HYDROLOGIC- AND SALT-BALANCE INVESTIGATIONS UTILIZING DIGITAL MODELS LOWER SAN LUIS REY RIVER AREA SAN DIEGO COUNTY, CALIFORNIA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 24-74

Prepared in cooperation with the
Joint Administration Committee of the
Santa Margarita and San Luis Rey
Watershed Planning Agencies

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16. Abstracts Hydrologic and salt balances were computed for the Pauma, Pala, Bonsall, and Mission ground-water basins of the San Luis Rey River watershed. Hydrologic budgets were tested for compatibility with known hydrologic parameters by constructing and verifying near-steady-state and transient-state models. Near-steady-state inflow and outflow were calculated to be 3.7 cubic hectometres per year for Pauma basin, 3.1 cubic hectometres per year for Pala basin, 6.6 cubic hectometres per year for Bonsall basin, and 8.3 cubic hectometres per year for Mission basin. In 1972 annual net difference between inflow and outflow was -2.8 cubic hectometres per year for Pauma, -1.0 cubic hectometre for Pala, +0.1 cubic hectometre per year for Bonsall, and +1.5 cubic hectometres per year for Mission. Salt-balance calculations for 1972 indicate that salt inflow exceeded salt outflow by 2,000 tonnes per year in Pauma basin, 640 tonnes per year in Pala basin, 2,400 tonnes per year in Bonsall basin, and 3,800 tonnes per year in Mission basin.

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Rogers C. B. Morton, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, 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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Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric (SI)*
acre	4.047×10^{-1}	ha (hectare)
acre-ft (acre-foot)	1.233×10^{-3}	hm^3 (cubic hectometre)
acre-ft (acre-foot)	1.233×10^{3}	m^3 (cubic metre)
acre-ft per acre	3.048×10^{-1}	m (metre)
ft (foot)	3.048×10^{-1}	m (metre)
gal (gallon)	3.785×10^{-3}	m^3 (cubic metre)
gal/d (gallon per day)	3.785×10^{-3}	m^3/d (cubic metre per day)
(gal/d)/ft (gallon per day per foot)	1.242×10^{-2}	m^2/d (square metre per day)
$(gal/d)/ft^2$ (gallon per day per square foot)	4.074×10^{-2}	m/d (metre per day)
(gal/min)/ft (gallon per minute per foot)	1.242×10^{-2}	$(m^3/min)/m$ (cubic metre per minute per metre)
lb/acre (pound per acre)	1.121	kg/ha (kilogram per hectare)
mi (mile)	1.609	km (kilometre)
mi^2 (square mile)	2.590	km^2 (square kilometre)
ton (ton, short)	9.072×10^{-1}	t (metric ton or tonne)

HYDROLOGIC- AND SALT-BALANCE INVESTIGATIONS UTILIZING DIGITAL MODELS

LOWER SAN LUIS REY RIVER AREA, SAN DIEGO COUNTY, CALIFORNIA

By Joe A. Moreland

ABSTRACT

The Joint Administration Committee of the Santa Margarita and San Luis Rey Watershed Planning Agencies was designated as the agency to conduct studies leading to the development of a comprehensive water-quality management plan for the two watersheds. Hydrologic and salt balances for the Pauma, Pala, Bonsall, and Mission ground-water basins in the San Luis Rey River valley needed to develop the plan were difficult to compute because of the lack of data.

Hydrologic models constructed and verified for 1958-72 for Pauma and Pala basins and for 1946-72 for Bonsall and Mission basins were beneficial in developing the hydrologic balances. Inflow and outflow to the basins used in model verification were consistent with known physical and hydrologic characteristics of the basins.

Near-steady-state inflows and outflows were estimated to be:

Basin	Acre-feet per year	Cubic hectometres per year
Pauma	3,000	3.7
Pala	2,500	3.1
Bonsall	5,400	6.6
Mission	6,700	8.3

In 1972, outflow exceeded inflow by about:

Basin	Acre-feet per year	Cubic hectometres per year
Pauma	2,300	2.8
Pala	800	1.0
Bonsall	-100	-.1
Mission	-1,200	-1.5

The computed inflows and outflows were used to compute salt balances for each basin for near-steady state and for 1972. The 1972 computations indicate that salt inflow exceeded salt outflow by:

Basin	Tons per year	Tonnes per year
Pauma	2,200	2,000
Pala	700	640
Bonsall	2,600	2,400
Mission	4,200	3,800

INTRODUCTION

In late 1970 the Joint Administration Committee (JAC) of the Santa Margarita and San Luis Rey Watershed Planning Agencies was designated as the agency to conduct planning studies leading to the development of a comprehensive water-quality management plan for the Santa Margarita-San Luis Rey River watersheds. Beginning in 1971, the U.S. Geological Survey, in cooperation with JAC, undertook several phases of the committee's numerous tasks. Work by the Geological Survey included preliminary analysis of hydrologic and water-quality data, development of water-level and water-quality monitoring networks, collection of hydrologic data, evaluation of the feasibility of constructing models of the ground-water basins within the two watersheds, construction and utilization of models to study the hydrologic and salt balances for Pauma, Pala, Bonsall, and Mission ground-water basins, and development of a salt balance for the shallow alluvial aquifer underlying Pauba Valley.

Results of thus-far completed phases of the total investigation have been summarized in part in two Geological Survey open-file reports by Irwin and Giessner (1971) and Moreland (1972).

This report summarizes the hydrologic- and salt-balance investigations in the Pauma, Pala, Bonsall, and Mission ground-water basins. Results of the salt-balance investigations made in the Pauba Valley area of the Santa Margarita watershed are included in a separate report (written commun., J. W. Warner, 1974).

Purpose and Scope

The specific purpose of this study was to compute hydrologic and salt balances for the four ground-water basins of the lower San Luis Rey River area. As an aid in the development of the hydrologic balances, digital hydrologic models of the basins were constructed.

The scope of the study included evaluation of the geohydrologic framework of the basins, development of transient-state hydrologic models, estimation and verification by model techniques of all significant items of inflow and outflow to the basins, and computation of salt balances for the basins. This work required analysis of drillers' logs and specific-capacity tests of wells to define hydraulic conductivity of the basin aquifers, estimation of storage coefficients, computation of pumpage from land use and consumptive use, determination of the quantity and distribution of recharge from surface runoff, computation of subsurface inflow and outflow, selection of model periods, and estimation of quality of all inflow and outflow.

Location and General Features of the Area

The San Luis Rey River drains approximately 560 mi^2 (1,450 km^2) of mountainous area in northern San Diego County, Calif., and forms a watershed with a series of valleys separated by narrow, steep-walled canyons. The valleys are underlain by various thicknesses of unconsolidated alluvial fill that serve as storage for ground water. Four major constrictions in the San Luis Rey River valley separate the valley fill into five major ground-water basins--Warner, Pauma, Pala, Bonsall, and Mission. Warner basin, not included in this investigation, occupies the valley area of the upper San Luis Rey River. Pauma, Pala, Bonsall, and Mission basins are in the lower San Luis Rey River area (fig. 1).

Pauma basin extends from a point near the confluence of the San Luis Rey River and Paradise Creek to a constriction in the valley near Frey Creek (fig. 2). Pala basin extends from this constriction downstream to a bedrock constriction between Monserate Mountain on the north and Lancaster Mountain on the south (fig. 2). A stream-gaging station in the narrows (San Luis Rey River at Monserate Narrows, near Pala) is operated by the Geological Survey. Bonsall basin extends from Monserate Narrows to the narrow canyon downstream from Bonsall. The Geological Survey stream-gaging station (San Luis Rey River near Bonsall) is at the downstream end of the basin. Mission basin extends from near the Bonsall station to a point about 2 mi (3 km) inland from the coast where the river passes through a narrow canyon before reaching the Pacific Ocean. Streamflow leaving the basin is recorded by the Geological Survey gage San Luis Rey River at Oceanside.

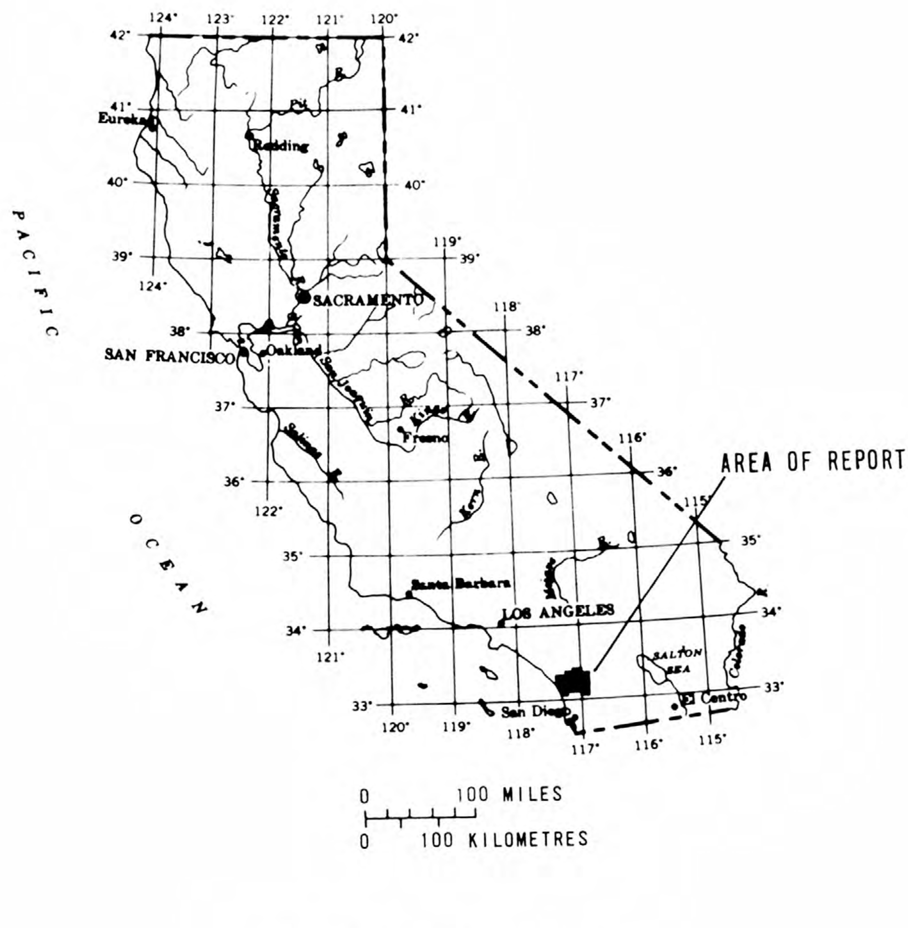
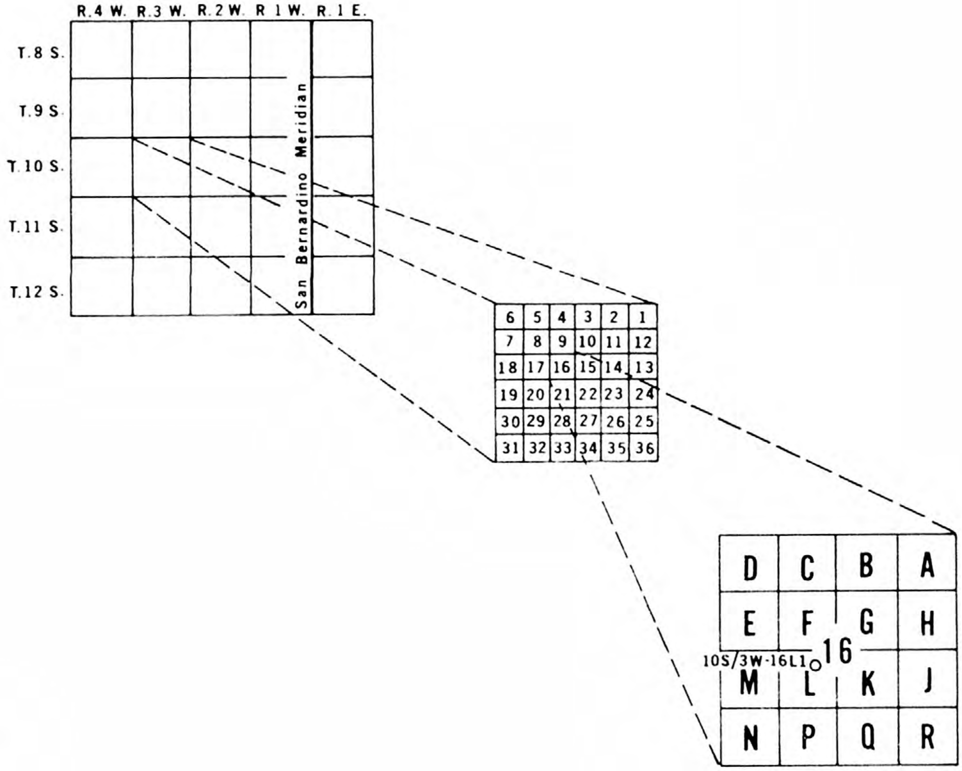


FIGURE 1.--Index map.

Well-Numbering System

Wells are numbered according to their location in the rectangular system for the subdivision of public land. For example, in the number 10S/3W-16L1, the part of the number preceding the slash indicates the township (T. 10 S.), the part between the slash and the hyphen indicates the range (R. 3 W.), the number between the hyphen and the letter indicates the section (sec. 16), and the letter indicates the 40-acre (16-ha) subdivision of the section. Within the 40-acre (16-ha) tract wells are numbered serially, as indicated by the final digit. Thus, well 10S/3W-16L1 is the first well to be listed in the NE¼SW¼ sec. 16, T. 10 S., R. 3 W., San Bernardino base line and meridian as shown in the diagram below.



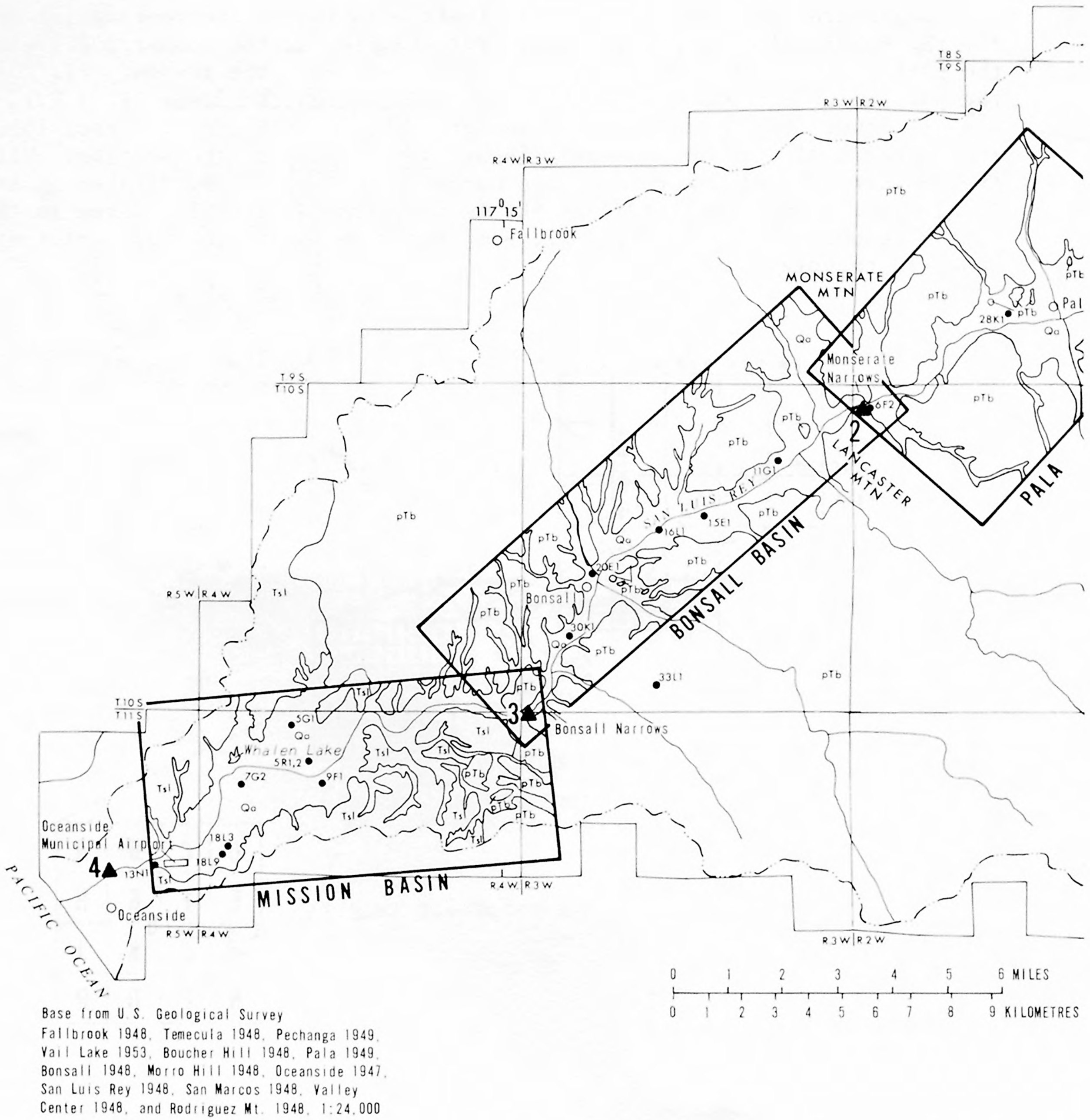


FIGURE 2.--Map of the lower San Luis Rey River valley area showing generalized geology, location of selected wells, and ground-water basins.

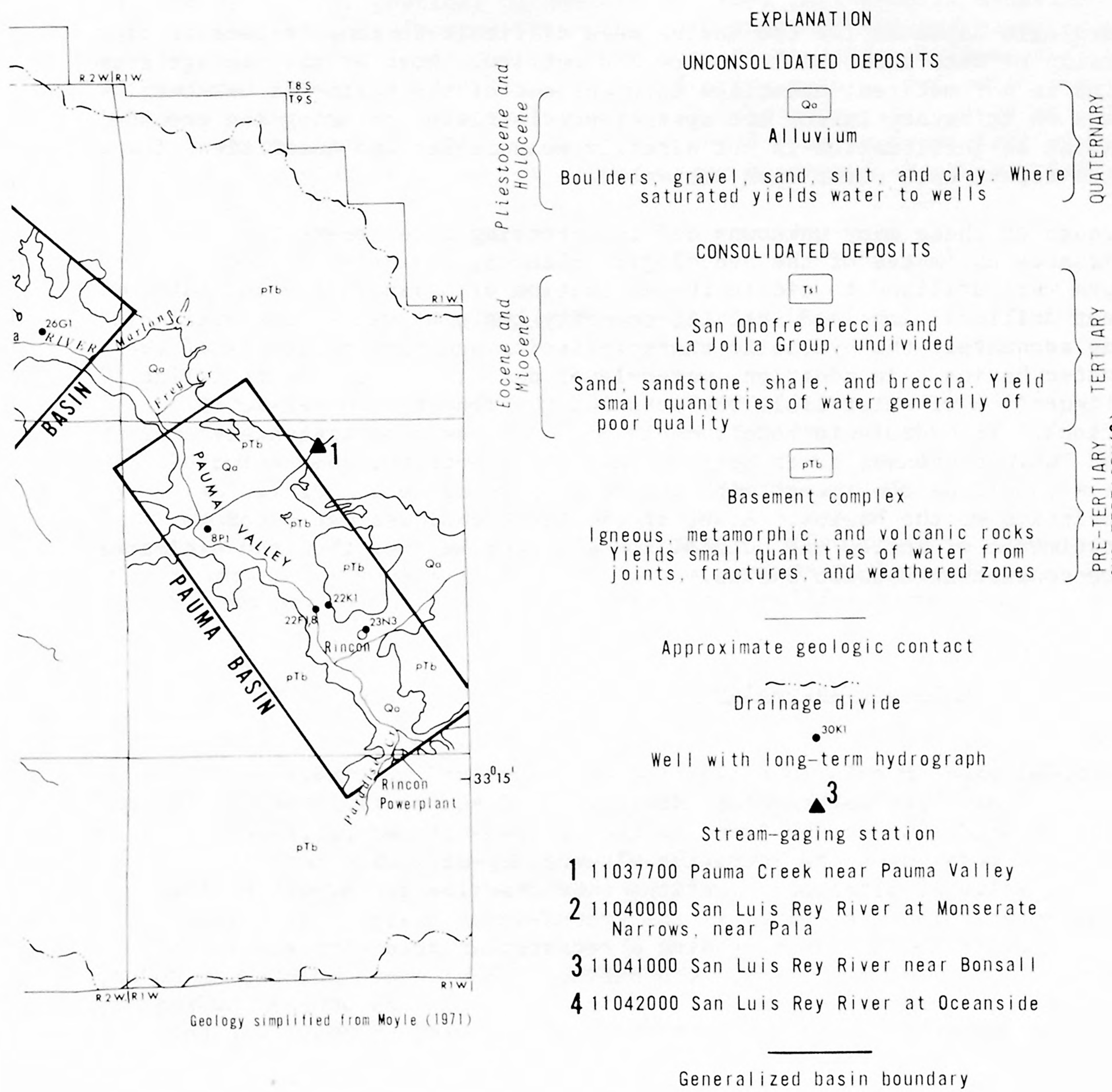


FIGURE 2.--Continued.

HYDROLOGIC MODELS

Hydrologic balances for the basins were difficult to compute because of the sparsity of data about basin inflow and outflow. Most of the pumpage from the basins is not metered; underflow into and out of the basins is unknown; gaged data on tributary inflow are sparse; precipitation entering the ground-water basins as infiltration is not directly measurable; and quantities of irrigation return have never been estimated.

Because of these many unknowns and the pressing requirement for reconnaissance estimates of the hydrologic balances, digital-modeling techniques were utilized to aid in the evaluation of basin inflow and outflow. Sufficient drillers' logs and specific-capacity tests of wells were available to define adequately the hydraulic characteristics and base altitudes of the ground-water basins. In addition, water-level data were adequate to define the configuration of water-table surfaces and the long-term water-level fluctuations. If hydrologic models could be developed that adequately simulated known responses to changes in inflow and outflow, the estimated quantities should be consistent with the known physical and hydrologic characteristics of the basins. Also, if similar techniques were used to obtain estimates of inflow and outflow for all four basins, then the estimates should be consistent between basins.

General Discussion of the Ground-Water Model

The model used in this investigation was developed by Pinder and Bredehoeft (1968). The mathematical derivation of the model is beyond the scope of this study but can be found in the above-mentioned reference. Basically, the model uses the iterative alternating-direction implicit procedure to solve simultaneous equations that describe ground-water flow between adjacent, discrete points in the ground-water basin. The discrete points are established by superimposing a rectangular grid with spacing of 500 to 1,000 ft (150 to 300 m) over the basin. The discrete points, or nodes, are defined as the center points of the compartmented areas bounded by the grid lines. Parameters assigned to the node are assumed to apply for the entire area of the compartment.

For each node in the model the following information is required: (1) Hydraulic conductivity, (2) storage coefficient, (3) altitude of base of aquifer, (4) altitude of initial water level, (5) dimension of the nodal compartment, and (6) net rate of inflow or outflow (excluding subsurface flow from adjacent nodes).

In addition, appropriate conversion factors, duration of modeled period, length of initial time step, maximum allowable error, maximum number of iterations, and rate of infiltration of precipitation must be supplied.

The model uses the above information to generate water-level conditions that mathematically satisfy the physical parameters of the system and the rate of inflow and outflow applied. During verification of the model, adjustments to the physical parameters and (or) inflow-outflow estimates are made to achieve satisfactory agreement between generated and observed water levels. If the model can then be used to generate adequately several sets of water-level conditions resulting from differing sets of inflow-outflow data (without altering the physical parameters), the model is said to be verified. Inflow and outflow for each model period would then be consistent with the physical characteristics of the ground-water basin and observed water-level fluctuations.

Assumptions Required for Modeling

Modeling of a ground-water basin is accomplished by substituting an artificial system, or model, for the actual system. To do this, the real system must be simplified considerably--the degree of simplification depending upon the complexity of the model. In this investigation the model used for each basin was capable of simulating two-dimensional horizontal flow in an unconfined aquifer with an irregular boundary. (The model has the capability of simulating a confined aquifer, but, for reasons to be explained, this feature was not used.) The assumptions for simplification were:

1. Ground-water flow is limited to two-dimensional horizontal flow--vertical flow is ignored.

2. Physical parameters of the system are constant for each node--hydraulic conductivity, storage coefficient, and altitude of the base of the aquifer are not variable within a specific nodal compartment.

3. The basin is bounded by an impermeable boundary--the outermost nodes must have a hydraulic conductivity of zero.

4. Discharge from or recharge to a node occurs at a constant rate over the entire nodal compartment--a pumping well has an area equal to the area of the nodal compartment in which it occurs, and water-level decline reflects this large effective radius of the well.

5. Infiltration of precipitation, modeled as vertical leakage, occurs at a constant rate over the entire basin.

6. Changes in ground-water storage occur instantaneously with change in water level--no provisions are made for slow release from storage.

7. Recharge occurs instantaneously--transit time through the unsaturated zone is ignored.

8. Inflow and outflow occur at a constant rate through each model period--if the model period is longer than a pumping season, seasonal fluctuations in pumping are ignored and pumping is averaged over the entire model period.

Most of these assumptions have little consequence when long-term cause and effect relations are considered. However, the assumption that the aquifers in Pauma and Mission basins are unconfined systems is important.

In local areas in these two basins, the aquifers are composed of coarse-grained permeable material overlain by fine-grained less permeable confining members. Water levels in wells perforated in the lower, more permeable zones clearly display artesian or confined characteristics during periods of short-term pumping. Immediate response to pumping in nearby wells, marked differences in water levels between closely spaced wells perforated in different zones, slow response to recharge, and large recovery at the end of pumping seasons demonstrate this confinement. However, over longer periods, slow drainage from the fine-grained material occurs and the basins apparently respond to long-term stresses as if they were a single, unconfined aquifer.

In both basins much of the aquifer system is composed of thin, unconfined aquifers. Large declines of water levels in these areas are accompanied by correspondingly large declines in transmissivity (hydraulic conductivity times saturated thickness).

Because the ground-water model is designed to simulate either (not both) confined or unconfined aquifers, major program changes would have been required to simulate confined conditions in one part of a basin and unconfined conditions in the rest of the basin. Time limitations precluded such major revisions, so the basins were modeled as wholly unconfined aquifers. Thus, simulation of the short-term effects of pumping from the confined parts of the aquifers is not accurate for these models. However, reasonably good agreement was attained between generated and observed water levels for long-term conditions.

Model Periods

The procedure followed in selecting a model period for the four ground-water basins was to analyze long-term hydrographs of wells in each basin and then select a beginning time when water levels were near the historical high, and thus at or near steady-state conditions. The average inflow and outflow for near-steady-state conditions were calculated. The near-steady-state conditions were modeled using the calculated average inflows and outflows to insure that the basins were in equilibrium and to provide initial water levels for use in subsequent transient-state models. The inflows and outflows used probably do not represent true steady-state values but rather the conditions required to maintain the initial head conditions in equilibrium. Also, the values are not unique solutions--only the most probable.

In Pauma and Pala basins, near-steady state was selected as the conditions immediately following 1958, an unusually wet year. In Bonsall and Mission basins, near-steady state was selected as the 1946 water year[1] following a 3-year period of above-average streamflow past the gage near Bonsall (fig. 3).

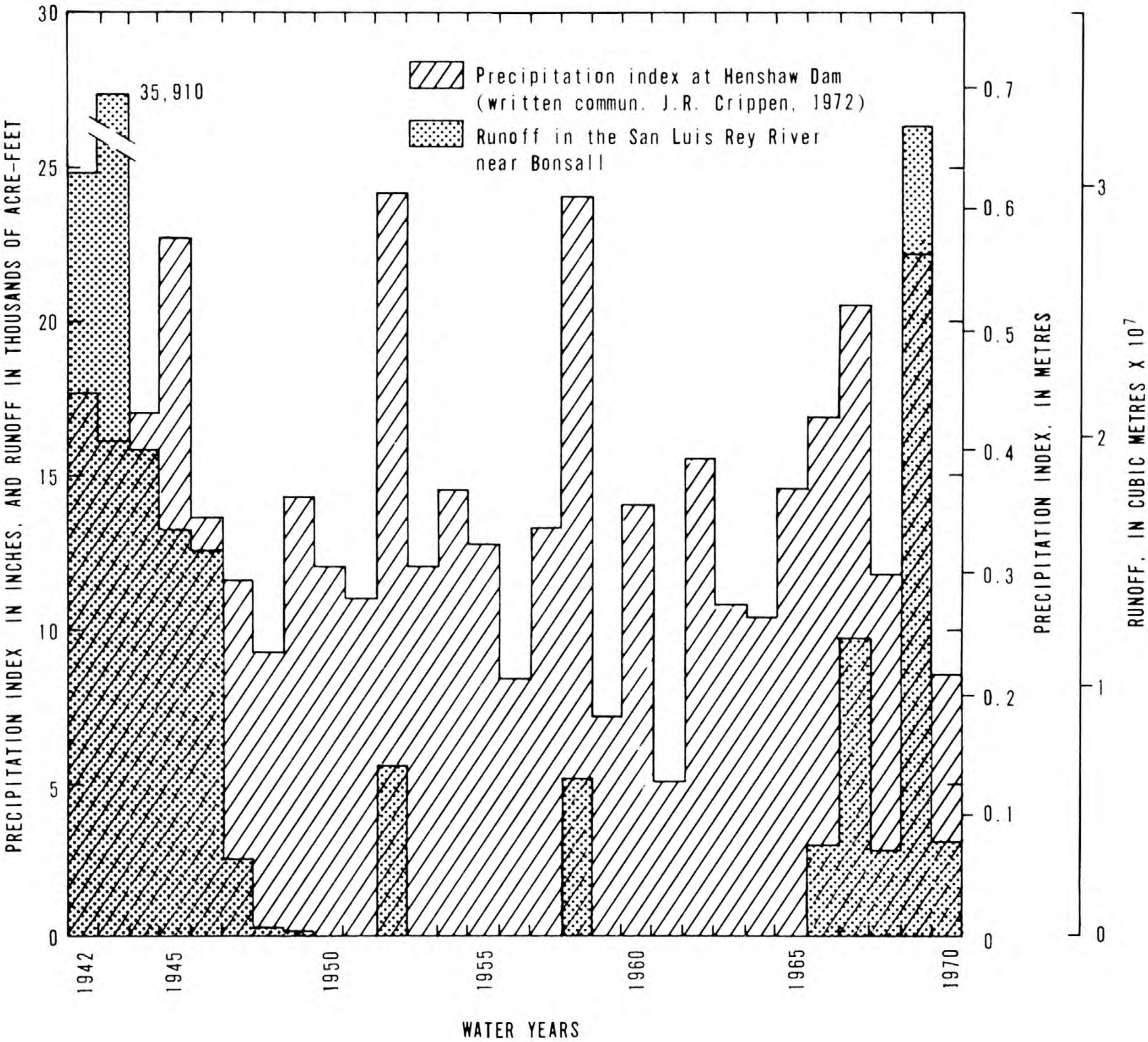


FIGURE 3.--Precipitation index at Henshaw Dam and runoff in the San Luis Rey River near Bonsall.

[1]The water year is that 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.

The years from the initial conditions through 1972 were then grouped into several time steps or model periods. The groupings were made on the basis of water-level response to significant changes in inflow and outflow. In general, the model periods were determined on the basis of annual precipitation; however, streamflow entering the basins and pumpage from the basins were also considered.

In Pauma basin the model periods included 1959-61 (dry period), 1962 (wet period), 1963-65 (dry period), 1966-67 (wet period), 1968 (dry period), January-June 1969 (wet period), and July 1969-December 1972 (near-average period). In Pala basin water-level data were insufficient to warrant detailed analysis of the basin, so the model periods were combined to include 1959-65 (dry period), 1966-68 (near-average period), January-June 1969 (wet period), and July 1969-December 1972 (near-average period). In Bonsall and Mission basins the model periods included 1947-51 (dry period), January-June 1952 (wet period), July 1952-December 1957 (dry period), January-June 1958 (wet period), July 1958-December 1965 (dry period), 1966-68 (near-average period), January-June 1969 (wet period), and July 1969-December 1972 (near-average period).

After determination of the average annual rate of inflow and outflow for each model period, the models were stressed, period by period, to generate water-level conditions resulting from each set of hydrologic conditions. Water levels generated by one model period were used as the starting point for the next model period. Thus, the accuracy of subsequent model periods depended upon the accuracy of all previous model periods.

GEOHYDROLOGIC FRAMEWORK OF THE GROUND-WATER BASINS

Pauma Basin

Pauma basin is the basin farthest upstream in the lower San Luis Rey area. Beginning about 2 mi (3 km) southeast of Rincon (fig. 2) the basin extends downstream a distance of about 7½ mi (12 km) to a constriction in the valley floor formed by the toe of a thick alluvial fan. Most of the land in the valley is used for agriculture. The major crops are citrus and avocados. Two golf courses occupy several hundred acres of the valley floor. The main use of water is for irrigation, although some is used for domestic purposes for the growing population. Most of the water used in the basin is pumped from local ground-water supplies. Lesser quantities of water are imported by the Yuima County Water District, and a small part is obtained by surface diversions from Pauma Creek and releases from the Rincon powerplant.

Pauma basin is bounded by a basement complex of metamorphic and igneous rocks that are almost impervious. Locally, the surficial zone of this bordering and underlying basement complex is highly fractured and weathered and contains some usable ground water. Most wells completed in this surficial zone have low yields and are not an important source of ground water. The alluvial material that fills the basin has been divided into three units (California Department of Water Resources, 1965): (1) River-channel deposits and younger alluvium, both of Holocene age; (2) alluvial fan deposits, of Pleistocene age; and (3) older alluvium, of Pleistocene age.

River-channel deposits and younger alluvium underlie the San Luis Rey River channel. These deposits range in thickness from 0 along the periphery of the basin to 130 ft (40 m) in the central part of the basin. The deposits are composed of boulders, gravel, sand, silt, and clay. Where saturated, they freely yield water to wells. The units, although of limited thickness and areal extent, are a significant source of ground water in Pauma basin.

Alluvial fan deposits, primarily the Rincon, Pauma, and Aqua Tibia Fans (Howes, 1955), cover about 1,100 acres (450 ha) of Pauma basin. The fans have a maximum thickness of about 370 ft (115 m). They are composed of heterogeneous detrital material washed down from the mountains to the north of the area and are of low permeability. Although wells completed in the fan deposits have lower specific capacities (less than 10 (gal/min)/ft or 0.1 (m^3/min)/m of drawdown) than do wells in the younger alluvial deposits, the fan deposits constitute a significant source of water supply. Locally, the fan deposits apparently are in hydraulic continuity with the underlying older alluvium and thus serve as a source of recharge to that unit.

During the depositional history of Pauma basin, alluvial fan deposits apparently extended across the valley floor in the vicinity of Frey Creek, damming the flow of the San Luis Rey River (Howes, 1955). A large lake was formed (Howes, 1955) as evidenced by an extensive layer of fine-grained lake deposits, which are variously called tule beds, lake beds, or black silt or clay by local drillers. The layer overlies, and effectively confines, an extensive deposit of older alluvium composed of well-sorted layers of gravel, sand, silt, and clay. This permeable older alluvium is a major source of ground water. The unit has a maximum thickness of about 160 ft (50 m) near the center of the basin. The specific capacity of wells perforated in both the older and younger alluvium ranges from about 10 to 60 (gal/min)/ft (0.1 to 0.7 (m^3/min)/m) of drawdown.

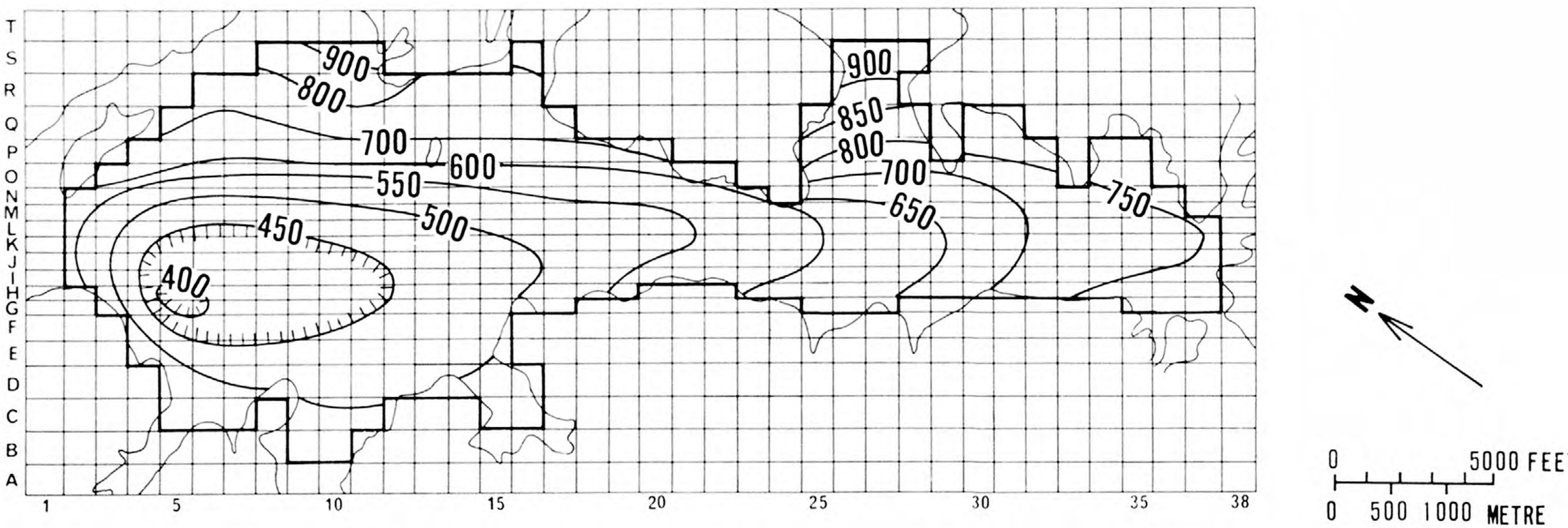
The altitude of the base of the aquifer system (fig. 4) was determined from drillers' logs. The base of the aquifer, in most logs, is the contact between alluvial deposits and the underlying bedrock. However, beneath the alluvial fans, the base of the aquifer was selected as the bottom of the deepest permeable zone penetrated by wells and may not include underlying silt and clay deposits of low permeability that overlie the basement complex.

Hydraulic conductivity (fig. 4) of the aquifer was determined from specific-capacity tests of wells and water-level data. Transmissivity of the total saturated thickness was determined from the equation (Thomasson and others, 1960):

$$T \approx SC \times 2000,$$

where T = transmissivity in gallons per day per foot, and
SC = specific capacity in gallons per minute per foot of drawdown.

Hydraulic conductivity was then determined by dividing transmissivity by the total saturated thickness.



ALTITUDE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

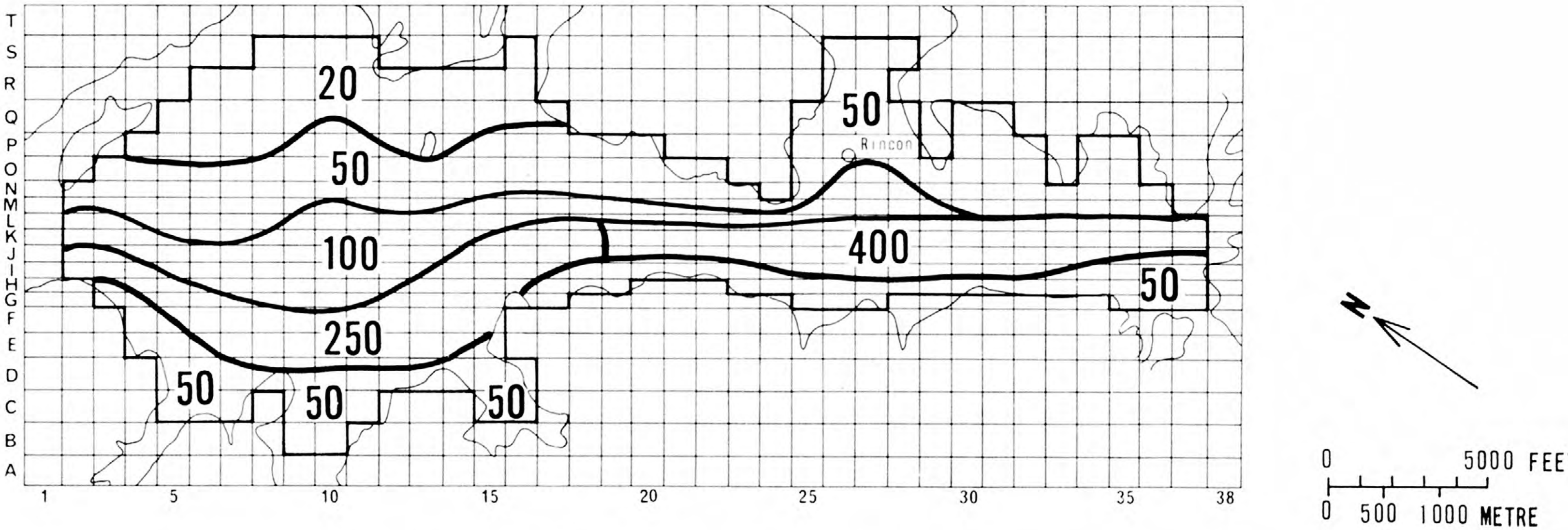
Boundary of modeled area

(Conversion factor: 1 foot = 0.3048 metre)

400

Base contour

Shows altitude of base of aquifer. Contour intervals 50 and 100 feet. Datum is mean sea level



HYDRAULIC CONDUCTIVITY

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

50

Area of equal hydraulic conductivity, in gallons per day per square foot

(Conversion factor: 1 gallon per day per square foot=0.04074 metre per day)

FIGURE 4.--Altitude of base of aquifer and modeled hydraulic conductivity, Pauma basin.

The computed hydraulic conductivity of the fan deposits ranges from 20 to 50 (gal/d)/ft^2 (0.8 to 2 m/d). The hydraulic conductivity of the downstream parts of the fan deposits is higher because of better sorting of the alluvial material. The hydraulic conductivity of both the younger alluvium and the river-channel deposits is about 400 (gal/d)/ft^2 (16 m/d) and the conductivity of the older alluvium is about 250 (gal/d)/ft^2 (10 m/d).

Model-verified storage coefficients (fig. 5) were 10 percent for the alluvial fan deposits and 12 percent for the younger and older alluvium.

Pala Basin

Pala basin extends from the downstream end of Pauma basin to the bedrock constriction between Monserate Mountain and Lancaster Mountain (fig. 2). From the upstream end of the basin to the confluence of the San Luis Rey River and Marlon Creek, the river channel is in a steep-walled, narrow canyon incised in the toe of alluvial fan deposits. Only four wells are in this 2-mi (3-km) reach, and few water-level data are available. For this reason, this part of the basin was not modeled. Below this upstream canyon, the river spreads out over a 1½-mi (2½-km) wide valley floor near Pala. The valley again narrows 1½ mi (2½ km) west of Pala, and the lower 3 mi (5 km) of the basin is only 1,000-2,000 ft (300-600 m) wide.

Land use in the basin is primarily for diversified agriculture, including four dairies in the lower canyon area. The water supply is derived almost entirely from ground water and is used for irrigation, dairy operation, and domestic purposes.

The aquifer system in Pala basin is bounded by nearly impervious metamorphic and igneous rocks. The aquifer system includes alluvial fan deposits and younger alluvium. No older alluvium has been identified in this basin. The valley fill in Pala basin is much thinner than in Pauma basin. Maximum thickness penetrated by wells is reported to be 244 ft (74 m) in well 9S/2W-26G1. Altitude of the base of the aquifer is shown in figure 6. The specific capacities of wells completed in fan deposits range from less than 1.0 to about 2.5 (gal/min)/ft (0.01 to 0.03 (m^3/min)/m) of drawdown. The specific capacity of wells in the younger alluvium and river-channel deposits ranges from about 13 to more than 115 (gal/min)/ft (0.16 to more than 1.4 (m^3/min)/m) of drawdown. Most of the water pumped in this basin is derived from the younger alluvium.

Hydraulic conductivity (fig. 6) of the fan deposits ranges from 20 to 100 (gal/d)/ft^2 (0.8 to 4 m/d). In the central part of the basin, the hydraulic conductivity of younger alluvium is about 750 (gal/d)/ft^2 (30 m/d). In the downstream part of the basin, because of better sorting and less fine-grained material in the younger alluvium, the hydraulic conductivity is about 1,000 (gal/d)/ft^2 (40 m/d).

Model-verified storage coefficients (fig. 7) are 9 percent in the fan deposits and 12 percent in the younger alluvium.

Bonsall Basin

Bonsall basin occupies a narrow (less than 1-mi or 2-km wide), elongate section of the river valley extending from the downstream end of Pala basin to the Geological Survey gage, about 3 mi (5 km) downstream from Bonsall (fig. 2). Ground-water pumpage from this basin supplied much of the water used for irrigation of citrus and avocado groves in the Fallbrook area prior to delivery of imported water to Fallbrook in 1948. Local truck farms, citrus groves, and golf courses currently use most of the water pumped in the area.

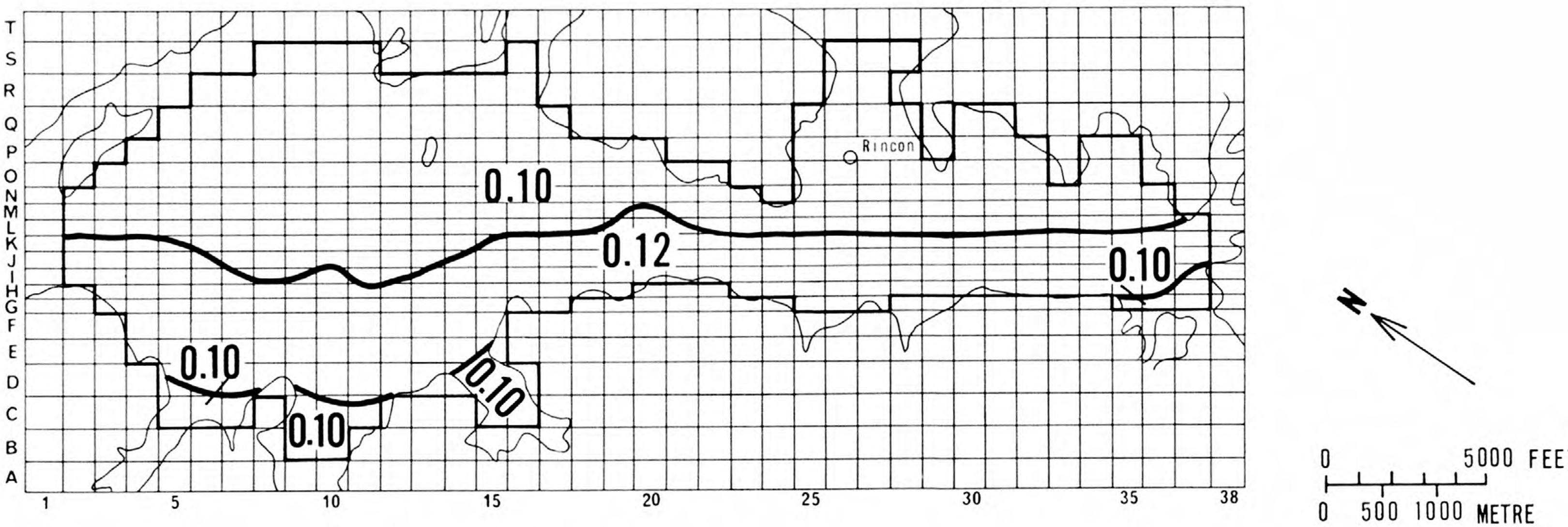
There is some domestic use of ground water, although reportedly the historical deterioration in water quality has severely limited this use during recent years. Imported water is used extensively both for irrigation and for domestic use.

As in Pauma and Pala basins, the basin is bordered and underlain by metamorphic and igneous rocks. Several stream channels are incised in the weathered and fractured bedrock. The main part of the basin underlies the San Luis Rey River valley and includes older alluvium along the periphery and in the major tributary valleys and younger alluvium and river-channel deposits along the main stem of the valley. No data are available on the specific capacity of wells in the older alluvium. The specific capacity of wells perforated in younger alluvium and river-channel deposits ranges from about 25 to 140 (gal/min)/ft (0.3 to 1.7 (m^3/min)/m).

The thickness of the alluvial fill is probably less than 130 ft (40 m) throughout the basin and probably averages 80 ft (25 m). Altitude of the base of the aquifer (fig. 8) was determined primarily from maximum reported depths of wells, by assuming that local drillers bottomed their wells in bedrock.

Hydraulic conductivity of the older alluvium was estimated to be 20 (gal/d)/ft^2 (0.8 m/d) (fig. 8). The younger alluvium and river-channel deposits seem to increase in permeability in a downstream direction as in Pala basin. As computed from specific-capacity tests, hydraulic conductivity of this unit ranges from about 1,000 (gal/d)/ft^2 (40 m/d) in the upstream part to about 2,000 (gal/d)/ft^2 (80 m/d) in the lower end of the basin.

Storage coefficients (fig. 9) appear to be higher in Bonsall basin than in Pauma or Pala basin. The model-verified storage coefficient of poorly sorted younger alluvium in the tributary valleys and of older alluvium is 12 percent, and the model-verified storage coefficient of better sorted alluvium underlying the main valley is 16 percent.



STORAGE COEFFICIENT

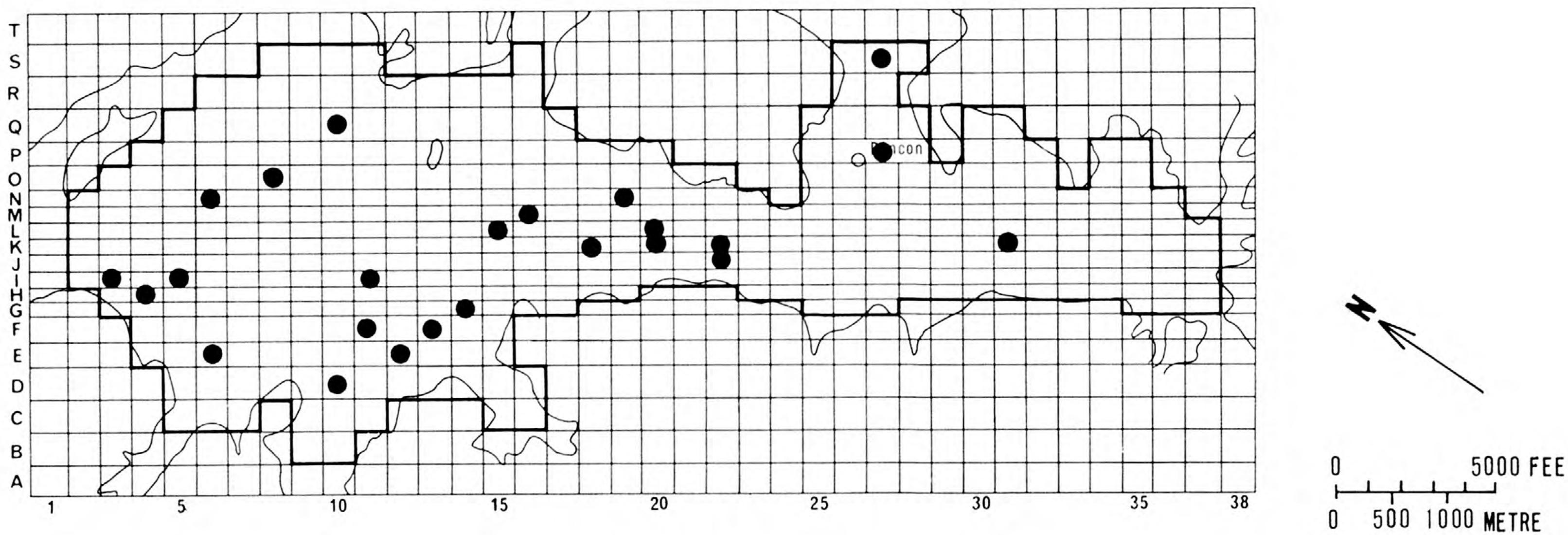
EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

0.10

Area of equal storage coefficient



PUMPAGE

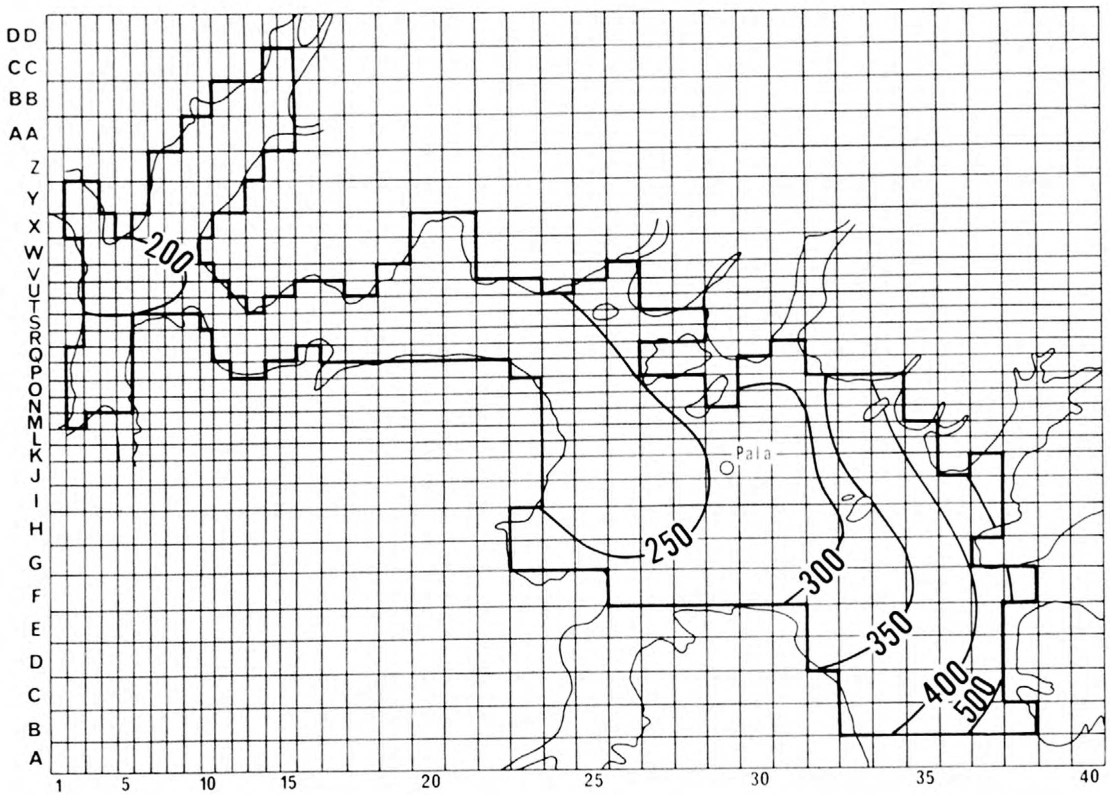
EXPLANATION

Contact between alluvium and virtually non-water bearing material

Boundary of modeled area

Modeled pumpage node

FIGURE 5.--Storage coefficient and location of modeled pumpage, Pauma basin.



ALTITUDE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

300

Base contour

Shows altitude of base of aquifer. Contour intervals 50 and 100 feet. Datum is mean sea level

Boundary of modeled area

(Conversion factor: 1 foot=0.3048 metre)

N

0 5000 FEET

0 500 1000 METRE

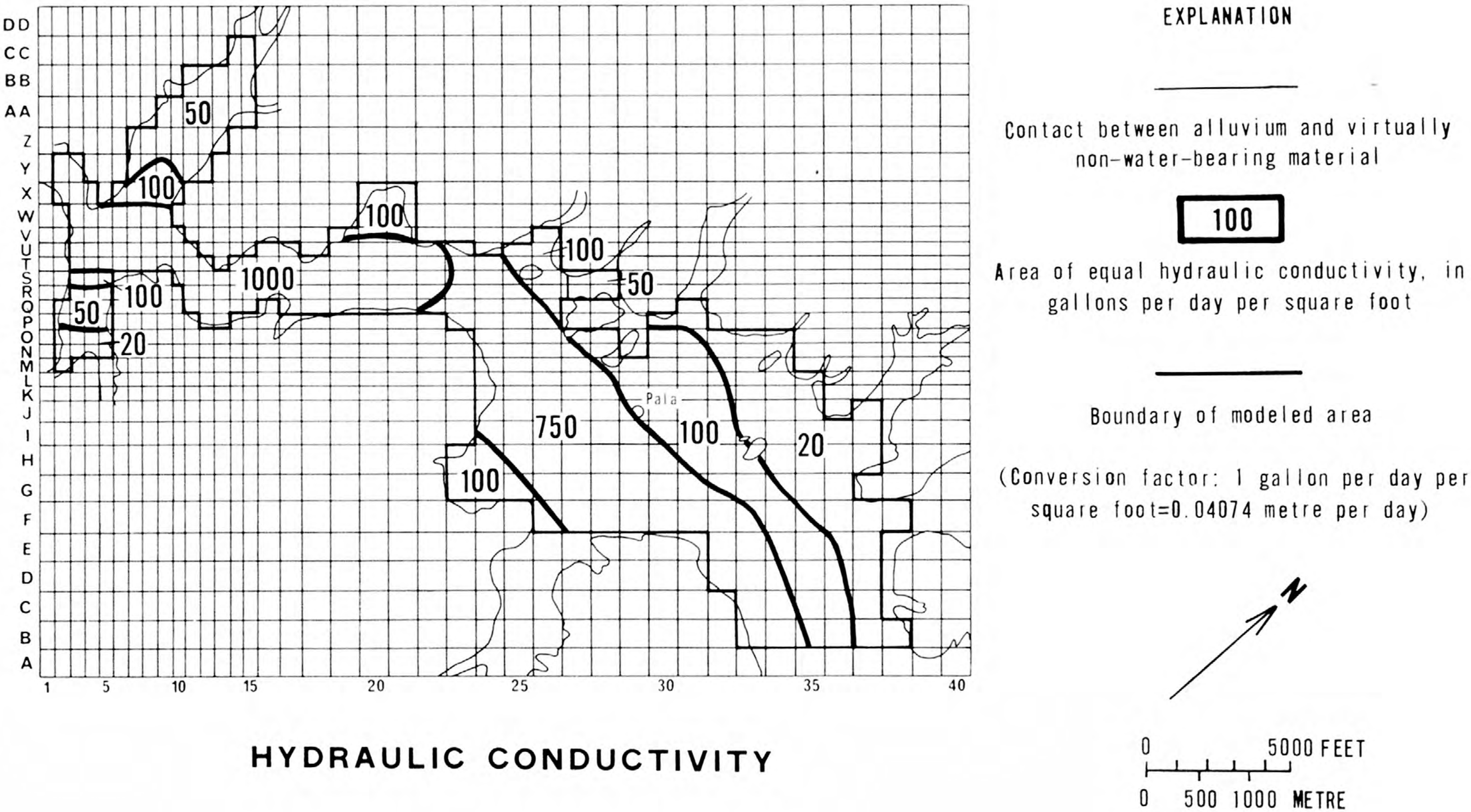
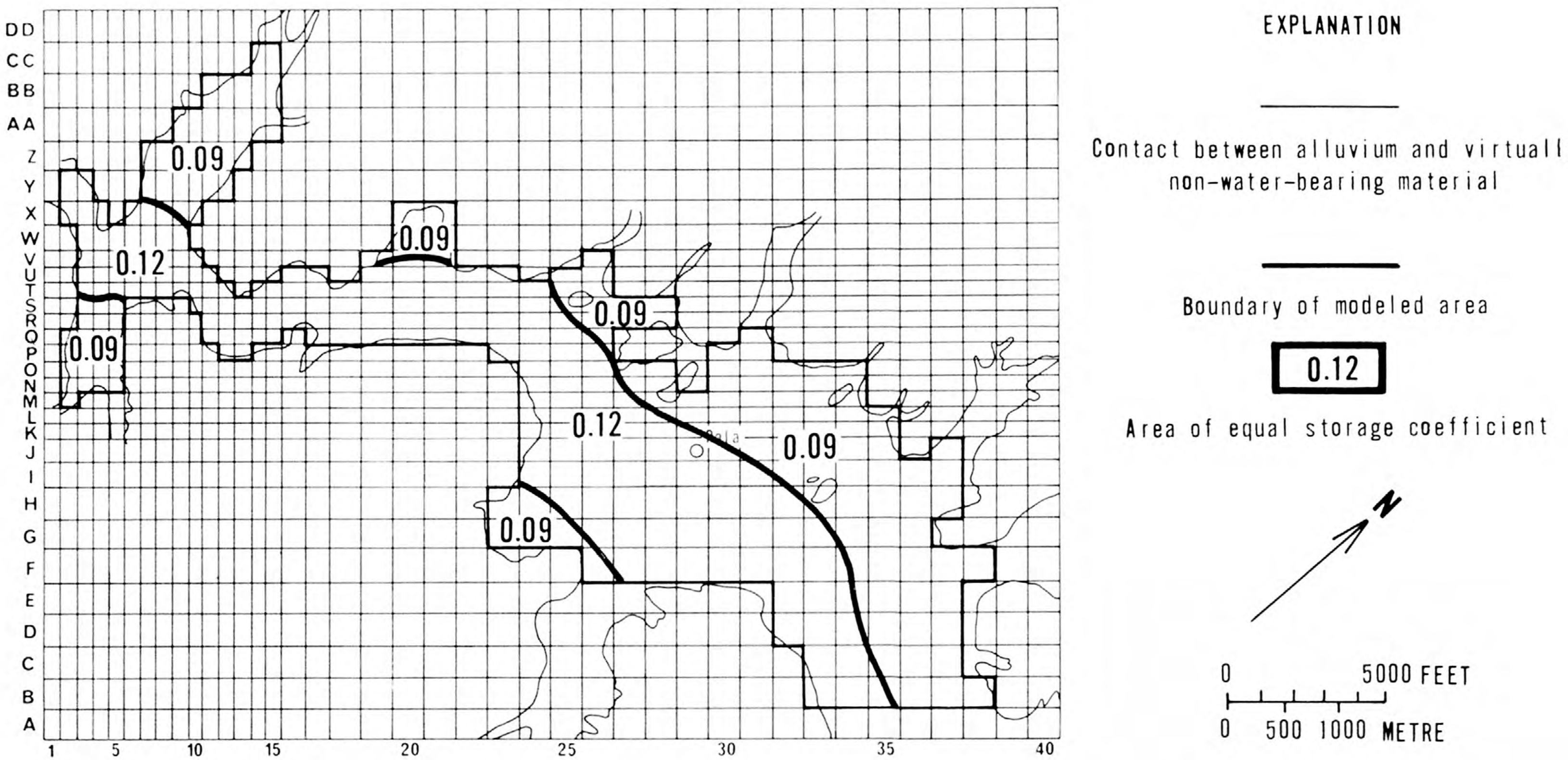
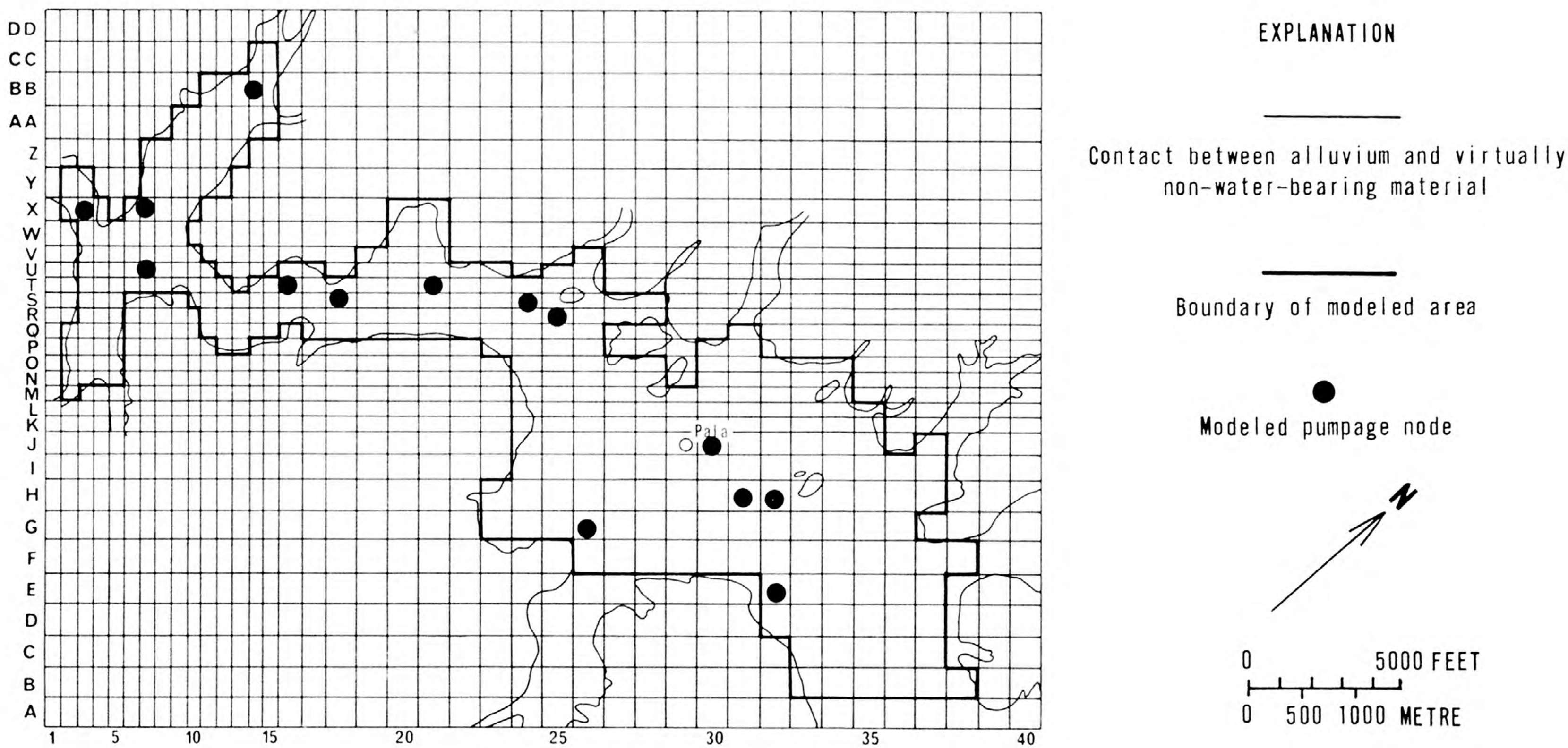


FIGURE 6.--Altitude of base of aquifer and modeled hydraulic conductivity, Pala basin.

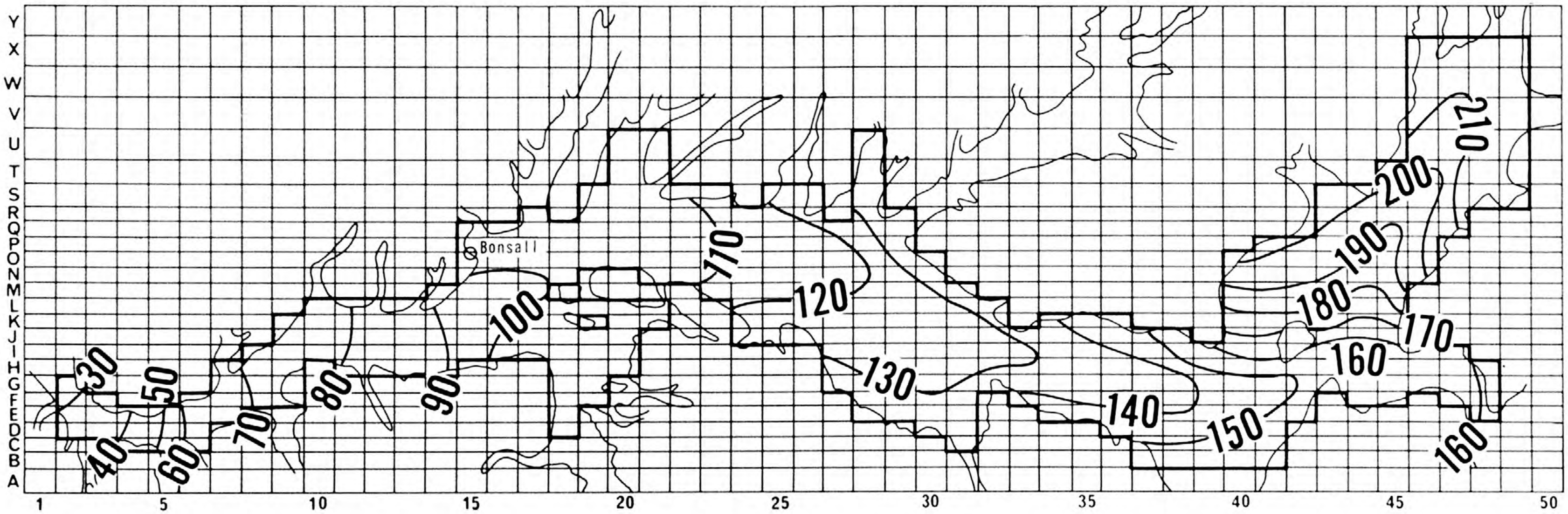


STORAGE COEFFICIENT



PUMPAGE

FIGURE 7.--Storage coefficient and location of modeled pumpage, Pala basin.



ALTITUDE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

—90— Base contour

Shows altitude of base of aquifer. Contour interval 10 feet. Datum is mean sea level

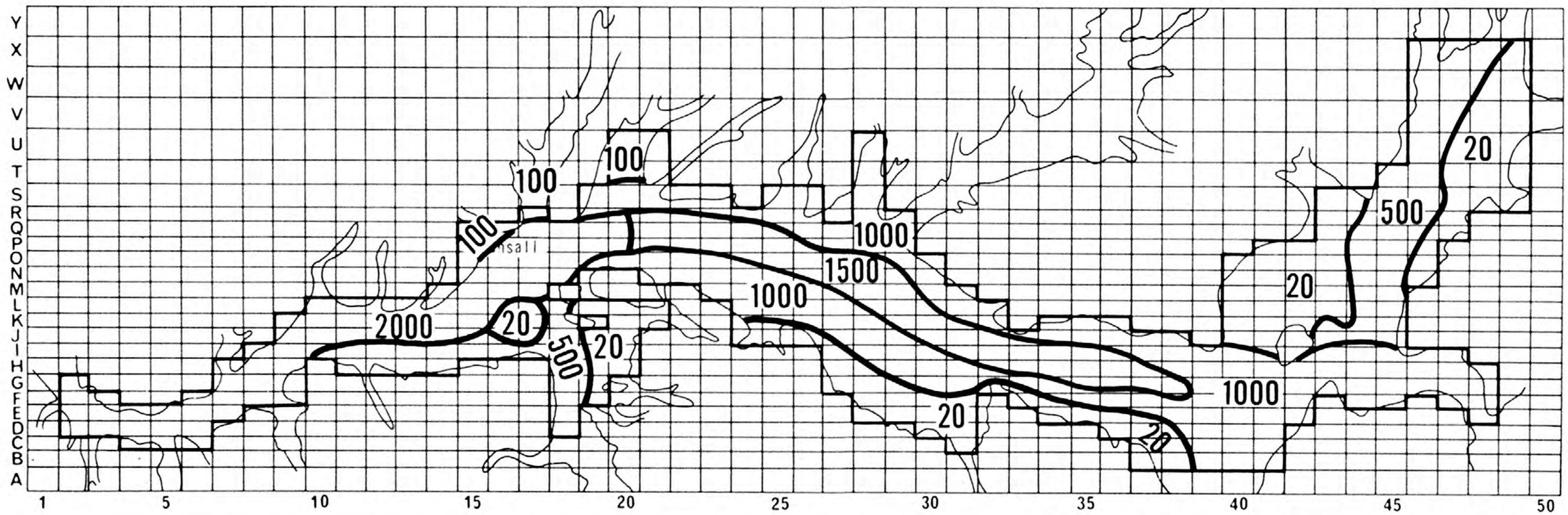
Boundary of modeled area

(Conversion factor: 1 foot = 0.3048 metre)

N

0 5000 FEET

0 500 1000 METRE



HYDRAULIC CONDUCTIVITY

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

20

Area of equal hydraulic conductivity, in gallons per day per square foot

(Conversion factor: 1 gallon per day per square foot=0.04074 metre per day)

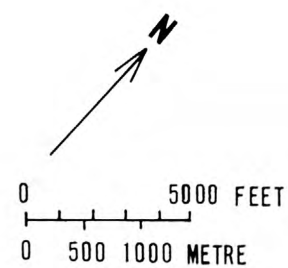
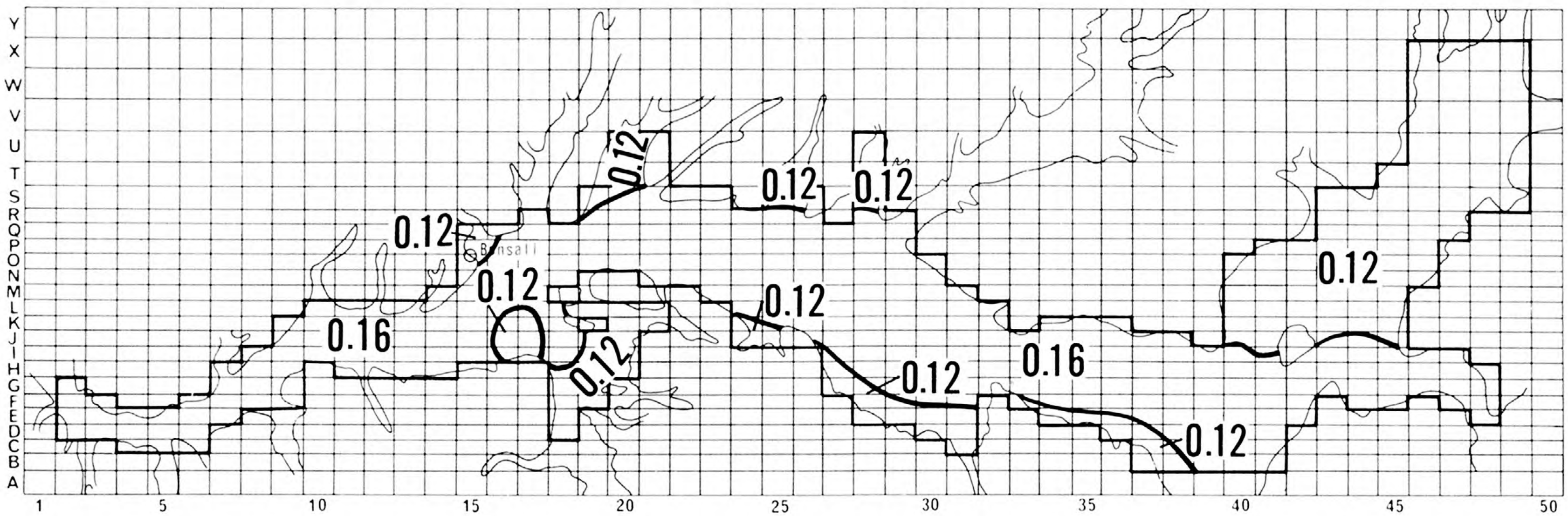


FIGURE 8.--Altitude of base of aquifer and modeled hydraulic conductivity, Bonsall basin.



STORAGE COEFFICIENT

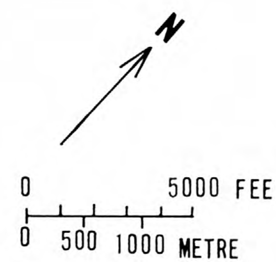
EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

0.16

Area of equal storage coefficient



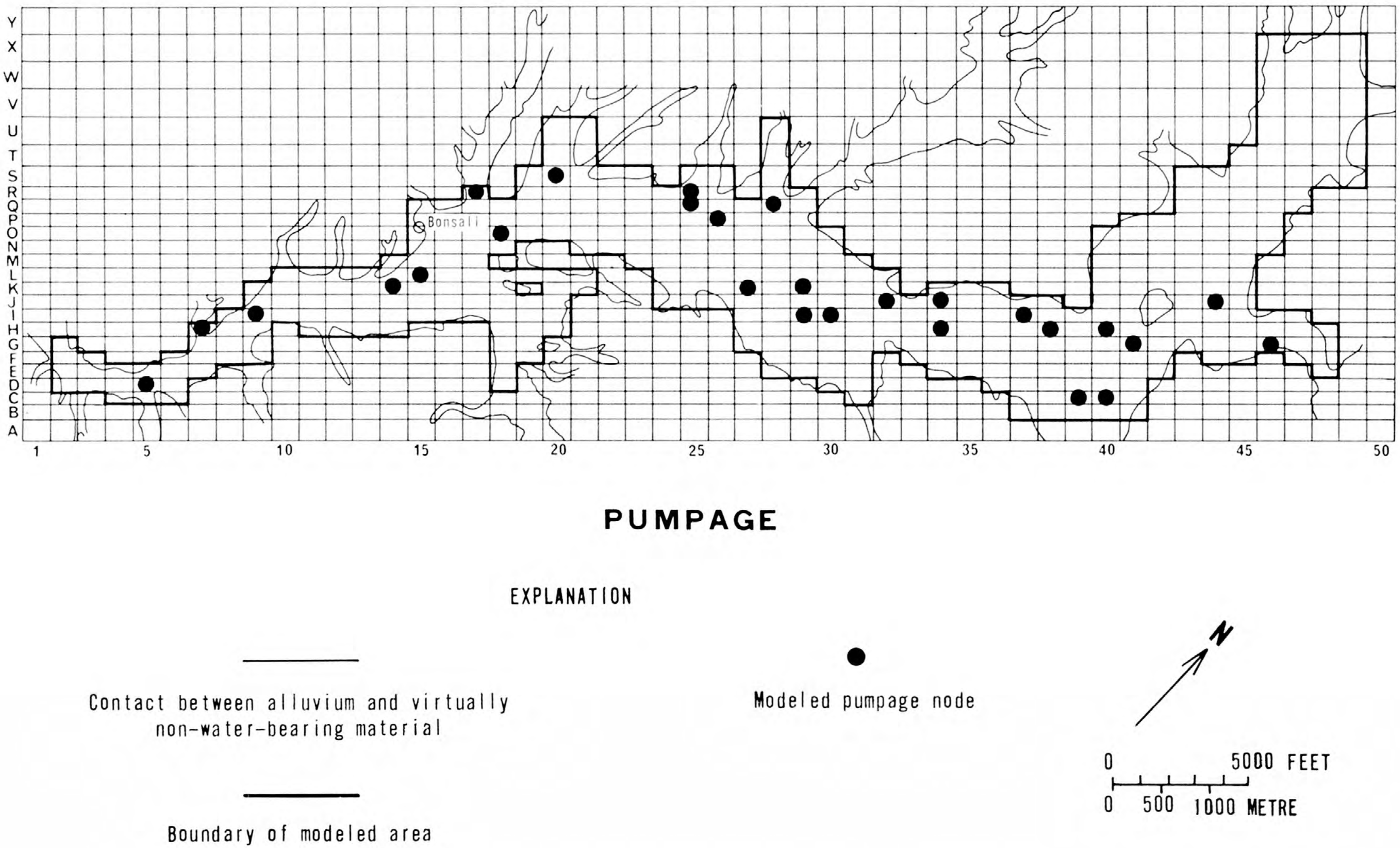


FIGURE 9.--Storage coefficient and location of modeled pumpage, Bonsall basin.

Mission Basin

Mission basin begins in the narrow canyon at the downstream end of Bonsall basin and extends downstream approximately 4 mi (6 km) before it spreads in a broad alluvial plain to a width of about 1½ mi (2½ km). At the downstream end of the basin, the San Luis Rey River enters a narrow canyon about 2 mi (3 km) inland from the Pacific Ocean.

Historically, this basin was the site of large truck and field farms and citrus orchards. The agricultural areas are being replaced by urban expansion. Ground water pumped from the basin has been used extensively for irrigation and for export to the cities of Oceanside and Carlsbad (south of Oceanside; not in fig. 2). Since the late 1950's pumpage for irrigation and export has declined considerably, reportedly because of the increasing concentration of dissolved solids in the ground water. Much of the urbanized area now receives imported water from the city of Oceanside, but agricultural use of the ground water continues. In 1958 the city of Oceanside began transporting reclaimed sewage water to Whalen Lake on the northwest side of the valley for recharge to the ground-water basin. Large declines in ground-water levels, which had occurred prior to that time, have since been reversed owing to a combination of the recharge operation and reduced pumpage.

Mission basin, unlike the previously described ground-water basins, is bounded mostly by marine sedimentary deposits of Tertiary age. These deposits include the San Onofre Breccia, of Miocene age, and the La Jolla Group of Eocene age. The ground water in both of these units is saline (California Department of Water Resources, 1960). The San Onofre Breccia borders and underlies the basin on the downstream, western edge (fig. 2). It is composed of cemented sand, sandy shale, and shale (California Department of Water Resources, 1960) that are of very low permeability. The La Jolla Group borders and underlies most of the rest of Mission basin with the exception of the northern edge of the upstream canyon which is bounded by pre-Tertiary basement complex (fig. 2). The La Jolla Group consists of fine-grained, well-sorted, well-compacted, and generally slightly cemented sand with a few beds of sandy shale and shale (California Department of Water Resources, 1960). The formation is only slightly permeable.

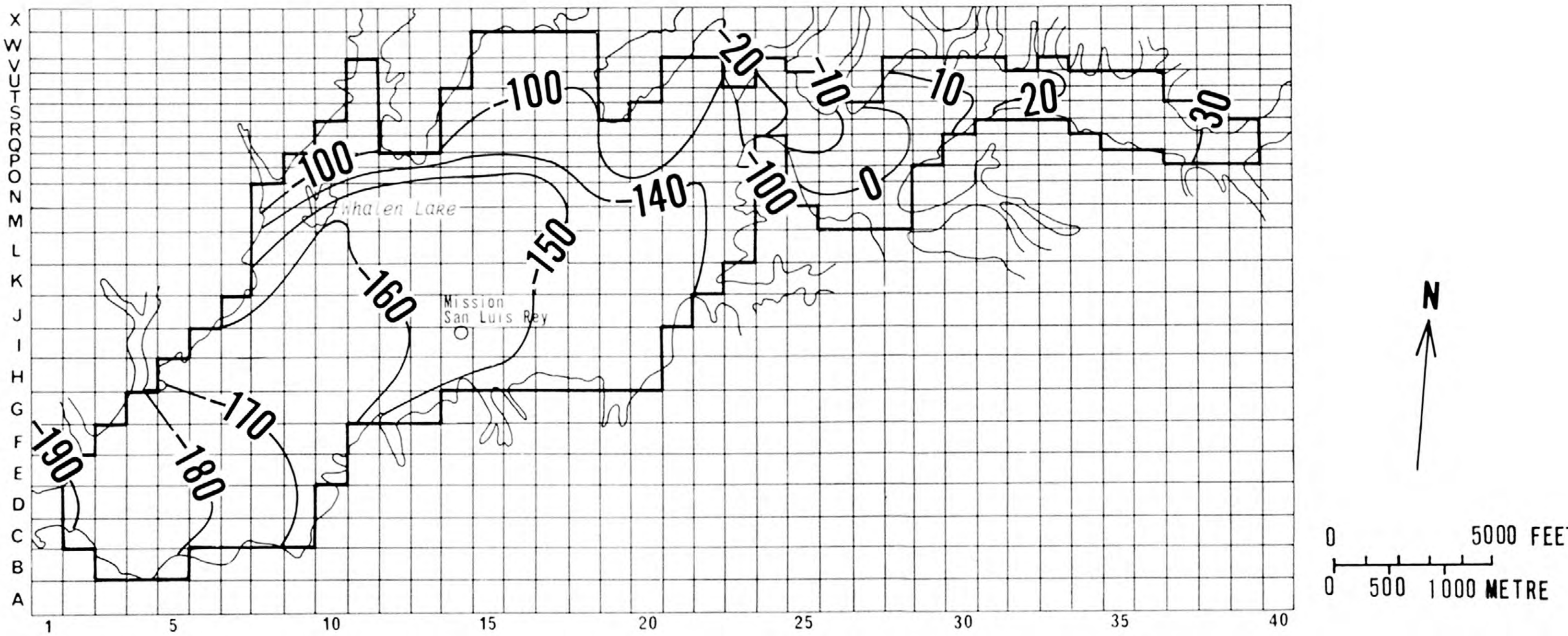
Overlying the marine deposits is a thick sequence of younger alluvium and river-channel deposits consisting of clay, silt, sand, and gravel, which, according to drillers' logs, attain a maximum thickness of 220 ft (65 m). Near the middle of the basin, the basal part of the aquifer consists of coarse, clean sand and gravel. Overlying this very permeable zone in the eastern and northern parts of the basin is a thick sequence of fine sand, silt, and clay that locally confines the ground water in the underlying basal aquifer. Slow drainage from the confining member into the more permeable lower zone causes the system to operate similarly to a water-table aquifer under long-term conditions.

Seawater intrusion and lateral and upward migration of saline water from the older marine deposits have occurred during past periods of lowered water levels (California Department of Water Resources, 1960). This intrusion has resulted in very poor quality water in much of the basin.

The altitude of the base of the aquifer system (fig. 10) was selected, for modeling purposes, as the base of the lowermost permeable zone that overlies the marine sediments. In the river canyon at the upstream end of the basin, the base of the aquifer was assumed to coincide with the maximum well depths.

Specific capacities of wells in the basin range from about 25 to 150 (gal/min)/ft (0.3 to 1.9 (m^3/min)/m), which suggest transmissivities ranging from 50,000 to 300,000 (gal/d)/ft (600 to 4,000 m^2/d). Hydraulic conductivities (fig. 10) were calculated to be 2,000 (gal/d)/ft^2 (80 m/d) in the upstream canyon, and range from 500 to 1,250 (gal/d)/ft^2 (20 to 50 m/d) in the thicker, finer grained downstream part of the basin.

Model-verified storage coefficients (fig. 11) were 12 percent in the downstream part of the basin and 16 percent in the upstream part of the basin.



ALTITUDE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

(Conversion factor: 1 foot=0.3048 metre)

—160—

Base contour

Shows altitude of base of aquifer. Contour interval, in feet, is variable. Datum is mean sea level

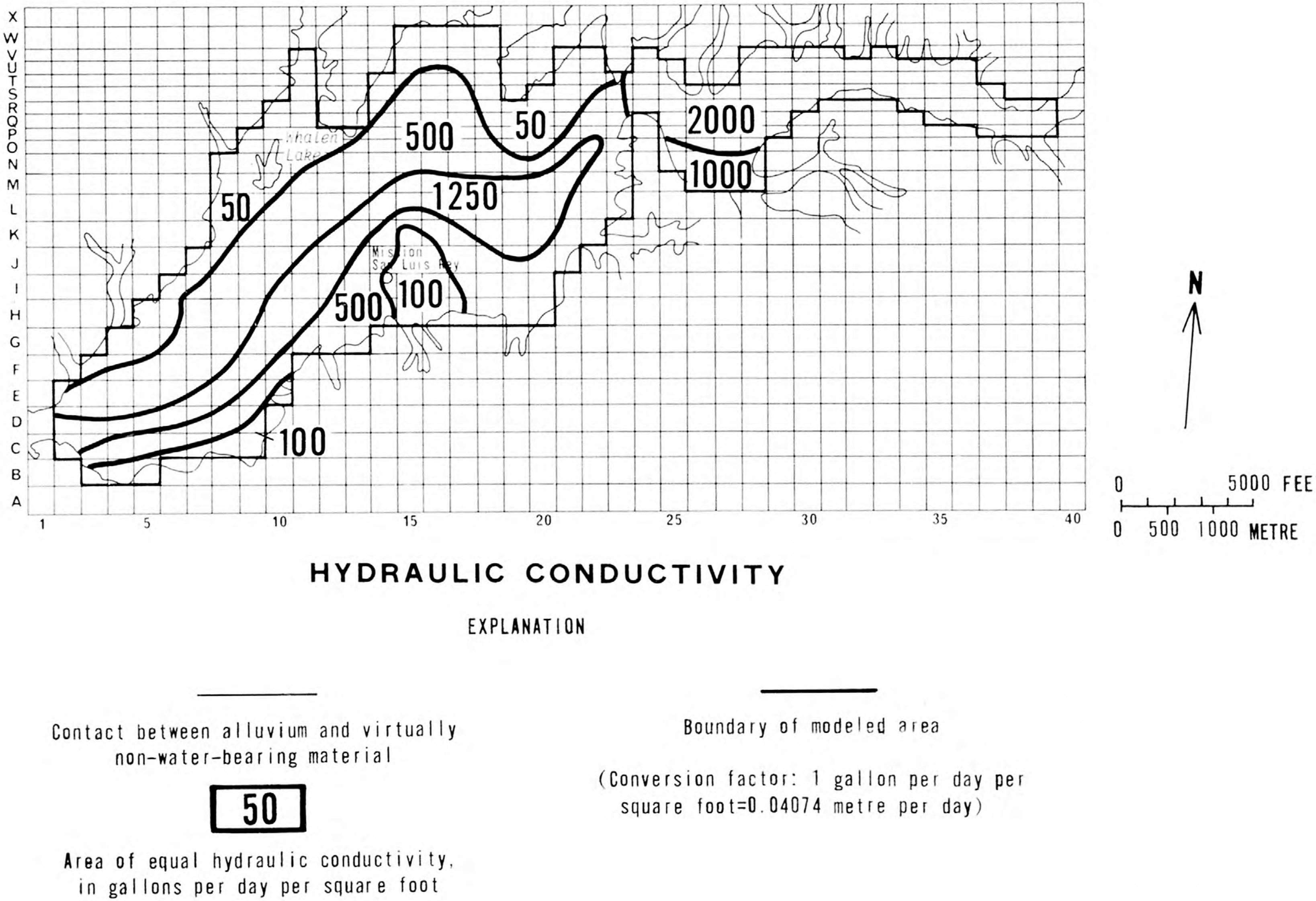
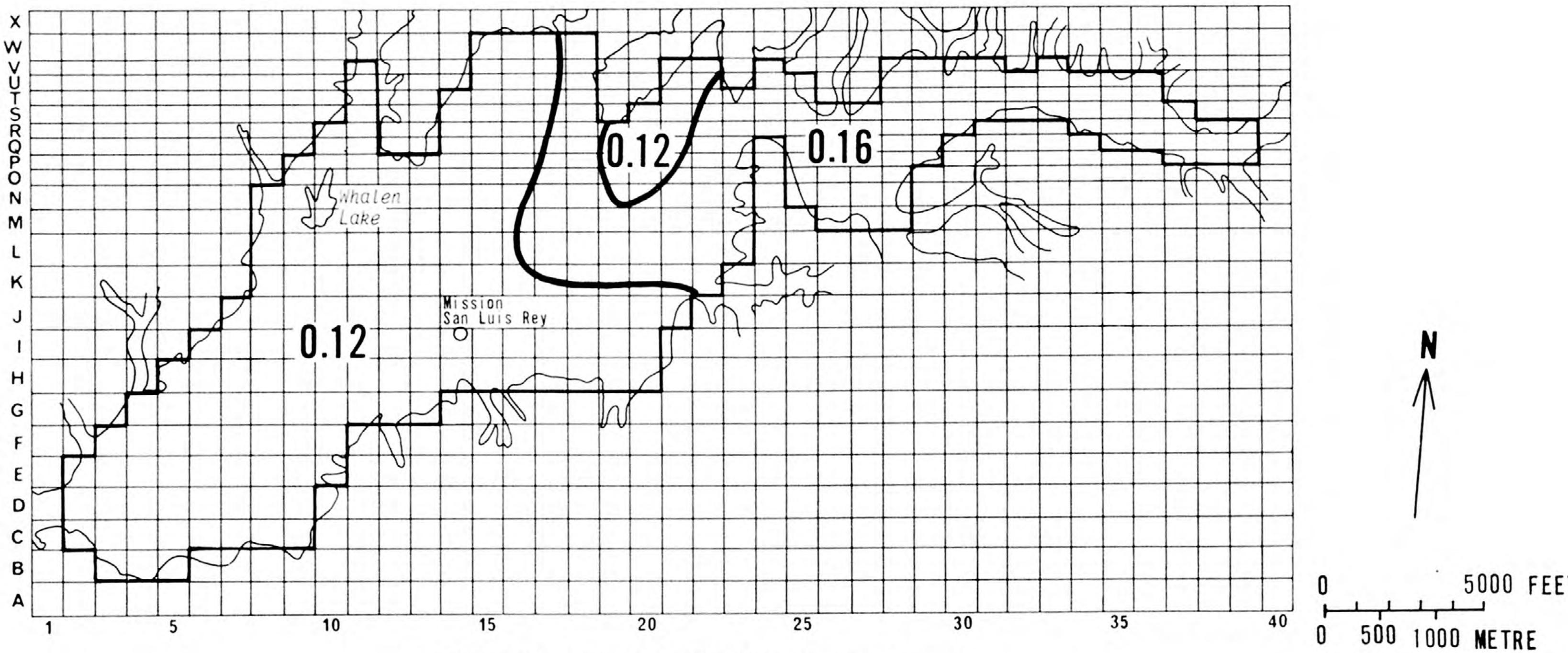


FIGURE 10.--Altitude of base of aquifer and modeled hydraulic conductivity, Mission basin.



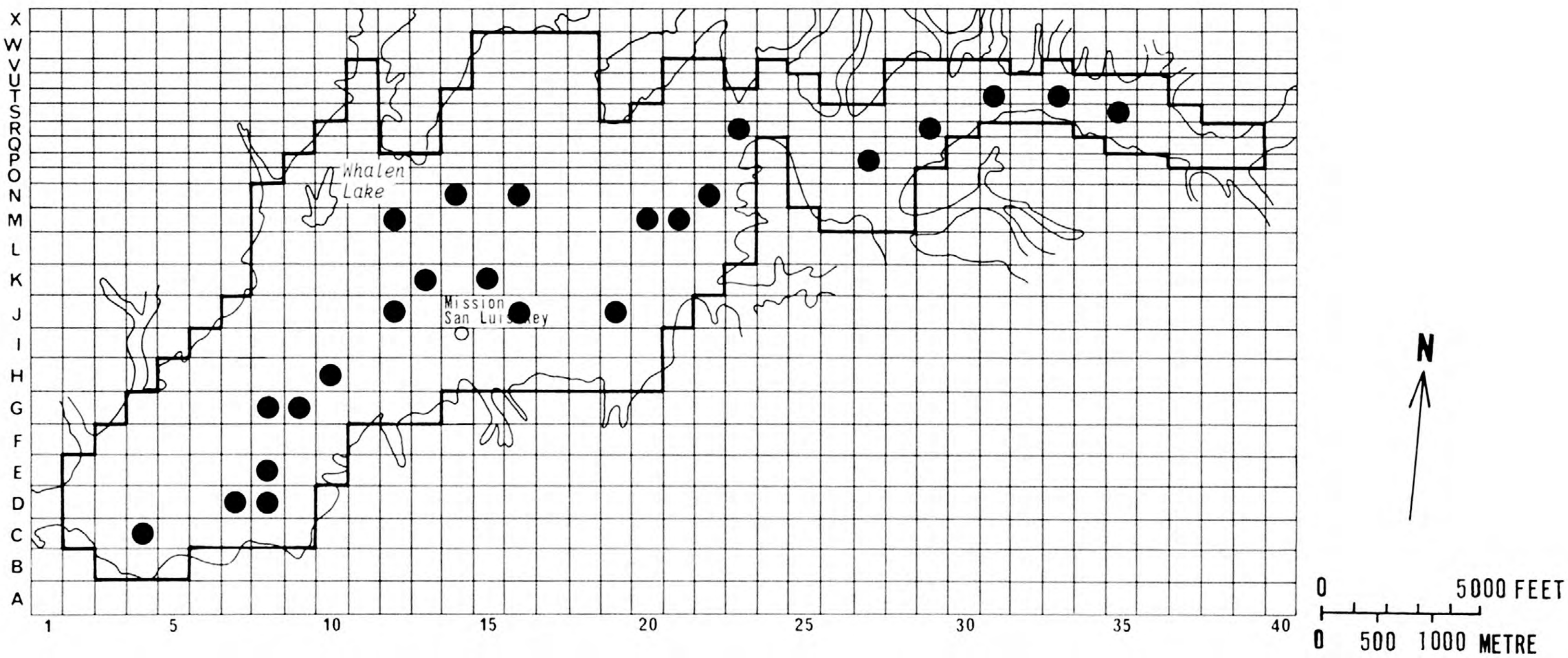
STORAGE COEFFICIENT

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

0.12 Area of equal storage coefficient



PUMPAGE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Modeled pumpage node

Boundary of modeled area

FIGURE 11.--Storage coefficient and location of modeled pumpage, Mission basin.

HYDROLOGIC BALANCE

Inflow

Infiltration of Precipitation

Infiltration of precipitation that falls directly on the permeable alluvium of the ground-water basins is generally a minor item of inflow. A large part of precipitation is used consumptively by vegetation or evaporates rapidly from the land surface. Runoff may occur during intense precipitation or in areas where surface permeability is low. Any water remaining after removal by these three processes becomes recharge to the ground-water basin.

Muckel and Blaney (1945) indicated that consumptive use by native vegetation on the valley floor of the San Luis Rey River ranges from 1.3 ft (0.4 m) per year for sparse growths of brush and trees in Mission basin to 4.6 ft (1.4 m) per year for dense growths of brush and trees in Pauma and Pala basins. The lowest consumptive use reported by Muckel and Blaney was 0.6 ft (0.2 m) per year for bare wasteland, such as in the stream channel. Mean annual precipitation on the ground-water basins as reported by California Department of Water Resources (1972b, pl. 30) ranges from 1.0 ft (0.3 m) per year in Mission basin to 1.7 ft (0.5 m) per year in Pauma basin.

During years of below-average precipitation very little rain percolates past the root zones of the native vegetation to the underlying ground-water body. In this investigation, the contribution to ground water from infiltration of precipitation in Pauma and Pala basins was assumed to be zero during dry years. In Bonsall and Mission basins, in areas where the water table in the past has been relatively shallow and much of the area consisted of bare wasteland, inflow from infiltration or direct precipitation was estimated to be 0.1 ft (0.03 m) per year.

During years of average or slightly above-average precipitation, inflow for each of the basins was estimated to be 0.15 ft (0.045 m) per year. During the wet years 1952, 1958, and 1969, an estimated 0.25 ft (0.075 m) per year infiltrated to the ground-water basins.

The modeled infiltration of precipitation is listed in tables 1, 2, 3, and 4.

TABLE 1.--*Hydrologic balance of the Pauma ground-water basin*

[In acre-feet per year, except Net for period and Cumulative net in acre-feet]

	Near-steady state	1959-61	1962	1963-65	1966-67	1968	January-June 1969	July 1969-72
				Inflow				
Infiltration of precipitation	880	0	880	0	880	0	2,920	880
Subsurface inflow	1,000	1,600	1,400	1,400	1,300	1,300	1,300	1,300
Infiltration in tributaries	320	290	300	290	1,000	500	7,400	1,100
Infiltration in San Luis Rey River	780	450	1,010	500	3,020	1,900	19,400	1,600
Irrigation return	0	1,270	1,140	1,140	1,140	1,140	1,140	1,390
Waste discharge	0	0	0	10	10	20	20	20
Net inflow	2,980	3,610	4,730	3,340	7,350	4,860	32,180	6,290
				Outflow				
Metered pumpage	0	0	0	0	2,840	3,230	940	3,480
Unmetered pumpage	0	6,300	5,700	6,740	3,260	3,510	2,620	4,670
Subsurface outflow	980	700	480	220	200	200	200	200
Phreatophytes	[1]2,000	100	200	100	200	200	200	200
Net outflow	2,980	7,100	6,380	7,060	6,500	7,140	3,960	8,550
				Net				
Annual net	0	-3,490	-1,650	-3,720	+850	-2,280	+28,220	-2,260
Net for period	0	-10,470	-1,650	-11,160	+1,700	-2,280	+14,110	-7,910
Cumulative net	0	[2]-11,670	-13,320	-24,480	-22,780	-25,060	-10,950	-18,860

[1]Includes 700 acre-feet per year of rising water.
[2]Includes 1,200 acre-feet cumulative net withdrawals prior to 1959.

TABLE 2.--*Hydrologic balance of the Pala ground-water basin*

[In acre-feet per year, except Net for period and Cumulative net in acre-feet]

	Near-steady state	1959-65	1966-68	January-June 1969	July 1969-72
		Inflow			
Infiltration of precipitation	640	0	640	2,130	0
Subsurface inflow	1,010	820	850	850	850
Infiltration in tributaries	670	330	1,050	2,000	670
Infiltration in San Luis Rey River	200	0	1,210	3,000	100
Irrigation return	0	540	670	670	670
Waste discharge	0	40	70	70	100
Net inflow	2,520	1,730	4,490	8,720	2,390
		Outflow			
Metered pumpage	0	0	0	0	0
Unmetered pumpage	0	2,190	2,480	2,480	2,480
Subsurface outflow	480	380	250	260	480
Phreatophytes	910	250	250	250	250
Rising water	1,130	0	0	0	0
Net outflow	2,520	2,820	2,980	2,990	3,210
		Net			
Annual net	0	-1,090	+1,510	+5,730	-820
Net for period	0	-7,630	+4,530	+2,860	-2,870
Cumulative net	0	-7,630	-3,100	-240	-3,110

TABLE 3.--*Hydrologic balance of the Bonsall ground-water basin*

[In acre-feet per year, except Net for period and Cumulative net in acre-feet]

	Near-steady state	1947-51	January-June 1952	July 1952-57	January-June 1958	July 1958-65	1966-68	January-June 1969	July 1969-72
				Inflow					
Infiltration of precipitation	780	520	2,580	520	2,580	520	1,300	2,580	780
Subsurface inflow	480	420	420	570	570	530	400	350	570
Infiltration in tributaries	1,200	450	10,200	900	6,300	900	3,760	5,000	2,280
Infiltration in San Luis Rey River	2,690	1,710	18,860	1,390	15,420	40	2,470	14,000	150
Irrigation return	280	370	370	430	880	1,150	1,560	1,560	1,560
Waste discharge	0	0	0	0	0	10	20	20	30
Net inflow	5,430	3,470	32,430	3,810	25,750	3,150	9,510	23,510	5,370
				Outflow					
Metered pumpage	1,180	2,780	3,760	2,090	720	910	620	480	280
Unmetered pumpage	1,130	1,670	2,220	2,530	2,310	2,840	4,090	3,990	2,730
Subsurface outflow	390	340	390	340	340	360	390	390	390
Phreatophytes	2,090	1,500	2,090	1,500	2,090	520	960	1,500	1,260
Rising water	640	0	0	0	0	0	640	640	640
Net outflow	5,430	6,290	8,460	6,460	5,460	4,630	6,700	7,000	5,300
				Net					
Annual net	0	-2,820	+23,970	-2,650	+20,290	-1,480	+2,810	+16,410	+70
Net for period	0	-14,100	+11,980	-14,580	+10,140	-11,100	+8,430	+8,200	+240
Cumulative net	0	-14,100	-2,120	-16,700	-6,560	-17,660	-9,230	-1,030	-790

TABLE 4.--*Hydrologic balance of the Mission ground-water basin*

[In acre-feet per year, except Net for Period and Cumulative net in acre-feet]

	Near-steady state	1947-51	January-June 1952	July 1952-57	January-June 1958	July 1958-65	1966-68	January-June 1969	July 1969-72
Inflow									
Infiltration of precipitation	820	550	1,370	820	1,370	550	820	1,370	820
Subsurface inflow[1]	390	1,770	2,020	2,520	2,970	2,240	720	390	390
Infiltration in tributaries	1,050	100	2,840	300	2,840	300	590	2,840	590
Infiltration in San Luis Rey River	3,650	590	9,180	0	4,800	0	2,890	9,330	1,910
Irrigation return	810	1,130	1,130	1,320	1,510	1,320	1,360	1,120	1,120
Waste discharge	0	0	0	0	0	2,380	3,750	1,800	880
Net inflow	6,720	4,140	16,540	4,960	13,490	6,790	10,130	16,850	5,710
Outflow									
Metered pumpage	3,000	5,480	4,520	4,350	990	1,700	120	40	10
Unmetered pumpage	2,700	3,380	3,380	4,210	2,520	4,400	4,520	2,490	3,050
Subsurface outflow	720	0	0	0	0	0	720	720	720
Phreatophytes	300	70	70	0	0	0	0	140	140
Rising water	0	0	0	0	0	0	0	200	600
Net outflow	6,720	8,930	7,970	8,560	3,510	6,100	5,360	3,590	4,520
Net									
Annual net	0	-4,790	+8,570	-3,600	+9,980	+690	+4,770	+13,260	+1,190
Net for period	0	-23,950	+4,280	-19,800	+4,990	+5,180	+14,310	+6,630	+4,160
Cumulative net	0	-23,950	-19,670	-39,470	-34,480	-29,300	-14,990	-8,360	-4,200

[1]Includes seawater intrusion and inflow from underlying La Jolla Group.

Subsurface Inflow

Subsurface inflow to the basins occurs in three ways: (1) Subsurface flow between basins through the valley fill that underlies the San Luis Rey River, (2) underflow in the alluvium-filled canyons that are tributary to the basins, and (3) underflow from consolidated and semiconsolidated rocks that form the basin boundaries. Item 1, above, in Mission basin, also includes seawater intrusion, which has occurred at times since 1947 when ground-water gradients sloped landward owing to intensive pumping in the basin (California Department of Water Resources, 1960).

Item 3, above, is assumed to be negligible in Pauma, Pala, and Bonsall basins because the rocks that form the basin boundaries are of low permeability. In Mission basin, however, the La Jolla Group, which is composed of semiconsolidated sand, sandstone, and shale, forms most of the basin boundaries. Although this unit is less permeable than the alluvial valley fill, it contains an appreciable quantity of ground water and is more permeable than the igneous and metamorphic bedrock that underlies the other basins. The quantity of inflow to Mission basin from the La Jolla Group cannot be determined by using existing data; however, a reasonable indication of underflow was probably obtained from the hydrologic model.

Subsurface flow between basins was calculated from Darcy's law,

$$Q = PIA$$

where Q = underflow
P = hydraulic conductivity
I = hydraulic gradient
A = cross-sectional area.

Subsurface inflow from minor tributary canyons generally is small and was included in the estimate of surface inflow from the tributary streams.

The combined values of subsurface inflow from all sources for selected time periods are listed in tables 1-4.

Seepage Losses from Surface Inflow

Surface inflow into the ground-water basins is derived from streamflow in the San Luis Rey River and from runoff in tributary streams. Since the construction of Henshaw Dam in 1922, flow in the San Luis Rey River that enters Pauma basin has been limited to releases from the Rincon powerplant, spill or overflow at the Escondido diversion (located in the canyon upstream from Pauma basin), and local runoff downstream from the dam.

Estimates of seepage losses--infiltration--in the San Luis Rey River (tables 1-4) are based on the above inflows to Pauma basin as reported by J. R. Crippen (written commun., 1972), and on records from three stream-gaging stations: San Luis Rey River at Monserate Narrows, near Pala; San Luis Rey River near Bonsall; and San Luis Rey River at Oceanside. Reasonably accurate estimates of seepage losses in the river in Bonsall and Mission basins were possible because of the location of the gaging stations near the boundary of the basins. However, current streamflow records are not available for flow that leaves Pauma basin and enters Pala basin. Estimates of seepage losses in these two basins are therefore less accurate. For modeling purposes, the total recharge was apportioned between the two basins, based primarily upon the size and duration of floodflows and upon the available aquifer storage space in each basin.

Inflow from seepage of tributary runoff is difficult to assess because of limited data on discharge. Pauma Creek (tributary to Pauma basin) has been gaged continuously since 1964, and miscellaneous measurements are available for several small streams tributary to Bonsall basin. To augment these limited data, the California Department of Water Resources (1972a) computed annual volumes of runoff for all major tributaries to the four ground-water basins. In applying these computations, estimates of runoff for dry years were reasonable for the purposes of this study. In those years the total quantity of runoff computed was assumed to infiltrate to the ground-water basins. However, the runoff estimates for flood years commonly yielded total quantities of inflow that were in excess of the combined measured outflow and increases in ground-water storage. If all the runoff for flood years was assumed to infiltrate, the required increase in ground-water storage would have been excessive. Therefore, independent estimates of seepage losses for years of high flow were made using the computed volumes of runoff for years of low flow and the few gaged discharges available for 1941, a wet year (Muckel and Blaney, 1945). No additional data on high flows are available. Because of the uncertainty of these estimates, tributary inflow has been adjusted (within rational limits) where necessary to obtain reasonable mass balances for the basins. Modeled values of infiltration of tributary inflow are listed in tables 1-4.

Irrigation Return

The California Department of Water Resources (1968) estimated that the average irrigation efficiency (consumptive use ÷ applied water x 100) for the San Luis Rey area is about 70 percent. Annual consumptive use of applied water for various crops listed in the same report indicates a range from 0.5 acre-ft per acre (0.15 m) for grain crops in Mission basin to 2.6 acre-ft per acre (0.8 m) for alfalfa in the inland basins. In the report applied-water rates were computed by dividing the consumptive-use requirements by the irrigation efficiency. The difference between the applied water and consumptive use is assumed to be irrigation return.

Nearly all water used in the area is for irrigation of agriculture. Therefore, to simplify computations, irrigation return (tables 1-4) was obtained by multiplying total pumpage, minus exports, by 30 percent.

Reclaimed Sewage

Sewage-treatment facilities within the study area rely primarily on percolation and evaporation from oxidation ponds for disposal of treated sewage. Effluent percolating to the water table is considered herein to be recharge to the ground-water basin. The effluent from most of the treatment plants is metered. Since 1959 the city of Oceanside has pumped the combined treated effluent from its three water-treatment facilities to Whalen Lake for recharge in Mission basin. This treated water has contributed significantly to the rise in water level in Mission basin during recent years (see fig. 15).

In Pauma basin, Pauma Valley Community Services District has discharged sewage effluent to percolation ponds since about 1963. In Bonsall basin, Rainbow Municipal Water District has operated two sewage-disposal plants since about 1958.

Four dairies in Pala basin also discharge wastes to the ground-water basins. Local dairymen estimate that water used for cooling milk, washing cows, and cleaning barns produces about 30 gal (0.1 m^3) of waste water per day per cow (oral commun., A. C. Bowen, 1973). The dairies currently milk an estimated 2,000 to 3,000 cows, which results in a total waste discharge of 60,000 to 90,000 gal/d (230 to 340 m^3/d) or 70 to 100 acre-ft (80,000 to 100,000 m^3) per year.

The quantities of effluent percolating to ground water, including dairy wastes, are listed in tables 1-4.

Outflow

Pumpage

Ground water is the source of most of the water pumped in the basins. In addition to local use, much of the pumped water in past years was used outside the boundaries of the ground-water basins, and some water was exported out of the watershed. Pumpage by the major exporters and by some local water districts is metered. However, pumpage for much irrigation and domestic use has not been metered.

The main use of water is for irrigated agriculture; pumpage for this purpose was computed from water duty for various crop uses. This method has the advantage of being rapid and economical, and requires only land-use maps and consumptive-use requirements of irrigated crops. An irrigation-efficiency factor is applied to consumptive use to arrive at the applied rate of water. The applied rate per crop is multiplied by the acres of that crop to give the total applied water, or pumpage.

Applied water rates used in the investigation were obtained from the California Department of Water Resources (1968) land- and water-use study. In some instances these applied rates were adjusted after consulting with local water users. For example, the applied rate for the irrigation of avocados was increased from 1.4 acre-ft per acre (0.4 m) to 2.4 acre-ft per acre (0.7 m) in Pauma basin because of reported local salt-leaching requirements not considered by the California Department of Water Resources study.

The method of computation of unmetered pumpage for Pauma basin is given in table 5. All lands irrigated with unmetered pumpage were planimetered to obtain the area of each land-use classification. This acreage was then multiplied by the appropriate rate of application. Land-use maps were available for 1958 and 1967 for all basins. In addition, aerial photographs taken in 1946 were helpful in estimating pumpage prior to 1958 for Bonsall and

TABLE 5.--*Unmetered pumpage, Pauma basin*

Land-use category	Area of category served by unmetered pumpage 1958 (acres)	Rate of applied water[1] (acre-feet per year)	Applied water 1958 (acre-feet)	Area of category served by unmetered pumpage 1967 (acres)	Rate of applied water[1] (acre-feet per year)	Applied water 1967 (acre-feet)
Citrus	1,585	1.4	2,220	1,497	1.4	2,100
Avocado	202	2.4	480	121	2.4	290
Deciduous fruit	54	2.4	130	20	2.4	50
Truck crop	527	1.1	580	100	1.7	170
Pasture	1,022	1.7	1,740	56	3.1	170
Grain	0			368	.8	290
Semi-agricultural and incidental	91	1.1	100	4	1.1	5
Urban and suburban	0			67	2.4	160
Commercial	0			4	7.4	30
Total[2]	3,480		5,250	2,240		3,260

[1]Rates may differ between 1958 and 1967 because of differences in crop types and irrigation practice.
[2]Rounded to three significant figures.

Mission basins. Computation of unmetered pumpage for the other basins was made in a similar fashion. To avoid duplication, only the total acres served by unmetered pumpage and the computed unmetered pumpage for 1958 and 1967 are given in table 6.

It was assumed that irrigated acreage increased in a straight-line fashion between the data years of 1958 and 1967. In Pauma basin, the computed pumpage for each modeled period was then increased or decreased to reflect differences in annual precipitation for the period in question. Model results indicated that this adjustment was not a significant factor in the long-term water budgets. Therefore, pumpage for the remaining basins was simply computed from the long-term average rate of applied water for each crop.

Table 6 lists the total irrigated acres supplied by unmetered pumpage and the corresponding computed pumpage in 1958 and 1967 for each ground-water basin. Unmetered pumpage for other periods was computed from straight-line projections of irrigated acres supplied by unmetered pumpage. Modeled pumpage (metered and unmetered) is listed in tables 1-4.

Figures 5, 7, 9, and 11 show the model nodes used in distributing the computed pumpage. Actual distribution of the pumpage was a subjective procedure of evaluating the wells and the model outputs.

TABLE 6.--*Unmetered pumpage, lower San Luis Rey River basins*

	Area served by unmetered pumpage 1958 (acres)	Unmetered pumpage 1958 (acre-feet)	Area served by unmetered pumpage 1967 (acres)	Unmetered pumpage 1967 (acre-feet)
Pauma basin	3,480	5,250	2,240	3,260
Pala basin	[1]710	[2]2,010	[3]960	[4]2,480
Bonsall basin	1,080	2,490	1,880	3,990
Mission basin	2,688	5,050	2,395	4,520

[1]Does not include 270 acres served by wells located in the canyon downstream from Pauma basin and upstream from Pala.

[2]Does not include 420 acre-feet supplied to the 270 acres mentioned in footnote 1.

[3]Does not include 520 acres served by wells located in the canyon downstream from Pauma basin and upstream from Pala.

[4]Does not include 720 acre-feet supplied to the 520 acres mentioned in footnote 3.

Consumptive Use by Phreatophytes

In several areas along the San Luis Rey River, brush and trees (phreatophytes) derive water directly from ground water. Most of the phreatophytes are in the narrow reaches of the river valley where the water table is near the surface. Consumptive use by phreatophytes was estimated to be 4.0 to 4.6 ft (1.2 to 1.4 m) per year for this area (Muckel and Blaney, 1945), but part of this total is derived from precipitation and surface flow in the river. The part derived from these two sources is dependent on the quantity of precipitation available and upon the duration of flow.

In this study net annual withdrawal from the ground-water body by phreatophytes (tables 3-6) was estimated to be 1.0 to 1.4 acre-ft per acre (0.3 to 0.4 m) in areas where the water table is 10 to 30 ft (3 to 9 m) below land surface and 2.0 acre-ft per acre (0.6 m) in areas where the water table is less than 10 ft (3 m) below land surface.

Subsurface Outflow

Subsurface outflow (tables 1-4) from the ground-water basins occurs only as underflow between basins. The outflow from an upstream basin thus becomes inflow for the downstream basin. This quantity was calculated earlier as subsurface inflow. Subsurface outflow from Mission basin occurs as underflow to the canyon downstream from the basin and was calculated in the same fashion as subsurface inflow.

Rising Water

When the water table is sufficiently high to intersect the land surface, ground-water discharge occurs as streamflow. When this condition exists, flow in the river continues for relatively long periods after floodflow has ceased. This situation has occurred at the downstream end of Pauma Valley, at Monserate Narrows, at Bonsall Narrows, and in recent years at the downstream end of Mission basin. During the early years of the modeled period rising water did not occur near the lower end of Mission basin because of heavy pumping near the old Oceanside Municipal Airport.

Estimates of rising water (tables 1-4) were obtained by analyzing streamflow records from the gages at the downstream end of the basins. Floodflows were subtracted from the total flow to obtain the base flow at the gage. From this quantity, estimates of surface contributions during low-flow conditions (tributary runoff, irrigation-return flow, urban runoff from storm drains, and sewage effluent) were subtracted to arrive at flow from rising ground water.

Model Verification

Model verification is essentially a trial-and-error procedure to attain acceptable agreement between water levels generated by the model and actual water-level data. During verification a comparison is made both areally with head distribution maps for specific time periods and time-wise with hydrographs at specific nodes. The verification process was done in two steps: (1) Near-steady-state conditions were modeled to verify the modeled hydraulic conductivity, saturated thickness, and quantities and distribution of near-steady-state recharge and discharge and to obtain initial head distributions representing equilibrium conditions in the aquifer; and (2) transient-state conditions were modeled to verify the response of the model to transient inflow-outflow and storage coefficients and to verify further the modeled hydraulic conductivity and saturated thickness.

Near-Steady State

An initial period was selected for each basin when the aquifers were full or nearly full and when the basins were assumed to be in equilibrium with inflow and outflow. Estimates were made of all inflow and outflow items and initial estimates were made for the hydraulic characteristics of the aquifer. Model-generated head distributions were then compared with actual water-level data. Adjustments were made in both inflow-outflow data and hydraulic characteristics (care being taken not to make illogical or unjustifiable changes) until an acceptable match was obtained. The model-generated water-level contours thus obtained were consistent with the conceptual models of the basins and with equilibrium hydrologic conditions. These head distributions were used as the starting points for the transient-state models.

The near-steady-state estimates of inflow and outflow were rough approximations at best and, in view of the uncertainty in the hydraulic conductivity and saturated thickness data, do not constitute a unique solution. However, the equilibrium state achieved in the near-steady-state simulation allowed a stable starting point for transient-state simulation.

Transient State

Transient-state verification was accomplished using the same trial-and-error procedure as in the steady-state verification, with one important difference--physical parameters were held constant, and only quantities and distribution of inflow and outflow were adjusted. In some instances satisfactory agreement could not be obtained by making acceptable and justifiable modifications in inflow and outflow. This indicated that adjustments in the physical parameters were required. Revisions in these parameters necessitated returning to the initial near-steady-state conditions and rerunning all previously completed modeled periods. Through these processes each successfully completed modeled period tended to strengthen the validity of the results of all previous periods.

The relative accuracies of the estimates for various items of inflow and outflow were considered in the verification process. The various items of the hydrologic budgets, listed in estimated order of decreasing accuracy of available data are:

1. Metered pumpage
2. Waste discharge
3. Infiltration of low flows in the San Luis Rey River in Bonsall and Mission basins
4. Infiltration of low flows in the San Luis Rey River in Pauma basin
5. Infiltration of floodflows in Bonsall and Mission basins
6. Subsurface flows between basins
7. Unmetered pumpage
8. Irrigation return
9. Infiltration of precipitation
10. Rising water
11. Use by phreatophytes
12. Infiltration of floodflows in the San Luis Rey River in Pauma and Pala basins
13. Infiltration of tributary inflow
14. Subsurface inflow to Mission basin from underlying marine sediments.

Adjustments were more commonly made in the least accurate items unless reasonable justification could be shown for changing the more accurate estimates.

The areal distribution of certain inflow and outflow items was also an important option in adjusting the models during verification. By varying the rates of recharge or discharge at specific nodes within limits of known information and without altering the total quantities involved, significant changes in the resulting head distributions could be achieved.

An example of this procedure is the distribution of recharge through infiltration of flow in the San Luis Rey River. If very high rates of infiltration were assumed, it was possible in many cases to model the total estimated quantity of infiltration of surface inflow in a short reach of the river at the upstream end of each basin. If lower rates of infiltration were assumed, the length of the recharge reach had to be increased proportionately to obtain the same total quantity of inflow. Thus, with lower infiltration rates, recharge could be decreased in the upstream reaches and increased in the lower parts of the basin without altering the total quantity.

Distribution of pumpage could likewise be adjusted to some degree. If several wells were in proximity to a large citrus orchard, for example, the distribution of pumpage from each well required to satisfy the water needs of the orchard was highly subjective. Obvious limitations such as maximum pumping rates, ownership of the wells, barriers to pipelines (major highways), and equipment installed in the wells were considered in distributing the pumpage.

Figures 12, 13, 14, and 15 show the final comparison of hydrographs of selected wells and the model-generated hydrographs of their corresponding nodes. The model-generated hydrographs were constructed by plotting the final head value generated at the node for each modeled period. No attempt was made to project hydrographs or extrapolate records where water-level data were lacking, as in well 10S/1W-8P1 (fig. 12). Because the model-verification procedure was a trial-and-error method of duplicating historic data, it was decided that projecting well hydrographs could result in matching preconceived concepts of the system's responses to stress. Rather, the models were relied upon to gain a more thorough understanding of the basins where data were lacking.

Figures 16, 17, 18, and 19 show model-generated head distribution, plotted as water-level contours, for near-steady-state and 1972 conditions. To compare the model-generated data to actual data, water-level measurements available from wells are plotted. Water-level contour maps were not constructed from actual data for the same reason that hydrographs were not extrapolated. A comparison of the actual water levels with the contours of the model-generated head values provides an indication of the degree of accuracy of the models.

The hydrographs and the model-generated contour maps illustrate that water-level response to various stresses was simulated reasonably well by the models. Thus, the hydrologic budgets developed in this investigation are consistent with the physical and hydrologic characteristics of the basins. Further, because similar techniques were employed in estimating quantities for each basin, the budgets should be consistent between basins.

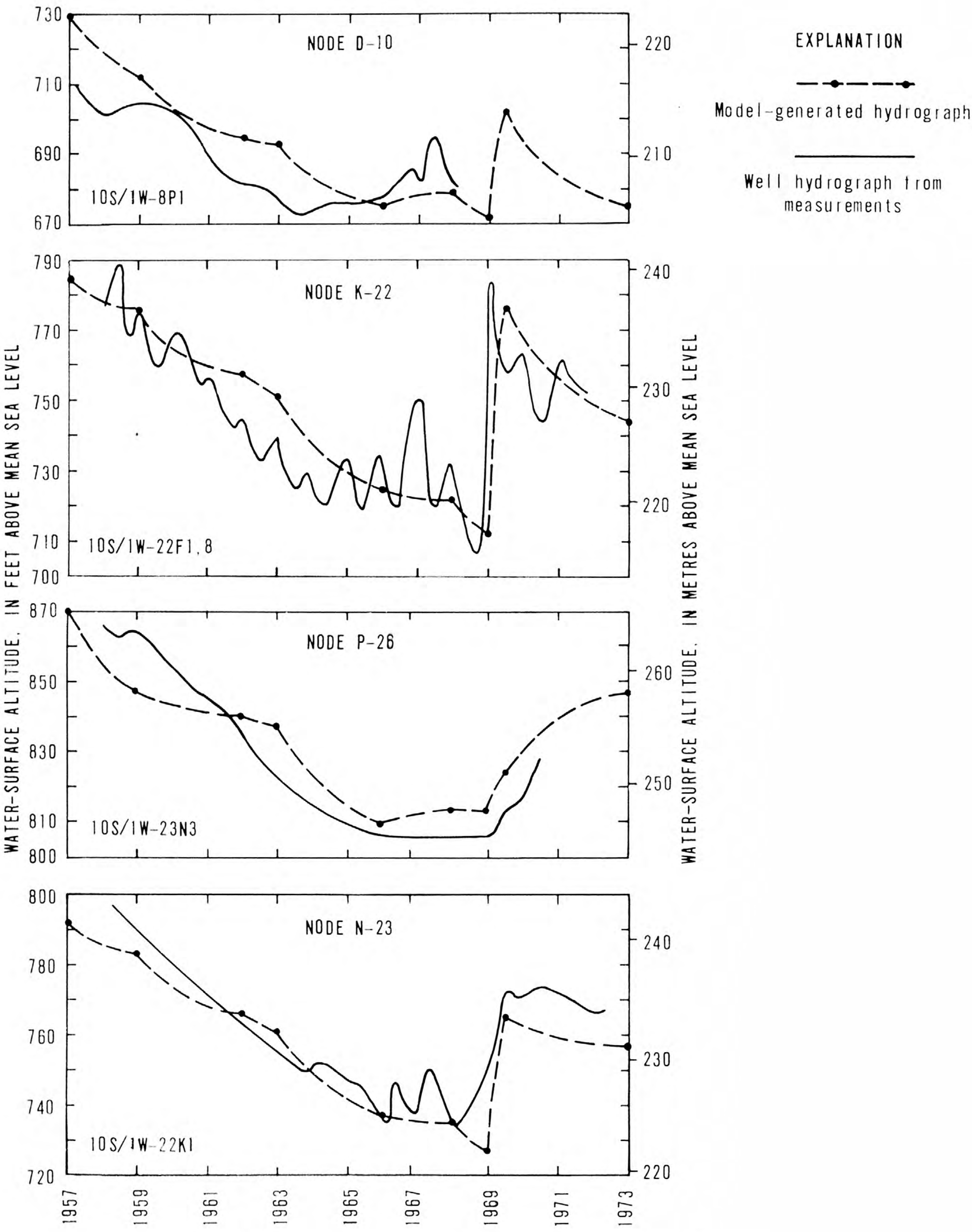


FIGURE 12.--Hydrographs of wells in Pauma basin.

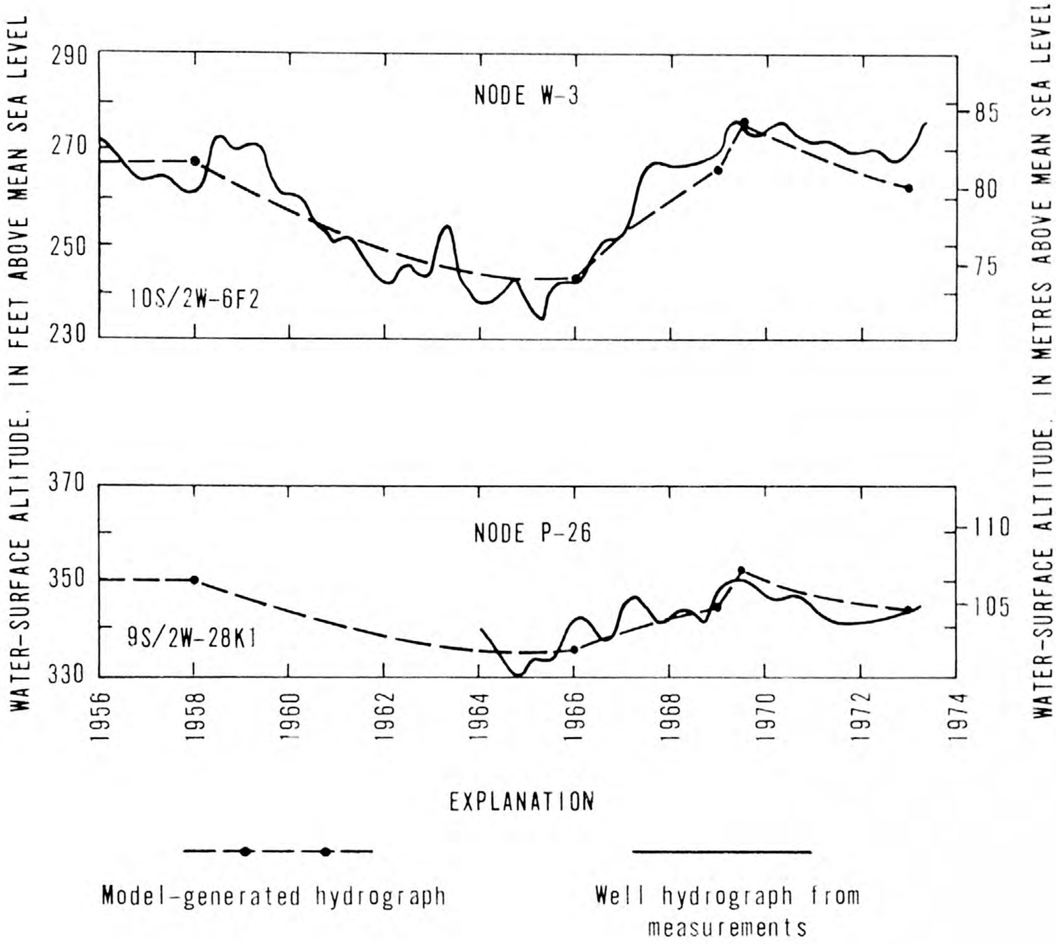


FIGURE 13.--Hydrographs of wells in Pala basin.

The estimated quantities of inflow and outflow for each basin would be more reliable than if they had been arrived at independently. Although more accurate methods may be used in the future to estimate specific quantities (for example, power records to compute pumpage), the successfully constructed models show that the estimated quantities are mutually consistent and are in accord with the hydrologic history of the area.

Tables 1, 2, 3, and 4 list the various items of the hydrologic budgets as verified by the models.

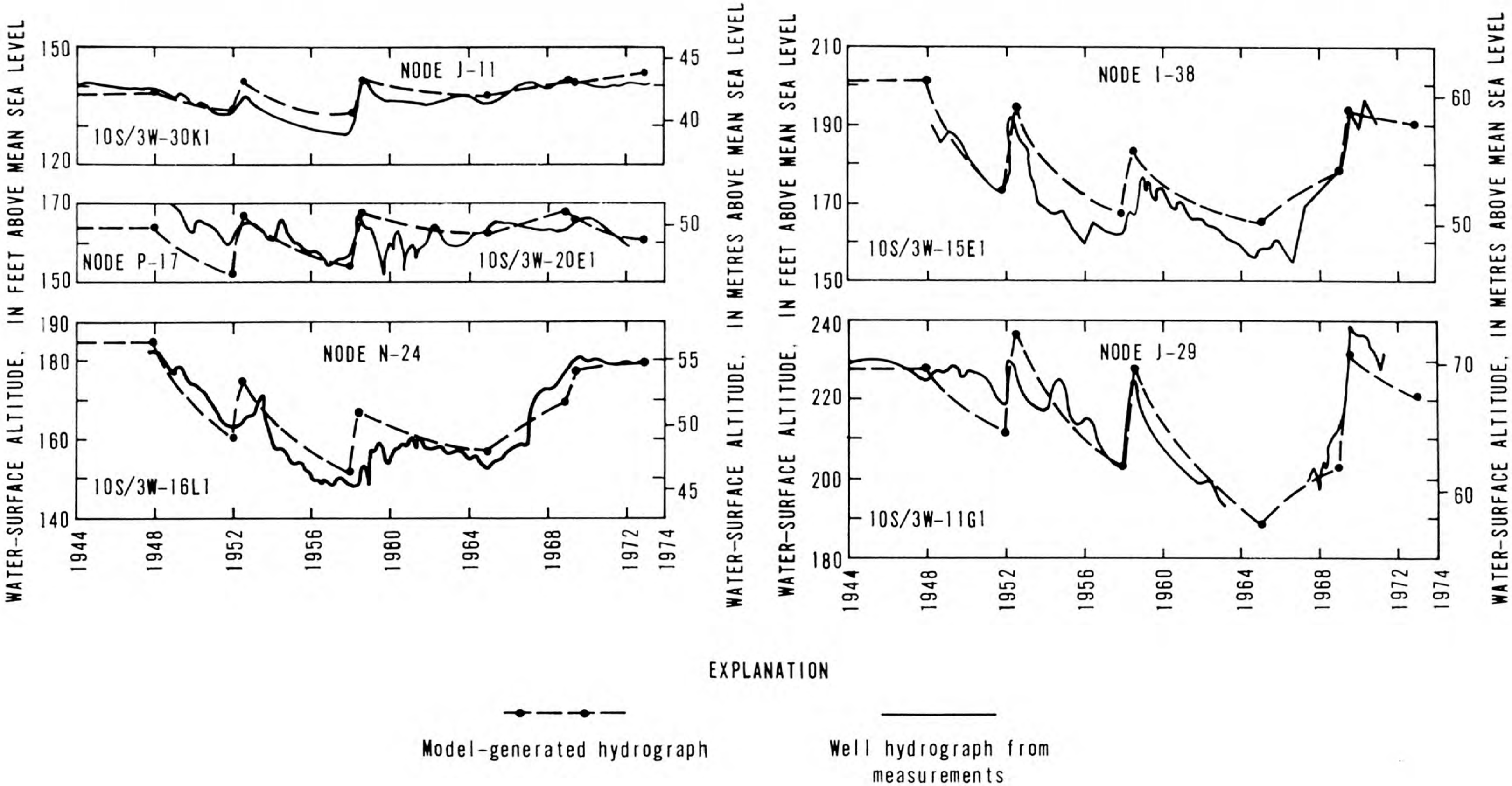


FIGURE 14.--Hydrographs of wells in Bonsall basin.

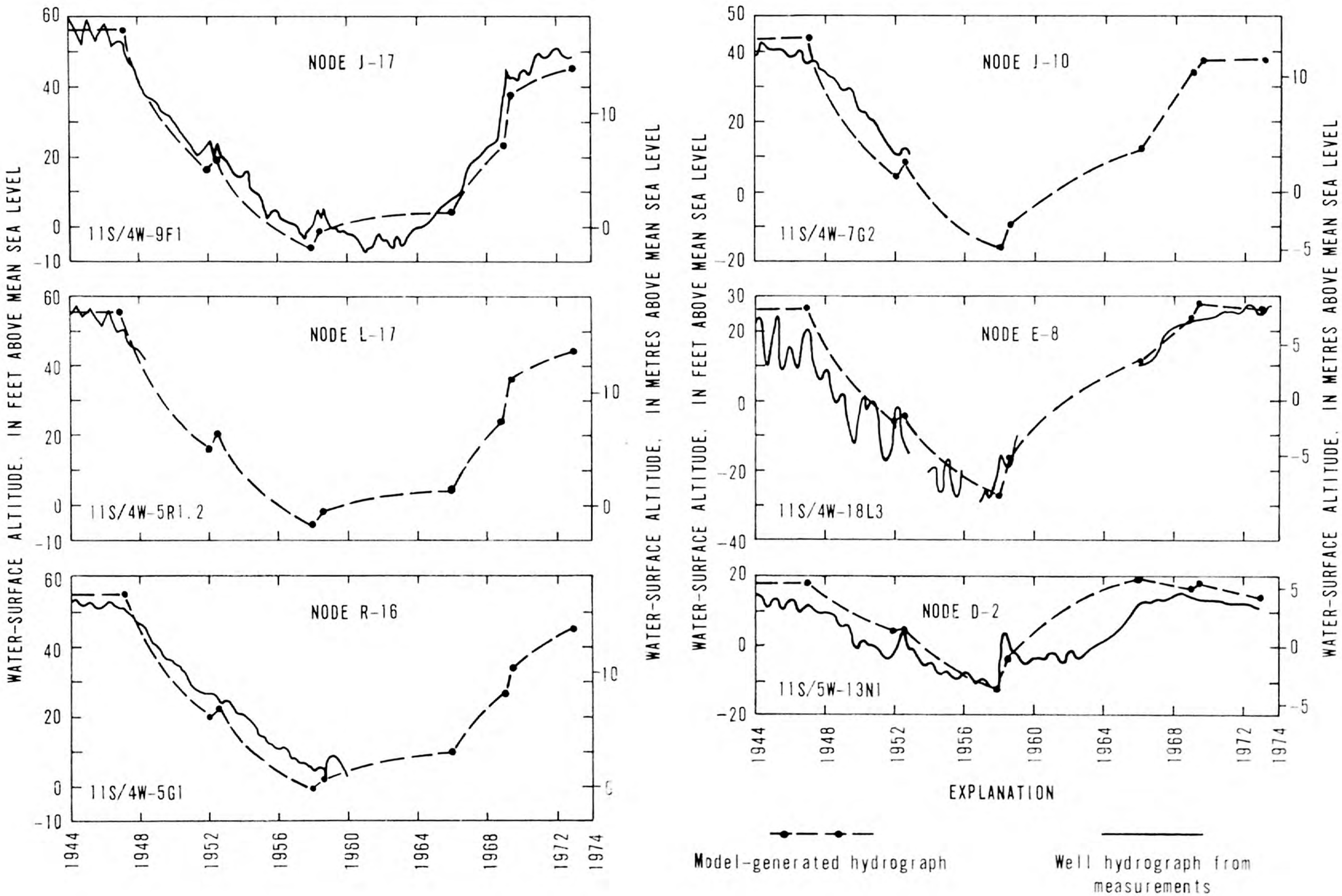
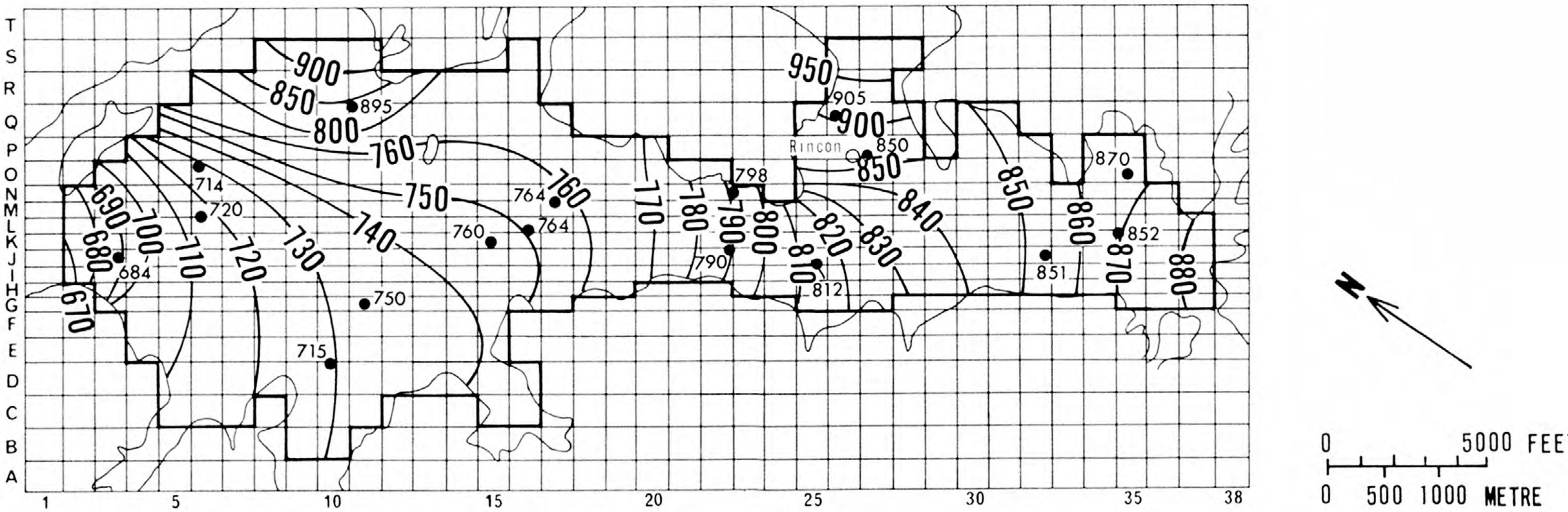


FIGURE 15.--Hydrographs of wells in Mission basin.



NEAR-STEADY STATE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

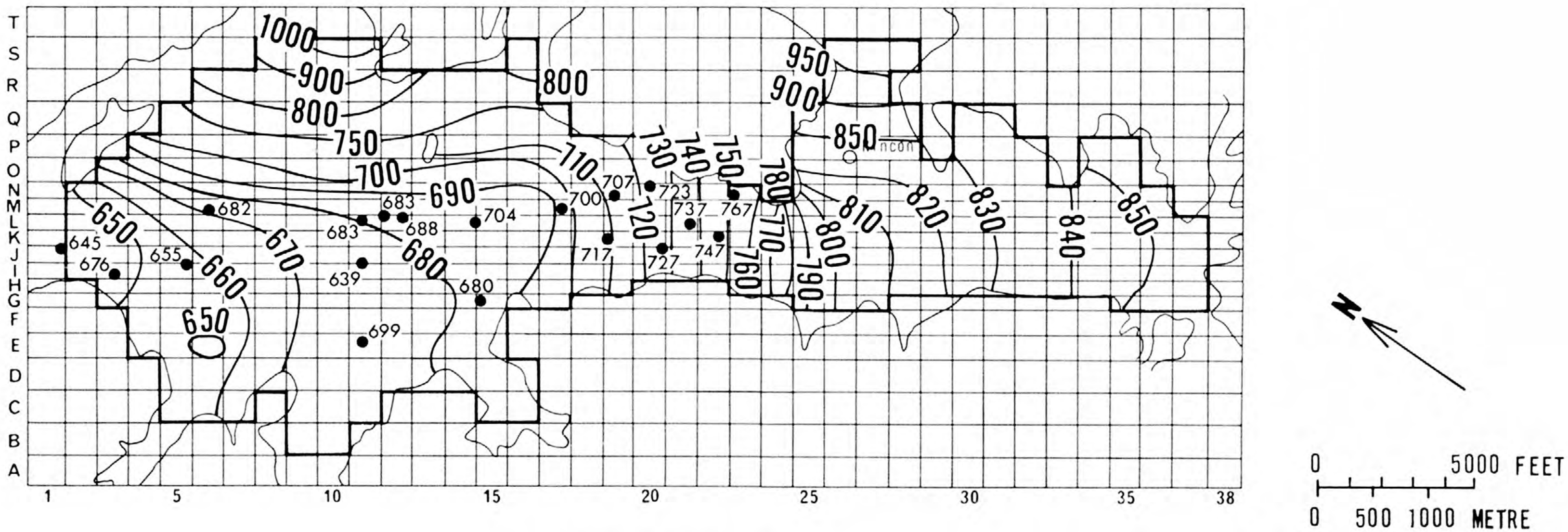
—840—

Model-generated water-level contour. Shows altitude of water level. Contour interval, in feet, is variable. Datum is mean sea level

● 895

Water-level measurement, in feet

(Conversion factor: 1 foot=0.3048 metre)



AUTUMN 1972

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

—660—

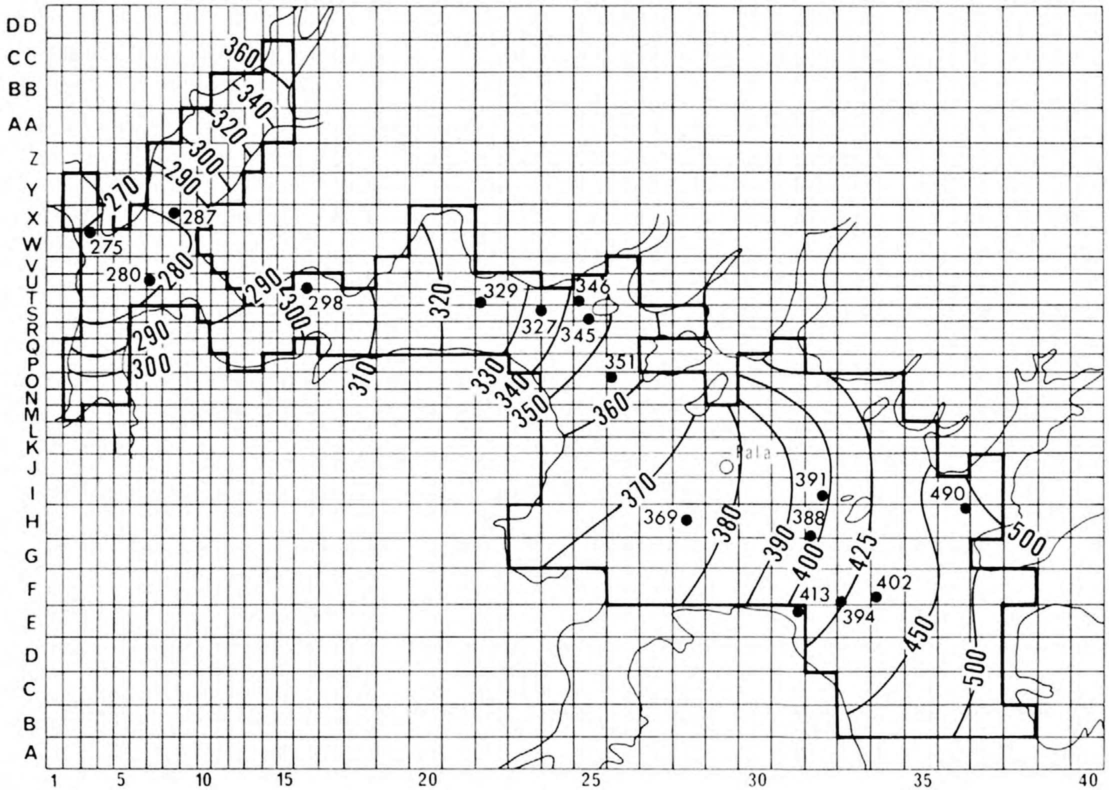
Model-generated water-level contour. Shows altitude of water level. Contour interval, in feet, is variable. Datum is mean sea level

●645

Water-level measurement, in feet

(Conversion factor: 1 foot=0.3048 metre)

FIGURE 16.--Model-generated water-level contours, Pauma basin.



NEAR-STEADY STATE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

—— 290 ——

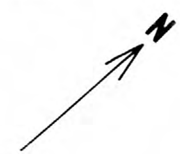
Model-generated water-level contour. Shows altitude of water level. Contour interval, in feet, is variable. Datum is mean sea level

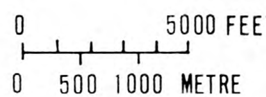
Boundary of modeled area

● 346

Water-level measurement, in feet

(Conversion factor: 1 foot=0.3048 metre)





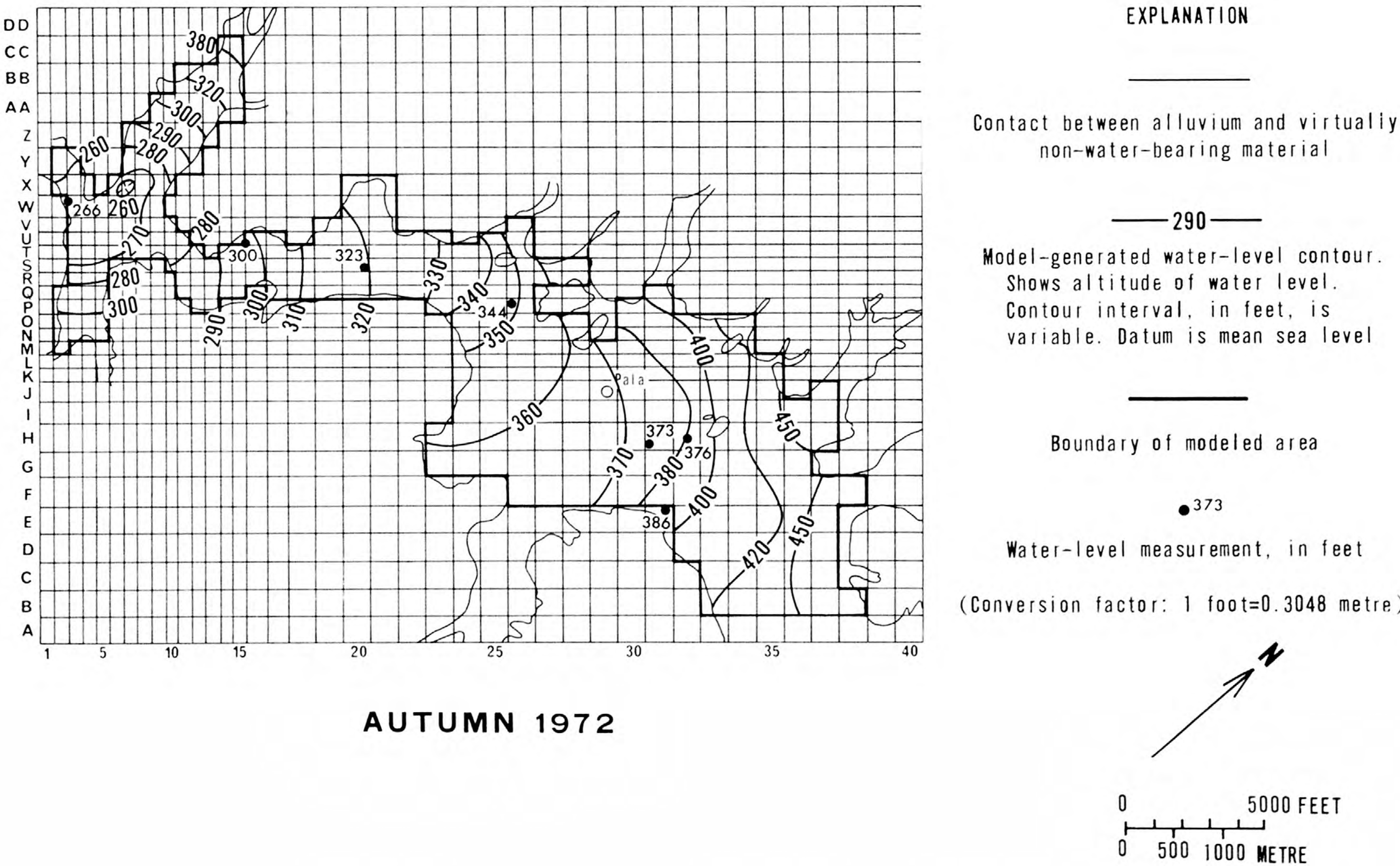
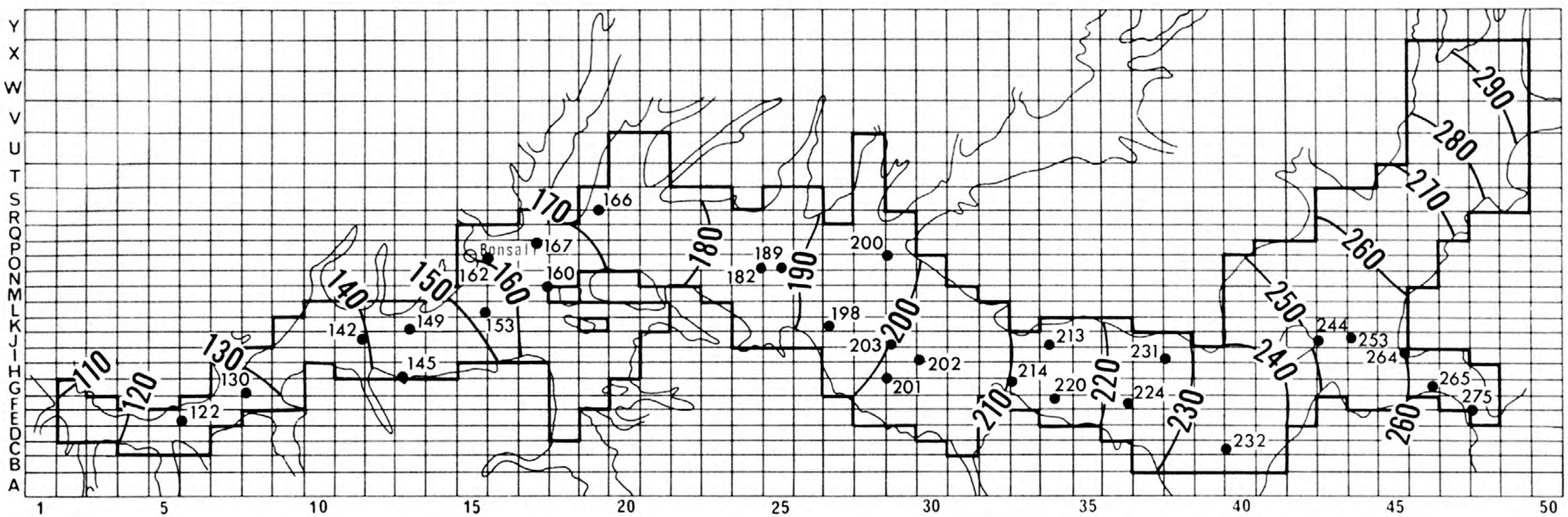


FIGURE 17.--Model-generated water-level contours, Pala basin.



NEAR-STEADY STATE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

—140—

Model-generated water-level contour. Shows altitude of water level. Contour interval 10 feet. Datum is mean sea level

●166

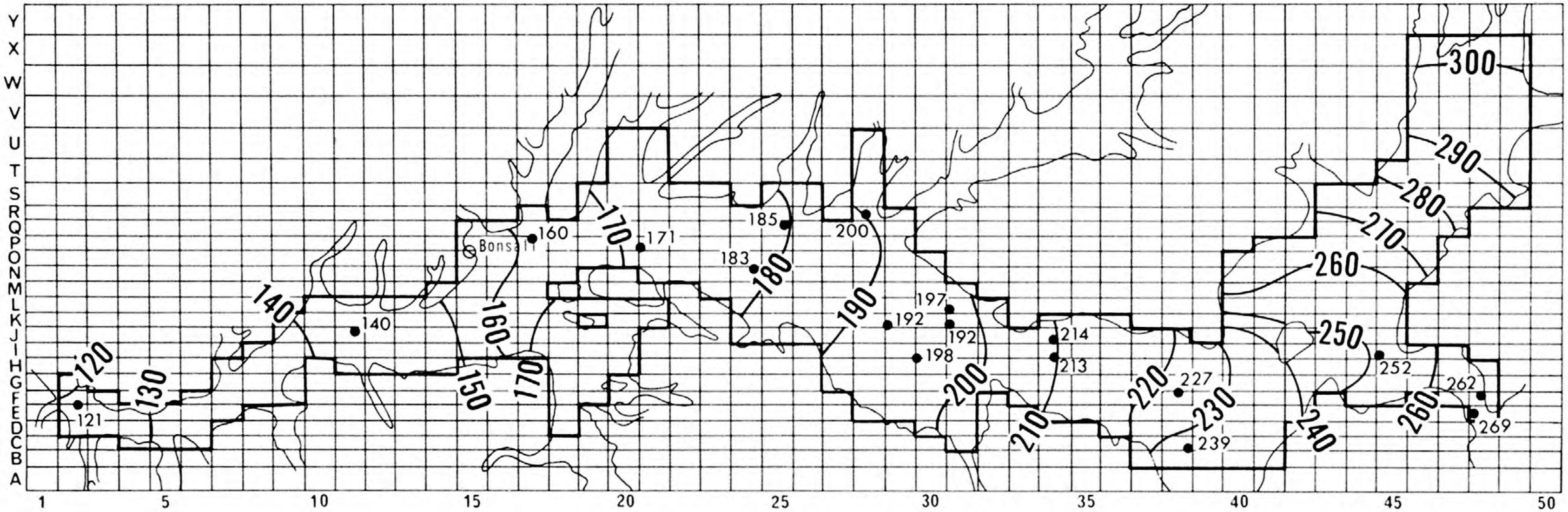
Water-level measurement, in feet

(Conversion factor: 1 foot = 0.3048 metre)

N

0 5000 FEET

0 500 1000 METRE



AUTUMN 1972

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

—190—

Model-generated water-level contour. Shows altitude of water level. Contour interval 10 feet. Datum is mean sea level

● 185

Water-level measurement, in feet

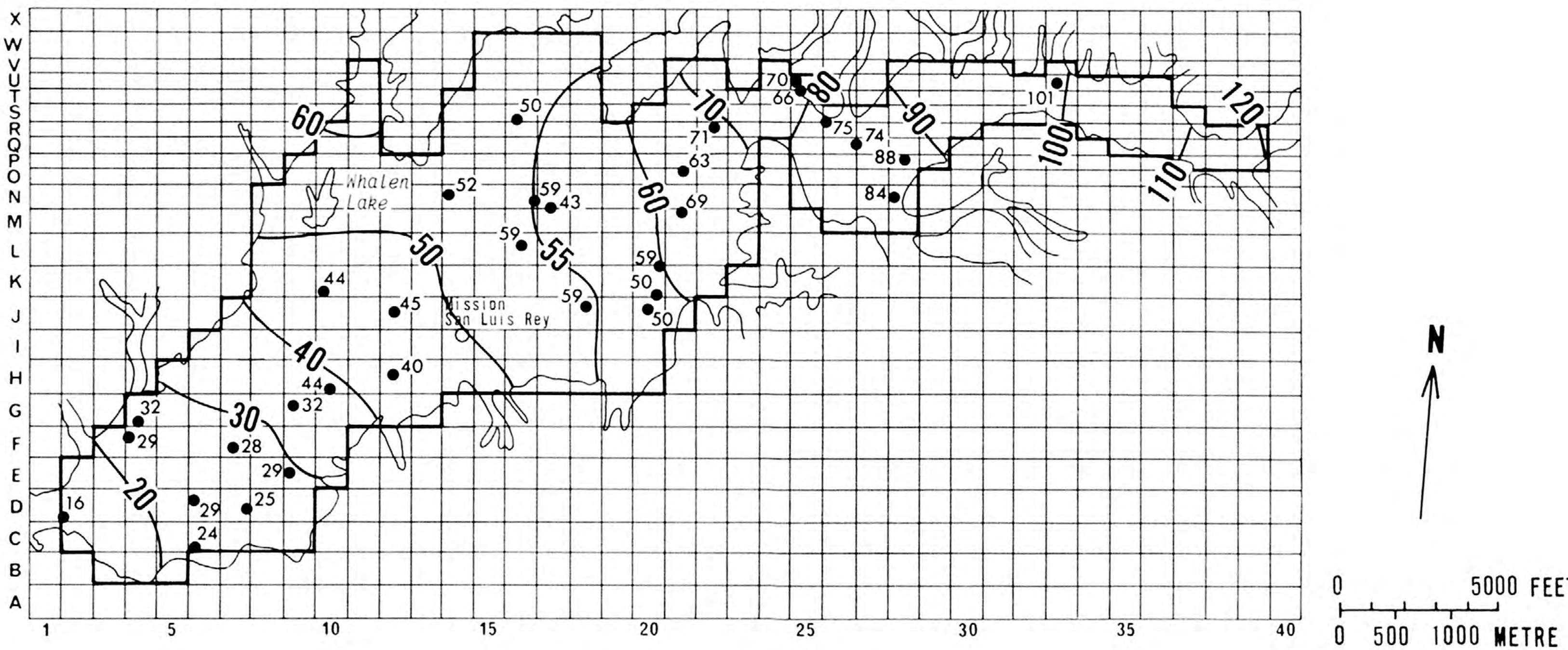
(Conversion factor: 1 foot = 0.3048 metre)

N

0 5000 FEET

0 500 1000 METRE

FIGURE 18.--Model-generated water-level contours, Bonsall basin.



NEAR-STEADY STATE

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

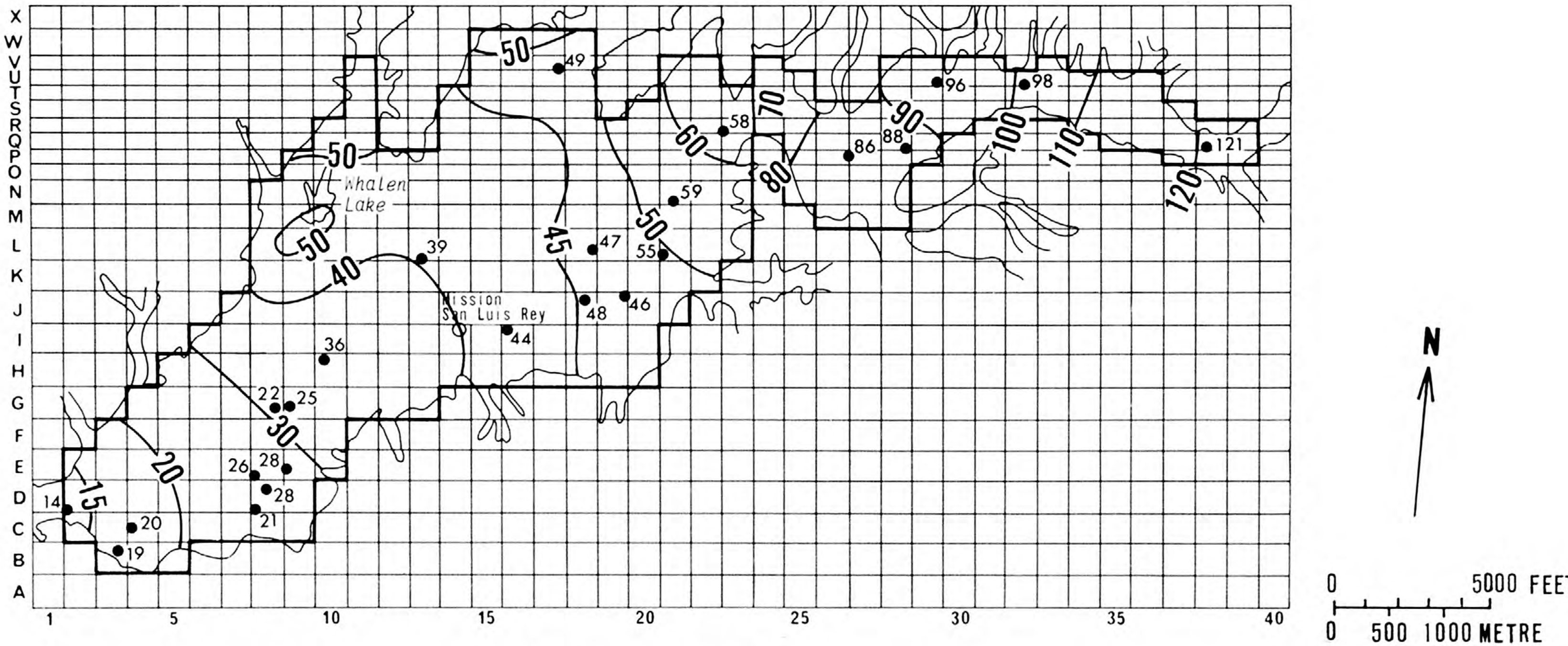
—60—

Model-generated water-level contour. Shows altitude of water level. Contour intervals 5 and 10 feet. Datum is mean sea level

●43

Water-level measurement, in feet

(Conversion factor: 1 foot=0.3048 metre)



AUTUMN 1972

EXPLANATION

Contact between alluvium and virtually non-water-bearing material

Boundary of modeled area

—— 90 ——

Model-generated water-level contour. Shows altitude of water level. Contour intervals 5 and 10 feet. Datum is mean sea level

● 86

Water-level measurement, in feet

(Conversion factor: 1 foot=0.3048 metre)

FIGURE 19.--Model-generated water-level contours, Mission basin.

SALT BALANCE

The term "salt balance" as applied to a ground-water basin is defined as the mass balance of total salts brought into the ground-water basin, total salts removed from the ground-water basin, and the gain or loss of salts in storage. No attempt was made in this study to determine the details of either the distribution of salts within the basin or the concentration of salts in the ground water. For purposes of computation, it was assumed that all salts carried into the system, by whatever means, eventually enter the ground-water body. No attempt was made to determine salt buildup in the unsaturated zone or chemical interaction within the system.

Salt Inflow

Most of the salt enters the system (1) as dissolved salts carried in inflowing water, (2) as part of wastes discharged into the system, and (3) as fertilizers. Recirculation and the accompanying concentration of salts by evapotranspiration of irrigation water and by domestic use of pumped ground water do not affect the total salt balance. However, if applied irrigation and domestic water originates outside the system, its salt load becomes an addition; likewise if water is extracted and exported for use outside the system, its salt load is an item of outflow.

Table 7 summarizes salt-balance calculations in the four basins for near-steady-state conditions and for 1972 conditions.

Precipitation

Rainwater is not completely free of dissolved solids. Smog and dust in the air, salt spray from the ocean, and individual gaseous constituents in the atmosphere all contribute soluble material to precipitation. No analyses of precipitation are available for the study area, but analyses from other areas suggest that the concentration of dissolved solids ranges from about 10 mg/l (milligrams per litre) in inland areas to 15 mg/l near the ocean (Hem, 1970). Unlike the hydrologic budget wherein only a small part of total precipitation enters the ground-water system, most of the salt in precipitation is assumed to enter the ground-water body. Evapotranspiration removes only the water, leaving the salt load behind to be later leached to the ground-water body. The only part of the dissolved material in precipitation that does not enter into the salt balance is the relatively small quantity carried away as surface runoff following rare, intense storms. No appreciable surface runoff occurred during the two periods (near-steady state and 1972) chosen for the computation of salt balance in this investigation.

TABLE 7.--*Salt balance, Lower San Luis Rey River basins*

	Pauma basin		Pala basin		Bonsall basin		Mission basin	
	Near-steady state (tons)	1972 (tons)	Near-steady state (tons)	1972 (tons)	Near-steady state (tons)	1972 (tons)	Near-steady state (tons)	1972 (tons)
Inflow								
Precipitation	130	90	90	60	90	70	110	90
Subsurface inflow	410	880	560	640	290	930	530	1,170
Tributary inflow	110	370	230	230	740	3,350	570	320
San Luis Rey River inflow	300	820	100	70	1,430	160	2,480	4,420
Imported water	0	200	0	0	0	1,240	0	0
Waste discharge	0	50	0	270	0	50	0	1,240
Fertilizer application	0	700	0	240	190	360	210	430
Total salts in	950	3,110	980	1,510	2,740	6,160	3,900	7,670
Outflow								
Subsurface outflow	550	300	290	780	530	1,170	880	1,860
Rising water	390	0	690	0	870	1,910	0	1,550
Exported water	0	590	0	0	1,280	460	2,940	20
Total salts out	940	890	980	780	2,680	3,540	3,820	3,430
Net								
Total salts left in basin	+10	+2,220	0	+730	+60	+2,620	+80	+4,240

Subsurface Inflow

The chemical quality of subsurface inflows is generally known from analyses of water samples from wells in the areas where underflow occurs. Dissolved-solids concentration in subsurface flow between basins historically has ranged from about 300 mg/l for inflow to Pauma basin to more than 20,000 mg/l for seawater intrusion into Mission basin.

Tributary Inflow

The quality of tributary inflow is related to the source of the runoff. In Pauma basin, much of the tributary flow originates in undeveloped areas and is of excellent quality. In Bonsall basin, however, much of the flow is derived from irrigation return and surface runoff from orchards or urbanized areas, and its quality is much poorer. The few chemical analyses of tributary flow available in the study area suggest that the concentration of dissolved solids ranges from about 250 mg/l for floodflows from undeveloped areas to about 1,700 mg/l for low flows from developed areas.

San Luis Rey River Inflow

Water quality in the San Luis Rey River is related to the rate and duration of flow and to the source of the water making up the flow. The quality of surface flow varies along the river, so the interpretation of data must take into consideration the location of the sampling point. In general, high flows entering Pauma basin are of excellent quality. Dissolved-solids concentrations generally range from about 250 to 350 mg/l. As surface flows pass through Pauma basin and enter Pala basin the dissolved-solids concentration increases to as much as 300 to 500 mg/l. Surface flow leaving Pala basin and entering Bonsall basin ranges from 350 to 800 mg/l dissolved solids. Low flows in Bonsall basin are derived largely from irrigation return and tributary flow from the Fallbrook area. These low flows often contain in excess of 2,000 mg/l dissolved solids. Floodflows in the area, however, may contain less than 400 mg/l dissolved solids. In Mission basin, most of the flow leaving the basin is derived from discharges from Whalen Lake and contains about 2,000 mg/l dissolved solids.

Imported Water

Water is imported to the study area by Yuima Municipal Water District and by Rainbow Municipal Water District. Most of the imported water delivered within the ground-water basins is used for irrigation. The concentration of dissolved solids in imported water, which is obtained from the Colorado River Aqueduct, averages about 750 mg/l.

Waste Discharge

The city of Oceanside pumps all its reclaimed sewage water to Mission basin for recharge to the ground-water basin. Although the quality varies widely, it generally averages about 1,300 mg/l dissolved solids. In Pauma basin, Pauma Valley Community Services District discharges about 20 acre-ft (25,000 m^3) of sewage effluent per year, which contains an average concentration of about 2,000 mg/l dissolved solids. Rainbow Municipal Water District operates two sewage disposal plants in Bonsall basin, which discharge a total of 30 acre-ft (37,000 m^3) per year. The effluent contains about 1,200 mg/l dissolved solids.

Fertilizer Application

The rates of fertilizer application used in this study were derived from studies by Water Resources Engineers, Inc. (1969) in the Santa Ana River basin. In that study average application rates were: 230 lb/acre (260 kg/ha) for residential lawns and pasture, 400 lb/acre (450 kg/ha) for truck crops, and 700 lb/acre (780 kg/ha) for subtropical and deciduous fruits. Total applied fertilizer was computed by multiplying total acreage in each classification by the appropriate application rate. The assumption was made that all applied fertilizer is a part of total salt input to the area.

Salt Outflow

For this investigation, the salt outflow from each ground-water basin was limited to the dissolved solids in subsurface outflow, exported water, and rising water that leaves as base flow in streams. Salt removed by crops was not considered.

Subsurface Outflow

Subsurface outflow from the ground-water basins is restricted to underflow between basins and subsurface outflow to the ocean. The outflow from an upstream basin thus becomes inflow for the downstream basin. This quantity was calculated previously in this report as subsurface inflow.

Rising Water

The quality of rising water was determined from samples of low flow in the San Luis Rey River and from ground-water samples collected from wells near the downstream ends of the basins. Rising water currently (1973) occurs only in Bonsall and Mission basins. In Bonsall basin, the dissolved-solids concentration of rising water averages about 2,200 mg/l. In Mission basin the rising water contains about 1,900 mg/l dissolved solids.

Exported Water

In the past a considerable part of the water pumped in Bonsall and Mission basins was exported for use outside the ground-water basins. In recent years the quantity of this exported water has declined, reportedly because of the poor quality of water in the basins. The present concentration of dissolved solids in water pumped for export is about 1,200 mg/l in Bonsall basin and about 1,300 mg/l in Mission basin.

In Pauma basin, Yuima Municipal Water District pumps about 1,200 acre-ft per year (1,500,000 m^3) for irrigation of citrus and avocado groves that are located on the older fan deposits northeast of Rincon. Although this is not, as such, an export from the ground-water basin and some of the contained salt may eventually return to the ground-water body, it is considered as an export from the modeled part of the basin. The average dissolved-solids concentration in this water is 360 mg/l.

Calculation

The method of calculation of annual salt balance for the Pauma basin is given in table 8. The other three basins were similarly computed. The quantity of flow in acre-feet multiplied by the salt content in milligrams per litre and by a conversion factor of 0.00136 yields the total salt load in tons per year.

TABLE 8.--*Salt balance, Pauma basin*

	Near-steady state			1972		
	Quantity of flow (acre-feet per year)	Quality of flow (dissolved solids in milligrams per litre)	Salt-load (tons)	Quantity of flow (acre-feet per year)	Quality of flow (dissolved solids in milligrams per litre)	Salt-load (tons)
Inflow						
Precipitation	9,800	10	130	6,850	10	90
Subsurface inflow	1,000	300	410	1,300	500	880
Tributary inflow	320	250	110	1,000	250	340
San Luis Rey River inflow	780	280	300	2,020	300	820
Imported water	0	--	0	200	750	200
Waste discharge	0	--	0	20	2,000	50
Fertilizer application	0	--	0	--	--	700
Total salts in			950			3,080
Outflow						
Subsurface outflow	980	410	550	200	1,100	300
Rising water	700	410	390	0	--	0
Exported water	0	--	0	1,200	360	590
Total salts out			940			890
Net						
Total salts left in basin			+10			+2,190

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