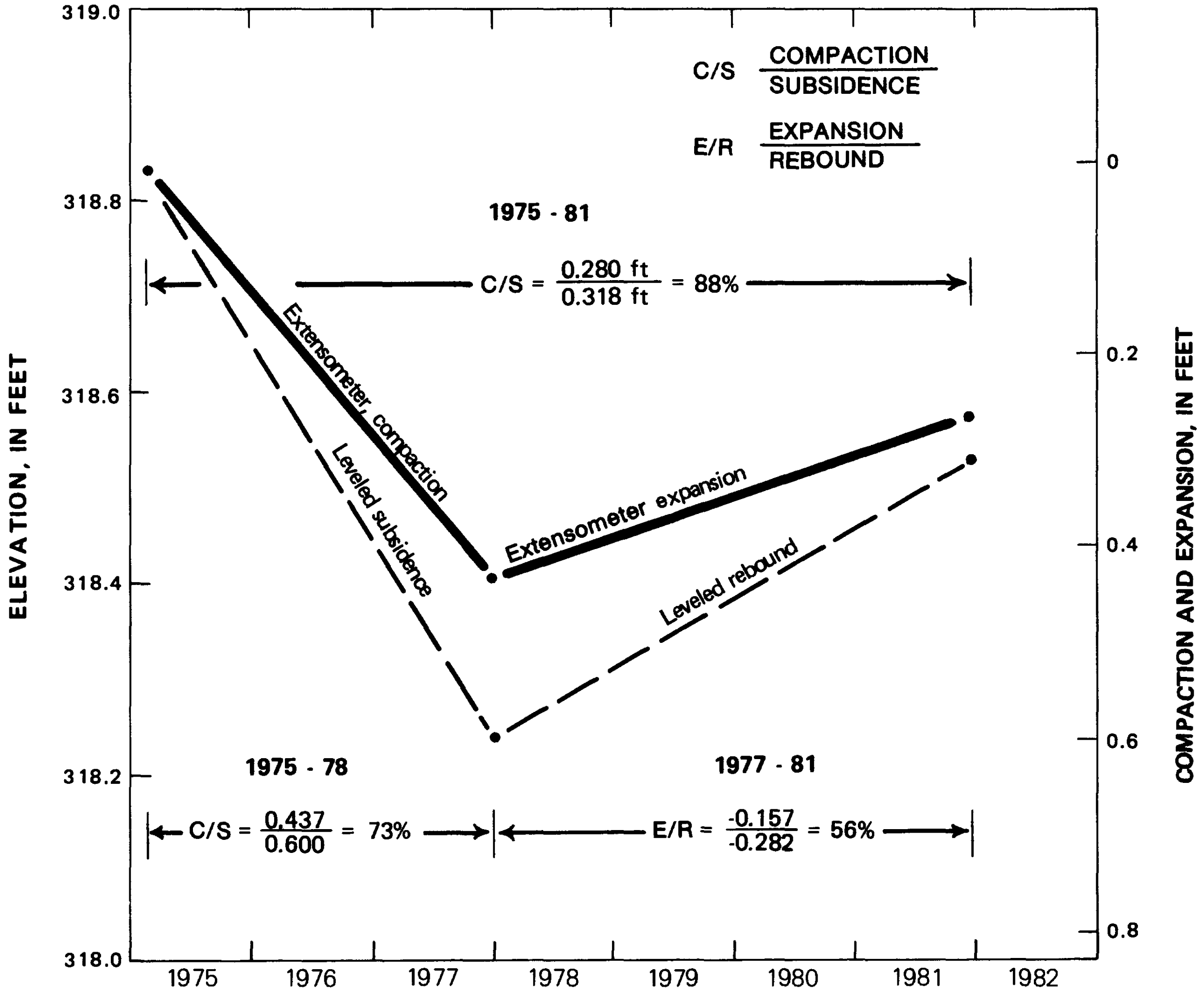


FIGURE 40. — Compaction/subsidence and expansion/rebound ratios at extensometer site 16/15—34N.

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