THE GROUND-WATER FLOW SYSTEM IN INDIAN WELLS VALLEY, KERN, INYO, AND SAN BERNARDINO COUNTIES, CALIFORNIA

By Charles Berenbrock *and* Peter Martin

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Conversion Factors

Multiply	By	To obtain
acre	0.004047	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
foot per day per foot [(ft/d)/ft]	1	meter per day per meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.003785	cubic meter per minute
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Vertical Datum

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Water-Quality Information

Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the weight of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is about the same as for concentrations in parts per million.

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By **Charles Berenbrock** *and* **Peter Martin**

ABSTRACT

Ground water is virtually the sole source of water supplies in Indian Wells Valley. Demand for ground water has increased significantly for municipal and military uses since 1945 and for agricultural uses since 1979. The study described in this report involved updating and evaluating the hydrologic data base compiled for the two-dimensional ground-water flow model previously developed for Indian Wells Valley and analyzing the three-dimensional aspects of the ground-water flow system.

The valley floor covers an area of about 300 square miles and is underlain by unconsolidated deposits that range in thickness from 0 feet along the perimeter of the valley to more than 2,000 feet in the west-central part. The unconsolidated deposits have been divided into shallow and deep aquifers. Prior to ground-water development in the valley, water flowed from the deep aquifer to the shallow aquifer, moving through the deep aquifer from areas of recharge along the margins of the valley toward China Lake in the central part of the valley. Water was discharged from the shallow aquifer by evapotranspiration from the area in and around China Lake. Prior to ground-water development, recharge to the deep aquifer was balanced by evapotranspiration from the shallow aquifer.

Ground-water development since the 1920's has modified the direction of ground-water movement in both the shallow and deep aquifers. From 1920 to 1985, ground-water pumpage, predominantly from the deep aquifer, increased from 1,000 to more than 22,000 acre-feet per year. The pumping, centered in the intermediate area (between Ridgecrest and Inyokern), has caused water levels in the deep aquifer to decline more than 80 feet in the intermediate area.

A three-dimensional finite-difference model was developed and calibrated to simulate steady-state conditions as approximated by 1920-21 water levels and transient-state conditions for 1920-85. The ground-water system in the valley was simulated as two layers. Layer 1, the upper layer, represents the shallow aquifer; and layer 2, the lower layer, represents the deep aquifer. Model calibration was considered acceptable when the difference between model-simulated heads and measured values was 5 feet or less. Because data in the northern part of the valley are sparse, conditions there cannot be simulated adequately.

From 1920 to 1985, 548,900 acre-feet of ground water was pumped from Indian Wells Valley. Results of the transient-state model simulation indicate that 86 percent (469,560 acre-feet) of this pumpage was derived from storage, about 10 percent (54,380 acre-feet) was derived from decreases in evapotranspiration from layer 1, and about 4 percent (24,410 acre-feet) was derived from artificial recharge of wastewater and shrubbery-irrigation water. The model indicated that pumping induced about 28,870 acre-feet of ground water to flow from layer 1 to layer 2 during 1920-85. The rate of vertical leakage from layer 1 to layer 2 increased from zero in 1920 to about 1,550 acre-feet in 1985. These model simulations indicate that the ground-water quality of layer 2 could become degraded by water of poor quality (dissolved-solids concentration greater than 1,000 milligrams per liter) contained in layer 1.

Several model simulations were used to estimate the aquifer response to different pumpage patterns that could be used as management alternatives. Results of the simulations indicate that redistributing the pumping from the intermediate and Ridgecrest areas to either the southwestern or western parts of the valley would reduce water-level declines in the intermediate and Ridgecrest areas. However, vertical leakage from layer 1 to layer 2 would be reduced only if pumping were redistributed to the southwestern part of the valley.

INTRODUCTION

Ground water is virtually the sole source of water in Indian Wells Valley for municipal, military, industrial, and agricultural uses. Demand for ground water in Indian Wells Valley has increased significantly for municipal and military uses since 1945, and for agricultural uses since 1979. Future municipal growth at Ridgecrest and Inyokern and planned programs at China Lake Naval Weapons Center (NWC) will further increase the demand for water in the valley. Since 1966, annual ground-water pumpage has exceeded estimates of mean annual recharge (Dutcher and Moyle, 1973; Lipinski and Knochenmus, 1981). To plan for anticipated growth in Indian Wells Valley, there is a need to evaluate ground-water conditions and to estimate changes resulting from current and projected pumpages and recharge in the valley.

In 1971, a two-dimensional mathematical ground-water flow model was developed by the U.S. Geological Survey (Bloyd and Robson, 1971) to make a quantitative assessment of the geohydrology of Indian Wells Valley. The model has proved to be a useful tool to simulate water levels in the deep aquifer. However, because of the two-dimensional structure of the model, it cannot simulate vertical ground-water movement between the deep and shallow aquifers. In recent years, there has been a growing concern about the possible movement of water from the shallow aquifer, which locally contains water of poor quality, to the heavily pumped deep aquifer. Increased understanding of the three-dimensional aspects of the aquifer system is needed to efficiently manage the ground-water resources of Indian Wells Valley.

Purpose and Scope

In 1980 the U.S. Geological Survey, in cooperation with the China Lake Naval Weapons Center and the Indian Wells Valley Water District, developed a 10-year plan to study the aquifer system of Indian Wells Valley (Lipinski and Knochenmus, 1981). One of the objectives of the plan was to collect data that could be used to gain an understanding of the three-dimensional aspects of the deep and shallow aquifers in the valley. Initial information indicated that the ground-water flow model previously developed for the valley (Bloyd and Robson, 1971) does not adequately represent the three-dimensional flow system.

The purpose of the study described in this report was to update and evaluate the hydrologic data base compiled for the two-dimensional flow model previously developed and then to evaluate the three-dimensional aspects of the ground-water flow system. The scope of the study included developing a three-dimensional mathematical ground-water flow model for the valley. The model was developed and calibrated using geologic and hydrologic data presented in the Bloyd and Robson report and data collected for the 10-year-plan study. After the model had been calibrated, it was used to simulate the response of the aquifer system to three hypothetical pumpage patterns that represented possible ground-water-resources management alternatives.

Description of the Study Area

Indian Wells Valley (fig. 1) is in the northwestern part of the Mojave Desert in southern California, about 125 miles north of Los Angeles. The valley is bounded on the west by the Sierra Nevada, on the north by a low ridge of volcanic rocks and the Coso Range, on the east by the Argus Range, and on the south by the El Paso Mountains. The surrounding mountains and hills slope steeply to the broad valley floor, which in turn slopes gently toward China Lake, a large dry lake, or playa, in the east-central part of the valley. Most of

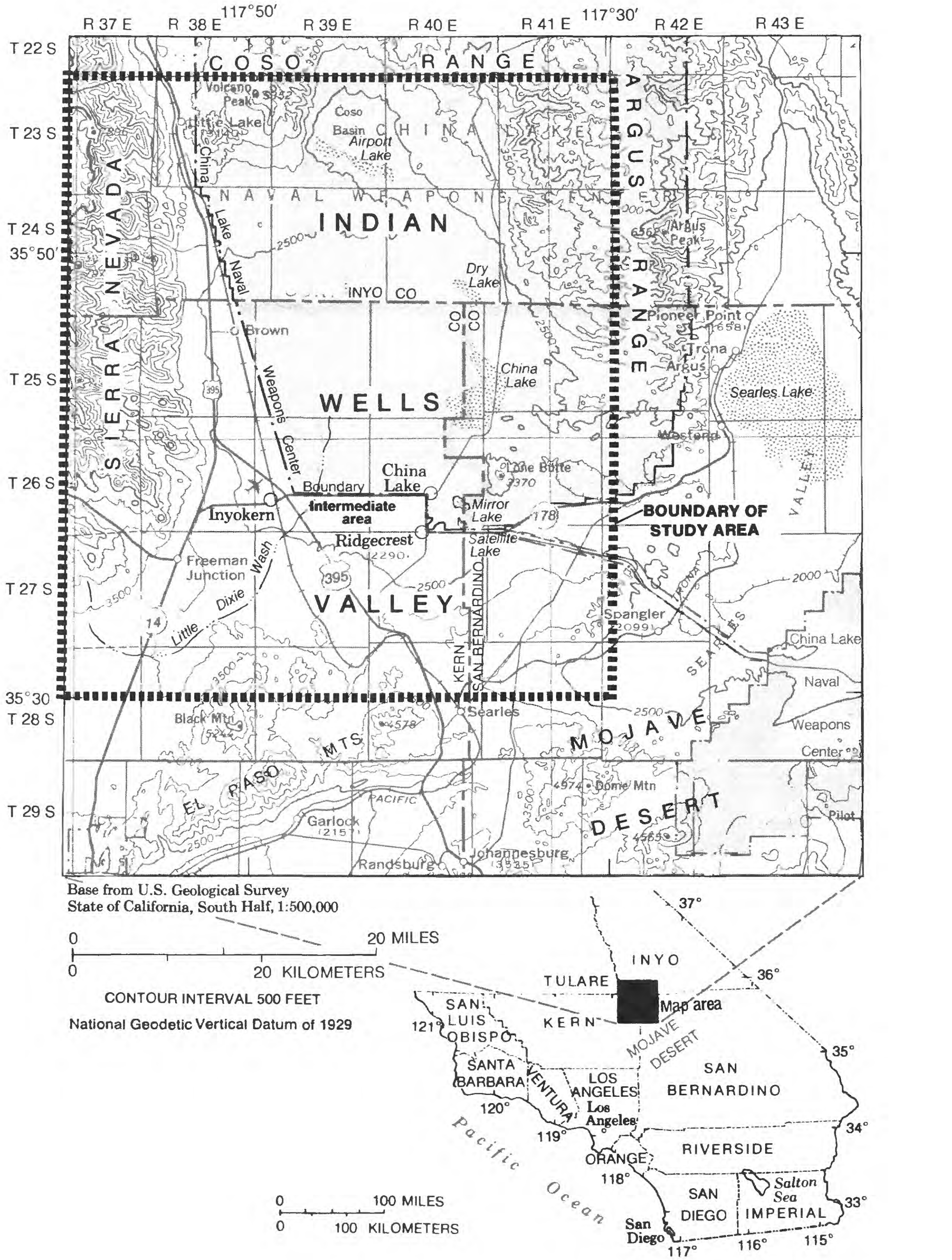


Figure 1. Location of study area.

the 300-square-mile valley floor ranges in altitude from 2,175 to 2,400 feet above sea level. China Lake, at an altitude of about 2,150 feet, is at the lowest part of the valley.

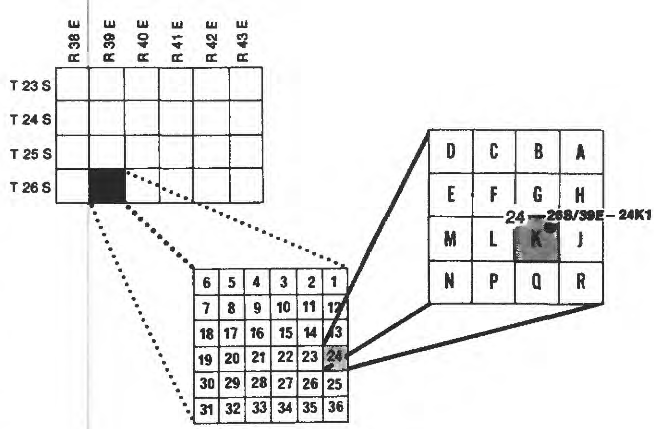
Indian Wells Valley has an arid climate; average annual precipitation on the valley floor is 4 to 6 inches. Although rainfall occurs infrequently during the summer, most of the precipitation (which includes occasional snowfall) occurs during October-March. Summers are characterized by very hot days and warm nights, and winters by generally warm days and cool nights.

The communities of Ridgecrest and China Lake, with a combined population of about 25,000 in 1986, cover about 18 mi^2 in the southeastern part of the valley (fig. 1). The town of Inyokern, with a population of about 2,500, covers 0.25 mi^2 in the southwestern part of the valley. The area between Ridgecrest on the east and Inyokern on the west side of the valley is known as the intermediate area (fig. 1). There is no perennial surface flow on the valley floor, and current water needs in the valley are met through development of ground-water resources.

Most of the land in Indian Wells Valley is Federal land under the jurisdiction of China Lake Naval Weapons Center (NWC) (fig. 2). The valley is predominantly undeveloped desert except near the communities of Ridgecrest, Inyokern, and China Lake and about 1,700 acres of land in the northwestern part of the valley that has been extensively irrigated for alfalfa since 1979.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public lands in California. For example, in well number 26S/39E-24K1, the part of the number preceding the hyphen indicates the township (T. 26 S.) and range (R. 39 E.); the number following the hyphen indicates the section (sec. 24); and the letter (K) following the section number indicates the 40-acre subdivision. Within the 40-acre subdivision, wells are sequentially numbered in the order in which they are inventoried (1). The area covered by this report lies entirely in the southeast quadrant of the Mount Diablo base line and meridian.



EXPLANATION FOR FIGURE 2

LAND USE AND OWNERSHIP--

- China Lake Naval Weapons Center
- U.S. Bureau of Land Management
- Urban and built-up land
- Private (patented) land
- State land
- Irrigated alfalfa
- Irrigated fruits, pistachio trees, and grapes

WASTEWATER-TREATMENT PLANTS--

1 Ridgecrest Regional Wastewater Treatment Facility

2 Ridgecrest Sanitation District Treatment Plant

3 Inyokern Community Services District Plant

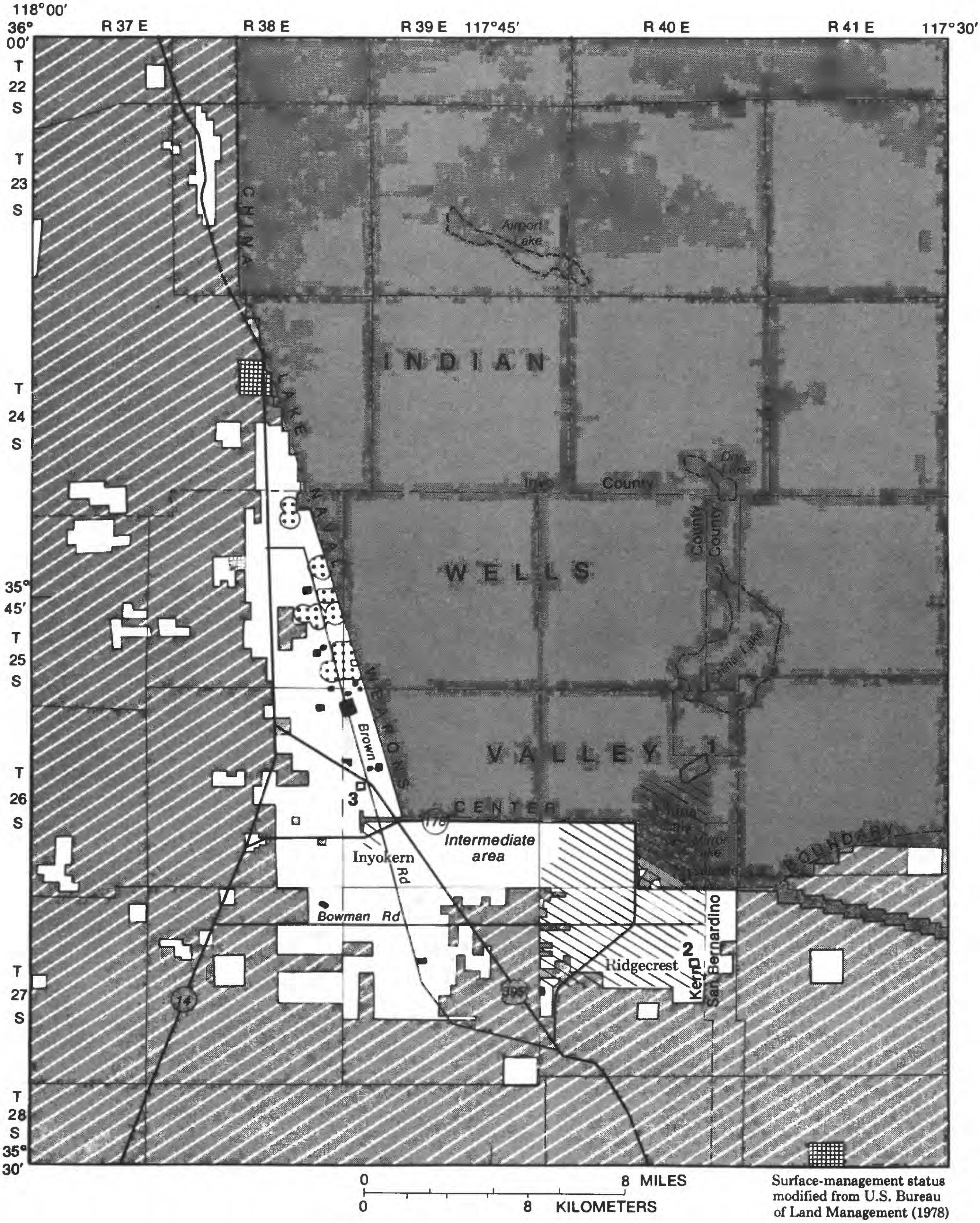


Figure 2. Land use and ownership in study area, 1985.

GROUND-WATER SYSTEM

The geohydrology of Indian Wells Valley is discussed in detail in reports by Von Huene (1960), Zbur (1963), Kunkel and Chase (1969), and Dutcher and Moyle (1973), and only a brief summary of the geohydrology is included here. Active faults and earthquakes in the valley and vicinity are discussed in detail in reports by Roquemore and Zellmer (1983a, 1983b, 1986). The reader is referred to these reports for a more complete description of the geohydrology of Indian Wells Valley.

Definition of the Aquifer System

Indian Wells Valley is a structural and topographic depression in the southwestern part of the Basin and Range province. For this study, the lithologic units mapped by Von Huene (1960), Zbur (1963), and Kunkel and Chase (1969) are grouped in the Indian Wells Valley area into two categories: (1) consolidated rocks, which commonly have low porosity and permeability and do not readily transmit water, except where highly fractured, and (2) unconsolidated deposits, which generally transmit water readily.

The consolidated rocks include the basement complex, continental deposits, and volcanic rocks. The basement complex consists of pre-Tertiary igneous and metamorphic rocks and underlies the younger rocks and deposits of Indian Wells Valley and composes the surrounding mountains and hills (fig. 3). The continental deposits of Tertiary age overlie the basement complex. A seismic refraction study by Zbur (1963) and geologic and electric logs of several wells that penetrate the continental deposits (fig. 4) indicate that these deposits become consolidated with depth and probably have low permeability. Kunkel and Chase (1969, p. 16) reported that the continental deposits are indurated and poorly sorted; they considered the deposits to be virtually non-water bearing. The volcanic rocks include the Miocene Black Mountain Basalt near the El Paso Mountains (Diggles and others, 1985, p. C6) and Quaternary unnamed volcanic rocks (Kunkel and Chase, 1969, p. 22). The volcanic rocks are nearly impermeable except where weathered or fractured and are not considered an important source of ground water.

The unconsolidated deposits include alluvium, and lacustrine, playa, and sand-dune deposits. The alluvium of Pleistocene and Holocene age includes older alluvium, younger alluvium, alluvial fans, and elevated pediment veneers and stream-terrace deposits. These deposits consist of unconsolidated moderately to well-sorted gravel, sand, silt, and clay and generally are highly permeable. The percentage of silt and clay increases toward the central part of the valley and China Lake. The lacustrine

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EXPLANATION FOR FIGURE 3

GEOLOGIC UNITS

UNCONSOLIDATED DEPOSITS --

Quaternary

Sand dunes (Holocene)

Sand dunes and playa deposits (Holocene)

Playa deposits (Holocene)

Alluvium (Holocene and Pleistocene)

Lacustrine deposits (Pleistocene)

CONSOLIDATED ROCKS --

Quaternary and Tertiary

Volcanic rocks (Pleistocene and Miocene)

Tertiary

Continental deposits (Pliocene and Miocene)

Pre-Tertiary

Basement complex

FAULTS--Dashed where approximate

A—A' LINE OF GEOLOGIC SECTION

BOUNDARY OF SHALLOW AQUIFER (Kunkel and Chase, 1969)

WELL SHOWN IN GEOLOGIC SECTION (figure 4)

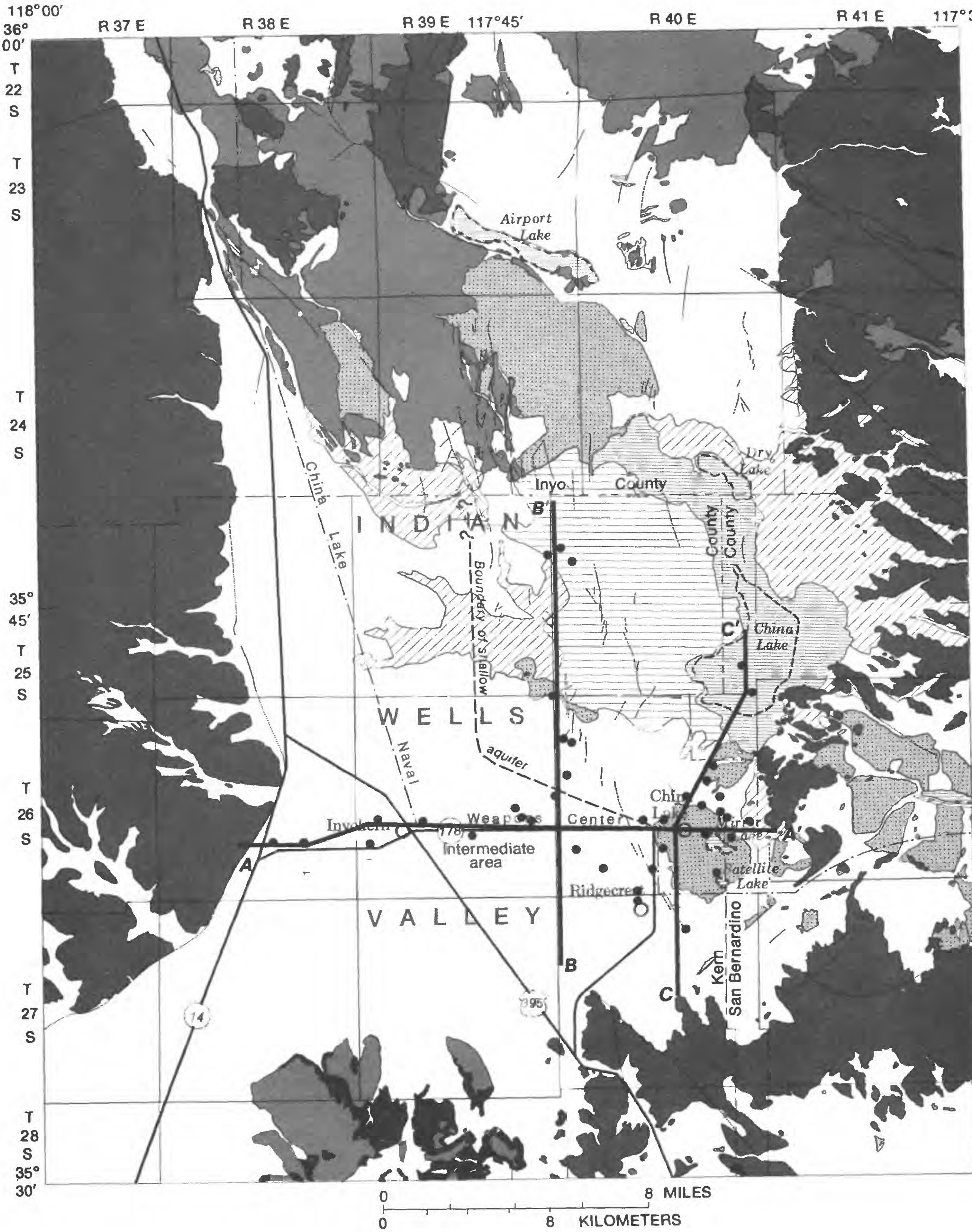


Figure 3. Generalized geology of Indian Wells Valley and location of geologic sections.

deposits include both the older and younger lacustrine deposits of Kunkel and Chase (1969, p. 19, 27). These low-permeability deposits consist predominantly of silt and silty clay of Pleistocene age (Kunkel and Chase, 1969, p. 19, 22, 27-28). The lacustrine deposits are interbedded with and overlie the alluvial deposits in the central part of the valley. The playa deposits, of Holocene age, also generally are of low permeability, consisting of silt and clay with occasional sand lenses. The sand-dune deposits, of Holocene age, consist of a thin veneer of windblown sand (100 feet or less in thickness) covering the underlying deposits (Warner, 1975, p. 8). These sand deposits are not considered a source of ground water because they generally are above the water table.

The greatest thickness of unconsolidated deposits, about 2,000 feet, occurs in the west-central part of the valley (Zbur, 1963; Dutcher and Moyle, 1973, p. 9). The unconsolidated deposits vary greatly in lithology, both vertically and areally, toward the central and eastern parts of the valley. On the basis of lithologic logs from wells, previous investigators have divided the unconsolidated deposits in the valley into two main aquifers: (1) the shallow aquifer (shallow water body of Kunkel and Chase, 1969) and (2) the deep aquifer (main water body of Kunkel and Chase, 1969).

The shallow aquifer includes (from land surface to the top of the deep aquifer) sand-dune deposits, playa deposits, younger lacustrine deposits, shallow alluvium where underlain by lacustrine deposits, and probably some older lacustrine deposits. The shallow aquifer as defined by Kunkel and Chase (1969) extends from China Lake westward to the center of the valley and from the area south of Airport Lake southward to the community of China Lake (fig. 3). The base of the shallow aquifer is poorly defined. For the purpose of this study, however, the base was assumed to slope from an altitude of 1,950 feet above sea level on the west to an altitude of 1,850 feet on the east beneath China Lake. This assumption was based in part on the geologic and electric logs of several wells that were drilled through the shallow aquifer near the community of China Lake (fig. 4).

The water-bearing deposits in the shallow aquifer consist primarily of fine sand, silt, and clay of low permeability. These deposits confine or partly confine the underlying deep aquifer in the eastern part of the valley. The shallow aquifer does not yield water freely to wells and contains water of poor quality (dissolved-solids concentration greater than 1,000 mg/L) (Warner, 1975; Berenbrock, 1987). Prior to the 1940's some wells perforated in this aquifer were used for domestic and ranching supplies; since the 1940's, however, this aquifer (probably because of its poor quality) has supplied water only for fire protection and maintenance of buildings for NWC. Most of the wells drilled in this aquifer are used as observation wells to monitor ground-water quality and levels.

The deep aquifer includes the total saturated thickness of the alluvium and lacustrine deposits where the shallow aquifer is not present and the alluvium and lacustrine deposits that underlie the shallow aquifer in the eastern part of the valley (fig. 3). The base of the deep aquifer is the base of the alluvium. Beneath most of the central part of the valley, the saturated thickness of the deep aquifer is estimated to be at least 1,000 feet (Kunkel and Chase, 1969, p. 39). The deep aquifer in most places is unconfined; however, in the eastern part of the valley the deep aquifer is confined by silt and clay lenses of the lacustrine and playa deposits. This aquifer consists of medium-to-coarse sand and gravel of high permeability and is the main source of water to wells in Indian Wells Valley. The deep aquifer commonly yields more than 1,000 gal/min to wells, and some wells in the intermediate and Inyokern areas yield more than 2,000 gal/min. The dissolved-solids-concentration in samples from wells perforated in the deep aquifer generally is less than 1,000 mg/L (Warner, 1975). Wells perforated in the deep aquifer near Inyokern; in the intermediate area; and in the southwest part of the study area near the Little Dixie Wash (fig. 1) have dissolved-solids concentrations less than 400 mg/L (Berenbrock, 1987).

Natural Recharge and Discharge

Natural recharge to the ground-water system in the valley consists almost entirely of runoff from the surrounding mountains. Because infiltration of the runoff occurs near the mountain front where the runoff first crosses the unconsolidated deposits of the valley, the natural recharge is termed "mountain-front recharge." Little, if any, direct infiltration of precipitation recharges the ground-water system in Indian Wells Valley. Precipitation averages only 4 to 6 in/yr on the valley floor, and most is lost to evaporation, which averages about 80 in/yr from ponded waters (Farnsworth and others, 1982). Precipitation that infiltrates into the soil eventually is consumed by natural and cultivated plants that can transpire several feet of water per year if the water is available in the root zone.

Prior to extensive pumping in the valley, recharge to the ground-water system was balanced by natural discharge. Except for a small amount of ground-water outflow to Salt Wells Valley, natural discharge occurred almost entirely by evapotranspiration from the shallow aquifer in the vicinity of China Lake in the eastern part of the valley. By mapping areas of phreatophytes and moist lands present in 1912 in and around China Lake and multiplying the areas by assigned evapotranspiration rates, Lee (1912, p. 422) estimated evapotranspiration in the valley to be 31,600 acre-ft/yr. The total area of evapotranspiration as determined by Lee was about 9,400 acres. The assigned evapotranspiration rates were determined from a linear relation between a maximum evapotranspiration rate when the water table is at land surface and a zero evapotranspiration rate at a depth of 8 feet below land surface where evapotranspiration ceases (Lee, 1912, p. 413).

Kunkel and Chase (1969, p. 64) considered Lee's estimate to be inaccurate because when the estimate was made in 1912, maps of the area were poor, aerial photographs were not available, and little work had been done on evapotranspiration rates for the various phreatophytes. Using modern maps, Kunkel and Chase (1969, p. 69) classified 33,000 acres of moist lands in and around China Lake as areas of evapotranspiration. They then assigned evapotranspiration rates to the area on the basis of a nonlinear relation between a maximum evapotranspiration rate when the water table is at land surface and zero evapotranspiration when the depth to water approaches 10 feet below land surface. The nonlinear relation was based on research in other desert basins since Lee's work in 1912 (Smith and Skarn, 1927; Lee, 1942; Young and Blaney, 1942; Blaney, 1952).

Using the revised values for area and evapotranspiration rates, Kunkel and Chase (1969, p. 69) estimated the total ground-water discharge by evapotranspiration for 1912 to be 11,000 acre-ft/yr, about 20,600 acre-ft/yr less than Lee's (1912) estimate. The main reason for the difference in the estimates is that Kunkle and Chase used a nonlinear relation between evapotranspiration and depth to water. The maximum evapotranspiration rates used by both Lee (1912) and Kunkel and Chase (1969, p. 69) are about the same; however, the nonlinear relation between evapotranspiration and depth to water (used by Kunkel and Chase) predicts much lower evapotranspiration rates than the linear relation (used by Lee) as the depth to water increases. For example, for bare soil where the depth to water is 5 feet below the land surface, the nonlinear relation predicts

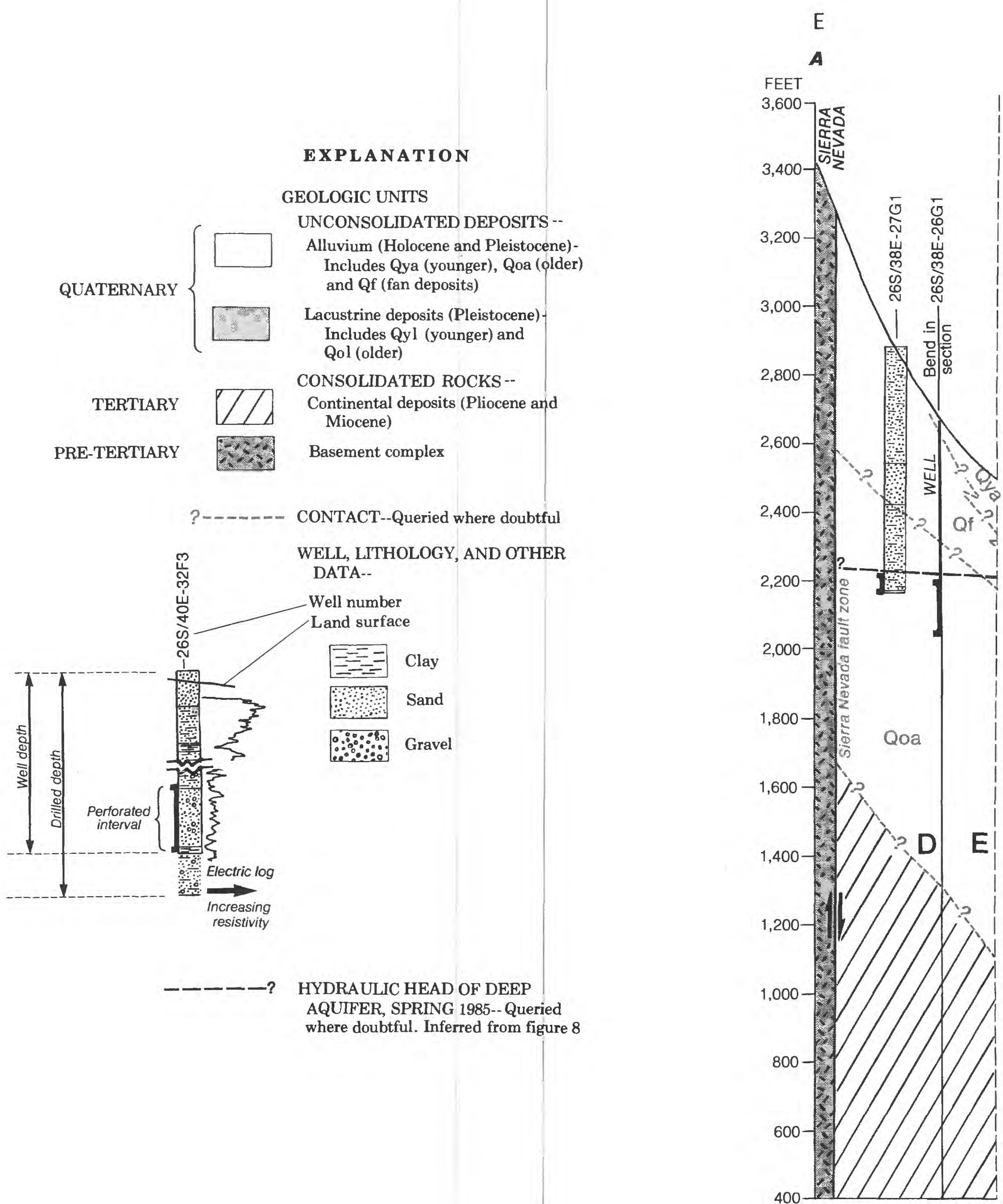
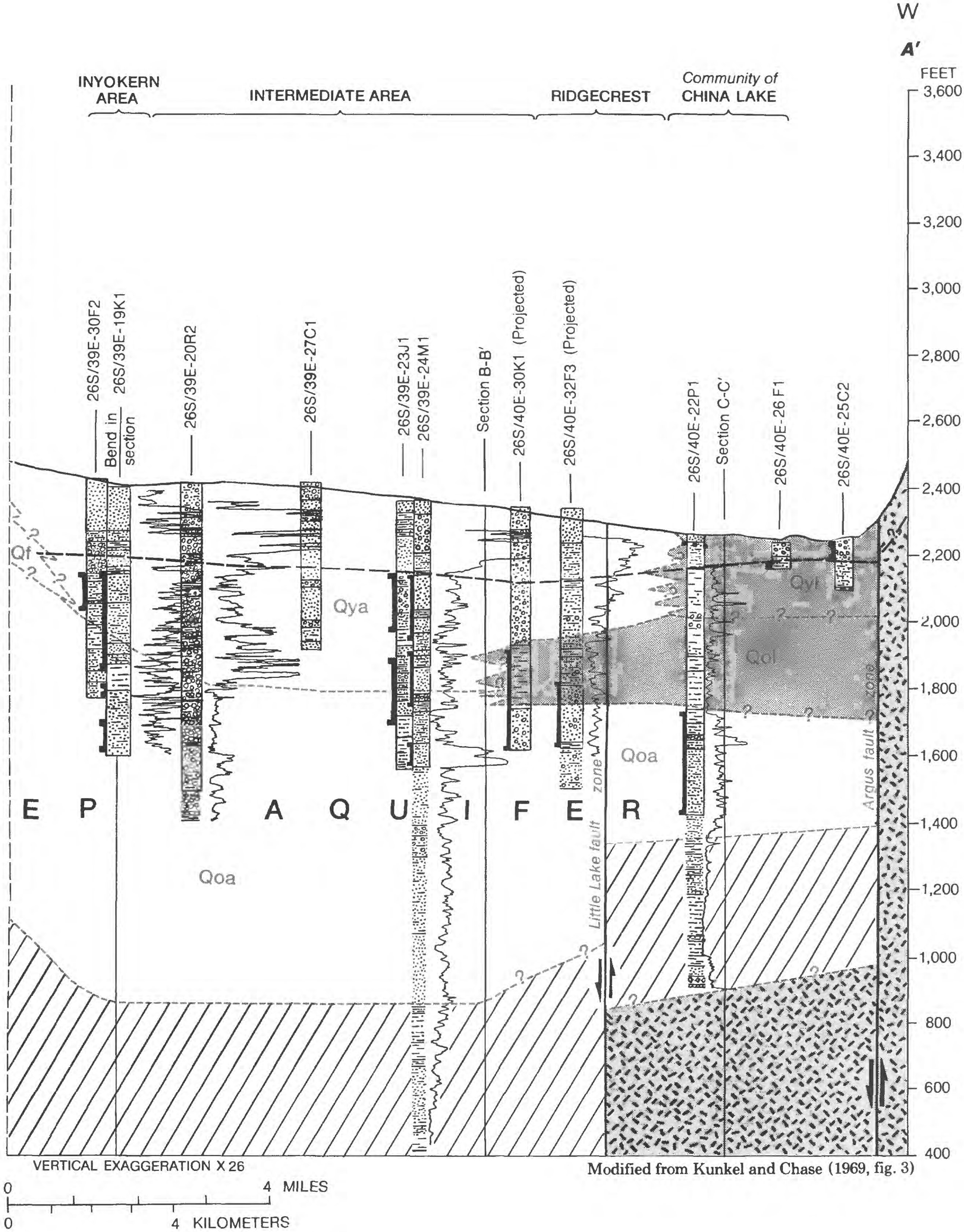


Figure 4. Diagrammatic geologic sections of the Indian Wells Valley ground-water basin.



Modified from Kunkel and Chase (1969, fig. 3)

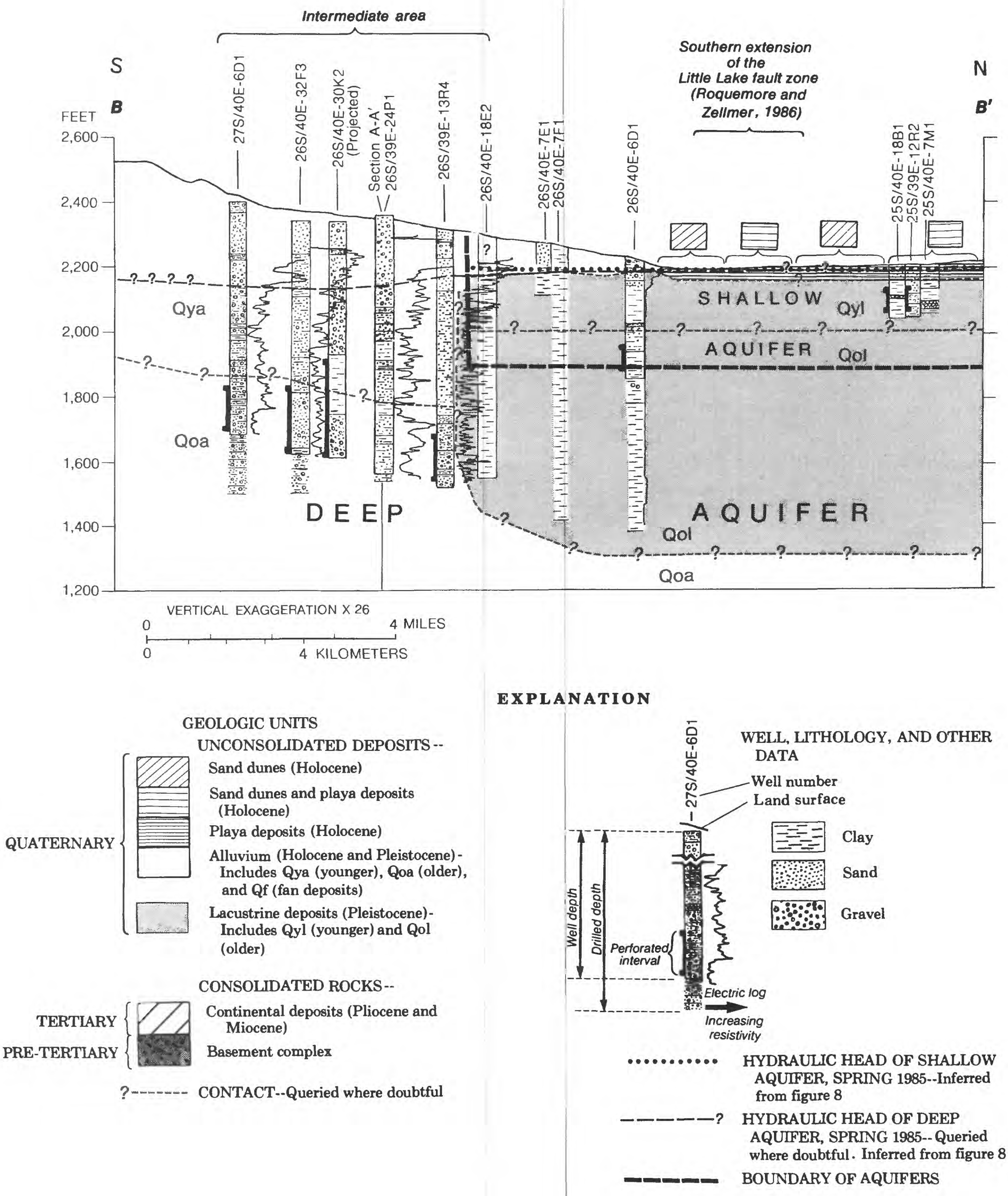
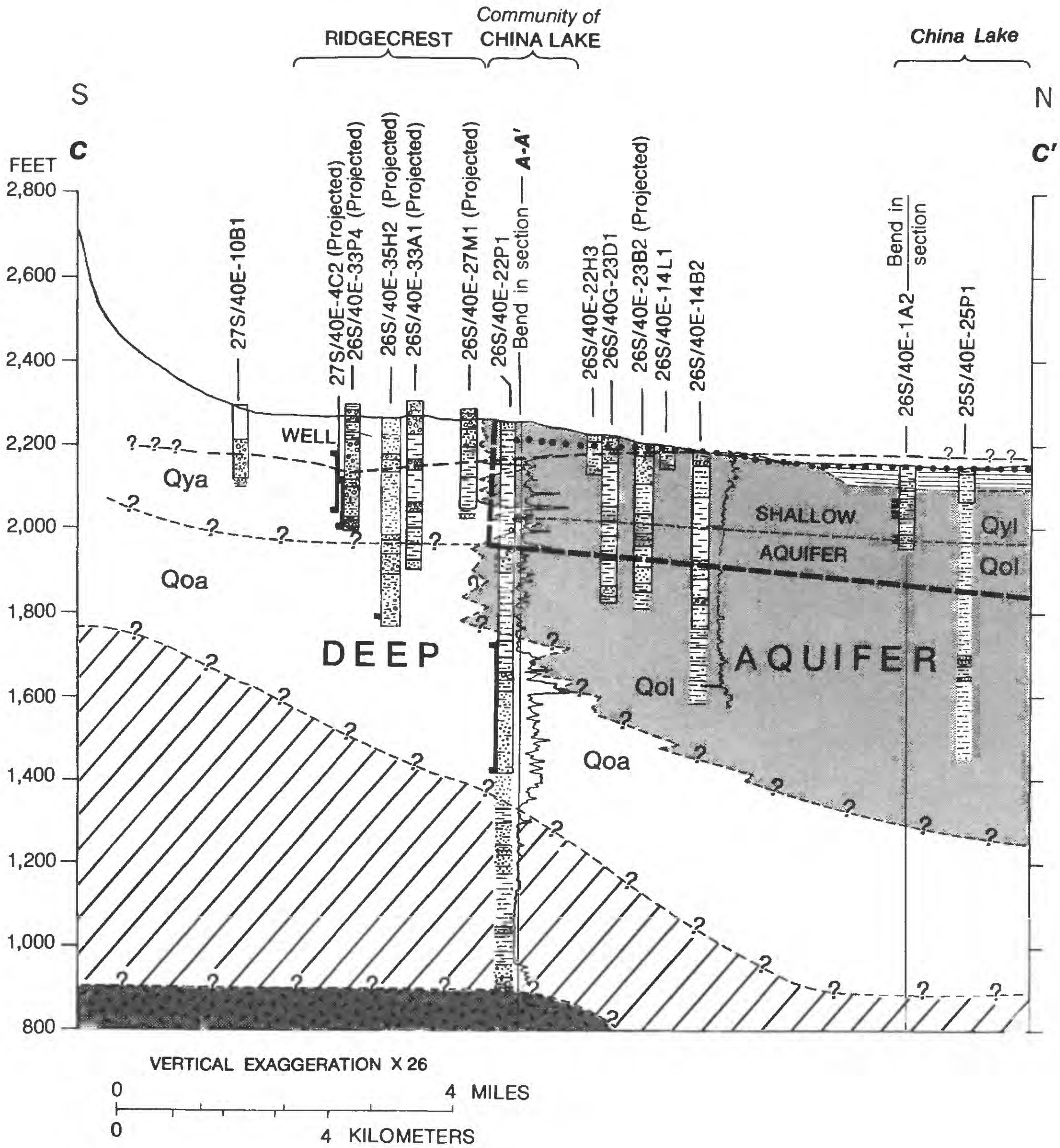


Figure 4. Diagrammatic geologic sections of the Indian Wells Valley ground-water basin--Continued.


RIDGECREST
Community of
CHINA LAKE
China Lake
S
N
C
C'
FEET
2,800
2,600
2,400
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
27S/40E-10B1
27S/40E-4C2 (Projected)
26S/40E-33P4 (Projected)
26S/40E-35H2 (Projected)
26S/40E-33A1 (Projected)
26S/40E-27M1 (Projected)
26S/40E-22P1
Bend in section
A-A'
26S/40E-22H3
26S/40G-23D1
26S/40E-23B2 (Projected)
26S/40E-14L1
26S/40E-14B2
Bend in section
26S/40E-1A2
25S/40E-25P1
WELL
Qya
Qoa
DEEP
SHALLOW
AQUIFER
Qyl
Qol
AQUIFER
Qol
Qoa
VERTICAL EXAGGERATION X 26
0
4 MILES
0
4 KILOMETERS

an evapotranspiration rate of about 0.25 ft/yr (Kunkel and Chase, 1969, p. 67); whereas, the linear relation predicts an evapotranspiration rate of about 2 ft/yr (Lee, 1912, p. 413).

In addition to revising Lee's (1912, p. 422) estimate of evapotranspiration for 1912, Kunkel and Chase (1969, p. 69) estimated the total evapotranspiration for 1953. The total area of evapotranspiration for 1953 was assumed to be the same as in 1912; however, different evapotranspiration rates were assigned to areas according to the measured depth to water in 1953. Total ground-water discharge by evapotranspiration in 1953 was estimated by Kunkel and Chase (1969, p. 66) to be 8,000 acre-ft, about 3,000 acre-ft less than their revised estimate of evapotranspiration for 1912. Kunkel and Chase (1969, p. 66) attributed the decrease in evapotranspiration to an increase since 1912 in ground-water pumpage from the deep aquifer. They suggested that the increased pumpage caused a net decline in water levels in the shallow aquifer near China Lake, thereby reducing evapotranspiration.

Comparison of 1953 water levels with measurements made in 1912 seems to indicate that there was a net water-level decline from 1912 to 1953 in the shallow aquifer near China Lake. The area of greatest apparent water-level decline was in the lake bottom. Kunkel and Chase (1969, p. 69) estimated that a decline of 1.5 feet resulted in a reduction in evapotranspiration from the lake bottom of 2,160 acre-ft/yr. However, the apparent water-level decline might be the result of insufficient water-level measurements in 1912. Lee (1912, p. 421) augered one hole in the southwest corner of the lake bottom. The depth to water in this hole was 4.3 feet below land surface. On the basis of this measurement, Lee (1912, p. 422) estimated that the average depth to water beneath the China Lake bottom was 4.5 feet. In 1953, Kunkel and Chase (1969, p. 65) estimated the depth to water beneath the lake bottom on the basis of water-level measurements at eight wells in the shallow aquifer. The depth to water in the wells ranged from 4.5 to 8.4 feet and averaged 6.0 feet. Thus, the 1953 data indicate a wide range in the depth to water beneath the lake bottom. Therefore, the apparent water-level decline from 1912 to 1953 in the shallow aquifer may be the result of Lee's single lake-bottom measurement not adequately representing the depth to water in the China Lake area and not the result of ground-water pumpage since 1912. In fact, water-level hydrographs of selected wells perforated in the shallow aquifer (fig. 5) show that water levels measured in the 1950's were not significantly different from measurements in 1920. On the basis of these hydrographs, the predevelopment natural ground-water discharge by evapotranspiration probably lies somewhere between Kunkel and Chase's (1969, p. 69) estimates of 11,000 acre-ft/yr for 1912 and 8,000 acre-ft/yr for 1953.

Bloyd and Robson (1971, p. 12) used the 1912 and 1953 estimates of average annual evapotranspiration by Kunkel and Chase (1969, p. 69) as initial estimates of natural recharge and discharge for the model that they developed. In calibrating the model, Bloyd and Robson determined the natural recharge and discharge to be 9,850 acre-ft/yr. Bloyd and Robson distributed all the recharge along the front of the mountains surrounding the valley. This recharge then was distributed to the different stream-drainage areas in the mountains on the basis of drainage area above the 4,500-foot altitude in the Sierra Nevada and above the 5,000-foot altitude in the Coso and Argus Ranges. However, during model calibration, this distribution resulted in too much recharge from the Coso and Argus Ranges and not enough from the Sierra Nevada. A trial-and-error process then was used to distribute recharge until model-computed water levels matched measured water levels. As a result of this process, Bloyd and Robson (1971, p. 13) determined that about 64 percent (6,280 acre-ft/yr) of the recharge originates from the Sierra Nevada on the west side of the valley, about 32

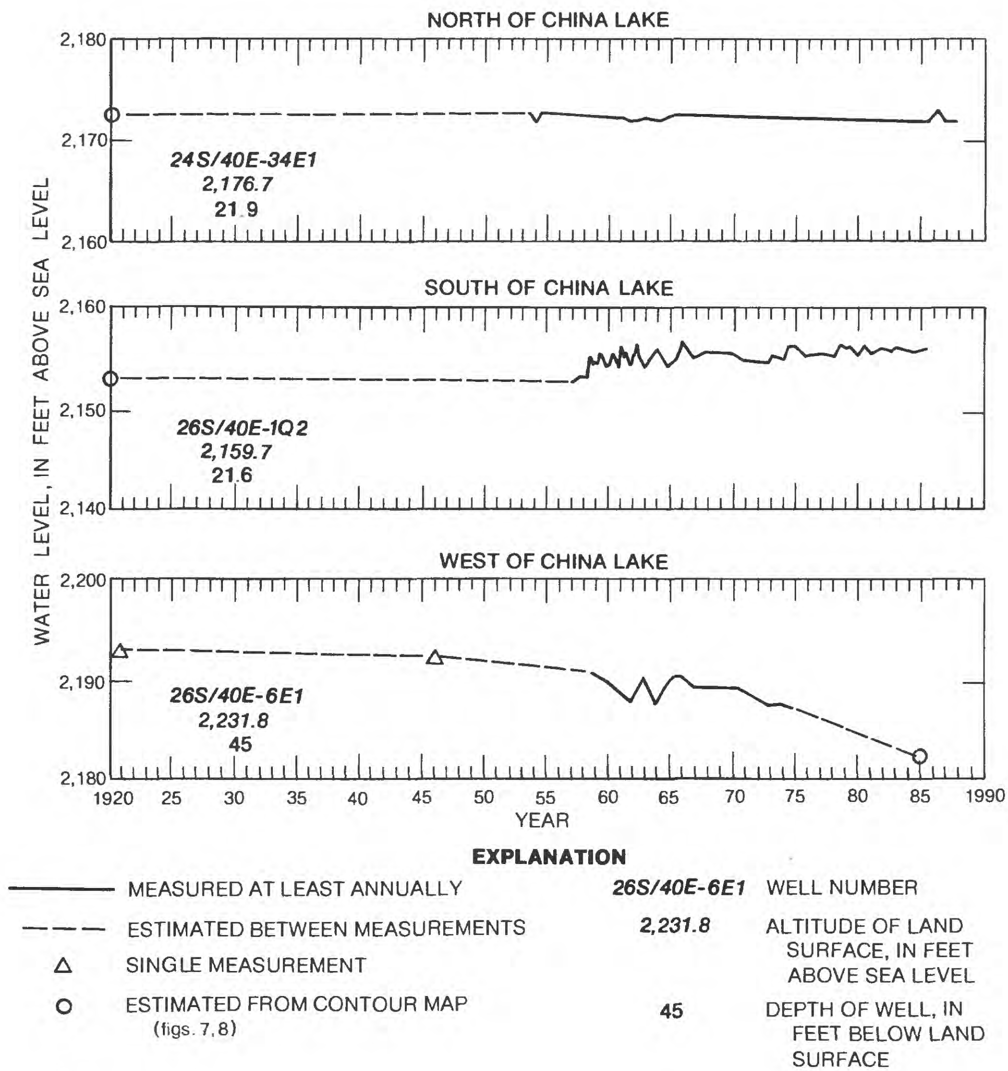


Figure 5. Hydrographs of three wells in the shallow aquifer, 1920-85.

percent (3,170 acre-ft/yr) originates in the Coso and Argus Ranges on the north and northeast sides of the valley, and about 4 percent (400 acre-ft/yr) originates in the El Paso Mountains on the south side of the valley.

Ground-Water Development

Ground water is pumped in Indian Wells Valley for military, industrial, municipal and domestic, and agricultural-irrigation supplies. The quantities and distribution of pumpage prior to 1920 are unknown. The annual distribution of the various pumpages for 1920-85 is shown graphically in figure 6. Military, industrial, and municipal pumpages are metered supplies; domestic and agricultural-irrigation pumpages are estimated. Prior to the location of NWC at China Lake in 1944, pumpage for agricultural irrigation was the main use of ground water; from 1944 to 1978, pumpage for NWC (military pumpage) and pumpage for municipal supplies were the main uses of ground water; and since 1979, agricultural-irrigation, military, and municipal pumpages have been the main uses of ground water (fig. 6).

Irrigation pumpage prior to 1977 is based on estimates by previous investigators of consumptive use of the crops grown in the valley. From 1920 to 1951, irrigation pumpage is estimated to

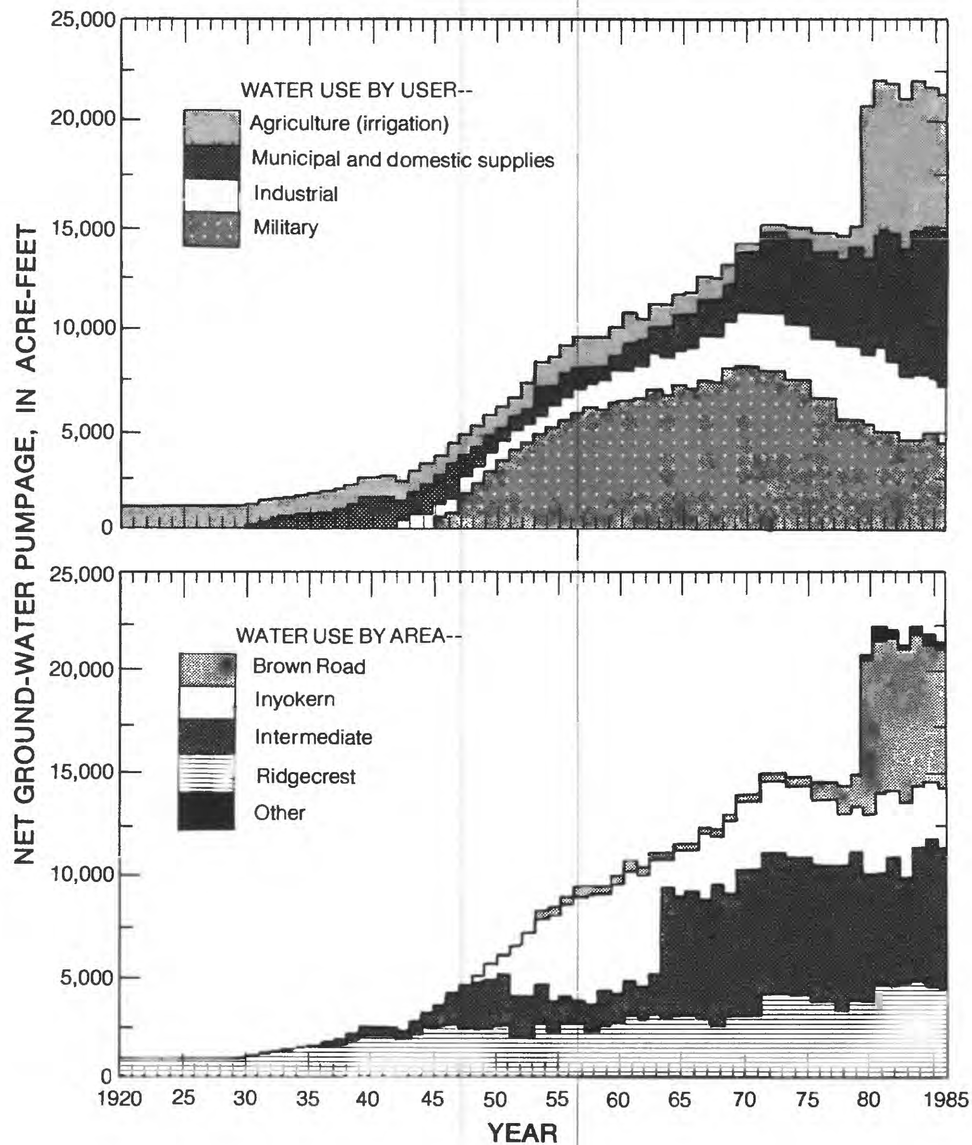


Figure 6. Components of annual net pumpage from the Indian Wells Valley ground-water basin, 1920-85.

have averaged 1,000 acre-ft/yr on the basis of reports by Thompson (1929, p. 166), Bailey (1946, p. 45), Wilcox and others (1951, p. 9), and Dutcher and Moyle (1973, p. 79). During this period, most of the irrigation pumpage was along Bowman Road in the southeastern part of the valley (fig. 2). From 1952 to 1968, the irrigation pumpage along Bowman Road probably continued at about 1,000 acre-ft/yr; and additional irrigation pumpage, ranging from 350 to 490 acre-ft/yr (Bloyd and Robson, 1971, p. 20), occurred, mostly along Brown Road, in the northwestern part of the valley. In 1969, irrigation pumpage along Bowman Road ceased (Pierre St.-Amand, China Lake Naval Weapons Center, oral commun., 1986), and most of the estimated 300 to 800 acre-ft/yr of pumpage from 1969 to 1976 occurred along Brown Road (Mallory, 1979, p. 16).

Irrigation pumpage from 1977 to 1985 was estimated for this study by multiplying the consumptive use of crops by the irrigated acreage. Consumptive-use values used in this study are given in table 1. Irrigated crop acreage was estimated from a field survey made in 1985 (fig. 2) and from aerial photographs and reports from farmers for undocumented years. The 1985 field survey indicated that total irrigated acreage was about 1,760 acres; about 96 percent of this acreage consisted of alfalfa (table 1). Almost all the pumping for irrigation was along Brown Road in the northwestern part of the valley (fig. 2).

Most of the ground water pumped for municipal and military supplies returns to wastewater-treatment plants in the valley. The wastewater-treatment plants rely primarily on evaporation from shallow ponds for the disposal of the wastewater. NWC has discharged its wastewater to the Ridgecrest Regional Wastewater Treatment Facility (formerly the NWC Wastewater Treatment plant) (fig. 2) since 1953. The city of Ridgecrest discharged its wastewater to the Ridgecrest Sanitation District Treatment Plant (fig. 2) from the mid-1950's until 1975. Since 1976, the city of Ridgecrest has diverted all its wastewater to the Ridgecrest Regional Wastewater Treatment Facility. The town of Inyokern has discharged its wastewater to the Inyokern Community Services District Plant (fig. 2) since the early 1970's.

Table 1. *Pumpage estimates for crops grown in Indian Wells Valley, 1985*

[Number of acres irrigated is based on a 1985 field survey of Indian Wells Valley. Crop consumptive-use data from Israelsen and Hansen (1962). Acre-ft/yr, acre-feet per year]

Crop	Number of acres irrigated	Crop consumptive use (acre-ft/yr)	Estimated pumpage (acre-ft/yr)
Alfalfa	1,686	4.0	6,744
Apricots and other fruits	7	2.1	99
Pistachios	23	1.75	40
Grapes	2	3.0	6

Most of the wastewater discharge to the treatment plants is evaporated; some of the wastewater, however, recharges the underlying ground water. Ground-water recharge from the treatment plants is calculated as the difference between wastewater entering the different plants and the potential evaporation from the sewage ponds at the plants. The potential evaporation from the ponds is estimated by multiplying the area of the ponds by the potential evaporation rate of 80 in/yr reported by Farnsworth and others (1982) for ponded water in the valley (see Supplemental Data A). At the Ridgecrest Regional Wastewater Treatment Facility, water is diverted from the ponds for watering the NWC golf course (Supplemental Data A). Also, wastewater at the Ridgecrest Sanitation District Treatment plant is diverted from the ponds for watering nearby alfalfa fields. None of the wastewater diverted from the ponds for watering the golf course and agricultural fields recharges the ground water (Warner, 1975, p. 17).

Although most of the water that is pumped for municipal and military supplies is discharged at wastewater-treatment plants, some of the water is used for lawn and shrubbery watering. Most of the water used for watering is lost to evapotranspiration; however, Warner (1975, p. 14) noted the existence in the shallow aquifer of a recharge mound centered near sec. 22, T. 26 S., R. 40 E. Warner believed that the mound was the result of recharge from shrubbery watering and leakage from water and sewer lines. Water levels in this area have risen about 20 feet from the 1950's to 1985. For the purposes of this report, this recharge is referred to as shrubbery-irrigation recharge. The amount of recharge resulting from shrubbery watering is not known precisely; but, on the basis of water-level changes from 1920 to 1985 and a specific yield of 10 percent, shrubbery-irrigation recharge probably averaged about 90 acre-ft/yr during 1950-85.

Ground-Water Movement

Prior to ground-water development in the valley, ground water moved through the deep aquifer from areas of recharge along the margins of the valley toward China Lake and into the shallow aquifer (Warner, 1975, p. 12). Water-level contours for the shallow and deep aquifers (fig. 7) constructed from water-level measurements made in 1920 and 1921 (Supplemental Data B) are considered representative of predevelopment conditions in the valley. The water-level contours (fig. 7) indicate that water in the deep aquifer discharged into the shallow aquifer. Thus, ground-water discharge from the deep aquifer was virtually the only source of recharge to the shallow aquifer and was the only significant discharge from the deep aquifer. Ground water was discharged from the shallow aquifer by evapotranspiration from the areas in and around China Lake.

Ground-water development since the 1920's has modified the direction of ground-water movement in both the shallow and deep aquifers. From 1920 to 1985, ground-water pumpage, predominantly from the deep aquifer, increased from about 1,000 to more than 22,000 acre-ft/yr (fig. 6). To show the effect of ground-water development in the valley, water-level contours for both the shallow and deep aquifers (fig. 8) were constructed from water-level measurements (Supplemental Data C) made primarily during spring 1985.

The spring 1985 water-level contours of the shallow aquifer (fig. 8) do not show any depressions in the water table related to pumpage. In fact, the water-level contours for spring 1985 are almost the same as the 1920-21 contours. The only significant difference is the presence of a shrubbery-irrigation recharge mound (described in the preceding section) near the community of China Lake.

For the deep aquifer, however, comparison of the water-level contours for 1920-21 with those for spring 1985 (figs. 7 and 8) indicates that pumpage from the deep aquifer has caused a distinct cone of depression in the intermediate area west of Ridgecrest. Pumping from 1920 to 1985 has caused water levels in the deep aquifer to decline more than 80 feet in the center of the depression and has caused a reversal of the direction of ground-water movement in the deep aquifer in the area north and east of Ridgecrest (fig. 8). Ground water of poor quality (dissolved-solids concentration greater than 1,000 mg/L) (table 2) underlies China Lake in both the shallow and deep aquifers to the north of the depression and Mirror and Satellite Lakes in the deep aquifer to the east of the depression. Therefore, the spring 1985 ground-water flow pattern (fig. 8) suggests that

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EXPLANATION FOR FIGURE 7

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

WATER-LEVEL CONTOUR--Shows altitude of water level. Dashed where approximately located. Queried where doubtful. Contour interval 10 feet. Datum is sea level

2150—?— Shallow aquifer

2200—?— Deep aquifer

DIRECTION OF GROUND-WATER MOVEMENT--

→ Shallow aquifer

→ Deep aquifer

WELL AND SITE NUMBER--(See data table B)

○66 Shallow aquifer

●102 Deep aquifer

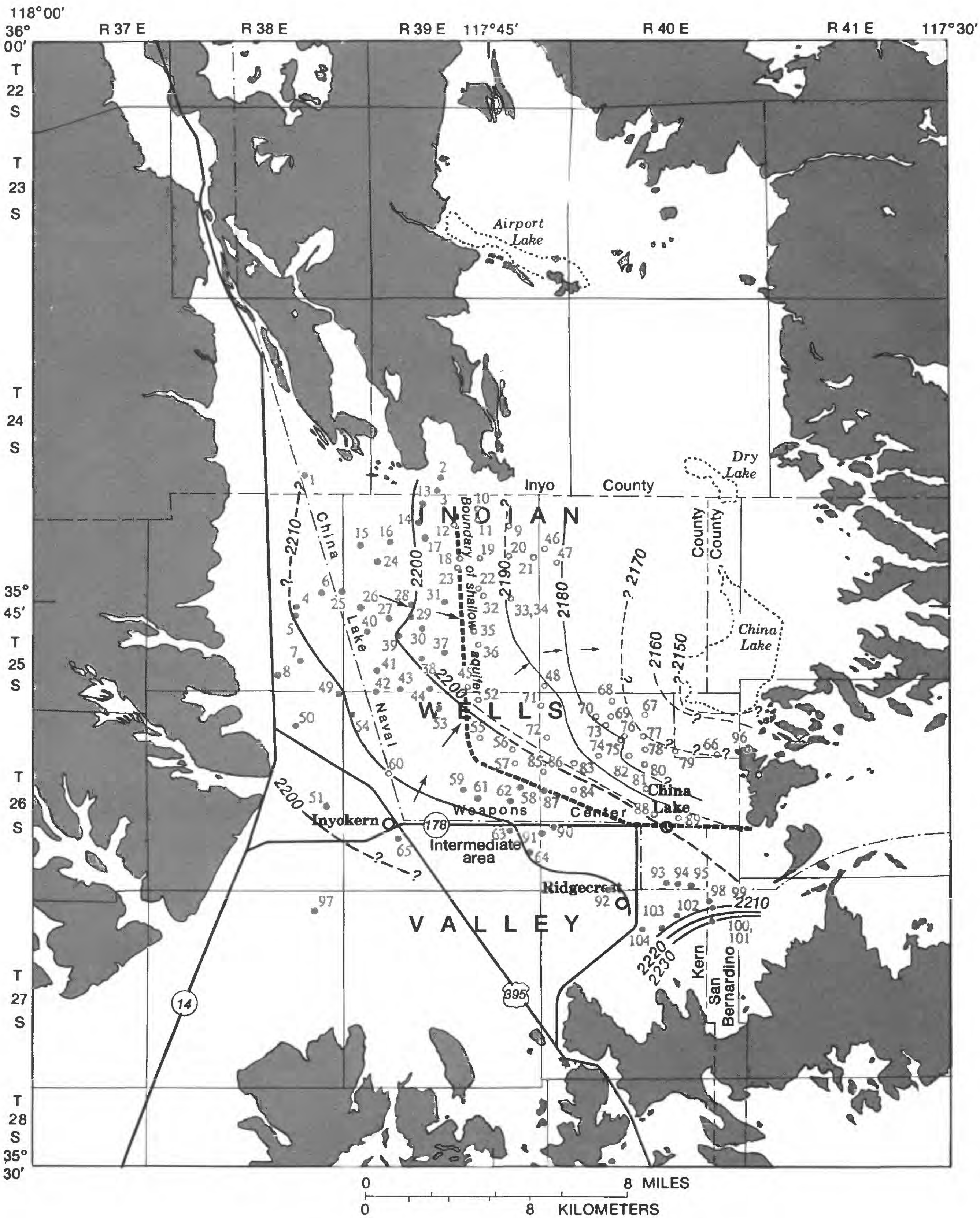


Figure 7. Water-level contours and direction of ground-water movement in the shallow and deep aquifers, 1920-21.

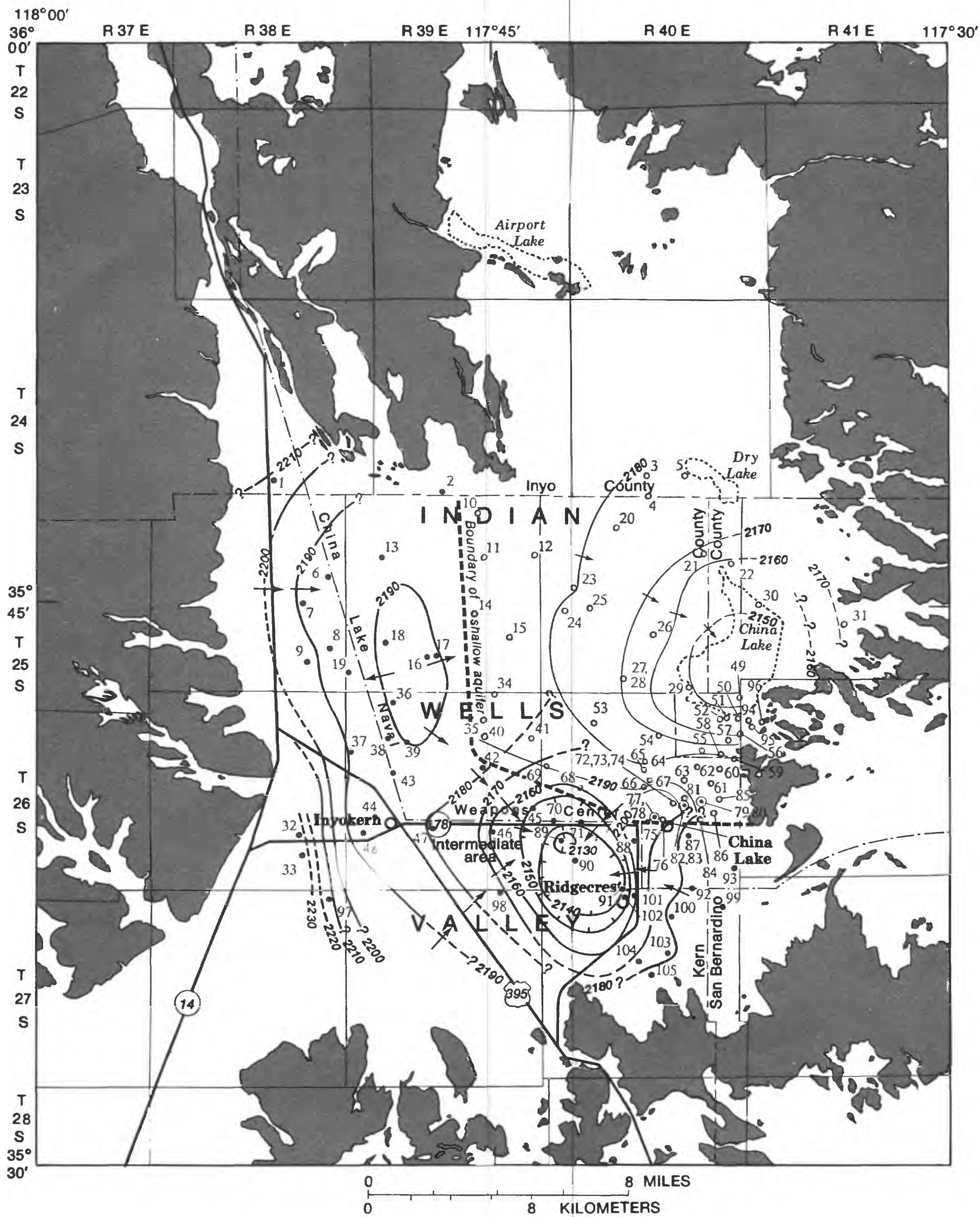


Figure 8. Water-level contours and direction of ground-water movement in the shallow and deep aquifers, spring 1985.

the deep aquifer is subject to quality degradation west of China Lake in the areas of greatest pumpage. Available data (fig. 9) from wells in the Ridgecrest area indicate that the dissolved-solids concentration of ground water has increased significantly in some wells.

The Indian Wells Valley area is an intensely faulted structural depression. Geologic and geophysical data indicate that several major faults exist within the valley (figs. 3 and 4). Previous investigators (Bloyd and Robson, 1971; Dutcher and Moyle, 1973) believed that many of these faults were barriers to ground-water movement because water-level differences were observed across the faults. Data collected during this study, however, did not indicate the presence of abnormal water-level differences across any of the faults in the valley. Water-level differences observed by previous investigators may have been the result of inaccurate land-surface datums or the result of comparing water levels in wells perforated at different depths. For the purposes of this study, none of the faults within the valley were considered to be barriers to ground-water movement.

EXPLANATION FOR FIGURE 8

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

WATER-LEVEL CONTOUR--Shows altitude of water level, spring 1985. Dashed where approximately located. Queried where doubtful. Contour interval 10 feet. Datum is sea level

2220 ? Shallow aquifer

2190 ? Deep aquifer

DIRECTION OF GROUND-WATER MOVEMENT--

Shallow aquifer

Deep aquifer

WELL AND SITE NUMBER--(See data table C)

95 Shallow aquifer

93 Deep aquifer

In addition to fault-related barriers, most previous investigators mapped ground-water barriers not related to fault zones. Most of these mapped barriers are located at the contact between permeable coarse alluvial deposits and less-permeable fine lacustrine deposits. The most commonly mapped barrier is the "China Lake barrier" south of China Lake (Warner, 1975, p. 13). Although ground-water movement is affected by the transition from permeable to less-permeable deposits, this transition is properly mapped as an areal change in lithology rather than as a barrier. For the purposes of this report, the term "barrier" is not used to describe the transition from permeable to less-permeable deposits.

Conceptualization of the Ground-Water System

As described in the preceding sections of this report, the ground-water system is a thick reservoir of unconsolidated deposits bounded on its sides and bottom by consolidated rocks (fig. 10*A*). Water-bearing properties of the unconsolidated deposits vary from place to place. Generally, the most productive deposits are along the southwestern and western parts of the valley. Deposits in the eastern part of the valley are predominantly finer materials and are much less productive. Water in the unconsolidated deposits is present under both confined and unconfined conditions. Water is unconfined at and near the upper surface of saturation (the water table). Interbedded silt and clay in the central and eastern parts of the valley causes considerable confinement of water in the deeper unconsolidated deposits, and water levels in wells in this area vary with depth of the well's perforated interval.

The ground-water reservoir underlying Indian Wells Valley functions as a three-dimensional system. Generally, water flows from recharge areas near the margins of the valley toward the areas in and around China Lake, where it leaves the system as evapotranspiration. There

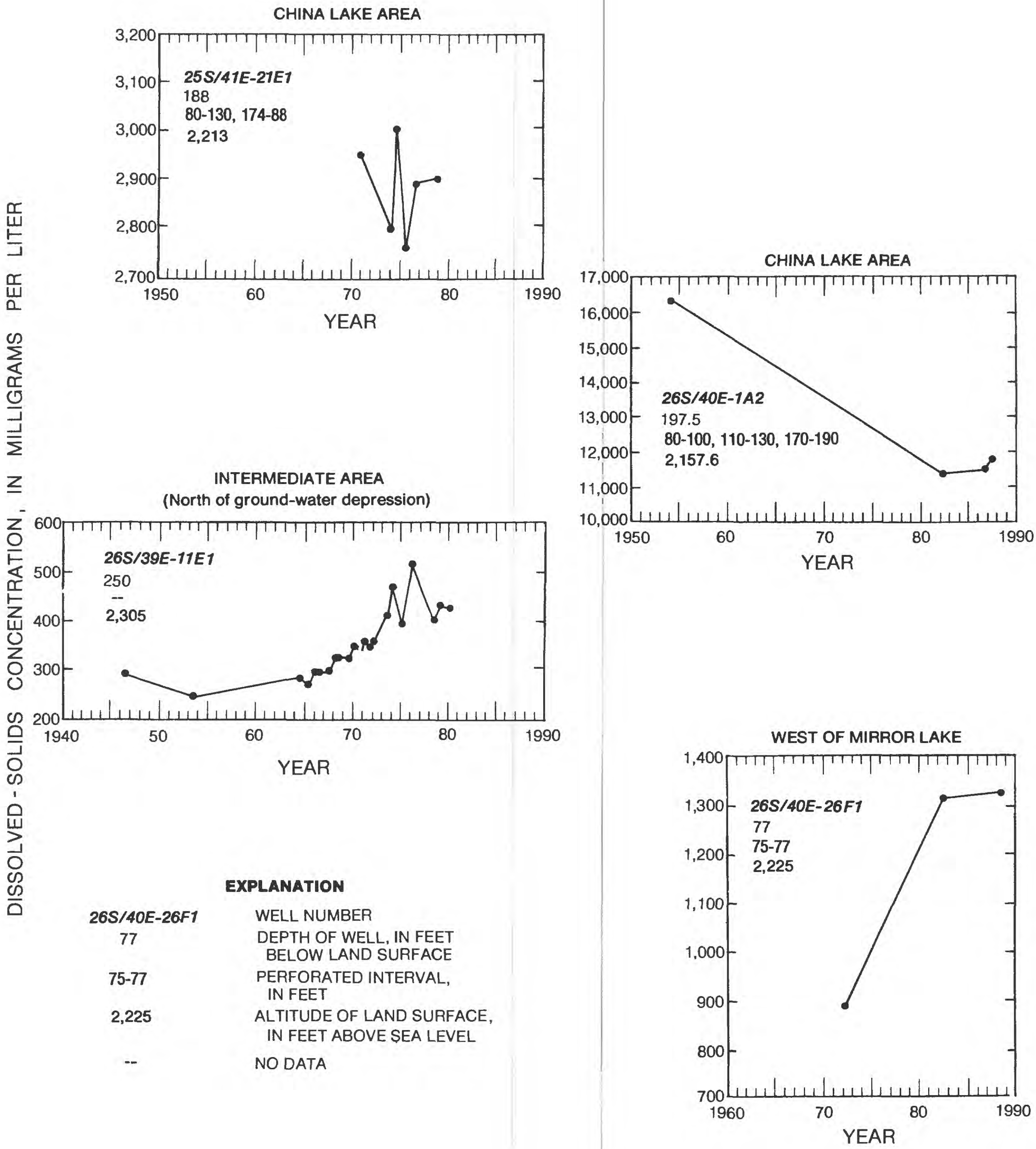


Figure 9. Dissolved-solids concentration at selected wells in Indian Wells Valley.

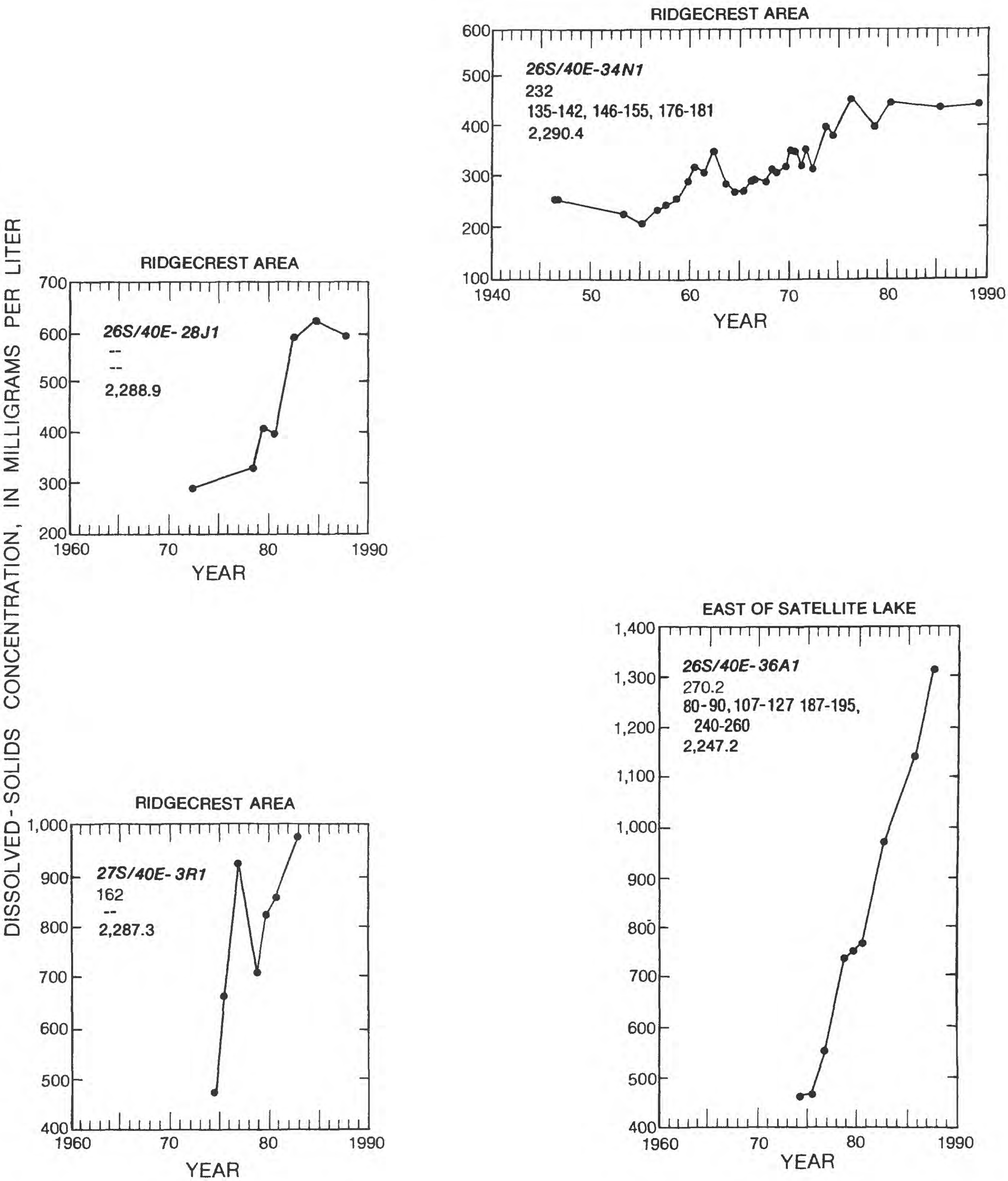

DISSOLVED-SOLIDS CONCENTRATION, IN MILLIGRAMS PER LITER
RIDGECREST AREA
26S/40E-34N1
232
135-142, 146-155, 176-181
2,290.4
600
500
400
300
200
100
1940
50
60
70
80
1990
YEAR
RIDGECREST AREA
26S/40E-28J1
--
--
2,288.9
700
600
500
400
300
200
1960
70
80
1990
YEAR
EAST OF SATELLITE LAKE
26S/40E-36A1
270.2
80-90, 107-127 187-195,
240-260
2,247.2
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
1960
70
80
1990
YEAR
RIDGECREST AREA
27S/40E-3R1
162
--
2,287.3
1,000
900
800
700
600
500
400
1960
70
80
1990
YEAR

Table 2. *Dissolved-solids concentration in samples from selected wells in eastern Indian Wells Valley*

[Altitude of land surface in feet above sea level. Depth of well and perforated interval in feet below land surface. --, no data; mg/L, milligrams per liter]

Location	Well No.	Altitude of land surface	Depth of well	Perforated interval	Date	Dissolved-solids concentration (mg/L)	Monitored aquifer
North of ground-water depression	26S/39E-13R3	2,318	300	130-170, 200-220, 240-260	5/30/87	223	Deep
North of ground-water depression	13R4	2,318	800	640-800	1/18/89	826	Deep
China Lake	26S/40E-1A2	2,157.6	197.5	80-100, 110-130, 170-190	9/17/86	11,400	Shallow
West of China Lake	6C1	2,195	620	500-600	5/30/87	60,700	Deep
West of China Lake	6D1	2,216	320	276-300	5/30/87	9,050	Deep
West of China Lake	6D2	2,216	260	120-200	5/30/87	8,710	Shallow
South of China Lake	11J1	2,173.9	18.3	--	6/11/85	9,670	Shallow
South of China Lake	15N2	2,234.8	101	99-101	6/11/85	2,890	Shallow
South of China Lake	23B2	2,210	360	300-340	5/27/87	1,190	Deep
South of China Lake	23B3	2,210	240	180-220	5/27/87	1,240	Shallow
South of China Lake	23D1	2,223	400	385-400	5/26/87	2,090	Deep
South of China Lake	23D2	2,223	185	170-185	5/26/87	5,420	Shallow
Community of China Lake	22P1	2,258.7	830	530-830	5/27/87	1,070	Deep
Community of China Lake	22P2	2,262.8	75	73-75	6/10/86	1,240	Shallow
Community of China Lake	22P3	2,260	425	400-425	5/26/87	1,230	Deep
Community of China Lake	22P4	2,260	215	200-215	5/26/87	1,890	Shallow
Community of China Lake	23G1	2,213.04	57	55-57	6/11/85	6,750	Shallow
East of Mirror Lake	25C2	2,255	160	20-40, 60-80	5/28/87	956	Deep
West of Mirror Lake	26F1	2,225	77	75-77	7/08/88	1,320	Deep
West of Satellite Lake	35H1	2,243	160	55-70, 110-130	5/28/87	662	Deep
West of Satellite Lake	35H2	2,243	500	360-500	7/08/88	285	Deep
West of Satellite Lake	35Q2	2,251.47	127	125-127	1/19/89	894	Deep
Ridgecrest	28J1	2,288.9	--	--	9/17/87	[1]595	Deep
Ridgecrest	33P4	2,300	304	169-182, 198-216, 233-252, 256-272, 275-290	5/28/87	343	Deep
Ridgecrest	34N1	2,290.4	232	135-142, 146-155, 176-181	1/18/89	442	Deep
Ridgecrest	27S/40E-4B2	2,998	288	128-278	5/29/87	717	Deep
South Ridgecrest	8Q2	2,430	367	--	6/02/87	645	Deep
Southeast of Ridgecrest	2G3	2,258	--	--	7/08/88	1,350	Deep
Southeast of Ridgecrest	2J1	2,300	220	--	6/01/87	1,130	Deep

[1]Water-quality analysis furnished by Ridgecrest Hospital.

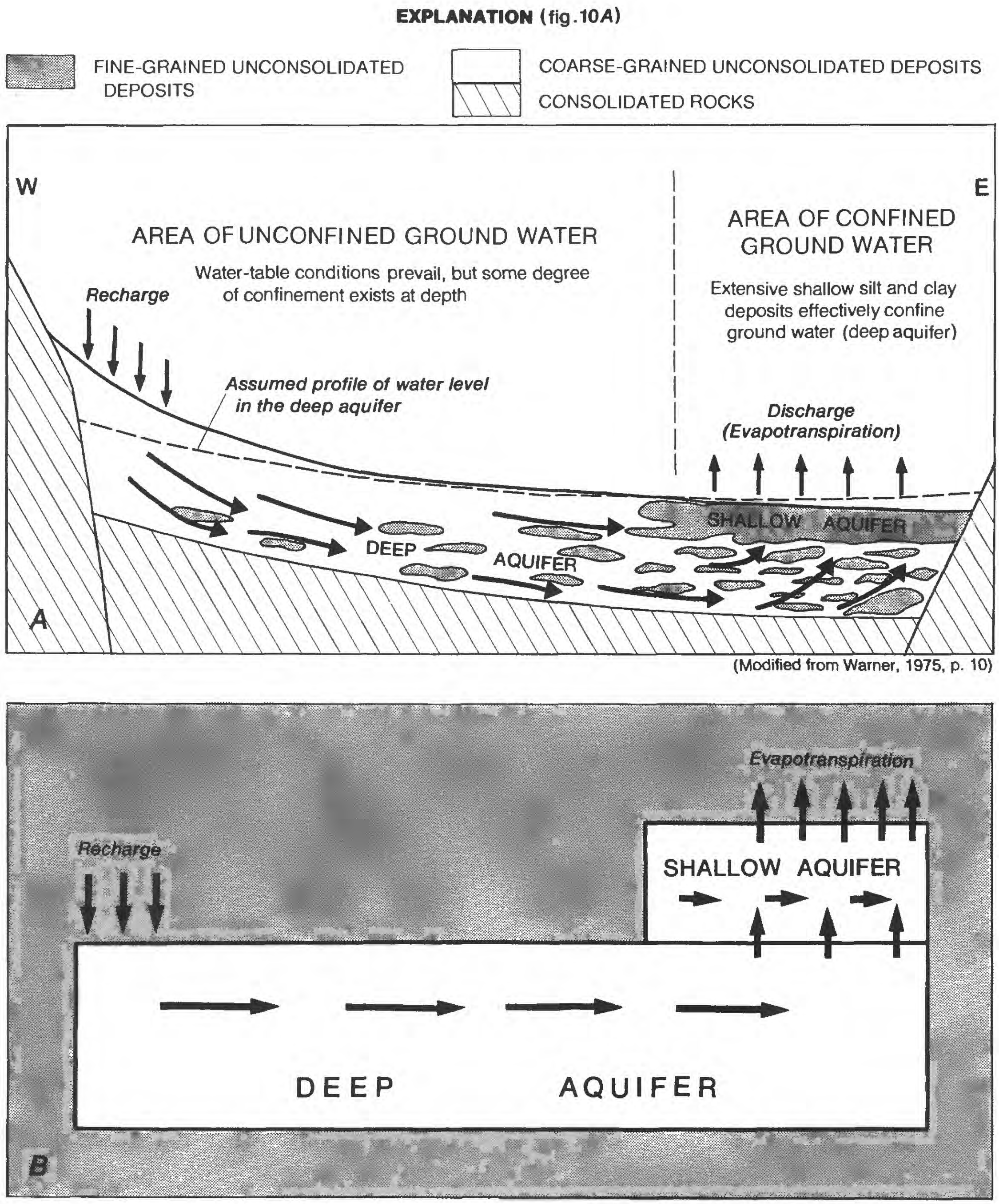


Figure 10. Conceptualization of the ground-water flow system in Indian Wells Valley. Arrows show direction of ground-water movement. *A*, Annotated diagrammatic section. *B*, Idealized ground-water movement.

is a downward vertical component of movement in the recharge areas and an upward vertical component of movement in the discharge areas (fig. 10*B*). Consequently, head varies both areally and with depth, and a multiple-layer concept is required to give a reasonable representation of the system.

In this study, the ground-water system in Indian Wells Valley was treated as a two-layer system that consists of a shallow aquifer and a deep aquifer. The shallow aquifer is unconfined. Water levels in wells that tap the shallow aquifer are at the approximate level of the water table. The shallow aquifer in the eastern part of the valley is assumed to be generally the zone that extends from land surface to an altitude ranging from 1,850 to 1,950 feet about sea level. The deep aquifer extends to the margins of the valley and represents the part of the unconsolidated deposits most affected by pumping. The deep aquifer in most places also approximates the water table; in the eastern part of the valley, however, the deep aquifer is confined by the silt and clay lenses of the lacustrine and playa deposits. The deep aquifer consists of unconsolidated deposits that overlie and are bounded by the consolidated deposits. This conceptualization of the ground-water system in Indian Wells Valley is illustrated in figure 10.

DEVELOPMENT AND CALIBRATION OF A THREE-DIMENSIONAL GROUND-WATER FLOW MODEL

The objective in constructing a mathematical ground-water flow model of Indian Wells Valley was to develop a better understanding of the aquifer system. A successful model could be used to predict water levels that are based on projected water-use requirements. The model simulates water levels on the basis of: (1) the ability of the aquifer to transmit water (transmissivity) and its capacity to store and release water (storage coefficient), (2) the quantity of water entering the aquifer (recharge), and (3) the quantity of water leaving the aquifer (discharge). Because of the complex geohydrologic relations in the ground-water system, the mathematical model cannot exactly duplicate the actual system. Model development requires the use of assumptions and approximations that simplify the physical system. It cannot be overemphasized that the model is only as accurate as the assumptions and data used in its development.

The mathematical-model code used in this study was developed by McDonald and Harbaugh (1984), and it utilizes the block-centered finite-difference numerical method of solution. A full explanation of the theoretical development, the solution technique used, and the mathematical treatment of each simulated condition is included in McDonald and Harbaugh (1984).

Model Construction

The aquifer system was simulated as two layers. Layer 1 of the model represents the shallow aquifer and layer 2 represents the deep aquifer.

In order to numerically define the aquifer system, it is necessary to: (1) divide the aquifer system into a grid, (2) determine the boundary conditions for the aquifer, (3) estimate the aquifer-property values within the model area, and (4) estimate the rates and distribution of recharge and discharge to the aquifer system.

MODEL GRID

The finite-difference techniques used in the model require that the ground-water system be divided into a grid of rectangular blocks. The model grid consists of 4,524 blocks (including

1,959 active blocks), each of which is 2,640 feet on a side. The finite-difference grid used for layers 1 and 2 is identical and is shown in figure 11. Average values for aquifer properties are assigned to each grid block, and average initial hydraulic head for each block is assigned at the center, or node, of each block.

MODEL BOUNDARIES

All model boundaries (fig. 11) coincide with the aquifer limits defined by geohydrologic interpretations, except in the southwestern part of the valley. The top boundary of layer 1 of the model is the water table. This is simulated as a free-surface boundary that is allowed to move vertically in response to imbalances between inflow and outflow. The lateral boundaries of layer 1 are simulated as no-flow boundaries. A no-flow boundary indicates that no water enters or leaves the system through the boundary. The location of no-flow boundaries of layer 1 (fig. 11) corresponds to zero thickness of layer 1 or to the contact between unconsolidated deposits and the less-permeable consolidated rocks. The top boundary of layer 2 in the unconfined areas near the natural recharge areas, where not overlain by layer 1, also is considered the water table. The lateral and bottom boundaries of layer 2 are simulated as no-flow boundaries. The location of no-flow boundaries of layer 2 (fig. 11) corresponds to the contact between unconsolidated deposits and the less-permeable consolidated rocks, except in the southwestern part of the valley. In this area, the no-flow boundary was placed at a sufficient distance from areas of interest so that the boundary will have little or no effect on model simulations for critical areas.

AQUIFER PROPERTIES

Data on the hydraulic conductivity of layer 1, the transmissivity of layer 2, the storage coefficient of both layers, and the vertical leakage between the layers are required to simulate ground-water flow in the valley. For Indian Wells Valley, these aquifer properties vary considerably because of the nonhomogeneity of the aquifer material. To simulate the variability precisely would require a model the size of the real system itself. The values of the aquifer properties used in the model should be considered average values that are representative of large blocks of the system.

Transmissivity and hydraulic conductivity.-- The transmissivity of layer 1 is calculated by the model and is the product of the hydraulic conductivity and the saturated thickness specified for each model block. The initial distribution of hydraulic conductivity for this model was based on the transmissivity distribution of layer 1 in the model by Bloyd and Robson (1971, p. 10) divided by the steady-state (1920-21) saturated thickness of layer 1. (Bloyd and Robson's transmissivity distribution was based on specific-capacity tests and drillers' logs compiled by Dutcher and Moyle, 1973.) The initial values then were modified during the steady-state calibration of the model until the final distribution of hydraulic conductivity of layer 1 was derived (fig. 12). The saturated thickness of layer 1 is calculated in the model as the difference between the water-level altitude and the bottom altitude of layer 1. The bottom altitude is the bottom of the shallow aquifer and was estimated from geologic and electric logs of several wells that fully penetrate the unit. The bottom altitude of the shallow aquifer ranges from about 1,850 feet above sea level near China Lake to about 1,950 feet along the western boundary of layer 1 (fig. 13).

The initial distribution of transmissivity used in layer 2 of this model was based on the distribution in the model by Bloyd and Robson (1971), which was derived from aquifer tests, specific-capacity tests, and drillers' logs compiled by Dutcher and Moyle (1973, pl. 4) and from additional geohydrologic information

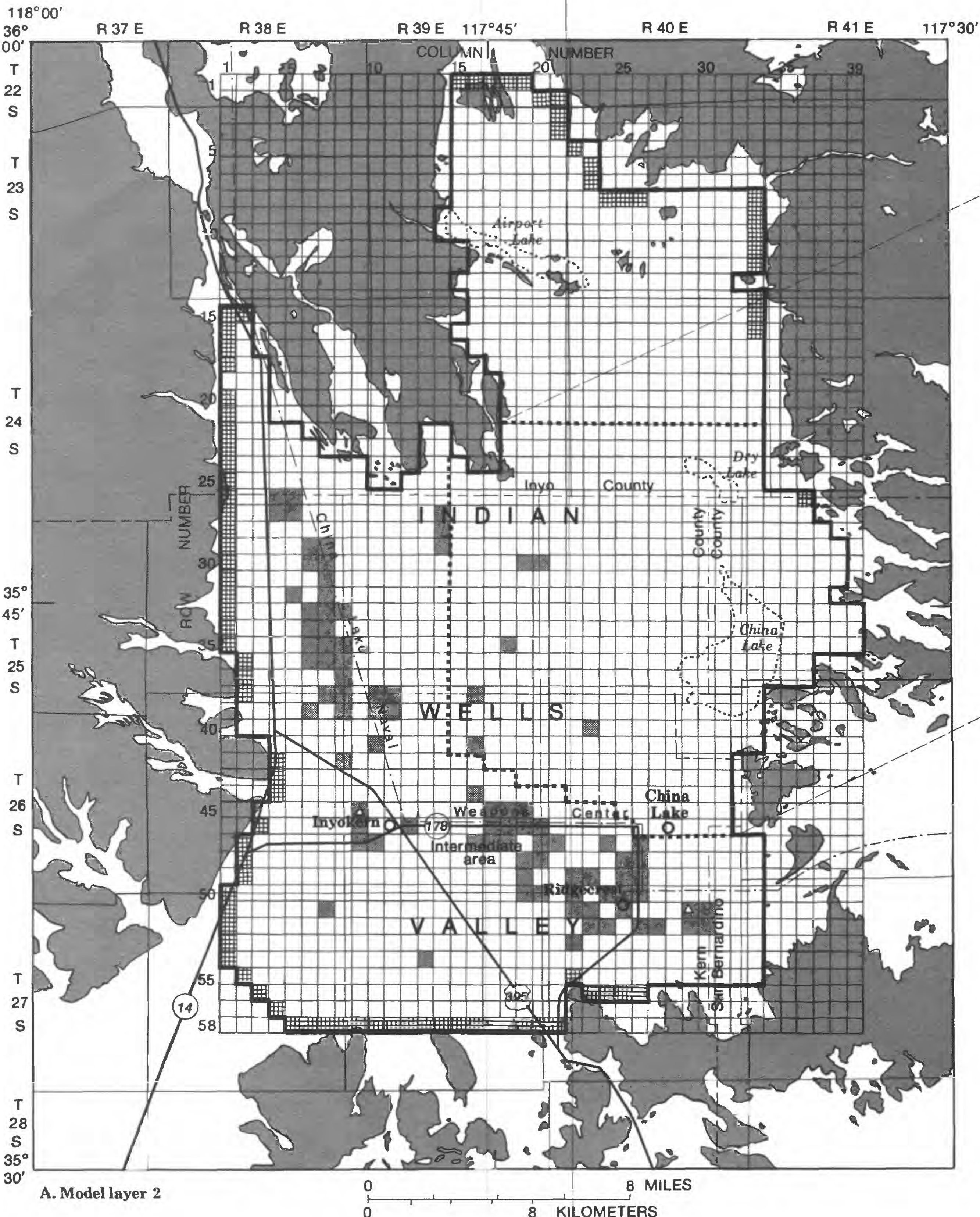
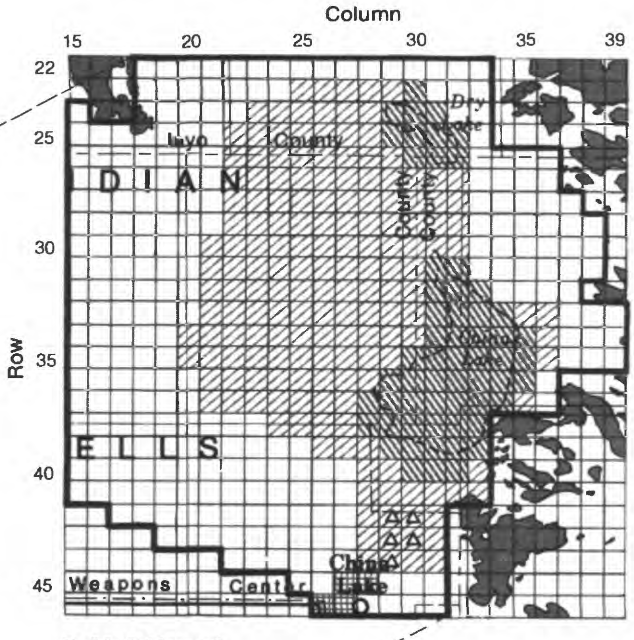


Figure 11. Grid network and areal distribution of recharge and discharge blocks for model layers 1 and 2.



B. Model layer 1

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA--No-flow boundary for layers 1 and 2

BOUNDARY OF MODELED AREA--Projected no-flow boundary for layer 1 in map A

RECHARGE AND DISCHARGE--

Mountain-front recharge (Layer 2)

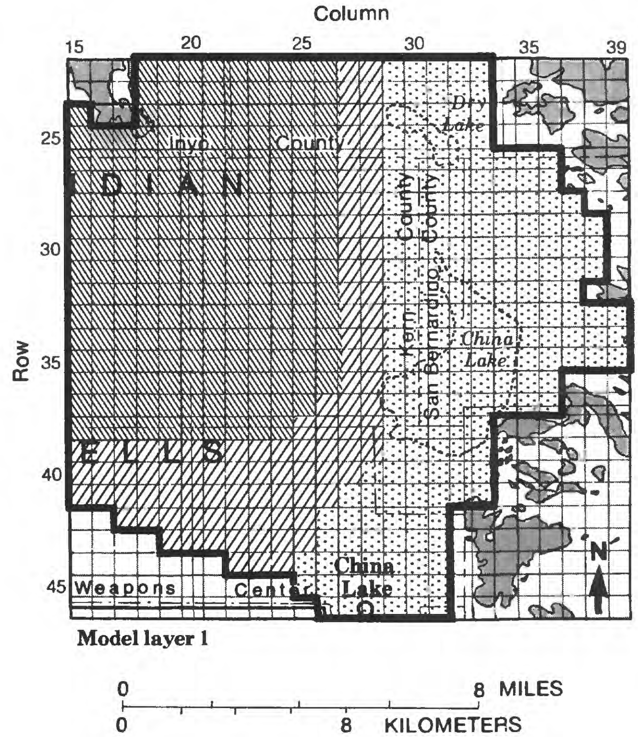
△ Wastewater recharge (Layer 1 and 2)

Shrubbery-irrigation recharge (Layer 1)

Evapotranspiration (Layer 1) of 25-percent plant cover

Evapotranspiration (Layer 1) of bare soil

Ground-water pumpage (Layer 2)



EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

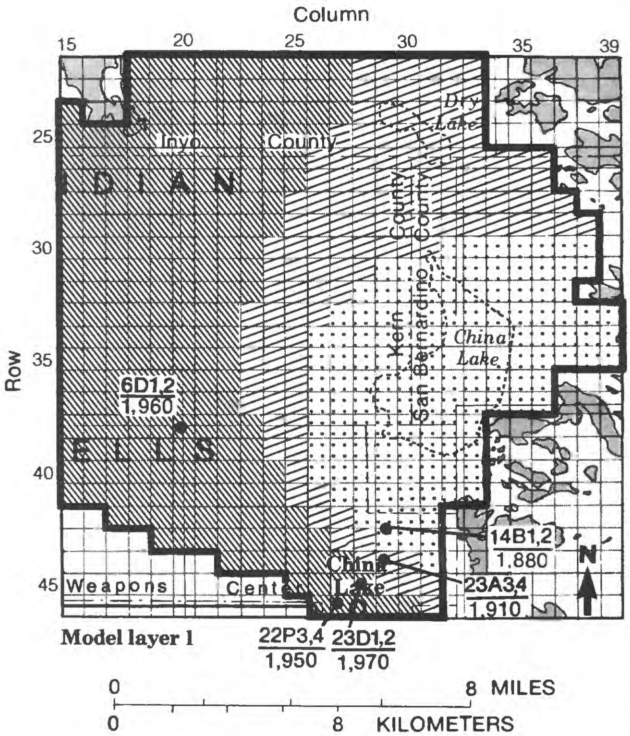
HYDRAULIC CONDUCTIVITY, IN FEET PER DAY

8

1

0.1

Figure 12. Areal distribution of hydraulic conductivity of layer 1, as simulated in the model. (Location of model layer 1 is shown in figure 11.)



EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

22P3,4 ● 1,950 — PAIRED WELLS -- Upper number is well number. Lower number is measured altitude of bottom of layer 1, in feet above sea level

ALTITUDE OF BOTTOM OF LAYER 1, IN FEET ABOVE SEA LEVEL--

1,950

1,900

1,850

Figure 13. Areal distribution of altitude of the bottom of layer 1, as simulated in the model. (Location of model layer 1 is shown in figure 11.)

collected since Dutcher and Moyle's study. Values of transmissivity were modified during the steady-state calibration of the model until the final distribution of transmissivity was derived (fig. 14).

Transmissivity of layer 2 of the model does not change with time. Because transmissivity is a product of the saturated thickness of the aquifer and the hydraulic conductivity, errors would be introduced in the model if water-level changes were a significant percentage of the total saturated thickness of the aquifer. Where layer 2 is unconfined, water-level changes are small compared to the total thickness of the aquifer and are assumed to have little effect on transmissivity.

EXPLANATION FOR FIGURE 14

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

TRANSMISSIVITY, IN FEET SQUARED PER DAY

36,800

30,100

20,050

6,700 -13,400

1,400 - 6,700

Less than 1,400

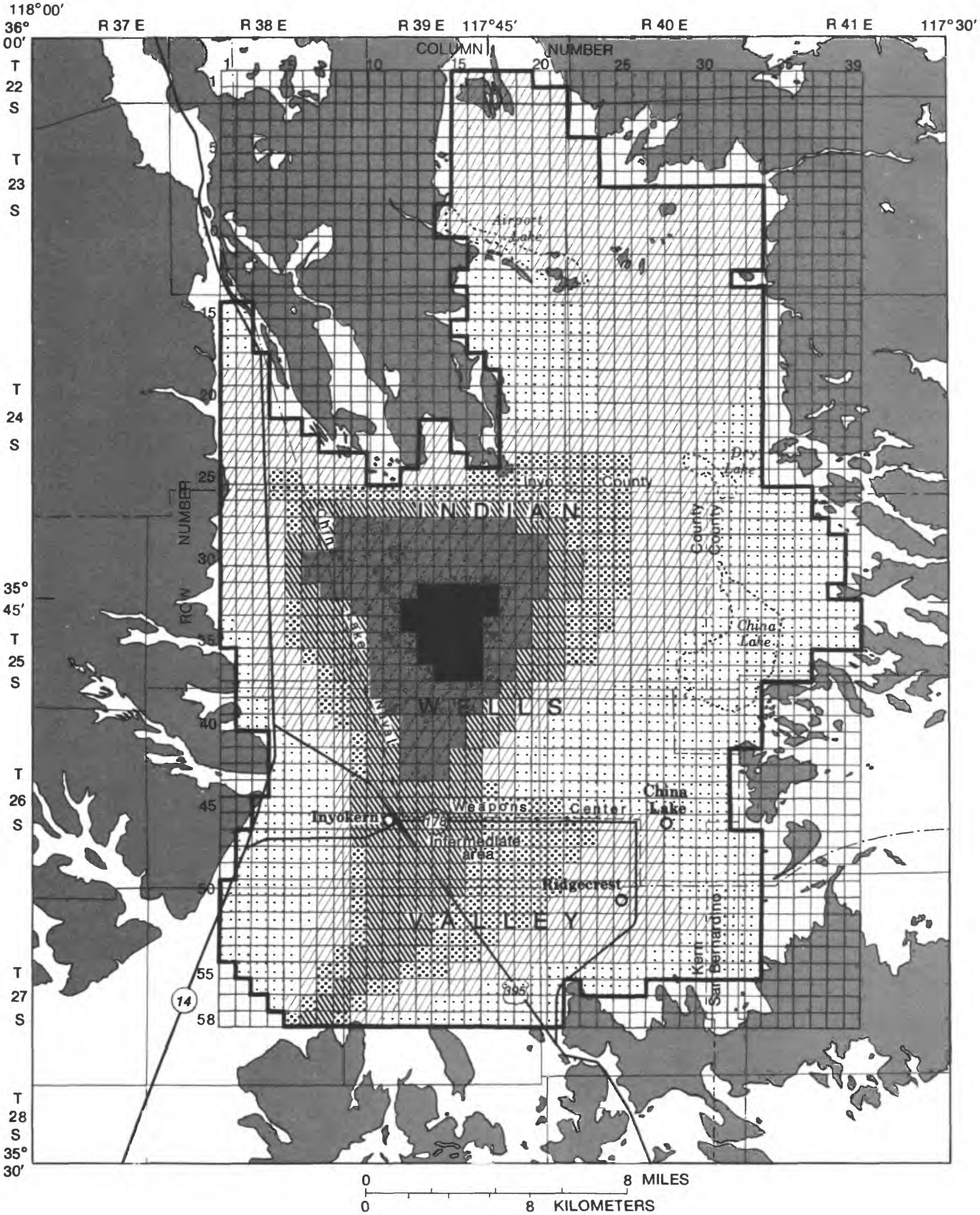


Figure 14. Areal distribution of transmissivity of layer 2, as simulated in the model.

Storage coefficient.--Layer 1 was simulated as unconfined. The average specific yield of the saturated material in the shallow aquifer was estimated by Dutcher and Moyle (1973, p. 19), from inspection of lithologic logs, to be 10 percent. On the basis of this estimate, a uniform storage coefficient of 0.10 (see Dutcher and Moyle, 1973, p. 19) was assumed to be representative of layer 1 and was not modified during model calibration. Transient-state model calibrations were used to estimate storage coefficients for layer 2. The calibration procedure was started by using initial estimates of storage coefficient from Dutcher and Moyle (1973, pl. 4) and additional analysis of lithologic logs. Layer 2 was simulated as unconfined, except in the eastern part of the model area where the deep aquifer is confined by the shallow aquifer (layer 1 of the model). Also, extensive deposits of silt and clay in the intermediate and Ridgecrest areas cause partial confinement of layer 2. The model-calibrated distribution of storage coefficient for layer 2 is shown in figure 15. The storage coefficients used for the model do not change with time.

Leakage between layers.--Vertical leakage of water between layers 1 and 2 occurs whenever there is a difference in hydraulic head between those layers. The rate at which this leakage occurs is described by the equation:

$$Q = \frac{KV}{B}(H2 - H1), \qquad (1)$$

where:

- Q is the vertical leakage, in volume flux per unit area $[LT^{-1}]$,
- KV is the effective value of vertical hydraulic conductivity between nodes $[LT^{-1}]$,
- B is the distance between nodes [L],
- $H1$ is the hydraulic head in layer 1 [L], and
- $H2$ is the hydraulic head in layer 2 [L].

$\frac{KV}{B}$ in the above equation is referred to as the leakance term in this report.

The McDonald and Harbaugh (1984, p. 139) model used for this study requires that the leakance term be entered as input data. Therefore, the leakance term is calculated (fig. 16) outside the model using the following equation:

$$\frac{KV}{B} = \frac{2}{\frac{B1}{KV1} + \frac{B2}{KV2}}, \qquad (2)$$

where:

- $\frac{KV}{B}$ is the leakance between layers $[T^{-1}]$,
- $KV1$ is the vertical hydraulic conductivity of material in layer 1 $[LT^{-1}]$,
- $KV2$ is the vertical hydraulic conductivity of material in layer 2 $[LT^{-1}]$,
- $B1$ is the saturated thickness of layer 1 [L], and
- $B2$ is the saturated thickness of layer 2 [L].

EXPLANATION FOR FIGURE 15

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

STORAGE COEFFICIENT

0.18

0.10

0.01

0.001

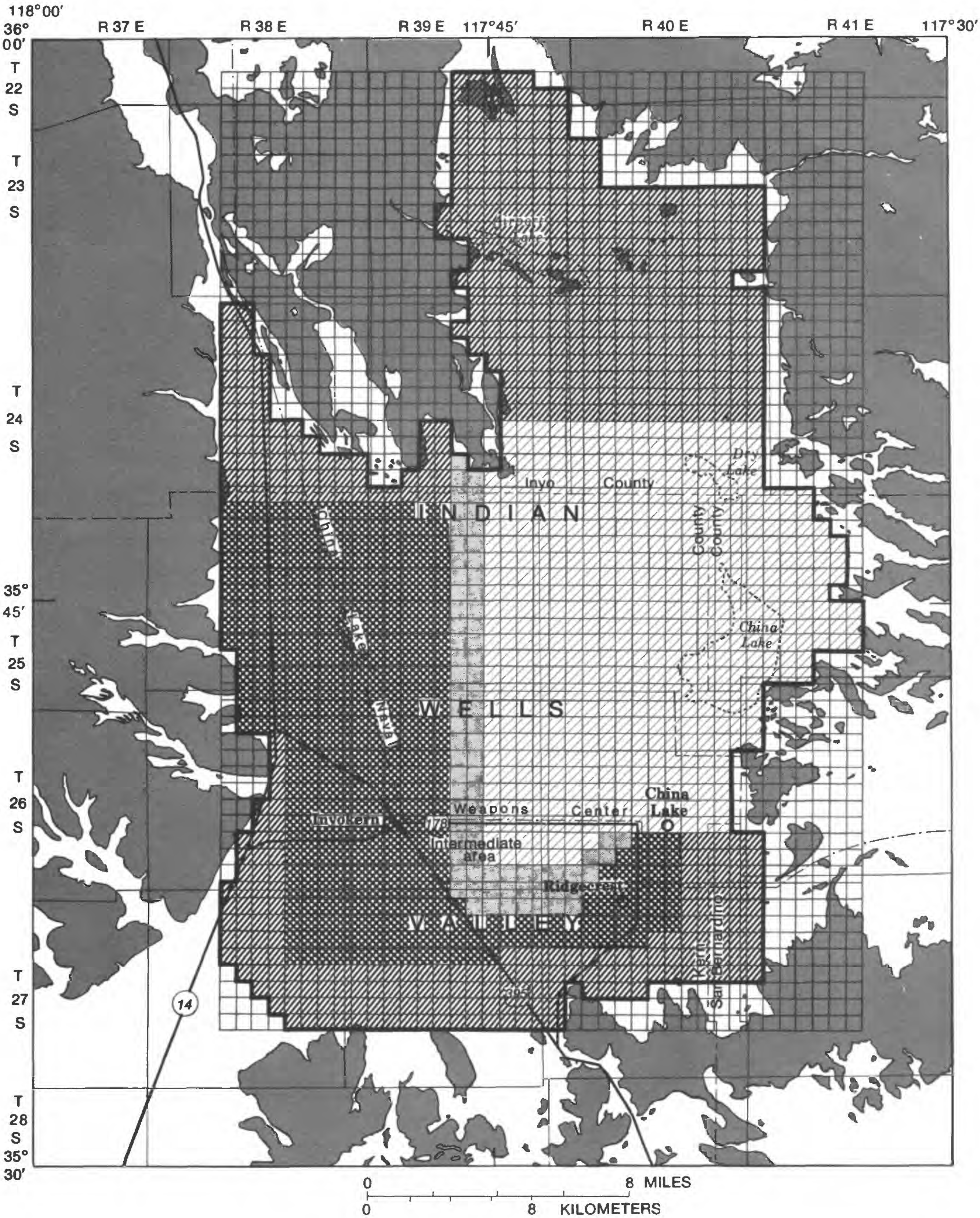
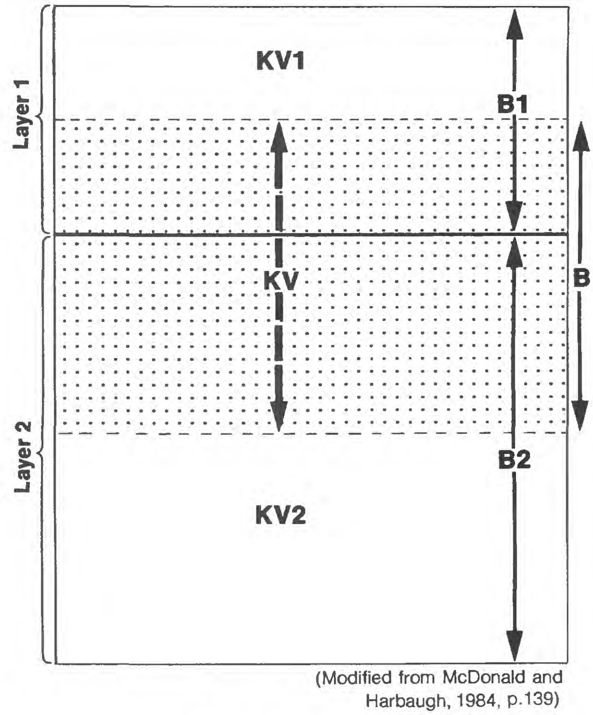


Figure 15. Areal distribution of storage coefficient of layer 2, as simulated in the model.



EXPLANATION

KV EFFECTIVE VALUE OF VERTICAL HYDRAULIC CONDUCTIVITY BETWEEN NODES [LT^{-1}]

B DISTANCE BETWEEN NODES [L]

KV1 VERTICAL HYDRAULIC CONDUCTIVITY OF MATERIAL IN LAYER 1 [LT^{-1}]

KV2 VERTICAL HYDRAULIC CONDUCTIVITY OF MATERIAL IN LAYER 2 [LT^{-1}]

B1 SATURATED THICKNESS OF LAYER 1 [L]

B2 SATURATED THICKNESS OF LAYER 2 [L]

Figure 16. Calculation of vertical hydraulic conductivity between adjacent blocks in layers 1 and 2.

The values of vertical hydraulic conductivity for layers 1 and 2 were assumed to be equal to one-hundredth of the horizontal hydraulic conductivity of the layers. The relation between vertical and horizontal hydraulic conductivity was not adjusted during model calibrations. The values of saturated thickness used in equation 2 were those that existed prior to extensive ground-water development in the area. Initial calculations of leakance indicated that the $B2/KV2$ term in equation 2 is negligible in comparison with the $B1/KV1$ term because $KV1$ is significantly lower than $KV2$. Consequently, leakance values were varied only to reflect calibration changes in the horizontal hydraulic conductivity of layer 1. The calculated values of leakance, in foot per day per foot, ranged from about 0.00001 beneath China Lake to about 0.001 beneath the western part of layer 1.

SIMULATED RECHARGE AND DISCHARGE

Recharge and discharge simulated in the model include mountain-front recharge, waste-water recharge, shrubbery-irrigation recharge, evapotranspiration, and ground-water pumpage (fig. 11). Recharge and discharge were simulated at constant rates over designated periods of time. No attempt was made to simulate seasonal or other short-term variations in recharge or discharge; instead, long-term average quantities were simulated. Each of these sources or sinks is discussed below.

Mountain-front recharge.--Mountain-front recharge from streamflow infiltration was simulated by recharge wells in model blocks in layer 2 (fig. 11) immediately adjacent to the mountains. The quantities of recharge originating from runoff in the mountain ranges surrounding the valley were estimated by Bloyd and Robson (1971, p. 15) to be 6,280 acre-ft/yr from the Sierra Nevada, 3,170 from the Coso and Argus Ranges, and 400 from the El Paso Mountains. These quantities were used in the model without modification. However, the distribution of recharge for particular mountain ranges was modified from the final distribution of Bloyd and Robson (1971, p. 15). For this model, the recharge was distributed according to stream-drainage areas above 4,500 feet in the Sierra Nevada and above 5,000 feet in the other mountain ranges (Bloyd and Robson, 1971, p. 12). This distribution of mountain-front recharge (shown in table 3) was not modified during model calibration as was done by Bloyd and Robson (1971, p. 18). Mountain-front recharge was assumed to remain constant throughout the simulation period.

Wastewater recharge.--Wastewater recharge was simulated by recharge wells in the blocks representing the areas of wastewater evaporation ponds (fig. 11). The annual wastewater recharge rates used in the model are shown in Supplemental Data A. Wastewater recharge from the Ridgecrest Regional Wastewater Treatment Facility was applied to layer 1, and wastewater recharge from the Ridgecrest Sanitation District and the Inyokern Community Services District was applied to layer 2.

Shrubbery-irrigation recharge.--Shrubbery-irrigation recharge was simulated by recharge wells in four model blocks near the community of China Lake (fig. 11*B*). Shrubbery-irrigation recharge prior to 1953 was assumed to be negligible and was not simulated. The rate of shrubbery-irrigation recharge for 1953 through 1985 was assumed to be constant and was calibrated during the transient-state model simulations to be about 0.15 ft/yr. Applied to the four model blocks, this rate yielded a value for shrubbery-irrigation recharge in the model of 100 acre-ft/yr.

Evapotranspiration.--Evapotranspiration by phreatophytes (25-percent plant cover) and evaporation from bare soil in the China Lake area were simulated at 170 model blocks in layer 1 (fig. 11*B*). A maximum evapotranspiration rate (Q_{max}) of 1.25 ft/yr (fig. 17) was assumed when the water table is at land surface for both phreatophyte and bare-soil areas, and evapotranspiration was assumed to decrease linearly to zero when the water table is greater than 10 feet below land surface in phreatophyte areas and greater than 7 feet below land surface in bare-soil areas (Kunkel and Chase, 1969, p. 67). The depth at which evapotranspiration ceases is termed the maximum effective depth of evapotranspiration (D_{max}).

Kunkel and Chase (1969, p. 67) estimated average annual evapotranspiration rates in the Indian Wells Valley for areas of 100-percent plant cover, 25-percent cover, and bare soil. These estimates were based on a nonlinear relation between evapotranspiration rate and depth of ground water (fig. 17). The model, however, can simulate only a linear relation between evapotranspiration and depth of ground water. Therefore, Q_{max} was chosen so that the linear relation used in the model would approximate the nonlinear relation used by Kunkel and Chase (1969, p. 67) for phreatophyte areas with 25-percent cover and bare-soil areas where the depth to ground water ranges from 3 to 6 feet below land surface (fig. 17). The range of 3 to 6 feet below land surface was chosen because it is the average depth to ground water in the area of evapotranspiration. The evapotranspiration rates for 100-percent plant cover were not simulated, because most of the valley has a cover of about 25 percent or less.

Ground-water pumpage.--Historical ground-water pumpage is simulated by discharge wells located at the grid node closest to the actual pumped wells. The measured pumpage was divided into 1-year-long pumping periods in the transient-state simulations. All pumpage is from layer 2. The annual distribution and quantities of pumpage are given in Supplemental Data D.

Table 3. *Annual mountain-front recharge for the Indian Wells Valley ground-water basin*

[acre-ft/yr, acre-feet per year]

Recharge	Model node Row	Model node Column	Recharge (acre-ft/yr)
Sierra Nevada			
Little Lake area	15	1	23
	15	2	23
Subtotal			46
Fivemile Canyon	15	1	266
	16	1	266
Subtotal			532
Deadfoot Canyon	17	1	68
	18	1	68
Subtotal			136
Ninemile Canyon	20	1	243.5
	21	1	243.5
Subtotal			487
Unnamed area	21	1	4
	22	1	4
	23	1	4
Subtotal			12
Noname Canyon	23	1	118
	24	1	118
Subtotal			236
Unnamed area	25	1	2
Subtotal			2
County Line Canyon	26	1	11
	27	1	11
Subtotal			22
Boulder Canyon	28	1	21
Subtotal			21
Sand Canyon	28	1	329.5
	29	1	329.5
Subtotal			659
Unnamed area	30	1	7
	31	1	7
	32	1	7
	33	1	7
	34	1	7
Subtotal			35
Grapevine Canyon	35	1	330
Subtotal			330
Unnamed area	36	2	.5
	37	2	.5
Subtotal			1
Sierra Nevada--Continued			
Short Canyon	38	2	76
Subtotal			76
Indian Wells Canyon	42	4	190
	43	4	190
	44	4	189
Subtotal			569
Unnamed area	46	3	11
	47	2	11
	48	2	11
	49	2	10
	50	1	10
Subtotal			53
Unnamed area	51	1	8.5
	52	1	8.5
Subtotal			17
Freeman Canyon	53	1	491.5
	54	1	491.5
Subtotal			983
Little Dixie drainage area	55	2	100
	56	3	100
	57	4	100
	58	5	750
	58	6	750
	58	7	190
	58	8	25
	58	9	25
	58	10	25
Subtotal			2,065
Total for Sierra Nevada			6,282
Coso and Argus Ranges			
Coso Wash area	1	15	203
	1	16	203
	1	17	203
	1	18	203
	1	19	203
Subtotal			1,015
Petroglyph Canyon	2	20	170
	2	21	170
	3	21	170
	4	21	170
Subtotal			680
Unnamed area	5	22	53
Subtotal			53

Table 3. *Annual mountain-front recharge for the Indian Wells Valley ground-water basin*--Continued

Recharge	Model node Row	Model node Column	Recharge (acre-ft/yr)
		Coso and Argus Ranges--Continued	
Unnamed area	6	23	6.5
	7	23	6.5
Subtotal			13
Renegade Canyon	7	23	171
	8	24	168
	8	25	168
	8	26	168
Subtotal			675
Mountain Springs Canyon	8	33	344
Subtotal			344
Unnamed area	9	33	6
	10	33	6
Subtotal			12
Unnamed area	11	33	22.5
	12	33	22.5
Subtotal			45
Unnamed area	14	33	1
Subtotal			1
Wilson Canyon	15	33	162
	16	33	162
Subtotal			324
Burro Canyon	25	36	8
Subtotal			8
Total for Coso and Argus Ranges			3,170
		El Paso Mountains	
El Paso Mountains drainage area	58	11	10
	58	12	10
	58	13	10
	58	14	10
	58	15	90
	58	16	90
	58	17	80
	58	18	50
	58	19	10
	58	20	10
	58	21	5
	55	22	5
	56	23	5
	56	24	5
	56	25	5
	56	26	5
Subtotal			400
Total for El Paso Mountains			400
Grand total for Indian Wells Valley			9,850

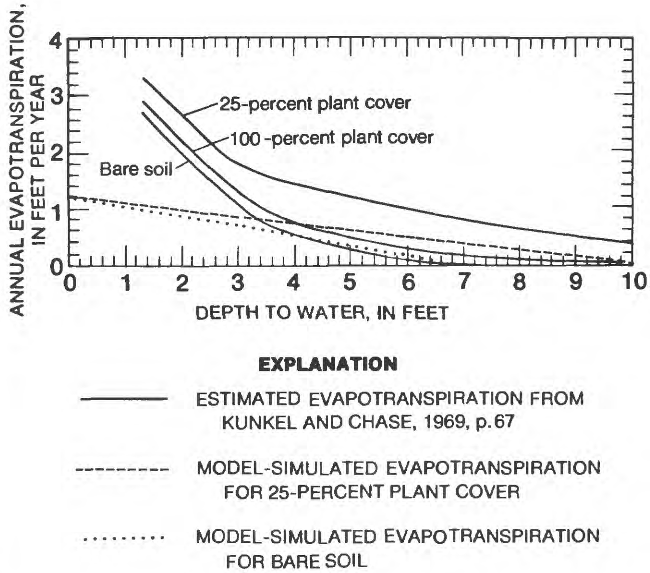


Figure 17. Estimated and model-simulated evapotranspiration in Indian Wells Valley.

Steady-State Calibration

The calibration of the ground-water flow model of Indian Wells Valley was begun by simulating steady-state conditions. A steady-state condition exists when natural inflow into the system equals outflow from the system, and storage does not change. In Indian Wells Valley, ground-water conditions in 1920-21 best represent steady-state conditions because pumpage was minimal, water levels are believed to have stabilized to the pumpage, and data were sufficient to permit reasonable simulation.

Steady-state water levels are dependent on the quantity and distribution of recharge to layer 2, the hydraulic conductivity of layer 1, the transmissivity of layer 2, the leakance between layers 1 and 2, and the quantity of evapotranspiration from layer 1 (Q_{max} and D_{max}). The estimates of recharge and discharge that are given in the preceding sections were used in the steady-state simulation. Hydraulic conductivity of layer 1, transmissivity of layer 2, and leakance between layers 1 and 2 were calibrated during the steady-state simulation of the model. Neither Q_{max} or D_{max} were modified during model calibration. These parameters were adjusted during numerous calibration runs until model-simulated hydraulic heads matched measured water levels.

The initial values used for the quantity and distribution of recharge, the hydraulic conductivity of layer 1, and the transmissivity of layer 2 were the values determined by Bloyd and Robson (1971) in a flow model that they developed and calibrated to simulate the ground-water flow system in the valley. The major differences between the values used in the calibration by Bloyd and Robson (1971) and the values used in the calibration of this model are: (1) recharge distribution used in this model was based on surface-drainage area of streams contributing recharge along the mountain front and was not modified during calibration, and (2) low values of transmissivity were not used to simulate barriers or faults in this model. The final model-calibrated transmissivities generally are close to values estimated from aquifer tests, specific-capacity tests, and drillers' logs, as shown in table 4. No well data were available along the northeastern part of the modeled area near Airport Lake; the transmissivity values used in the model in this area are those used by Bloyd and Robson (1971).

During steady-state calibration few adjustments were made to initial estimates of the hydraulic conductivity of layer 1 and the leakance between layers 1 and 2 because steady-state water levels were relatively insensitive to these parameters and few data were available for calibration. During the transient-state calibration, however, considerable adjustments were made to the leakance between layers 1 and 2.

Table 4. *Comparison of estimated and model-calibrated transmissivity values*

[ft^2/d, feet squared per day]

Well No.	Model node Row	Model node Column	Estimated transmissivity (ft^2/d × 1,000)	Model-calibrated transmissivity of layer 2 (ft^2/d × 1,000)
		Ridgecrest area		
26S/40E-32F3	49	22,23	[1]4	7
32K1	49	23	[1]8	7
27S/40E-4L1	51	25	[1]10	7
33P4	50	24,25	[1]3	7
		Intermediate area		
25S/40E-30K1	47	21	[1]11	13
26S/39E-24K1	45,46	19	[1]16 [2]20 [3]24	20
24M1	45	17,18	[1]6	8
26S/40E-30K2	47	21	[1]16	13
30K3	47	21	[1]13	13
		Inyokern		
26S/39E-19Q1	46	9	[1]13	20
30F1	47	9	[1]20	20
30J1	47	10	[1]19	20
		Other areas		
25S/39E-4R1	27,28	14	[1]17 [2]12 [3]32	25
35N1	38	16	[2]8 [3]34	30
35N2	38	16	[2]6 [3]25	30
26S/39E-17F2	43	11	[4]21	20
26S/40E-1A2	38	31	[1].3	.3
22P1	46	26	[1]2	2
36A1	48,49	32	[1]2	2

[1]Estimated from specific-capacity test. The specific capacity in units of gallons per minute per foot multiplied by 1,700 approximates the transmissivity in units of gallons per day per foot [based on study of valley-fill deposits in the Sacramento Valley of California (Thomasson and others, 1960, p. 222)].

[2]Based on aquifer test by Kunkel and Chase (1969, p. 60).

[3]Extrapolated from aquifer test for saturated thickness of 400 feet (Kunkel and Chase, 1969, p. 60).

[4]From U.S. Geological Survey data files, San Diego, California.

Model-simulated hydraulic heads of layers 1 and 2 generally approximated the measured water levels, as shown in figure 18. Model calibration was considered acceptable when the difference between model-simulated hydraulic head and measured water level was within ±5 feet. The largest discrepancies were in layer 2 in the southeastern part of the valley near Ridgecrest. A possible explanation for these discrepancies is that some irrigation pumpage occurred in this area prior to 1920 (see "Ground-Water Development" section). The amount of this pumpage is unrecorded and was not simulated in the model. The water budget generated by the model for steady-state conditions is shown in table 5.

Table 5. *Steady-state and transient-state water budgets*

[acre-ft/yr, acre-feet per year; acre-ft, acre-feet. Values are rounded]

Water-budget component	Steady state 1920 (acre-ft/yr)	Transient state 1920-85 (acre-ft)	Transient state 1985 (acre-ft/yr)
Inflow:			
Natural recharge			
Layer 1 (upper)	0	0	0
Layer 2 (lower)	9,850	650,100	9,850
Artificial recharge			
Layer 1	0	19,730	1,070
Layer 2	0	4,680	30
Total inflow	9,850	674,510	10,950
Outflow:			
Evapotranspiration			
Layer 1	9,850	595,720	6,570
Layer 2	0	0	0
Pumpage[1]			
Layer 1	0	0	0
Layer 2	0	548,900	21,530
Total outflow	9,850	1,144,620	28,100
Difference[2]	0	470,110	17,150
Storage depletion			
Layer 1	0	42,940	1,760
Layer 2	0	426,620	15,370
Total storage depletion	0	469,560	17,130

[1]Although previous investigators (see text) estimated an average pumpage for 1920-51 of 1,000 acre-ft/yr, pumpage for the steady-state water budget is assumed to have been minimal and thus it is set to zero.

[2]In theory, the difference (total outflow minus total inflow) values should be in exact agreement with total-storage-depletion values. The observed small differences between corresponding values are due to accumulation of small consistent errors and to independent rounding of large numbers.

Transient-State Calibration

Ground-water conditions in the valley during the period 1920-85 were used to calibrate the model to transient or time-dependent conditions. Transient conditions are the result of stress on the system imposed by man's use of the water resources. In Indian Wells Valley, stress is caused by pumping of ground water for military, industrial, municipal and domestic, and agricultural-irrigation supplies. During the transient period, total pumpage increased from 1,000 acre-ft/yr in 1920 to more than 22,000 acre-ft/yr in 1980 (fig. 6 and Supplemental Data D). Since 1959, annual ground-water pumpage has exceeded annual natural recharge (9,850 acre-ft/yr). The pumpage has caused water-level declines throughout most of layer 2. The greatest declines are observed near the intermediate area west of Ridgecrest where the greatest ground-water pumpage occurred. From 1920 through 1985, water levels in layer 2 declined more than 80 feet in the intermediate area and about 50 feet in the Ridgecrest and Inyokern areas. (See figs. 7 and 8.)

The magnitude of declines in hydraulic head is dependent on natural recharge, evapotranspiration (Q_{max} and D_{max}), ground-water pumpage, the storage coefficient of both layers, the hydraulic conductivity of layer 1, the transmissivity of layer 2, and the leakance between layers. For the transient-state calibration, the values of natural recharge, transmissivity, Q_{max}, and D_{max} were the same as those used during the steady-state simulation. Ground-water pumpages for military, municipal, and industrial purposes were measured and pumpages for agricultural irrigation and domestic purposes were estimated from land use; these values were entered into the model without modification (fig. 6). Therefore, the calibration procedure for transient-state conditions involved modification of estimates from prior reports of the storage coefficient for both layers and the

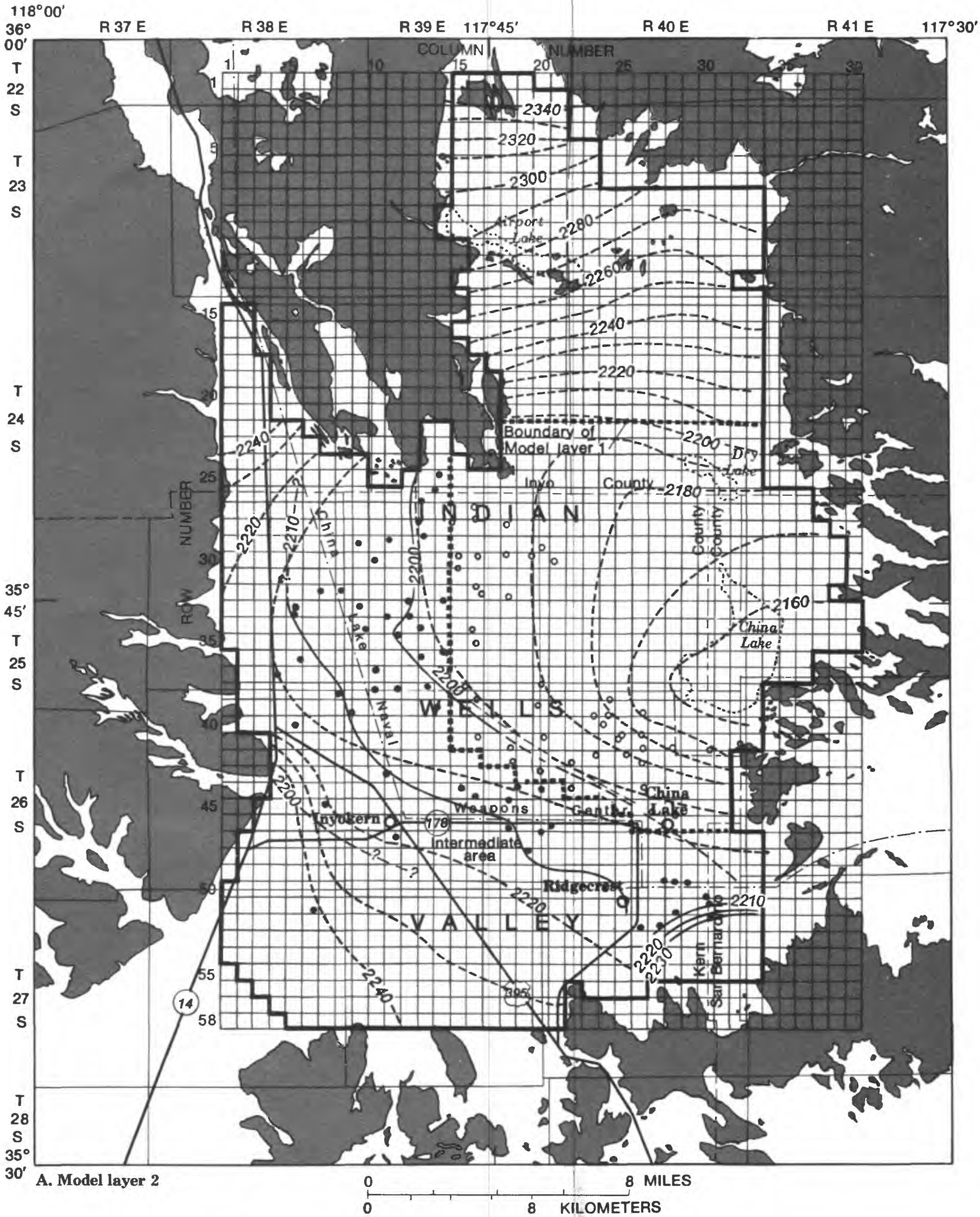
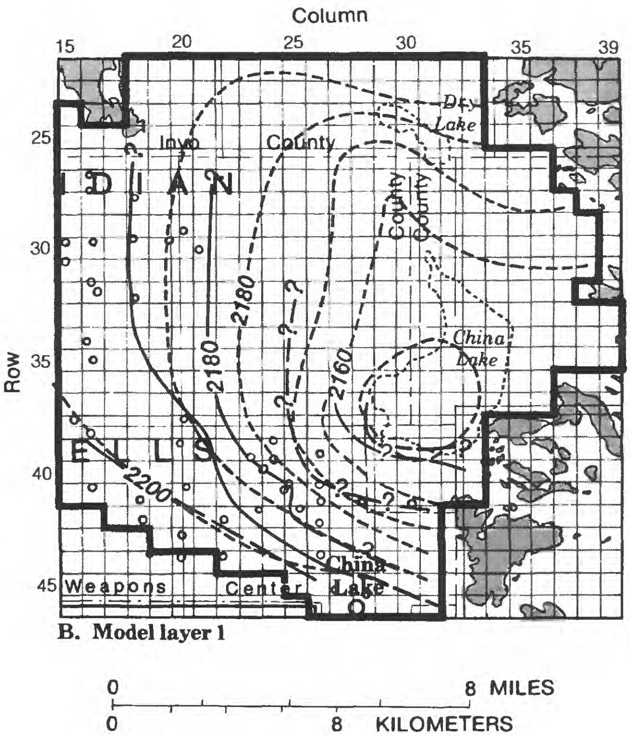


Figure 18. Contours of measured water levels and of model-simulated hydraulic heads in model layers 1 and 2 for steady-state conditions, 1920.



B. Model layer 1

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

----2200---- MODEL-SIMULATED HYDRAULIC-HEAD CONTOUR-- Shows altitude of hydraulic head as simulated by the steady-state model. Contour interval 10 feet. Datum is sea level

——2180——? WATER-LEVEL CONTOUR-- Shows altitude of water level, 1920-21. Dashed where approximately located. Queried where doubtful Contour interval 10 feet. Datum is sea level

MEASURED WATER LEVEL, 1920-21-- (See data table B and fig.7)

o Well in layer 1

• Well in layer 2

refinement of the leakance between layers until model-simulated hydraulic heads matched observed heads.

Hydraulic heads that were computed for steady-state conditions were used as initial conditions for the transient-state calibration. For the transient-state calibration, the period 1920-85 was divided into 66 yearly stress periods. Yearly stress periods were selected because available pumpage and water-level data did not justify discretization into shorter periods. Mountain-front recharge was assumed to be constant throughout the transient-state period. The transient-state calibration was started by adjusting initial estimates of the storage coefficient for both layers. Later, the leakance between layers was adjusted.

Water-level data from more than 20 wells with long-term records were used to calibrate the model. The model was calibrated to long-term trends in the measured data and not to seasonal or pumping-related trends. Figures 19 and 20 show representative hydrographs, after transient-state calibration, that illustrate the relation between model-simulated hydraulic heads and measured water levels. The model-simulated hydraulic heads generally are within 5 feet of measured values. The largest discrepancies were in layer 2 in the Inyokern area (well 26S/39E-19Q1, fig. 20). A possible explanation for these discrepancies is that the value reported for military pumpage for 1950-63 in the Inyokern area is too high (see fig. 6).

Water-level contour maps of layers 1 and 2 constructed from measured values were used to compare the transient response of the model with the actual system. Comparison of model-simulated hydraulic-head contours with contours constructed from measured water levels shows similar regional patterns of ground-water flow (fig. 21), and the contour values generally are within 5 feet of each other. The similarity

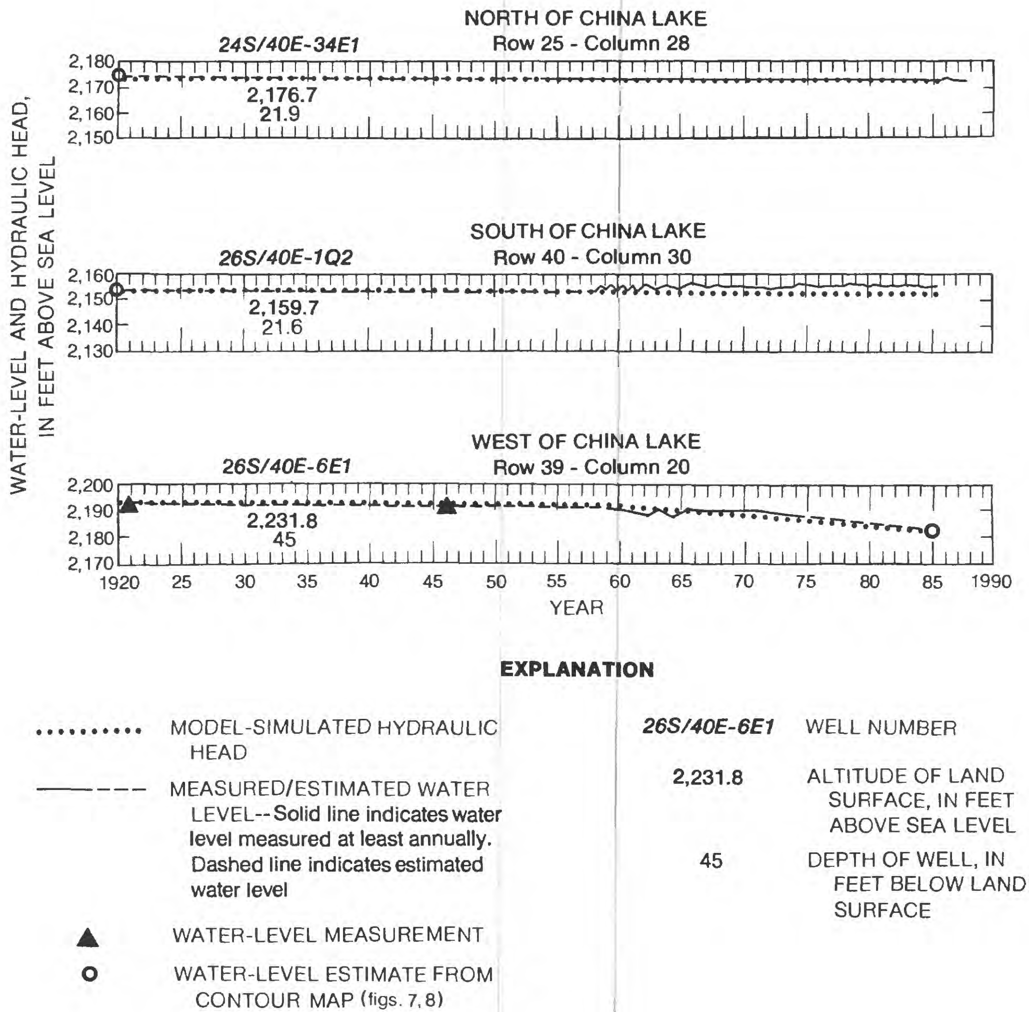


Figure 19. Measured or estimated water levels and model-simulated hydraulic heads, 1920-85, in model layer 1.

between model-simulated and measured values (figs. 19-21) indicates that the model closely approximates the hydraulic response of the ground-water system.

The model-generated water budget for the transient-state simulation is shown in table 5. During the simulation period, 548,900 acre-ft of ground water was pumped from the aquifer system. Results of the transient-state simulation indicate that about 86 percent (469,560 acre-ft) of this pumpage was derived from storage, about 10 percent (54,380 acre-ft) was derived from decreases in evapotranspiration from layer 1, and about 4 percent (24,410 acre-ft) was derived from artificial recharge of wastewater and shrubbery-irrigation water. Although artificial recharge due to wastewater from the Ridgecrest Regional Treatment Facility probably has increased the amount of water lost to evapotranspiration near the community of China Lake, the estimated total ground-water discharge by evapotranspiration decreased, because of pumping, from 9,850 acre-ft/yr in 1920 to about 6,570 acre-ft/yr in 1985 (table 5 and fig. 22).

The pumping induced about 28,870 acre-ft of ground water to flow from layer 1 to layer 2. During the simulation period, ground-water flow from layer 1 to layer 2 increased from zero in 1920 to about 1,550 acre-ft by the end of 1985 (fig. 23). The 1985 areal distribution of vertical leakage between layers as simulated by the model is presented in figure 24. As shown in figure 24, simulated vertical leakage from layer 1 to layer 2 occurred on the western and southern perimeters of layer 1, adjacent to the areas of greatest pumpage.

Sensitivity of the Model

Sensitivity analysis is a procedure that tests the model's sensitivity to changes in the input data. The procedure involves holding all input values constant except the one being analyzed and then varying that value. Changes in the model-simulated hydraulic heads in layer 2 were used to determine the sensitivity of the model. Exact values of hydraulic-head change from the sensitivity analysis should be viewed cautiously, but relative changes can provide insight as to how a particular input parameter may affect the results of the model.

To determine the sensitivity of the model, a series of steady-state and transient-state simulations were made in which recharge, transmissivity of layer 2, and the maximum evapotranspiration rate were varied by 0.5 to 2.0 times the calibrated value, and the hydraulic conductivity of layer 1 and the leakance between layers were varied by 0.1 to 10 times the calibrated value. Also made were transient-state simulations in which the storage coefficient of layer 2 was varied by 0.5 to 2.0 times the calibrated value. The pumpage in Indian Wells Valley is relatively well defined; therefore, a sensitivity analysis on the effect of changes in pumpage was not made. The steady-state and transient-state simulations were made using the calibrated steady-state heads as the starting heads. The transient-state runs simulated the period 1920-85.

For all the sensitivity simulations, drains were used in model blocks to simulate evapotranspiration. In the simulation, water could discharge from the model when the hydraulic head in layer 1 was higher than the land-surface altitude at a particular model block. Adding drains to the model was necessary because during some of the sensitivity simulations the maximum evapotranspiration rate at a particular model block (200 acre-ft/yr per block) was not high enough to keep the hydraulic head of layer 1 below the land-surface altitude. Because available data did not indicate artesian conditions in layer 1, the drains were added to discharge water not removed by the simulated evapotranspiration at a particular model block.

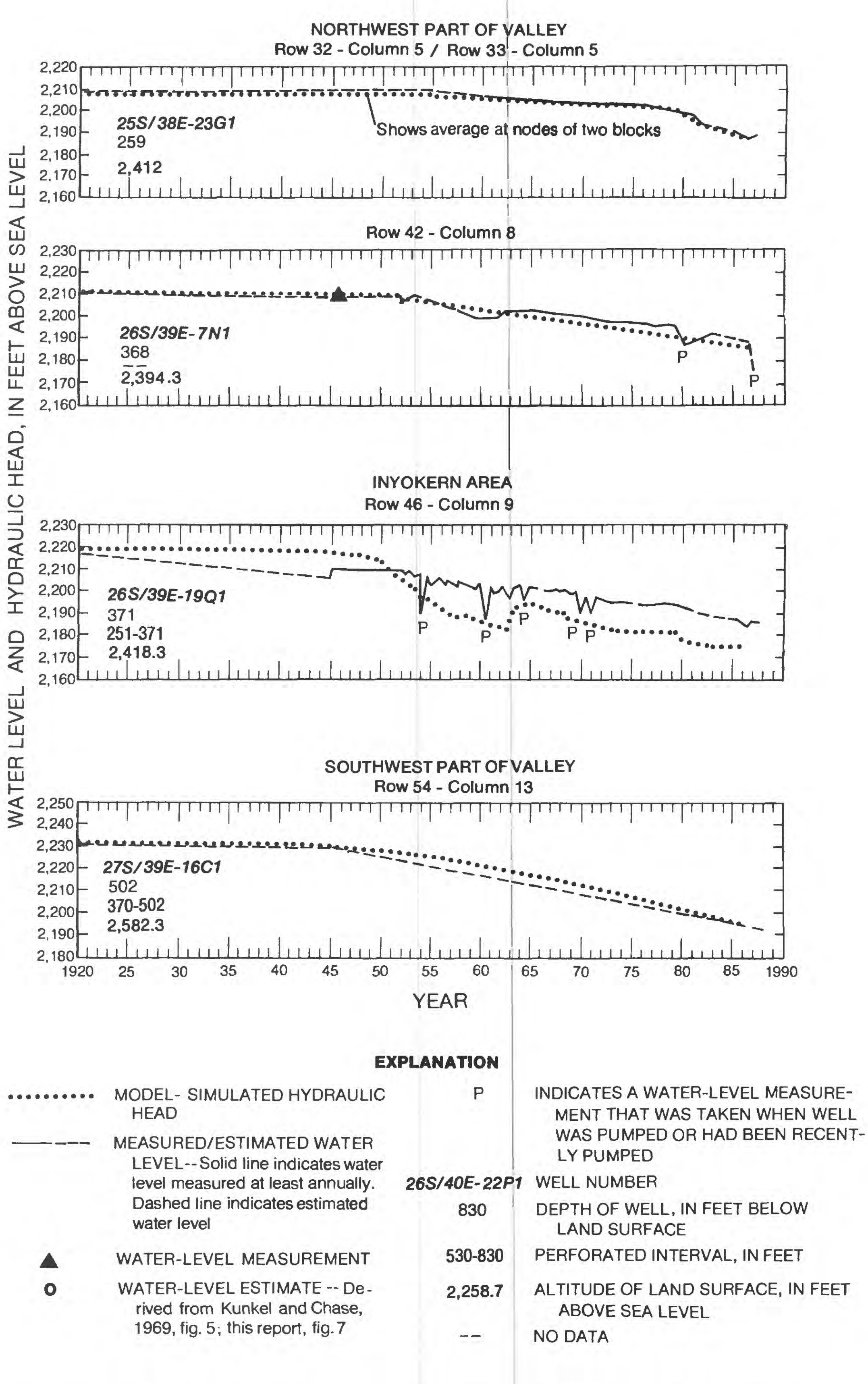
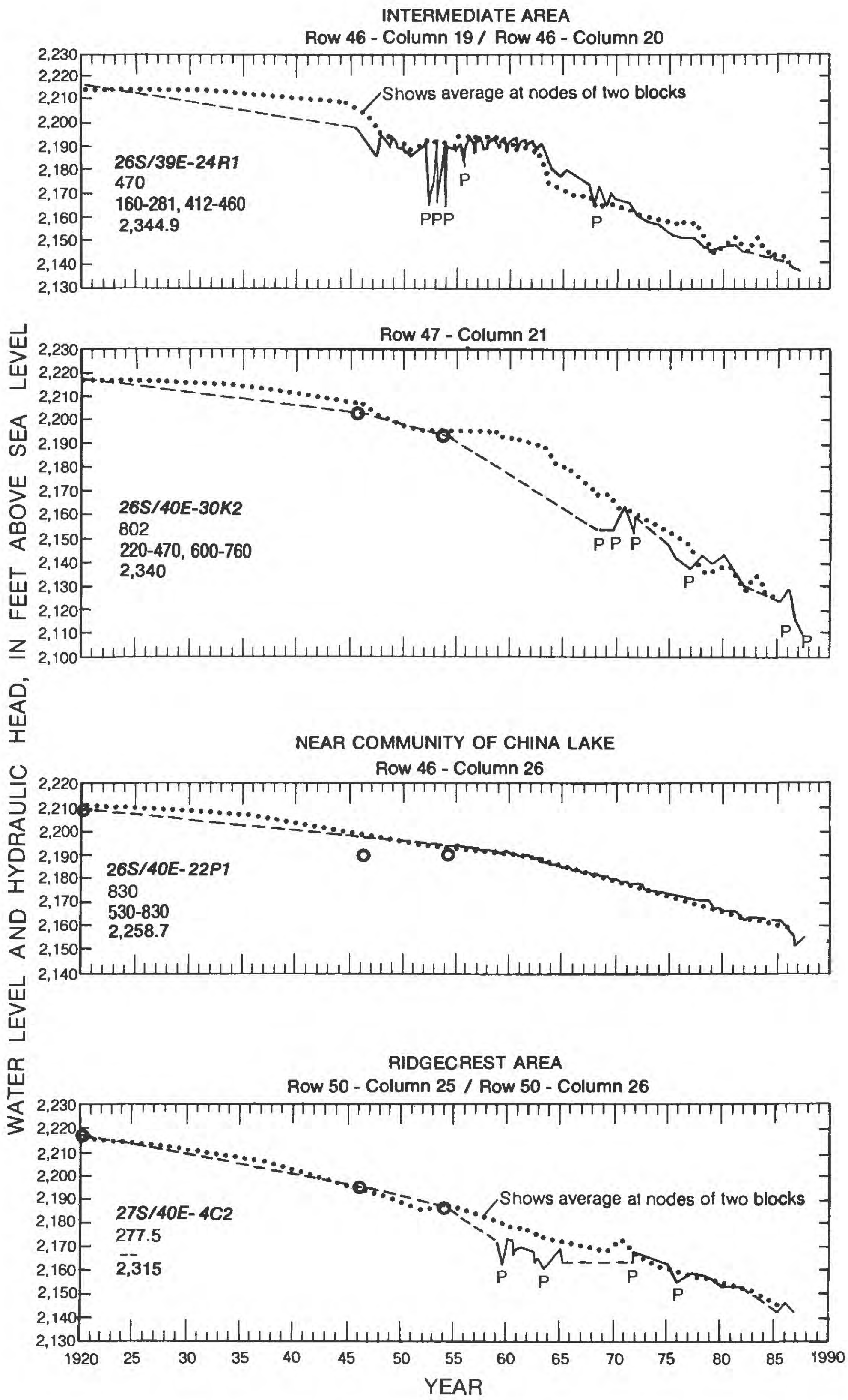


Figure 20. Measured or estimated water levels and model-simulated hydraulic heads, 1920-85, in model layer 2.



INTERMEDIATE AREA
Row 46 - Column 19 / Row 46 - Column 20
Shows average at nodes of two blocks
26S/39E-24R1
470
160-281, 412-460
2,344.9
PPP
P
P
Row 47 - Column 21
26S/40E-30K2
802
220-470, 600-760
2,340
P P P
P
P
P
NEAR COMMUNITY OF CHINA LAKE
Row 46 - Column 26
26S/40E-22P1
830
530-830
2,258.7
RIDGECREST AREA
Row 50 - Column 25 / Row 50 - Column 26
Shows average at nodes of two blocks
27S/40E-4C2
277.5
--
2,315
P
P
P
P
WATER LEVEL AND HYDRAULIC HEAD, IN FEET ABOVE SEA LEVEL
2,230
2,220
2,210
2,200
2,190
2,180
2,170
2,160
2,150
2,140
2,130
2,120
2,110
2,100
1920
25
30
35
40
45
50
55
60
65
70
75
80
85
1990
YEAR

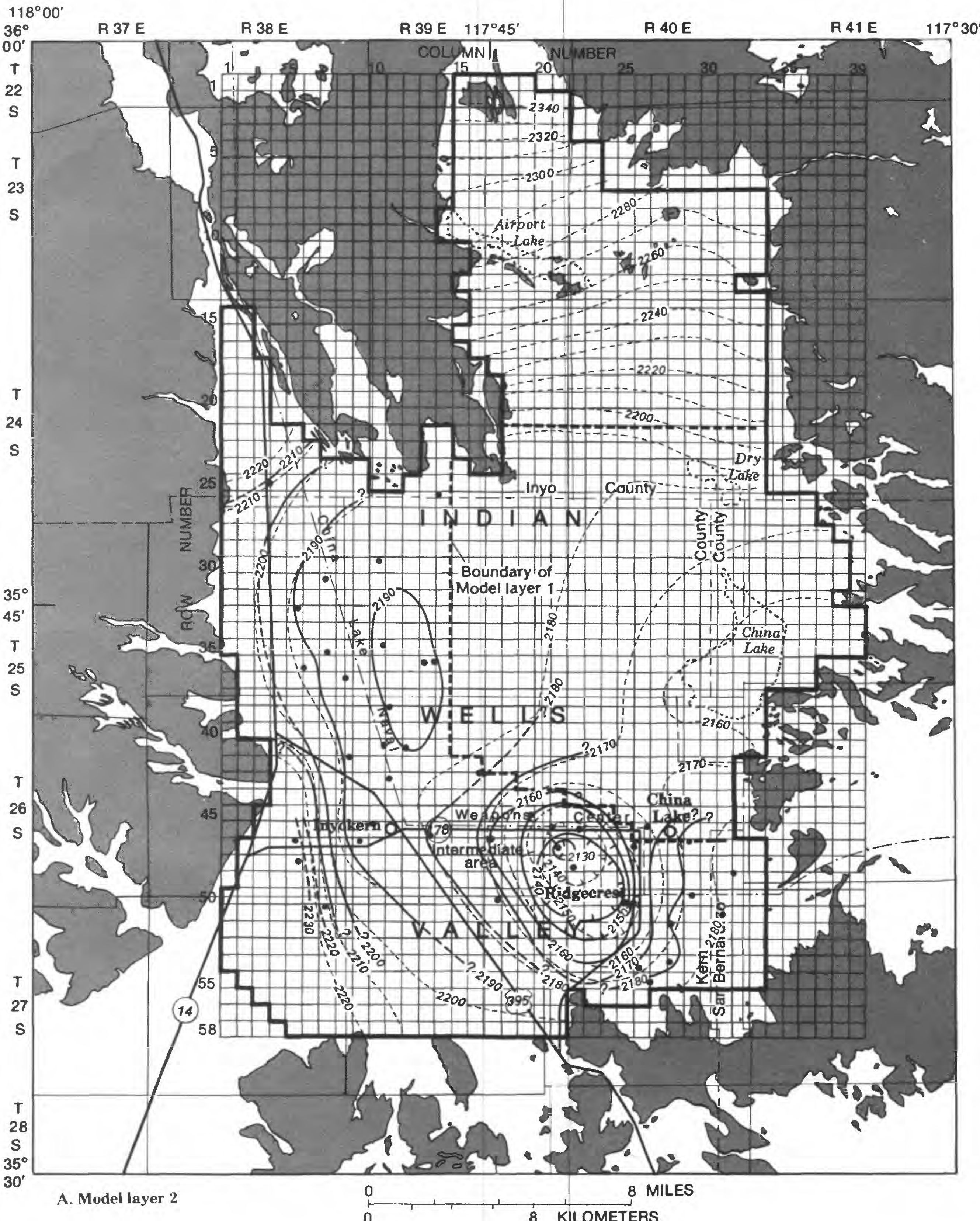
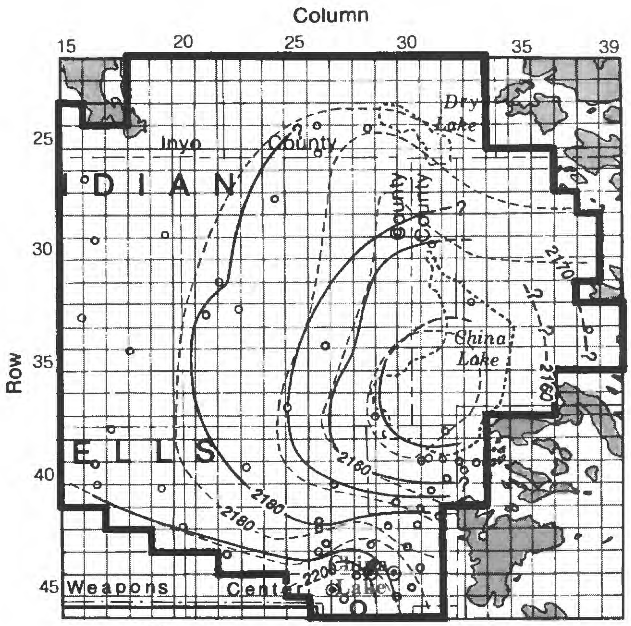


Figure 21. Contours of measured water levels and of model-simulated hydraulic heads in model layers 1 and 2 at the end of transient-state simulation, 1985.



B. Model layer 1

0 8 MILES
0 8 KILOMETERS

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

2200 MODEL-SIMULATED HYDRAULIC-HEAD CONTOUR--Shows altitude of hydraulic head as simulated by the steady-state model. Contour interval 10 feet. Datum is sea level

2200 ? WATER-LEVEL CONTOUR--Shows altitude of water level, 1985-86. Dashed where approximately located. Queried where doubtful. Contour interval 10 feet. Datum is sea level

MEASURED WATER LEVEL, 1985-86--(See data table C)

- Well in layer 1
- Well in layer 2
- Wells in layers 1 and 2 located near eac other

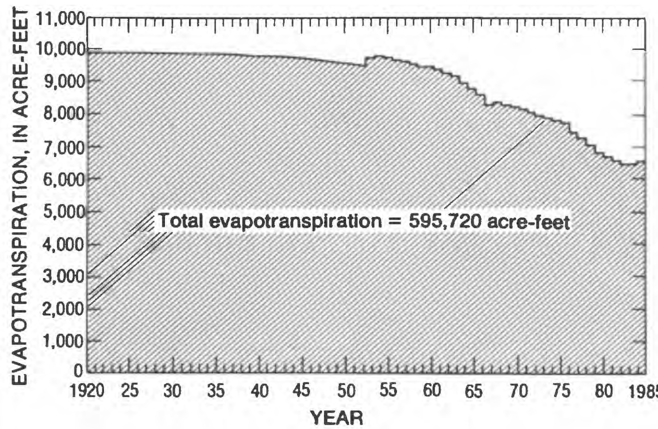
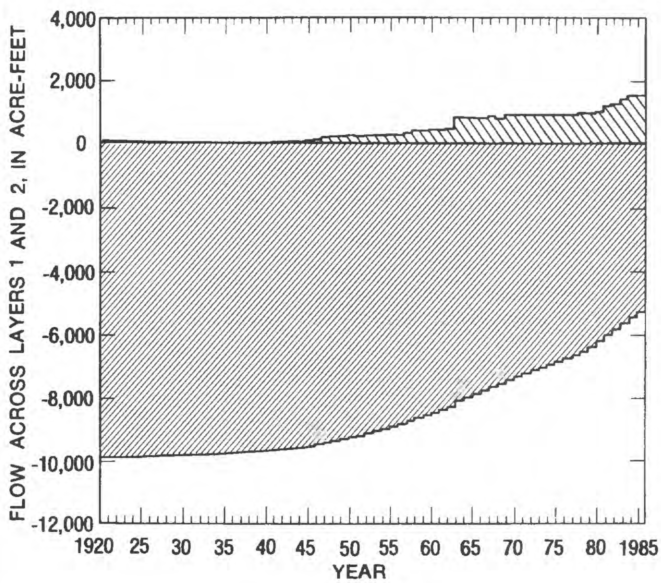


Figure 22. Model-simulated evapotranspiration from layer 1, 1920-85.



EXPLANATION

FLOW FROM LAYER 1 TO LAYER 2--
Total leakage: 28,870 acre-feet

FLOW FROM LAYER 2 TO LAYER 1--
Total leakage: 561,680 acre-feet

Note: Positive value indicates flow from layer 1 to layer 2; negative value indicates flow from layer 2 to layer 1

Figure 23. Components of model-simulated leakage between layers 1 and 2, 1920-85.

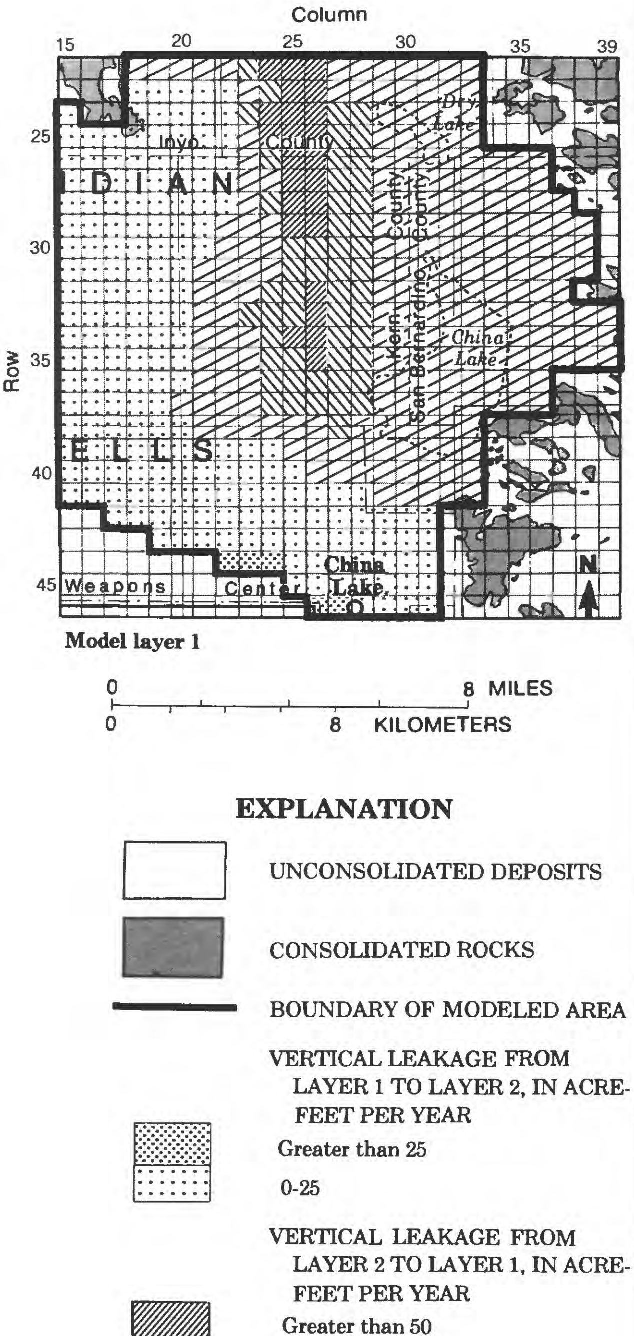


Figure 24. Areal distribution of model-simulated leakage between layers 1 and 2, 1985.

The rate at which water can discharge into a drain is approximated in the model using the equation:

$$Q_D = C_D(H-L), \qquad (3)$$

where

Q_D is the rate of water flowing into the drain $[L^3T^{-1}]$,

C_D is the conductance of the interface between the aquifer and the drain $[L^2T_{-1}]$,

H is the hydraulic head in layer 1 near the drain [L], and

L is the land-surface altitude at the drain [L].

When the hydraulic head of layer 1 (H) is less than the land-surface altitude (L), there is no flow into the drain. The coefficient C_D was set equal to 0.1 ft^2/s for all the drains in the model because this value was found not to retard the flow of water in model blocks.

Results of the sensitivity simulations (figs. 25 and 26) indicate that both the steady-state and transient-state models are most sensitive to changes in recharge and transmissivity of layer 2. Varying the recharge or transmissivity by 0.5 time and (also) by 2.0 times the calibrated values results in model-simulated hydraulic-head changes in layer 2 of 10 to 50 feet or more over most of the modeled area for both the steady-state and transient-state models. The transient-state model also was sensitive to changes in storage coefficient of layer 2. Varying the storage coefficient of layer 2 by 0.5 time the calibration value results in hydraulic-head changes of 10 to 50 feet over the southern and western parts of the valley, and varying the storage coefficient by 2.0 times results in hydraulic-head changes of 10 to 25 feet in the southern part of the valley. Also, reducing leakance by one-tenth in the transient-state model resulted in hydraulic-head changes of 10 to 25 feet along the perimeter of the modeled area; whereas, in the central part of the valley, changes were less than 10 feet. Model-simulated heads in layer 2 were relatively insensitive to variations in the values of the other parameters (figs. 25 and 26).

There has been concern by some residents in Indian Wells Valley that the quantity of recharge determined by Bloyd and Robson (1971, p. 12) and subsequently used in this model (9,850 acre-ft/yr) is significantly less than the actual recharge to the valley. The sensitivity simulations presented in figures 25 and 26 indicate that if all the other model parameters are accurately known, then recharge cannot be significantly varied from the value determined by Bloyd and Robson (1971) without causing a significant difference between model-simulated hydraulic heads and measured water levels for both steady-state and transient-state conditions. However, if the other parameters are poorly known, then the recharge could be quite different from the value determined by Bloyd and Robson (1971).

Not all model parameters are independent of each other, and changing one parameter during calibration might necessitate changing another parameter (Luckey and others, 1986, p. 49). During model calibration it was apparent that recharge and the transmissivity of layer 2 were closely interrelated. Therefore, the effects of simultaneously varying these parameters were evaluated. As shown in figure 27, simultaneously varying recharge and the transmissivity of layer 2 by 2.0 times the calibrated values resulted in model-simulated hydraulic heads that were about 6 feet higher than measured water levels throughout most of the model for steady-state conditions. Although the model-simulated hydraulic heads are higher than measured water levels, they are not unreasonable. These results suggest that recharge and transmissivity could be significantly higher than the values used in the model. However, the values of transmissivity used in the calibrated model approximate measured values throughout most of the valley (table 4). Therefore, significant changes in the transmissivity of layer 2 and in recharge, because of the interrelation between these parameters, are unreasonable.

Simulations of Aquifer Response to Management Alternatives

Having been verified as capable of simulating the hydraulic-head response of the aquifer due to pumping, the model can be used to estimate changes in hydraulic head resulting from proposed management alternatives such as changing the quantities and distribution of pumpage and (or) artificial recharge.

For this study, three simulations were used to determine the aquifer response to different pumpage patterns suggested by cooperators. Determining the quantity of ground-water flow from layer 1 to layer 2 was of particular importance because layer 1 contains ground water of poor quality (dissolved-solids concentration greater than 1,000 mg/L) that could degrade the ground-water quality of layer 2. Previous investigations (Dutcher and Moyle, 1973; Warner, 1975; Mallory, 1979) have indicated that water-level declines could result in ground-water quality being degraded in areas of heavy pumping. Future investigations might focus on ground-water quality, rather than quantity, because quality may be the most important factor affecting future utilization of ground water in the valley.

Each of the management simulations were run, using the model-simulated hydraulic heads at the end of 1985 as initial conditions, for thirty 1-year stress periods representing the time period 1986-2015. Natural ground-water recharge, which was assumed to be constant and the same as in steady-state conditions (9,850 acre-ft/yr), totaled 295,500 acre-ft by the end of the simulation. Total pumpage in the valley, which was assumed to remain the same

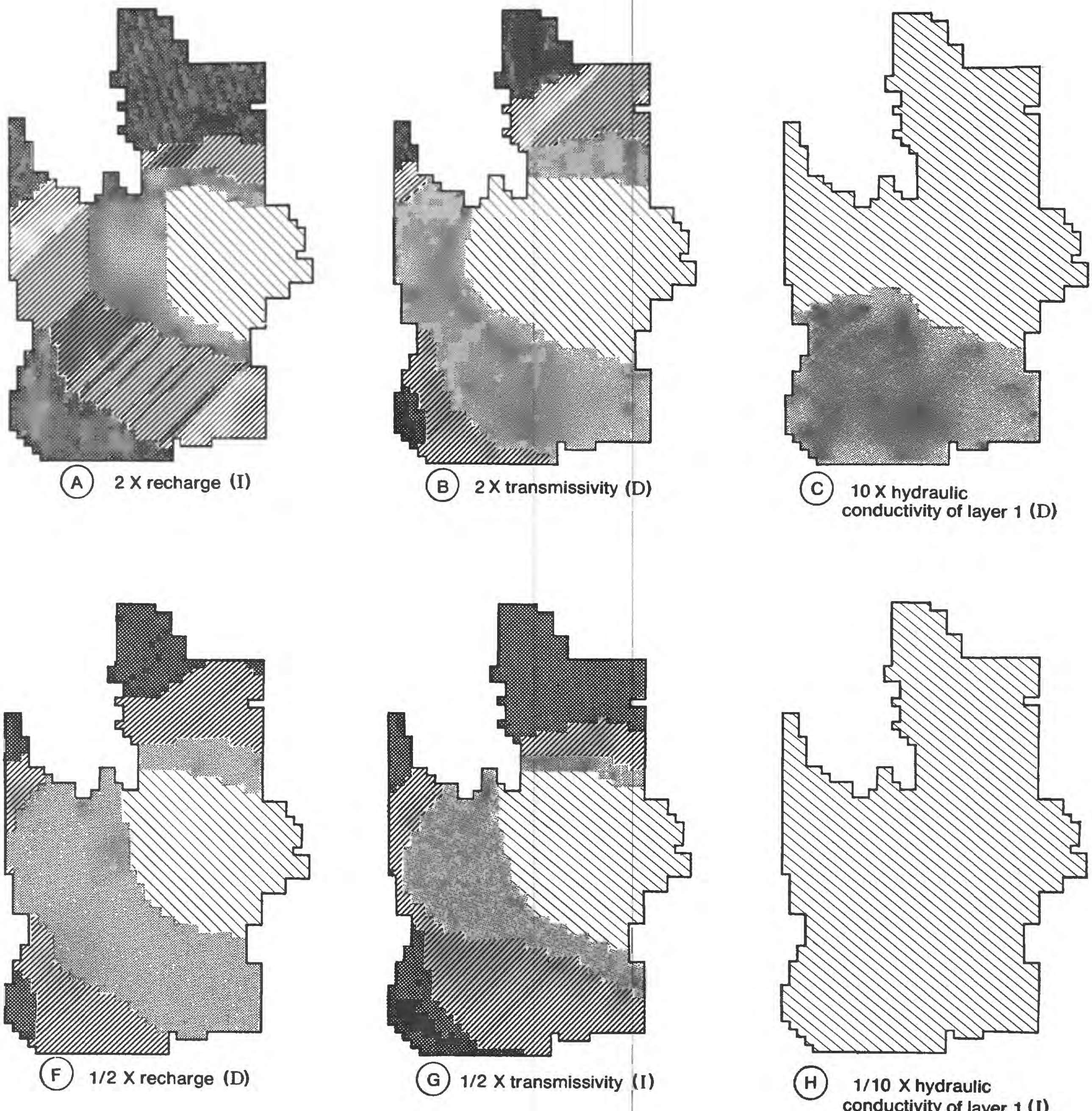
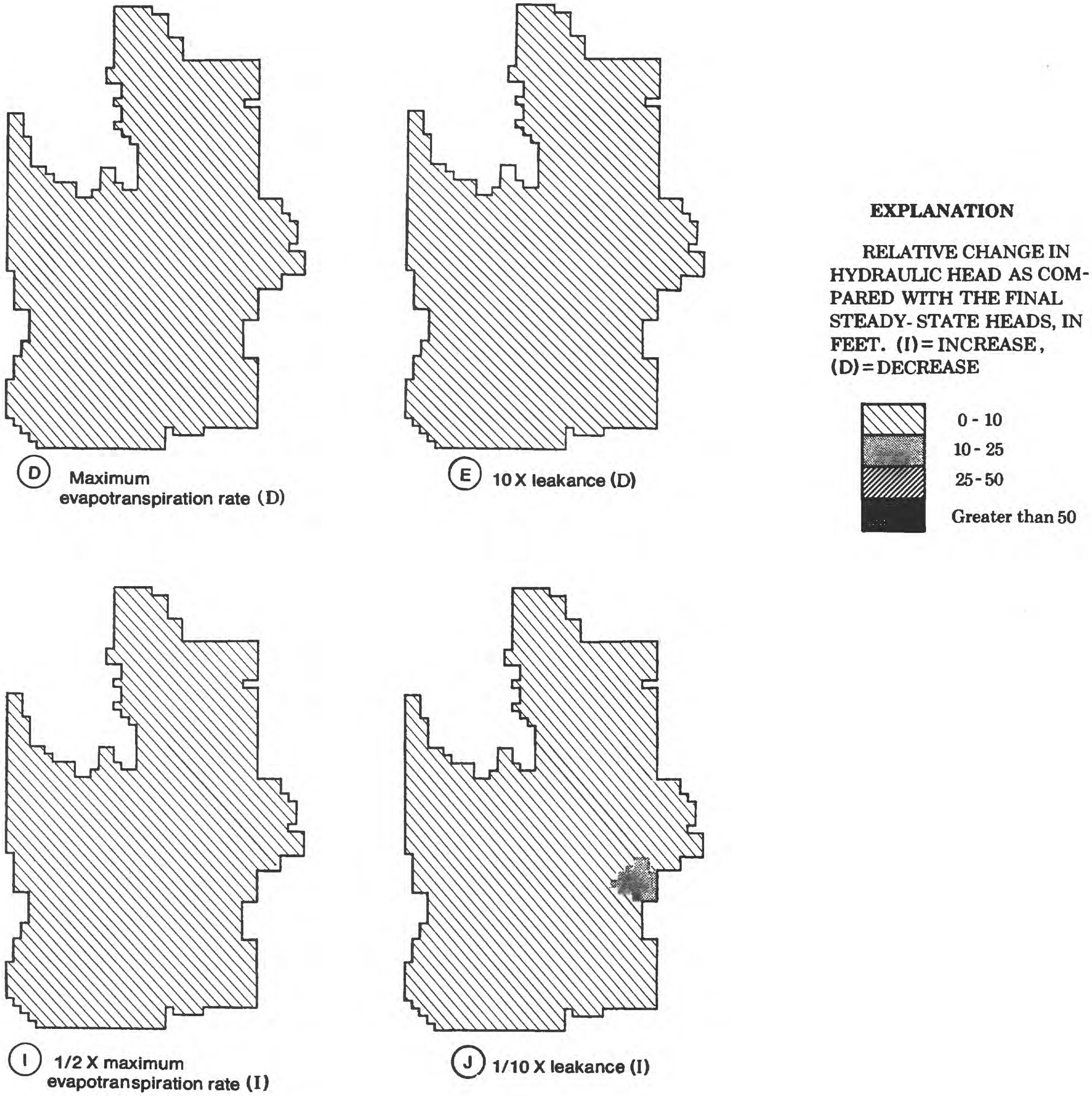


Figure 25. Sensitivity of model-simulated hydraulic heads in layer 2 to changes in natural recharge, transmissivity, hydraulic conductivity of layer 1, maximum evapotranspiration rate, and leakance during steady-state conditions.


D Maximum evapotranspiration rate (D)
E 10 X leakance (D)
I 1/2 X maximum evapotranspiration rate (I)
J 1/10 X leakance (I)
EXPLANATION
RELATIVE CHANGE IN HYDRAULIC HEAD AS COMPARED WITH THE FINAL STEADY- STATE HEADS, IN FEET. (I) = INCREASE, (D) = DECREASE
0 - 10
10 - 25
25 - 50
Greater than 50

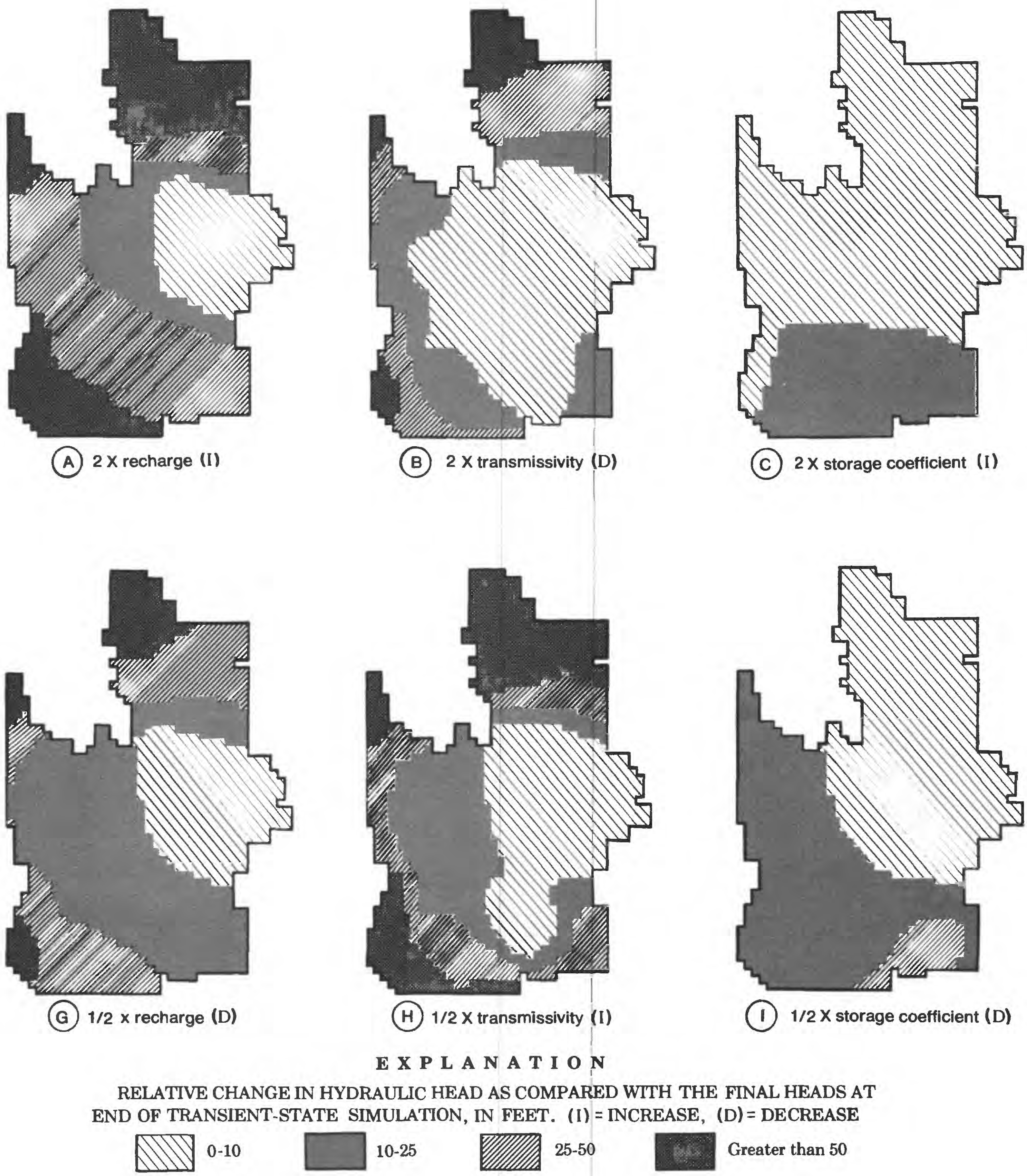
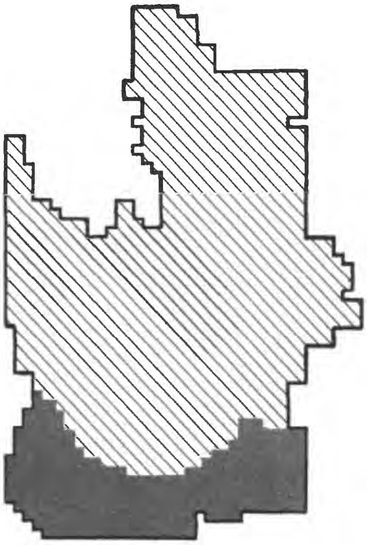
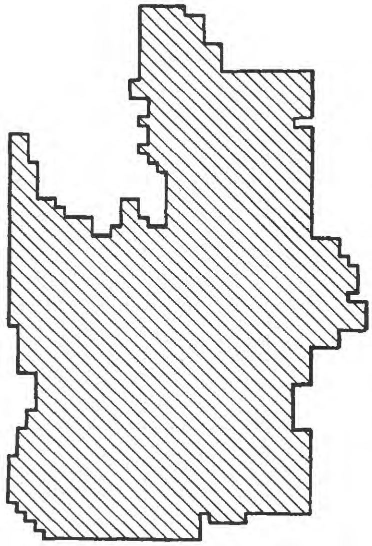


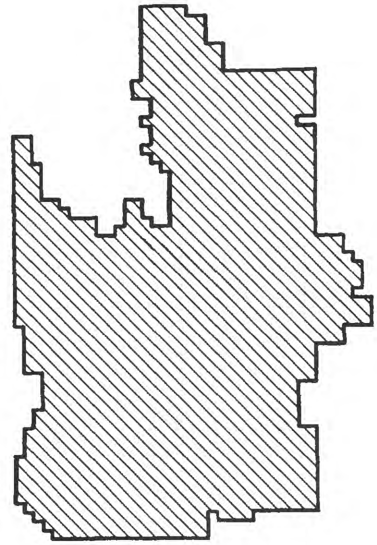
Figure 26. Sensitivity of model-simulated hydraulic heads in layer 2 to changes in natural recharge, transmissivity, hydraulic conductivity of layer 1, maximum evapotranspiration rate, and leakance at the end of transient-state simulation.



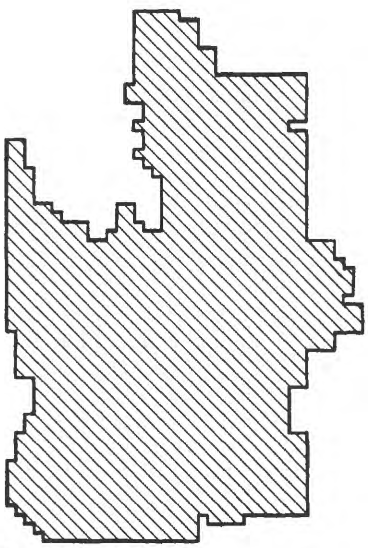
(D) 10 X hydraulic conductivity of layer 1 (D)



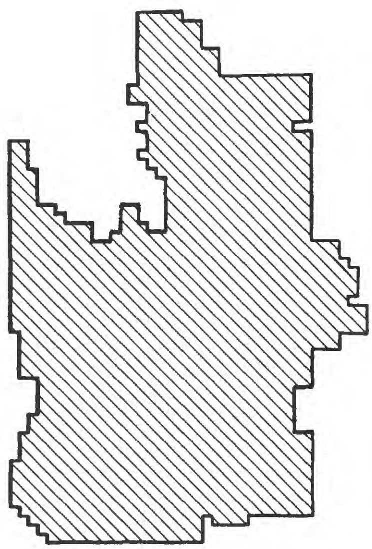
(E) 2 X maximum evapotranspiration rate (D)



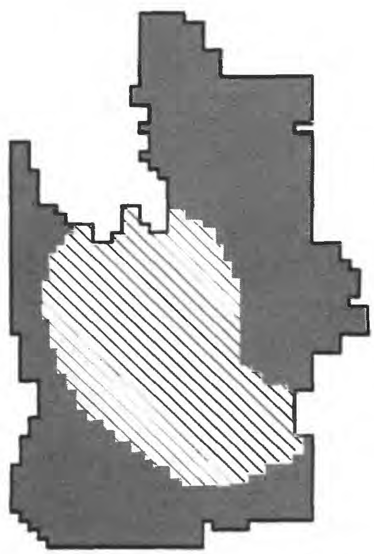
(F) 10 X leakance (D)



(J) 10 X hydraulic conductivity of layer 1 (I)



(K) 1/2 X maximum evapotranspiration rate (I)



(L) 1/10 X leakance (I)

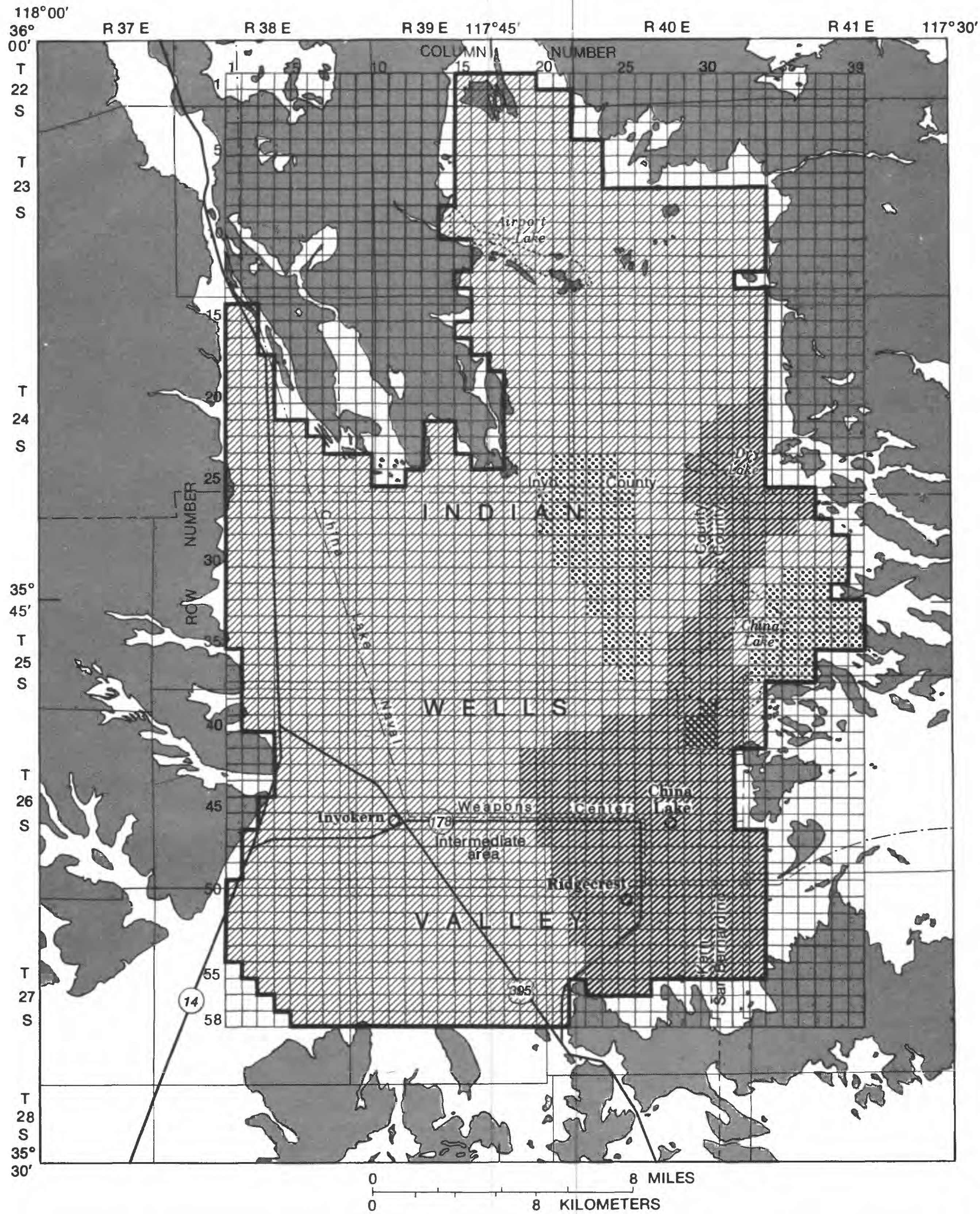


Figure 27. Sensitivity of the model to 2.0 times the calibrated recharge and transmissivity for steady-state conditions.

as in 1985 (21,526 acre-ft/yr), totaled 645,780 acre-ft by the end of the simulation. In two of the simulations, the distribution of pumpage was changed. Table 6 shows the water budget generated by the management simulations, and figure 28 shows the pumpage locations for the management simulations.

In the first management simulation, it was assumed that the distribution of pumpage would remain the same as during 1985 (fig. 11). During the simulation period, model-calibrated heads in layer 2 were projected to decline between 20 and 40 feet in the Ridgecrest and intermediate areas and between 20 and 30 feet in the northwestern and southwestern parts of the valley (figs. 29-30). Declines of less than 10 feet were projected in the northeastern part of the valley far from the pumping areas. Results from this simulation also indicated that about 71 percent (458,980 acre-ft) of the pumpage (645,780 acre-ft) was derived from storage, about 24 percent (153,370 acre-ft) was derived from decreases in evapotranspiration from layer 1, and about 5 percent (33,030 acre-ft) was derived from artificial recharge of wastewater and shrubbery-irrigation water (table 6). By the end of the simulation period, about 56,950 acre-ft of vertical leakage from layer 1 to layer 2 was projected to occur.

EXPLANATION FOR FIGURE 27

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODEL LAYER 2

RELATIVE CHANGE IN HYDRAULIC HEAD AS COMPARED WITH THE FINAL STEADY-STATE HEADS, IN FEET

8

7

6

Less than 5

Table 6. *Model composite water budget for management simulations 1, 2, and 3 for the period 1986-2015*

[Values are rounded]

Water-budget component	Cumulative quantity, 1986-2015, in acre-feet		
	Management simulation		
	1	2	3
Inflow:			
Natural recharge			
Layer 1 (upper)	0	0	0
Layer 2 (lower)	295,500	295,500	295,500
Artificial recharge			
Layer 1	32,070	32,070	32,070
Layer 2	960	960	960
Total inflow	328,530	328,530	328,530
Outflow:			
Evapotranspiration			
Layer 1	142,130	146,200	125,430
Layer 2	0	0	0
Pumpage			
Layer 1	0	0	0
Layer 2	645,780	645,780	645,780
Total outflow	787,910	791,980	771,210
Difference[1]	459,380	463,450	442,680
Storage depletion			
Layer 1	58,240	49,250	68,180
Layer 2	400,740	413,820	374,110
Total storage depletion	458,980	463,070	442,290

[1]In, theory, the difference (total outflow minus total inflow) values should be in exact agreement with total-storage-depletion values. The observed small differences between corresponding values are due to accumulation of small consistent errors and to independent rounding of large numbers.

The purpose of the second management simulation was to determine the response of the aquifer to pumping in the southwestern part of the valley. The Indian Wells Valley Water District (IWVWD) has considered placing several municipal supply wells in this area to alleviate the large water-level declines in the intermediate and Ridgecrest areas. In this simulation it was assumed that all IWVWD pumpage from the intermediate and Ridgecrest areas would be relocated to the southwestern part of the valley (fig. 28). The total IWVWD

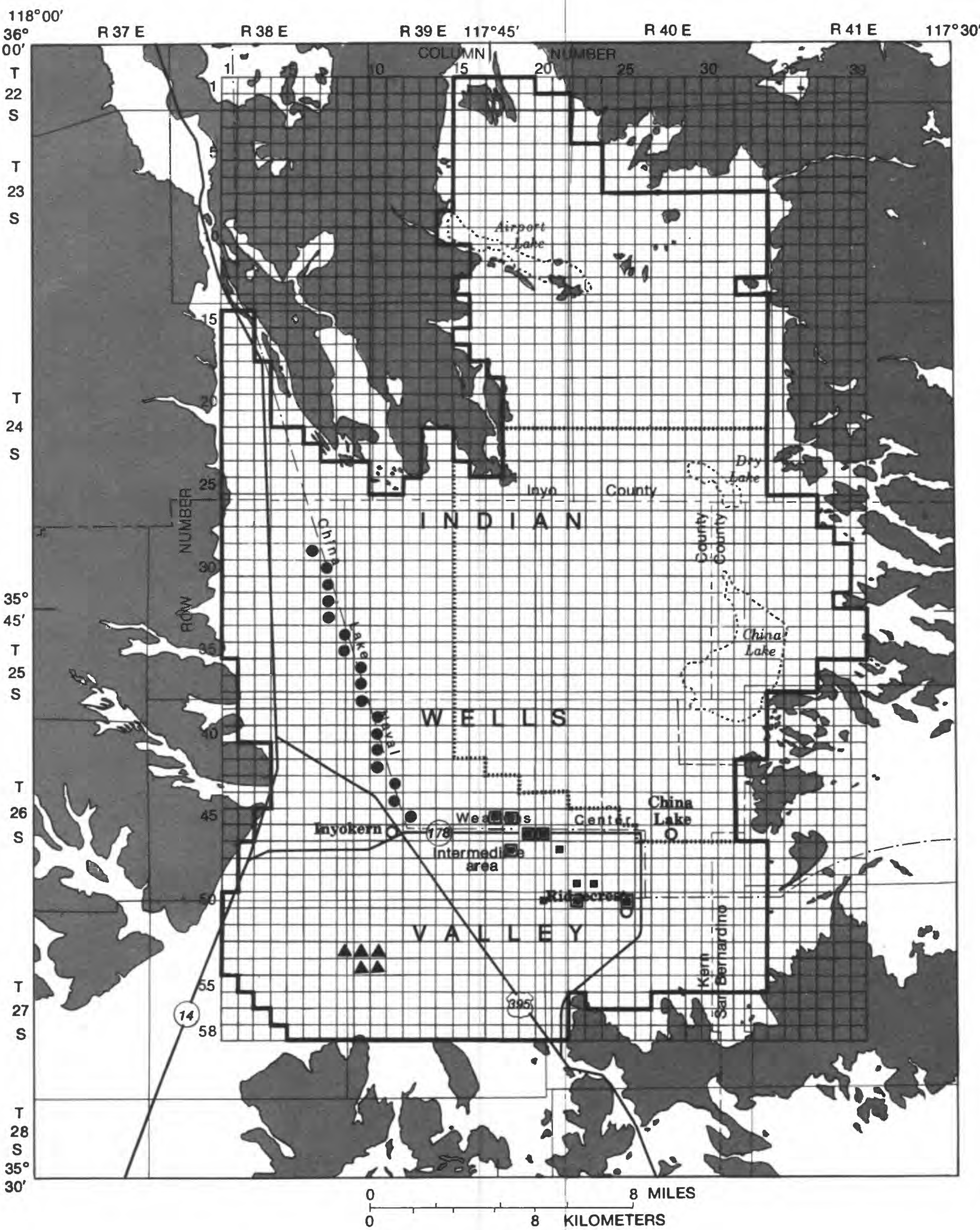


Figure 28. Location of selected model pumpage nodes for management simulations 1 through 3, 1986-2015.

EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA--
No-flow boundary for layers 1 and 2

BOUNDARY OF MODELED AREA--
Projected no-flow boundary for layer 1

MODEL NODES --

■ Municipal, military, and industrial pumpage in the intermediate and Ridgecrest areas for simulation 1

▲ Municipal (Indian Wells Valley Water District) pumpage for simulation 2

□ Military and industrial pumpage in the intermediate and Ridgecrest areas for simulation 2

● Relocated municipal, military, and industrial pumpage from the intermediate and Ridgecrest areas for simulation 3

pumpage in 1985 was about 5,000 acre-ft/yr (IWVWD, written commun., 1986) was divided equally into five model nodes in layer 2 (fig. 28). During the simulation period, model-simulated hydraulic heads in layer 2 declined by more than 50 feet in the southwestern part of the valley, whereas in the intermediate and Ridgecrest areas, declines ranged from less than 10 feet to about 20 feet (figs. 29 and 31). Model-simulated declines in hydraulic head in the northwestern and northeastern parts of the valley were about the same as projected in the first simulation. Model simulation 2 indicated that about 463,070 acre-ft of the water pumped from the system was withdrawn from storage, about 4,090 acre-ft greater than in simulation 1; model simulations also indicated that about 146,200 acre-ft was discharged by evapotranspiration from layer 1, about 4,070 acre-ft greater than in simulation 1 (table 6). By the end of the simulation period, about 47,390 acre-ft of water was induced to flow from layer 1 to layer 2; this is about 9,560 acre-ft less than in simulation 1.

Results of the second management simulation show that locating IWVWD pumpage in the southwestern part of the valley increases water-level declines in the Inyokern and southwestern areas while reducing declines in the intermediate and Ridgecrest areas. In addition, moving pumping away from layer 1 reduces the quantity of vertical leakage from layer 1 to layer 2.

The purpose of the third management simulation was to determine the response of the aquifer to spreading pumpage along the western part of the valley. The NWC, Kerr McGee Chemical Corporation, and IWVWD have considered relocating their total pumpage (about 11,000 acre-ft/yr in 1985) (Supplemental D) from the Ridgecrest and intermediate areas to the area along NWC's western boundary to alleviate water-level declines in the Ridgecrest and intermediate areas and to reduce the quantity of vertical leakage from layer 1 to layer 2. This pumpage was divided equally into

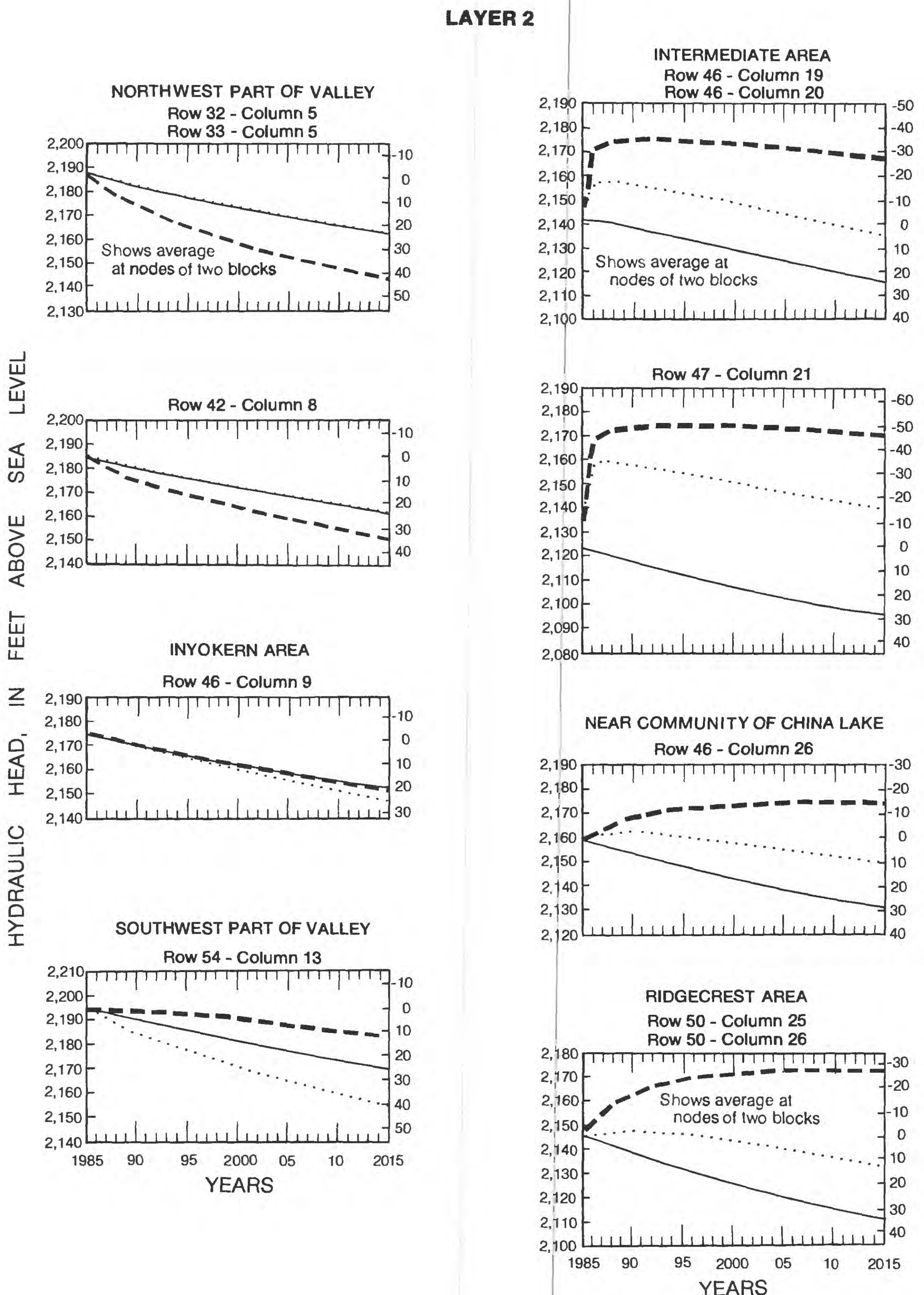
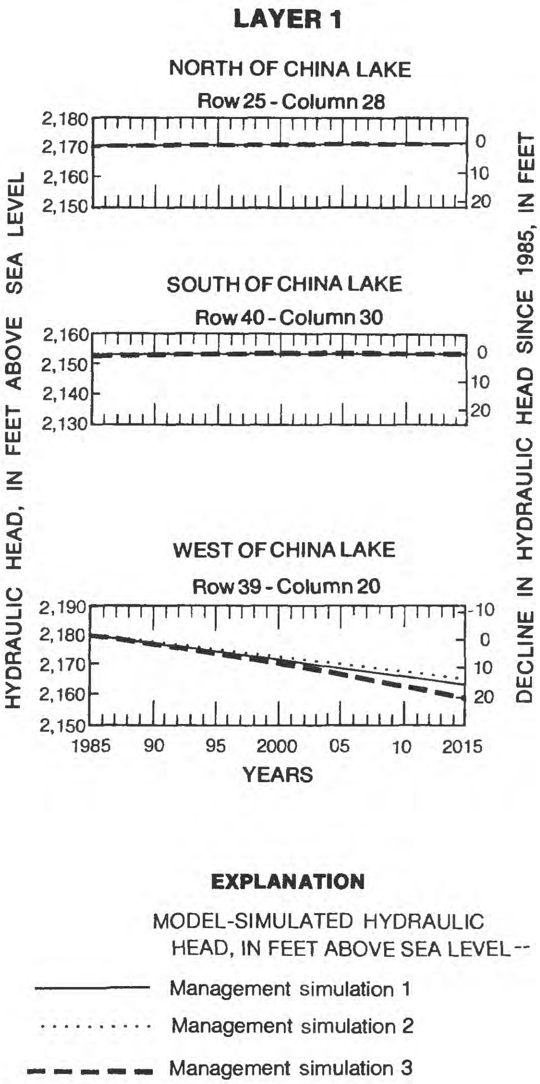


Figure 29. Model-simulated decline in hydraulic head at selected nodes for management simulations 1 through 3, 1986-2015. Negative values indicate rise in hydraulic head.



17 nodes along NWC's western boundary (fig. 28). During the simulation period, model-simulated heads in layer 2 declined by more than 30 feet along NWC's western boundary, whereas model-simulated hydraulic heads in the intermediate and Ridgecrest areas rose by as much as 30 feet (figs. 28 and 32). Model simulation 3 indicated that about 442,290 acre-ft of the water pumped from the system was withdrawn from storage, about 16,690 acre-ft less than in simulation 1; the model also indicated that about 125,430 acre-ft was discharged by evapotranspiration from layer 1, about 16,700 acre-ft less than in simulation 1 (table 6). Despite the higher model-simulated hydraulic heads in the intermediate and Ridgecrest areas, vertical leakage from layer 1 to layer 2 (about 68,400 acre-ft) was about 15,450 acre-ft more than in simulation 1. The largest fluxes of vertical leakage from layer 1 to layer 2 are projected to occur along the western perimeter of layer 1.

Results of the third simulation show that spreading pumpage along the western part of the valley reduces water-level declines near the intermediate and Ridgecrest areas while increasing water-level declines in the western part of the valley. However, because the pumpage in the third simulation is adjacent to a larger part of layer 1, the quantity of vertical leakage from layer 1 to layer 2 is greater than in the first and second simulations.

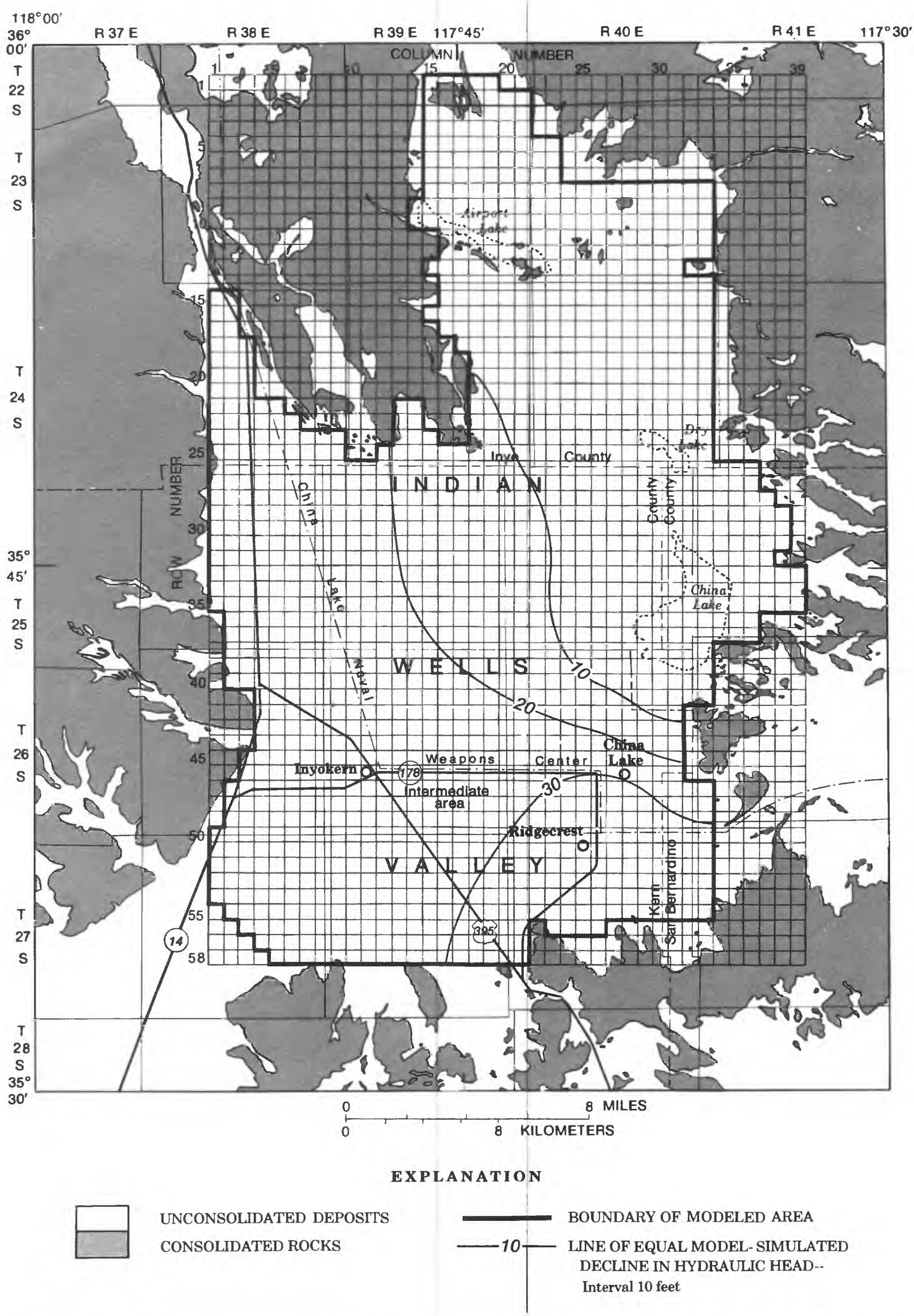
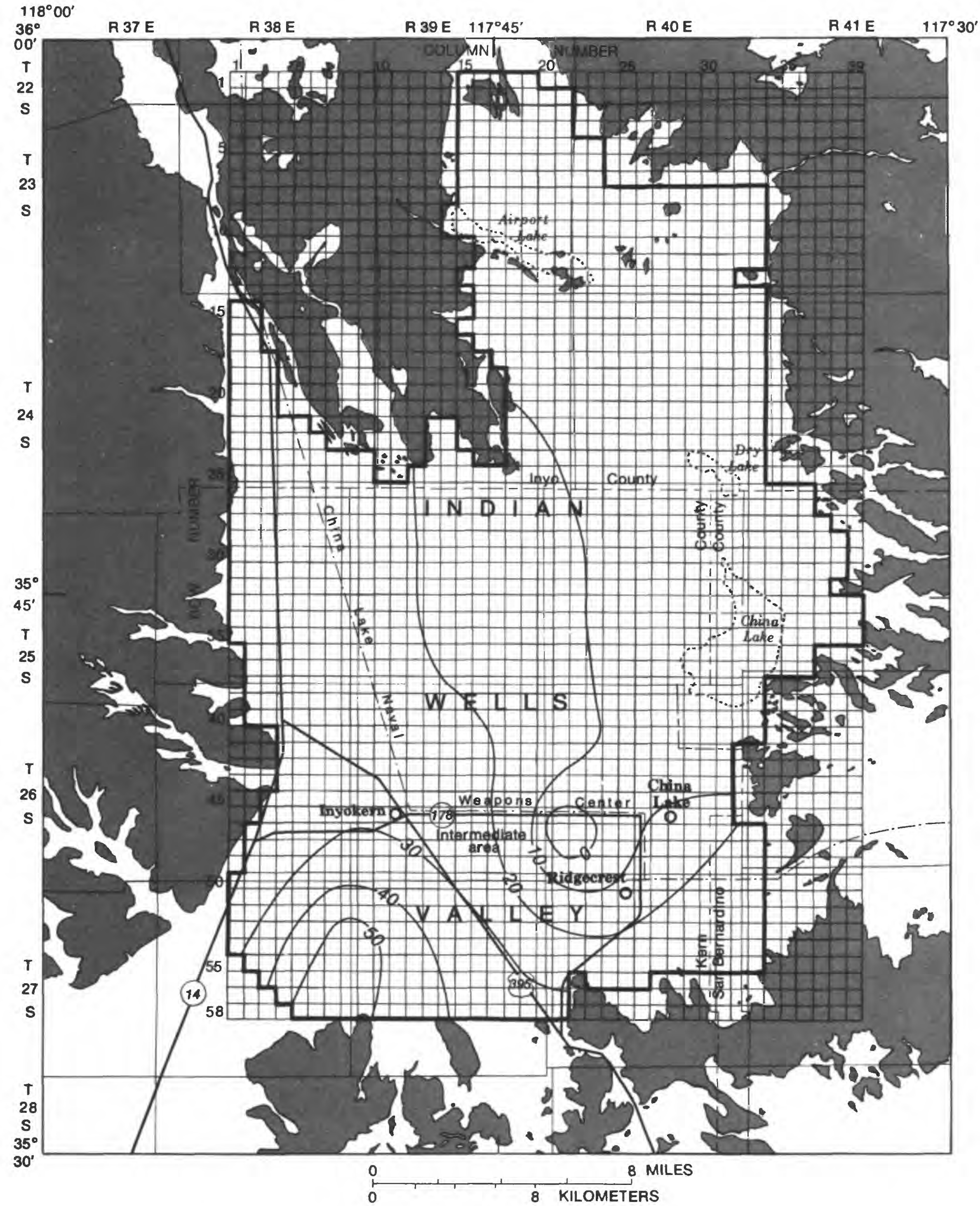


Figure 30. Model-simulated declines in hydraulic heads of layer 2 at the end of management simulation 1, 2015.



EXPLANATION

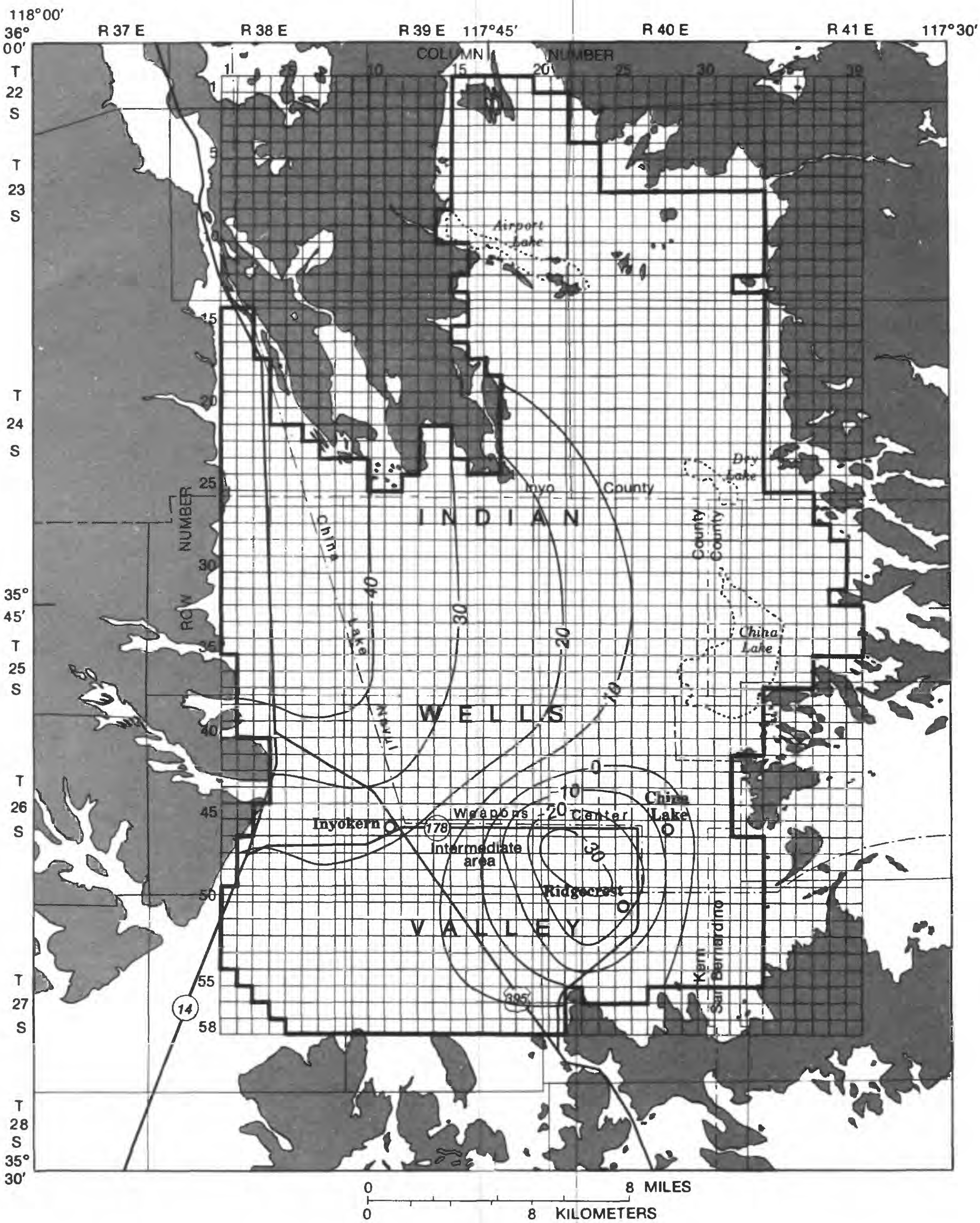
UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

—10— LINE OF EQUAL MODEL-SIMULATED DECLINE IN HYDRAULIC HEAD-- Interval 10 feet

Figure 31. Model-simulated declines in hydraulic heads of layer 2 at the end of management simulation 2, 2015.



EXPLANATION

UNCONSOLIDATED DEPOSITS

CONSOLIDATED ROCKS

BOUNDARY OF MODELED AREA

—20— LINE OF EQUAL MODEL-SIMULATED DECLINE IN HYDRAULIC HEAD-- Negative value indicates rise in head. Interval 10 feet

Figure 32. Model-simulated declines in hydraulic heads of layer 2 at the end of management simulation 3, 2015.

Limitations of the Model

A digital model can be a useful tool for projecting aquifer response to changes in the aquifer system. However, the accuracy with which a model can project aquifer response is directly related to the accuracy and adequacy of the input data used to calibrate the model. When using the model to make projections, it is important to realize the limitations of the model.

The Indian Wells Valley model has been calibrated to simulate long-term trends in hydraulic heads within specific parts of the modeled area. As shown in figures 19 and 20, the model closely matches measured water-level trends. However, in the northern part of the modeled area where there are few water-level measurements and where no stresses have been applied to the system, there is uncertainty about the accuracy of the model-simulated heads.

Because few data are available in the northern part of the valley, the recharge and transmissivity distribution determined by Bloyd and Robson (1971) for this area was used in the model with only slight modifications. However, model-simulated hydraulic heads in this part of the model are higher than available measured water levels (table 7); thus, these input data may be in error. Several steady-state and transient-state simulations were run to determine the effect on the model-simulated heads of decreasing the quantity of recharge originating along the Coso and Argus Ranges. The simulations with lower recharge rates more closely match the observed water levels (table 7). Lower recharge rates along the Coso and Argus Ranges, however, have little impact on model-simulated hydraulic heads in other parts of the model (table 7).

Results of these simulations suggest that more geohydrologic data would need to be collected before the northern part of the valley can be simulated adequately. In addition, the present model should not be used to project the response of the aquifer to any proposed management alternatives that may involve pumpage from the northern part of the valley. However, the model can be used to project the aquifer response in other parts of the valley.

Another limitation of the model is that the transmissivity values used to simulate layer 2 of the model do not change with time. Because transmissivity is calculated as a product of the saturated thickness of the layer and the average hydraulic conductivity, the model will underestimate hydraulic-head declines in areas of pumping if changes in the saturated thickness of layer 2 are large compared with the total thickness of the layer. As of 1985, changes in the saturated thickness of layer 2 are less than 10 percent of the total thickness of the layer and thus should have little impact on the transmissivity values used in the model.

The simulation of evapotranspiration is another major limitation of the model. The model simulates evapotranspiration as a linear relation although it is, in reality, a nonlinear relation. The linear relation used in the model closely approximates the nonlinear relation when the depth to ground water ranges from 3 to 6 feet below land surface. When the depth to ground water is less than 3 feet below land surface, however, the linear relation used in the model will underestimate the actual quantity of evapotranspiration.

Table 7.--*Comparison of measured water levels and model-simulated hydraulic heads in Indian Wells Valley using different rates of recharge from the Coso and Argus Ranges*

[Measured water levels and hydraulic heads in feet above sea level. --, no data]

Well No.	Model node		Earliest available water-level measurement		Steady-state model-simulated hydraulic head				1985-86 water-level measurement		1985 transient-state model-simulated hydraulic head			
					Total recharge, in acre-feet per year: 9,850	8,265	7,472	7,076			Total recharge, in acre-feet per year: 9,850	8,265	7,472	7,076
					Coso and Argus Ranges recharge, in acre-feet per year: 3,170	1,585	792	396			Coso and Argus Ranges recharge, in acre-feet per year: 3,170	1,585	792	396
	Row	Column	Date	Water level					Date	Water level				
Wells in the northern part of Indian Wells Valley														
23S/38E-22N1	9,10	16	1954	[1]2,197.00	2,293.11	2,235.33	2,206.32	2,191.78	--	--	2,293.04	2,235.25	2,206.24	2,191.70
24S/39E-26M1	23	18	6/13/60	2,187.40	2,241.31	2,188.65	2,186.40	2,185.25	--	--	2,187.84	2,183.33	2,181.02	2,179.80
26N1	23,24	18	6/20/60	2,187.00	2,216.76	2,188.77	2,186.76	2,185.03	--	--	2,187.06	2,183.02	2,180.95	2,179.85
33D1	24,25	14	1920	2,195.30	2,197.52	2,196.10	2,195.31	2,194.90	--	--	2,186.86	2,185.30	2,184.47	2,184.03
33D2	24,25	14	8/27/59	2,195.33	2,197.52	2,196.10	2,195.31	2,194.90	--	--	2,186.86	2,185.30	2,184.47	2,184.03
24S/40E-6A1	14	23,24	4/29/46	2,196.20	2,253.45	2,215.39	2,196.23	2,186.67	--	--	2,253.15	2,215.06	2,195.92	2,186.30
20J1	23	24	9/2/59	2,186.03	2,188.75	2,183.21	2,180.36	2,178.92	--	--	2,186.82	2,181.13	2,178.24	2,176.61
30J1	23	24	3/30/53	2,181.00	2,188.75	2,183.21	2,180.36	2,180.29	--	--	2,186.82	2,181.13	2,178.24	2,176.61
Wells in the western and southern parts of Indian Wells Valley														
25S/38E-23G1	32,33	5	1921	2,208.50	2,208.06	2,206.97	2,206.35	2,206.02	4/5/85	2,189.00	2,187.12	2,185.95	2,185.31	2,184.98
26S/40E-22P1	46	26	1920-21	[2]2,210	2,210.70	2,209.93	2,209.50	2,209.27	1/7/86	2,159.65	2,158.93	2,158.15	2,157.71	2,157.49
30K2	47	21	1920-21	[2]2,217	2,217.10	2,216.23	2,215.73	2,215.47	4/3/85	2,124.41	2,124.02	2,123.12	2,122.61	2,122.34
27S/40E-4C2	50	25,26	1920-21	[2]2,218	2,216.63	2,215.80	2,215.32	2,215.07	4/1/85	2,146.84	2,145.31	2,144.45	2,143.97	2,143.72

[1]Water level from St.-Amand (1986, p. 30).
[2]Estimated from contour map in figure 7.

SUMMARY

This report describes results of a study to update and evaluate the hydrologic data base compiled for a two-dimensional ground-water flow model previously developed for Indian Wells Valley and to analyze the three-dimensional aspects of the ground-water flow system.

The valley floor covers an area of about 300 mi^2 and is underlain by unconsolidated deposits that range in thickness from zero feet along the perimeter of the valley to about 2,000 feet in the west-central part. Beneath China Lake the unconsolidated deposits consist predominantly of silt and clay. In the remainder of the valley the unconsolidated deposits consist predominantly of sand, gravel, and silt. Consolidated rocks of low permeability form the lower and the perimeter boundaries of the aquifer system. The unconsolidated deposits were divided into shallow and deep aquifers by previous investigators. The shallow aquifer extends from China Lake westward to the center of the valley and from the area south of Airport Lake southward to the community of China Lake. The deep aquifer extends throughout the valley and underlies the shallow aquifer in the eastern part of the valley.

Prior to ground-water development in the valley, ground water moved through the deep aquifer from areas of recharge along the margins of the valley toward China Lake and into the shallow aquifer. Ground water was discharged by evapotranspiration from the shallow aquifer in and around China Lake, and recharge to the deep aquifer was balanced by evapotranspiration from the shallow aquifer. Estimates by previous investigators of evapotranspiration prior to ground-water development range from 9,850 to 31,600 acre-ft/yr. For this study, the evapotranspiration rate of 9,850 was determined to be the most reasonable.

Ground water is virtually the sole source of water supplies in Indian Wells Valley. From 1920 through 1985, ground-water pumpage, predominantly from the deep aquifer, increased from 1,000 to more than 22,000 acre-ft/yr. The pumping, centered in the intermediate area between Ridgecrest and Inyokern, has caused water levels in the deep aquifer to decline more than 80 feet in the intermediate area and has reversed the direction of ground-water movement in the deep aquifer in the area north and east of Ridgecrest. Ground water of poor quality (dissolved-solids concentration greater than 1,000 mg/L) underlies China Lake; therefore, the deep aquifer is subject to quality degradation west of China Lake in the areas of greatest pumpage. Available data from wells in the Ridgecrest area indicate that the dissolved-solids concentration of ground water has increased significantly in some wells.

A three-dimensional finite-difference ground-water flow model was developed and calibrated to steady-state conditions as represented by 1920-21 water levels and to transient-state conditions for 1920-85. Model calibration was considered acceptable when the difference between model-simulated heads and measured heads was 5 feet or less.

The initial values used for the quantity and distribution of recharge, the hydraulic conductivity of layer 1, and the transmissivity of layer 2 were based on a previous flow model that was developed for Indian wells Valley. The major differences between the values used in the previous model and the values used in the calibration of this model are: (1) the recharge distribution used in this model was based on drainage areas of streams that contribute recharge, and it was not modified during calibration, and (2) low values of transmissivity were not used to simulate barriers or faults in this model.

From 1920 to 1985, 548,900 acre-ft of ground water was pumped from the aquifer system. Results of the transient-state simulation indicate that about 86 percent (469,560 acre-ft) of this pumpage was derived from storage, about 10 percent (54,380 acre-ft) was derived from decreases in evapotranspiration from layer 1, and about 4 percent (24,410 acre-ft) was derived from artificial recharge of wastewater and shrubbery-irrigation water. The model indicated that pumping induced about 28,870 acre-ft of ground water to flow from layer 1 to layer 2, and the annual rate of vertical leakage increased from zero to about 1,550 acre-ft. Vertical leakage from layer 1 to layer 2 was simulated as occurring on the western and southern perimeters of layer 1, adjacent to the areas of greatest pumpage. Because layer 1 contains ground water of poor quality, leakage of ground water from layer 1 to layer 2 could degrade the quality of water in layer 2.

The calibrated model was used to simulate several suggested management alternatives designed to control water-level declines in the intermediate and Ridgecrest areas and to decrease the quantity of leakage from the shallow aquifer to the deep aquifer. Results of simulations indicate that redistributing pumpage from the intermediate and Ridgecrest areas to either the southwestern or western parts of the valley reduces water-level declines in the intermediate and Ridgecrest areas. However, vertical leakage from layer 1 to layer 2 is reduced only if pumpage is redistributed to the southwestern part of the valley.

The model developed and calibrated for this study closely duplicates measured water levels over long periods throughout most of the modeled area. However, in the northern part of the valley where there are few water-level measurements and where no stresses have been applied to the system, there is uncertainty about the accuracy of the model-simulated hydraulic heads. Additional geohydrologic data would need to be collected before the northern part of the valley can be simulated adequately.

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Supplemental Data A: *Estimates of annual recharge from the percolation of wastewater to the ground-water system in Indian Wells Valley, 1953-85*

[All values in acre-feet per year. Potential evaporation is estimated by multiplying the area of sewage ponds by the potential evaporation rate of 80 inches per year reported for ponded water in the valley (Farnsworth and others, 1982). --, no data; NWC, China Lake Naval Weapons Center]

Year	Waste-water inflow	Potential evapora-tion	Diverted flow to NWC golf course	Estimated recharge
RIDGECREST REGIONAL WASTEWATER TREATMENT FACILITY				
1953	1,246	[3]255	373	619
1954	1,430	255	372	803
1955	1,532	255	372	905
1956	1,554	255	372	927
1957	1,458	255	372	831
1958	1,593	255	513	825
1959	1,573	255	506	812
1960	1,392	[5]603	475	314
1961	1,429	603	686	139
1962	1,557	603	755	198
1963	1,542	603	689	249
1964	1,534	603	761	170
1965	1,589	603	647	389
1966	1,604	603	733	268
1967	999	603	510	0
1968	1,589	603	510	475
1969	1,664	603	670	391
1970	1,739	603	670	466
1971	1,814	603	670	541
1972	1,889	603	670	616
1973	1,964	603	750	611
1974	2,039	603	750	686
1975	2,114	603	750	761
1976	2,189	603	750	836
1977	2,264	[7]1,440	750	74
1978	2,339	1,440	750	149
1979	2,414	1,440	1,000	0
1980	2,500	1,440	1,000	60
1981	2,623	1,440	1,000	183
1982	2,698	1,440	1,000	258
1983	2,881	1,440	1,000	441
1984	3,224	1,440	1,120	664
1985	3,529	1,440	1,120	969

Year	Waste-water inflow	Potential evapora-tion	Diverted flow to alfalfa fields	Estimated recharge
RIDGECREST SANITATION DISTRICT TREATMENT PLANT[1]				
1953	--	--	--	--
1954	500	[4]133	388	0
1955	600	133	388	79
1956	600	133	388	79
1957	600	133	388	79
1958	650	133	388	129
1959	650	133	388	129
1960	650	133	388	129
1961	700	133	388	179
1962	700	133	388	179
1963	700	133	388	179
1964	750	133	388	229
1965	750	133	388	229
1966	750	133	388	229
1967	790	133	388	269
1968	790	133	388	269
1969	790	133	388	269
1970	790	133	388	269
1971	790	133	388	269
1972	790	133	388	269
1973	790	133	388	269
1974	790	133	388	269
1975	790	133	388	269
1976	790	133	388	269
1977	--	--	--	--
1978	--	--	--	--
1979	--	--	--	--
1980	--	--	--	--
1981	--	--	--	--
1982	--	--	--	--
1983	--	--	--	--
1984	--	--	--	--
1985	--	--	--	--

Year	Waste-water inflow	Potential evapora-tion	Estimated recharge
INYOKERN COMMUNITY SERVICES DISTRICT PLANT[2]			
1953	--	--	--
1954	--	--	--
1955	--	--	--
1956	--	--	--
1957	--	--	--
1958	--	--	--
1959	--	--	--
1960	--	--	--
1961	--	--	--
1962	--	--	--
1963	--	--	--
1964	--	--	--
1965	--	--	--
1966	--	--	--
1967	--	--	--
1968	--	--	--
1969	--	--	--
1970	--	--	--
1971	--	--	--
1972	--	--	--
1973	16	[6]40	0
1974	24	40	0
1975	27	40	0
1976	20	40	0
1977	19	40	0
1978	30	40	0
1979	40	40	0
1980	51	40	11
1981	61	40	21
1982	72	40	32
1983	58	40	18
1984	72	40	32
1985	72	40	32

[1]Since 1976, all wastewater from the city of Ridgecrest has been diverted to the Ridgecrest Regional Wastewater Treatment Facility.

[2]Operation of plant began in 1973.

[3]Based on evaporation-pond area of about 38 acres.

[4]Based on evaporation-pond area of 20 acres.

[5]Based on evaporation-pond area of about 90 acres.

[6]Based on evaporation-pond area of 6 acres.

[7]Based on evaporation-pond area of about 216 acres.

Supplemental Data B: *Water-level measurements at selected wells in Indian Wells Valley used to represent 1920-21 ground-water conditions*

[Data are from U.S. Geological Survey files and from Moyle (1968). Site number indicates location of well in figure 7. Date given is year or month, day, and year water level was measured. Altitude of land surface and altitude of water level in feet above sea level. Depth of well in feet below land surface; --, no data.]

Site No.	Well No.	Altitude of land surface	Depth of well (feet)	Date	Altitude of water level	Monitored aquifer
1	24S/38E-35E1	2,417.8	213	1921	2,209.3	Deep
2	24S/39E-33D1	2,263.3	57.6	2/03/20	2,195.3	Deep
3	33N1	2,254.5	161.4	2/03/20	2,195.0	Deep
4	25S/38E-23G1	2,412	259	1921	2,208.5	Deep
5	23K1	2,440	242.5	1921	2,203	Deep
6	24C1	2,329	135	1921	2,206	Deep
7	35B1[1]	2,402.8	298	1920	2,217.8	Deep
8	35M1	2,454	350	1921	2,210	Deep
9	25S/39E-1N1	2,213	--	2/03/20	2,190.2	Shallow
10	2E1	2,227.4	210.5	2/03/20	2,190.9	Shallow
11	2M1	2,226.2	30	2/03/20	2,190.6	Shallow
12	3P1	2,235.6	--	1921	2,194.1	Shallow
13	4F1	2,265	--	2/03/20	2,197.33	Deep
14	4P1	2,265	145	2/03/20	2,187	Deep
15	7K1	2,301.7	57	1920	2,202.7	Deep
16	8G1	2,280	75	2/03/20	2,206.2	Deep
17	9G1	2,255	62.3	1921	2,196.5	Deep
18	10Q1	2,240	45	1921	2,194	Shallow
19	11N1	2,228.1	107	1921	2,194.1	Shallow
20	12N1	2,211.00	162	1921	2,187	Shallow
21	12R1	2,200.9	180.5	1921	2,183.9	Shallow
22	14N1	2,224.1	200	1921	2,192.1	Shallow
23	15C1	2,240	150	1920	2,196	Shallow
24	17D1	2,271.1	88	1921	2,202.1	Deep
25	18N1	2,280	128	1921	2,205	Deep
26	19K1	2,244	231	1921	2,204	Deep
27	20P1	2,250	--	1921	2,214	Deep
28	21D1	2,237.3	46.7	1921	2,200.3	Deep
29	21M1	2,231	--	1921	2,196.5	Deep
30	21P1	2,226.9	35.8	1920	2,194.9	Deep
31	22D1	2,229.8	101	1921	2,194.8	Deep
32	23D1	2,220.4	24	1921	2,190.4	Shallow
33	24D1	2,209.8	26.7	1921	2,189.8	Shallow
34	24D2	2,203.5	--	1921	2,183.5	Shallow
35	26D2	2,212.4	21	1921	2,192.9	Shallow
36	26E1	2,212	15	1921	2,191.5	Shallow
37	27M1	2,221.5	25	1920	2,193.5	Deep
38	28P1	2,228.9	160.7	1921	2,198.4	Deep
39	29B1	2,228.8	--	1921	2,197.3	Deep
40	30B1	2,240	16.9	1921	2,207.5	Deep
41	32E1	2,248	44	1921	2,202.5	Deep
42	32N1	2,257.8	51.8	1921	2,204.8	Deep
43	32R1	2,266	--	1921	2,205	Deep
44	33Q1	2,260.5	60.2	1921	2,200.5	Deep
45	34R1	2,251.2	58.5	1921	2,194.2	Shallow
46	25S/40E-7M1	2,197.2	148	1920	2,182	Shallow
47	18B1	2,195	160	1921	2,181	Shallow
48	31N1	2,200.1	16.3	1920	2,195.1	Shallow
49	26S/38E-1A1	2,310	105	1920	2,215	Deep
50	2Q1	2,429.6	269.7	1920	2,214.6	Deep
51	24G1	2,479.4	--	1921	2,212.4	Deep

See footnote at end of table.

Supplemental Data B: *Water-level measurements at selected wells in Indian Wells Valley used to represent 1920-21 ground-water conditions*--Continued

Site No.	Well No.	Altitude of land surface	Depth of well (feet)	Date	Altitude of water level	Monitored aquifer
52	26S/39E-2D1	2,258.8	97.8	1/27/20	2,195.9	Shallow
53	4H1	2,276.1	68.3	1920	2,206.1	Deep
54	26S/39E-6M2	2,315	--	1920	2,205	Deep
55	11E2	2,305	220	1/27/20	2,210.3	Shallow
56	12N1	2,301	108.9	1921	2,204	Shallow
57	13D1	2,305	--	1/27/20	2,196	Shallow
58	13P1	2,335.7	134.4	1/27/20	2,206.2	Deep
59	15Q1	2,365.6	272.9	1/20/20	2,205.6	Deep
60	17F1	2,361.1	147.5	1921	2,210.1	Deep
61	23E1	2,372.3	190	1/27/20	2,209.3	Deep
62	24E1	2,355.8	148.2	1921	2,206.3	Deep
63	25D1	2,372.9	272	1920	2,212.9	Deep
64	25Q1	2,378.8	--	1920	2,208.8	Deep
65	29G1	2,435	427	1920	2,204	Deep
66	26S/40E-1P1	2,165	--	1/30/20	2,162.1	Shallow
67	3N1	2,184.5	--	1920	2,171.5	Shallow
68	4E1	2,185	--	1921	2,170.5	Shallow
69	4N1	2,195	--	1920	2,177	Shallow
70	5Q1	2,205	--	1/29/20	2,173.3	Shallow
71	6E1	2,231.8	45	1/--/21	2,192.8	Shallow
72	7E1	2,271.1	86	1921	2,196.1	Shallow
73	8A1	2,205	208	1/29/20	2,174	Shallow
74	8Q1	2,254.7	56.9	1921	2,185.7	Shallow
75	9F1	2,215	--	1921	2,184	Shallow
76	9G1	2,209.5	27.3	1920	2,177.5	Shallow
77	10E1	2,199.2	11.6	1/19/20	2,175.2	Shallow
78	10N1	2,214.6	134.2	1921	2,173.1	Shallow
79	11N1	2,192	10	1921	2,172	Shallow
80	15E1	2,223.2	110.1	1921	2,174.7	Shallow
81	15N1	2,241.1	225	1921	2,183.6	Shallow
82	16B1	2,225	--	1921	2,175	Shallow
83	17E1	2,276.2	69	1921	2,197.2	Shallow
84	17N1	2,293	178.1	1921	2,206	Shallow
85	18E1	2,297	119.4	1921	2,201	Shallow
86	18E2	2,295	90	1921	2,205	Shallow
87	18N1	2,316.1	175.85	1921	2,208.1	Deep
88	22R1	2,250	--	1/13/20	2,193.6	Shallow
89	23N1	2,250	--	1/13/20	2,203	Shallow
90	30C2	2,337.9	--	1921	2,204.9	Deep
91	30E1	2,351.1	135.1	1921	2,209.1	Deep
92	33N1	2,325	--	1920	2,220	Deep
93	34R1	2,264	72	1/13/20	2,204.4	Deep
94	35N1	2,261.5	29.2	1/31/20	2,206.5	Deep
95	35Q1	2,258	--	1921	2,210	Deep
96	26S/41E-7N1	2,180	--	1/30/20	2,166.7	Shallow
97	27S/38E-1M1	2,639	305.6	1921	2,345	Deep
98	27S/40E-1E1	2,280	90	1920	2,205	Deep
99	1M1	2,296.3	199	1920	2,201.3	Deep
100	1N1	2,325	--	1921	2,232	Deep
101	1N2	2,325	--	1921	2,232	Deep
102	2N1	2,280	--	1920	2,200	Deep
103	10B1	2,292.5	170.8	1920	2,205.5	Deep
104	10D1	2,301.3	--	1920	2,206.3	Deep

[1]The perforated interval for this well, 25S/38E-35B1, is 200-298 feet below land surface.

Supplemental Data C: *Water-level measurements at selected wells in Indian Wells Valley used to represent spring 1985 ground-water conditions*

[Site No. indicates location of well in figure 8. Altitude of land surface and altitude of water level in feet above sea level. Depth of well and perforated interval in feet below land surface. --, no data]

Site No.	Well No.	Altitude of land surface	Depth of well	Perforated interval	Date	Altitude of water level	Monitored aquifer
1	24S/38E-33J2	2,480	375	240-375	5/14/85	2,208.62	Deep
2	24S/39E-33N1	2,254.5	161	--	4/23/85	2,189.90	Deep
3	24S/40E-32H1	2,178.8	111.5	--	4/22/85	2,175.52	Shallow
4	33N1	2,175.8	15.9	--	4/22/85	2,172.61	Shallow
5	34E1	2,176.7	21.9	--	4/22/85	2,171.73	Shallow
6	25S/38E-13L1	2,320	444	109-444	4/04/85	2,184.54	Deep
7	23G1	2,412	259	--	4/05/85	2,189.00	Deep
8	25L1	2,239.2	--	212-232	4/04/85	2,185.83	Deep
9	35B1	2,402.8	298	200-298	5/14/85	2,195.72	Deep
10	25S/39E-2E1	2,227.4	210.5	--	4/23/85	2,187.63	Shallow
11	11N1	2,228.1	107	--	4/23/85	2,188.47	Shallow
12	12R1	2,200.9	180.5	--	4/22/85	2,181.52	Shallow
13	17D1	2,271.1	88	--	4/23/85	2,188.67	Deep
14	22J1	2,215.4	144	--	4/24/85	2,187.37	Shallow
15	26H1	2,202.8	186	--	5/13/85	2,185.01	Shallow
16	28P1	2,228.9	160.7	--	4/24/85	2,191.02	Deep
17	28R1	2,227.9	122.4	--	4/24/85	2,190.11	Deep
18	29M1	2,232	140.7	--	4/23/85	2,190.31	Deep
19	31E1	2,283.7	164	--	4/04/85	2,184.26	Deep
20	25S/40E-8A1	2,183.18	18.8	12.8-18.8	4/22/85	2,176.59	Shallow
21	11K1	2,166.4	62.3	--	4/22/85	2,170.20	Shallow
22	12Q1	2,160.6	14.5	--	4/22/85	2,157.70	Shallow
23	18R1	2,183	31.3	--	4/23/85	2,180.25	Shallow
24	19L1	2,281.2	10.7	--	4/23/85	2,172.22	Shallow
25	20F1	2,179.5	182.6	--	4/23/85	2,178.74	Shallow
26	27E1	2,168.7	18.7	9.2-18.7	4/22/85	2,165.53	Shallow
27	33L1	2,171.1	171	70-90, 110-130	4/23/85	2,170.19	Shallow
28	33L2	2,171	22	2-22	4/23/85	2,169.27	Shallow
29	35P1	2,158.8	15.4	8.3-15.4	4/22/85	2,151.03	Shallow
30	25S/41E-19L1	2,157.8	23.5	21.9-23.5	4/02/85	2,155.70	Shallow
31	28B1	2,238.6	161.8	127-161.8	4/02/85	2,171.21	Shallow
32	26S/38E-26G1	2,600	502	442-502	4/04/85	2,232.65	Deep
33	35B1	2,575	400	340-400	5/14/85	2,234.99	Deep
34	26S/39E-2C1	2,248.3	76.4	--	4/24/85	2,188.77	Shallow
35	2N1	2,285.7	158.5	--	4/23/85	2,189.17	Shallow
36	5F1	2,276.7	200	100-200	4/24/85	2,190.61	Deep
37	7N1	2,394.3	368	--	4/04/85	2,189.13	Deep
38	8E1	2,318	880	570-880	5/13/85	2,188.05	Deep
39	8K1	2,321	180.2	--	4/24/85	2,190.42	Deep
40	11E1	2,305	250	--	4/23/85	2,189.18	Shallow
41	12G1	2,276	137	--	4/03/85	2,188.91	Shallow
42	14E1	2,334.2	242.3	--	4/24/85	2,185.94	Deep
43	17F2	2,355	881	681-881	5/13/85	2,186.81	Deep
44	19Q1	2,418.3	371	251-371	4/04/85	2,186.16	Deep
45	24K1	2,347.4	323.1	190-197, 230-278, 287-301	4/03/85	2,148.74	Deep
46	26C1	2,394.9	249	--	4/04/85	2,155.15	Deep
47	28B6	2,417	365	280-365	4/04/85	2,178.48	Deep
48	30F1	2,433.5	385	250-321, 369-386	4/25/85	2,187.91	Deep
49	26S/40E-1A2	2,157.6	197.5	80-100, 110-130, 170-190	4/22/85	[1]2,157.60	Shallow
50	1J1	2,161.78	18	--	4/03/85	2,158.98	Shallow
51	1Q1	2,161.6	21.8	--	4/02/85	2,158.84	Shallow
52	1Q2	2,159.7	21.6	--	4/02/85	2,155.57	Shallow
53	5P1	2,206	125	40-98	4/23/85	2,176.90	Shallow

See footnote at end of table.

Supplemental Data C: *Water-level measurements at selected wells in Indian Wells Valley used to represent spring 1985 ground-water conditions*--Continued

Site No.	Well No.	Altitude of land surface	Depth of well	Perforated interval	Date	Altitude of water level	Monitored aquifer
54	26S/40E-10F1	2,188.8	43.3	37-43.3	4/03/85	2,172.60	Shallow
55	11J1	2,173.9	18.3	--	4/02/85	2,171.29	Shallow
56	12A1	2,167.8	21.4	--	4/02/85	2,164.83	Shallow
57	12G1	2,170.4	22.3	--	4/02/85	2,164.70	Shallow
58	12Q1	2,175.7	21.8	--	4/02/85	2,175.11	Shallow
59	12R1	2,181.5	20.9	--	4/02/85	2,181.43	Shallow
60	13C1	2,189.1	21.5	--	4/02/85	2,185.21	Shallow
61	13M1	2,196.2	22.2	--	4/02/85	2,189.09	Shallow
62	14B1	2,186.5	22	20-22	4/01/85	2,185.07	Shallow
63	14L1	2,201	57	55-57	4/01/85	2,193.24	Shallow
64	15E1	2,223.2	110.1	--	4/03/85	2,179.69	Shallow
65	15E2	2,226.1	197.8	--	4/03/85	2,181.05	Shallow
66	15N1	2,241.1	225	--	4/23/85	2,184.20	Shallow
67	15N2	2,234.8	101	99-101	4/03/85	2,180.90	Shallow
68	17N1	2,293	178.1	--	4/25/85	2,160.31	Shallow
69	18E1	2,297	119.4	--	4/24/85	2,190.46	Shallow
70	19P1	2,336	261	192-220, 253-259	5/13/85	2,147.20	Deep
71	20N1	2,311.9	190.1	--	4/02/85	2,154.31	Deep
72	22H1	2,226.62	49	47-49	4/02/85	2,205.93	Shallow
73	22H2	2,227.03	77	75-77	4/02/85	2,206.72	Shallow
74	22H3	2,226.23	97	95-97	4/01/85	2,206.31	Shallow
75	22P1	2,258.7	830	530-830	4/02/85	2,163.65	Deep
76	22P2	2,262.8	75	73-75	5/12/85	2,224.05	Shallow
77	22P3	2,260	415	400-415	4/02/85	2,167.78	Deep
78	22P4	2,260	215	200-215	4/02/85	2,222.05	Shallow
79	23B2	2,217.46	52	50-52	4/02/85	2,188.39	Shallow
80	23B3	2,217.71	77	75-77	4/01/85	2,189.40	Shallow
81	23C1	2,213.75	40.2	--	4/23/85	2,194.65	Shallow
82	23D1	2,223	400	385-400	4/05/85	2,189.24	Deep
83	23D2	2,223	185	170-185	4/05/85	2,194.17	Shallow
84	23J1	2,228.32	60	58-60	4/01/85	2,189.04	Shallow
85	24C1	2,211.98	45.4	43.5-45.5	4/02/85	2,186.79	Shallow
86	24M1	2,226.85	67	65-67	4/02/85	2,186.60	Shallow
87	26F1	2,225	77	75-77	4/01/85	2,187.44	Deep
88	28J1	2,288.9	--	--	4/15/85	2,167.81	Deep
89	30K2	2,340	760	220-470, 600-760	4/03/85	2,117.41	Deep
90	32D1	2,340.9	279	--	4/23/85	2,139.92	Deep
91	33P4	2,300	304	169-182, 198-216, 233-252, 256-272, 278-290	4/01/85	2,133.72	Deep
92	35Q2	2,251.47	127	125-127	4/01/85	2,182.48	Deep
93	36A1	2,247.2	270.2	80-90, 107-127, 187-195, 240-260	4/01/85	2,174.13	Deep
94	26S/41E-7D1	2,160.2	21.2	--	4/03/85	2,158.68	Shallow
95	7E1	2,166.46	36	30-36	4/02/85	2,161.70	Shallow
96	7G1	2,177	31.5	29.5-31.5	4/02/85	2,156.75	Shallow
97	27S/38E-1G1	2,555	399	344-399	4/11/85	2,211.14	Deep
98	27S/39E-2B1	2,440	288	--	4/04/85	2,177.79	Deep
99	27S/40E-1K1	2,318.1	--	--	4/23/85	2,181.78	Deep
100	3R1	2,287.31	162.3	--	4/01/85	2,182.07	Deep
101	4A1	2,305	273	--	4/01/85	2,160.23	Deep
102	4C2	2,315	280	150-280	4/01/85	2,143.74	Deep
103	10R1	2,380	262.5	--	4/01/85	2,174.10	Deep
104	15D1	2,385	240	--	4/01/85	2,172.28	Deep
105	15L1	2,470	277.5	--	4/01/85	2,213.30	Deep

[1]Well flowing. Value represents the altitude-measuring point of the well.

Supplemental Data D1: *Annual pumpage from*

[All values in acre-feet per year. Pumpage data for the period 1928-68 based on Bloyd and Robson (1971, p. 19-20). --, no pumpage. For

Well No.	Model node Row	Model node Column	1920	1921	1922	1923	1924	1925	1926	1927
				Ridgecrest area						
	49	25	--	--	--	--	--	--	--	--
	47	26	--	--	--	--	--	--	--	--
	47	24	--	--	--	--	--	--	--	--
	52	26,27	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
26S/40E-32E1	49	22	--	--	--	--	--	--	--	--
26S/40E-33A1	48,49	25,26	--	--	--	--	--	--	--	--
26S/40E-33P2,-33P4, 27S/40E-4C1,-4C2	50	24,25	--	5	5	5	5	5	5	5
26S/40E-34N1	50	26	--	--	--	--	--	--	--	--
27S/40E-4L1	51	25	--	--	--	--	--	--	--	--
Subtotal			1,000	1,005	1,005	1,005	1,005	1,005	1,005	1,005
				Intermediate area						
	48	20	--	--	--	--	--	--	--	--
	48	19	--	--	--	--	--	--	--	--
26S/39E-23J1,-24M1	45	17,18	--	--	--	--	--	--	--	--
26S/39E-24K1	45,46	19	--	--	--	--	--	--	--	--
26S/39E-24Q1,-24P1	46	19	--	--	--	--	--	--	--	--
26S/39E-24R1, 26S/40E-19N1,-30E2	46	20	--	--	--	--	--	--	--	--
26S/39E-25D2	46,47	17,18	--	--	--	--	--	--	--	--
26S/39E-25E1	47	18	--	--	--	--	--	--	--	--
26S/39E-26D1,-26E1	47	16	--	--	--	--	--	--	--	--
26S/39E-28C2	46	12	--	--	--	--	--	--	--	--
26S/40E-19P1	46	20	--	--	--	--	--	--	--	--
26S/40E-30E1	47	20	--	--	--	--	--	--	--	--
26S/40E-30K1	47	21	--	--	--	--	--	--	--	--
Subtotal			--	--	--	--	--	--	--	--
				Inyokern area						
26S/39E-19K1	45,46	9	--	--	--	--	--	--	--	--
26S/39E-19Q1,-19P1,-30C1	46	--	--	--	--	--	--	--	--	--
26S/39E-30F1,-30F3,-30J1	47	9	--	10	10	10	10	10	10	10
Subtotal			--	10	10	10	10	10	10	10
				Other areas						
	42	8	--	--	--	--	--	--	--	--
25S/39E-4R1	27,28	14	--	--	--	--	--	--	--	--
25S/39E-9J1	29	14	--	--	--	--	--	--	--	--
25S/39E-12R1	30	19,20	--	--	--	--	--	--	--	--
25S/39E-26H1	35	18	--	--	--	--	--	--	--	--
25S/39E-35N1	38	16	--	--	--	--	--	--	--	--
26S/39E-5F1	38,39	10,11	--	--	--	--	--	--	--	--
26S/39E-11E1	41	16	--	--	--	--	--	--	--	--
26S/40E-5P1	40	23	--	--	--	--	--	--	--	--
Subtotal			--	--	--	--	--	--	--	----
				Agricultural area (northwest)						
25S/38E-25P1	35,36	6,7	--	--	--	--	--	--	--	--
25S/39E-30N1	35,36	8	--	--	--	--	--	--	--	--
25S/39E-31E2	37	8	--	--	--	--	--	--	--	--
Subtotal			--	--	--	--	--	--	--	--
Total			1,000	1,015	1,015	1,015	1,015	1,015	1,015	1,015

those nodes for which there is no associated State well number, there is no entry under Well No. heading]

1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939
Ridgecrest area--Continued											
--	--	--	75	175	225	275	300	350	400	500	700
--	--	--	--	--	--	--	25	25	25	50	50
--	--	--	--	--	--	--	--	--	25	25	25
1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
--	--	--	--	--	--	--	--	--	--		--
--	--	--	--	--	--	--	--	--	--	--	--
5	5	105	205	205	205	205	205	205	205	255	305
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
1,005	1,005	1,105	1,280	1,380	1,430	1,480	1,530	1,580	1,655	1,830	2,080
Intermediate area--Continued											
--	--	--	--	--	50	100	150	200	250	300	300
--	--	--	--	--	--	--	--	--	--	--	100
--	--	--	--	--	--	--	--	--	--	--	--
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--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	5	100	150	200	250	300	400
Inyokern area--Continued											
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
10	10	20	20	20	20	20	20	20	20	20	20
10	10	20	20	20	20	20	20	20	20	20	20
Other areas--Continued											
--	--	--	5	5	5	5	5	5	5	5	5
--	--	--	--	--	--	--	--	--	--	--	--
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--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	5	5	5	5	5	5	5	5	5
Agricultural area (northwest)--Continued											
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--
1,015	1,015	1,125	1,305	1,405	1,505	1,605	1,705	1,805	1,930	2,155	2,505

Well No.	Model node Row	Model node Column	1940	1941	1942	1943	1944	1945	1946	1947
				Ridgecrest area						
	49	25	700	700	700	700	700	700	700	700
	47	26	50	50	50	50	50	50	50	50
	47	24	25	25	25	25	25	25	25	25
	52	26,27	1,000	1,000	738	888	1,253	943	1,076	602
26S/40E-32E1	49	22	--	--	--	--	--	--	--	--
26S/40E-33A1	48,49	25,26	--	--	--	--	--	--	--	--
26S/40E-33P2,-33P4, 27S/40E-4C1,-4C2	50	24,25	355	405	455	505	540	650	775	850
26S/40E-34N1	50	26	--	--	--	--	--	190	19	243
27S/40E-4L1	51	25	--	--	--	--	--	--	--	--
Subtotal			2,130	2,180	1,968	2,168	2,568	2,558	2,655	2,470
				Intermediate area						
	48	20	300	300	300	300	300	300	300	300
	48	19	0	0	0	0	0	0	0	0
26S/39E-23J1,-24M1	45	17,18	--	--	--	--	--	--	--	--
26S/39E-24K1	45,46	19	--	--	--	--	--	72	208	277
26S/39E-24Q1,-24P1	46	19	--	--	--	--	--	7	180	401
26S/39E-24R1, 26S/40E-19N1, -30E2	46	20	--	--	--	--	--	149	220	500
26S/39E-25D2	46,47	17,18	--	--	--	300	300	300	300	300
26S/39E-25E1	47	18	--	--	--	--	--	--	--	--
26S/39E-26D1,-26E1	47	16	2	2	2	2	2	2	2	2
26S/39E-28C2	46	12	--	--	--	--	--	--	--	--
26S/40E-19P1	46	20	--	--	--	--	--	--	180	271
26S/40E-30E1	47	20	--	--	--	--	--	--	--	--
26S/40E-30K1	47	21	--	--	--	--	--	--	--	--
Subtotal			302	302	302	602	602	830	1,390	2,051
				Inyokern area						
26S/39E-19K1	45,46	9	--	--	--	--	--	--	--	--
26S/39E-19Q1,-19P1,-30C1	46	9	--	--	--	--	--	182	123	44
26S/39E-30F1,-30F3,-30J1	47	9	25	25	25	25	25	25	25	28
Subtotal			25	25	25	25	25	207	148	72
				Other areas						
	42	8	5	5	5	5	5	5	5	5
25S/39E-4R1	27,28	14	--	--	--	--	--	--	--	--
25S/39E-9J1	29	14	--	--	--	--	--	--	--	--
25S/39E-12R1	30	19,20	--	--	--	--	--	--	2	2
25S/39E-26H1	35	18	--	--	--	--	--	--	--	--
25S/39E-35N1	38	16	--	--	--	--	--	--	--	--
26S/39E-5F1	38,39	10,11	--	--	--	--	--	--	--	--
26S/39E-11E1	41	17	--	--	--	--	--	--	--	--
26S/40E-5P1	40	23	--	--	--	--	--	--	--	--
Subtotal			5	5	5	5	5	5	7	7
				Agricultural area (northwest)						
25S/38E-25P1	35,36	6,7	--	--	--	--	--	--	--	--
25S/39E-30N1	35,36	8	--	--	--	--	--	--	--	--
25S/39E-31E2	37	8	--	--	--	--	--	--	--	--
Subtotal			--	--	--	--	--	--	--	--
Total			2,462	2,512	2,300	2,800	3,200	3,600	4,200	4,600

1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
Ridgecrest area--Continued												
700	600	500	400	350	300	250	250	250	150	100	50	50
50	50	50	50	50	50	50	50	50	50	50	50	25
25	25	25	25	25	25	25	25	25	25	25	25	0
470	279	208	189	289	894	352	745	703	382	47	71	686
--	--	--	--	--	--	--	--	--	--	35	35	35
--	--	--	35	40	40	45	45	50	50	30	30	30
925	1,000	1,070	935	960	987	1,132	1,246	1,319	1,319	1,714	1,896	1,911
236	301	613	139	69	145	37	123	165	139	313	245	45
--	--	--	140	150	160	170	175	185	205	261	295	298
2,406	2,453	2,566	2,013	1,983	2,651	2,311	2,659	2,717	2,320	2,575	2,697	3,081
Intermediate area--Continued												
300	300	300	300	300	300	300	300	250	250	250	250	250
0	0	0	0	0	0	0	0	0	0	0	0	0
--	--	--	--	--	--	--	--	--	--	--	--	--
276	283	227	128	111	32	0	0	0	0	0	0	0
644	685	712	592	536	475	311	314	180	251	747	583	1,009
							384	297	441	338	237	142
482	534	677	416	547	558	411						
300	300	300	200	211	187	100	100	100	111	99	103	92
--	--	--	100	100	100	100	100	98	100	99	103	92
2	2	5	5	5	5	5	5	5	5	5	5	5
--	--	--	--	--	--	--	--	--	--	35	35	35
302	257	340	263	237	222	130	100	86	50	115	50	50
--	--	--	--	--	--	100	100	100	111	99	103	92
--	--	--	--	--	--	--	--	--	--	--	--	--
2,306	2,361	2,561	2,004	2,047	1,979	1,457	1,302	1,016	1,319	1,787	1,469	1,767
Inyokern area--Continued												
--	--	--	--	--	--	--	--	--	--	--	--	--
246	742	829	1,441	2,069	2,007	3,221	2,720	3,473	4,017	3,079	3,780	3,989
35	35	36	1,034	738	1,192	1,040	1,847	1,628	1,308	1,475	1,570	1,279
281	777	865	2,475	2,807	3,199	4,261	4,567	5,101	5,325	4,554	5,350	5,268
Other areas--Continued												
5	5	0	0	0	0	0	0	0	0	0	0	0
--	--	--	--	--	1	1	1	1	1	1	1	1
--	--	--	--	--	1	1	1	1	1	2	2	2
2	2	2	2	2	2	2	2	2	2	4	4	4
--	--	--	--	--	5	5	5	5	5	6	6	6
--	--	5	5	5	5	5	5	5	5	9	9	9
--	--	--	--	--	1	1	1	1	1	1	1	1
--	--	--	--	5	5	5	5	5	5	5	5	5
--	--	1	1	1	1	1	1	1	1	1	1	1
7	7	8	8	13	21	21	371	436	21	29	29	29
Agricultural area (northwest)--Continued												
--	--	--	--	350	350	350	350	350	350	385	385	385
--	--	--	--	--	--	--	--	30	30	35	35	35
--	--	--	--	--	--	--	--	35	35	35	35	35
--	--	--	--	350	350	350	350	415	415	455	455	455
5,000	5,600	6,000	6,500	7,200	8,200	8,400	9,000	9,400	9,400	9,400	10,000	10,600

Supplemental Data D1: *Annual pumpage from wells in model layer 2 for the period 1920-68*--Continued

Well No.	Model node Row	Model node Column	1961	1962	1963	1964	1965	1966	1967	1968
				Ridgecrest area						
	49	25	0	0	0	0	0	0	0	0
	47	26	50	50	50	50	50	50	50	0
	47	24	25	25	25	25	25	25	25	0
	52	26,27	222	183	267	419	35	335	84	563
26S/40E-32E1	49	22	35	35	35	35	35	35	35	35
26S/40E-33A1	48,49	25,26	32	34	34	36	28	0	0	0
26S/40E-33P2,-33P4, 27S/40E-4C1,-4C2	50	24,25	1,980	2,122	2,214	2,059	2,164	2,012	2,014	1,998
26S/40E-34N1	50	26	254	368	2	0	0	0	0	0
27S/40E-4L1	51	25	318	338	379	431	481	449	403	466
Subtotal			2,916	3,155	3,006	3,055	3,043	2,906	2,611	3,062
				Intermediate area						
	48	20	250	250	250	250	250	250	250	0
	48	19	0	0	0	0	0	0	0	0
26S/39E-23J1,-24M1	45	17,18	--	--	4,026	3,387	3,565	2,933	3,665	3,161
26S/39E-24K1	45,46	19	0	0	0	0	0	0	0	0
26S/39E-24Q1,-24P1	46	19	716	971	1,303	1,450	1,447	1,081	1,259	887
26S/39E-24R1, 26S/40E-19N1, -30E2	46	20	167	200	212	215	218	248	275	251
26S/39E-25D1	46,47	17,18	117	150	162	165	168	198	225	251
26S/39E-25E1	47	18	117	150	162	165	168	198	225	251
26S/39E-26D1,-26E1	47	16	6	7	8	9	10	11	14	16
26S/39E-28C2	46	12	35	35	35	35	35	35	35	35
26S/40E-19P1	46	20	50	50	50	50	50	50	50	0
26S/40E-30E1	47	20	117	150	162	165	168	198	225	251
26S/40E-30K1	47	21	--	--	--	--	154	662	735	914
Subtotal			1,575	1,963	6,370	5,891	6,233	5,864	6,958	6,017
				Inyokern area						
26S/39E-19K1	45,46	9	--	--	765	904	459	1,107	1,241	964
26S/39E-19Q1,-19P1,-30C1	46	9	4,034	3,741	372	766	1,237	1,186	864	1,727
26S/39E-30F1,-30F3,-30J1	47	9	1,426	1,792	138	635	282	917	199	822
Subtotal			5,460	5,533	1,275	2,305	1,978	3,210	2,304	3,513
				Other areas						
	42	8	0	0	0	0	0	0	0	0
25S/39E-4R1	27,28	14	1	1	1	1	1	2	2	3
25S/39E-9J1	29	14	2	2	2	2	2	12	13	9
25S/39E-12R1	30	19,20	4	4	4	4	1	9	7	5
25S/39E-26H1	35	18	6	6	6	6	6	31	31	18
25S/39E-35N1	38	16	9	9	9	9	9	15	15	11
26S/39E-5F1	38,39	10,11	1	1	1	1	1	3	2	2
26S/39E-11E1	41	17	5	5	5	5	5	18	26	29
26S/40E-5P1	40	23	1	1	1	1	1	10	11	11
Subtotal			21	29	29	29	26	100	107	108
				Agricultural area (northwest)						
25S/38E-25P1	35,36	6,7	280	280	280	280	280	280	280	280
25S/39E-30N1	35,36	8	20	20	20	20	20	20	20	20
25S/39E-31E2	37	8	20	20	20	20	20	20	20	20
Subtotal			320	320	320	320	320	320	320	320
Total			10,300	11,000	11,000	11,600	11,600	12,400	12,300	13,000

Supplemental Data D2: *Annual pumpage from wells in model layer 2 for the period 1969-76*

[All values in acre-feet per year. Pumpage data for the period 1969-76 based on an average of 2-year periods from Mallory (1979, p. 16). --, no pumpage. For those nodes for which there is no associated State well number, there is no entry under Well No. heading]

Well No.	Model node Row	Model node Column	1969	1970	1971	1972	1973	1974	1975	1976
				Ridgecrest area						
	50	22	1,713	1,713	820	820	690	690	690	690
	50	24	0	0	585	585	591	591	599	599
	50	26	0	0	12	12	11	11	0	0
	51	22	75	75	85	85	90	90	80	80
	51	23	75	75	75	75	75	75	0	0
	52	23	150	150	180	180	200	200	231	231
	52	24	70	70	85	85	75	75	77	77
	53	22	70	70	85	85	75	75	77	77
26S/40E-32E1	49	22	35	35	33	33	28	28	23	23
26S/40E-33P2,-33P4, 27S/40E-4C1,-4C2	50	24,25	370	370	1,685	1,685	1,574	1,574	1,420	1,420
27S/40E-4L1	51	25	500	500	500	500	700	700	590	590
Subtotal			3,058	3,058	4,145	4,145	4,109	4,109	3,787	3,787
				Intermediate area						
	44	16	100	100	0	0	0	0	0	0
26S/39E-23J1,-24M1	45	17,18	3,847	3,847	3,388	3,388	2,915	2,915	2,741	2,741
26S/39E-24R1, 26S/40E-19N1	46	20	284	284	0	0	0	0	0	0
26S/39E-25D2	46,47	17,18	734	734	585	585	591	591	599	599
26S/39E-25E1	47	18	284	284	585	585	591	591	599	599
26S/39E-26D1,-26J1	47	16	16	16	19	19	26	26	33	33
26S/39E-28C2	46	12	35	35	30	30	23	23	18	18
26S/40E-24P1	46	19	593	593	1,000	1,000	1,133	1,133	689	689
26S/40E-30E1	47	20	284	284	0	0	0	0	0	0
26S/40E-30K1	47	21	980	980	1,275	1,275	1,475	1,475	1,993	1,993
Subtotal			7,157	7,157	6,882	6,882	6,754	6,754	6,672	6,672
				Inyokern area						
26S/39E-19K1	45,46	9	633	633	411	411	557	557	965	965
26S/39E-19Q1,19P1,-30C1	46	9	1,855	1,855	2,094	2,094	1,650	1,650	1,174	1,174
26S/39E-30F1,-30F3,-30J1	47	9	864	864	950	950	1,132	1,132	975	975
Subtotal			3,352	3,352	3,455	3,455	3,339	3,339	3,114	3,114
				Other areas						
25S/39E-4R1	27,28	14	12	12	4	4	9	9	13	13
25S/39E-9J1	29	14	0	0	17	17	11	11	7	7
25S/39E-12R1	30	19,20	5	5	11	11	6	6	2	2
25S/39E-26H1	35	18	17	17	8	8	10	10	11	11
25S/39E-35N1	38	16	11	11	3	3	3	3	3	3
25S/39E-5F1	38,39	10,11	0	0	4	4	5	5	5	5
26S/39E-11E1	41	17	29	29	29	29	34	34	40	40
26S/40E-5P1	40	23	11	11	48	48	17	17	18	18
Subtotal			85	85	124	124	95	95	99	99
				Agricultural area (northwest)						
25S/38E-25P1	35,36	7,6	280	280	250	250	150	150	60	60
25S/39E-30N1	35,36	8	20	20	60	60	175	175	400	400
25S/39E-31E2	37	8	20	20	60	60	175	175	400	400
Subtotal			320	320	370	370	500	500	860	860
Total			13,972	13,972	14,976	14,976	14,797	14,797	14,532	14,532

Supplemental Data D3: *Annual pumpage from wells in model layer 2 for the period 1977-85*

[All values in acre-feet per year. --, no pumpage. For those nodes for which there is no associated State well number, there is no entry under Well No. heading]

Well No.	Model node Row	Model node Column	1977	1978	1979	1980	1981	1982	1983	1984	1985
					Ridgecrest area						
	52	23	316	400	400	883	1,062	1,241	1,420	1,600	1,600
	51	22	90	100	100	100	100	100	100	100	100
	52	24	88	100	100	100	100	100	100	100	100
	53	22	88	100	100	100	100	100	100	100	100
26S/40E-32E1	49	22	11	0	0	0	0	0	0	0	0
26S/40E-32F3	49	22,23	0	0	0	0	0	0	5	502	531
26S/40E-32K1	49	23	0	630	847	842	833	1,174	1,046	806	743
26S/40E-33	50	24	424	29	13	11	28	0	0	0	0
27S/40E-4B1,-4B2	50	25	830	446	634	640	801	703	1,123	1,081	1,127
26S/40E-33P4, 27S/40E-4C2	50	24,25	556	207	90	275	284	100	269	0	0
27S/40E-4L1	51	25	124	257	183	91	0	0	0	0	0
27S/40E-5D1	50	22	795	1,611	1,307	1,661	1,262	1,184	595	249	159
Subtotal			3,322	3,880	3,774	4,703	4,570	4,702	4,758	4,538	4,460
					Intermediate area						
26S/39E-23J1,-24M1	45	17,18	2,212	1,684	1,092	447	467	493	790	1,219	776
26S/39E-24P1	46	19	1,266	1,844	1,582	980	1,551	744	1,192	1,219	1,025
26S/39E-25E1	47	18	593	587	459	568	621	632	510	460	820
26S/39E-26D1,-26E1	47	16	34	35	35	35	35	35	35	35	35
26S/39E-28C2	46	12	17	16	16	16	16	16	16	16	16
26S/40E-30E2	46	20	612	722	723	675	542	533	781	660	399
26S/40E-30K1, -30K2,-30K3	47	21	2,380	2,367	2,345	2,634	3,111	2,704	3,083	3,101	3,403
27S/40E-6D1	50	20	0	0	0	0	0	0	149	464	294
Subtotal			7,114	7,255	6,252	5,355	6,343	5,157	6,556	7,174	6,768
					Inyokern area						
26S/39E-19K1	45	9	710	456	644	1,267	714	1,176	889	670	1,350
26S/39E-19Q1,-19P1	46	9	1,256	1,340	1,789	1,892	2,022	1,605	1,585	1,641	1,119
26S/39E-30F3	47	9	70	39	70	226	0	407	0	0	0
26S/39E-30J1,-30J2	47	10	400	410	420	429	445	460	475	485	500
Subtotal			2,436	2,245	2,923	3,814	3,181	3,648	2,949	2,796	2,969
					Other areas						
24S/38E-16J1,-16J2	19	3	350	361	336	681	342	183	265	350	350
25S/39E-4R1	27,28	14	12	10	10	10	7	4	1	8	10
25S/39E-9J1	29	14	8	10	10	13	11	2	5	7	10
25S/39E-12R1	30	19,20	2	2	2	2	2	2	2	2	2
25S/39E-26H1	35	18	10	10	10	10	10	10	10	10	10
25S/39E-35N1	38	16	3	3	3	3	3	3	3	3	3
26S/39E-5F1	38,39	10,11	5	5	5	5	5	5	5	5	5
27S/38E-1G1	51	7	--	--	--	--	--	--	--	3.5	3.5
27S/38E-16C1	54	13	--	--	--	--	--	--	--	3.5	3.5
27S/40E-2J1	51,52	29,30	50	50	50	50	50	50	50	50	50
Subtotal			440	451	426	774	430	259	341	442	447

Supplemental Data D3: *Annual pumpage from wells in model layer 2 for the period 1977-85*--Continued

Well No.	Model node Row	Model node Column	1977	1978	1979	1980	1981	1982	1983	1984	1985
				Agricultural area (northwest)							
	32	5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	35	6	3	3	3	3	3	3	3	3	3
	36	6	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	38	7	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	38	8	3	3	3	3	3	3	3	3	3
	39	6	49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5
	39	8	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	41	10	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	42	8	16	16	16	16	16	16	16	16	16
25S/38E-25P1	35,36	6,7	30	0	0	0	0	0	0	0	0
25S/38E-1C1	26,27	4,5	0	0	640	640	640	640	640	640	640
25S/38E-1L1	27	4,5	0	0	640	640	640	640	640	640	640
25S/38E-12P1,-13C1	29,30	6,7	0	0	1,184	1,184	1,184	1,184	1,184	1,184	1,184
25S/38E-13Q1	32	7	0	0	780	780	780	780	780	780	780
25S/38E-24P2	33,34	6,7	0	0	500	500	500	500	500	500	500
25S/38E-24J1	33	7,8	0	0	640	640	640	640	640	640	640
25S/38E-23J1	33	6	0	0	640	640	640	640	640	640	640
25S/38E-13L1	31	7	0	0	660	660	660	660	660	0	0
25S/38E-25J1	35	8	512	512	512	512	512	512	512	512	512
25S/38E-36B1	36	7	0	0	640	640	640	640	640	640	640
25S/38E-31D1,-36A1	37	8	552	552	552	552	552	552	552	552	552
Subtotal			1,248	1,218	7,542	7,542	7,542	7,542	7,542	6,882	6,882
Total			14,560	15,049	20,917	22,188	22,066	21,308	22,146	21,832	21,526