DEVELOPMENT AND USE OF A MATHEMATICAL MODEL OF THE SAN BERNARDINO VALLEY GROUND-WATER BASIN, CALIFORNIA

By William F. Hardt and C. B. Hutchinson

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS

OPEN-FILE REPORT 80-576

Prepared in cooperation with the
San Bernardino Valley Municipal Water District

September 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

For additional information write to:

District Chief
Water Resources Division
U.S. Geological Survey
345 Middlefield Road
Menlo Park, Calif. 94025

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CONVERSION FACTORS

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

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-ft (acre-foot)	0.001233	cubic hectometer
acre-ft/yr (acre-foot per year)	0.001233	cubic hectometer per year
ft (foot)	0.3048	meter
ft/d (foot per day)	0.3048	meter per day
(ft/d)/ft (foot per day per foot)	0.3048	meter per day per meter
ft^2/d (foot squared per day)	0.0929	meter squared per day
ft/mi (foot per mile)	0.1894	meter per kilometer
ft^3/s (cubic foot per second)	0.02832	cubic meter per second
ft/s (foot per second)	0.3048	meter per second
(gal/d)/ft (gallon per day per foot)	0.01242	meter squared per day
gal/min (gallon per minute)	0.06309	liter per second
(gal/min)/ft (gallon per minute per foot)	0.207	liter per second per meter
in (inch)	25.4	millimeter
in/yr (inch per year)	25.4	millimeter per year
mi (mile)	1.609	kilometer
mi^2 (square mile)	2.590	square kilometer

National Geodetic Vertical Datum of 1929 is a geodetic datum derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific Coasts and as such does not necessarily represent local mean sea level at any particular place. To establish a more precise nomenclature, the term "NGVD of 1929" is used in place of "Sea Level Datum of 1929" or "mean sea level."

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ABSTRACT

A considerable part of the San Bernardino urbanized area overlies formerly swampy lands with a history of flowing wells. This area, upgradient from and adjacent to the San Jacinto fault, contains a zone in an alluvial ground-water basin that is under artesian pressure. Since about 1945, withdrawals have exceeded recharge and caused head declines of more than 100 feet.

Artificial recharge of imported northern California water in the upgradient areas may cause ground-water levels to rise, which could cause abandoned but unplugged artesian wells to resume flowing. If this should happen, structures, particularly building foundations and basements, could be subject to damage.

A two-layer Galerkin finite-element digital model was used for predicting the rate and extent of the rise in water levels from 1975 to 2000. Six hydrologic conditions were modeled for the basin. Artifical recharge of one-half entitlement and full entitlement from the California Aqueduct were each coupled with low, average, and high natural recharge to the basin.

According to model predictions, the greatest water level rises will be along the San Bernardino Mountain front. This area encompasses the artificial recharge sites and also has a thick section of unsaturated sediments for storing ground water. The formerly swampy lands between Warm Creek and the Santa Ana River adjacent to the San Jacinto fault have little additional storage capacity, and water levels could rise to the land surface as early as 1983 under maximum recharge conditions and 1970-74 average pumping conditions. If pumping rates are reduced in the Warm Creek area, water levels may rise to land surface prior to the dates predicted by the model, regardless of the artificial-recharge program.

INTRODUCTION

The San Bernardino Valley (fig. 1) is in the service area of the California Water Project. The Project comprises a major system of storage and conveyance facilities for exporting water from northern California to water-deficient areas elsewhere in the State (California Department of Water Resources, 1957). The artificial recharge of this water imported to the valley could create problems for the current basin water-management program, and it is imperative that the potential effects on the natural hydrologic system be known.

Historically, the valley has had an ample supply of ground water derived from stream runoff, primarily from the San Gabriel and San Bernardino Mountains. This water moves toward the southwestern part of the valley where the San Jacinto fault acts as a barrier to ground-water flow. This barrier causes upward movement of ground water that, prior to extensive pumping, resulted in about 10 mi^2 of marshland northeast of the fault.

In the 1870's, test drilling revealed that the aquifer underlying the marshland was under artesian pressure and that wells would flow with heads more than 50 ft above land surface. This abundant supply of flowing water led to increased agricultural development. In the late 1940's a combination of below-normal precipitation and increased ground-water pumping resulted in a lowering of the potentiometric head. The artesian water levels are currently (1979) 50 to 150 ft below land surface, and the swampy areas are dry.

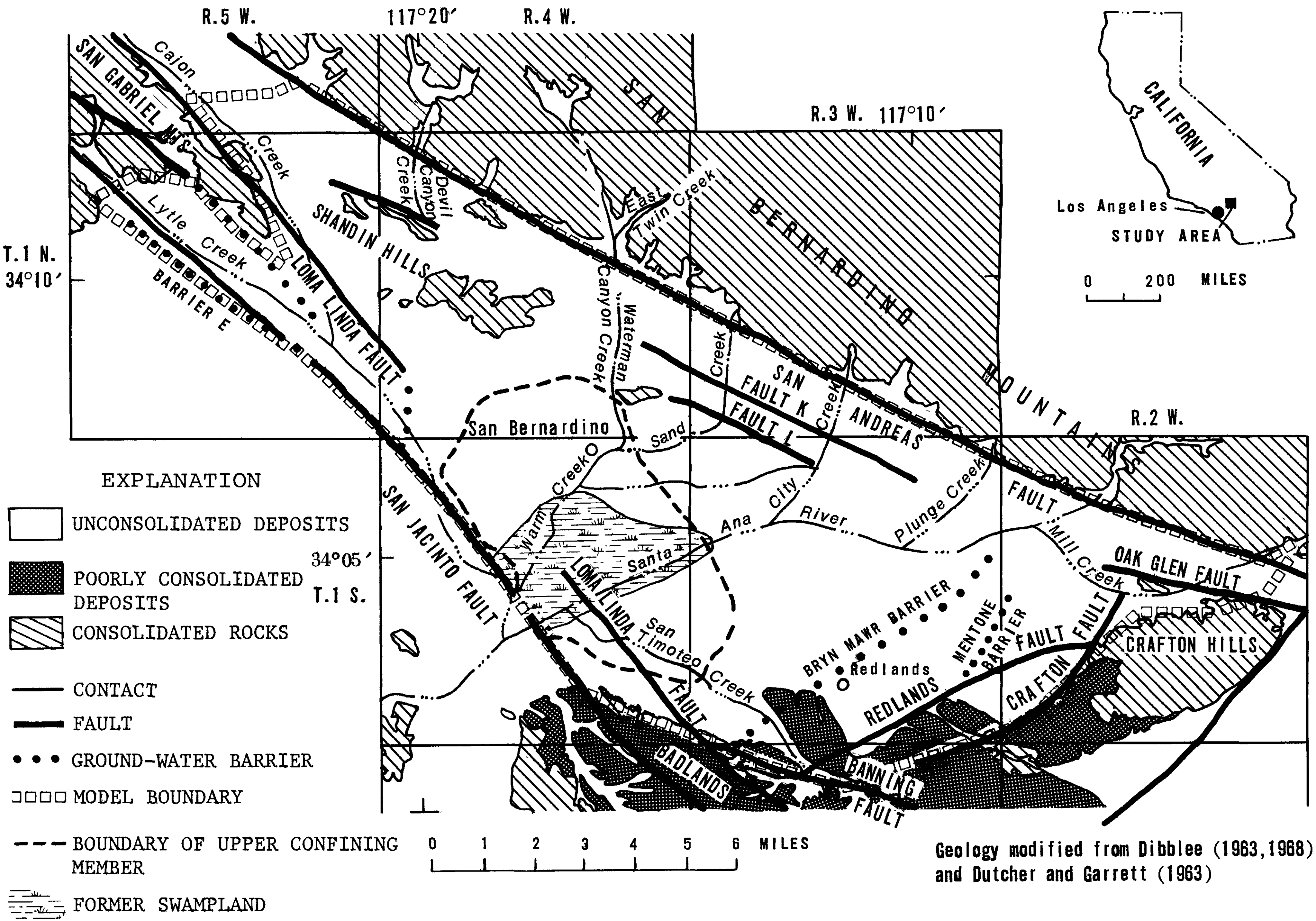


FIGURE 1. -- Geographic setting and generalized geology of model area in San Bernardino Valley.

A considerable part of the urbanized San Bernardino area is built over the formerly swampy lands that contained flowing wells. Many wells in this area were abandoned but were not plugged or destroyed. Some wells are presumed to be buried beneath buildings and roads. Serious problems could occur if artificial recharge of imported water, combined with natural recharge, resulted in the artesian heads in these wells again extending above the land surface. If abandoned wells flow or if the soil becomes waterlogged, buildings, public works, and utilities could be damaged. The potential for liquefaction from seismic shaking exists in all alluviated parts of the study area, but this danger is of concern particularly in sandy and silty soil within the swampy area if water levels approach land surface (Fife and others, 1976, p. 10).

In 1954 the San Bernardino Valley Municipal Water District (SBVMWD) was organized to provide supplemental water for the San Bernardino area to alleviate the depletion of local ground-water supplies. The Water District contracted with the California Department of Water Resources for a maximum entitlement of 48,000 acre-ft of imported water in 1973, increasing annually to 102,600 acre-ft by 1990. By controlling the quantity and distribution of this imported water for artifical recharge, the Water District plans to optimize the storage in the basin. Overfilling the basin must be avoided to prevent damage from rising ground water.

Purpose and Scope

This study was done in cooperation with the SBVMWD. The primary purpose was to evaluate the aquifer response (rising ground-water levels), with time, caused by the combined effects of natural recharge to the valley, artificial recharge of imported water, and ground-water pumping, particularly in the confined area of the San Bernardino Valley. The tool used to evaluate these hydrologic relations is a finite-element mathematical model. The model provides the information necessary to define water-management alternatives pertaining to distribution, location, and amount of recharge and pumping in order to avoid the possible detrimental effects of ground-water levels rising to near land surface in urbanized San Bernardino.

An initial effort to evalute the aquifer response was developed by Durbin and Morgan (1978). They described the development and use of a mathematical well-response model. The model simulates water-level changes that would occur in selected wells as the result of artificial recharge to the ground-water basin. The well-response model was used to generate a series of water-level hydrographs representing the response of ground water in the basin to various combinations of pumping rates, artificial-recharge rates, and natural-recharge rates.

The scope of this study involved three phases of activity: (1) Organizing and evaluating the geohydrologic data in order to develop a conceptual model of the ground-water basin of the San Bernardino Valley; (2) developing a steady-state and transient-state digital-computer model of the basin; and (3) using the computer model to predict ground-water levels under selected management schemes, primarily in the artesian areas of the basin.

Location and General Features

San Bernardino Valley is a semiarid inland valley in southwestern San Bernardino County, about 60 mi east of Los Angeles. The term "San Bernardino Valley" was first used by Mendenhall (1905, p. 9) for an area of indefinite limits beyond the San Bernardino area. Eckis (1934, p. 153) applied the term to that part of the upper Santa Ana Valley east of the San Jacinto fault. Dutcher and Garrett (1963, p. 17) further restricted the term to the area used and defined for this study. The model area covers about 120 mi^2 and lies in a northwest-pointing wedge formed between the San Andreas and San Jacinto faults (fig. 1). The valley is bordered on the northwest by the San Gabriel Mountains, on the northeast by the San Bernardino Mountains, on the south by the Badlands and the Crafton Hills, and on the southwest by a low east-facing escarpment of the San Jacinto fault. Broad alluvial fans, which extend from the base of the mountains and hills that surround the valley, coalesce to form a broad, sloping alluvial plain in the central part of the valley. The land surface slopes generally to the southwest with gradients ranging from 75 to 150 ft/mi on the edges of the basin and from 30 to 50 ft/mi in the central part near the San Jacinto fault.

The ground-water reservoir in the valley consists of alluvial deposits of sand, gravel, and boulders interspersed with lenticular deposits of silt and clay. The maximum depth to bedrock is about 1,200 ft below land surface. In the southwestern part of the valley, adjacent to the San Jacinto fault, the unconsolidated deposits contain numerous clay layers that act as leaky confining beds. Previous investigators (Dutcher and Garrett, 1963) acknowledged that individual sand and clay units could be correlated for only short distances, but they did recognize three aquifers, each separated by 50 to 300 ft of clay and silt. A clay layer upgradient of the San Jacinto fault confines the aquifer system over about 25 mi^2 of the central part of the valley. The position of the demarcation line between the confined and unconfined parts of the aquifer changes constantly because of the varying recharge-discharge relation within the ground-water basin. In the confined area are the formerly swampy lands, comprising about 10 mi^2, near Warm Creek and the Santa Ana River.

Mechanisms for recharging the ground-water basin are infiltration from streams, ground-water inflow and percolation of irrigation returns, and precipitation on the valley floor. Streams contribute most of the recharge to the basin, and irrigation return has become less important as agricultural lands become urbanized. Three main tributary streams contribute more than 60 percent of the recharge to the ground-water system; they are the Santa Ana River, Mill Creek, and Lytle Creek. Lesser contributors include Cajon Creek, Devil Canyon Creek, Waterman Canyon-East Twin Creek, City Creek, Plunge Creek, and San Timoteo Creek. Ground-water inflow, estimated to be less than 10 percent of the total recharge, occurs only from the Badlands in the southeastern part of the study area. Precipitation on the valley floor is of even less importance to basin recharge.

Within the study area are several faults and other barriers that restrict ground-water movement, and water-level differences across these restrictions are 50 ft or more. Some faults are only partial barriers to ground-water movement, such as the Loma Linda fault in specific areas or Fault K in the deeper part of the basin (fig. 1).

Well-Numbering System

Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the well number 1S/1W-2P1, the part of the number preceding the slash indicates the township (T. 1 S.); the number and letter following the slash indicate the range (R. 1 W.); the number following the hyphen indicates the section (sec. 2); the letter following the section number indicates the 40-acre subdivision of the section according to the lettered diagram below. The final digit is a serial number for wells in each 40-acre subdivision. The area lies entirely in the northwest and southwest quadrants of the San Bernardino base line and meridian.

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

CONCEPTUAL MODEL

The development of a sound conceptual model of the San Bernardino Valley ground-water basin is prerequisite to the development of a representative mathematical model. The components of the conceptual model include:

1. Definition of the aquifer system--Thickness and areal extent of aquifers and confining beds were estimated from analyses of lithologic and geophysical logs and published data.
2. Model boundaries--The perimeter of the aquifer system was selected on the basis of its geologic and hydrologic characteristics, particularly faults, and partitioned into no-flow and constant-flow segments.
3. Aquifer parameters--Transmissivity, storage, and leakage were estimated from pumping tests of wells, lithologic logs, and published data from comparable areas.
4. Surface-water movement--The amount and distribution of surface-water inflow to and outflow from the basin were determined from gaging-station records and estimated for ungaged streams.
5. Ground-water levels and movement--The direction and amount of ground-water flow were estimated from water-level maps and a knowledge of the hydraulic properties of the aquifer system. Water-level data for selected wells were obtained from computerized historical records.
6. Water budget--Conditions of recharge, discharge, and storage in the basin were estimated from streamflow, pumpage, weather, and water-level records.

The components of the conceptual model were idealized under steady-state and transient-state conditions. Calibration of the mathematical model consisted of refining the estimates of the components of the conceptual model until model-generated water levels matched observed water levels.

Definition of the Aquifer System

For the purpose of this study, rock units have been classified, according to their ability to yield water, as (1) consolidated rocks (basement complex) that are virtually non-water-bearing, (2) poorly consolidated alluvial and lacustrine deposits that yield small quantities of ground water, and (3) unconsolidated deposits of water-bearing alluvium and river-channel fill that yield large quantities of ground water.

The consolidated rocks underlie the alluvium and river-channel deposits and make up the bordering hills and mountains. These rocks are nearly impermeable except where fractured or weathered and are not an important source of ground water. They are important to the aquifer system because they surround the valley area at higher altitudes and receive the major part of the precipitation that falls within the drainage area. The runoff from these surrounding areas flows onto the steep alluvial fans and permeable unconsolidated deposits and contributes the largest quantity of recharge to the ground-water basin.

The poorly consolidated alluvial and lacustrine deposits crop out in the southern part of the study area between the San Jacinto fault and the Crafton Hills. These deposits are composed of sand, gravel, silt, and clay but are older, more consolidated, and yield much less water than the younger unconsolidated alluvial deposits. The hydraulic properties of these deposits were described by Dutcher and Fenzel (1972). Well yields were generally less than 400 gal/min, well specific capacities ranged from 1 to 10 (gal/min)/ft of drawdown, and aquifer hydraulic conductivity ranged from 7 to 29 ft/d.

The unconsolidated deposits constitute the reservoir for storing large quantities of water beneath the land surface for later withdrawal by pumping. These deposits consist of younger and older alluvium composed of gravel, sand, silt, and clay. In general, the alluvium closer to the mountains is coarser but more poorly sorted than the alluvium farther from the mountain front. The better sorted zones of sand and gravel are more permeable and, where saturated, yield water freely to wells. The river-channel fill overlies the alluvium in the major stream channels. These deposits are highly permeable, and as a result, there are large seepage losses from streams to the ground-water basin. Sites where such deposits occur are therefore highly useful as spreading grounds. The hydraulic properties of these deposits were described by Dutcher and Garrett (1963, p. 51-56). Well yields were as much as 2,000 gal/min, well specific capacities averaged 20 to 35 (gal/min)/ft of drawdown, and hydraulic conductivity ranged from 40 to 94 ft/d.

The base of the ground-water reservoir was determined from about 280 of the deepest of 1,300 water-well drillers' logs examined (California Department of Water Resources, 1971). The base was fixed either at the consolidated basement-complex rocks or at the unconsolidated deposits that, because of low-permeability material such as clay or cemented gravel, preclude withdrawal of large quantities of water. From this information the thickness of the water-bearing deposits within the alluvium was compiled by Fife and others (1976). Figure 2 is modified from the work of these investigators and shows the areas of greatest thickness of water-bearing deposits.

The greatest thickness of water-bearing deposits is more than 1,200 ft and occurs adjacent to the northeast side of the San Jacinto fault between San Bernardino and the Santa Ana River. This area coincides with the formerly swampy land within the confined area. From here the basin deposits generally become progressively thinner northwest toward the San Gabriel Mountains, north toward the San Bernardino Mountains, and northeast toward the Mill Creek area.

The general area of confined water was originally defined by Mendenhall (1905) and later by Dutcher and Garrett (1963), based on their knowledge of the hydrology and extent of the confining clay bed. These investigators realized that the area of the confining clay bed is not static but varies depending on the variations in inflow-outflow relations. The confined area, as defined by Durbin and Morgan (1978, p. 7), was used as a guideline in this model in order to utilize the same nodal points for continuity. For this study, however, a detailed analysis was made of the driller's logs to precisely define the vertical and lateral extent of the major confining clay bed in the Warm Creek area. This analysis was of primary importance to the basin hydrology and to the model because an extensive confining clay layer separates the upper and lower aquifers in the central part of the valley. Figure 3 shows that this clay layer is more than 300 ft thick in the central part of the area of ground-water confinement and thins toward the upland parts of the valley. The surface of the clay layer ranges from 1,200 ft above sea level in the upper reaches of the Santa Ana River valley to less than 700 ft above sea level at the San Jacinto fault, a slope of about 120 ft/mi to the southwest.

A near-surface deposit with low hydraulic conductivity acts as a confining member above the upper aquifer in the confined part of the valley in the Warm Creek area. This shallow clay cap was identified when wells drilled only 50 to 100 ft yielded flowing water. The confining member is discontinuous; it may be absent, thinner, or locally leaky near Warm Creek (Dutcher and Garrett, 1963, p. 63).

To further define the aquifer system for model representation, six geologic sections were constructed by interpreting selected water-well drillers' logs (figs. 4-7). These sections show the extensive confining clay layer that was used to separate the confined part of the basin into two model layers. This confining unit is predominantly clay but includes some sand and gravel lenses. The upper model layer (layer 1) is above the clay layer, and the lower model layer (layer 2) is below the clay layer. All the sections show that the greatest thickness of water-bearing deposits is in layer 2 (beneath the clay layer as represented by the lower model layer).

Although a previous study (Dutcher and Garrett, 1963) recognized two artesian aquifers beneath the major clay layer, all lower artesian aquifers, if present, were grouped into one system (layer 2) because of computer limitations. This concept of representing the basin by a two-layer model was strengthened by a test well (1S/4W-10B1) (figs. 2 and 3). This well was drilled in the confined area to a depth of 875 ft and bottomed in bedrock. The alluvium was 825 ft thick, and only two aquifers were encountered. Unconfined to confined conditions prevail in the aquifer from land surface to a depth of 344 ft. Between 344 and 616 ft a confining clay bed was encountered, with confined conditions in the aquifer below 616 ft.

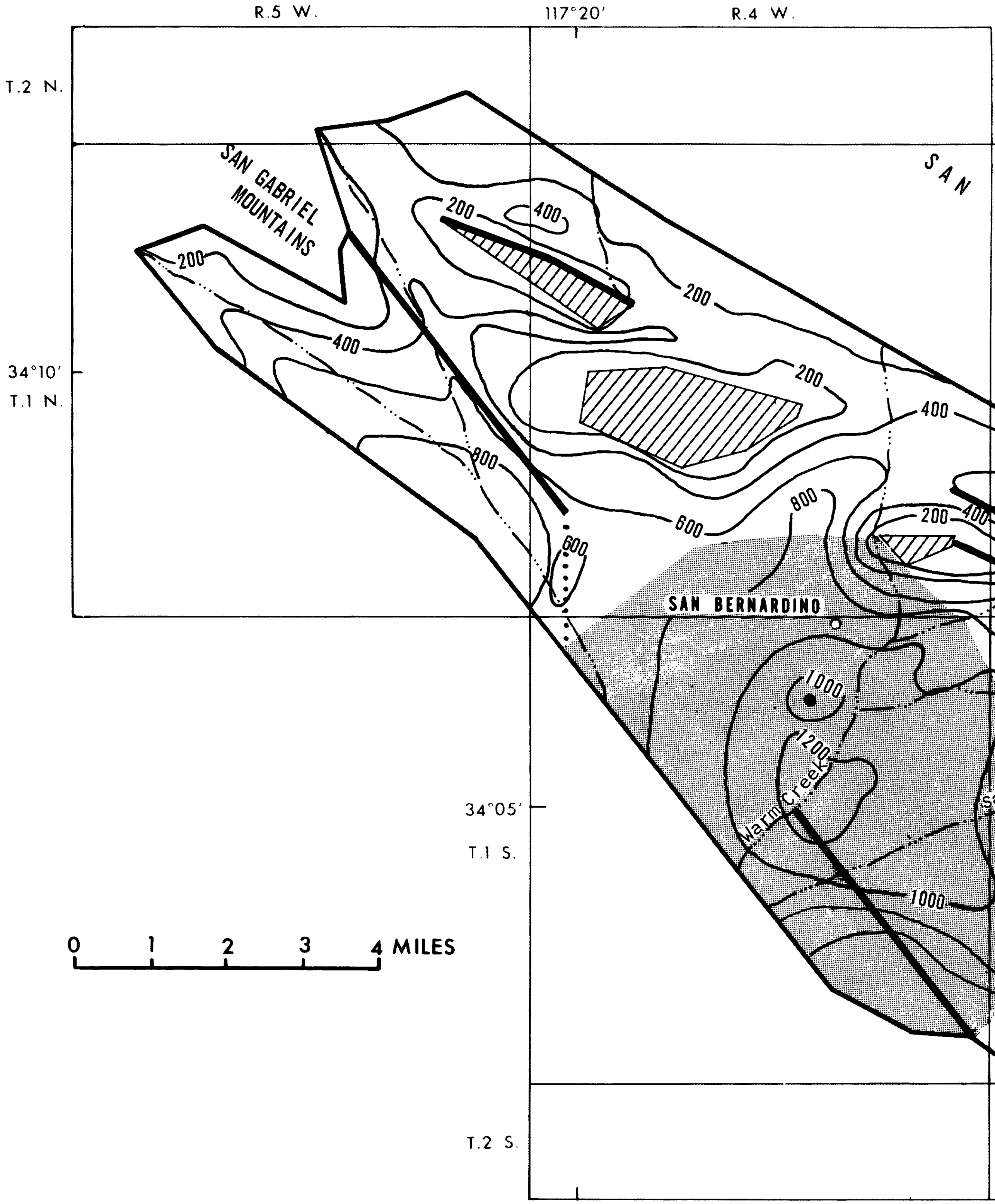
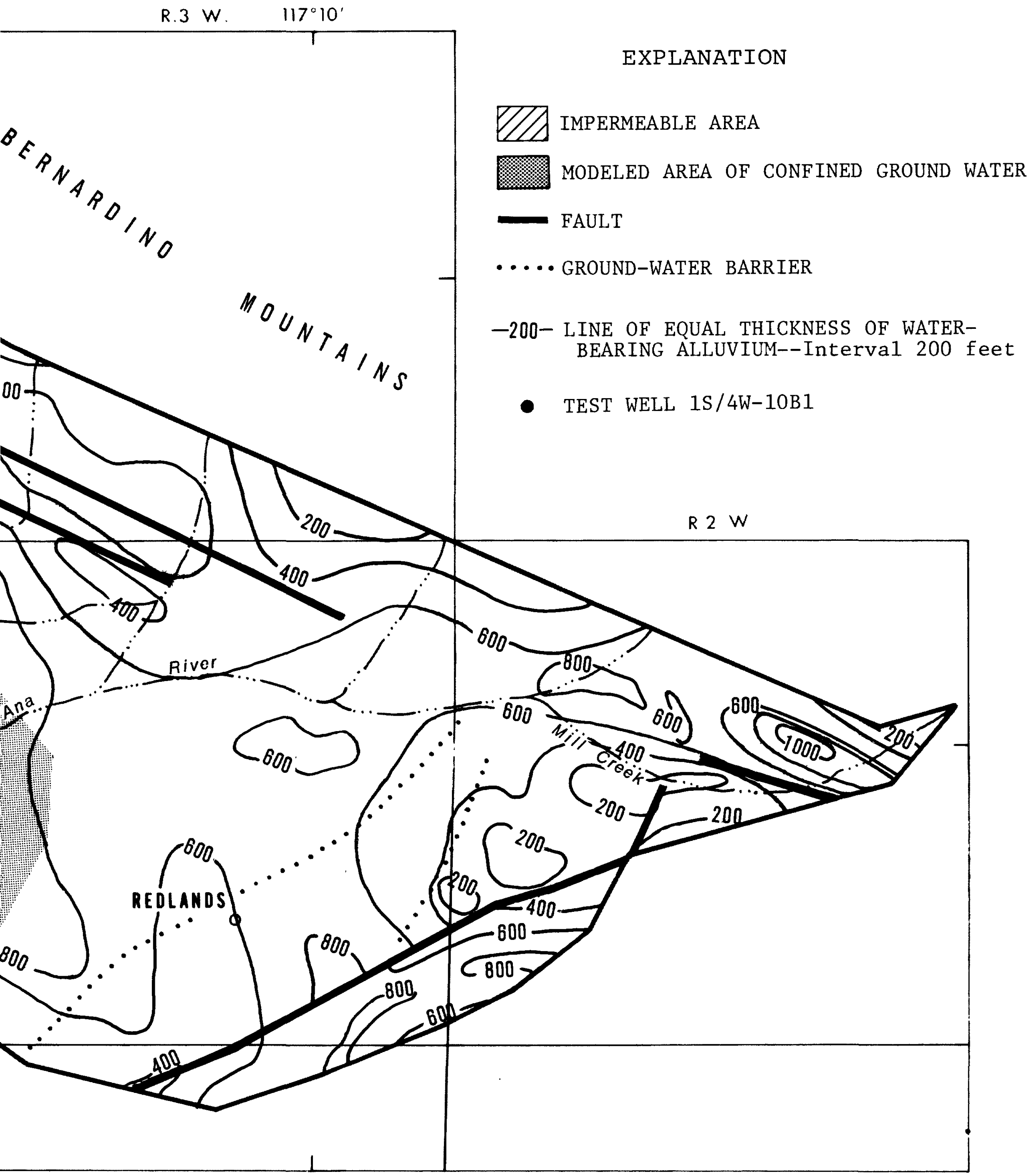


FIGURE 2. -- Thickness of



Modified from Fife and others (1976, pl. 5B)

ater-bearing alluvium.

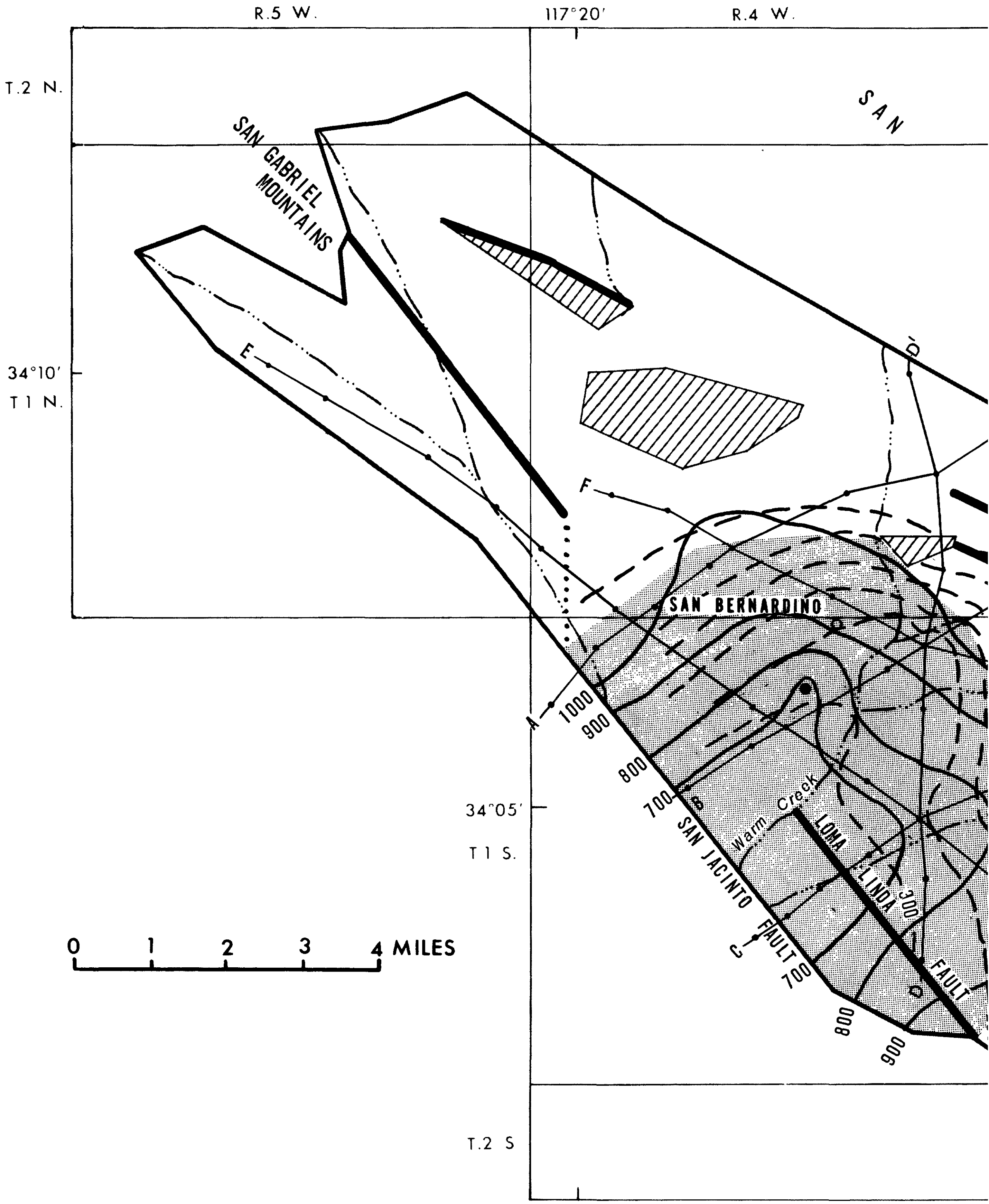
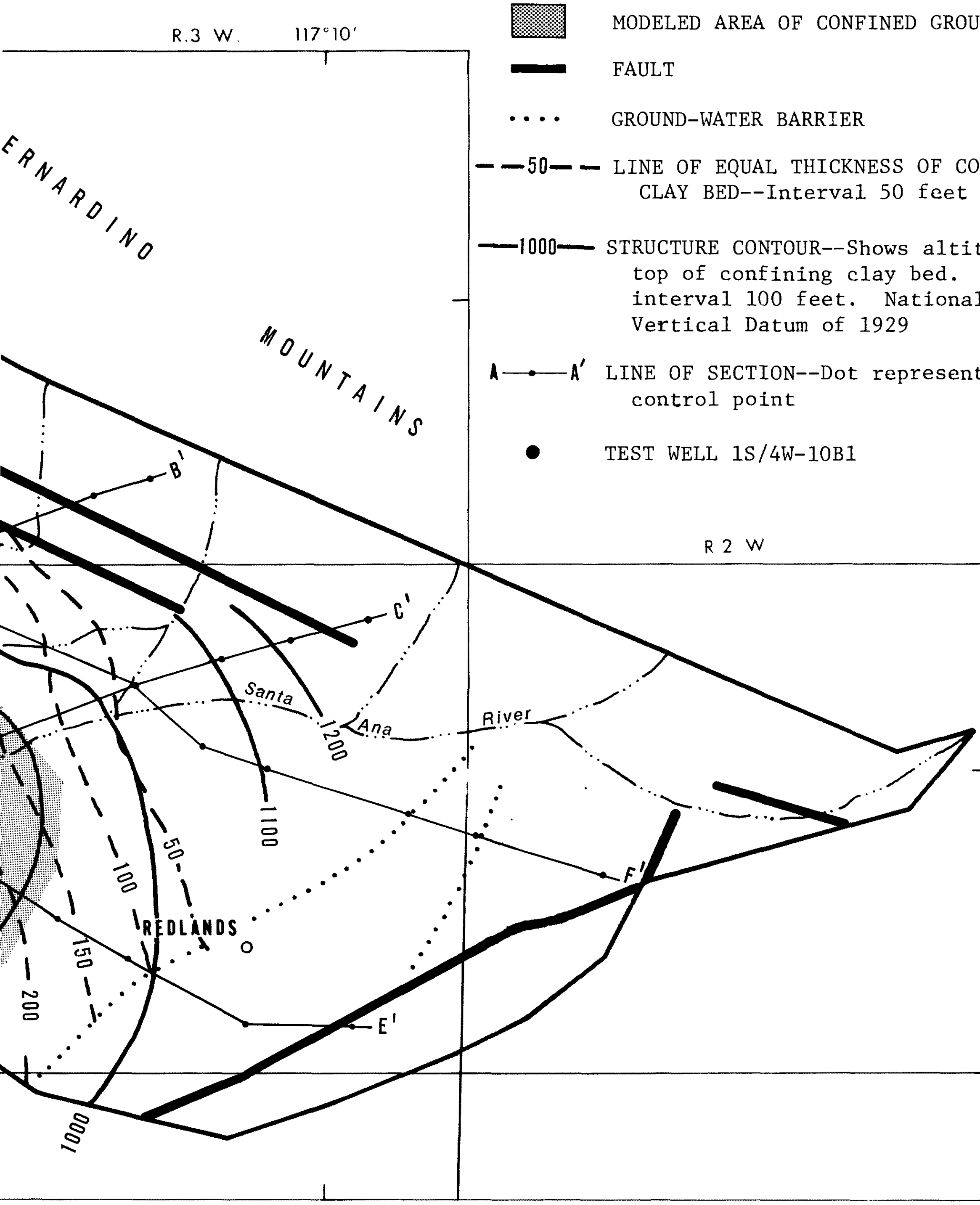


FIGURE 3. -- Contours showing altitude



EXPLANATION

IMPERMEABLE AREA

MODELED AREA OF CONFINED GROUND WATER

FAULT

GROUND-WATER BARRIER

—50— LINE OF EQUAL THICKNESS OF CONFINING CLAY BED--Interval 50 feet

—1000— STRUCTURE CONTOUR--Shows altitude of top of confining clay bed. Contour interval 100 feet. National Geodetic Vertical Datum of 1929

A—•—A' LINE OF SECTION--Dot represents well-control point

● TEST WELL 1S/4W-10B1

and thickness of confining clay bed.

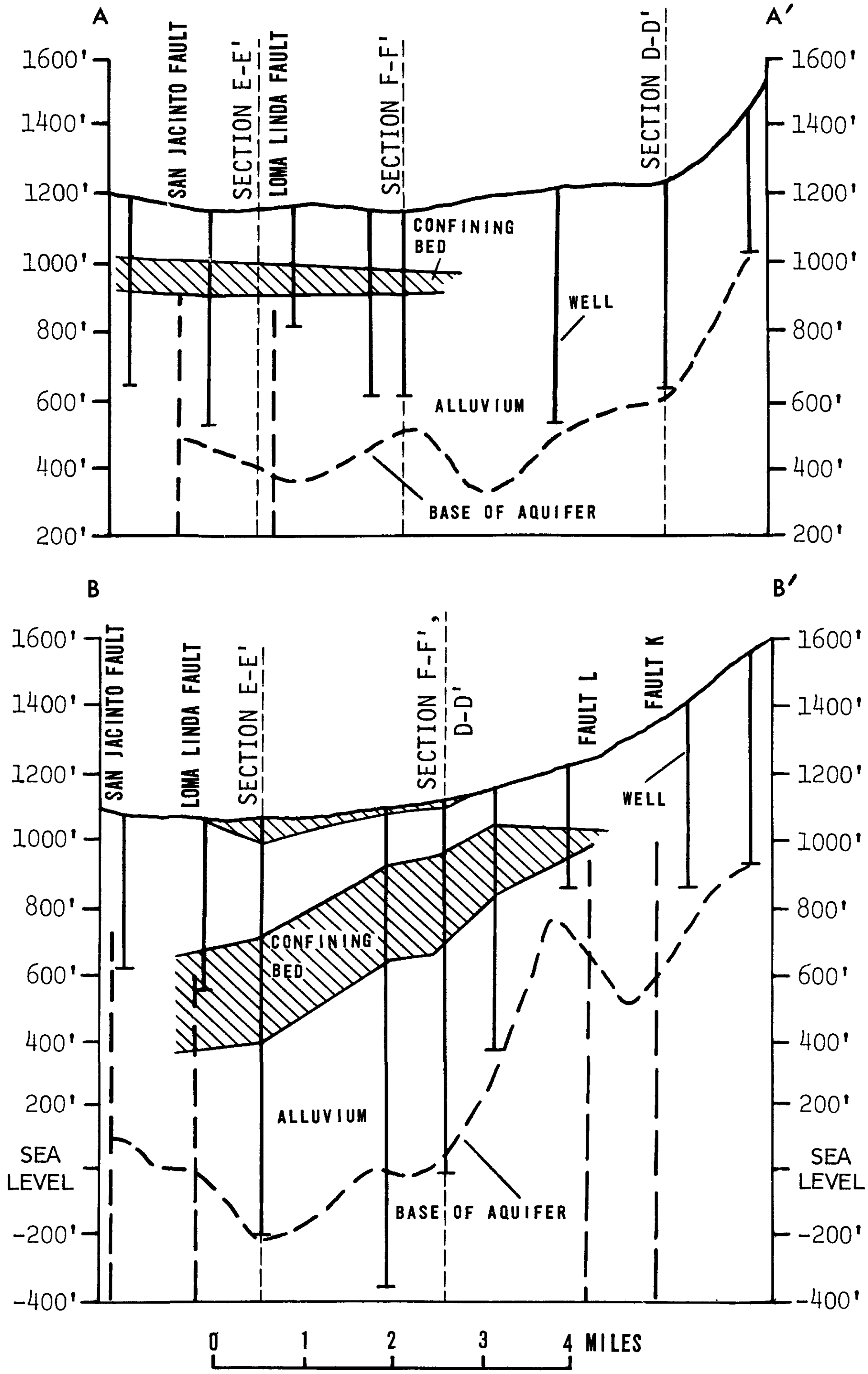


FIGURE 4. -- Geologic sections A-A' and B-B'. See figure 3 for location of sections.

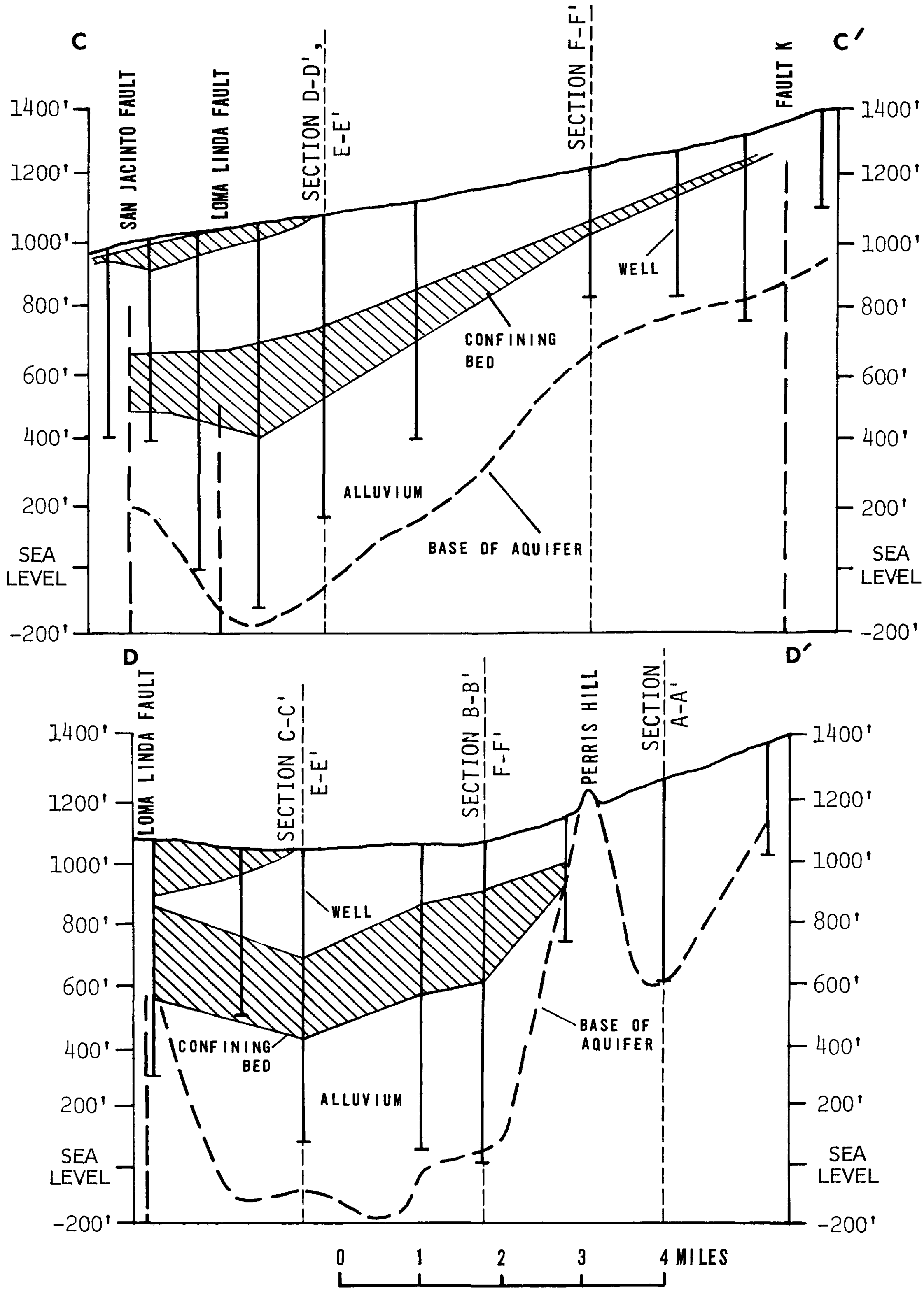


FIGURE 5.--Geologic sections C-C' and D-D'.
See figure 3 for location of sections.

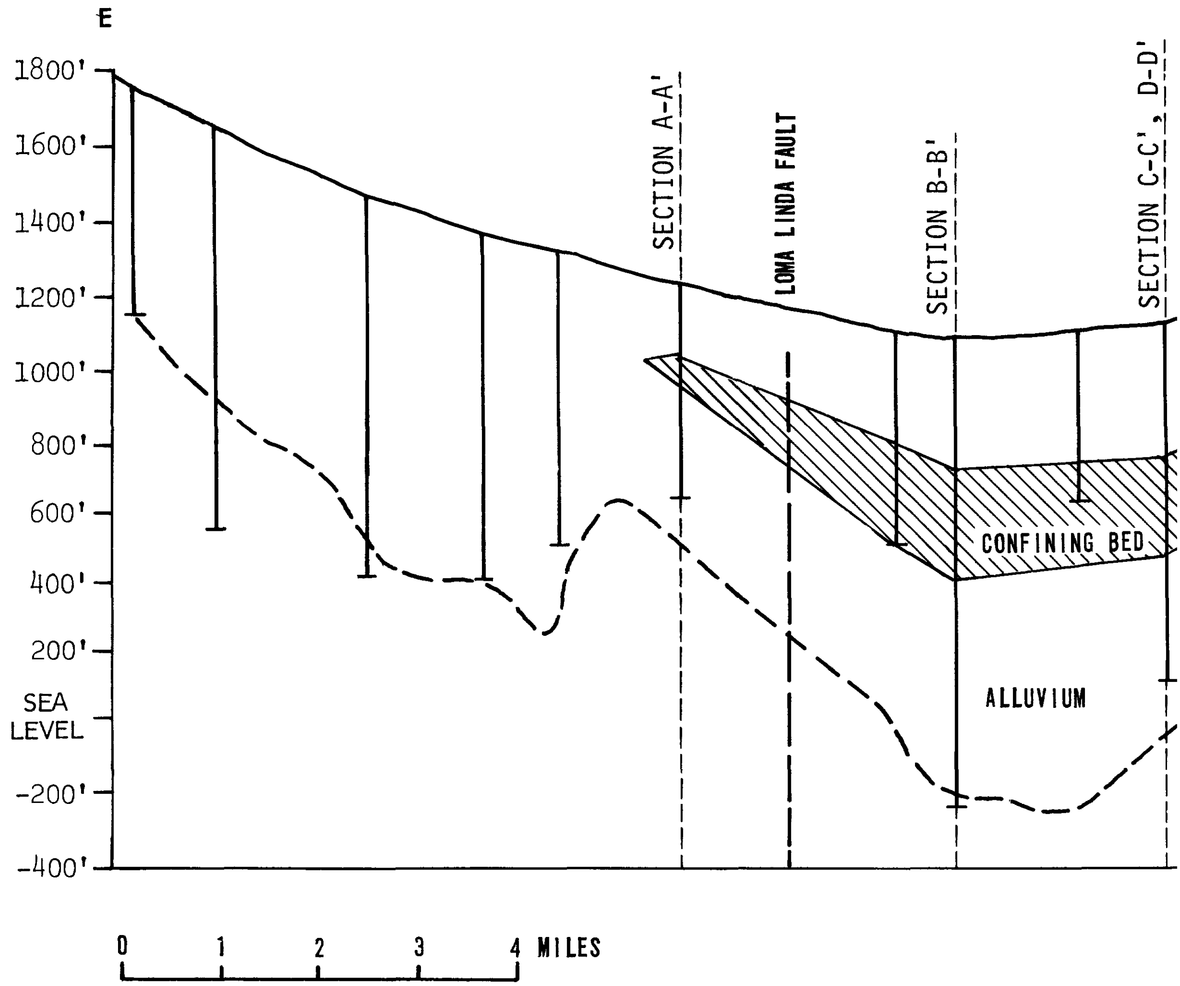
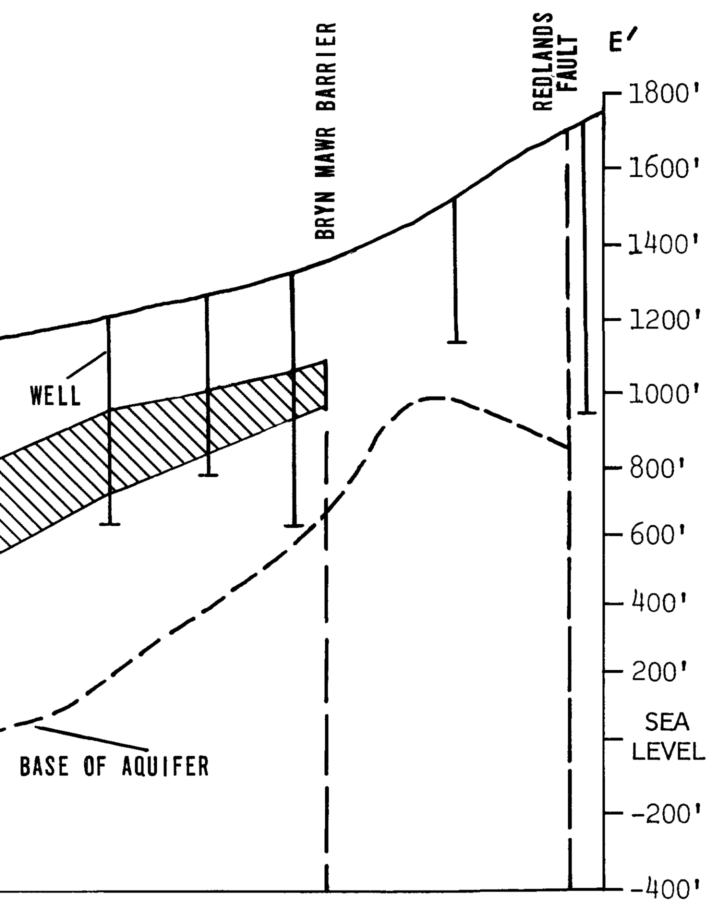


FIGURE 6.--Geologic section E-E'. See figure 3 for

Boundaries

Two concepts apply to model boundaries. First, they define the geographic area to be considered. Second, the conditions assigned at these boundaries (specified flow or specified head) affect the computed water levels. The general boundary of the model coincides primarily with faults and other barriers consisting of either no-flow segments along consolidated-rock boundaries or constant-flow segments in the unconsolidated or poorly consolidated deposits where ground water flows across or over the faults. In areas where fault boundaries are missing and the unconsolidated and poorly consolidated deposits extend beyond the model study area, the model boundaries were chosen so the cause-and-effect relations (pumpage and recharge) outside the model would have a minimal effect on the flow system inside the model area.

A no-flow boundary was assigned to the front of the San Bernardino Mountains along the San Andreas fault zone, except where the numerous streams enter the alluvial basin. These streams are modeled as constant-flow boundaries through which surface flow and underflow enter the model area as recharge. Barrier E along the northwest side of the model has an extremely low transmissivity and was considered a no-flow boundary (fig. 1). A barrier is defined as a subsurface obstruction to the flow of ground water that cannot be mapped because of the lack of surface



ocation of section.

evidence.

Constant-flow segments of the model boundary were assigned for areas of recharge or discharge. Discharge as ground-water underflow across the San Jacinto fault ranged from 14,300 to 18,000 acre-ft/yr in the period 1938-49 (Dutcher and Garrett, 1963, p. 105). To simplify the model, a constant outflow of 15,200 acre-ft/yr was used. This was justified because the yearly differences in underflow were small compared to the total basin discharge. Recharge as ground-water underflow across the Crafton fault ranged from 8,150 to 5,350 acre-ft/yr in the period 1927-67 (Dutcher and Fenzel, 1972, p. 29).

In the unconsolidated water-bearing deposits of the basin are other geologic configurations that affect ground-water flow and must be considered in modeling. They include faults and barriers, consolidated-rock highs or lows, and extensive clay beds. Generally, the faults and barriers are zones of low hydraulic conductivity (permeability) and behave as dams to ground-water flow. The interior faults are modeled with different transmissivities for layers 1 and 2, depending on the measured water levels across the impediment, the depth to water, and the geologic environment at the fault. Where the consolidated rocks are at or near land surface the alluvial deposits are thin and transmissivity is low. The confining clay layer in the artesian area separates the upper and lower model layers. The bottom of the water-bearing alluvium or the top of the consolidated rocks is considered as the bottom of the model on the basis of permeability contrasts along this interface.

Aquifer Parameters

Values of transmissivity and storage coefficient for the water-bearing deposits and leakage coefficient for confining clay bed are required to model this valley. Aquifer transmissivity throughout the valley and storage coefficient for the part of the valley where the aquifer is unconfined were derived by the California Department of Water Resources (1971). Estimates of transmissivity were based on well specific-capacity tests. Storage coefficient, which for an unconfined aquifer is equated to specific yield, was derived by assigning yield values to the different materials recorded on a driller's log and computing a total value. About 1,100 well-drillers' logs were used in these storage-coefficient calculations. The storage coefficient for the confined part of the valley was determined from aquifer performance tests in the study area and other areas with similar sediments. A confined-aquifer storage coefficient may be thousands of times smaller than an unconfined-aquifer specific-yield value and represents a pressure response rather than a dewatering of

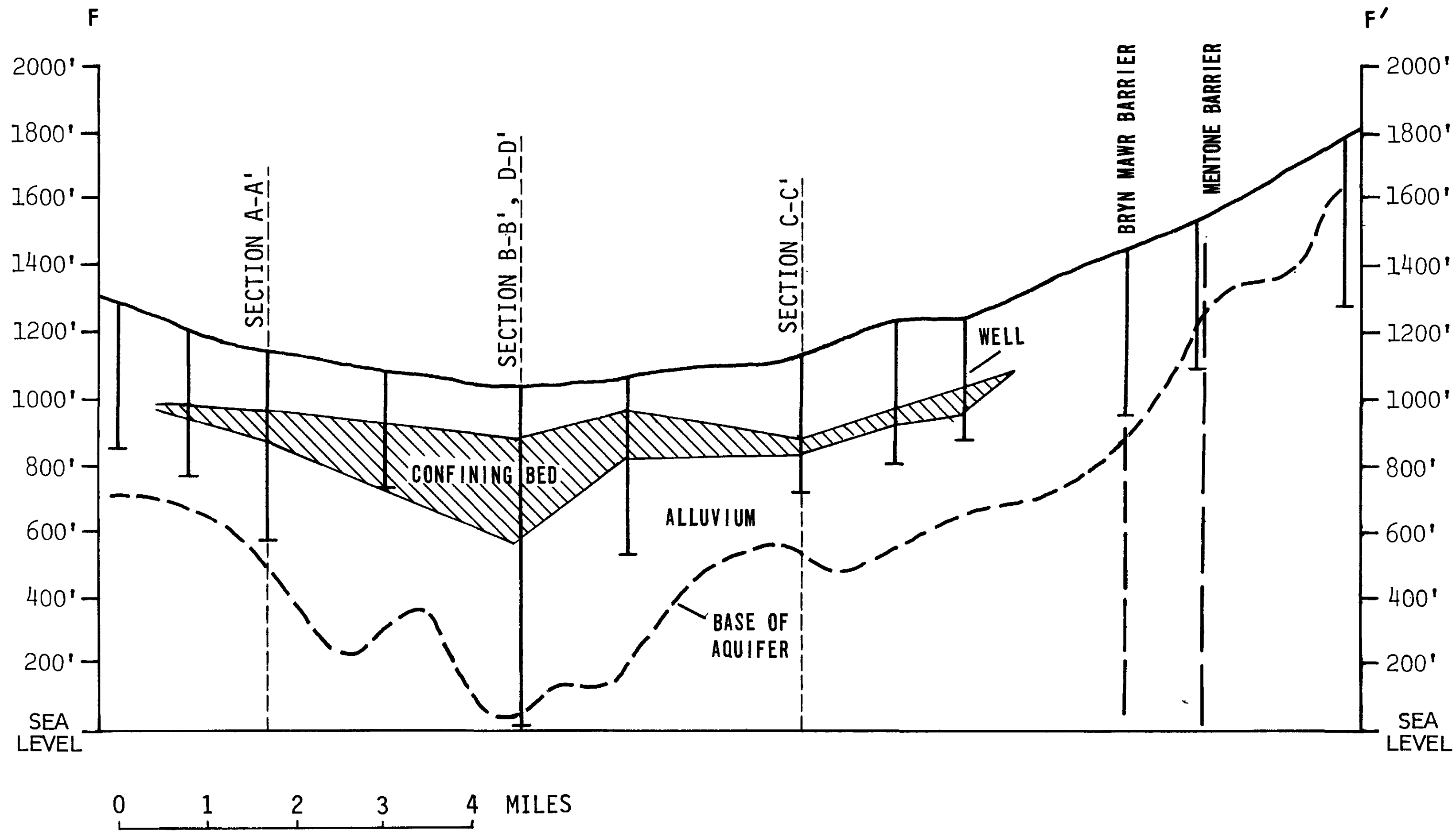


FIGURE 7.--Geologic section F-F'. See figure 3 for location of section.

the sediments. Leakage of water through the confining bed was computed by the mathematical model from inputs of vertical hydraulic conductivity (permeability) and thickness of the bed as developed specifically for this study.

Based on several interrogations of the mathematical model, these initial values of aquifer characteristics were adjusted and refined during the calibration period. The changes were generally reasonable and the values were consistent with the prototype system.

The final values of aquifer transmissivity for the basin were reduced in some areas by a maximum of about 20 percent from the initial values. Transmissivities ranged from 670 ft^2/d (5,000 [gal/d]/ft) along the San Bernardino Mountain front to 66,800 ft^2/d (500,000 [gal/d]/ft) in the center of the basin in the confined area. Where the faults are barriers to ground-water movement, transmissivities of less than 670 ft^2/d were modeled, based primarily on head drop across the fault.

The aquifer transmissivity representing the total thickness of the water-bearing alluvium was proportioned to the two layers of the model. Generally, in the unconfined part of the basin where confining layers are absent, the transmissivity values were arbitrarily divided about evenly between the two layers. In the confined zone in the south-central part of the valley, the lower layer (layer 2) includes all water-bearing deposits beneath the confining clay member and has a higher transmissivity value because of greater aquifer thickness. Any decrease in permeability with depth, due to compaction of interbedded clays and silts, was considered to be insignificant.

Figures 8 and 9 show the configuration and range of transmissivity values used in the model for the upper (layer 1) and lower (layer 2) layers respectively. The maps show that the faults and barriers are characterized by low transmissivities in the lower layer. Some of the faults or barriers do not reach the land surface, and some ground water moves over the top of the barrier through permeable sediments, as represented by the upper layer in the model.

The fault representations in the model extend beyond the known occurrence of the actual faults in some instances. Where the fault extension is not presently warranted, the fault and adjacent aquifers were modeled at the same transmissivity values to negate improper influence of the fault on the ground-water flow system. If future studies indicate that the fault extends beyond its present limits, the model transmissivity for the fault can be changed.

Values of aquifer storage coefficients used in the model ranged from 0.15 in the unconfined part of the valley to 0.0001 in the confined aquifer (fig. 10). The storage coefficients in the upper layer (layer 1) are generally typical of unconfined aquifers except in the central part of the confined area. Here, clay beds near the surface cause some confinement, and the upper aquifer has storage coefficients typical of confined aquifers. The storage coefficients in the lower layer (layer 2) are typical of artesian conditions except on the northwest and southeast edges of the model where clay layers are absent and unconfined conditions prevail at depth. From the basin boundaries to the center of the confined area beneath the clay body, the storage coefficients are progressively smaller.

The confining bed is a semipermeable layer through which ground water is conveyed or leaked between the underlying (layer 2) and the overlying (layer 1) aquifers. Leakage, expressed as the "leakance coefficient," is the ratio of hydraulic conductivity to the thickness of the confining bed. The leakance coefficient in the confined part of the valley ranged from 0.0012 to 0.00009 (ft/d)/ft. In the unconfined part of the valley, the confining bed was assumed to be 1 ft thick, and the leakance coefficient was assigned a constant 0.03 (ft/d)/ft, based on sparse field data and studies in nearby areas of comparable geology.

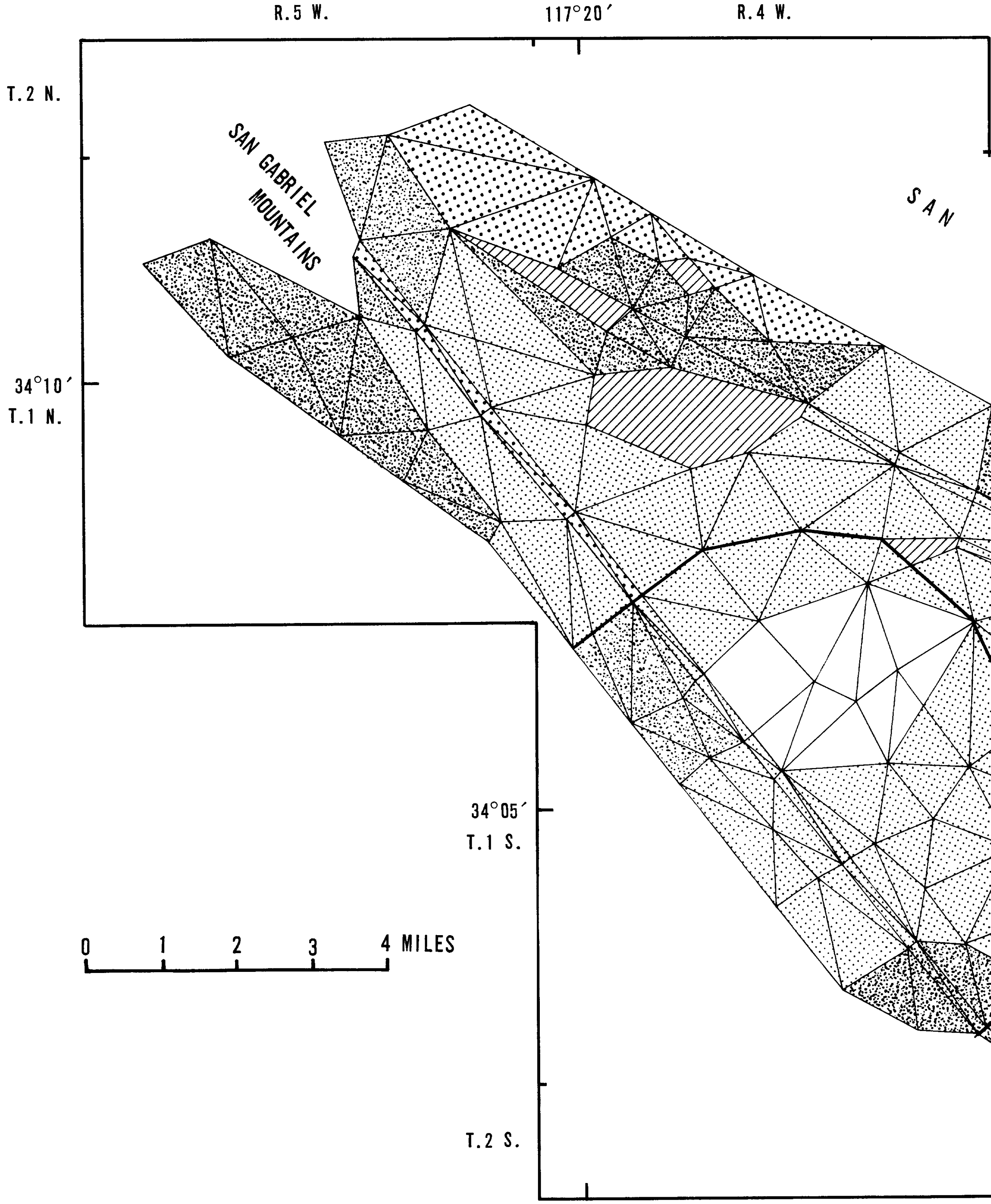
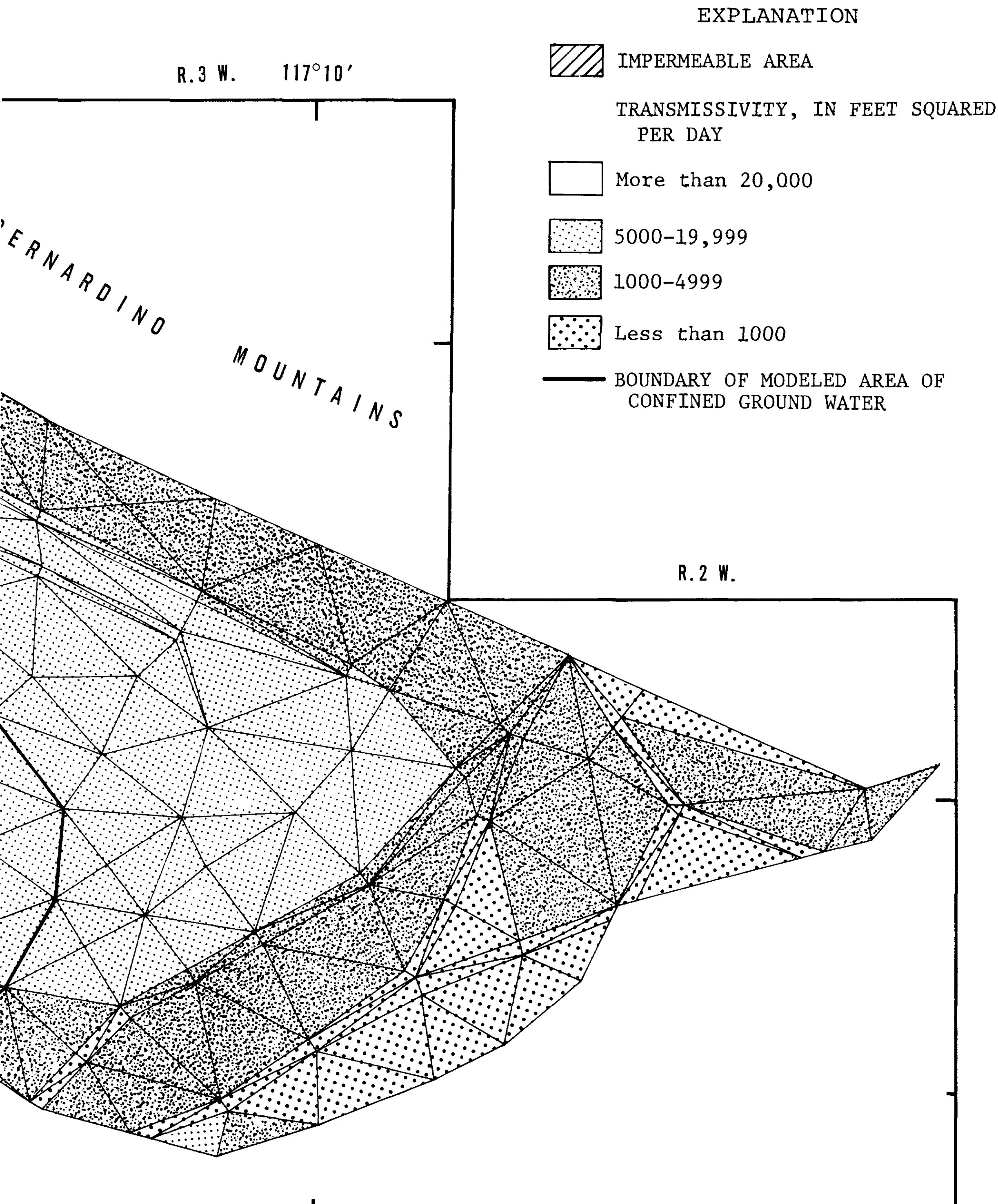


FIGURE 8. -- Aquifer transmissivity



of upper model layer.

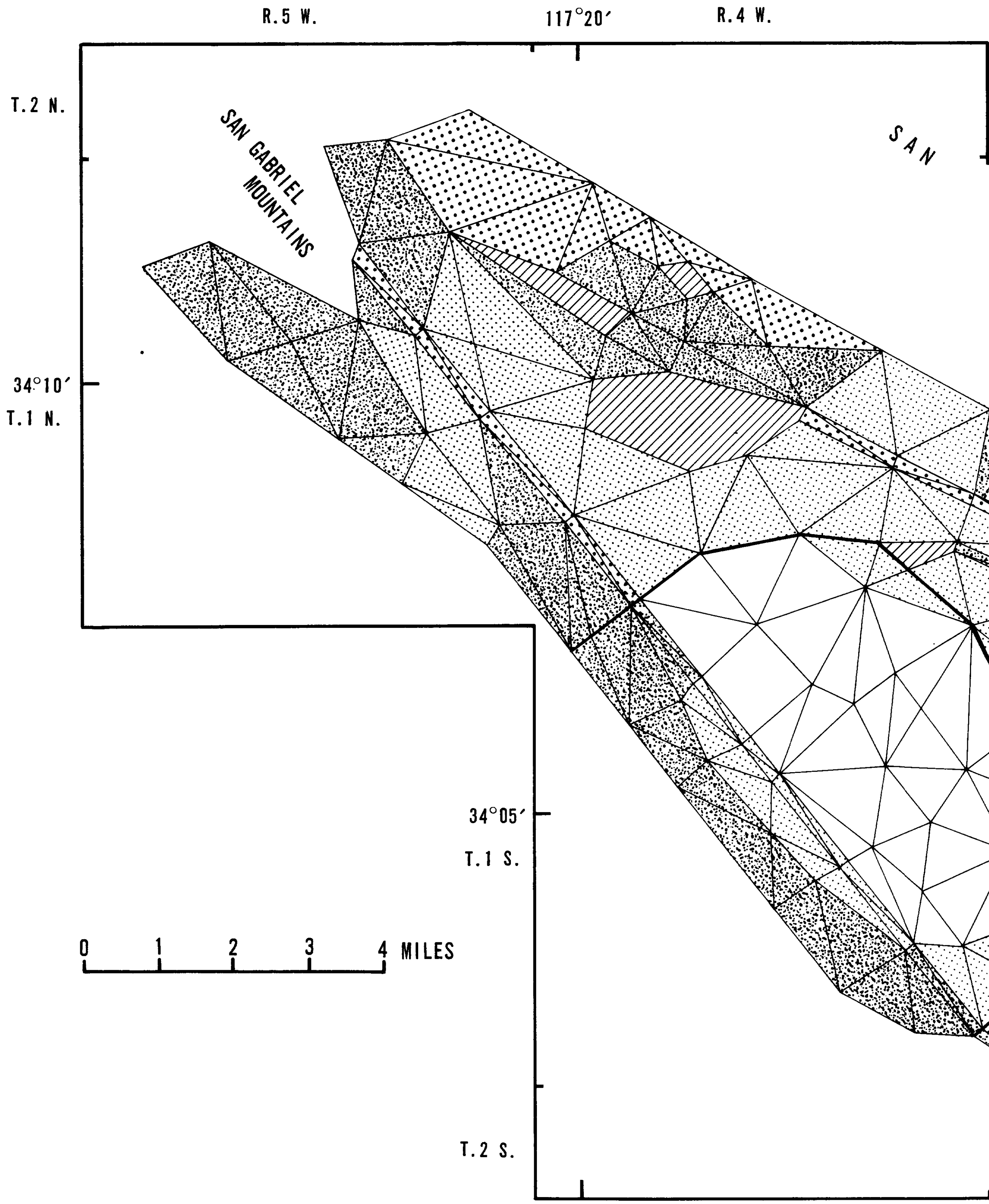
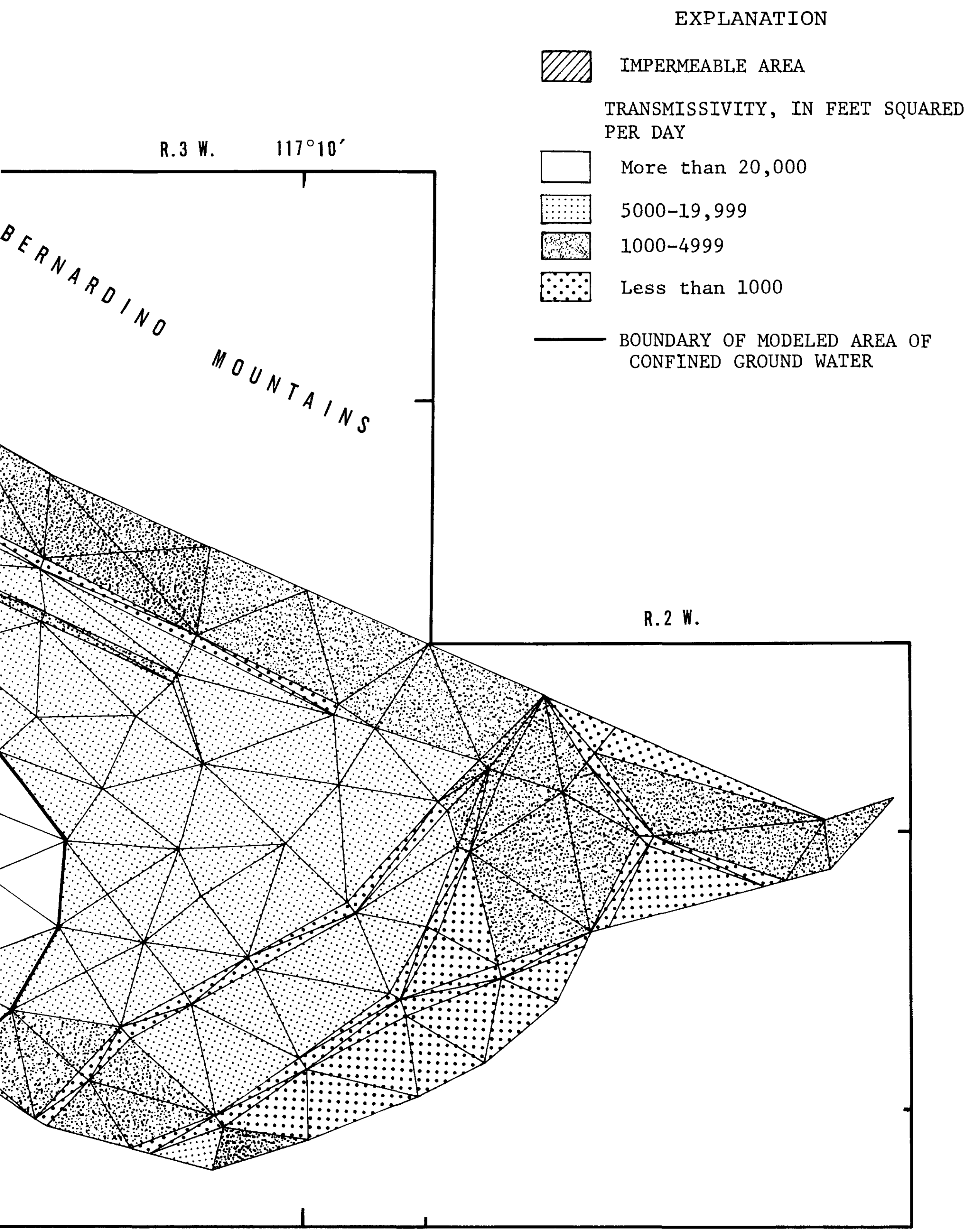


FIGURE 9. -- Aquifer transmissivity



of lower model layer.

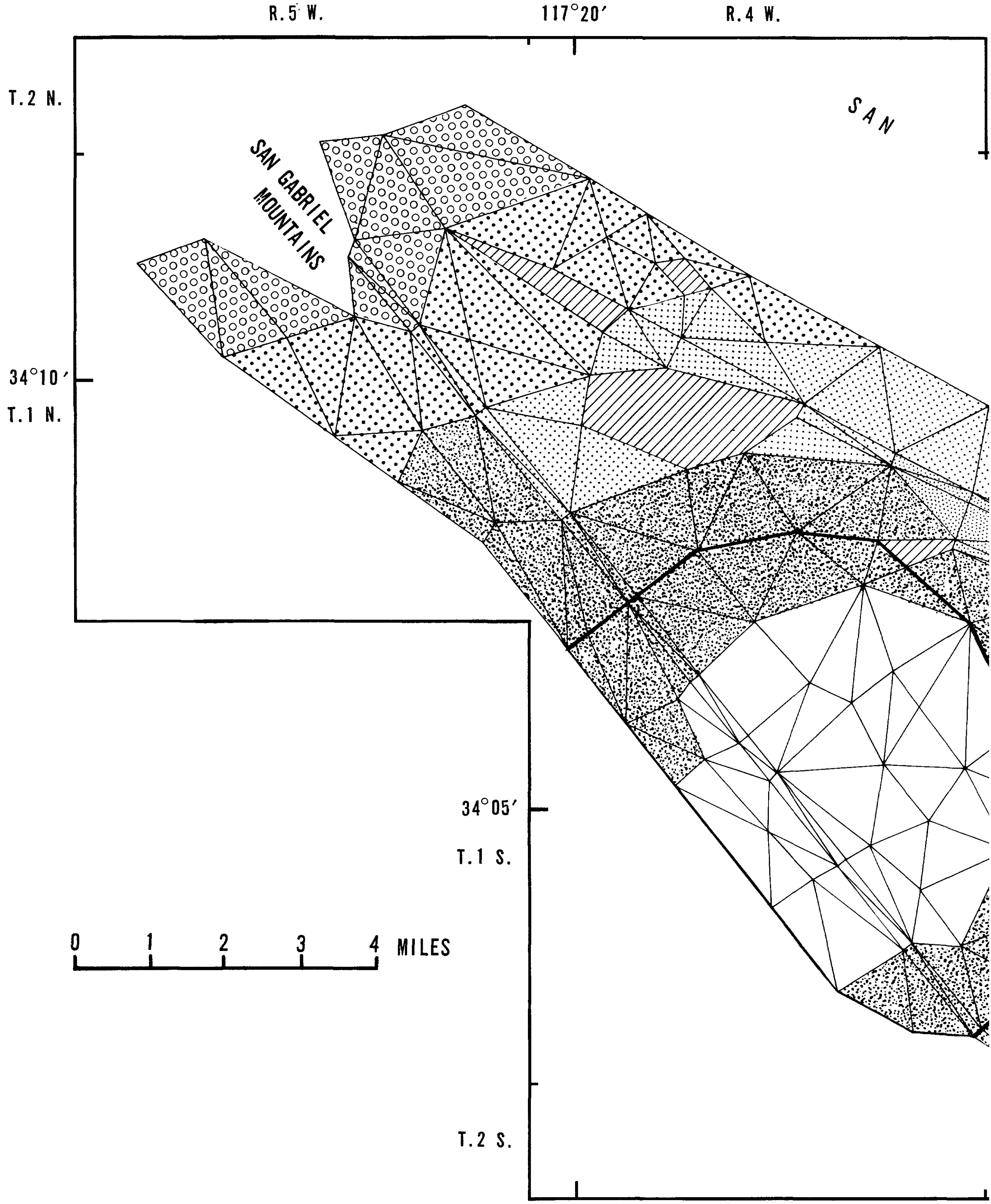
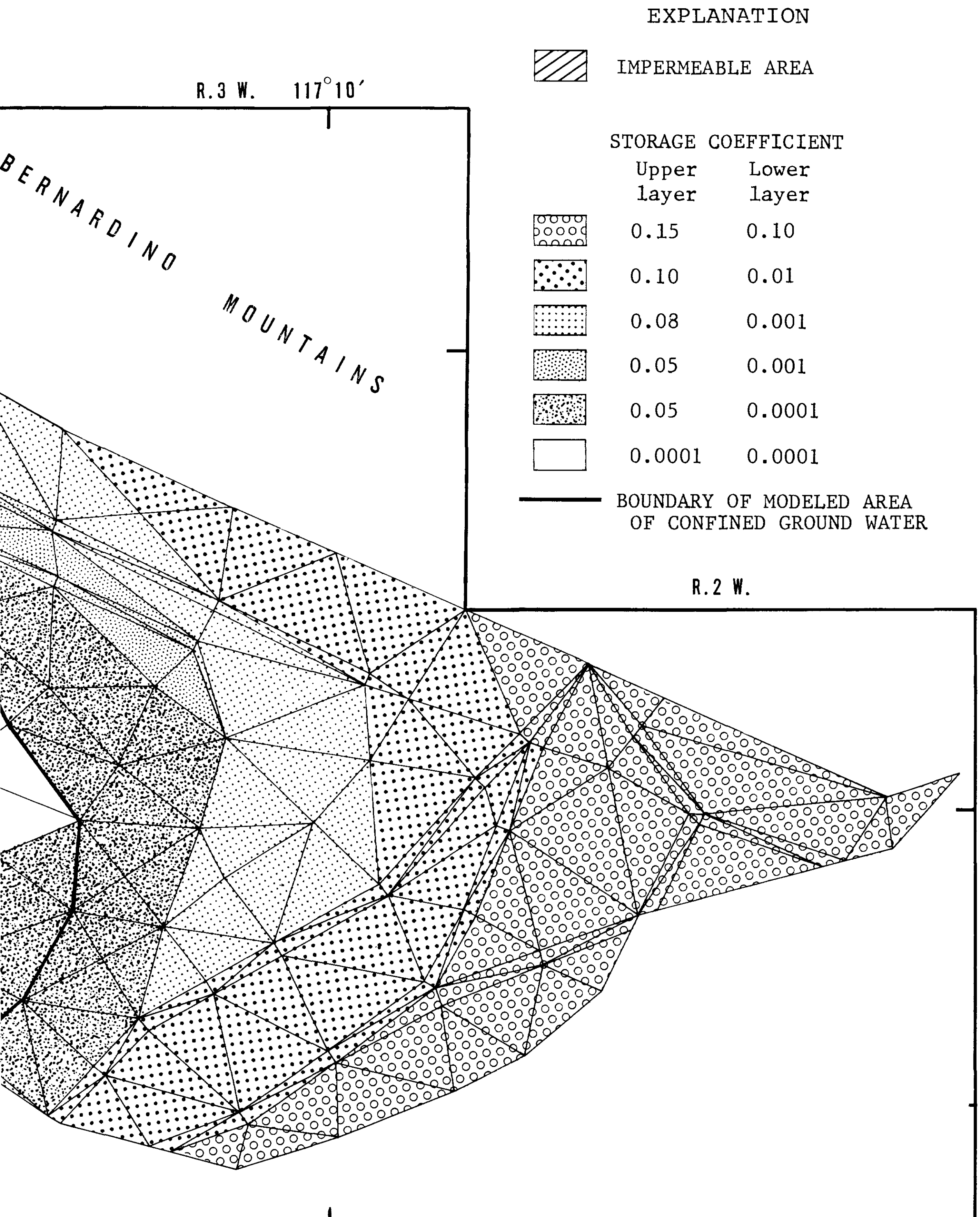


FIGURE 10.-- Aquifer storage coefficients



for upper and lower model layers.

The values of transmissivity, storage coefficient, and leakance coefficient used in each layer of the model for the 296 elements that compose the study area are shown in the section on "Hydraulics Data for Model."

Surface-Water Movement

Practically all the surface inflow to the valley along the San Gabriel and San Bernardino Mountain fronts is measured at selected gaging stations (fig. 11) as is the outflow of Warm Creek, Lytle Creek, and the Santa Ana River. The data show that, except during high flows caused by infrequent flooding, the inflows are much larger than the outflows. Thus, it is concluded that most of the surface flow that enters the valley seeps into the aquifer.

The distribution of streamflow as recharge to the ground-water basin is not restricted to the porous stream channels. Canals and pipelines constructed near the stream entrances to the valley divert surface flow from the San Bernardino Mountains to other parts of the valley at lower altitudes for agricultural use. In particular, flow from the Santa Ana River is diverted to Redlands and farmlands between the river and the San Bernardino Mountains. Flow from the smaller streams such as Devil Canyon, Waterman Canyon-East Twin, City, Plunge, and San Timoteo Creeks, generally is recharged locally into the aquifer within a few miles of the mountain front with no surface-flow loss out of the study area.

The larger streams, such as the Santa Ana River, Mill Creek, and Lytle Creek, transmit large volumes of water in a short time during flood periods. Some of the flow leaves the study area and is available for downstream use. Although the aquifer above the San Jacinto fault cannot absorb all the available water in this short time period, artificial-recharge facilities adjacent to the river slow the movement and enhance percolation to the aquifer. Nearly two-thirds of the valley recharge is derived from the Santa Ana River, Mill Creek, and Lytle Creek.

Table 1 shows the average measured surface-water inflow to the valley. The beginning of record for these stations ranged from 1897 for the Santa Ana River near Mentone to 1952 for Plunge Creek near East Highlands. All the other stations were established in the early 1900's. Termination of the period of record for this study was 1974 in order to coincide with the end of the calibration period for the transient-flow model. The total measured inflow averaged about 143,000 acre-ft/yr.

The outflow of surface water from the study area was gaged at three sites (table 2 and fig. 11). The period of record at these stations is shorter than for the inflow stations, the oldest of the three, Santa Ana River at E Street, having been established in 1940. Most of the outflow is the result of infrequent, short-duration storms causing floodflows, such as those occurring in 1938, 1952, and 1969. The rest of the time, outflow is minimal. The table shows that the measured outflow averaged about 35,000 acre-ft/yr. Thus, during the period 1945-74, the net surface-water inflow to the study area was at least 108,000 acre-ft/yr. Not all this water was available for recharge to the ground-water system, because of losses to consumptive use and evapotranspiration. Increased runoff from areas on Warm Creek and the Santa Ana River that are impermeable due to urbanization is of minor importance in this study. The amount of outflow measured for the 1945-74 model period reflects little pre-urbanized runoff. The section on water budget relates the contribution of surface water to the total recharge for the conceptual model that was simulated by the mathematical model.

TABLE 1. - Average measured surface-water inflow to San Bernardino Valley

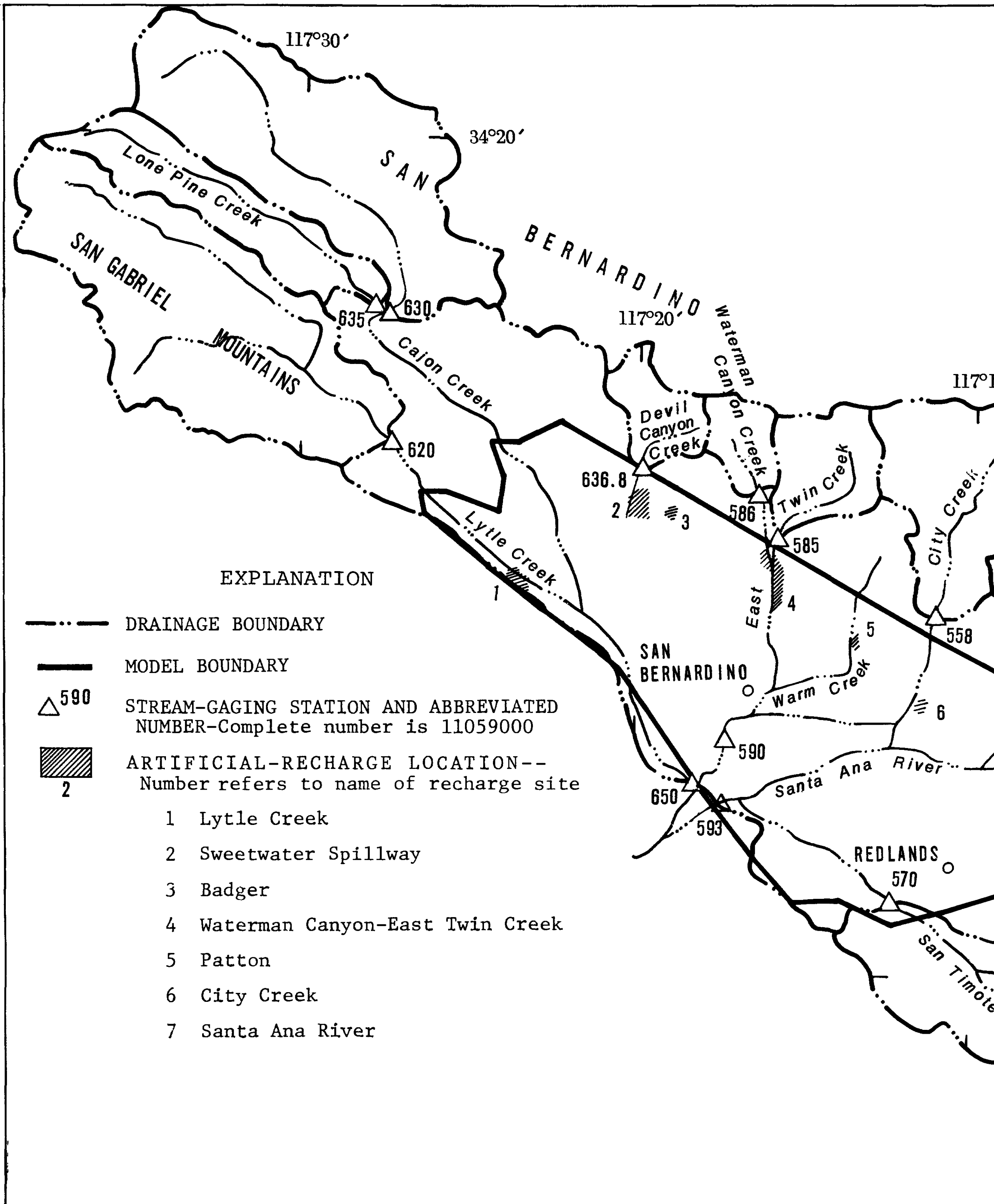
Station No.	Station name	Period of record (water year)[1]	Drainage area (mi^2)	Inflow (acre-ft/yr)
11051500	Santa Ana River near Mentone	1897-1975	209	[2]58,390
11054000	Mill Creek near Yucaipa	1929-75	42.4	[2]24,490
11055500	Plunge Creek near East Highlands	1952-75	16.9	[2]5,480
11055800	City Creek near Highland	1925-75	19.6	[2]7,460
11057000	San Timoteo Creek near Redlands	1926-68, 1973-75	119	971
11058500	East Twin Creek near Arrowhead Springs	1920-75	8.8	3,200
11058600	Waterman Canyon Creek near Arrowhead Springs	1912-14, 1920-75	4.6	1,850
11062000	Lytle Creek near Fontana	1904-75	46.3	[2]30,570
11063000	Cajon Creek near Keenbrook	1920-70	40.6	6,590
11063500	Lone Pine Creek near Keenbrook	1920-38, 1949-75	15.1	1,040
11063680	Devil Canyon Creek near San Bernardino	1913-14, 1934-75	5.5	[2]2,590
Total			527.8	142,631

[1]The water year is the period from October 1 of one year through September 30 of the following year and is designated by the calendar year in which it ends.

[2]Combined flow, includes diversions.

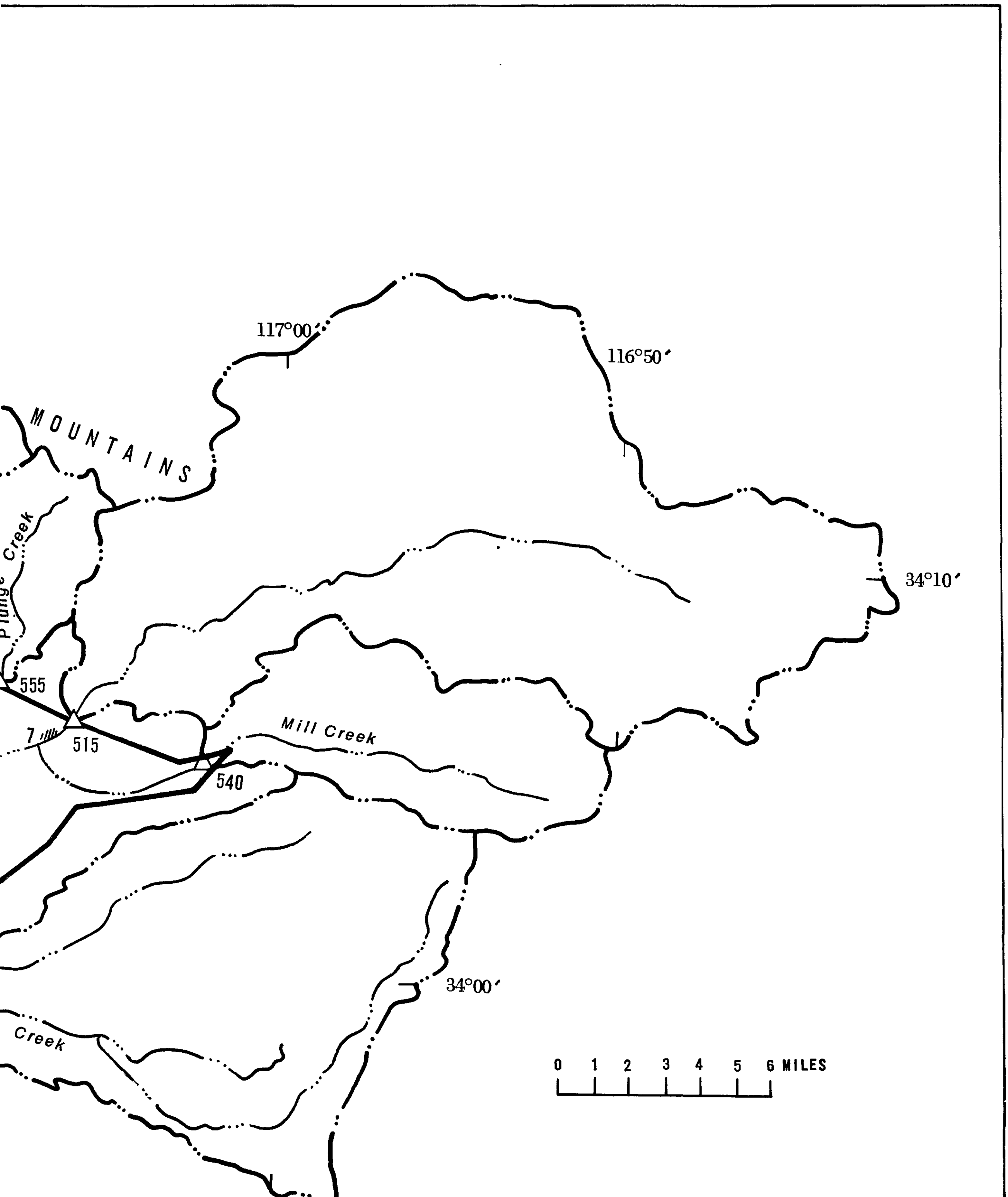
TABLE 2. - Average measured surface-water outflow from San Bernardino Valley

Station No.	Station name	Period of record (water year)	Drainage area (mi^2)	Outflow (acre-ft/yr)
11059000	Warm Creek Floodway at San Bernardino	1962-75	47.8	5,610
11059300	Santa Ana River at E Street near San Bernardino	1940-54, 1966-75	532	24,252
11065000	Lytle Creek at Colton	1958-75	172	4,820
Total			751.8	34,682



Base from U.S. Geological Survey
1:250,000 quadrangles

FIGURE 11. -- Drainage areas tributary to model and location



of stream-gaging stations and artifical-recharge sites.

Ground-Water Levels and Movement

Ground-water movement in the San Bernardino Valley generally follows the surface-drainage pattern. Surface water enters the aquifer through permeable deposits near the mountain fronts and along the stream channels. Ground-water inflow occurs only along the southeast edge of the study area, through the poorly consolidated deposits of the Badlands. Ground water generally moves southwestward, except in the Lytle and Cajon Creek areas where it moves southeastward, and converges toward a common line of discharge at the San Jacinto fault beneath the Santa Ana River. Where the clay layers are continuous over a large area, such as beneath the city of San Bernardino in the central part of the model area, the ground water, prior to extensive development, was confined. The potentiometric head is above the confining beds in this area, and because the San Jacinto fault restricts ground-water flow, ground water is forced through and around the clay beds into the overlying strata and onto the land surface. Consequently, significant components of vertical flow are created in the ground-water flow regimen. Historically, potentiometric heads above land surface existed in the Warm Creek area adjacent to the north side of the San Jacinto fault. This area of rising water, evidenced by flowing wells and springs where subsurface impermeable barriers caused ground water to reach the land surface, were given the old Spanish name of cienaga (Mendenhall, 1905, p. 47).

Of particular importance to this study is the potentiometric-head relation between the confined aquifer and the overlying unconfined system. Because the altitude of the confining bed is at least 1,200 ft above sea level in the upper reaches of the Santa Ana River, potentiometric heads in the lower parts of the valley theoretically could rise to nearly the same level. The lowest land-surface altitude in the valley is about 980 ft above sea level at the intersection of the San Jacinto fault and the Santa Ana River. If the theoretical heads are approached, or if pumping in the confined area ceases, the land could once again become waterlogged.

Historical well data show that before the basin was overdeveloped, the deep wells in the confined area had higher heads than the shallow wells. The confining clay layer abutting the San Jacinto fault is the primary cause of the artesian head and rising water in the formerly swampy lands between Warm Creek and the Santa Ana River.

The height of the potentiometric heads and the areal extent of the artesian zone were determined by Lippincott in 1892 when the shut-in pressures were measured on 55 artesan wells in the confined area (Lippincott, 1902a, p. 84). This study indicated that most of these wells had potentiometric heads 10 to 40 ft above land surface. Four wells southeast of the Santa Ana River and adjacent to San Timoteo Creek had potentiometric heads 50 to 75 ft above land surface.

Long-term hydrographs of several wells in the valley remained relatively flat during the period 1944-45, indicating little change in ground-water storage; therefore, during 1945 the basin was considered to be in hydrologic equilibrium (steady state).

The 1945 water-level contour map of the basin was prepared under the assumption that the water table in the upper aquifer and the potentiometric surface of the lower aquifer generally coincided outside the confined area (fig. 12). Inside the confined area the water table was at or near land surface and the potentiometric surface was represented between 0 and about 75 ft above land surface. The water table was generally between 1,000 and 1,125 ft above sea level in the area of confined ground water and more than 1,800 ft above sea level in the upper reaches of the valley. Gradients were about 50 ft/mi in the confined area, increasing outward to about 200 ft/mi.

Figure 13 shows the measured composite water-table/potentiometric-surface contours for spring 1975, a period considered to be representative of the end of the model period (December 1974). (To account for the change in flow conditions during 1945 and 1974, see the section on Water Budget for discussion of the hydrologic effects of pumping and recharge.) Because of extensive ground-water pumping from wells of different depths perforated generally from near land surface to the bottom of the well, head measurements for the separate aquifers are not possible. Water-level measurements throughout the basin in 1975 generally were between 940 and 1,050 ft above sea level in the area of confined ground water and were more than 1,800 ft above sea level in the upper reaches of the valley. Gradients averaged less than 25 ft/mi in the confined area, increasing outward to about 200 ft/mi.

Changes in the configuration of the water table between 1945 and 1975 reflect the effects of pumping in the central part of the valley coupled with below-average rainfall. During 1945, rainfall was normal, the aquifers were full, and natural discharge occurred as evapotranspiration in the confined area, as underflow across the top of the San Jacinto fault, and as springflow along the banks of Warm Creek and the Santa Ana River adjacent to the fault. The water-level gradients toward the discharge area were steep and apparently controlled by the level of Warm Creek. By 1975 a broad, flat cone of depression had developed over the central part of the valley, ground-water discharge by evapotranspiration and springflow had ceased, and water-level declines were greater than 100 ft in the heavily pumped areas near San Bernardino. Water levels remained constant in the upper reaches of the valley, owing to both natural recharge from streams entering the valley and artificial recharge by pond infiltration.

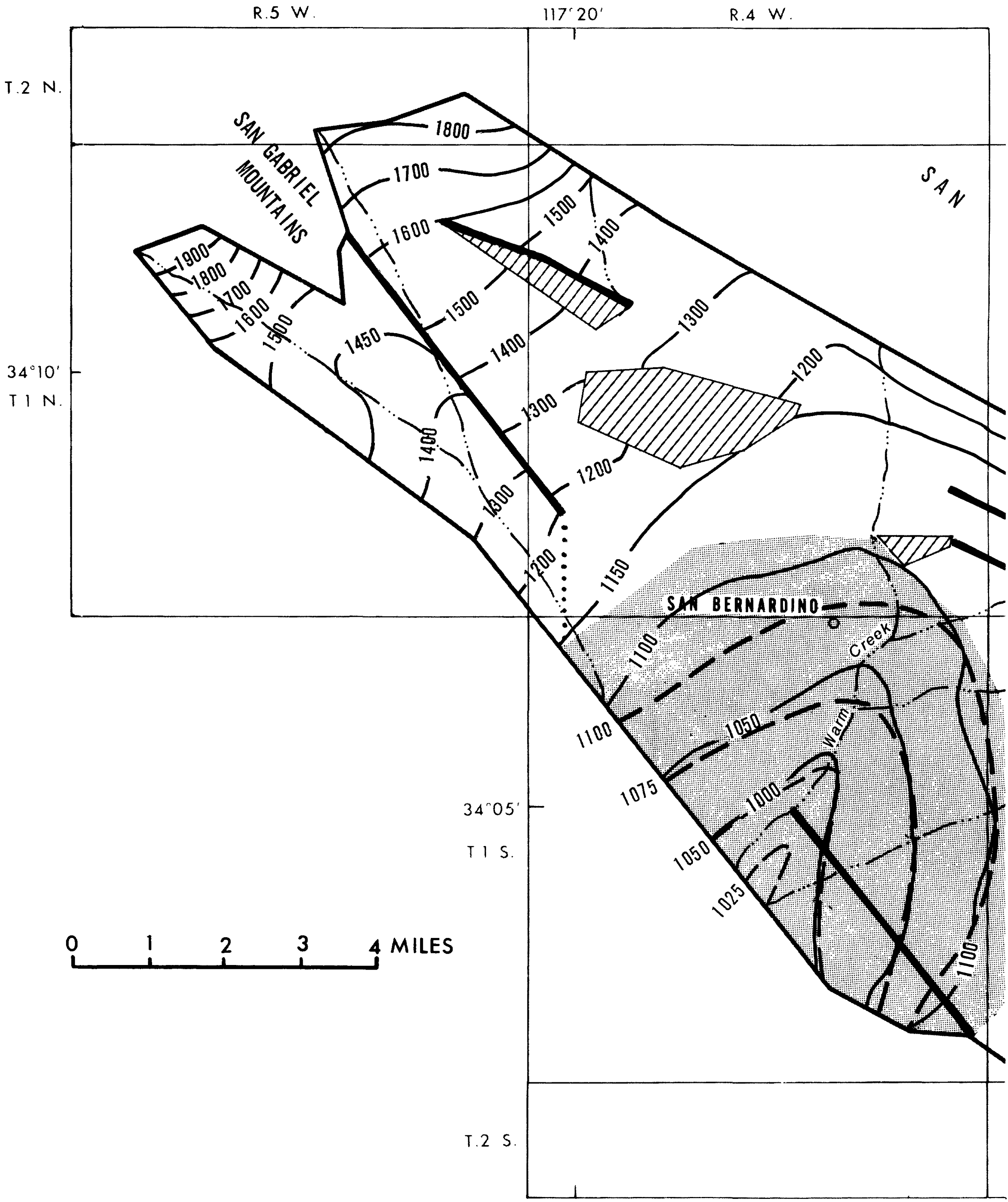


FIGURE 12. -- Water level

EXPLANATION

IMPERMEABLE AREA

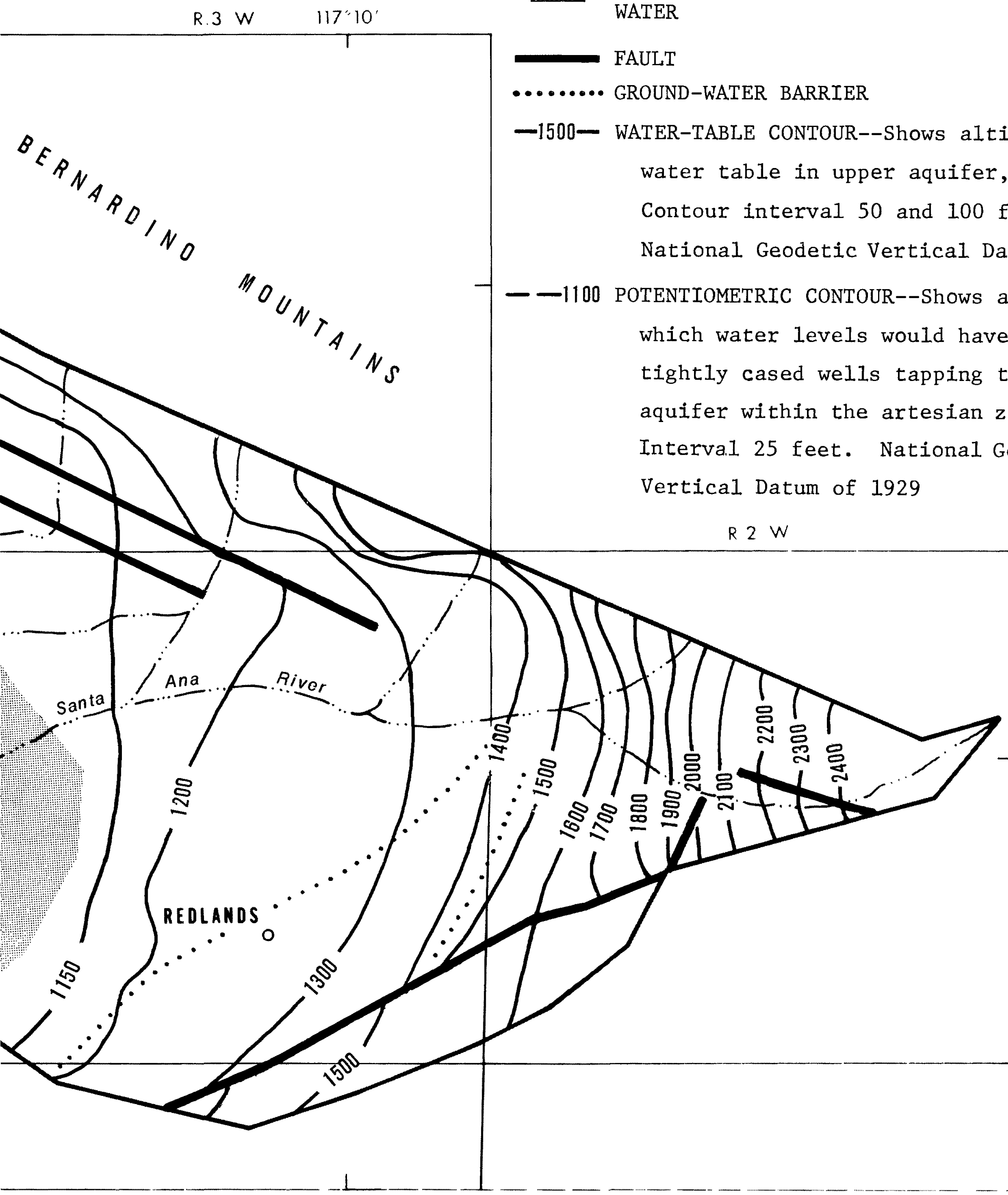
MODELED AREA OF CONFINED GROUND WATER

FAULT

GROUND-WATER BARRIER

—1500— WATER-TABLE CONTOUR--Shows altitude of water table in upper aquifer, 1945. Contour interval 50 and 100 feet. National Geodetic Vertical Datum of 1929

— —1100 POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells tapping the lower aquifer within the artesian zone, 1945. Interval 25 feet. National Geodetic Vertical Datum of 1929



contours, spring 1945.

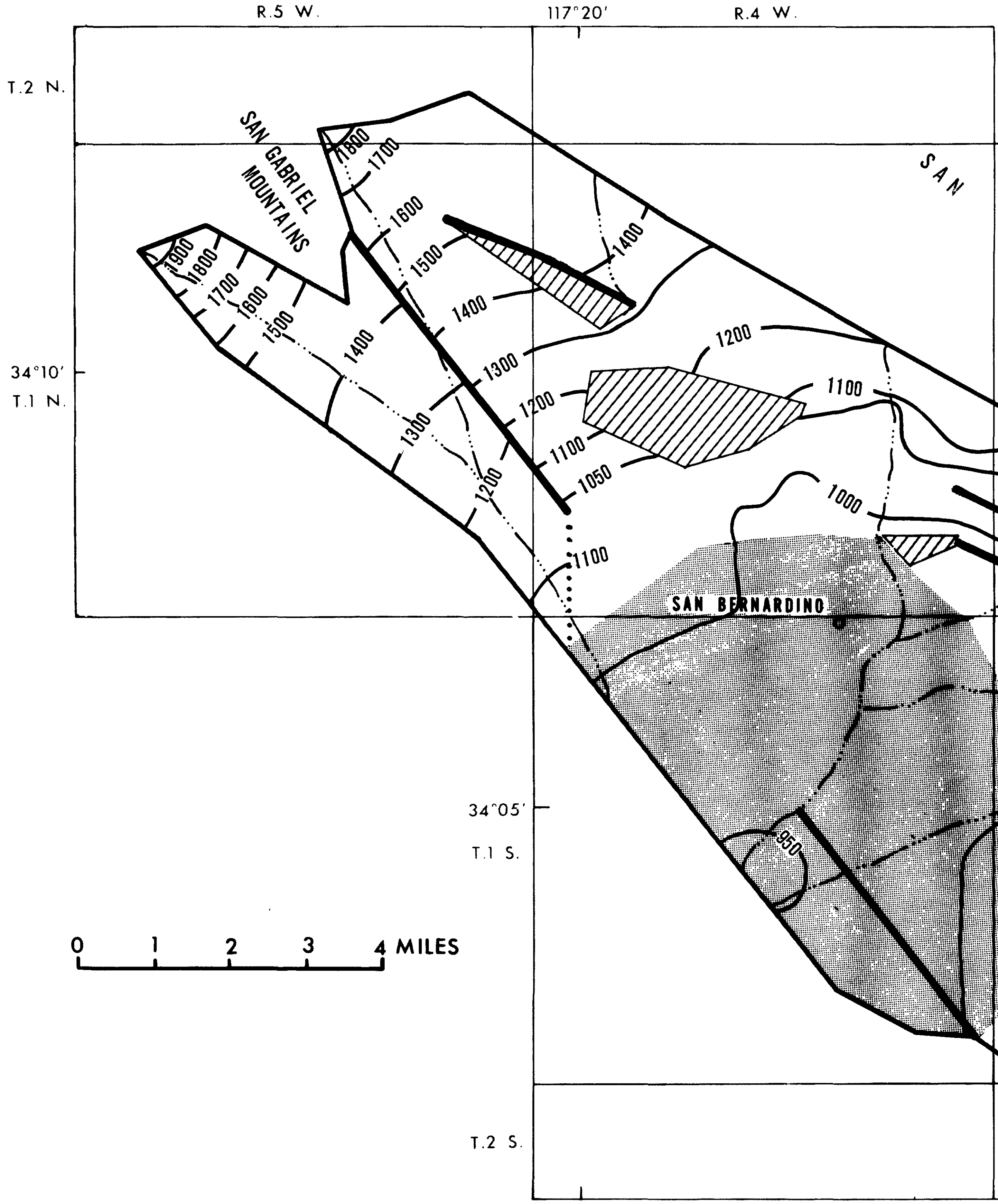


FIGURE 13. -- Water-level

EXPLANATION

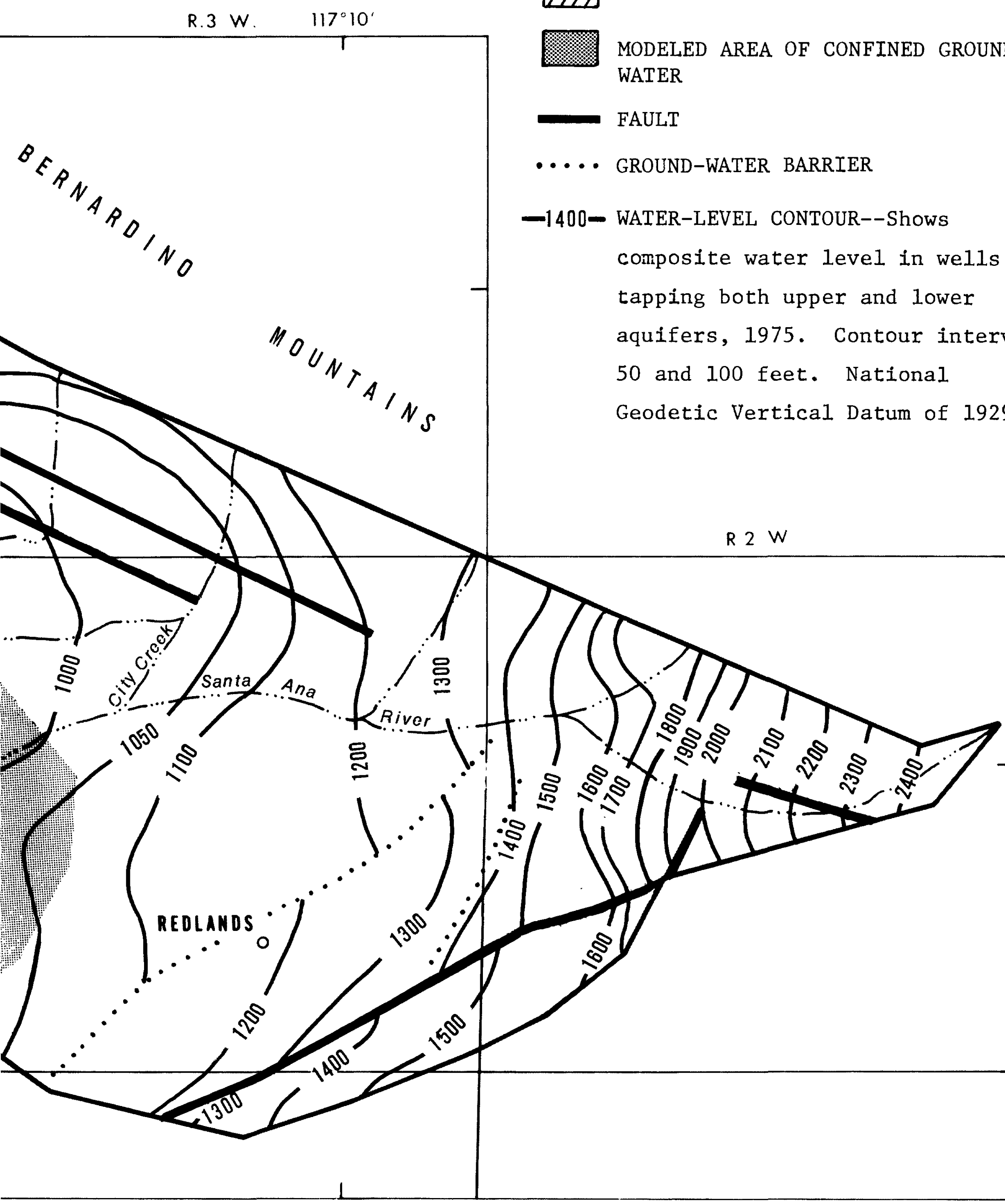
IMPERMEABLE AREA

MODELED AREA OF CONFINED GROUND WATER

FAULT

GROUND-WATER BARRIER

—1400— WATER-LEVEL CONTOUR--Shows composite water level in wells tapping both upper and lower aquifers, 1975. Contour interval 50 and 100 feet. National Geodetic Vertical Datum of 1929



contours, spring 1975.

Water Budget

The conceptual model of the San Bernardino Valley ground-water basin incorporates two water budgets: (1) A 1945 budget representing steady-state conditions of hydrologic equilibrium, where inflow matched outflow, resulting in zero change in storage; and (2) a 1945-74 budget representing transient-state conditions where annual inflow did not match outflow, resulting in a net depletion in storage.

The steady-state and transient-state water budgets are expressed by the two equations:

Steady state:
Inflow=Outflow

$$I_{ar}+I_{gw}+I_{sw}+I_{p}=O_{gw}+O_{p}+O_{et} \quad (1)$$

Transient state:
Inflow-Outflow=Change in storage

$$[I_{ar}+I_{gw}+I_{sw}+I_{p}]-[O_{gw}+O_{p}+O_{et}] = \Delta S \quad (2)$$

where:

I_{ar} = Inflow as artificial recharge through percolation basins constructed along the mountain front and the Santa Ana River (San Bernardino Valley Municipal Water District, written commun., 1973).

I_{gw} = Inflow as ground-water movement across Crafton fault and recharge to the basin. The data were obtained from the report by Dutcher and Fenzel (1972).

I_{sw} = Inflow as net surface-water seepage along stream channels and diversions. The steady-state value was derived by subtracting surface-water outflow from the total gaged inflow and estimated surface-water inflow from ungaged areas. Subsequent values used in the transient-state budget were derived by directly proportioning steady-state inflow with gaged flow in the Santa Ana River. Transient-state flow ranged from 30 to 200 percent of the steady-state flow.

I_{p} = Inflow as recharge from direct precipitation on the valley floor. The value of this component as recharge to the ground-water system was determined to be small, based on infiltration studies in semiarid climates (Young and Blaney, 1942). The effect of any recharge by precipitation was generally accounted for in the adjusted value of pumpage return to the upper aquifer

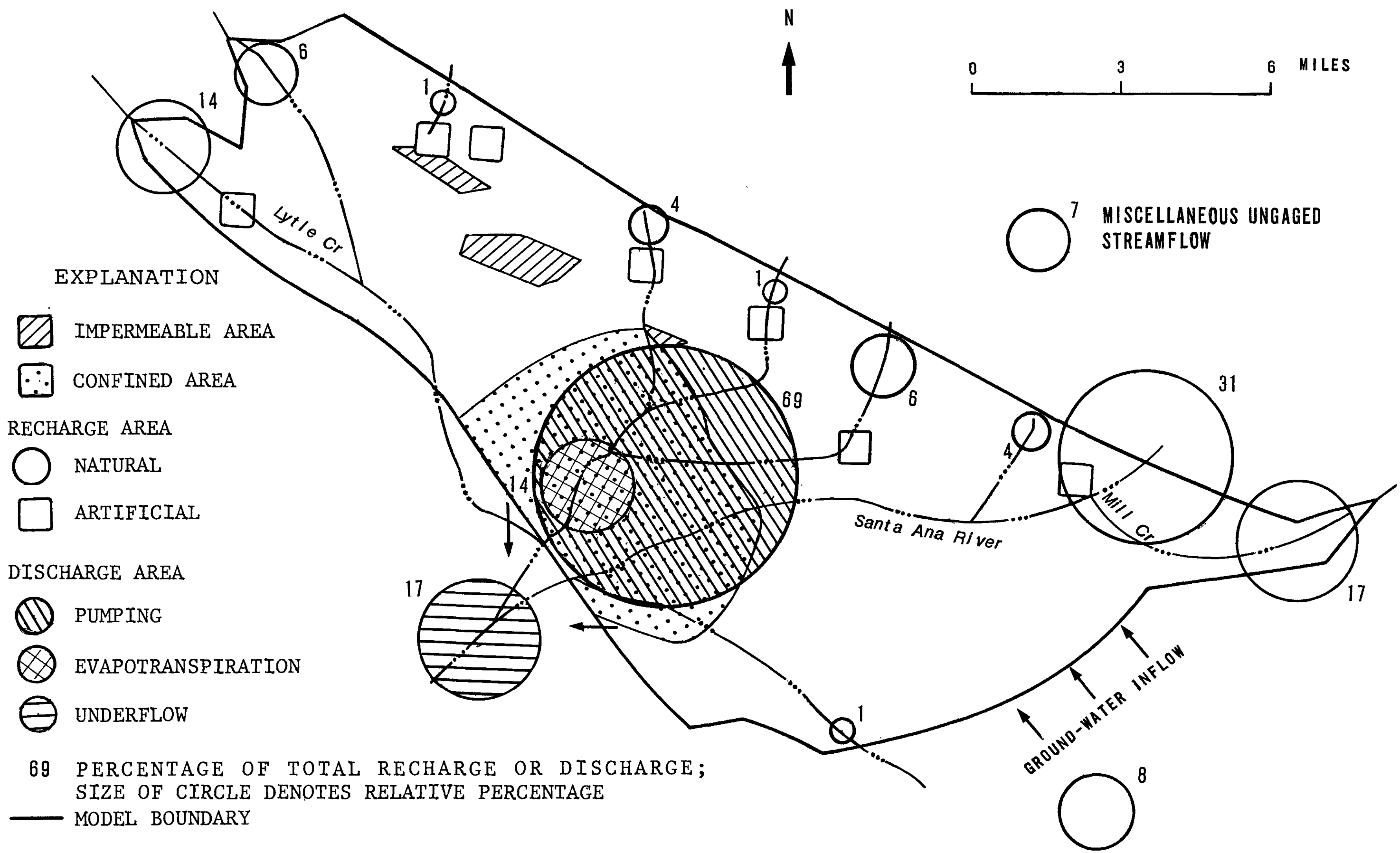


FIGURE 15. -- Steady state (1945) water budget.

MATHEMATICAL MODEL

Basis of the Mathematical Model

The mathematical model of the San Bernardino Valley represents the prototype of a two-aquifer system. The aquifers are linked in the model through a leakage term that represents vertical flow through the confining layer of silt and clay deposits. A Galerkin procedure using finite elements was chosen for this mathematical model over methods using finite differences because a more flexible approach is possible with more precise simulation of irregular boundaries and faults. The elemental method was applied by Pinder and Frind (1972) to a single-aquifer groundwater system. Durbin (1978), in a study of Antelope Valley, Calif., extended this model method to a two-aquifer system and replaced the rectangular element shape with triangles. These model advancements were incorporated into a later study by Durbin and Morgan (1978) on the well-response model of the Bunker Hill ground basin, which has nearly the same boundaries as San Bernardino Valley. The present study covers the same general area but in more detail with respect to geohydrologic data and a finer nodal network for the model. The basic computer program by Durbin was modified and adjusted to fit the objectives of this study.

The fundamental concept of the Galerkin finite-element method is to replace a continuous function with values of the function that are specified at a finite number of discrete points called nodes. Function values between these points are calculated using continuous interpolating functions defined over a finite number of small areas called elements.

The general equation that approximately describes the flow of water in each aquifer of a two layered mathematical model is:

$$\frac{\partial}{\partial x}T\frac{\partial h}{\partial x}+\frac{\partial}{\partial y}T\frac{\partial h}{\partial y}-S\frac{\partial h}{\partial t}-W-\frac{K}{b}(h-h_a)=0, \quad (3)$$

where:

- T = transmissivity of aquifer,
- h = hydraulic head in aquifer,
- S = storage coefficient of the aquifer,
- W = flux of a source or sink (pumpage or recharge),
- K = vertical hydraulic conductivity of the clay layer that separates the two aquifers,
- b = thickness of the clay layer,
- h_a = hydraulic head in the adjacent aquifer,
- x and y = cartesian coordinates, and
- t = time.

For simplicity, the upper (layer 1) and the lower (layer 2) layers of the mathematical model have identical grid patterns, with the elements and nodes numbered the same for each layer. The model network consists of 296 elements and 178 nodes (pl. 1). The physical properties of the aquifer, such as transmissivity, storage coefficient, and, where appropriate, the thickness and vertical permeability (hydraulic conductivity) of the confining clay member, are assigned to elements (triangles), and the recharge, discharge, and potentiometric head are assigned to the nodes or vertices of the triangles. The elements are more closely spaced where data are more abundant in the confined area. The key wells used in the well-response study by Durbin and Morgan (1978) of the Bunker Hill ground-water basin and the areas of potential artificial recharge of imand from streamflow.

O_{gw} = Outflow as ground-water discharge across the San Jacinto fault. The average value of this component was estimated from conclusions of Dutcher and Garrett (1963).

O_p = Outflow as net ground-water pumpage from the basin. Net pumpage is equal to gross pumpage less the percentage of this pumpage which is returned to the aquifer. Gross pumpage for the period 1945-74 was estimated from several reports (California Department of Water Resources, 1971; Albert A. Webb Associates, 1973a, 1973b; and Hanson and Harriger, 1976a, 1976b). The pumpage distribution between the upper and lower aquifers was based on the perforated intervals and depths of wells. Pumpage return in the upper aquifer was estimated as 30 percent of gross pumpage except (1) in the Warm Creek-Santa Ana River area of the confined aquifer from 1945 to 1950 when no pumpage was returned because the water was at or near land surface, and (2) in the well field adjacent to the Santa Ana River where ground water was pumped and exported out of the basin to Riverside. No pumpage was returned to the lower aquifer because of the confining clay above it and the availability of the upper aquifer to receive this return flow. The distribution of pumping wells is shown in figure 14.

O_{et} = Outflow as evapotranspiration from the upper aquifer. The evapotranspiration rate was 0.0000001 ft/s in the swampy area about Warm Creek where the water table was at land surface and proportionately decreased to zero as the depth to the water table reached 10 ft. This estimated evapotranspiration rate is about 50 percent of the long-term (1959-72) evaporation rate of 76.46 in/yr from a standard class-A evaporation pan in San Bernardino (San Bernardino County Flood Control District, 1975).

Δ_S = Change in ground-water storage. This change results from stresses imposed on the aquifer system through increases or decreases of the flow components. Annual storage changes were derived as residuals of the water-budget equations.

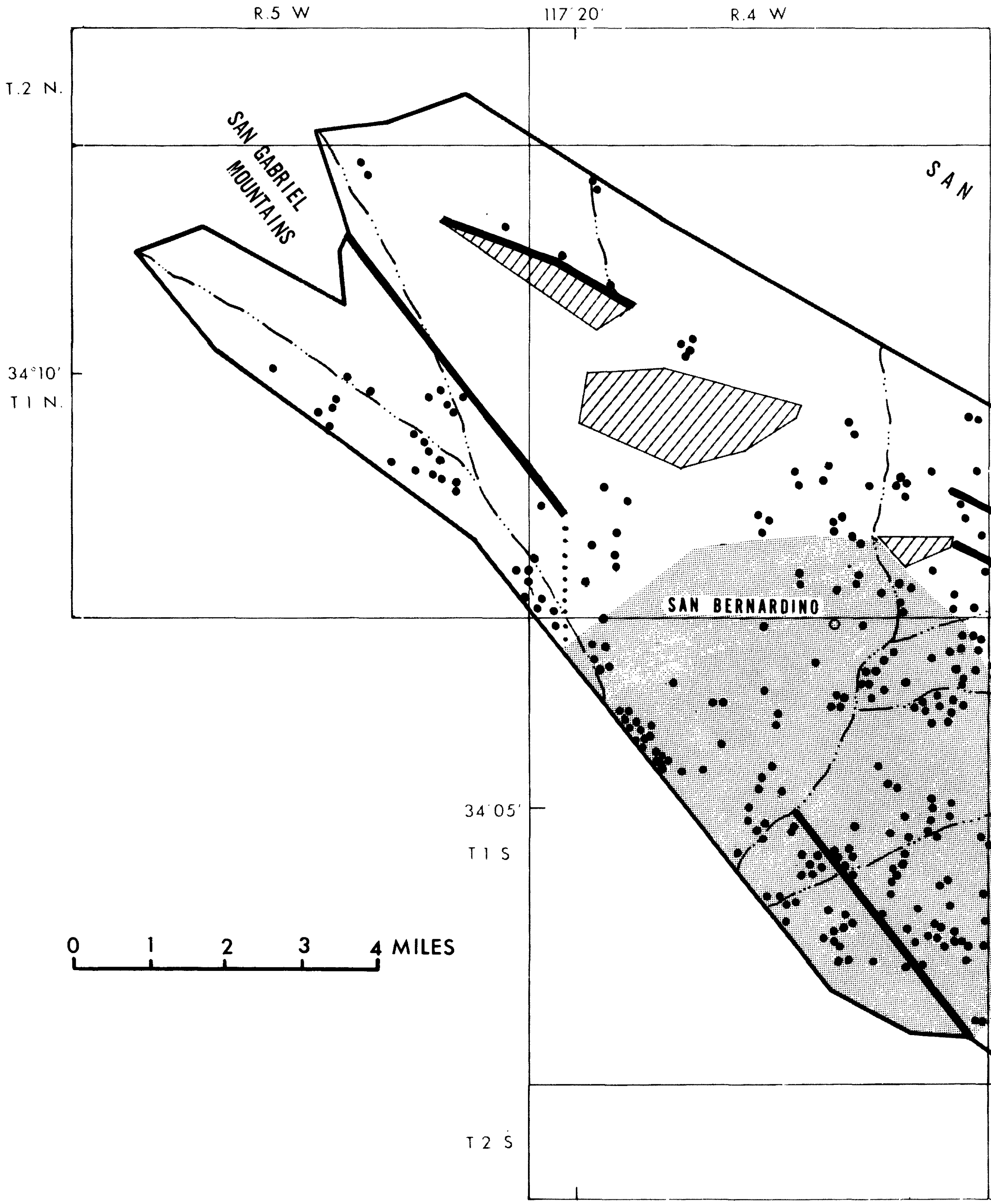


FIGURE 14. -- Location of

ported water were also made nodal points for this study, which consists of the larger area within the San Bernardino Valley. In the peripheral parts of the basin where data are lacking, definition of elements is less profuse.

The geohydrologic relations in the Bunker Hill ground-water basin are extremely complex and cannot be described exactly or duplicated by a mathematical model. Model development requires the use of assumptions and approximations that simplify the physical system. The model, however, is only as accurate as the assumptions and data used in its development. The model output should be evaluated with these limiting factors in mind, and with the recognition that the model only approximates the conceptualized prototype.

Some of the principal simplifying assumptions that relate directly to the mathematical model are:

1. Ground-water movement within an aquifer is only horizontal.
2. Ground-water movement within the confining clay member is only vertical.
3. Hydraulic-head changes within the confining clay member do not cause corresponding changes in the volume of water that is stored in these deposits.
4. Changes in ground-water storage in the aquifers occur instantaneously with changes in hydraulic head.
5. The physical parameters of the system do not change with the state of the system.
6. The aquifers are bounded by both no-flow and constant-flow boundaries.
7. Recharge occurs instantaneously.
8. The aquifers are isotropic.
9. The barrier effect of faults can be represented by a zone of low transmissivity.

In applying the model to the study area, the following approximations are used:

1. The San Bernardino Valley basin consists of unconfined, partly confined, and confined aquifers that are to some extent hydraulically connected. As a practical matter, the model basin is conceptualized as a two-aquifer system. The upper layer (layer 1) represents the aquifer from the land surface to a depth of about one-third of the aquifer, and the lower layer (layer 2) represents the bottom two-thirds of the ground-water basin. The model layers are separated by an extensive clay bed which is as much as 300 ft thick in the confined area and which is assumed to be 1 ft thick in the unconfined area. The mechanics of the model program require a separation between model layers, even in the unconfined areas where none is present. By assuming a small thickness of 1 ft, however, the head differential between layers is not significant, and the water table can be represented as one surface.
2. Because of the type of formations that compose the ground-water basin, confined ground water occurs to some extent throughout the basin. This local confinement is insignificant, however, in those parts of the basin designated as water table and is not accounted for in the water-table part of the model.
3. Transmissivity values used in this model do not change with time. They are computed as a product of a specified thickness of water-bearing sediments and a depth averaged hydraulic conductivity. Errors in the model would be introduced if changes in saturated thickness due to water-level changes were not small compared to the total thickness of the aquifer. In the actual basin the change in saturated thickness compared to the total thickness has indeed been small over

the period of study, and had little effect on transmissivity values used in the model. Because hydraulic conductivity varies considerably along any vertical section of the basin, depending generally on the type of material in the section, transmissivity as used in the model should be considered an effective or average value not related to specific strata or geologic formations.

4. The values of storage coefficient used for the model do not change with time but are a function of location in the basin. In the actual basin, storage coefficients can vary considerably with time, largely as a function of changing discharge and recharge conditions, the lack of homogeneity of the material in the aquifers, and potential aquifer compaction. Significant vertical, as well as areal and temporal, changes occur in storage-coefficient values because of the nonhomogeneity of material in a vertical section of the basin. The model makes no provision for vertical changes. Areal distribution of storage-coefficient values is accomplished in the model by assigning appropriate values to the individual elements. The model, therefore, is rather limited in its ability to accommodate the various changes in storage coefficient that actually occur. For this reason, the elemental values used are more properly termed average storage coefficients and cannot be specifically related to any particular stratum or geologic formation. The storage coefficients of layers 1 and 2 are modeled as artesian to water table depending on the hydraulic characteristics of the basin sediments, particularly the clay and silt layers.

5. Quantities of basin recharge and discharge applied to or simulated by the model occur at constant rates over designated periods, such as yearly intervals. Quantities of recharge to and discharge from the actual basin, however, are highly variable with space and time, depending on ever-changing climatic or management conditions. The model does not accommodate these short term variations but applies average flow over a simulation period that is compatible with modeling practicality and the objectives of the study.

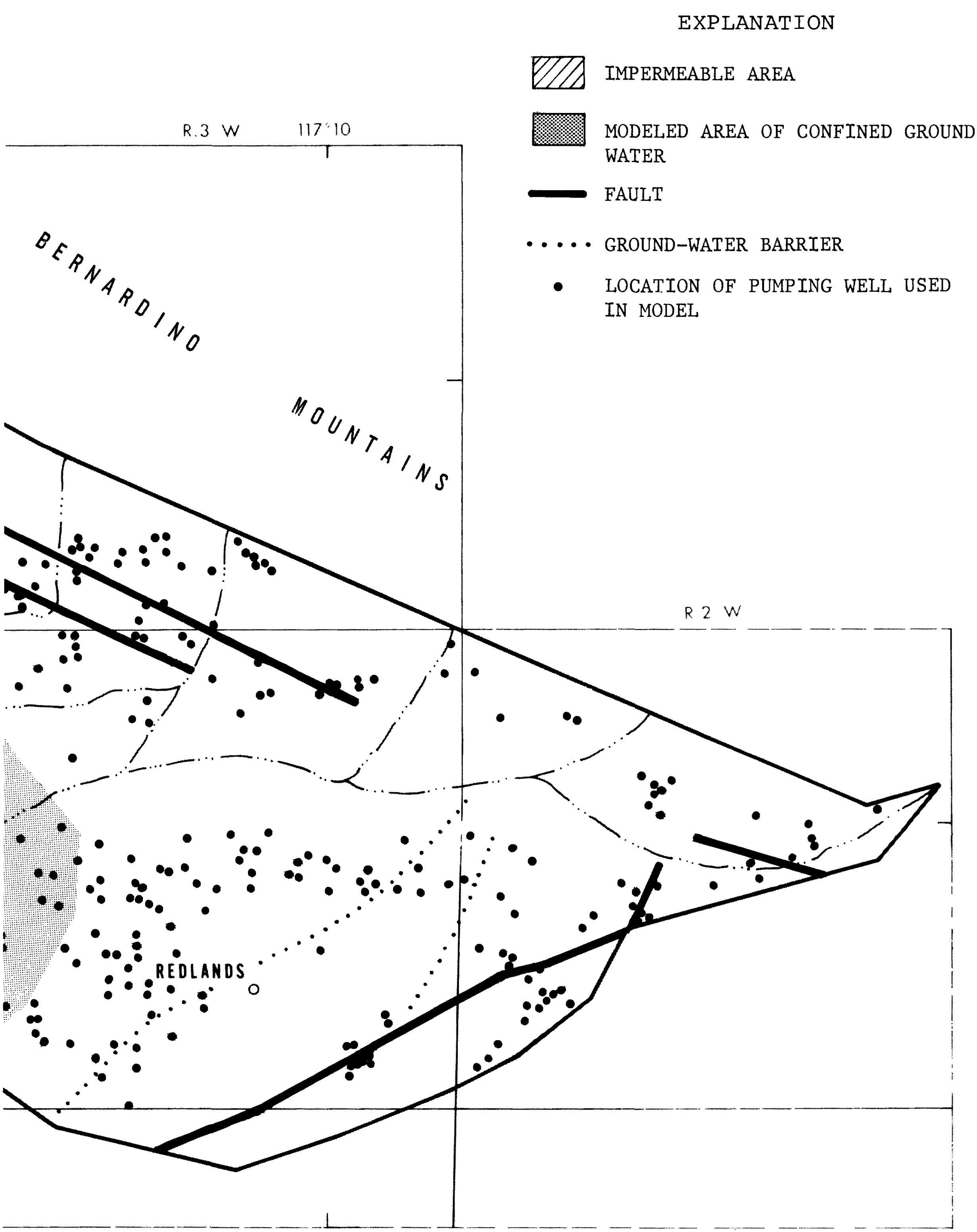
6. The hydrologic boundaries of the ground-water basin can be simulated by the model as constant-flow or no-flow boundaries.

7. Pumpage from the basin is simulated by grouping individual wells to the nearest node and totaling their discharge.

To use the mathematical model as a predictive tool, it must first be calibrated. Models are calibrated by combining estimated distributions of the transmissivity and storage coefficient with sets of known or estimated ground-water recharge. The combination of aquifer parameters and flow conditions that best fit the field data and conceptual model of the basin is said to be determined when model-generated water levels approximate historical water levels within a predetermined limit of accuracy. Calibration is by trial-and-error rearrangement of the distribution of model inputs in order to improve upon the fit of model-generated water levels to observed water levels with each successive simulation.

Specifically, the first step in calibrating the San Bernardino Valley model was to simulate water levels under steady-state conditions (1945). Basin recharge and transmissivity distributions, developed as a result of this predevelopment simulation, were transferred, where appropriate, directly to the simulation of water levels under stressed or transient-state conditions (1945-74). In addition, known pumpage and estimated aquifer storage-coefficient distributions were then added to the transient-state model. Successive simulations were made until a satisfactory storage-coefficient transmissivity and ground-water inflow matrix was developed for the model.

Quantitative information or parameters generated as a result of model simulations are referred to in this



pumping wells used in model.

Table 3 gives the values for the components of the water-budget equations, and figure 15 illustrates the steady-state water budget for 1945, based on a percentage of total recharge or discharge. During 1945 the steady-state condition was assumed, where inflow and outflow were equivalent at about 134,000 acre-ft. During the period 1945-74, drier-than-average conditions prevailed, and the transient-state condition was assumed with average yearly inflow of about 106,000 acre-ft, average outflow of about 139,000 acre-ft, and a resulting average depletion in storage of about 33,000 acre-ft. For the 30 year water-budget period, the total storage depletion was about 985,000 acre-ft. In comparison, studies by the San Bernardino Valley Municipal Water District (1977, p. 24) for the Bunker Hill basin showed net depletion over this period of nearly 700,000 acre-ft. The current study area is larger, as it also includes the Redlands, Reservoir, Mill Creek, Mentone, and Lytle Creek subareas.

TABLE 3. - Values for components of the water-budget equations, 1945-74

[in acre-feet]

Year	Inflow: Artificial recharge I_{ar}	Inflow: Ground water I_{gw}	Inflow: Surface water I_{sw}	Inflow: Precipitation I_p	Outflow: Ground water O_{gw}	Outflow: Consumptive use pumpage O_p	Outflow: Evapotranspiration O_{et}	Ground-water storage change Δs
1945	0	7,700	125,900	0	15,200	88,900	29,900	-400
1946	0	7,700	125,900	0	15,200	92,500	22,400	+3,500
1947	0	7,700	88,200	0	15,200	103,300	14,800	-37,400
1948	0	7,700	75,600	0	15,200	114,800	13,400	-60,100
1949	0	7,700	88,200	0	15,200	108,600	12,300	-40,200
1950	0	7,700	63,000	0	15,200	110,900	8,500	-63,900
1951	0	7,700	63,000	0	15,200	114,500	13,200	-72,200
1952	0	7,700	138,600	0	15,200	86,900	4,600	+39,600
1953	0	7,700	63,000	0	15,200	124,600	6,100	-75,200
1954	0	7,700	113,400	0	15,200	109,200	1,800	-5,100
1955	0	7,700	75,600	0	15,200	124,900	0	-56,800
1956	0	7,700	63,000	0	15,200	140,200	0	-84,700
1957	0	7,700	63,000	0	15,200	116,600	0	-61,100
1958	0	7,700	176,300	0	15,200	112,400	0	+56,400
1959	0	7,700	63,000	0	15,200	192,000	0	-136,500
1960	0	7,700	63,000	0	15,200	132,600	0	-77,100
1961	0	7,700	37,800	0	15,200	149,400	0	-119,100
1962	0	7,700	88,200	0	15,200	129,800	0	-49,100
1963	0	7,700	50,400	0	15,200	123,100	0	-80,200
1964	0	7,700	50,400	0	15,200	134,000	0	-91,100
1965	0	7,700	113,400	0	15,200	116,900	0	-11,000
1966	0	7,700	163,700	0	15,200	19,300	0	+36,900
1967	0	7,700	151,100	0	15,200	138,500	0	+5,100
1968	0	7,700	75,600	0	15,200	122,500	0	-54,400
1969	0	7,700	251,900	0	15,200	101,400	0	+143,000
1970	0	7,700	100,800	0	15,200	120,500	0	-27,200
1971	0	7,700	75,600	0	15,200	125,000	0	-56,900
1972	1,300	7,700	63,000	0	15,200	123,500	0	-66,700
1973	32,200	7,700	138,600	0	15,200	107,300	0	+56,000
1974	16,200	7,700	100,800	0	15,200	109,100	0	+400
Total								-985,500
Average								-32,850

report as model-generated information or parameters. The validity and accuracy of this information are not to be construed as having been determined by actual measurement. The calibrations were subjective and, to a large extent, based on trial and error within acceptable physical limits.

Simulation of the Steady-State Condition (1945)

The purpose of the steady-state simulation was to verify, by the model, the estimated values of the steady-state water budget, aquifer transmissivity, and leakance coefficient of the confining clay member. These parameters in each layer were adjusted during approximately 100 calibration runs, until water levels at 65 percent of the nodes simulated within a range of 10 ft those observed in 1945. Because the aquifer was assumed to be in hydrologic equilibrium, aquifer storage coefficients were not involved in the steady-state simulation. The total steady-state recharge to the model was computed to be about 185 ft^3/s or nearly 134,000 acre-ft/yr. Most of this recharge consisted of stream inflow from Lytle Creek, Cajon Creek, Devil Canyon, Waterman Canyon-East Twin Creek, Plunge Creek, City Creek, Mill Creek, San Timoteo Creek, and the Santa Ana River. The surface flow was modeled as recharge to the ground-water system through a series of nodes representing the downstream channel where recharge took place. Additional basin recharge was also modeled, representing canal diversion from the streams for agricultural lands, particularly in the highlands along the San Bernardino Mountains and in the Redlands area. Lesser amounts of recharge were programed along the periphery of the basin to account for ungaged runoff from the surrounding mountains. Precipitation falling directly on the study area was not modeled separately but was combined with the amount of recharge to be returned to the aquifer from application of water to the ground for agricultural use.

The only subsurface inflow that was modeled was along the southeast border, from the Badlands to Crafton Hills. The recharge for the model period and for future predictions was kept constant at 7,700 acre-ft/yr, although inflow decreased slightly in later years because of increased ground water pumping outside the model area. Dutcher and Fenzel (1972, p. 29) computed total underflow to the San Bernardino Valley as 7,200 acre-ft/yr in 1945. An additional 500 acre-ft/yr was added to account for recharge by local precipitation and ungaged surface flow.

Most of the discharge from the modeled ground-water system was by wells. All the large producing wells and many small wells were located, and pumpage was allocated to the nearest nodes. As many as 20 wells in the vicinity of a node were grouped together to represent the composite pumpage.

As the model is two layers, the pumping from each layer was determined by well depth and location and length of casing perforations. In general, pumpage from wells less than 300 ft deep was assigned to the upper model layer. Pumpage from wells perforated only below 300 ft was assigned to the lower model layer. Pumpage from wells perforated in both aquifers was prorated, depending on the length of perforations in each aquifer system.

In the confined part of the study area, particularly in the swampy area about Warm Creek, the Santa Ana River, and other areas where the depth to water was less than 10 ft below land surface, no recharge either from irrigation return or streamflow was programed into the model, because storage space was not available. Where the depth to water was greater than 10 ft below land surface and aquifer storage was available, 30 percent of the total pumpage was considered as being recharged to the upper aquifer in the model. No return recharge was programed directly into the lower aquifer because of the confining clay above it. Ground-water discharge from the basin by the pumping of wells is represented in the model as the net extraction rather than by gross pumpage. For modeling purposes, where discharge by pumping occurs at the same nodes used for recharge by irrigation return or by rivers and streams, the net value is the resultant modeled.

The principal area of flowing wells, ground-water discharge to the surface drainages, and high ground-water levels is adjacent to Warm Creek and the Santa Ana River. No pumpage return was modeled here because of high ground-water levels. In this area about 55 wells are pumped and water is exported to the Riverside area by pipeline and canal. This pumpage system salvages a portion of the water that would be lost by evapotranspiration or would flow out of the area in the Santa Ana River.

Ground-water losses from evapotranspiration and from discharge to the swamplands about Warm Creek were determined by the model to be about 41 ft^3/s (30,000 acre-ft) in 1945, based on an evapotranspiration rate of 0.0000001 ft/s and an area of about 10 mi^2. The long-term (1959-72) evaporation rate in San Bernardino from a Weather Bureau class-A evaporation pan was 76.46 in/yr (San Bernardino County Flood Control District, 1975, p. 54). The quantity of water that actually evaporates and transpires from the soil is less than from an open pan because water is not always available and soil cover inhibits evaporation. Studies in the Victorville area indicated that the potential evapotranspiration was about 43 percent of the pan evaporation (Hardt, 1971, p. 7). Durbin (1978, p. 14, 15) summarized the work of Lee (1912) and Robinson (1958) in Antelope Valley regarding evapotranspiration from salt grass, which is typically found about swampy lands. These studies indicated that evapotranspiration from salt grass virtually stops where the depth to the water table is greater than 10 ft and is about 86 in/yr with the water table 1 ft below land surface.

Subsurface discharge from the basin is only through the alluvial sediments over the top of the buried San Jacinto fault near the Santa Ana River. According to Dutcher (1956, p. 11), the ground-water outflow from the San Bernardino Valley from 1936 to 1949 ranged from 23,700 acre-ft in 1936 to 14,300 acre-ft in 1948. The discharge used for the model was kept constant at 21 ft^3/s (15,200 acre-ft/yr) and was simulated at nodes 59, 77, and 96 for a 3-mile stretch bisected by the Santa Ana River.

An important part of developing the steady-state model was to determine the aquifer transmissivity for the basin and then subdivide it between the two model layers. The transmissivity values, combined with the water budget, required some modification for the model to match the historical water levels. A problem in verifying the steady-state model was the relatively flat ground-water gradient generated by the model from the inflow, or recharge areas along the mountain front to the outflow, or swampy lands adjacent to the San Jacinto fault. In the recharge area the model ground-water levels were too low, and in the confined area they were too high. To obtain proper gradients, recharge values were increased beyond reason along the mountain front, requiring equally unreasonable amounts of discharge in the artesian area, and still the gradients could not be sufficiently raised. To maintain recharge within reasonable limits, the model aquifer transmissivities were reduced as much as 20 percent in some parts of the basin.

The clay layer between the two layers of the model is thickest in the center of the study area adjacent to the San Jacinto fault. The clay restricts vertical water movement and is one reason for head differences between the shallow and deep parts of the aquifer. Historical data are scarce for explicitly defining the amount of head differences and the distribution pattern, but, according to Lippincott (1902a, p. 77, 88), heads in the deeper part of the basin in the Warm Creek area near the San Jacinto fault were commonly 10 to 40 ft above land surface. Based on the head separation between these aquifer systems and numerous water-level measurements during 1945 in wells of various depths throughout the basin, the hydraulic conductivity (permeability) of the clay was determined to be about 0.00000035 ft/d after several adjustment runs. This value seems reasonable in relation to measured clay permeabilities in other areas. With the hydraulic conductivity and clay thickness known, a leakance coefficient was computed by the model for each grid element.

Simulation of Transient-State Conditions (1945-74)

The steady-state model (1945) components of recharge, discharge, aquifer transmissivity, and leakance coefficient of the confining bed between the model layers were calibrated for a zero change in ground-water storage. A transient-state calibration was required for the period 1945-74, as ground-water pumping after 1945 was in excess of natural recharge and part of the water was derived from aquifer storage. Consequently, water levels were lowered more than 100 ft in some parts of the basin. Because of the depletion in aquifer storage, the transient-state model required values of storage coefficient and yearly records of pumpage and recharge for each layer in the model. Storage coefficients in each layer were adjusted during approximately 30 calibration runs until model-generated water-level data matched measured water levels from selected wells throughout the valley.

The water budget for the transient-state condition from 1945 to 1974 is largely dependent upon the history of ground-water pumping in the valley. Agricultural irrigation from ground water started about 1870 when wells drilled in the lower part of the valley yielded large quantities of flowing water. Well drilling continued, and by 1905 more than 900 wells had been drilled, and about 20,000 acres were under irrigation, using both surface water and ground water. By 1930 the total irrigated acreage was about 32,000 acres; however, by 1977 it had decreased to about 15,000 acres.

Urbanization of the San Bernardino Valley has continuously increased since the late 1800's, with most of the growth since about 1945 as a result of the end of World War II. In 1900 about 1,000 acres was under urban development, primarily at Redlands. By 1930 urban growth affected other parts of the valley and included about 12,000 acres. By 1960 the urbanized area was nearly 35,000 acres, and by 1976 it had increased to 54,000 acres.

The increased use of ground water throughout the year is reflected in the annual gross pumping rate for the period 1935-74 (table 4). For the model period 1945-74, total pumpage was 4,975,000 acre-ft and annual pumpage ranged from 118,400 acre-ft in 1945 to 213,500 acre-ft in 1961. The yearly differences in pumpage, in part, reflect the amount of precipitation and, consequently, the amount of runoff available each year for agricultural irrigation. For the transient-state model the yearly pumpage was programed, and the method of distribution to the 76 nodes and model simulation was identical to the steady-state model. See table 3 for net pumpage programed into the model.

Pumpage for 1935 through 1960 was estimated by the California Department of Water Resources (1971) from land-use data. Pumpage for 1950 through 1974 was compiled in great detail by Albert A. Webb Associates, Inc. (1973a, 1973b) and by Hanson and Harriger (1976a, 1976b) from reports filed by well owners with the

TABLE 4. - Annual gross ground-water pumpage in San Bernardino Valley, 1935-74

Year	Pumpage (acre-ft)	Year	Pumpage (acre-ft)	Year	Pumpage (acre-ft)	Year	Pumpage (acre-ft)
1935	85,000	1945	118,400	1955	178,500	1965	167,100
1936	113,000	1946	135,500	1956	200,300	1966	170,500
1937	82,400	1947	136,400	1957	166,700	1967	154,200
1938	86,900	1948	151,700	1958	160,600	1968	174,900
1939	92,300	1949	142,900	1959	201,000	1969	144,900
1940	110,900	1950	158,500	1960	189,300	1970	172,200
1941	70,300	1951	163,600	1961	213,500	1971	178,600
1942	106,100	1952	124,100	1962	185,500	1972	176,700
1943	103,500	1953	178,100	1963	175,800	1973	153,300
1944	101,600	1954	156,100	1964	191,400	1974	155,600

California Water Rights Board. Values from these two sources for the overlapping period 1950-60 did not exactly agree, so the values determined by the California Department of Water Resources (1971) were multiplied by a small constant to ameliorate the disparity. See figure 14 for the location and distribution of the wells pumping ground water from the basin that were used in the model. Based on well-completion records, pumpage was proportioned between the upper and lower layers of the model.

Discharge also occurs as underflow through the alluvial sediments over the top of the San Jacinto fault. Dutcher and Garrett (1963) estimated that the average annual underflow ranged from 14,300 to 23,700 acre-ft from 1936 to 1949, depending upon the thickness of saturated sediments and ground-water gradient. Discharge in the model was kept constant at 15,200 acre-ft/yr during the 30-year transient-model period to simplify the model. The yearly differences in underflow discharge across the fault were relatively small compared to the total basin discharge. Long-term changes associated with wet and dry periods, and seasonal changes caused by nearby pumping and recharge from the Santa Ana River and Warm Creek tended to average out. The constant value used in the model was about 10 percent lower than the average underflow for 1936-49.

When the Mormons established the first settlement in San Bernardino in 1851, the surface flow of Warm Creek, the Santa Ana River, and lower City and Lytle Creeks was derived partly from springs and swamps in the artesian area upstream from the San Jacinto fault. The flow in Warm Creek in 1887 averaged between 75 and 80 ft^3/s; by 1900 that discharge was halved, and by 1955 all the channels were dry and the ditches abandoned (Scott, 1977, p. 51). The reduction in flow is attributed primarily to increased ground-water pumping. The transient-model verification correlated closely with the physical conditions. In 1945 the model discharge from the swampy area was about 30,000 acre-ft, diminishing to 1,800 acre-ft in early 1955. In late 1955, model evapotranspiration ceased as water levels dropped to more than 10 ft lower than Warm Creek and the Santa Ana River.

As a general rule, where the depth to water in the upper aquifer was greater than 10 ft below land surface, 30 percent of the total pumpage was recharged to this aquifer as irrigation-return water and was subtracted in the program from the total pumpage determined for the upper aquifer. Pumpage was modeled from the lower layer, but irrigation water was returned only to the upper layer. This model procedure was modified in the swampy area between Warm Creek and the Santa Ana River to account for 55 wells that pump ground water for export outside the valley and for recharge to the formerly swampy area where it had previously been rejected. Prior to 1951 no return water was programed because the upper aquifer was full. After 1951, the amount of recharge for the swampy area was adjusted partly by trial and error until there was a close correlation of model-generated water-level hydrographs with measured water levels in selected wells.

Artificial recharge of imported water from the California Aqueduct was started in November 1972, or about 2 years prior to the end of the calibration period. From November 1972 to December 1974 about 50,000 acre-ft was recharged, amounting to about one-half of the entitlement. This amount of recharge was placed in the node nearest to the recharge sites along the base of the San Bernardino Mountains.

Natural streamflow varies each year, affecting the amount of ground-water recharge. Since about 1947, the San Bernardino Valley has been in an extended dry period except for floods in 1952, 1958, 1965-67, 1969, and 1973. As a result of these climatic conditions, the modeled recharge for this transient-state model averaged about 106,000 acre-ft/yr (146 ft^3/s), which is less than the long-term average.

The variation in yearly ground-water recharge as related to streamflow was programed into the model by using flow in the Santa Ana River as an index. The index was determined by correlating for each year the flow in the Santa Ana River as related to the long-term average flow used in the steady-state model. This yearly ratio, which ranged from 0.3 to 1.4 for all years except 1969, was then multiplied by the steady-state recharge to obtain the yearly ground-water recharge derived from the streams. This procedure simplified the verification of the transient model in that the geographic distribution of recharge was held constant while the amount of recharge was adjusted higher or lower for annual changes.

The floods of 1969 caused flows in the river channels that were greatly in excess of the long-term average with large quantities of surface water flowing out of the study area. Thus, the resulting ratio used to compute ground-water recharge for 1969 resulted in model water levels that were much higher than the measured water levels, particularly in the confined area adjacent to the San Jacinto fault. When the recharge ratio was lowered to account for basin recharge only, and excluded surface water outflow, the computed water levels in the confined area were comparable with the measured water levels, but in the unconfined peripheral part of the model they were less precisely correlated. As the confined area is of first importance to the local water district because of a potential rising-water problem, the calibration was set primarily for the confined area.

The analysis of the transient-state model condition was enhanced by comparing the water-level decline in the valley as measured in 12 observation wells, seven of which were in the confined area. Hydrographs from 1945 to 1974 for the 12 wells show the water-level decline resulting from a combination of less natural recharge due to climatic conditions and increased ground-water pumping (fig. 16). (See figs. 18 and 19 for well locations.) In general, all the hydrographs show water-level declines from 1945 to the middle 1960's, hence levels started to rise slightly and then rose sharply due to the flood of 1969.

The model-computed hydrographs closely approximate the observed hydrographs for eight wells in the central part of the valley, including the area of confined ground water. In the remaining four wells (1S/3W-21H1, 1S/3W-32J1, 1N/4W-16E1, and 1N/5W-23P4), which are located in the upland areas of the valley, the approximations are not as good. At well 1N/5W-23P4, apparently either the

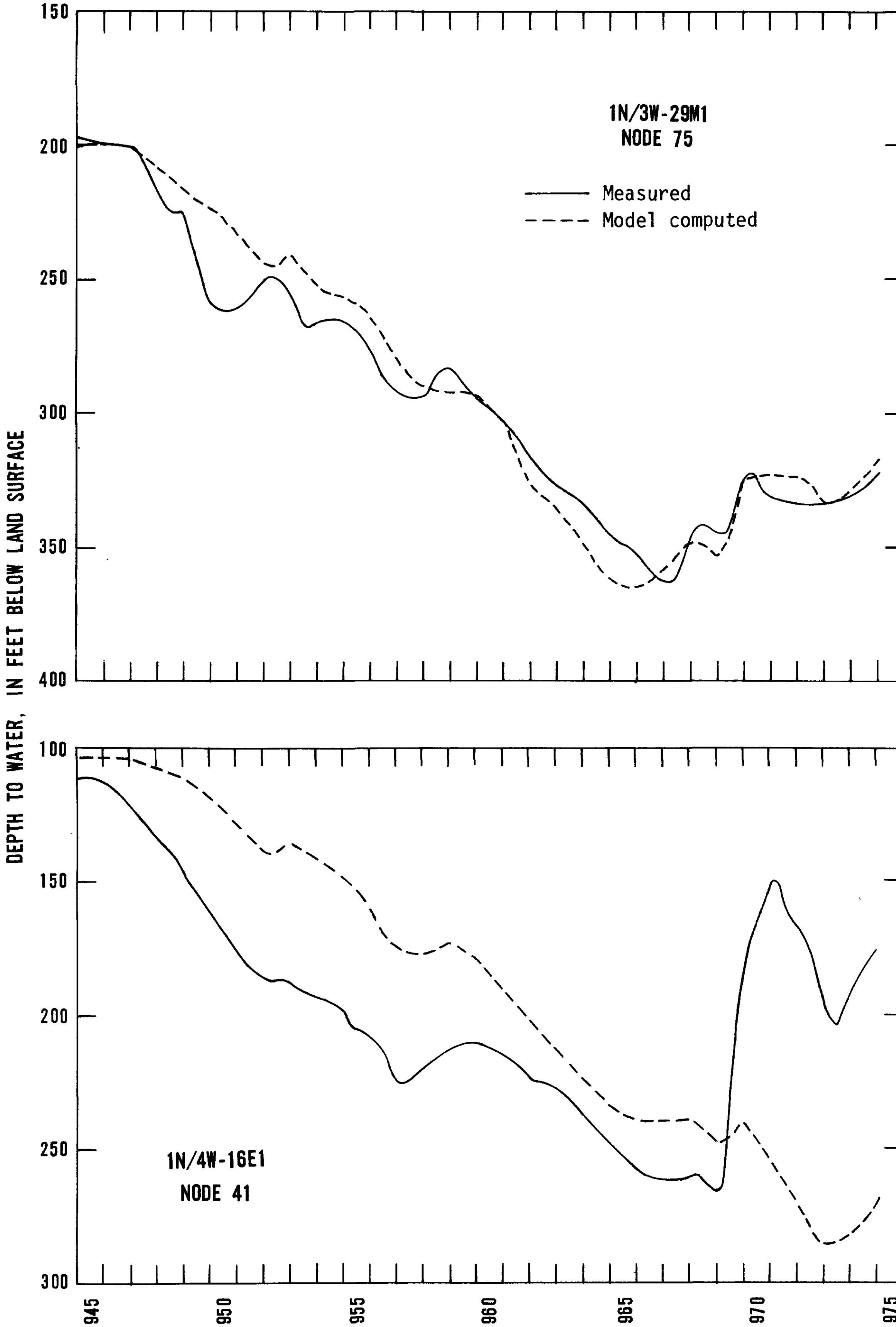


FIGURE 16.--Hydrographs showing water-level data for selected observation wells (1945-74).

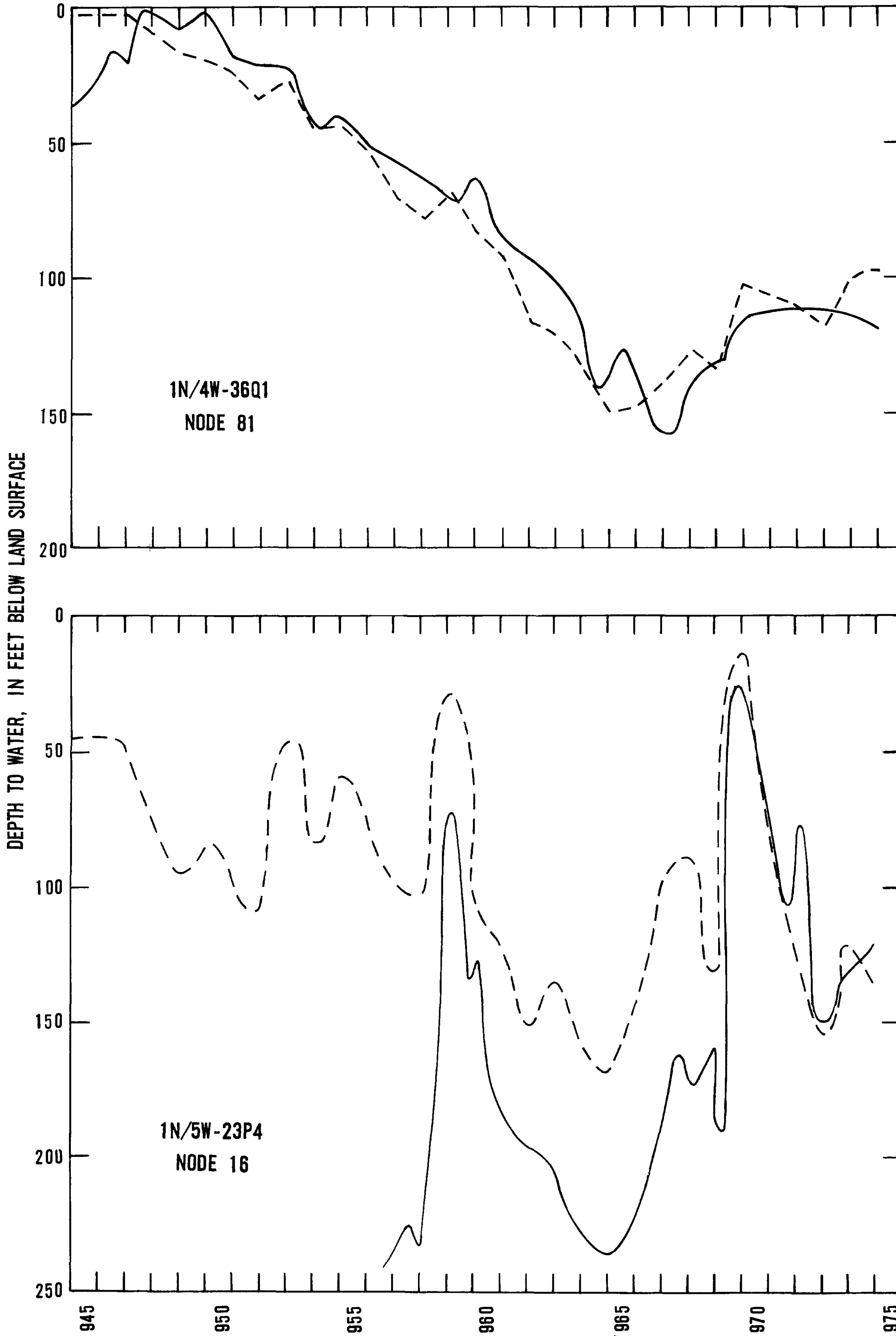


FIGURE 16.--Continued.

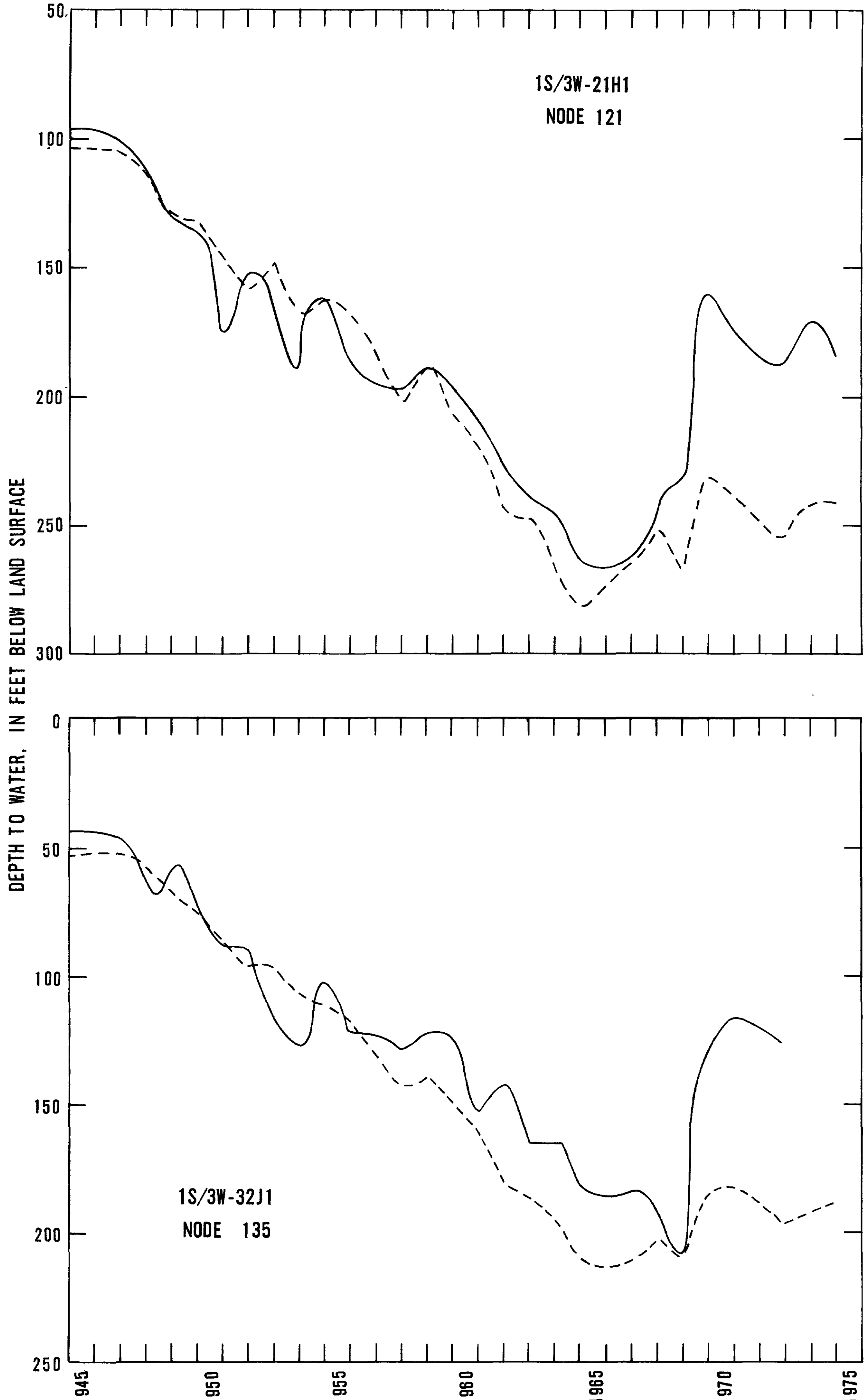


FIGURE 16.--Continued.

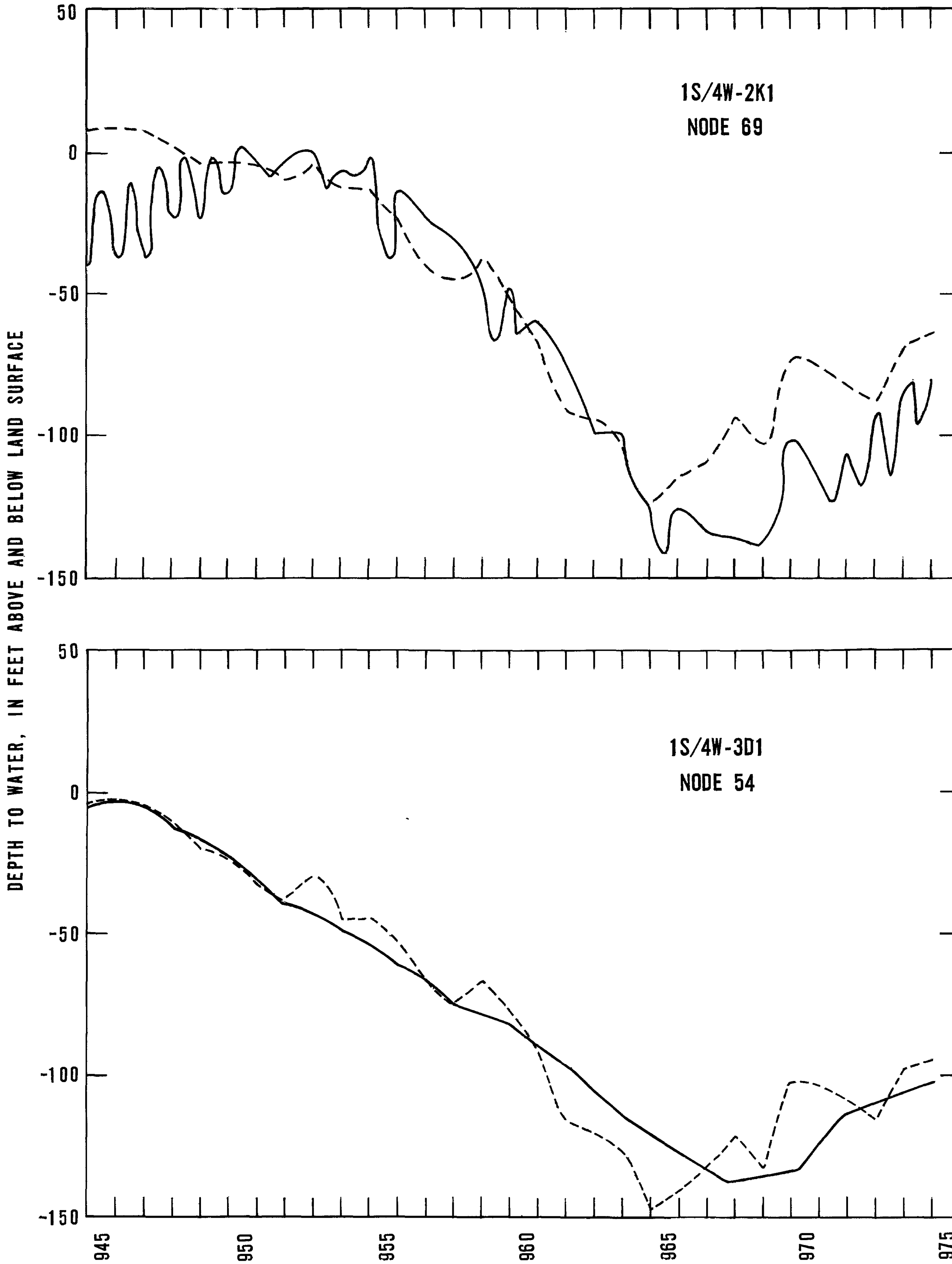


FIGURE 16.--Continued.

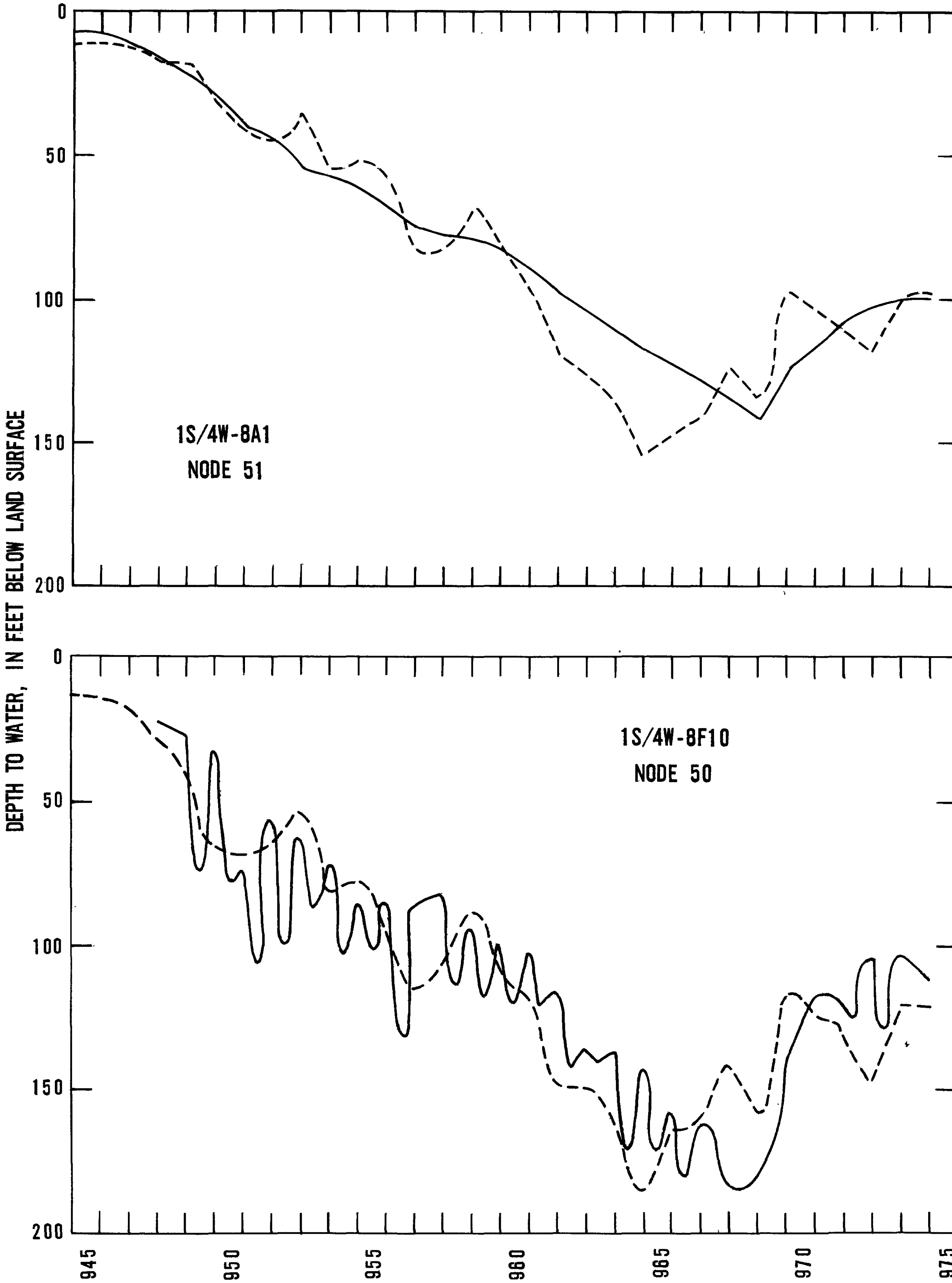


FIGURE 16.--Continued.

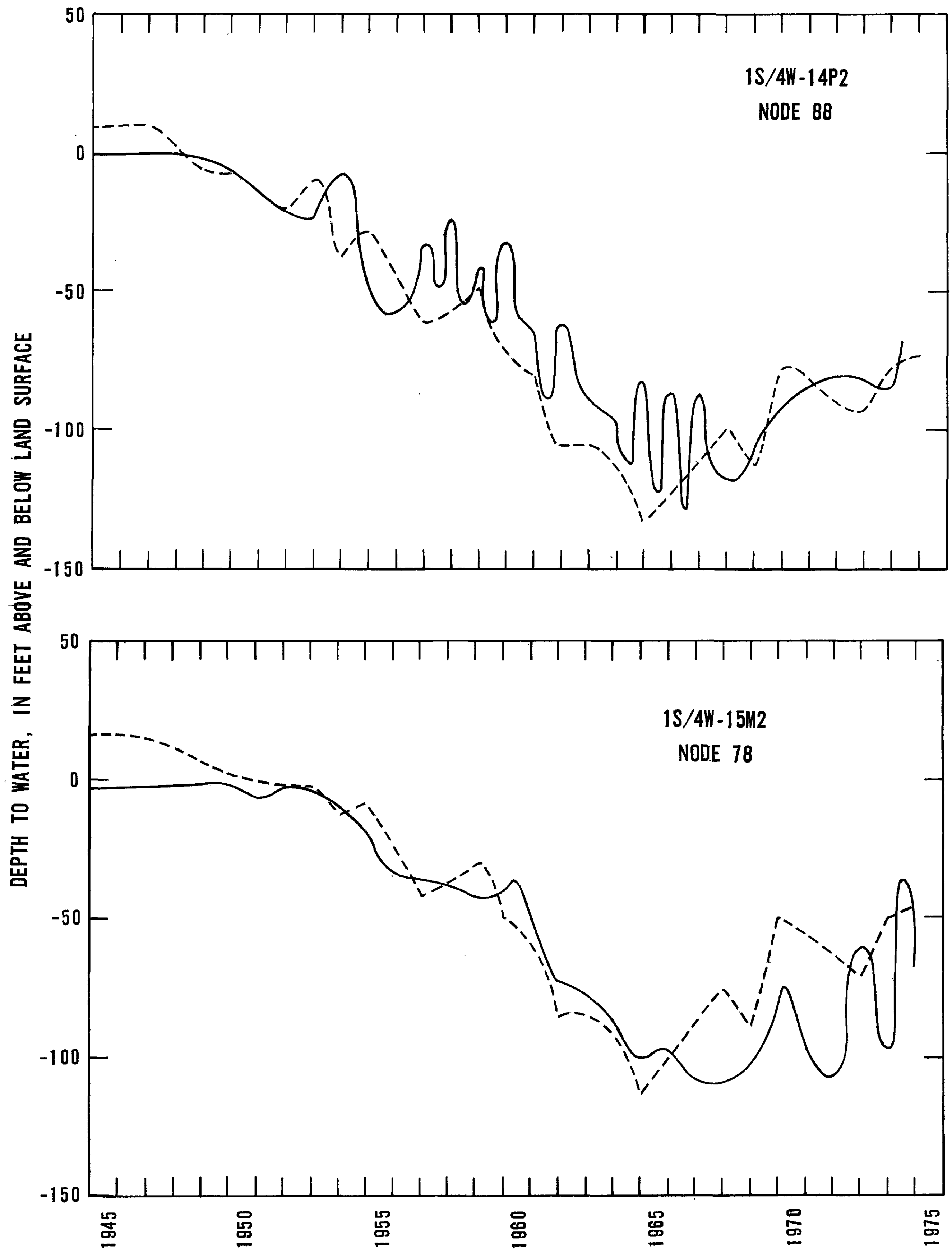


FIGURE 16.--Continued.

model cannot duplicate the very large fluctuations observed in the well (greater than 150 ft), or annual recharge is related to flow more in Lytle Creek than in the Santa Ana River, upon which recharge relations in the valley are based. At wells 1S/3W-21H1, 1S/3W-32J1, and 1N/4W-16E1 the water-level correlation between the model and field data are acceptable except for the floods of 1969. Water levels rose excessively during 1969, probably as a result of a change in distribution of recharge, owing to flooding in this extremely wet year. In subsequent years flooding did not occur, and computed water-level trends closely approximate those observed.

Predicting water-level trends in the area of confined ground water was of prime importance, so emphasis was placed on correlating model-computed and observed water levels in this area, as exemplified by the seven selected wells. The other four hydrographs are shown to document the difficulty encountered in modeling this valley of diverse geohydrologic characteristics. Table 5 describes the wells used in the transient-state model calibration and presents information on the year each well was completed, well depth, perforated interval, record of water-level data available, and the model node number representing the well. The altitude of land surface at each well was obtained from land surveying records. Model-generated water levels for the observation wells were adjusted for various pumping distributions between the two layers by computing a composite water level, using the mathematical method of Sokol (1963).

By the satisfactory simulation of the actual data with the transient-state model, the model is considered ready for use as a predictive tool.

TABLE 5. - Data for selected observation wells used for model calibration[1]

Well No. (see figs. 18 and 19 for location)	Model node No.	Year well completed	Altitude (land-surface datum)	Perforated interval (ft)	Well depth (ft)	Year water-level record began	Estimated percentage of pumpage (upper layer)
11N/3W-29M1	75	1932	1,345	238-396	408	1932	100
1N/4W-16E1	41	1918	1,412	186-406	415	1918	30
1N/4W-36Q1	81	1931	1,097	--	696	1931	40
1N/5W-23P4	16	1929	1,470	200-630	647	1930	40
1S/3W-21H1	121	1929	1,318	--	426	1939	75
1S/3W-32J1	135	1935	1,263	--	420	1935	80
1S/4W-2K1	69	1904	1,056	--	581	1916	85
1S/4W-3D1	54	1935	1,096	[2]1135-677	[2]778	1936	53
1S/4W-8A1	51	1917	1,094	101-482	482	1933	59
1S/4W-8F10	50	1947	1,099	226-758	818	1947	0
1S/4W-14P2	88	1912	1,023	--	580	1915	70
1S/4W-15M2	78	1931	985	24-572	603	1933	63

[1]See figure 16 for 1945-74 actual and model water levels.
[2]Cement plug at 460 ft.

Simulation of Water-Level Changes (1975-2000) under Various Recharge Conditions

To simulate water-level trends for the period 1975-2000, projected quantities of natural recharge from surface-water sources, artificial recharge of imported water, and ground-water pumping were programed into the model. In simulating future water-level trends by the model, the greatest unknown is the quantity and distribution of natural recharge. To alleviate this problem, low, average, and high recharge-condition periods were programed on the basis of the very small probability, 0.06 (Durbin and Morgan, 1978), that the average recharge rates for a 25-year period will be either 20-percent greater (high) or 20-percent smaller (low) than the long-term average. The distribution of the natural-recharge nodes was held constant as in the transient-state condition.

The distribution of artifical recharge of imported water is based on a percentage of the half or full entitlement that was allotted to the recharge sites in the following manner: Santa Ana River, 50 percent; Sweetwater, 20 percent; Waterman Canyon-East Twin Creek, 10 percent; City Creek, 10 percent; Badger, 5 percent; and Patton, 5 percent (L. W. Rowe, oral commun., 1977).

The Water District contract with the California Department of Water Resources for imported water from the aqueduct is for a maximum entitlement of 48,000 acre-ft of water in 1973, increasing annually to 102,600 acre-ft by 1990. The artificial-recharge program was started in November 1972, but as of December 31, 1977, only about 97,000 acre-ft of water had been delivered for recharge, or about one-third of the full entitlement. Less than the entitled water was received because of the statewide drought from 1975 to 1977, when the water was not available. For the transient model run through 1974, the actual amounts of imported water recharged were programed into the model. For planning and management purposes, however, starting with 1975 the artificial recharge for the predictive model runs was set at one-half and full entitlement. Table 6 shows the half and full entitlement of imported water and the distribution for each proposed recharge site (see fig. 11 for location of artifical-recharge sites).

Ground-water pumping rates used for the predictive model runs were the average for the 5-year period 1970-74, amounting to 165,000 acre-ft/yr. Excepted was the Devil Canyon area, where the projected pumping rate was represented by a 20-percent increase over the average (L. W. Rowe, oral commun., 1977).

To be effective, large-scale recharge practices require permeable sediments at and below the land surface to allow water to percolate downward and a thickness of unsaturated sediments above the water table sufficient to store the water. In order to determine the location, depth, and configuration of the unsaturated sediments above the water table, a depth to water map is helpful. Figure 17 shows the depth to water below the ground in the spring of 1977. The contours are based on water levels measured under the upper Santa Ana Valley cooperative well-measuring program (San Bernardino Valley Municipal Water Conservation District and San Bernardino Valley Municipal Water District, 1977). With the top of the ground-water surface defined, the model simulations of water-level changes from 1975 to 2000 under various recharge conditions can be better evaluated for future planning of recharge .

The greatest depth to water ranges from 200 to more than 300 ft below the ground in the Lytle Creek area and along the San Bernardino Mountain front. Geologically, these areas are conducive to artificial recharge because of high aquifer hydraulic conductivity and large storage capacity for water. The central part of

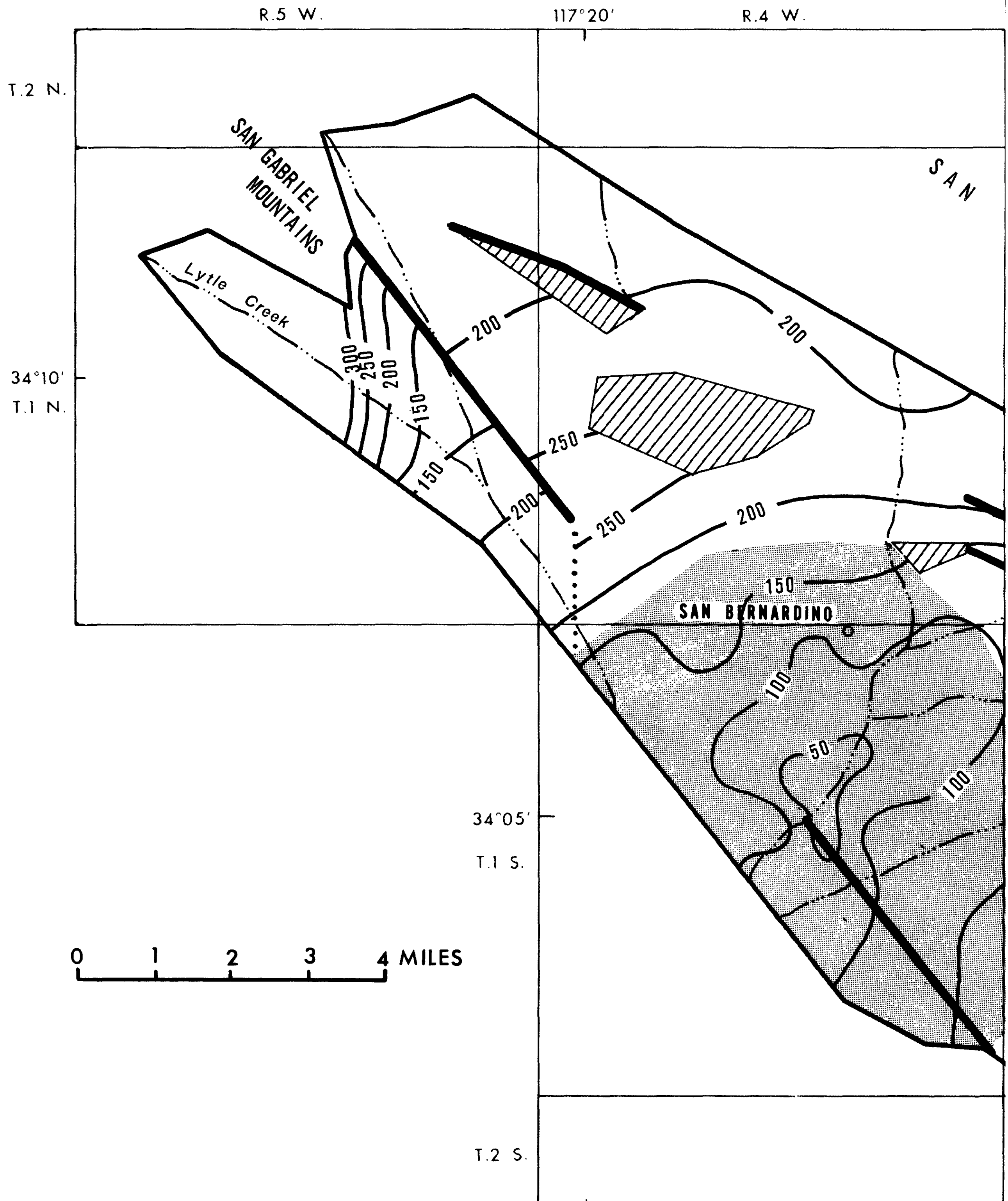
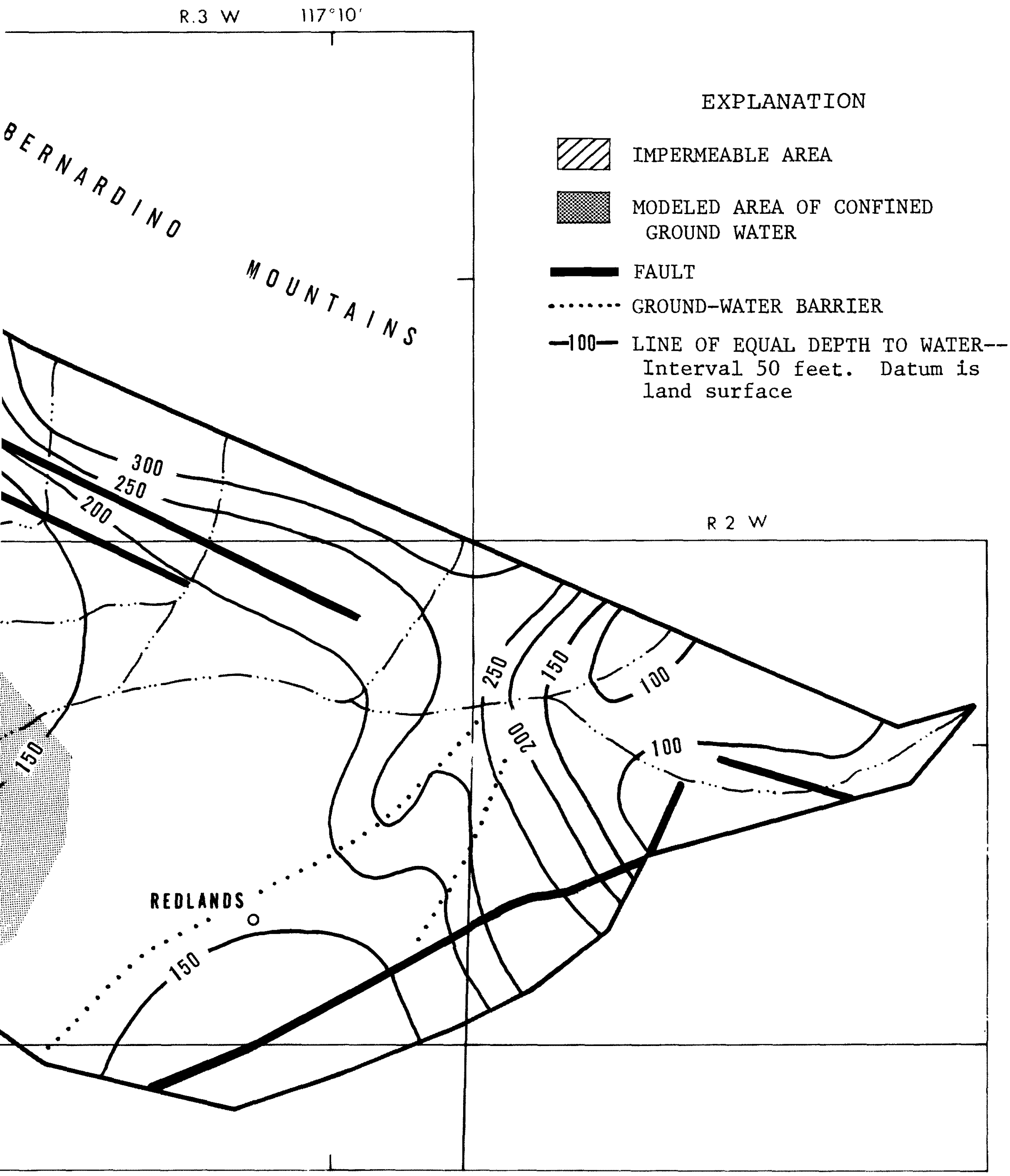


FIGURE 17. -- Depth to



ground water, spring 1977.

TABLE 6. - Entitlement and distribution of imported State project water for the San Bernardino Valley

Year	Entitlement (acre-ft)		Distribution of imported State project water							
			Santa Ana River (50 percent)		Sweetwater (20 percent)		Waterman Canyon East Twin, and City Creeks (10 percent)		Badger and Patton (5 percent)	
	Full amount	One-half amount	Full amount	One-half amount	Full amount	One-half amount	Full amount	One-half amount	Full amount	One-half amount
1975	52,500	26,250	26,250	13,125	10,500	5,250	5,250	2,625	2,625	1,312
1976	55,000	27,500	27,500	13,750	11,000	5,500	5,500	2,750	2,750	1,375
1977	57,500	28,750	28,750	14,375	11,500	5,750	5,750	2,875	2,875	1,437
1978	60,000	30,000	30,000	15,000	12,000	6,000	6,000	3,000	3,000	1,500
1979	62,500	31,250	31,250	15,625	12,500	6,250	6,250	3,125	3,125	1,562
1980	65,500	32,750	32,750	16,375	13,100	6,550	6,550	3,275	3,275	1,638
1981	68,500	34,250	34,250	17,125	13,700	6,850	6,850	3,425	3,425	1,712
1982	71,500	35,750	35,750	17,875	14,300	7,150	7,150	3,575	3,575	1,788
1983	74,500	37,250	37,250	18,625	14,900	7,450	7,450	3,725	3,725	1,862
1984	78,000	39,000	39,000	19,500	15,600	7,800	7,800	3,900	3,900	1,950
1985	81,500	40,750	40,750	20,375	16,300	8,150	8,150	4,075	4,075	2,038
1986	85,000	42,500	42,500	21,250	17,000	8,500	8,500	4,250	4,250	2,125
1987	89,000	44,500	44,500	22,250	17,800	8,900	8,900	4,450	4,450	2,225
1988	93,000	46,500	46,500	23,250	18,600	9,300	9,300	4,650	4,650	2,325
1989	97,000	48,500	48,500	24,250	19,400	9,700	9,700	4,850	4,850	2,425
1990	101,500	50,750	50,750	25,375	20,300	10,150	10,150	5,075	5,075	2,538
1991[1]	102,600	51,300	51,300	25,650	20,520	10,260	10,260	5,130	5,130	2,565
2000	102,600	51,300	51,300	25,650	20,520	10,260	10,260	5,130	5,130	2,565

[1]Entitlements and distributions are the same for each year between 1991 and 2000.

the basin within the confined area has the least amount of water-storage potential. Here, depth to water as of spring 1977 ranged from 50 to 150 ft below the land surface.

Of particular significance to a potential problem of rising ground water in the confined area is the head-response relation resulting from recharge to the unconfined system in the peripheral area. The key factor in controlling rising ground-water levels in the confined area is to maintain pumping by wells sufficient to keep water levels low and avoid overcharging the intake area. Historically, the confined area has been heavily pumped, which has lowered water levels. Currently, a trend is developing whereby pumping of ground water from this area is shifting to peripheral areas of higher altitude (G. L. Fletcher, oral commun., 1978). If this trend continues, water levels in the confined area may rise regardless of the artificial-recharge program.

In using the model to simulate water levels for the period 1975-2000, each of the three recharge conditions (low, average, and high) was programed together with one-half and full entitlement of artificial recharge. Thus, six model runs were programed to project a wide range of hydrologic conditions affecting water levels in the basin to the year 2000. Water levels were simulated for each of the six hydrologic conditions in 12 representative observation wells, seven of which are in the artesian area (see table 5 and figs. 18 and 19).

Results of the model runs (table 7) show the predicted composite water-level changes under various recharge conditions for 12 observation wells for the years 1980, 1990, and 2000. In general, the artificial-recharge program coupled with various amounts of natural recharge results in a rise of water levels in these wells. Under maximum recharge conditions, the greatest water-level rises are along the San Bernardino Mountain front and in the Redlands area.

The table shows that for long-term average natural-recharge conditions the increase in composite water levels resulting from one-half and full entitlement (conditions B and E) by the year 2000 ranges from 97 ft at well 1N/4W-16E1 (Devil Canyon area) to only 22 ft at well 1S/4W-8A1 (confined area). Because of the shallow depth to water in the lower Warm Creek-Santa Ana River area, the water levels in wells 1S/4W-2K1, 14P2, and 15M2 rise to land surface prior to 2000.

Figure 18 shows simulated water-level changes in the upper and lower aquifers representing the minimum recharge condition of the six model runs for the period 1975-2000. The natural recharge is assumed to be 20 percent below the long-term (steady-state) average, and artificial recharge is one-half entitlement, with pumping kept constant at the 1970-74 average rate of 165,000 acre-ft/yr plus a 20-percent increase in the Devil Canyon area. The area of maximum water-level rise is the Devil Canyon area, between the Shandin Hills and the San Bernardino Mountains, a result of artificial recharge at the Sweetwater and Badger sites. The ground-water movement southward is restricted by the Shandin Hills, and the ground water must move southeastward. Artificial recharge at Waterman Canyon-East Twin Creek, City Creek, Patton, and the Santa Ana River is reflected by water-level rises of more than 50 ft for the 25-year period (1975-2000), but these maximum rises do not reach the lower Warm Creek-Santa Ana River area adjacent to the San Jacinto fault. Under this minimum recharge condition, water levels do not reach land surface anywhere in the basin. No artificial recharge was programed into Lytle Creek, Cajon Creek, or Mill Creek, and water levels decline as local ground-water pumping is in excess of natural recharge. These areas seem to be hydrologically favorable as potential sites for artificial-recharge operations.

TABLE 7. - Predicted model water-level changes[1] (1980-2000) for various natural- and artificial-recharge conditions, in feet of water-level rise or decline(-)

[A, low; B, average; and C, high natural recharge with 50-percent entitlement of artificial recharge. D, low; E, average; and F, high natural recharge with 100-percent entitlement of artificial recharge]

Well No. (see figs. 18 and 19 for location)	1980						1990						2000					
	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
1N/3W-29M1	17	29	39	39	49	59	35	59	80	89	104	114	49	78	101	109	115	121
1N/4W-I6E1	-23	-15	-4	28	35	44	4	28	54	112	129	144	20	54	84	140	151	158
1N/4W-36Q1	20	29	37	36	43	50	32	50	66	69	77	83	41	64	82	84	[2]87	[2]87
1N/5W-23P4	-1	20	43	7	26	48	-28	18	66	-5	38	82	-55	15	76	-18	39	92
1S/4W-2K1	17	26	34	32	37	44	27	47	[2]54	[2]54	[2]54	[2]54	36	[2]54	[2]54	[2]54	[2]54	[2]54
1S/4W-3D1	20	29	37	33	41	50	28	47	64	62	75	80	35	59	77	75	84	89
1S/4W-8A1	19	28	41	32	40	47	26	45	62	59	70	78	33	57	74	69	79	84
1S/4W-8F10	19	29	47	32	39	48	25	45	70	56	66	79	31	56	81	66	73	84
1S/4W-14P2	14	24	31	29	37	41	25	44	[2]60	[2]60	[2]60	[2]60	34	58	[2]60	[2]60	[2]60	[2]60
1S/4W-15M2	15	24	32	28	30	[2]35	24	[2]35	[2]35	[2]35	[2]35	[2]35	32	[2]35	[2]35	[2]35	[2]35	[2]35

[1]Water-level change based on composite head in wells screened opposite both upper and lower layers.
[2]Water level at land surface.

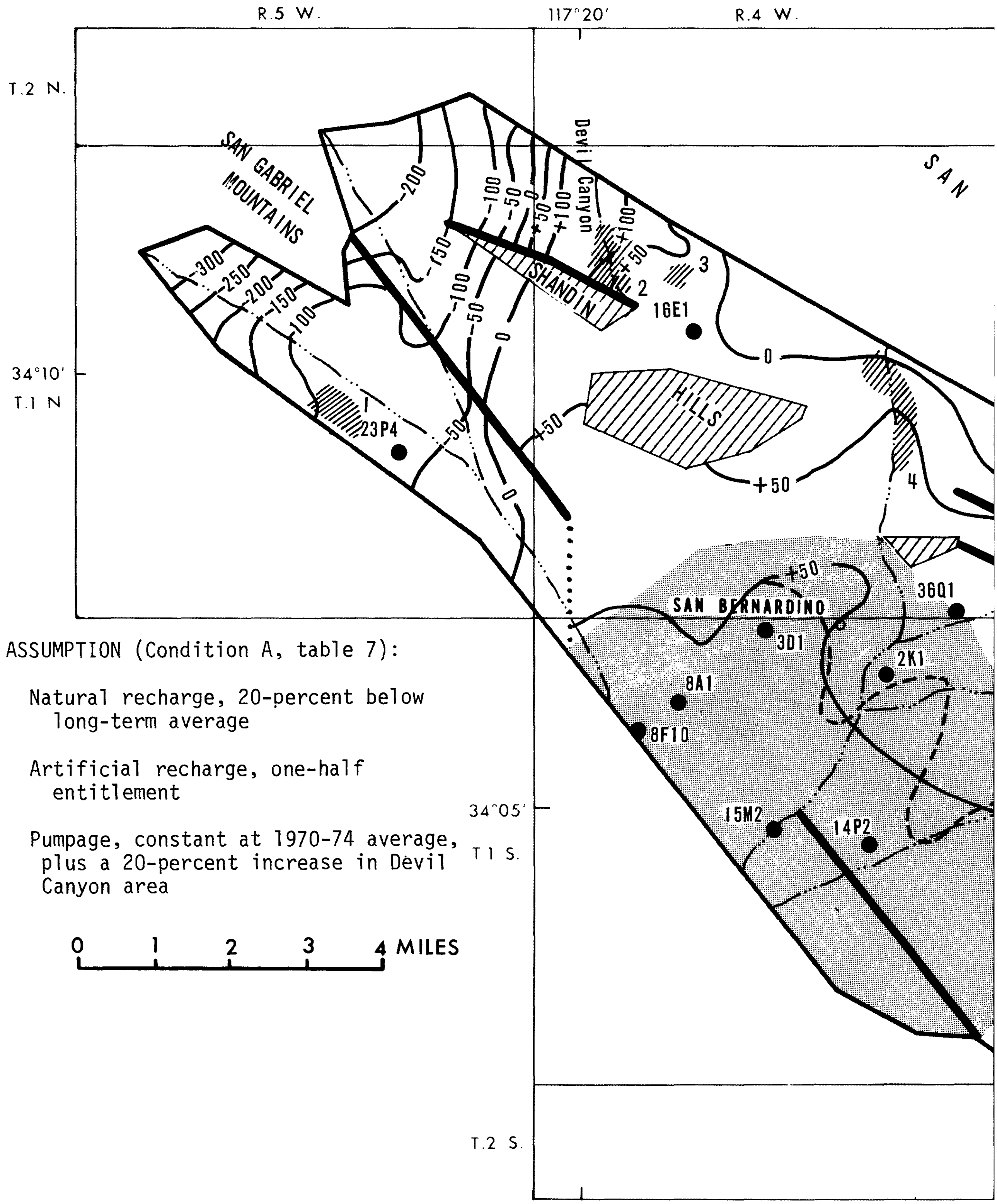
Figure 19 shows simulated water-level changes in the upper and lower aquifers representing the maximum-recharge conditions for the period 1975-2000. The natural recharge is assumed to be 20 percent above the long-term (steady-state) average, and artificial recharge is full entitlement, with pumping kept constant at the 1970-74 average rate of 165,000 acre-ft/yr plus a 20-percent increase in the Devil Canyon area. The area of maximum water-level rise coincides with the location of the artificial-recharge sites along the front of the San Bernardino Mountains. The effects of this recharge program are noticed throughout the confined area, but because evapotranspiration discharge modifies the water levels in the upper aquifer, the rise in the upper aquifer is less than the rise in the lower aquifer. By the year 2000 the Sweetwater recharge site will be able to recharge only about 10,000 acre-ft/yr or about 50 percent of the allotted percentage of artificial recharge, City Creek only about 4,000 acre-ft/yr or about 40 percent, and the Santa Ana River only about 26,000 acre-ft/yr or about 50 percent. According to the model, the aquifer cannot physically absorb all the programed artificial recharge at these sites, under the assumed hydrologic conditions, without waterlogging the land. At the Badger and Patton sites the total allotment can be recharged. At Waterman Canyon-East Twin Creek, imported water in excess of the 10,000 acre-ft/yr allotment can be recharged, but because this recharge site is closest to the confined area, rising water above land surface may again result if too much water is recharged.

As a result of the artificial-recharge program, water levels in several of the selected observation wells in the confined area will rise to within 10 ft of the land surface or reach the land surface under the assumed conditions. Table 8 shows the year in which this will occur.

The area between Warm Creek and the Santa Ana River adjacent to the San Jacinto fault will be the first affected by rising water, as exemplified by wells 1S/4W-14P2 and 15M2. Well 14P2 will have a water level within 10 ft of land surface during the middle 1990's under one-half entitlement and average or high natural recharge. Under full entitlement, high water will be a problem in the middle 1980's with all natural-recharge conditions. Well 15M2 under one-half entitlement will have high-water problems about 10 years earlier than well 14P2. Under full entitlement, rising water could be a problem by 1980 with the recharge conditions assumed since 1975. Long-term historical water-level records indicate that well 2K1 is an effective monitor of the head response to recharge from the Waterman Canyon-East Twin Creek drainage. Under full entitlement, high water levels may create waterlogging problems between 1982 and 1990, depending on the amount of natural recharge.

The simulated water-level changes from 1975 to 2000 under minimum and maximum recharge conditions are bracketed by figures 18 and 19. These two model conditions cover the extremes in recharge, except for floods of infrequent short duration. Four other model runs, not diagramed for this report, are bracketed by the above conditions. Inspection of the six model simulations indicates that a feasible way to control rising water in the confined area is by pumping ground water from the confined area. The aquifer system can be considered similar to a surface reservoir that is regulated by controlling discharge at the outlet. The relation between recharge and discharge is direct, in that areas with increased quantities of ground-water extractions can accommodate more recharge water.

By interrogating this model through the simulation of other recharge-discharge schemes, alternative ground-water management plans can be formulated to avoid overpressuring the confined area. To document the predicted results derived from the model, the Water District has key monitoring wells between the recharge sites and the formerly swampy area to measure the effects of the recharge program.



ASSUMPTION (Condition A, table 7):

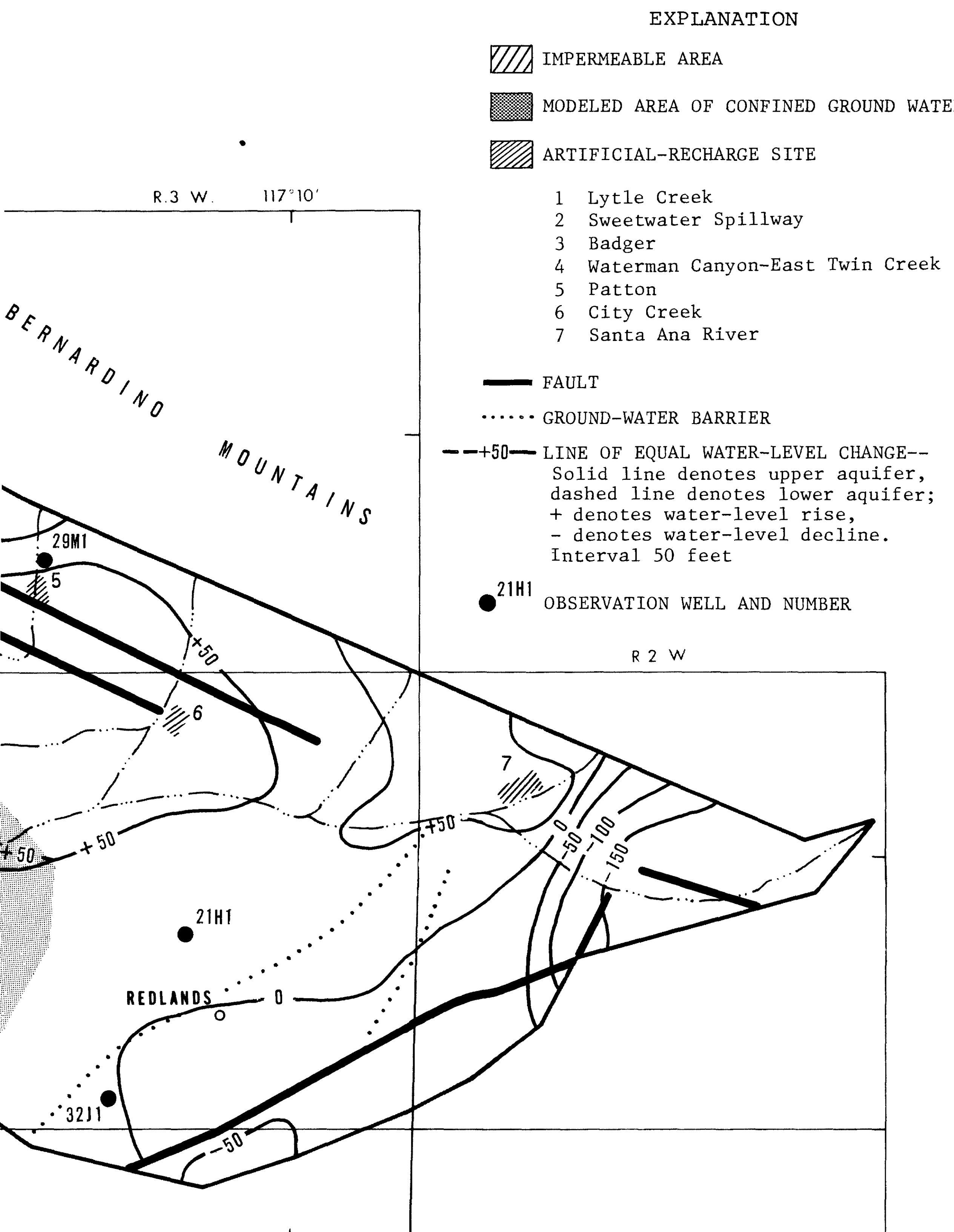
Natural recharge, 20-percent below long-term average

Artificial recharge, one-half entitlement

Pumpage, constant at 1970-74 average, plus a 20-percent increase in Devil Canyon area

0 1 2 3 4 MILES

FIGURE 18. -- Simulated water-level changes



1975-2000) under minimum-recharge conditions.

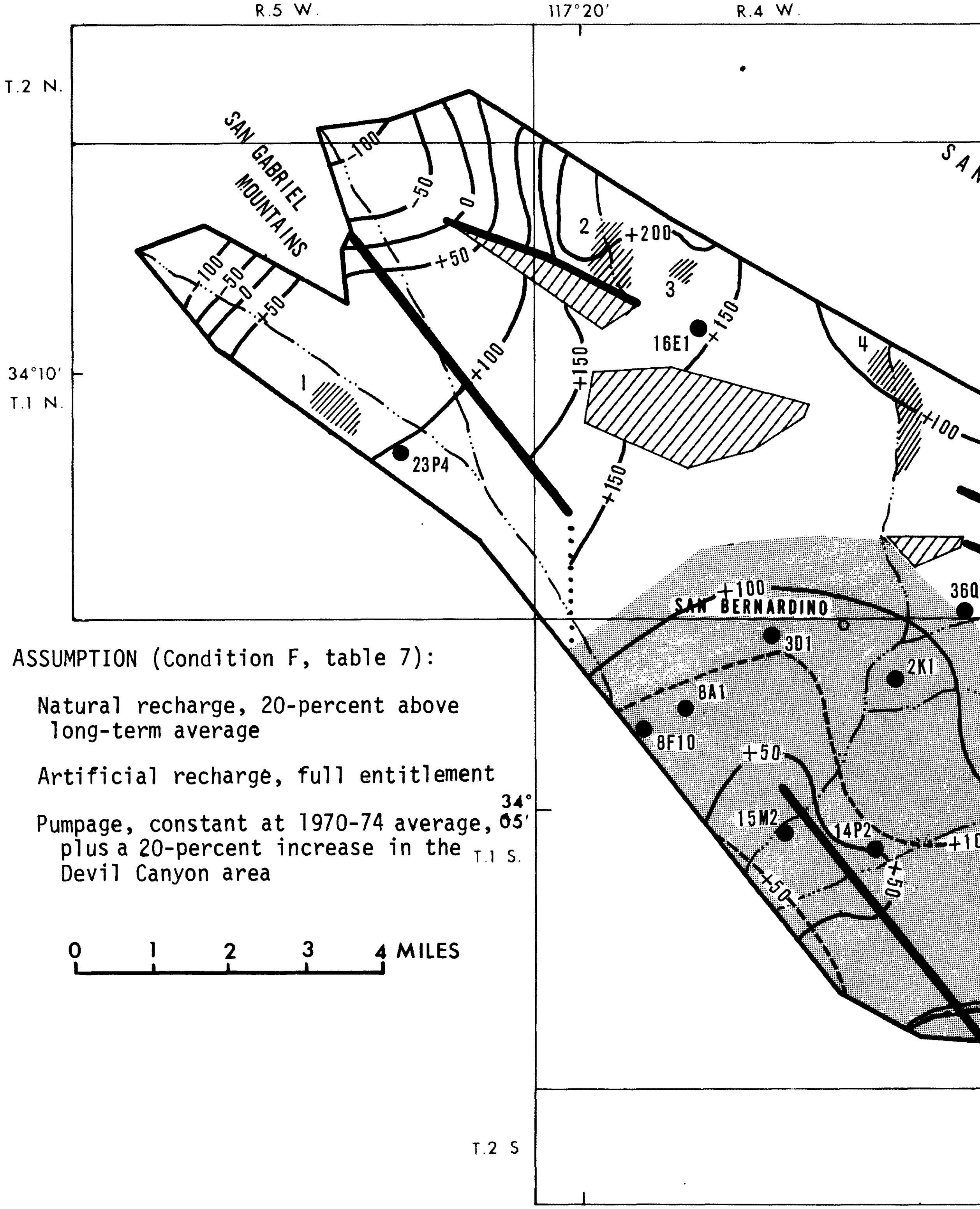
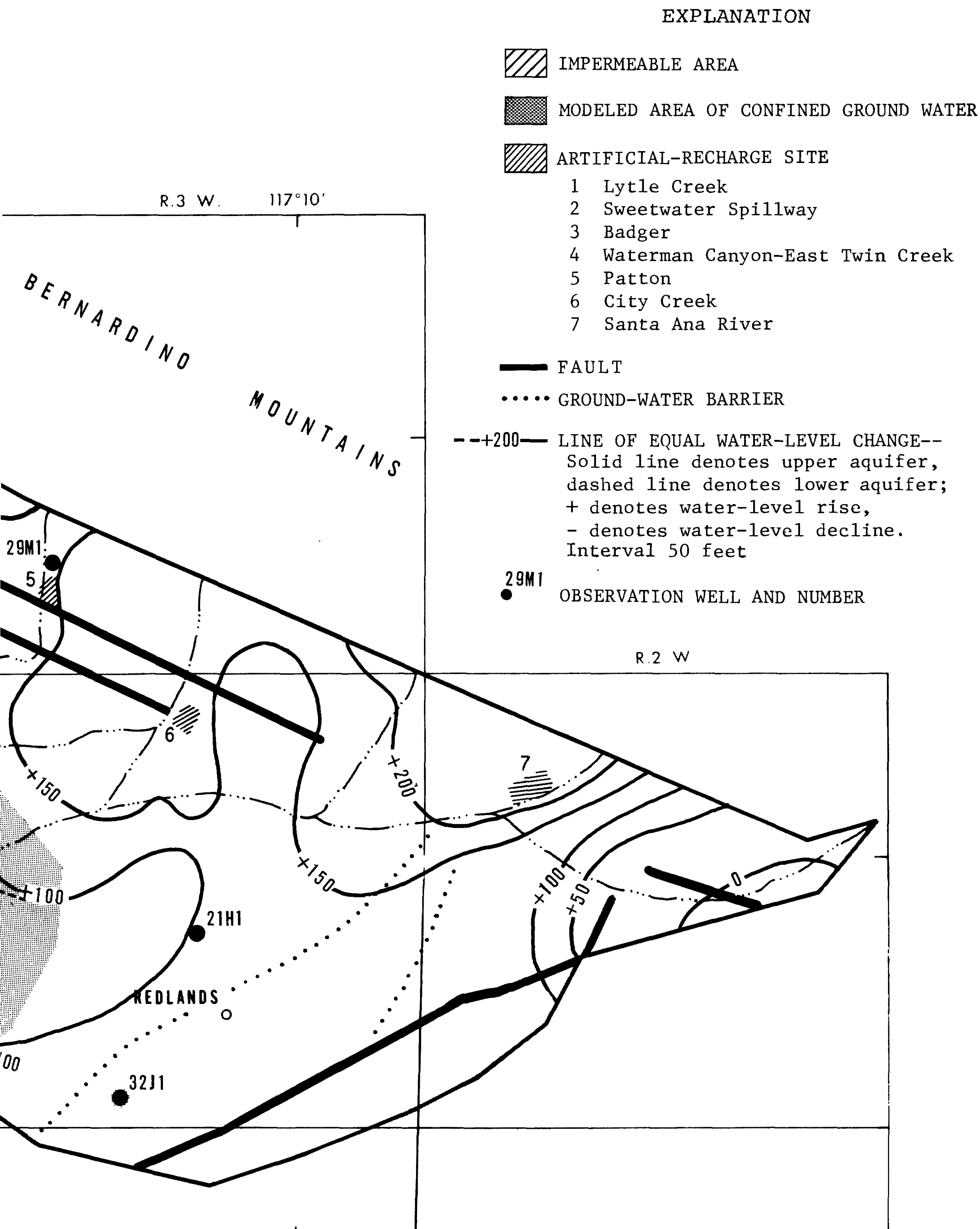


FIGURE 19. -- Simulated water-level change



(1975-2000) under maximum-recharge conditions.

TABLE 8. - Approximate year in which water level will rise to indicated depth below land surface for various natural and artificial recharge conditions

Artificial recharge condition	50-percent entitlement						100-percent entitlement					
Natural-recharge condition	Low		Average		High		Low		Average		High	
Depth below land surface datum, in feet	10	0	10	0	10	0	10	0	10	0	10	0
Well No.[1]												
Devil Canyon Area												
1N/4W-16E1	(2)	(3)	(2)	(3)	(2)	(3)	(2)	(3)	1997	(3)	1992	1996
Artesian Area												
1N/4W-36Q1	(2)	(3)	(2)	(3)	(2)	(3)	1996	(3)	1991	1997	1989	1996
1S/4W-2K1	(2)	(3)	1994	(3)	1985	1993	1985	1990	1982	1987	1982	1985
1S/4W-3D1	(2)	(3)	(2)	(3)	(3)	(3)	(2)	(3)	1993	(3)	1990	1994
1S/4W-8A1	(2)	(3)	(2)	(3)	(2)	(3)	(2)	(3)	(2)	(3)	1992	(3)
1S/4W-14P2	(2)	(3)	1997	(3)	1992	(3)	1988	1995	1985	1991	1984	1988
1S/4W-15M2	1992	(3)	1986	(3)	1983	1991	1980	1984	1980	1984	1980	1983

[1]See figures 18 and 19 for well location.
[2]Water level does not rise to within 10 ft of land surface by 2000.
[3]Water level does not rise to land surface by 2000.

SUMMARY AND CONCLUSIONS

Importation of northern California water through the California aqueduct and subsequent recharge to the San Bernardino Valley ground-water basin will create added stress on the natural hydrologic system. Care must be exercised that as a result of this supplemental water, ground-water levels do not approach land surface and cause property damage. Of particular concern is the former swampy area in urbanized southern San Bernardino where the potentiometric head in wells was 10 to 75 ft above land surface in the early 1900's.

About 90 percent of the natural recharge to the valley was derived from surface water inflow, with nearly two-thirds from the Santa Ana River, Mill Creek, and Lytle Creek. Prior to importation of supplemental water in November 1972 for recharge in the valley, ground-water depletion occurring as outflow (primarily by pumping) exceeded natural inflow. For the 30-year period from 1945 to 1974, 8 years showed an increase in ground-water storage; this was because of above-average recharge caused by flood conditions.

The infrequent and unpredictable floods, which result in greatly increased recharge to the aquifers, create the greatest problem to optimum basin management. For example, the floods of early 1969 alone accounted for more than 350,000 acre-ft of recharge to the basin (SBVMWD, 1977, p. 24). This amount of recharge from a short-duration flood is about three and one-half times greater than either the maximum yearly entitlement of imported water or the long-term average natural recharge. Thus, large slugs of uncontrolled recharge could create problems with efforts to maximize recharge during normal climatic conditions.

The valley's ground-water reservoir consists of alluvial deposits of sand, gravel, and boulders interspersed with lenticular beds of silt and clay. Previous investigators have recognized three aquifers, each separated by 50 to 300 ft of clay and silt, upgradient of the San Jacinto fault. However, a test well drilled in 1977 in San Bernardino bottomed in bedrock, and only two aquifers were encountered at this site. The greatest thickness of water-bearing deposits is about 1,200 ft and occurs adjacent to the northeast side of the San Jacinto fault between San Bernardino and the Santa Ana River. This area coincides with the formerly swampy land within the confined area. Aquifer transmissivities range from about 670 ft^2/d along the San Bernardino mountain front to 66,800 ft^2/d in the center of the basin. Aquifer storage coefficients range from 0.15 in the unconfined areas to 0.0001 in the confined areas.

The problem in the San Bernardino Valley is to balance the amount of natural and artificial recharge in the high-altitude area of the valley to the amount of pumping from the aquifers at the lower altitudes to avoid overfilling the ground-water reservoir. Ground-water pumpage ranged from 70,300 acre-ft in 1941 to 213,500 acre-ft in 1961, most of which was from the central part of the valley.

The formerly swampy area between Warm Creek and the Santa Ana River is at the lowest altitude in the basin, and all ground water moves toward this area. Flow in Warm Creek ceased in the middle 1950's, as pumpage was greater than recharge. Spring 1977 water-level measurements show that the minimum depth to water in this area is less than 50 ft. The perimeter of the basin receives most of the recharge to the aquifers, either as natural recharge from streamflow from the surrounding mountains or as artificial recharge at selected sites. Here, the water table is relatively deep, generally more than 200 ft below land surface, so that the unsaturated sediments have a capacity to store a large volume of water.

V

A two-layer Galerkin finite-element digital model was used for predicting the rate and extent of the rise in water levels from 1975 to 2000. Six hydrologic conditions were modeled for the basin. Artificial recharge of one-half and full entitlement from the California Aqueduct were each coupled with low, average, and high natural recharge to the basin, derived primarily from surface-water inflow to the valley.

Average long-term recharge of at least 108,000 acre-ft per year, calculated from historical records of streamflow, was used in the model for calibration purposes. As natural recharge is unknown for the predictive period 1975-2000, a range of conditions was programed for the model, based on the very small probability (0.06) that the average recharge rate for the 25-year period will be either 20 percent greater (high) or 20 percent smaller (low) than the long-term average.

The distribution of artificial recharge of imported water was allotted to the recharge sites in the following manner: Santa Ana River, 50 percent; Sweetwater, 20 percent; Waterman Canyon-East Twin Creek and City Creek, 10 percent; and Badger and Patton, 5 percent.

Under minimum recharge conditions, (one-half entitlement of import water and natural recharge at 20 percent below average) the area of maximum water-level rise for the model period 1975-2000 is between Shandin Hills and the San Bernardino Mountains, as a result of artificial recharge at the Sweetwater and Badger sites. Artificial recharge at Waterman Canyon-East Twin Creek, City Creek, Patton, and the Santa Ana River is reflected by water-level rises of more than 50 ft in these reaches but less in the lower Warm Creek-Santa Ana River area adjacent to the San Jacinto fault. Water levels did not reach land surface anywhere in the basin.

Under maximum-recharge conditions, (full entitlement of import water and natural recharge at 20 percent above average), the area of maximum water-level rises of 100 to 200 ft for the model period 1975-2000 coincides with the location of the artificial-recharge sites along the front of the San Bernardino Mountains. In the confined area, water-level rises are greater in the lower layer than in the upper layer. At the Sweetwater, City Creek, and Santa Ana River sites, the aquifer cannot absorb all the programed artificial recharge under maximum conditions with existing recharge sites. The Badger and Patton sites can absorb the allotted amount, and Waterman Canyon-East Twin Creek is the only site that can absorb more than the allotted amount. Because Waterman Canyon-East Twin Creek is the closest to the lower Warm Creek-Santa Ana River area, however, excessive recharge could cause rising water once again in the formerly swampy lands.

The lower Warm Creek-Santa Ana River area (formerly swampy lands) would be affected by water levels rising to land surface as early as 1983 under maximum recharge conditions and current pumping rates. The heaviest concentration of ground-water pumping has been in the confined area south of San Bernardino. If pumping is greatly reduced in this area, water levels could rise regardless of the artificial-recharge program. Any redistribution of pumping wells should be programed to intercept most of the ground-water movement to Warm Creek.

The model interrogations for this report were for only a selected number of specific management schemes. Other management alternatives can be appraised to predict varying distribution and location patterns under different amounts of recharge or discharge if monitoring wells throughout the confined aquifer indicate that rising water levels are becoming a problem. The artificial-recharge program must be flexible enough to respond to yearly variations in water supply and demand. The model in conjunction with a well-defined data-collection program can be a valuable aid to planners.

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HYDRAULICS DATA
FOR MODEL

HYDRAULICS DATA FOR MODEL

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
1	1,633	1,918	0.15	0.10	0.03
2	1,633	1,918	.15	.10	.03
3	1,633	1,918	.15	.10	.03
4	1,382	1,287	.15	.10	.03
5	2,445	2,877	.10	.01	.03
6	3,266	3,836	.10	.01	.03
7	3,266	3,836	.10	.01	.03
8	8,156	9,950	.10	.01	.03
9	1,633	1,918	.15	.10	.03
10	26	26	.15	.10	.03
11	26	26	.15	.10	.03
12	3,197	2,981	.15	.10	.03
13	1,382	1,287	.15	.10	.03
14	570	588	.15	.10	.03
15	225	233	.15	.10	.03
16	2,445	2,877	.05	.0001	.03
17	8,156	9,590	.10	.01	.03
18	26	26	.10	.01	.03
19	26	26	.10	.01	.03
20	6,402	5,953	.10	.01	.03
21	6,402	5,953	.10	.01	.03
22	6,402	5,953	.10	.01	.03
23	2,134	1,987	.10	.01	.03
24	570	588	.10	.01	.03
25	570	588	.10	.01	.03
26	458	475	.10	.01	.03
27	4,899	5,754	.05	.0001	.03
28	4,899	5,754	.05	.0001	.03
29	8,156	9,590	.05	.0001	.03
30	8,770	4,795	.05	.0001	.03
31	26	26	.10	.001	.03
32	26	26	.10	.001	.03
33	6,402	5,953	.10	.001	.03
34	6,402	5,953	.10	.001	.03
35	6,402	5,953	.10	.01	.03

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
36	1,140	1,184	0.10	0.01	0.03
37	1,140	1,184	.10	.01	.03
38	458	475	.10	.01	.03
39	458	475	.10	.01	.03
40	458	475	.10	.01	.03
41	8,770	1,918	.05	.0001	.0012
42	6,523	1,918	.05	.0001	.0012
43	6,523	1,918	.05	.0001	.0012
44	6,402	5,011	.08	.001	.03
45	2,134	1,987	.08	.001	.03
46	4,052	4,398	.08	.001	.03
47	4,968	4,968	.08	.001	.03
48	2,281	2,359	.08	.001	.03
49	2,281	2,359	.10	.01	.03
50	2,281	2,359	.08	.001	.03
51	458	475	.10	.01	.03
52	6,523	1,918	.05	.0001	.0012
53	881	449	.05	.0001	.0006
54	881	449	.05	.0001	.0012
55	8,536	7,940	.05	.0001	.0006
56	8,536	7,940	.05	.0001	.0012
57	4,968	4,968	.08	.001	.03
58	2,281	2,359	.08	.001	.03
59	2,281	2,359	.08	.001	.03
60	458	475	.10	.01	.03
61	916	475	.10	.01	.03
62	3,577	3,577	.05	.0001	.0003
63	3,577	3,577	.05	.0001	.0003
64	3,577	3,577	.05	.0001	.0002
65	3,577	3,577	.05	.0001	.0002
66	9,262	4,320	.05	.0001	.0002
67	9,262	4,320	.05	.0001	.0002
68	14,809	23,907	.05	.0001	.0002
69	14,809	23,907	.05	.0001	.0003
70	11,111	23,907	.05	.0001	.0003

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
71	6,411	5,962	0.05	0.0001	0.0012
72	5,244	7,785	.05	.0001	.0006
73	8,398	12,459	.05	.0001	.0012
74	10,498	15,569	.08	.001	.03
75	8,096	665	.08	.001	.03
76	2,048	2,359	.08	.001	.03
77	3,577	3,577	.05	.0001	.00015
78	3,577	3,577	.05	.0001	.00015
79	3,309	6,480	.0001	.0001	.00015
80	3,577	6,480	.0001	.0001	.00015
81	18,516	6,480	.0001	.0001	.00015
82	18,516	6,480	.0001	.0001	.00015
83	22,213	44,271	.0001	.0001	.00013
84	22,213	44,271	.0001	.0001	.00012
85	22,213	44,271	.0001	.0001	.00013
86	18,516	26,568	.05	.0001	.0002
87	11,111	13,288	.05	.0001	.0002
88	8,398	12,459	.05	.0001	.0004
89	8,096	665	.08	.001	.03
90	5,184	5,184	.08	.001	.03
91	5,184	5,184	.08	.001	.03
92	7,413	2,860	.0001	.0001	.00012
93	7,413	2,860	.0001	.0001	.00012
94	18,516	6,480	.0001	.0001	.00012
95	14,809	6,480	.0001	.0001	.00012
96	18,516	8,640	.0001	.0001	.00012
97	18,516	8,640	.0001	.0001	.00012
98	23,907	38,016	.0001	.0001	.0001
99	23,907	38,016	.0001	.0001	.0001
100	22,213	35,424	.0001	.0001	.00011
101	11,007	11,068	.05	.0001	.0002
102	8,398	12,459	.05	.0001	.0012
103	8,398	12,459	.05	.001	.03
104	8,096	665	.05	.001	.03
105	8,096	665	.05	.001	.03

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
106	5,184	5,184	0.08	0.001	0.03
107	11,111	2,860	.0001	.0001	.00012
108	19,872	6,480	.0001	.0001	.00012
109	19,872	6,480	.0001	.0001	.00012
110	19,872	8,640	.0001	.0001	.00012
111	19,872	8,640	.0001	.0001	.00012
112	18,516	38,016	.0001	.0001	.00009
113	18,516	38,016	.0001	.0001	.0001
114	23,907	38,016	.0001	.0001	.0001
115	22,213	35,424	.0001	.0001	.00011
116	22,213	35,424	.0001	.0001	.00011
117	22,213	35,424	.0001	.0001	.00011
118	22,213	35,424	.0001	.0001	.00011
119	22,213	35,424	.0001	.0001	.00011
120	18,516	19,872	.05	.0001	.00015
121	8,087	8,078	.05	.0001	.00024
122	11,189	2,454	.05	.001	.0006
123	8,398	12,459	.05	.001	.03
124	8,096	665	.05	.001	.03
125	1,711	1,771	.08	.001	.03
126	1,598	2,359	.08	.001	.03
127	11,111	2,860	.0001	.0001	.00015
128	13,323	6,480	.0001	.0001	.00015
129	14,809	6,480	.0001	.0001	.00015
130	14,809	35,424	.0001	.0001	.00009
131	14,809	35,424	.0001	.0001	.00011
132	14,809	35,424	.0001	.0001	.00012
133	14,809	35,424	.0001	.0001	.00011
134	14,809	35,424	.0001	.0001	.00011
135	14,809	35,424	.05	.0001	.00015
136	12,113	16,148	.05	.0001	.0002
137	12,113	16,148	.05	.0001	.00024
138	8,087	8,087	.05	.0001	.0003
139	11,189	2,454	.05	.001	.0006
140	8,398	12,459	.05	.001	.03

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
141	8,096	665	0.05	0.001	0.03
142	11,111	2,860	.0001	.0001	.00015
143	14,809	6,480	.0001	.0001	.00015
144	14,809	30,992	.0001	.0001	.0001
145	14,809	35,424	.0001	.0001	.0001
146	14,809	35,424	.0001	.0001	.00012
147	14,809	35,424	.0001	.0001	.00013
148	14,809	35,424	.0001	.0001	.00017
149	14,809	35,424	.0001	.0001	.00017
150	10,109	18,170	.05	.0001	.00024
151	8,087	16,148	.05	.0001	.00024
152	8,087	12,113	.05	.0001	.0004
153	12,131	11,811	.05	.0001	.0004
154	12,131	10,092	.05	.001	.0012
155	11,189	2,454	.05	.001	.0012
156	11,189	2,454	.05	.001	.0012
157	11,189	12,459	.05	.001	.03
158	11,189	12,459	.08	.001	.03
159	8,096	665	.08	.001	.03
160	8,096	665	.08	.001	.03
161	2,557	2,946	.08	.001	.03
162	1,711	1,771	.08	.001	.03
163	1,192	1,771	.10	.01	.03
164	1,192	1,771	.10	.01	.03
165	2,160	2,160	.05	.0001	.0002
166	2,160	2,160	.05	.0001	.0002
167	3,707	4,320	.05	.0001	.0002
168	3,707	4,320	.05	.0001	.0002
169	2,393	6,636	.05	.0001	.00011
170	10,731	20,736	.0001	.0001	.0001
171	11,111	26,568	.0001	.0001	.00011
172	11,111	22,136	.05	.0001	.00012
173	17,038	26,525	.05	.0001	.00017
174	16,183	16,148	.05	.0001	.00024
175	19,872	19,872	.05	.0001	.0004

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
176	19,872	19,872	0.05	0.0001	0.0004
177	16,183	16,148	.05	.001	.0006
178	10,109	10,092	.05	.001	.0012
179	8,087	8,078	.05	.001	.0012
180	8,087	8,078	.08	.001	.0012
181	8,087	8,078	.08	.001	.03
182	4,052	665	.08	.001	.03
183	1,728	1,728	.10	.01	.03
184	2,022	3,024	.05	.0001	.00012
185	3,024	6,636	.05	.0001	.00012
186	11,111	17,712	.05	.0001	.00013
187	7,076	7,068	.05	.0001	.00017
188	10,109	10,092	.05	.0001	.00024
189	12,131	12,113	.05	.0001	.00024
190	12,131	12,113	.05	.0001	.0004
191	14,161	14,135	.08	.001	.0012
192	12,131	12,113	.08	.001	.03
193	8,087	8,078	.08	.001	.03
194	8,087	8,078	.08	.001	.03
195	4,052	665	.10	.01	.03
196	1,728	1,728	.10	.01	.03
197	1,728	1,728	.10	.01	.03
198	3,456	3,456	.05	.0001	.00012
199	3,456	3,456	.05	.0001	.00015
200	3,456	3,456	.05	.0001	.00017
201	6,065	6,048	.10	.01	.0002
202	8,087	8,078	.10	.01	.00024
203	8,087	8,078	.08	.001	.0003
204	8,087	8,078	.08	.001	.0006
205	8,087	8,078	.08	.001	.0006
206	8,087	8,078	.08	.001	.0006
207	8,087	8,078	.08	.001	.0012
208	11,785	8,078	.08	.001	.0012
209	6,065	6,048	.08	.001	.03
210	6,065	6,048	.10	.01	.03

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
211	6,065	6,048	0.10	0.01	0.03
212	1,728	1,728	.10	.01	.03
213	778	475	.10	.01	.03
214	778	475	.10	.01	.03
215	778	475	.10	.01	.03
216	778	475	.10	.01	.03
217	2,186	536	.10	.01	.03
218	2,186	536	.10	.01	.03
219	1,564	536	.10	.01	.03
220	1,564	536	.10	.01	.03
221	1,564	536	.10	.01	.03
222	1,564	536	.10	.01	.03
223	6,065	6,048	.08	.001	.03
224	1,564	536	.10	.01	.03
225	1,564	536	.10	.01	.03
226	6,065	6,057	.10	.01	.03
227	6,065	6,048	.10	.01	.03
228	2,497	2,497	.10	.01	.03
229	2,497	2,497	.10	.01	.03
230	6,065	6,057	.10	.01	.03
231	1,728	1,728	.10	.01	.03
232	1,728	1,728	.15	.10	.03
233	1,728	1,728	.15	.10	.03
234	1,987	1,987	.10	.01	.03
235	1,987	1,987	.10	.01	.03
236	1,987	4,510	.10	.01	.03
237	2,652	6,022	.10	.01	.03
238	2,652	6,022	.10	.01	.03
239	3,318	7,517	.10	.01	.03
240	3,318	7,517	.10	.01	.03
241	3,318	7,517	.10	.01	.03
242	3,318	7,517	.10	.01	.03
243	3,974	9,020	.10	.01	.03
244	3,974	9,020	.10	.01	.03
245	2,272	2,445	.10	.01	.03

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
246	86	86	0.10	0.01	0.03
247	86	86	.10	.01	.03
248	86	52	.10	.01	.03
249	86	52	.10	.01	.03
250	104	52	.10	.01	.03
251	156	60	.10	.01	.03
252	467	354	.10	.01	.03
253	467	354	.10	.01	.03
254	933	665	.10	.01	.03
255	933	665	.10	.01	.03
256	2,497	2,445	.10	.01	.03
257	2,497	2,497	.10	.01	.03
258	1,728	2,497	.15	.10	.03
259	9,331	9,331	.15	.10	.03
260	1,089	1,089	.15	.10	.03
261	778	778	.15	.10	.03
262	778	778	.15	.10	.03
263	778	778	.15	.10	.03
264	104	104	.15	.10	.03
265	976	976	.15	.10	.03
266	976	976	.15	.10	.03
267	1,944	1,944	.15	.10	.03
268	2,333	2,333	.15	.10	.03
269	2,333	2,333	.15	.10	.03
270	1,555	1,555	.15	.10	.03
271	778	778	.15	.10	.03
272	778	778	.15	.10	.03
273	121	130	.15	.10	.03
274	121	130	.15	.10	.03
275	778	778	.15	.10	.03
276	778	778	.15	.10	.03
277	484	69	.15	.10	.03
278	484	69	.15	.10	.03
279	1,037	1,555	.15	.10	.03
280	1,037	1,555	.15	.10	.03

HYDRAULICS DATA FOR MODEL--Continued

Element No.	Transmissivity		Storage coefficient		Leakance coefficient ([ft/d]/ft)
	Upper layer (ft^2/d)	Lower layer (ft^2/d)	Upper layer	Lower layer	
281	1,037	1,555	0.15	0.10	0.03
282	484	432	.15	.10	.03
283	242	164	.15	.10	.03
284	181	78	.15	.10	.03
285	181	78	.15	.10	.03
286	484	69	.15	.10	.03
287	484	69	.15	.10	.03
288	484	69	.15	.10	.03
289	544	588	.15	.10	.03
290	484	432	.15	.10	.03
291	484	432	.15	.10	.03
292	1,236	1,037	.15	.10	.03
293	173	147	.15	.10	.03
294	1,236	1,037	.15	.10	.03
295	1,236	1,037	.15	.10	.03
296	1,236	1,037	.15	.10	.03

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