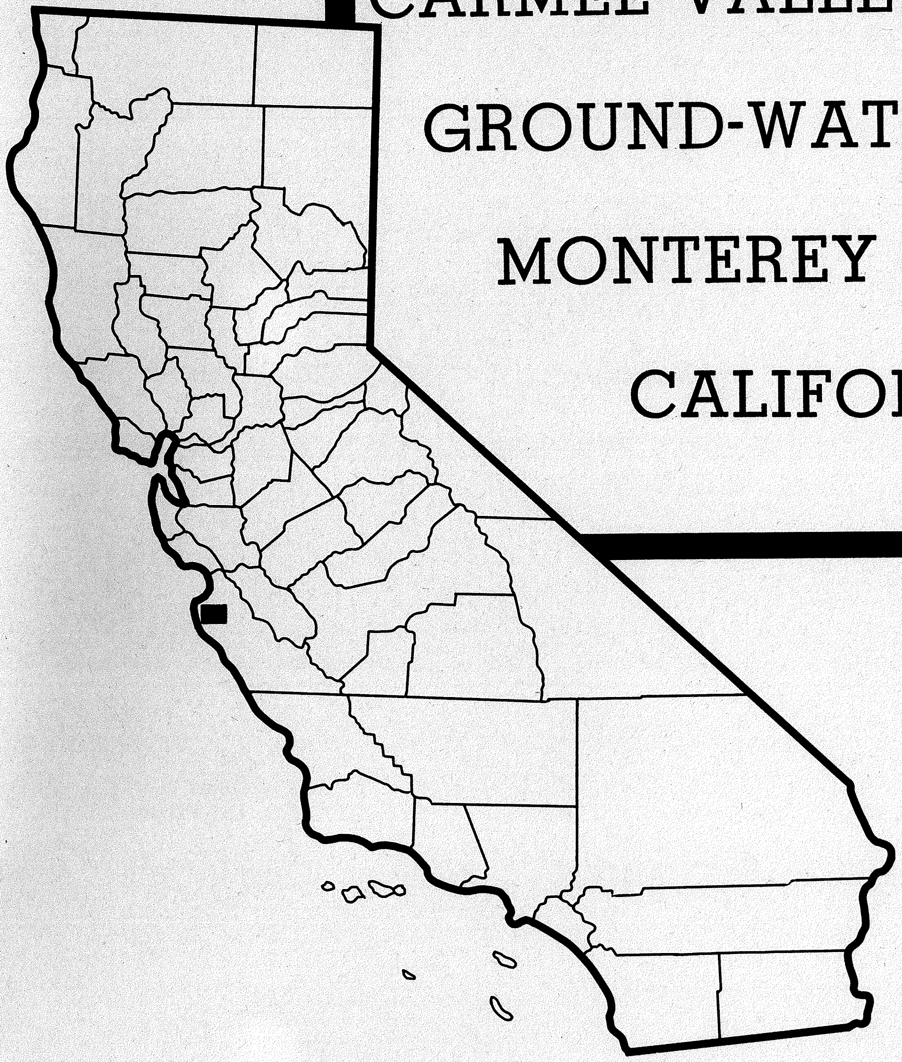
ANALYSIS OF THE CARMEL VALLEY ALLUVIAL GROUND-WATER BASIN, MONTEREY COUNTY, CALIFORNIA



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 83-4280

Prepared in cooperation with the
MONTEREY PENINSULA WATER MANAGEMENT DISTRICT

ANALYSIS OF THE CARMEL VALLEY ALLUVIAL GROUND-WATER BASIN, MONTEREY COUNTY, CALIFORNIA

By Glenn W. Kapple, Hugh T. Mitten, Timothy J. Durbin, and Michael J. Johnson

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4280

Prepared in cooperation with the
MONTEREY PENINSULA WATER MANAGEMENT DISTRICT

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Sacramento, California
June 1984

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Federal Building, Room W-2235
2800 Cottage Way
Sacramento, CA 95825

Copies of this report
can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, CO 80225
Telephone: (303) 236-7476

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

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

Multiply	By	To obtain
acres	0.4047	ha (hectares)
acre-ft (acre-feet)	0.001233	hm^3 (cubic hectometers)
acre-ft/yr (acre-feet per year)	0.001233	hm^3/a (cubic hectometers per year)
(acre-ft/acre)/yr (acre-feet per acre per year)	0.30402	m/a (meters per year)
ft (feet)	0.3048	m (meters)
ft^2/d (feet squared per day)	0.0929	m^2/d (meters squared per day)
ft/d (feet per day)	0.3048	m/d (meters per day)
ft/mi (feet per mile)	0.1894	m/km (meters per kilometer)
ft/yr (feet per year)	0.3048	m/a (meters per year)
ft^3/s (cubic feet per second)	0.02832	m^3/s (cubic meters per second)
$(ft^3/s)/mi^2$ (cubic feet per second per square mile)	0.01093	$(m^3/s)/km^2$ (cubic meters per second per square kilometer)
$(gal/d)/ft^2$ (gallons per day per square foot)	0.04047	m/d (meters per day)
gal/min (gallons per minute)	0.003785	m^3/min (cubic meters per minute)
(gal/min)/ft (gallons per minute per foot)	0.2070	m^2/s (meters squared per second)
inches	25.4	mm (millimeters)
in/yr (inches per year)	25.4	mm/a (millimeters per year)
kWh/acre-ft (kilowatthours per acre-foot)	2,919	J/m^3 (joules per cubic meter)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

Degree Fahrenheit is converted to degree Celsius by using the formula:
$°C = (°F-32)/1.8$.

The use of firm, brand, or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

ANALYSIS OF THE CARMEL VALLEY ALLUVIAL GROUND-WATER BASIN, MONTEREY COUNTY, CALIFORNIA

By Glenn W. Kapple, Hugh T. Mitten, Timothy J. Durbin,
and Michael J. Johnson

ABSTRACT

A two-dimensional, finite-element, digital model was developed for the Carmel Valley alluvial ground-water basin using measured, computed, and estimated discharge and recharge data for the basin. Discharge data included evapotranspiration by phreatophytes and agricultural, municipal, and domestic pumpage. Recharge data included river leakage, tributary runoff, and pumping return flow. Recharge from subsurface boundary flow and rainfall infiltration was assumed to be insignificant. From 1974 through 1978, the annual pumping rate ranged from 5,900 to 9,100 acre-feet per year with 55 percent allotted to municipal use principally exported out of the valley, 44 percent to agricultural use, and 1 percent to domestic use. The pumpage return flow within the valley ranged from 900 to 1,500 acre-feet per year. The aquifer properties of transmissivity (about 5,900 feet squared per day) and of the storage coefficient (0.19) were estimated from an average alluvial thickness of 75 feet and from less well-defined data on specific capacity and grain-size distribution. During calibration the values estimated for hydraulic conductivity and storage coefficient for the lower valley were reduced because of the smaller grain size there. The river characteristics were based on field and laboratory analyses of hydraulic conductivity and on altitude survey data.

The model is intended principally for simulation of flow conditions using monthly time steps. Time variations in transmissivity and short-term, high-recharge potential are included in the model. The years 1974 through 1978 (including "pre-" and "post-" drought) were selected because of the extreme fluctuation in water levels between the low levels measured during dry years and the above-normal water levels measured during the preceding and following wet years. Also, during this time more hydrologic information was available. Significantly, computed water levels were generally within a few feet of the measured levels, and computed flows were close to gaged riverflows for this simulation. However, the nonuniqueness of solutions with respect to different sets of data indicates the model does not necessarily validate the correctness of the individual variables. The model might be improved with additional knowledge of the distribution of confining sediments in the lower end of the valley and the aquifer properties above and below them. The solution algorithm could account for confinement or partial confinement in the lower end of the valley plus contributions from the Tularcitos aquifer.

INTRODUCTION

Background

The Monterey Peninsula and Carmel Valley obtain a large part of their water supply from ground water in Carmel Valley. During an extended period of drought their water supply is obtained almost entirely from pumping wells in the Carmel Valley. This increased pumping imposes a severe stress on the ground-water system. Such a drought occurred during 1976-77, and water-use and pumping restrictions were imposed during 1977. Because of a lack of knowledge of the aquifer system and the uncertainty of the water supply, the Monterey Peninsula Water Management District requested the U.S. Geological Survey to evaluate the ground-water resources in Carmel Valley.

Purpose

The purposes of this study were to provide a better understanding of the geohydrology of the Carmel Valley alluvial ground-water basin as an aid toward effective management of that basin and to identify areas of inadequate data in the ground-water basin.

Scope

The scope of this study included conceptualizing the geohydrology of the ground-water drainage basin based on existing information. Physical properties of the drainage basin were translated into mathematically usable numerical values, which in turn were used to develop and calibrate a digital flow model based on historical water-level, pumpage, and riverflow data.

Acknowledgments

The authors appreciate those persons and agencies who assisted in developing the data base for this project. Particular acknowledgment is given to Bruce Buel, Monterey Peninsula Water Management District; Dick Meffley, California Department of Water Resources; and personnel with the Monterey County Flood Control and Water Conservation District, California American Water Co. and Water West Corp., and the Monterey branch of the Pacific Gas and Electric Co.

DESCRIPTION OF THE STUDY AREA

Physical Setting

The Carmel basin is a small intermontane basin in the central coastal region of California, southeast of Monterey (fig. 1). The drainage basin has an area about 250 mi^2, but the valley floor containing the alluvial groundwater basin covers only about 6 mi^2. Urban and agricultural activities are confined primarily to the valley floor, which is long in comparison to its width--about 16 mi long and from 300 to 4,500 ft wide. Altitudes on the valley floor range from sea level at Carmel Bay to about 350 ft in the upper parts of the valley.

The drainage basin is bounded on the northeast by the Sierra de Salinas range with altitudes as high as 4,470 ft, and on the southeast by the Santa Lucia Range with altitudes up to 4,850 ft. Both ranges have steep slopes and dense foliage. North slopes rising from the valley floor average about 430 ft/mi, and south slopes average about 350 ft/mi. Slopes in the upper part of the drainage basin rise about 360 ft/mi. The Sierra de Salinas range, in the lower 7 or 8 mi of the drainage basin, has less vegetation and is characterized by a chaparral environment.

Carmel Valley has the typical coastal California wet-dry seasonal patterns; about 80 percent of the annual precipitation falls during January through April. Mean annual precipitation over the drainage basin ranges from 14 to 40 in/yr and averages about 17 in/yr at Carmel Valley (California Department of Water Resources, 1974, p. 5). Nonrecording rain gages are currently maintained at Monterey and at three sites in Carmel Valley--Carmel Valley, San Clemente, and Los Padres (fig. 2). Measured pan evaporation ranges from about 40 in/yr at Carmel to 60 in/yr at Carmel Valley. Mean monthly temperatures near the coast range from 54°F in the winter to 60°F in the summer; farther inland near Carmel Valley mean monthly temperatures range from 51°F to 64°F.

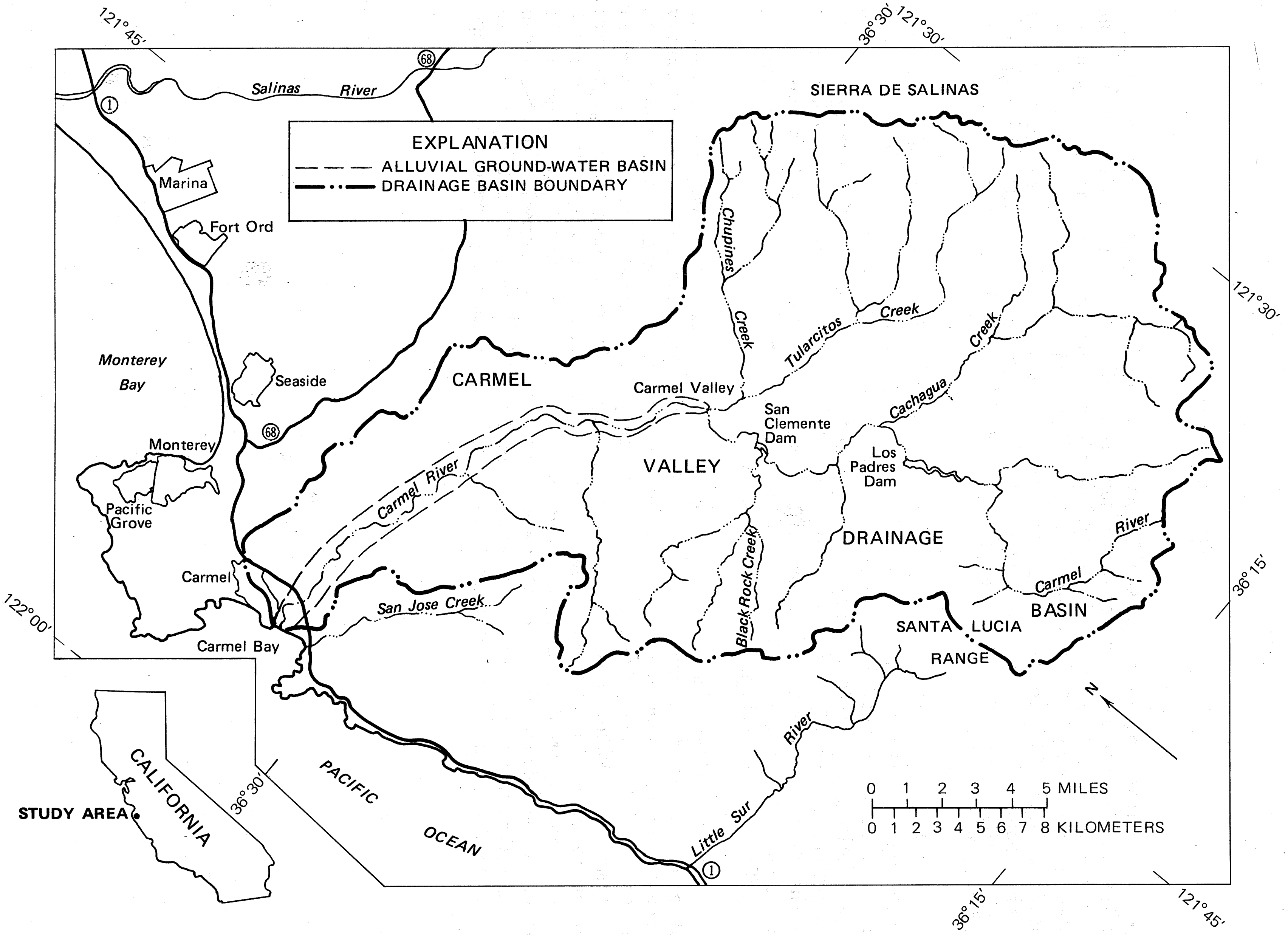


FIGURE 1. — Carmel Valley drainage basin and alluvial ground-water basin.

Surface-Water Hydrology

Drainage basin runoff occurs via the Carmel River. This runoff is gaged by the Geological Survey at Robles Del Rio in the upper part of the drainage basin and near Carmel near the coast (fig. 2, pl. 1A). The drainage basin rapidly reacts to rainfall with a high rate of discharge per unit area--peak discharge of record (1963-79) from the drainage basin was 8,620 ft^3/s (Jan. 26, 1969), and mean discharge was about 98 ft^3/s. The mean discharge represents an average runoff per unit area of about 0.4 $(ft^3/s)/mi^2$. For comparison, the Salinas basin just north of Carmel Valley with a drainage area of about 4,200 mi^2 has an average runoff per unit area of 0.1$(ft^3/s)/mi^2$.

On an annual average, the river gains over its course through the valley as additions from adjacent tributary streams exceed the amount of induced river leakage. During 1963 through 1979, the average inflow at Robles Del Rio was 80.8 ft^3/s, and outflow at Carmel was 97.4 ft^3/s. Monthly records indicate that, in general, the river gains during the first half of the year and loses during the second half--a response that would be expected on examination of seasonal pumping and rainfall patterns. Mean monthly flows from the two river gages for 1974 through 1978 are shown in figure 3. Inflow to the valley is regulated slightly by the Los Padres and San Clemente Reservoirs, which have a combined capacity of 4,600 acre-ft.

Recent river-channel degradation has occurred and, if it continues, needs to be considered in any long-range projections of future ground-water conditions. Over most of its 18-mi course, the Carmel River flows in a well-defined channel ranging from 20 to 150 ft in width through mostly unconsolidated alluvial deposits. Significantly, bank altitudes are as much as 30 ft below adjacent terraces, indicating a downcutting stream undergoing a cycle of headward erosion and river channel sediment removal. The most recent sediment transport in the river channel has been significantly altered by man, principally by the complete removal of sediment load by upstream reservoirs. The rate of channel degradation downstream from reservoirs is increased as the stream loses its sediment load and increases its tractive force to begin movement and removal of materials in the river channel through the valley floor. Man's extraction of sand and gravel from the channel floor further accelerates this lowering of river-channel altitudes. Carlson and Rozelle (1978) reported that from 1966 through 1974 the lower 10 mi of the river channel underwent degradation at a rate of 0.25 ft/yr. Declines in river-channel altitudes would directly lower natural water levels in the alluvial aquifer, and, consequently, some riparian vegetation would be deprived of water because maximum water-table altitudes during the dry season are controlled principally by recharge from the river.

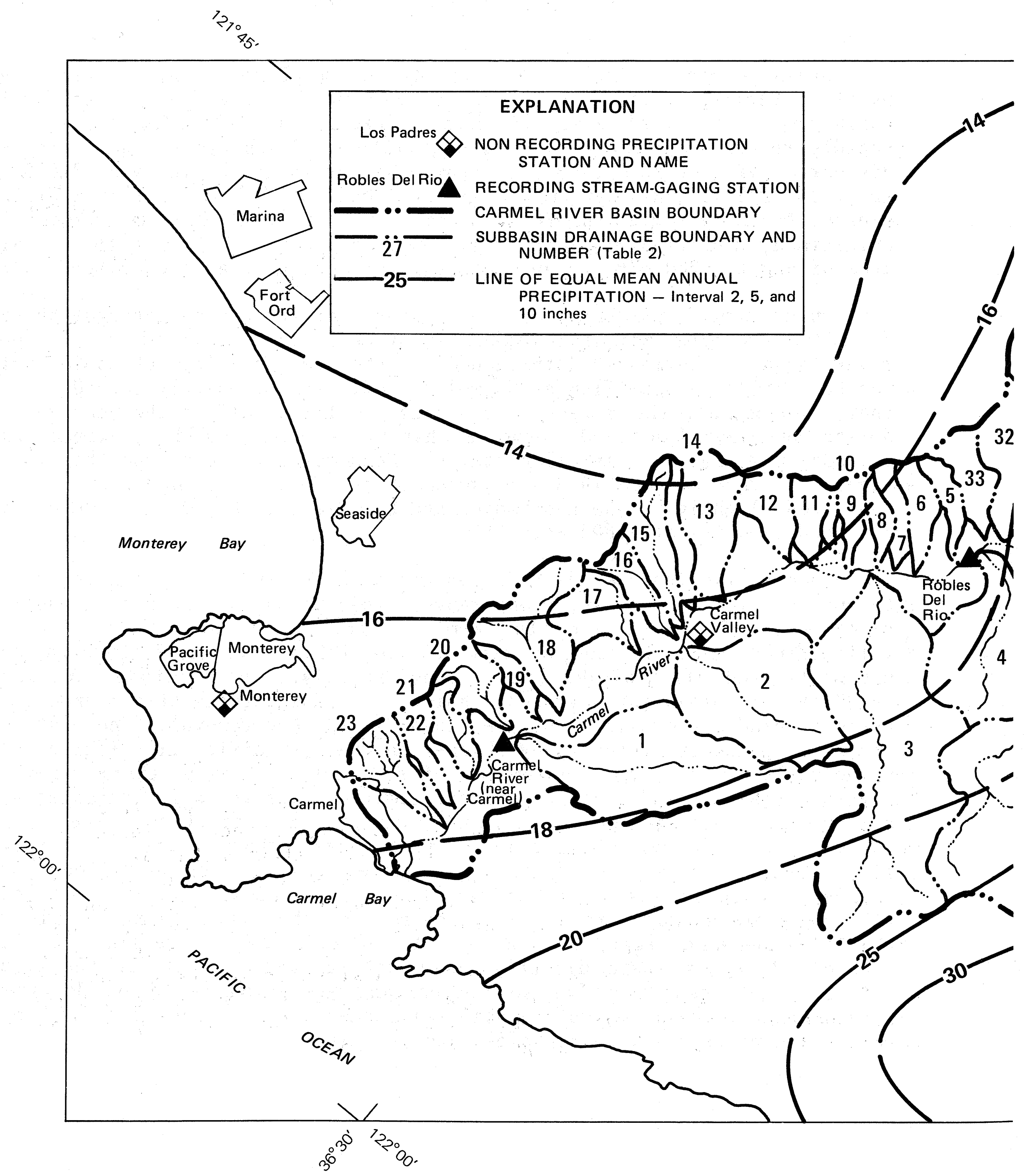
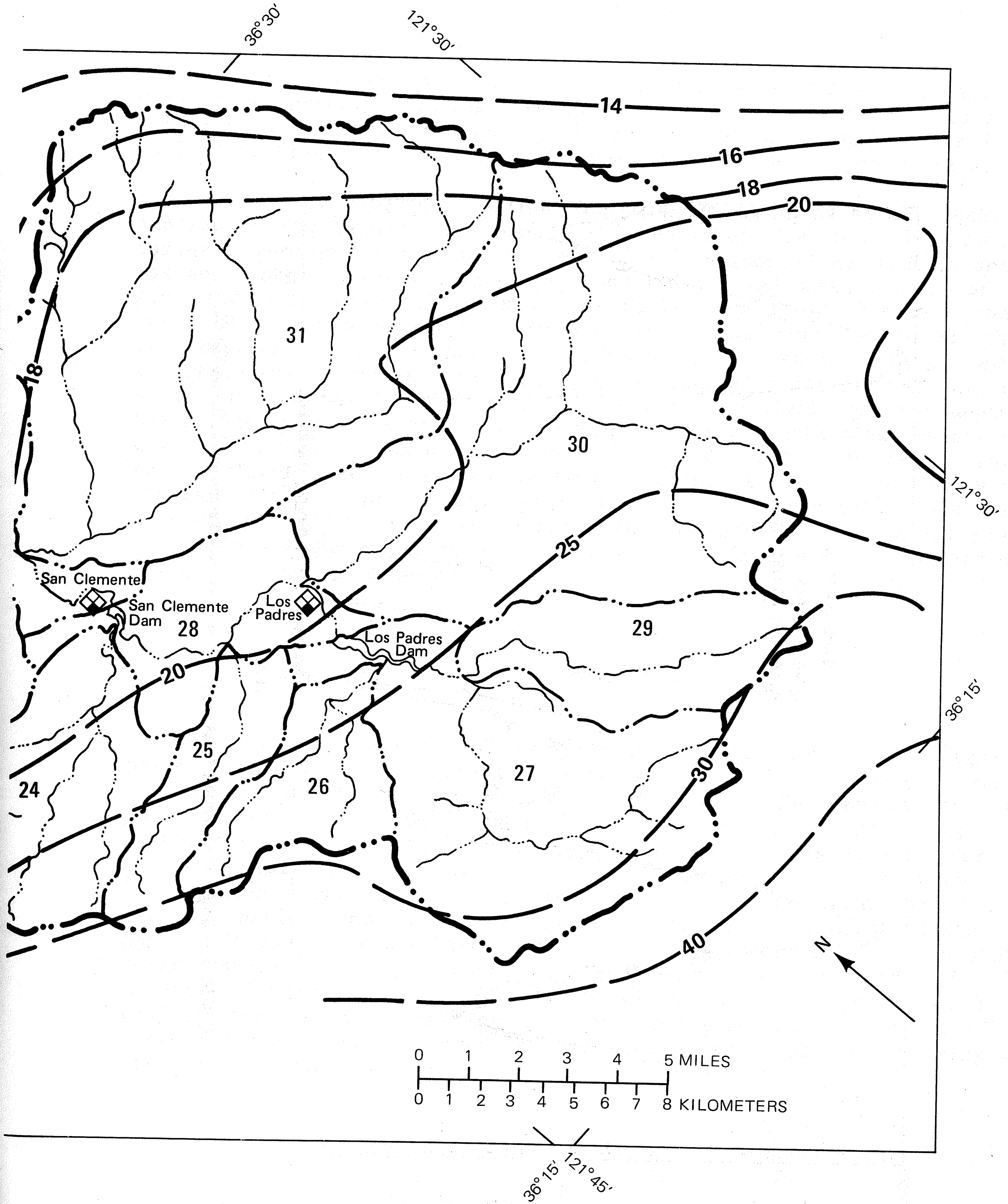


FIGURE 2. — Subbasin drainage areas and mean annual



precipitation in the Carmel Valley drainage basin.

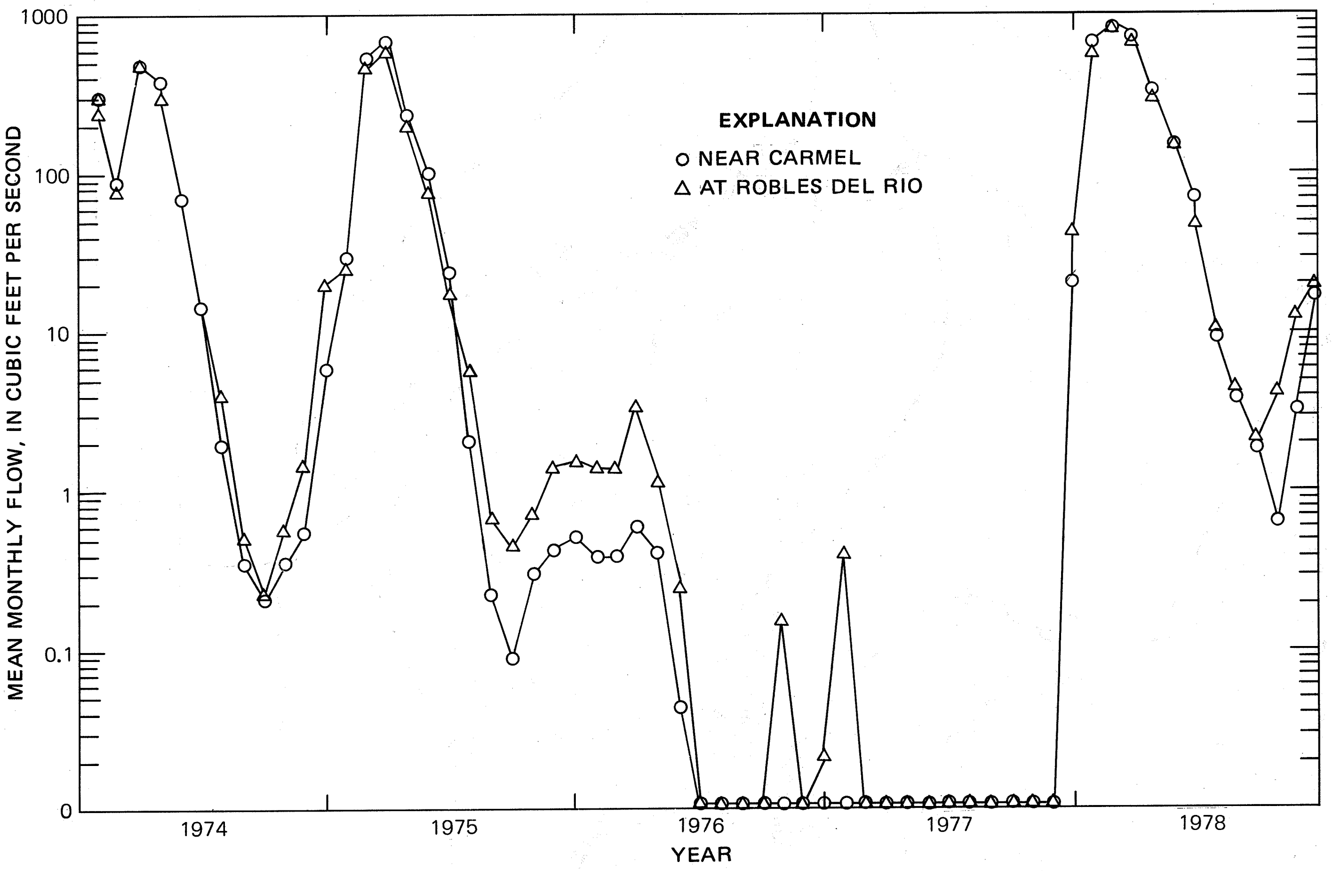


FIGURE 3. – Gaged mean monthly flows in the Carmel River near Carmel and at Robles Del Rio.

Geology

For modeling purposes the geology of the Carmel Valley was simplified to reflect its principal geologic features (pl. 1A). Those readers interested in detailed surface geology mapping are referred to Clark and others (1974) and to Fielder (1944), from which plate 1 was composited and generalized.

The Carmel River carved its valley while draining an erosional surface exposed during periods of uplift and sea-level decline. The complex and variable geologic units within the valley include three significant units: Basement rocks of pre-Tertiary age, consolidated sedimentary rocks of Tertiary age, and unconsolidated sediments of Quaternary age (table 1). The oldest rocks beneath the drainage basin are crystalline rocks of pre-Tertiary age that form the basement complex of the area. The basement rocks are exposed in a northwestward-trending belt, paralleling the major strike-slip faults of the area. They occur in the subsurface at a progressively greater depth toward the northeast. Successively younger Tertiary rocks have been deposited on the crystalline rocks. Although considerably folded into a series of anticlines and synclines that trend more westward, oblique to and truncated by regional faults, their general dip is also to the northeast. Southwesterly, successively older rocks are exposed at the surface. The Carmel River cuts across this sequence of folded Tertiary rocks offset by faulting and deposits younger Quaternary sediments.

Basement Rocks

The basement rocks of pre-Tertiary age are composed of igneous and metamorphic rocks. The metamorphic rocks are the Sur Series of Trask (1926) and consist mainly of biotite schist and gneiss. The igneous rocks are the Santa Lucia granites of Lawson (1893) and consist mainly of porphyritic granodiorite and quartz diorite. The basement rocks have a very uneven erosional surface upon which the younger Tertiary rocks rest unconformably. The basement complex is extensively exposed to the south and east of the drainage basin, with isolated outcrops north and at the mouth of the drainage basin. It is deeply weathered locally, and, where weathered and saturated, it could supply minor quantities of water to wells, sufficient for limited domestic and stock use. Only a few wells on the valley floor have been drilled through the overlying materials and penetrate the granite. Except where weathered, the basement rocks are considered non-water-bearing and are treated as a ground-water barrier.

TABLE 1. - Generalized geologic units of the Carmel Valley

Age	Geologic units	Maximum thickness (feet)	General lithologic character	Water-bearing properties
Quaternary	Younger alluvium and river deposits (Holocene)	180	Boulders, gravels, sand, silt, and clay.	Major water-bearing unit in the valley. Sufficient yields to supply municipal, agricultural, and domestic wells. Municipal wells yield from 200 to 2,000 gal/min. Domestic wells yield from 3 to 200 gal/min. Hydraulic conductivity assumed to be 30 to 64 ft/d.
	Older alluvium and terrace deposits (Pleistocene)	50	Gravel, sand, and clay.	Transmits water freely but generally lacks summer storage. In favorable places, may supply individual domestic wells.
Tertiary	Monterey Shale (Miocene)	700-1,000	Siliceous marine shale interbedded with sandstone in lower part.	Some domestic wells yield 15 to 30 gal/min from sandstone stringers and silicified fractures. Mudstone facies yield virtually no water.
	Tertiary sandstone units (Miocene and Paleocene)	900	Mostly marine sandstones; includes some beds of siltstone, conglomerate, and volcanic rock.	Limited well penetration and great variations in rock character limit knowledge of water-bearing properties. Locally, domestic supplies of generally less than 5 to 10 gal/min have been obtained from wells with reports of some well yields exceeding 100 gal/min. Hydraulic conductivity assumed to be 1 ft/d.
Pre-Tertiary	Basement complex		Igneous and metamorphic rocks.	Locally, wells yield small quantities from fractures or weathered zones. Supplies may be limited and unreliable.

Consolidated Sedimentary Rocks

The consolidated sedimentary rocks, several thousand feet thick, consist of Tertiary sandstone units of Paleocene and Miocene age and the overlying Monterey Shale of Miocene age. Within these units, only the Miocene sandstone beds and silicified fracture zones in the lower part of the Monterey Shale have any hydrologic significance (Thorup, 1979).

The Tertiary sandstone units of Paleocene age, referred to as the Carmelo Formation by Bowen (1965), consist of sandstone, siltstone, conglomerate, and shale. Erosion has removed most of these sediments from the present Carmel Valley; the small occurrences, known to be present only along the coastal part of the drainage basin, have no hydrologic significance.

The Tertiary sandstone units of Miocene age consist of a lower terrestrial unit of sandstone, siltstone, and conglomerate termed the red beds of Robinson Canyon (Robinson Canyon Member of the Chamisal Formation of Bowen, 1965), and a middle and upper sequence of marine sandstone with basaltic flows termed marine sandstone by Clark and others (1974). These sandstone units comprise what Thorup (1976) defines as the Tularcitos aquifer and include most of the strata lying between the basement complex and the Monterey Shale within the Carmel Valley. Outcrops of the sandstone units are numerous along the southern side of the drainage basin and in places are in direct contact with the alluvium. The character of these sandstone units varies greatly from one place to another and from one layer to another within the drainage basin. This variability, along with minimal well penetration, restricts our knowledge of the sandstone units' true water-bearing properties. The Tertiary sandstone units are assumed to have a hydraulic conductivity of about 1 ft/d, even though in some areas their hydraulic conductivity may be higher due to a higher degree of sediment sorting or fault-related fracturing. Because the hydraulic conductivity of these rocks probably is considerably less than that of the alluvium, the exchange of water between them and the alluvium is assumed to be limited. However, these sandstone units are believed to underlie one-third of the entire drainage basin with an average thickness of about 250 ft and therefore may contain considerable water in storage (Thorup, 1976). Most wells drilled into the unit yield at least enough water for domestic use, and a few wells yield considerably more.

The Monterey Shale of Miocene age consists of siliceous marine deposits occasionally interbedded with fine-grained sandstone that increases in abundance toward the base of the formation. Extensively exposed along the northern side of the drainage basin, it directly underlies the alluvium and conformably overlies the lower Miocene marine sandstone units. Although some domestic wells obtain water from sandstone stringers and fractures within the formation, the Monterey Shale is generally considered non-water-bearing and is treated in the model as a ground-water barrier.

Unconsolidated Sediments

The unconsolidated sediments include older alluvium and younger alluvium. The older alluvium of Pleistocene age generally consists of gravel and sand terrace deposits exposed on the north side of the river. Individual patches are small and typically situated on well-drained bluffs. Although this unit transmits water readily, its distribution is limited and erratic; therefore, it is not considered a significant aquifer in this study.

The younger alluvium of Holocene age along the valley floor is composed of poorly consolidated boulders, gravel, sand, and silt deposited by the Carmel River. Clay layers are thin and uncommon. Silt becomes more abundant downvalley. The basal part of the alluvium from Meadows Road to the ocean may contain water confined by a layer of nearly impermeable silt at depths of 30 to 40 ft (Greenwood, 1978). The younger alluvium is the most significant water-bearing unit in Carmel Valley, with hydraulic conductivities assumed to be 30 to 64 ft/d (see section on "Aquifer Properties").

Structure

A series of high-angle faults trends northwestward across the Carmel Valley area (principally strike-slip faulting that strikes N. 40° W). Oblique to the trend of these faults is a series of anticlines and synclines that trends westward and is truncated by faults. Strata north of the river are folded into several synclines and anticlines; those south of the river are folded into one predominant syncline. The important faults in the Carmel Valley are the Cypress Point fault, the Navy fault, and the Tularcitos fault (pl. 1A).

The Cypress Point fault extends across the mouth of the valley with an uplifted granite basement to the west. The Carmel River has cut through the uplifted western block of the basement rock to a depth of more than 86 ft below sea level. Thus, the uplifted granite is not an effective barrier to seawater intrusion at the river's mouth (California Department of Water Resources, 1974). However, the thinning of the unconsolidated sediments across the fault zone could have some effect on limiting seawater intrusion to the basal part of the alluvium and underlying formations just east of the fault.

The Navy fault cannot be traced through the alluvial deposits of the Carmel Valley. However, its near-alinement with the mapped Tularcitos fault to the southeast and its similarity in trends strongly suggest that these two faults are continuous (Clark and others, 1974). The alluvium is noticeably thinner in sec. 19, T. 16 S., R. 2 E., east of the fault alinements where the underlying formations are mostly granitic; west of the fault alinements the underlying rocks are mostly sedimentary, principally Monterey Shale.

Ground-Water System

The extent and thickness of the younger alluvium--the unconfined aquifer modeled in this study--is shown on plate 1B. This map is based almost entirely on an isopach map previously published by the California Department of Water Resources (1974) with minor modifications made by the Department in 1977 from post-1974 drillers' log information. Aquifer thickness ranges from about 30 ft at the drainage basin narrows in the upper basin to about 180 ft 1 mi from the mouth of the drainage basin.

At the mouth of the drainage basin, the aquifer thins due to an uplifted fault block west of the Cypress Point fault. This uplift impedes but does not stop ground-water movement across the fault. Seismic-refraction surveys (California Department of Water Resources, 1974) indicated that the depth of the alluvium across the mouth ranged from 32 ft north of the river to 86 ft at the river's edge. These data were confirmed within a few feet by an unpublished resistivity and seismic-refraction survey done by the Geological Survey in 1979 (J. C. Tinsley III and M. J. Johnson, oral commun., 1979). Because the alluvium is still in direct contact with saline waters to depths of at least 75 ft below sea level, the uplift is not an effective barrier to seawater intrusion.

Recharge to the aquifer is derived mainly from river infiltration which composes about 85 percent of the net recharge. The potential recharge rate from the river to the aquifer is high, perhaps 100 ft^3/s or more (Dames and Moore, 1973), and during normal or above-normal flow years, the water table recovers completely from the dry-season low. After the 2-year drought of 1976-77, precipitation that began in January 1978 caused water levels to recover by February 1978. Thus, it appears that the aquifer recovers in a month or less even after severe stressing. Water levels after recovery are often a few feet above the riverbed, indicating that additional and significant recharge occurs, mostly from tributary stream infiltration.

Ground-water flow is, generally, downvalley, with gradients ranging from about 50 ft/mi in the upper drainage basin to about 10 ft/mi toward the lower end. After recovery, water-table depths range from about 5 to 30 ft below land surface with an average of about 15 ft. During normal rainfall years, water-level fluctuation is about 5 to 15 ft; during drought years, water levels decline as much as 50 ft. Previous estimates of the aquifer's storage potential (California Department of Water Resources, 1974) indicate a total storage in the springtime of about 50,000 acre-ft. The report also estimates subsurface discharge to the ocean at about 140 acre-ft/yr.

DIGITAL MODEL

Conceptual Model

To develop a digital model of a complex ground-water system, a conceptual model of the system must be established on the basis of simplified geohydrologic assumptions. For Carmel Valley, the younger alluvium is considered to be the sole water-bearing formation and is conceptualized as a single-layer, unconfined, horizontal unit. The model was developed by making the following assumptions:

1. All ground-water movement is horizontal.
2. Changes in storage occur instantaneously.
3. Physical characteristics of the aquifer vary with time.
4. The aquifer is isotropic.
5. Recharge occurs instantaneously.
6. The underlying Monterey Shale and sandstone units are impermeable.
7. Hydraulic gradients equal the slope of the free surface and do not vary with depth.

Mathematical Model

Ground-water flow in a conceptual model can be described by the mathematical equation (Bear, 1972):

$$\frac{\partial}{\partial x}\left(bK\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(bK\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W,$$

where

b=aquifer thickness, which varies with x, y, and t;
K=hydraulic conductivity, which varies with x and y;
S=specific yield, which varies with x and y;
h=hydraulic head, which varies with x, y, and t;
W=composite of source-sink terms; and
t=time; x=abscissa; and y=ordinate.

For this study, the source-sink terms include components representing discharge from pumping, evapotranspiration, and the river; and recharge from river infiltration, pumpage return flow, and tributary stream infiltration.

River leakage is computed internally by the computer program as a function of the head differential between the river stage and ground-water level at the midpoint of each river reach length and the river flow width. The functional relation for river leakage rate (Q_R) derived from Durbin and others (1978, p. 49-50) is:

$$Q_R=C_R(h_R-h)W_RL,$$

where C_R is a proportionality constant (analogous to channel-bed hydraulic conductivity), h_R is the river stage, h is the ground-water level, W_R is the flow width, and L is the reach length.

The river stage is the channel-bed altitude plus the depth of flow in the river which may be approximated as a power function of inflow to each river reach. Thus, the stage is expressed functionally as:

$$h_R=H_R+a_dQ^{b_d},$$

where H_R is the channel-bed altitude, Q is the river discharge, and a_d and b_d are numerical coefficients. The flow width also was estimated by a power function:

$$W_R=a_wQ^{b_w},$$

where a_w and b_w are numerical coefficients.

Combining these equations produces the generalized leakage equation used in the model:

$$Q_R=C_R\left(H_R+a_dQ^{b_d}-h\right)a_wQ^{b_w}L.$$

The use of the functional relation for river leakage rate was described by Durbin and others (1978, p. 53-62). To use this relation in the model, the river was first divided into subreaches. The length of each subreach is equal to the sum of one-half the distance to each of the adjacent river nodes (pl. 1C). Then, for each subreach the continuity equation is:

$$Q_{IN}+Q_T-Q_R=Q_{OUT},$$

where Q_{IN} is the river inflow to the reach, Q_T is the tributary inflow, Q_R is the leakage rate, and Q_{OUT} is the river outflow from the reach. The computer program does not allow the leakage rate to exceed the sum of the river and tributary inflows at any reach.

The model includes calculations for each time step of the net quantity of water in storage and the rate of aquifer discharge to the ocean. Storage is calculated for each element on the basis of the element area, saturated thickness, and storage coefficient. Aquifer discharge is the flow through the eight elements adjacent to the ocean and is calculated on the basis of the water-table gradients and transmissivities for these elements.

Computer Code

The computer code used for this project is similar to that used previously by Durbin (1978). Modifications were made to the input-output sections, but the computational sections of the program remain unchanged. The Galerkin finite-element procedure with triangular elements was used. The program was executed on the U.S. Geological Survey's IBM compatible AMDAHL system in Reston, Va., and required about a half-second of execution time per time step.

Element Configuration

The element configuration used for the model and the location of river nodes are shown on plate 1C. This configuration consists of 832 elements and 525 nodes, designed such that each "line" of 5 nodes (or 8 elements) across the drainage basin is generally perpendicular to downgradient flow. Each line across the drainage basin was subdivided into four equal lengths such that the configuration across the drainage basin consists of five nodes and eight elements throughout the length of the drainage basin. Nodes and elements are numbered consecutively as illustrated on plate 1C, which shows the configuration of the first 32 elements in the lower part of the drainage basin and selected elements elsewhere.

The finite-element technique adapts well to areas with irregular geometry, such as Carmel Valley, as opposed to the finite-difference technique which must conform to straight-line configurations of rows and columns. Data input to the model is supplied either by node or element, and water levels are computed at each node location.

Model Input Data

The data used to develop this model, either measured, computed, or estimated, are outlined below:

1. Aquifer properties
2. Tributary-stream characteristics
3. River-channel characteristics
4. Evapotranspiration losses
5. Pumpage and pumpage return flow
    a. Municipal pumpage
    b. Agricultural pumpage
    c. Domestic pumpage.

As discussed in the following sections, some of these data are coded into the model by node and others by element. The model computes water levels and drawdowns at all nodes.

Aquifer Properties

Initial estimates of aquifer hydraulic conductivities and storage coefficients used in the model were based on specific-capacity test data and assumptions concerning the nature of the granular materials. Available specific-capacity test data show a high degree of divergence, even for repeated tests made on the same well, perhaps because tests made during wet periods are influenced by induced leakage from the river. Reliable dry-period data were available for seven wells in the drainage basin. Specific capacities from those tests ranged from 14.8 to 44.1 (gal/min)/ft, averaging 22 (gal/min)/ft. The average specific capacity converts to a transmissivity of 5,896 ft^2/d. The derived transmissivity data, though inconclusive, were used in conjunction with alluvial thickness data to initially estimate hydraulic conductivity for the model. Assuming an aquifer thickness of 110 ft for the test sites, hydraulic conductivity ranged from 30 to 64 ft/d and averaged about 60 ft/d.

The model-derived transmissivities reflect the assumption of time variance; the model recomputes transmissivity for changes in saturated thickness of the aquifer. For calibration, initial estimates of hydraulic conductivity were modified to obtain the best match between observed and computed water levels during the 1974-78 period.

Values for specific yield, also derived from calibration, ranged from 0.09 to 0.20 and averaged about 0.19. A specific yield of 0.20 was initially assumed as representative of sand-and-gravel-type materials such as those found in Carmel Valley (Davis and DeWiest, 1966).

Examination of drillers' logs did not reveal any discernible lithologic patterns in the drainage basin. These logs typically indicate a large amount of sand and gravel with intermixed sequences of clay, silt, shale, and boulders. There are a few logs available for the lower part of the drainage basin that indicate some increase in silt and clay. For the model, it was assumed that the lithologic properties of the aquifer were homogeneous, except in the lower drainage basin where the increase in silt and fine sand content presumably would decrease the hydraulic conductivity and the storage coefficient. The values used for these characteristics are shown in figure 4. Hydraulic conductivity was increased from a value of 30 ft/d near the river mouth to 64 ft/d about 3.5 mi up the drainage basin. Storage coefficients over this distance were increased from 0.09 to 0.20.

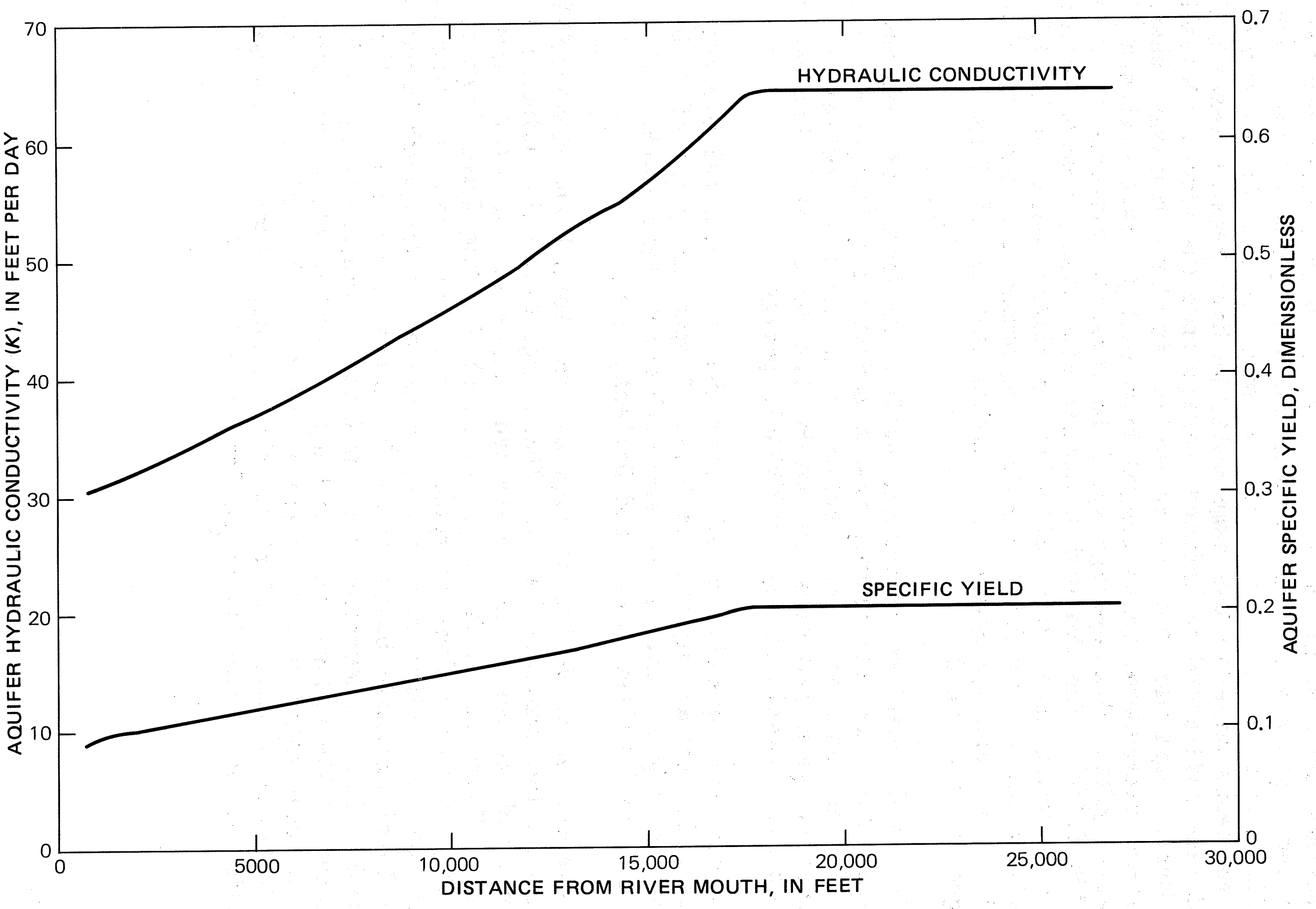


FIGURE 4. — Aquifer hydraulic conductivity and specific yield for a selected reach upstream of the mouth of the Carmel River.

Tributary-Stream Characteristics

The aquifer receives recharge from sources other than river leakage because ground-water levels in parts of the drainage basin are several feet higher than river-bed altitudes. Most of this recharge can be attributed to infiltration from tributary-stream channels. Tributary runoff that does not infiltrate to the water table contributes to riverflows and accounts for most of the 15-percent increase in annual discharge between the Robles Del Rio and Carmel gages (pl. 1D). The additional inflow from tributaries below the Robles Del Rio station increases the river's capability to recharge the aquifer. As a result, the runoff from ungaged tributary streams and the parts of this runoff that contribute to aquifer recharge and riverflows were estimated.

Monthly tributary runoff for 1974 through 1978 was estimated by correlating tributary subbasin areas, mean annual precipitation, and the streamflow records from the Robles Del Rio gage. First, the drainage basin was divided into subbasins and overlaid with mean annual precipitation contour lines taken from Rantz (1969) (fig. 2). Second, the area and mean annual precipitations were determined for each subbasin, and the percentage of tributary flow--based on subbasin areas and precipitation--was calculated for each tributary below the Robles Del Rio gage (table 2). Third, total monthly runoff for the tributaries below Robles Del Rio was estimated using the equation:

$$Q_T=Q_G \frac{\Sigma A_b P_b}{\Sigma A_a P_a},$$

where Q_T is the monthly tributary runoff, Q_G is the monthly gaged runoff at Robles Del Rio, and A_a, A_b, P_a, and P_b are the individual subbasin areas and mean annual precipitations above and below the Robles Del Rio gage. This computation indicates that tributary runoff is about 20 percent of the gaged runoff from the drainage basin upstream from Robles Del Rio.

The runoff computation and the previously calculated runoff percentages also provide an estimate of the monthly runoff from each tributary to the valley floor. To apportion this runoff accurately between the infiltration and river-inflow components would require either detailed information pertaining to the individual tributary-channel infiltration characteristics or field measurements of tributary flows. Such information was not available, and obtaining it is probably not warranted. For the purpose of this model, an estimate of tributary infiltrations was made by assuming that up to 15 percent of the net withdrawal from pumping could be replaced by tributary-stream infiltration. If the monthly tributary runoff was less than 15 percent of the withdrawal, then only the amount available was applied in the model as infiltration; if not, the excess was added to the riverflows. The total estimated monthly tributary infiltrations and river inflows for the period 1974-78 are shown in figure 5. During months in which the tributary runoff was less than 15 percent of the net withdrawal, the infiltration data represent the total tributary runoff (fig. 5); otherwise, the sum of the infiltration and inflow represents the total tributary runoff. In this model, tributary infiltration was applied at the nearest node to the tributary along the edge of the alluvium, and tributary inflows were applied at the nearest river node to the tributary confluences for each of the 23 subbasins.

TABLE 2. - Tributary subbasin areas, mean annual precipitation, and percentage of mean tributary flow

Subbasin No. (fig.2)	Tributary subbasin[1]	Area (square miles)	Mean annual precipitation (inches)	Percentage of mean tributary flow[2]
1	Potrero------------	5.20	18.2	11.2
2	Robinson------------	5.43	17.9	11.5
3	Las Gazas-----------	13.20	19.7	30.7
4	Hitchcock-----------	4.60	18.8	10.2
5	-- ------------	.61	17.0	1.2
6	-- ------------	.68	16.6	1.3
7	-- ------------	--	--	--
8	-- ------------	.58	16.5	1.1
9	-- ------------	.62	16.1	1.2
10	-- ------------	.10	16.2	.2
11	-- ------------	.85	15.6	1.6
12	Juan de Matte-------	1.01	15.5	1.8
13	Coyote--------------	1.78	14.9	3.1
14	Meadows-------------	.62	15.7	1.1
15	Buckeye-------------	1.78	15.1	3.2
16	Berwick-------------	1.16	16.0	2.2
17	De la Ordena--------	1.35	16.4	2.6
18	-- ------------	2.91	16.4	5.6
19	-- ------------	.54	17.0	1.1
20	Roach---------------	1.33	17.1	2.7
21	Martin--------------	.78	17.4	1.6
22	-- ------------	.81	17.6	1.7
23	Hatton--------------	1.35	17.7	2.8
24	San Clemente--------	15.6	23.6	--
25	Pine----------------	7.8	25.2	--
26	Danish--------------	8.1	27.5	--
27	Carmel River upstream from Los Padres Dam----	25.3	29.7	--
28	Carmel River upstream from San Clemente Dam--	12.9	20.1	--
29	Miller--------------	10.4	28.0	--
30	Cachagua------------	46.3	22.3	--
31	Tularcitos----------	56.3	18.3	--
32	Klondike------------	2.1	18.0	--
33	-- ------------	1.41	17.2	--

---

[1] Some tributary subbasins are not named.

[2] Percentage of tributary flow is given only for tributaries downstream from Robles Del Rio.

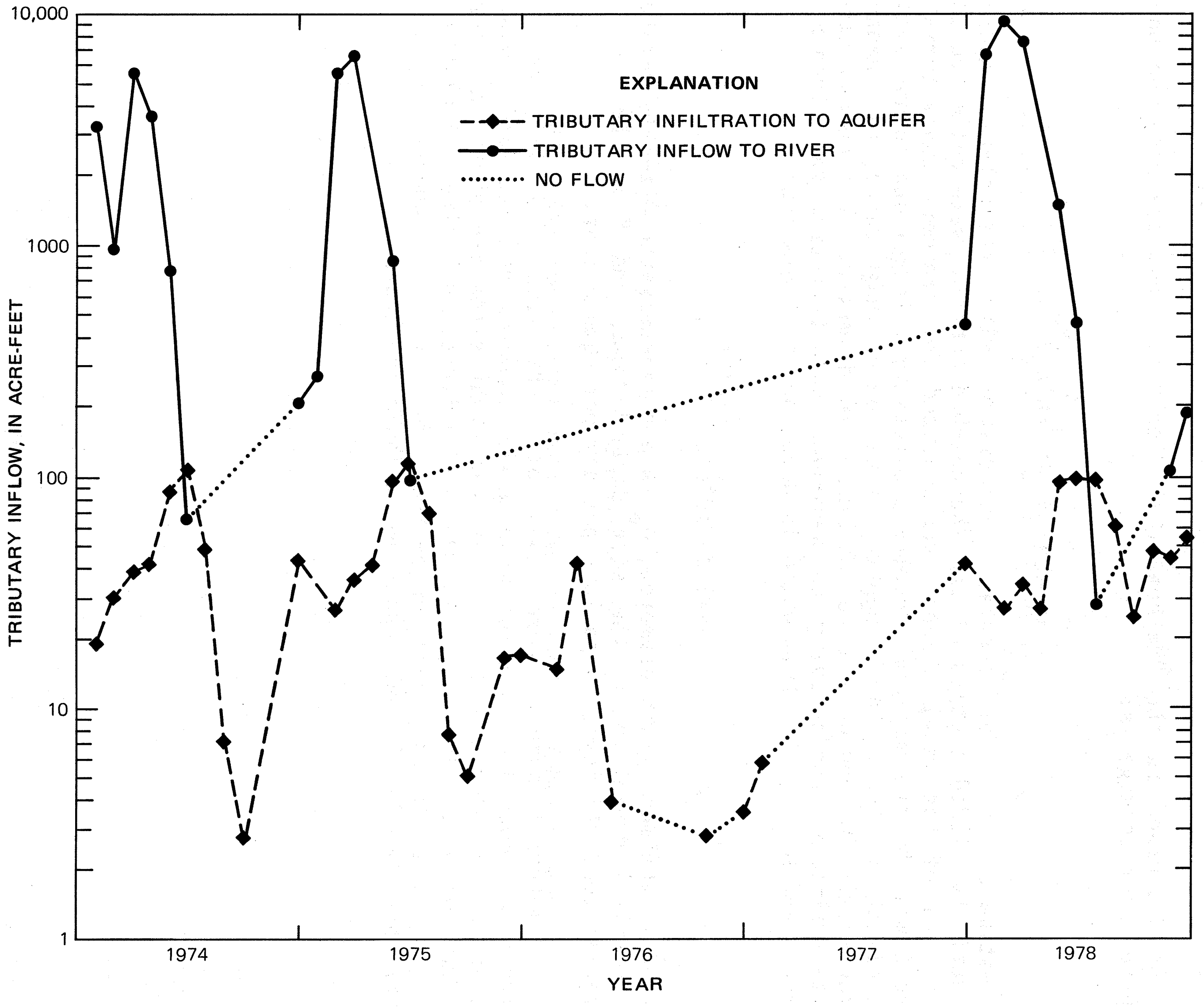


FIGURE 5. — Estimated monthly tributary infiltrations and inflow to Carmel River, 1974 through 1978.

River-Channel Characteristics

Model calculation of river leakage requires estimates of channel-bed hydraulic conductivity, channel width, and river stage. As would be expected, a cursory field examination of the channel bed indicated a decrease in grain size of the bed materials toward the mouth of the river. As hydraulic conductivity depends mostly upon the median grain size of porous material (Corey, 1969), the channel-bed conductivity and, consequently, the river-leakage potential will decrease downvalley.

As discussed in the "Mathematical Model" section, the equation used to compute river leakage is:

$$Q_R = C_R \left(H_R + a_d Q^{b_d} - h \right) a_w Q^{b_w} L.$$

To estimate C_R, the constant associated with channel-bed hydraulic conductivity, field samples of the channel-bed material were collected in the lower 5 mi of the river channel and analyzed for sediment characteristics. Above 5 mi, the bed material becomes progressively larger and is not amenable to sediment analysis. In the upper part of the drainage basin, the channel is characterized by boulders 6 to 12 inches in diameter. The method used to relate hydraulic conductivity to sediment characteristics was discussed by Krumbein and Monk (1942) from which is developed the relation:

$$K = 1.38 \times 10^4 \bar{d}^2 e^{-1.31 \sigma_\phi},$$

where $\bar{d}$ is the mean grain diameter, σ_ϕ is a characteristic directly related to the standard deviation of the size distribution, and K is the laboratory hydraulic conductivity[1], in gallons per day per square foot.

Bed-material samples were taken at eight sites (pl. 1E), and sieve analysis was done to determine mean grain diameter and standard deviation. Grain-size distributions for each of the eight sites are shown in figure 6, and the extracted data used in the hydraulic-conductivity calculation are shown in table 3; the relation between the hydraulic conductivity of the channel bed and the distance upstream is shown in figure 7.

---

[1] Laboratory hydraulic conductivity (K) in Darcy units, which does not include viscosity effects of water, equals 18.2 times the specific hydraulic conductivity (C_R), in gallons per day per square foot, at a water temperature of 60°F (Davis and DeWiest, 1966).

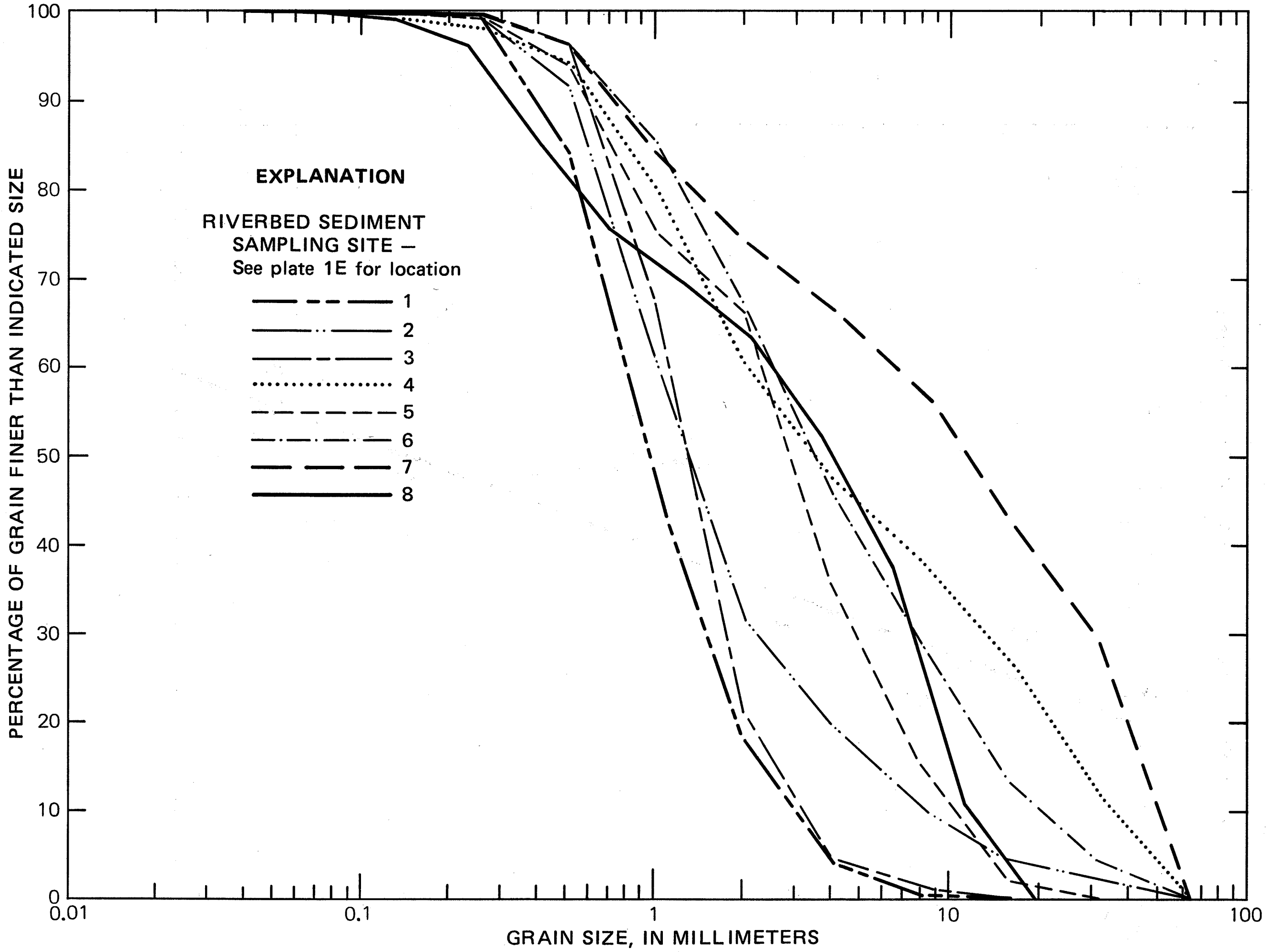


FIGURE 6. — Channel-bed grain size distribution at sites in the lower Carmel Valley river channel.

TABLE 3. - Data used to compute channel-bed hydraulic conductivity

[$\bar{d}$, mean grain diameter; σ_ϕ, characteristic directly related to the standard deviation of the size distribution; K_R, laboratory hydraulic conductivity. Location of sample sites is shown on plate 1E]

Sample No.	$\bar{d}$ (millimeters)	σ_ϕ (phi units)	K_R (gallons per day per square foot)	Upstream distance (thousands of feet)
1	0.58	1.10	1,040	0
2	.99	1.64	1,580	3.15
3	.74	1.60	940	6.20
4	1.40	2.16	1,610	10.25
5	1.13	.96	5,020	17.00
6	1.80	1.55	5,830	21.05
7	2.90	1.88	9,910	24.85
8	3.95	2.10	12,950	24.85

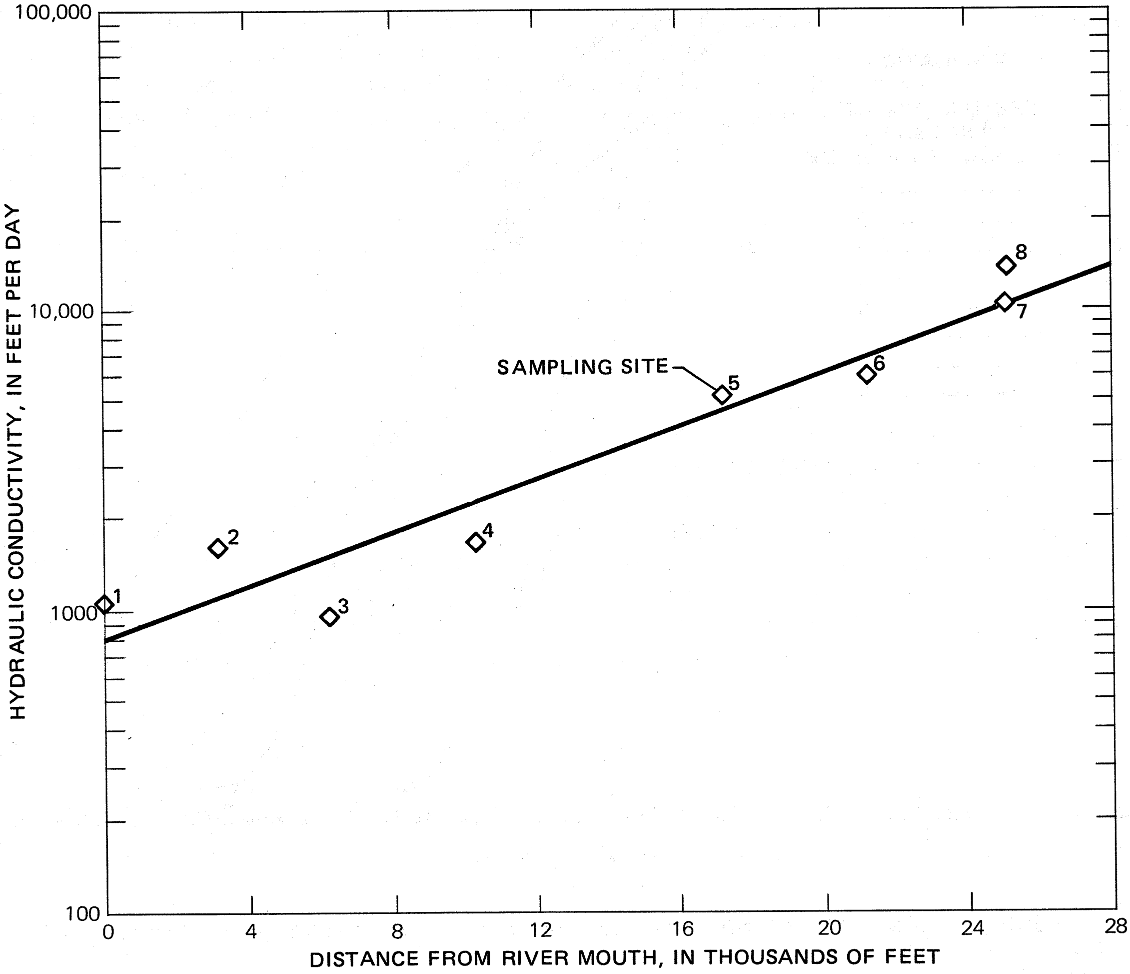


FIGURE 7. — Channel-bed hydraulic conductivity versus upstream distance from mouth of river, computed from the Krumbein-Monk relationship.

Information on the altitude of the channel bed (H_R) was obtained from George Nolte and Associates, San Jose, Calif., who made an evaluation of altitudes throughout the drainage basin using aerial photographs. Altitudes across the drainage basin were determined at more than 300 locations, with distances of several hundred feet between cross sections. These data were used to interpolate channel-bed altitudes for the model at each of the 103 river nodes (fig. 8). This information is currently being used in a flood-insurance study by George Nolte and Associates and is, at this time, (1983) unpublished.

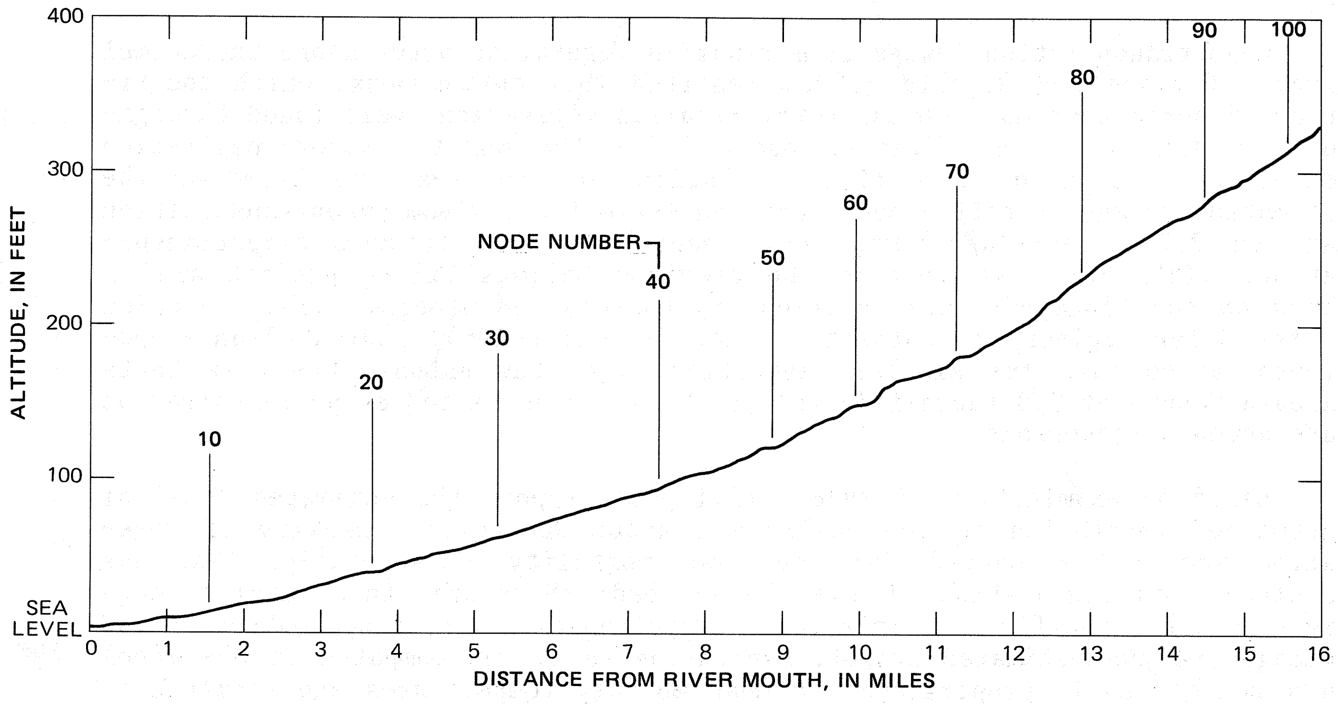


FIGURE 8. – Channel-bed altitude versus upstream river distance, with selected river node numbers for the Carmel River.

Characteristics for the flow-dependent river stage and width components of the leakage equation (a_d, b_d, a_w, and b_w) were derived from the channel geometry. The values thus obtained were a_d=0.3, b_d=0.38, a_w=1.0, and b_w=0.40. The model is not particularly sensitive to these characteristics because of the rapid recovery potential of the aquifer at normal to high riverflows and the relatively large time steps (monthly) used in the model. A more refined model analysis of river leakage would require considerably shorter time steps.

Evapotranspiration Losses

Evapotranspiration loss is the amount of ground water lost through transpiration of plants and evaporation. The rate at which this loss occurs declines from a maximum when the water table is at or near land surface to almost zero as the water table approaches the maximum depth penetrated by roots. Between this maximum depth and the water table there may be a point chosen (depending on the problem) at which the rate is considered insignificant.

Evapotranspiration losses from riparian vegetation occur along the Carmel River. Carlson and Rozelle (1978) reported that cottonwoods, which constituted 85 percent or more of the total riparian vegetation, were found throughout the length of the drainage basin. For the model, evapotranspiration losses were computed by a linear relation to head that was based on the estimated acreage of cottonwood trees, an estimated maximum evapotranspiration rate of 2.7 (acre-ft/acre)/yr, and a depth of 15 ft to zero evapotranspiration. This rate was used in the previous Salinas Valley project and is based on the Blaney-Criddle relationship (Durbin and others, 1978). Studies in the drier regions of southern California (Muir, 1964) indicated an evapotranspiration rate for similar vegetation along San Antonio Creek in Santa Barbara County of 3.0 (acre-ft/acre)/yr; thus the estimated evapotranspiration rate appears reasonable.

Based on examination of 1978 aerial photographs, the estimated total of cottonwood vegetation in the valley was about 200 acres. Density of vegetation was not accounted for, nor was mortality of vegetation that has resulted from degradation of the channel bed; therefore, this total acreage figure may be significantly in error. Evapotranspiration, based on cottonwood acreage and the estimated evapotranspiration rate, was computed in the model on a monthly basis proportional to mean monthly temperatures and altitude of the water table. The monthly distribution of evapotranspiration losses is shown in figure 9, and generated evapotranspiration rates for the entire drainage basin are shown in figure 10. The cycle shown in figure 9 is reflected in figure 10. Maximum evapotranspiration rates were about the same during the 1974-75 predrought years, decreased during the 1976-77 drought, and then increased in 1978, after the drought.

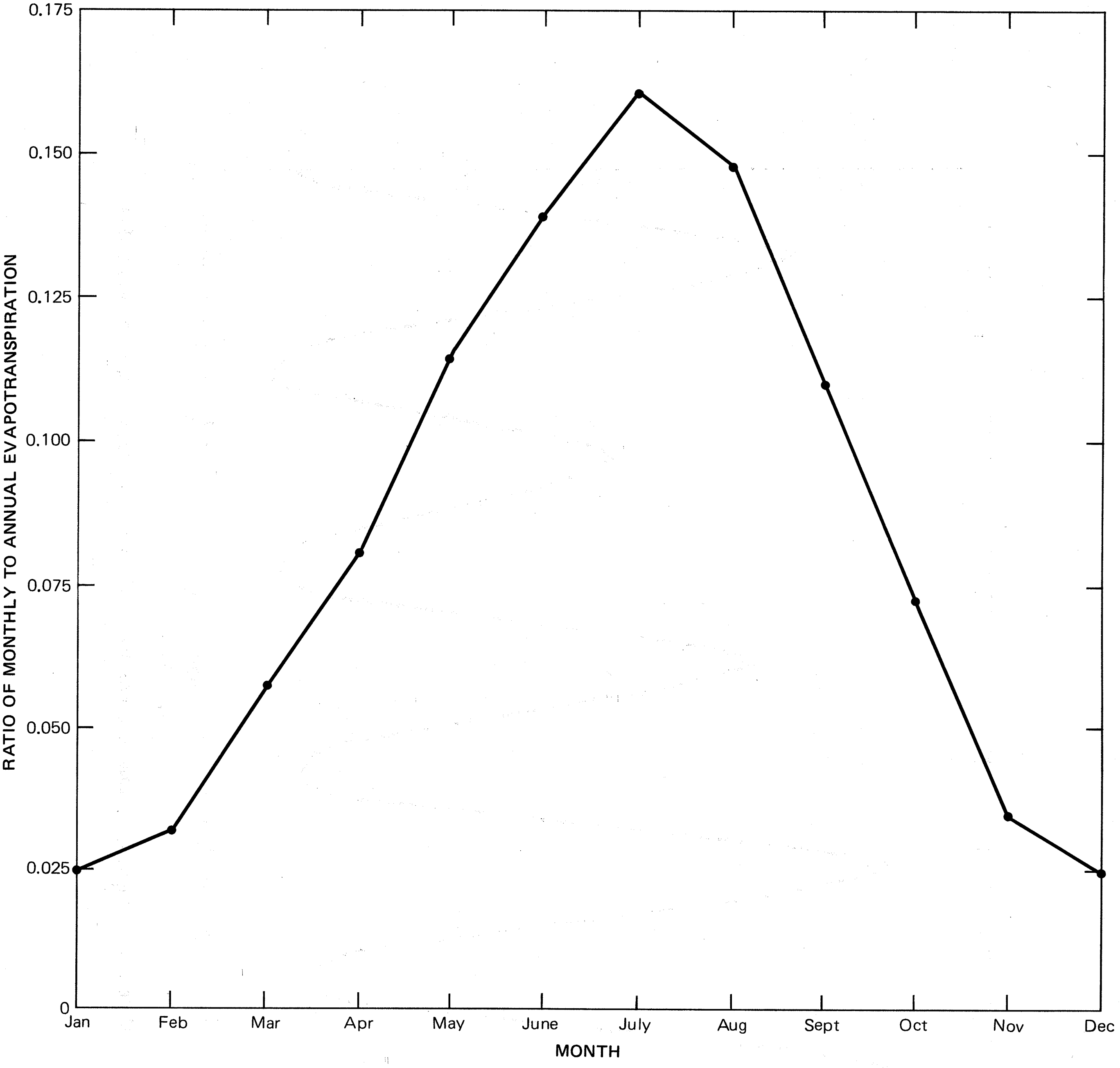


FIGURE 9. – Monthly distribution of phreatophyte evapotranspiration losses used in the digital model.

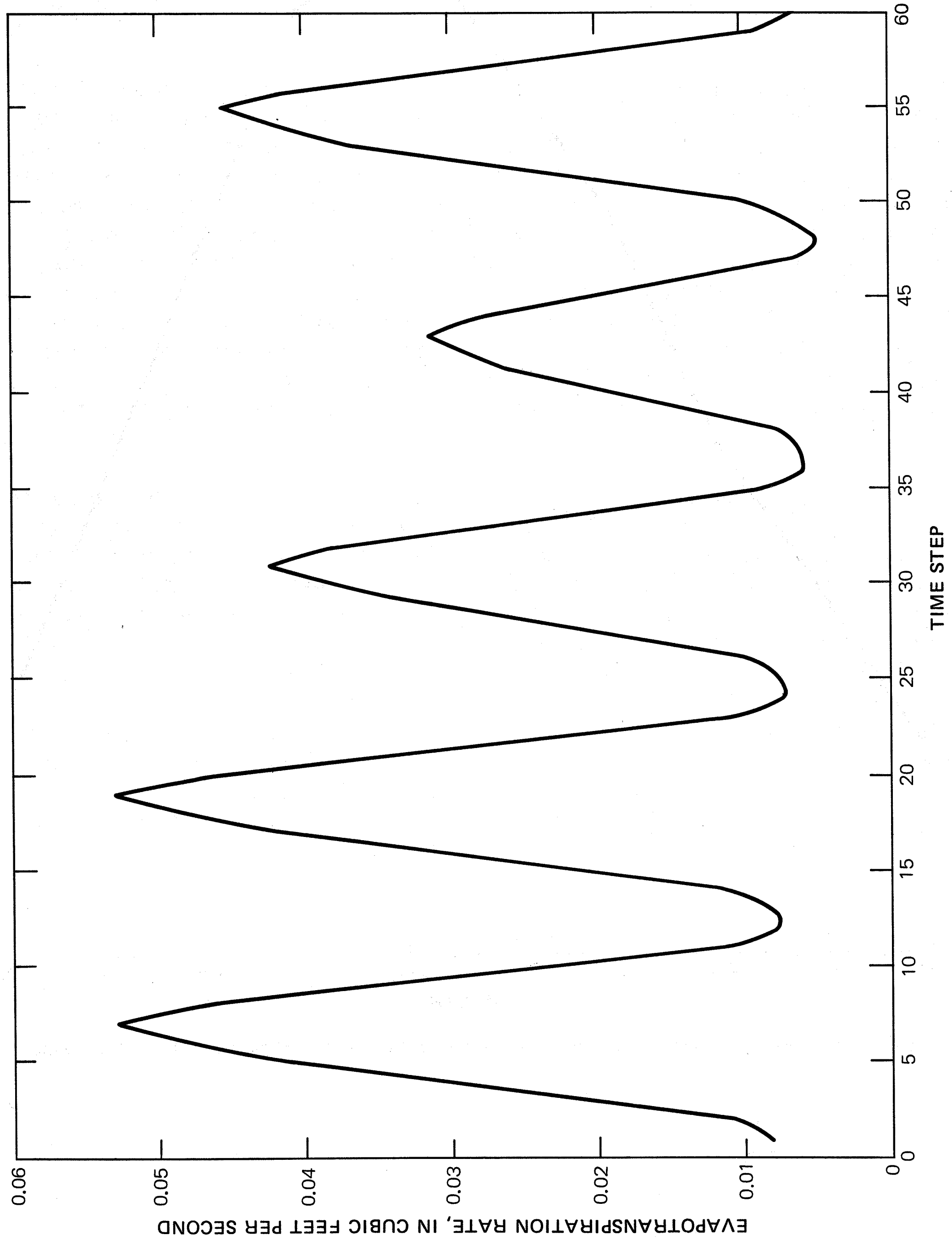


FIGURE 10. — Model computed total evapotranspiration rates for the 60 monthly time steps beginning in January 1974.

Pumpage and Pumpage Return Flow

Pumpage and pumpage return flow were calculated on a monthly basis for 1974 through 1978. For the model, pumpage was subdivided into three categories: municipal, which was tabulated from pumpage records obtained from the California American Water Co. and California Department of Water Resources; agricultural, which includes farmland and golf-course irrigation water estimated on the basis of electrical power use and pump-efficiency factors; and domestic, which includes estimates of pumpage from private wells for domestic use. The annual totals and net percentages for each category are summarized in table 4. During the 5 years, municipal use accounted for 55 percent of the pumpage, agricultural use accounted for 44 percent, and domestic use accounted for 1 percent. Return flows by type are disproportional to the pumpages by type, principally because much of the municipal water is diverted from the drainage basin. From 1974 through 1978 of the total return flow, that from municipal pumpage was 25 percent, that from agricultural pumpage was 72 percent, and that from domestic pumpage was 3 percent. The methods used to compute each total are described below.

TABLE 4. - Annual pumpage and return flow, in acre-feet per year, for 1974-78

Calendar year	Municipal		Agricultural		Domestic		Total	
	Pumpage	Return	Pumpage	Return	Pumpage	Return	Pumpage	Return
1974---------	2,879	259	1,823	601	53	27	4,755	887
1975---------	3,052	294	2,752	908	64	32	5,868	1,234
1976---------	5,772	401	3,280	1,083	89	42	9,141	1,526
1977---------	3,035	157	3,556	1,173	33	14	6,624	1,344
1978---------	3,368	991	2,843	938	119	58	6,330	1,487
Total-----	18,106	1,602	14,254	4,703	358	173	2,718	6,478
Percentage[1]	55.3	24.7	43.6	72.6	1.1	2.7		

[1] Figures represent the percentage of the total 5-year pumpage or return for each type of pumpage.

Municipal Pumpage.--California American Water Co. supplies more than 90 percent of the municipal pumpage. The company's distribution system consists of a single main pipeline that carries ground water as well as water diverted from the San Clemente Reservoir. More than 90 percent of the combined water is exported out of the drainage basin. Monthly meter records of pumpage for individual municipal wells, reservoir diversions, and water piped out of the drainage basin were obtained from California American Water Co. Net monthly deliveries to the drainage basin were calculated by subtracting the quantities diverted from the drainage basin via the pipeline from the sum of pumpage and reservoir diversions supplied to the pipeline. Unpublished monthly pumpage records also were available from Water West Corp., which does not pipe water out of the basin and services a smaller area of Carmel Valley.

Municipal return flow was calculated by first distributing the deliveries throughout the drainage basin according to a service-connection map obtained from the Monterey Peninsula Water Management District. All the drainage basin, except for a small area in the lower part serviced by the Carmel Sanitary District, uses soil-absorption systems. There are approximately 980 unsewered connections out of a total of 1,500 on the valley floor; for the model the monthly deliveries were apportioned equally among the 980 units. Return flow from municipal pumpage was calculated using a net 70 percent of the water supplied from each connection to a soil-absorption system and a net 70 percent of the water leached from each absorption system to the water table (Kennedy Engineers, 1979). Thus, the amount of return flow from municipal deliveries for each unsewered connection, estimated to be 50 percent, was distributed on the basis of unit usage per month.

Agricultural Pumpage.--Agricultural pumpage was calculated from monthly electrical-usage data and pump-efficiency tests obtained from the Pacific Gas and Electric Co. in Monterey. About 20 available pump tests were considered to be representative of the efficiency of the production wells, with energy factors ranging from 100 to 220 kWh/acre-ft. The average from these tests was 150 kWh/acre-ft and, except for the wells that had specific pump tests, the factor of 150 kWh/acre-ft was used to compute pumpage for all agricultural wells that did not have pump-efficiency tests.

Domestic Pumpage.--Domestic pumpage, which accounts for only about 1 percent of total pumpage, was estimated on a unit basis, assuming the same unit usage and return as for the municipal pumpage. There are about 110 domestic wells in the drainage basin.

The agricultural pumpage, the sum of municipal and domestic pumpage, and the total monthly pumpage from the drainage basin during 1974 through 1978 are shown in figure 11. The 1978 distribution of pumpage and recharge in the valley is shown by subsection on plate 1D.

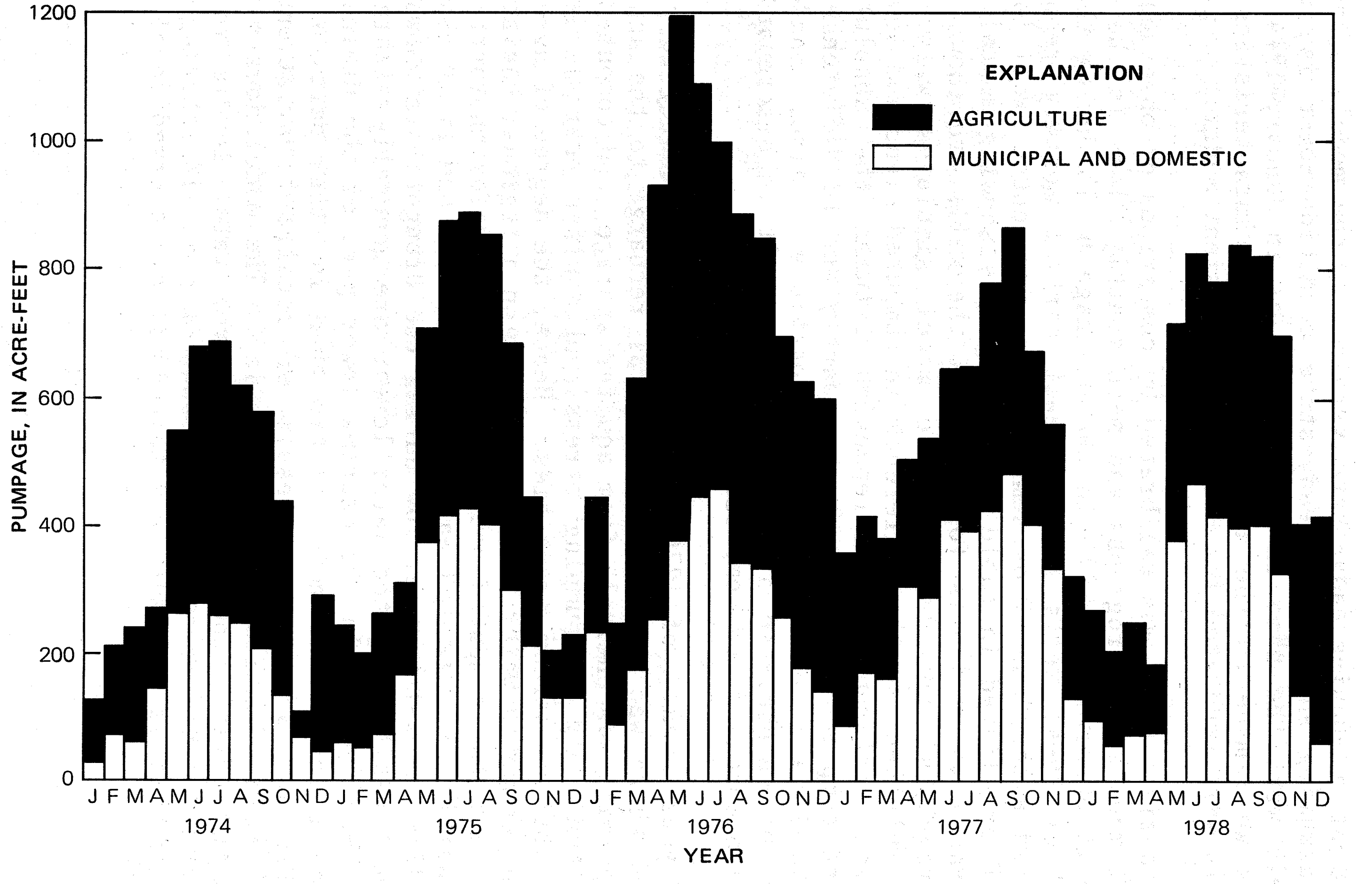


FIGURE 11. – Monthly pumpage from the Carmel Valley drainage basin, 1974 through 1978.

Model Calibration

The model was calibrated for calendar years 1974 through 1978 with monthly time steps and input data discussed in the previous section. During this process, adjustments were made of the aquifer hydraulic conductivity and storage coefficients and the river-channel characteristics. Recharge and discharge data were not changed. The first stage of the calibration involved development of a quasi-steady-state version of the model, using 1974 stress data and assuming an annual steady-state condition--that is, assuming that water levels were the same in January 1975 as in January 1974. Preliminary adjustments were made on the aquifer and river characteristics, and initial water levels were generated for use in the transient model.

The transient model was calibrated by comparison of observed and computed water-level maps and hydrographs and mean monthly flows in the Carmel River. There were 29 observation wells in the drainage basin during the calibration period; 12 of these wells had at least partial monthly records, and the remainder had either annual or semiannual measurements. Well locations shown on plate 1E are listed in table 5. Hydrographs showing monthly measured and model-generated water levels for seven of the wells are shown in figure 12. These hydrographs indicate that the model simulates water-level trends reasonably well because the difference in computed highs and lows agrees with the observed difference. Discrepancies between the absolute values of observed and computed water levels are partly due to differences in altitude between nodal and observation-well locations. Also, inadequate nodal definitions of channel-bed altitudes could result in discrepancies of 5 and 10 ft between observed and computed water levels.

The 2-year drought of 1976-77 provided an opportunity to simulate water levels when there was virtually no natural recharge to the aquifer. During this time pumping was entirely from aquifer storage, and computed water levels were dependent only on pumping stress and aquifer characteristics, not on river or tributary stream properties. Hence, the degree of agreement between observed and computed water levels, at least on a regional basis, is a measure of accuracy for the computed net discharge and aquifer characteristics during drought conditions. Computed water-level contours and field observations for December 1977--the water-level low during the drought--are shown on plate 1E. On a regional basis, computed water levels are generally within 10 ft of the measured water levels. In the extreme lower part of the drainage basin, the observed water levels are more erratic than in other parts of the drainage basin. This may occur as a result of localized variations in aquifer properties due to lenticular silt and clay. The model does not accommodate these irregularities. Computed and observed water levels for April 1978, after the aquifer had recovered, are shown on plate 1E. During this time the computed water levels were always within 13 ft of observed levels.

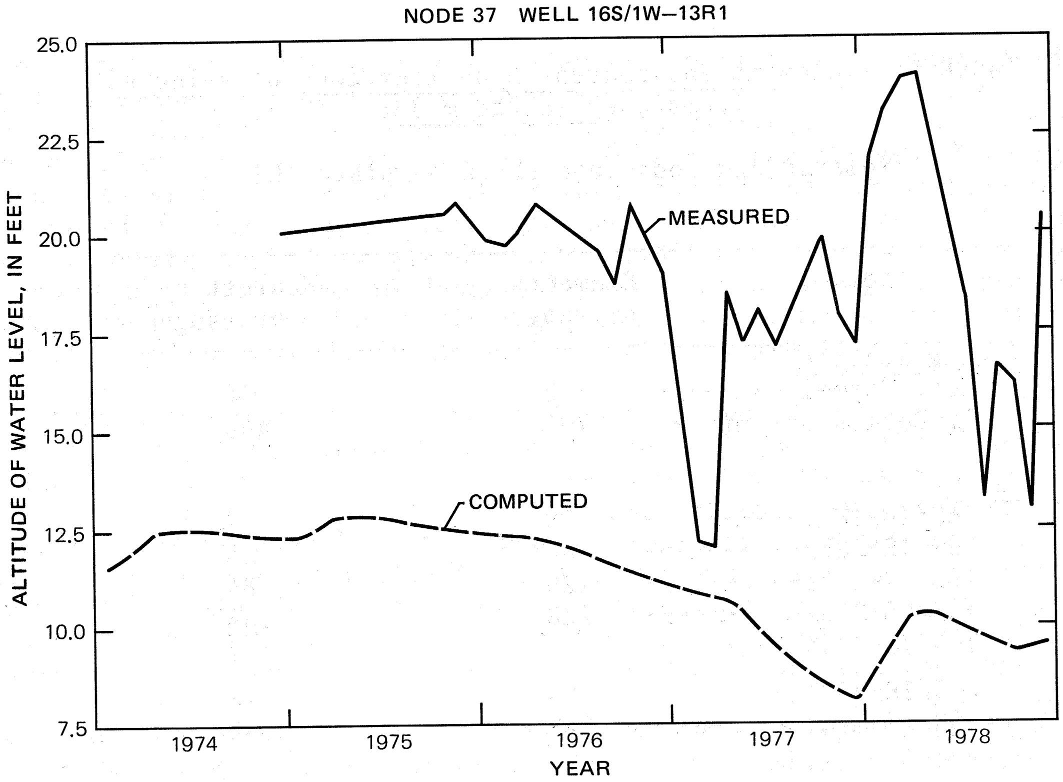
TABLE 5. - Element and nearest node locations of selected items used in the model

[Elements and nodes are shown on plate 1C]

Item	Elements or range	Nearest node or range
Gaging stations		
Near Carmel----------	142	94
At Robles Del Rio----	704	440
Wells		
16S/1W-13R1----------	58	37
16S/1E-18F2----------	87	54
16S/1E-17L3----------	126	84
16S/1E-22E2----------	228	148
16S/1E-22J1----------	267	167
16S/1E-25B1----------	363	227
16S/2E-32A1----------	548	348
Discharge-recharge subsections[1]		
1-----------------	1-32	1-25
2-----------------	25-72	26-50
3-----------------	65-112	51-75
4-----------------	105-152	76-100
5-----------------	145-192	101-125
6-----------------	185-232	126-150
7-----------------	225-272	151-175
8-----------------	265-312	176-200
9-----------------	305-352	201-225
10-----------------	345-392	226-250
11-----------------	385-432	251-275
12-----------------	425-472	276-300
13-----------------	465-512	301-325
14-----------------	505-552	326-350
15-----------------	545-592	351-375
16-----------------	585-632	376-400
17-----------------	625-672	401-425
18-----------------	665-712	426-450
19-----------------	705-752	451-475
20-----------------	745-792	476-500
21-----------------	785-832	501-525

---

[1] Subsection boundaries pass through elements and nodes.



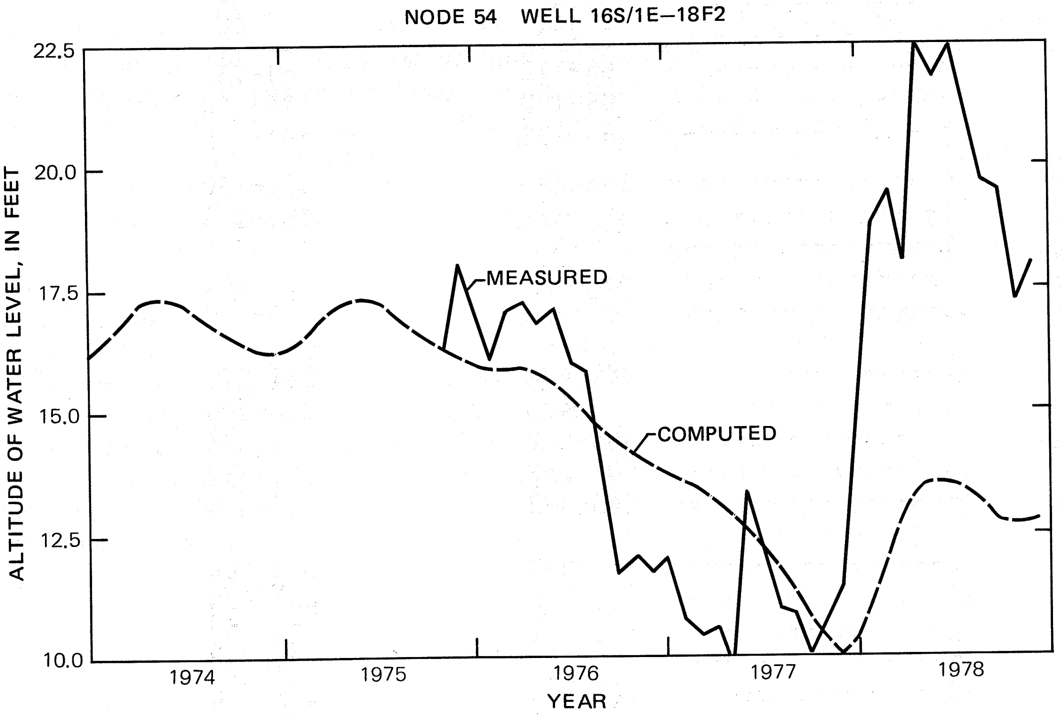


FIGURE 12. – Hydrographs showing monthly measured and model-generated water levels in seven wells in the Carmel Valley drainage basin.

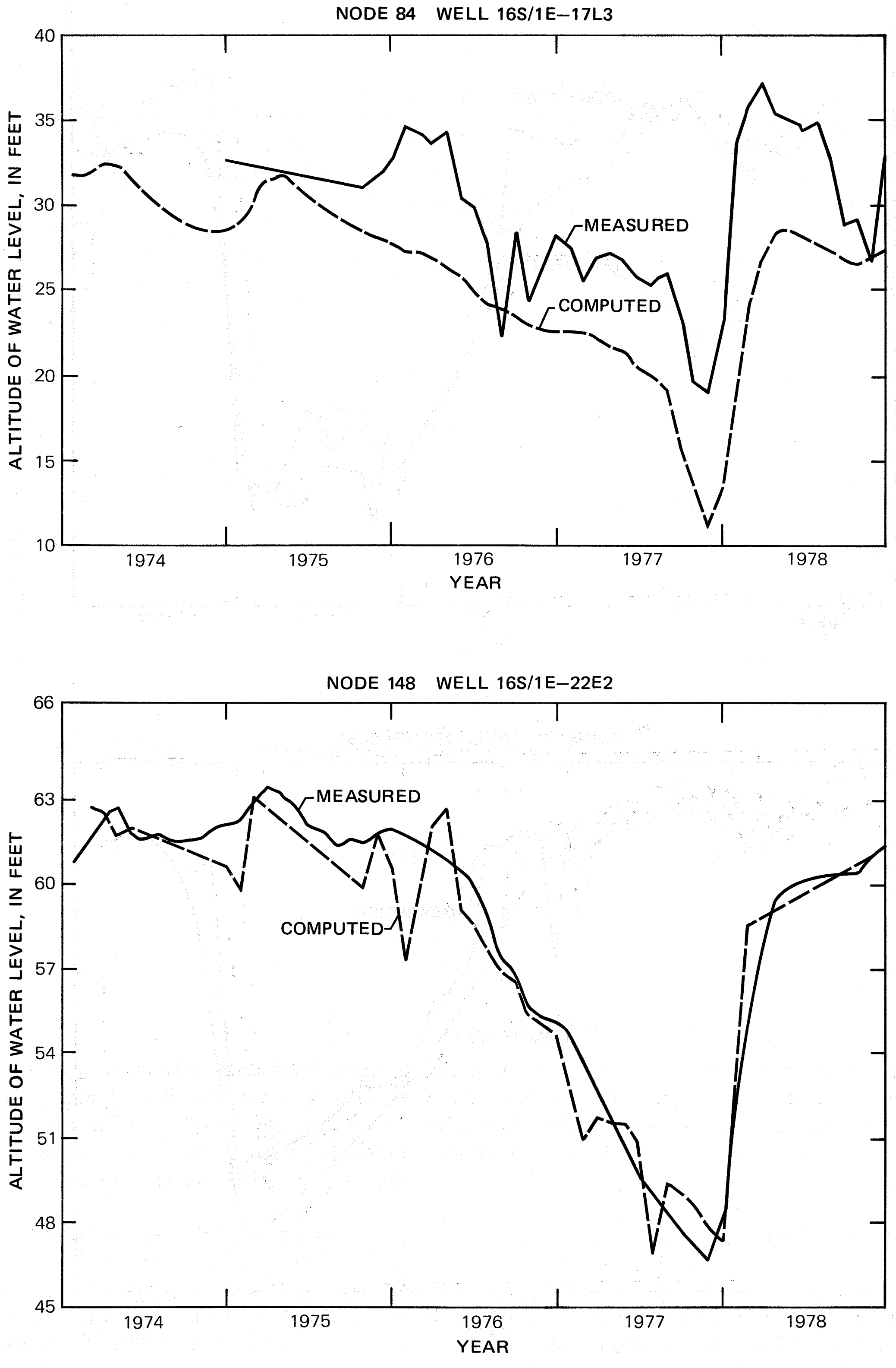
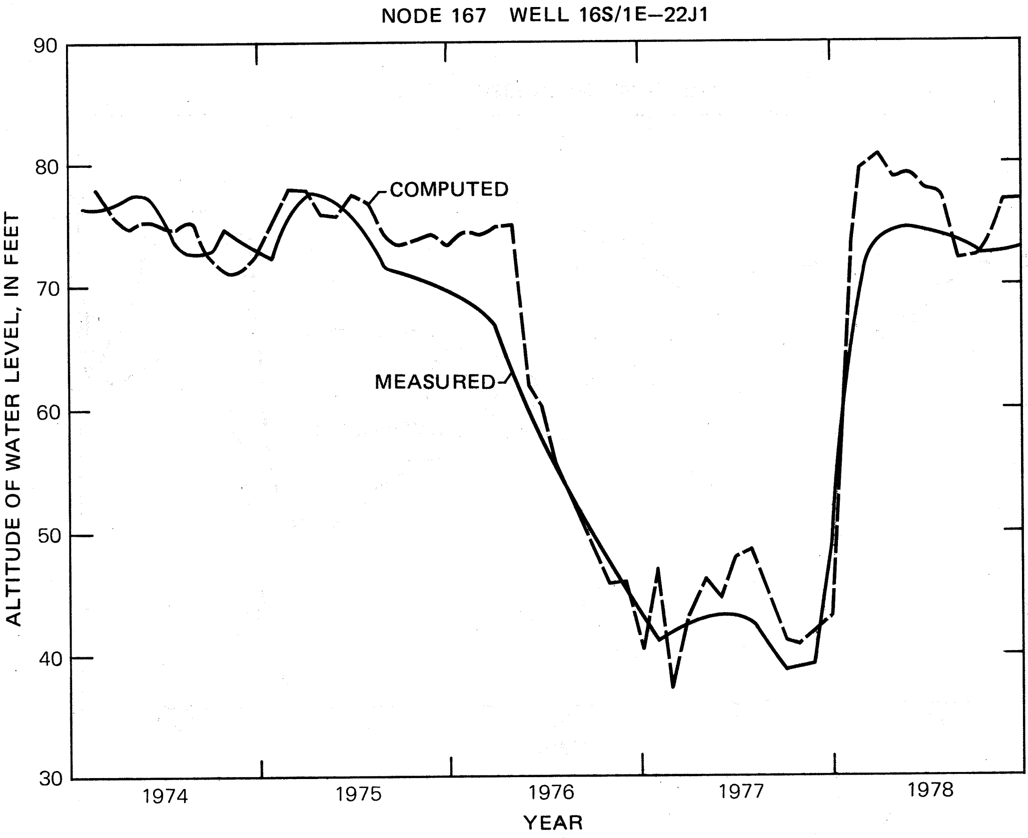
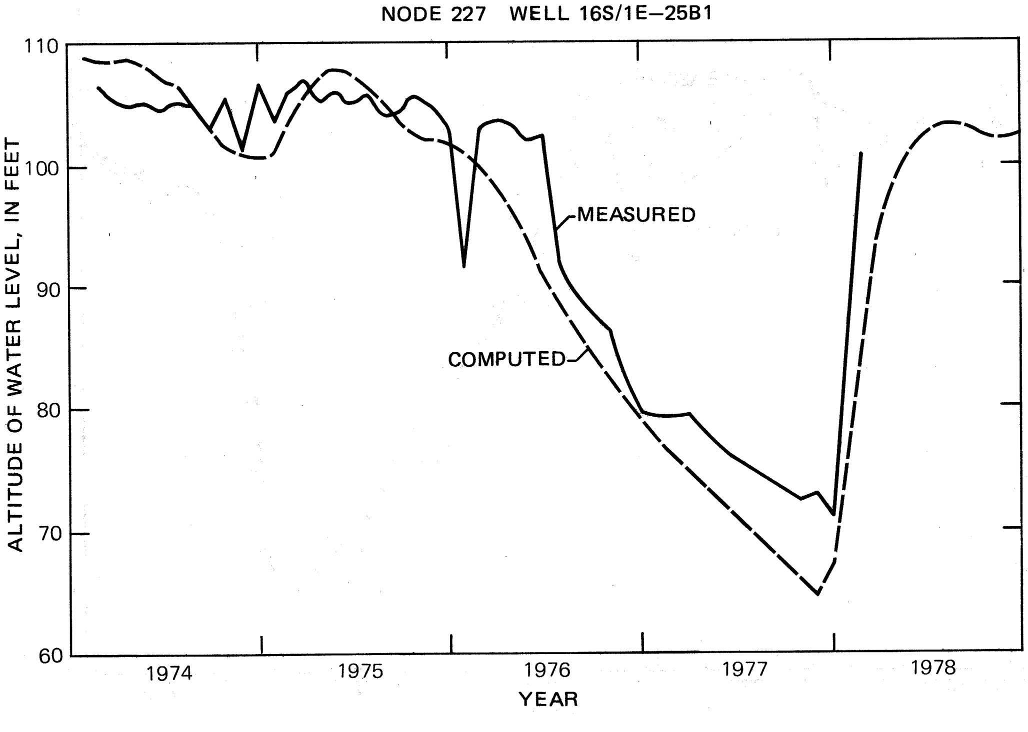


FIGURE 12. – Continued.



NODE 167 WELL 16S/1E–22J1



NODE 227 WELL 16S/1E–25B1

FIGURE 12. – Continued.

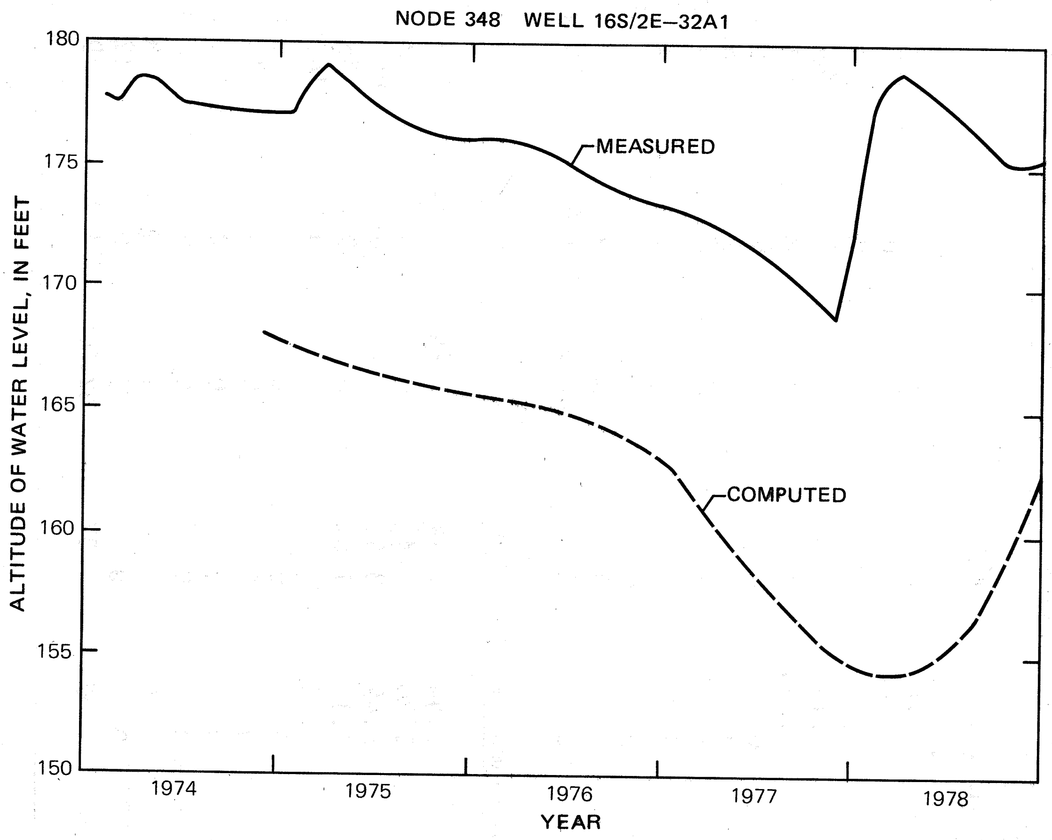


FIGURE 12. – Continued.

Mean monthly and model-generated flows in the Carmel River at the gages near Carmel and at Robles Del Rio are shown in table 6. Gage locations are shown on plate 1A. The table indicates that the model simulates riverflows very well. Differences in flows between the gages for measured and generated values have a correlation coefficient of 0.81.

Model-Generated Results.--In the spring, during normal rainfall years, the model computed a net storage of about 40,000 acre-ft (fig. 13) and an aquifer discharge rate to the ocean of about 215 to 230 acre-ft/yr (fig. 14). In the autumn, the computed storage of normal rainfall years declined to between 37,000 and 38,000 acre-ft. In the autumn of 1977, after a 2-year drought, storage was reduced to 32,000 acre-ft, and the discharge rate decreased to 156 acre-ft/yr. Imposed pumping restrictions lessened the effect of the drought on aquifer conditions. Had the 1976 pumping rates continued through 1977, the quantity of storage probably would have been reduced to less than 30,000 acre-ft and the aquifer discharge rate probably would have decreased to less than 100 acre-ft/yr.

TABLE 6. - Measured and computed flows, in cubic feet per second, in the Carmel River

	1974		1975		1976		1977		1978	
	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed
				Near Carmel (nearest node 94)						
January------	302	292	28.5	24.7	0.37	0	0	0	650	619
February-----	86.4	88.4	534	536	.38	0	0	0	789	855
March--------	479	559	672	674	.58	.26	0	0	698	743
April--------	375	363	233	226	.40	0	0	0	324	325
May----------	70	83.4	98.5	86.7	.044	0	0	0	145	158
June---------	14.7	14.4	23.0	16.6	0	0	0	0	66.1	48.9
July---------	1.97	2.80	2.01	3.53	0	0	0	0	8.81	7.11
August-------	.35	.11	.22	0	0	0	0	0	3.58	1.29
September----	.21	0	.09	0	0	0	0	0	1.79	0
October------	.35	0	.30	0	0	0	0	0	.59	.47
November-----	.56	.10	.41	0	0	0	0	0	3.09	7.71
December-----	5.68	17.8	.50	0	0	0	20.5	2.4	16.4	15.8
				At Robles Del Rio (nearest node 440)						
January------	253	258	26.1	26.6	1.44	1.44	0.40	0.21	574	586
February-----	77.6	78.9	465	476	1.36	1.34	0	0	754	771
March--------	479	490	577	591	3.49	3.41	.01	0	647	662
April--------	310	317	194	199	1.11	1.03	0	0	285	292
May----------	72.7	74.2	77.0	78.8	.25	.19	0	0	142	145
June---------	14.7	14.8	17.6	17.9	0	0	0	0	48.0	48.8
July---------	4.10	4.10	5.88	5.95	0	0	0	0	10.4	10.4
August-------	.51	.52	.68	.73	0	0	0	0	4.29	4.29
September----	.22	.23	.45	.50	0	0	0	0	2.15	2.16
October------	.58	.58	.72	.76	.16	.05	0	0	4.14	4.14
November-----	1.48	1.47	1.43	1.46	0	0	0	0	12.7	12.8
December-----	20.4	20.7	1.51	1.53	.02	.07	42.3	41.2	19.8	20.8

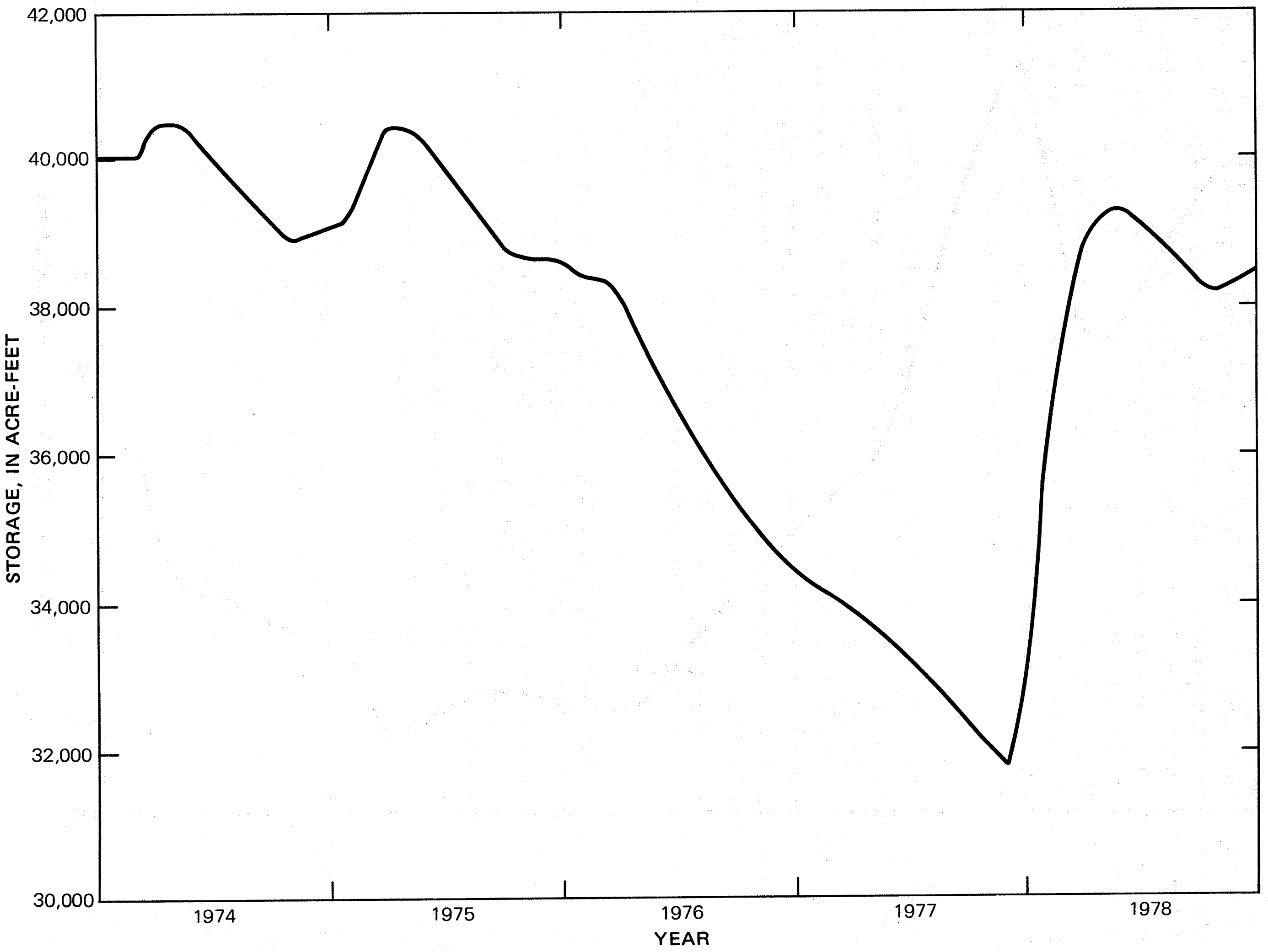


FIGURE 13. – Total aquifer storage in the modeled area.

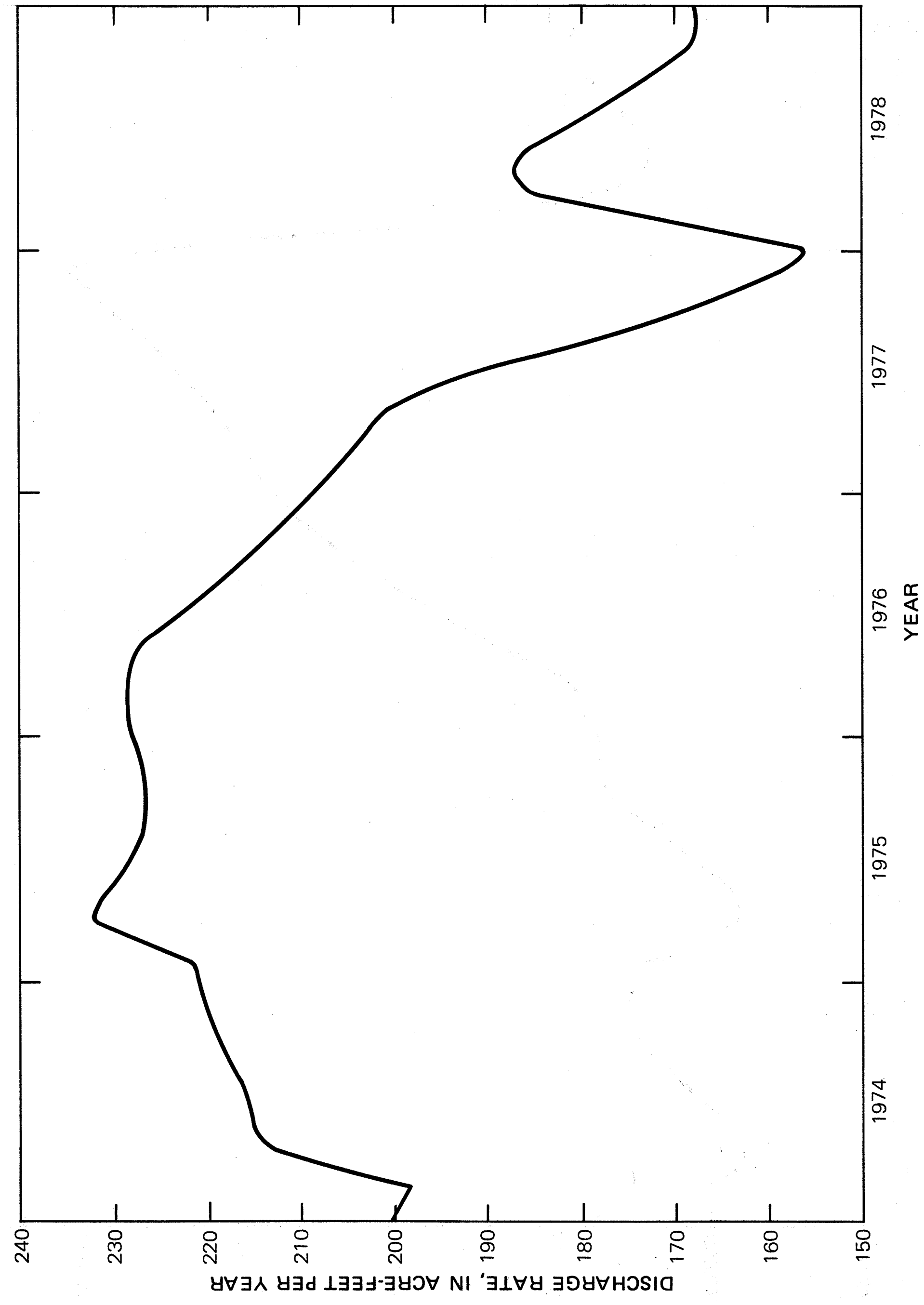


FIGURE 14. — Aquifer discharge to ocean.

SUMMARY AND CONCLUSIONS

Rapid urban growth and droughts cause stress on the ground-water system in the Carmel Valley drainage basin. A two-dimensional, digital, ground-water flow model was developed and calibrated using available data from 1974 through 1978 to provide a better understanding of the geohydrology of the drainage basin, and to identify areas of inadequate data. Pumping rates during those years ranged from 5,900 to 9,100 acre-ft/yr, with 55 percent allotted to municipal use principally exported out of the valley, 44 percent to agricultural use, and 1 percent to domestic use. Pumpage return flow within the valley ranged from 900 to 1,500 acre-ft/yr. Discharge from phreatophytes was estimated from the acreage of cottonwood trees, assuming an evapotranspiration rate of 2.7 acre-ft/yr. Tributary runoff from the 23 major subbasins was calculated by correlation from the gaged inflows at the Robles Del Rio station, and above and below that station from the drainage areas and mean annual precipitation over the subbasins. This calculation indicates that tributary flow to the basin below the gage was about 20 percent of the gaged inflow.

The thickness of the alluvium averages 75 ft and is adequately defined by well logs. Hydraulic conductivities were, for the most part, derived from the calibration process. Transmissivity averaged 5,900 ft^2/d, and storage coefficients averaged 0.19. Hydraulic conductivity and storage coefficients in the lower valley were reduced during calibration from the original estimates. The calibrated model produced lower hydraulic conductivities and storage coefficients in the lower part of the valley and probably reflects the presence of silt, clay, and fine-grained sand in the younger alluvium found there. The reduction in storage coefficients, however, was not indicative of a confined aquifer condition.

Channel-bed samples were collected and analyzed from the lower 5 mi of the river, and hydraulic conductivities for the channel bed were determined on the basis of sediment characteristics. The analysis indicated a downstream decrease from about 10,000 to 1,000 $(gal/d)/ft^2$. These data were used in the model as part of the river-leakage calculation along with aerial-survey data defining altitude of the river channel. Other characteristics, pertaining to flow-dependent flow widths and depths, were estimated and adjusted during calibration.

Model calibration is reasonable except in the extreme lower part of the drainage basin. Discrepancies in this area could result from localized and undefined lenticular silt and clay. On a regional basis, computed water levels were within a few feet of observed levels. Toward the end of the 1976-77 drought, computed water levels were within 13 ft of the measured water levels.

The model is intended principally for simulation of flow conditions using monthly time steps. The data base used to develop this model is adequate for present purposes, but the nonuniqueness of solutions with respect to different sets of data indicates the model does not necessarily validate the correctness of the individual variables. For example, an error in net pumpage could be counterbalanced by an error in the storage coefficients. Possible improvements of the data and the computational algorithm might include:

1. Samples could be collected from small-diameter wells drilled in the lower end of the valley. Drilling would provide knowledge of the distribution of confining sediments and aquifer properties above and below them.
2. Additions could be made in the solution algorithm used for future modeling studies with a more refined data base. The model could account for confinement or partial confinement in the lower end of the valley. The model also might include contributions from the Tularcitos aquifer.

In the process of defining a conceptual model and building and running the mathematical model, it became apparent that the single most important source of recharge to the alluvial ground-water basin is the Carmel River. Not only does the Carmel River with its tributary flows account for most of the recharge to the alluvial aquifer, but its sustained flow into the pumping season helps to moderate the lowering of water levels. The Carmel Valley alluvial aquifer is a river-channel aquifer composed of deposited river sediments; water levels in these river sediments are principally maintained by the altitude of the bottom of the river's present channel when there is riverflow.

Construction of reservoirs upstream from the alluvial valley has removed most of the river's sediment load previously used to build the alluvial aquifer and maintain the altitude of the river channel. Although regulated flow may have made the Carmel River more effective as a recharging source throughout a larger part of the year, the loss of upstream sediment transported to the alluvial valley coupled with the river's removal and man's extraction of sand and gravel from the river channel in the alluvial valley has caused declines in river-channel altitudes. Declines in river-channel altitudes directly cause lower water levels in the alluvial aquifer even if no pumping stress were present. With or without pumping stress, the water table during the dry season can be no higher than the altitude of the adjacent river channel. Consequently some riparian vegetation on adjacent banks or terraces would be partially or completely deprived of water during the dry season.

Superimposed on this hydrogeologic system is a considerable dry-season pumping stress. Given the present river-channel geometry, the model addresses the effects of increased pumping stress throughout a severe drought cycle when the Carmel River ceases to be an effective source of recharge during a 2-year drought. It appears that after severe stressing the aquifer will recover to its natural water level, defined by river-bed altitude, within a month or less of sustained riverflow.

SELECTED REFERENCES

Bear, Jacob, 1972, Dynamics of fluids in porous media: New York, American Elsevier, 764 p.

Bowen, O. E., 1965, Stratigraphic structure and oil possibilities in Monterey and Salinas quadrangles, California, in American Association of Petroleum Geologists: 40th Annual Meeting Pacific Section, Bakersfield, Calif., p. 48-67.

______1969, Geologic map of the Monterey quadrangle, California: California Division of Mines, scale 1:24,000.

California American Water Co., Monterey Peninsula District, 1976, Canada de la Segunda pipeline, and Begonia Iron Removal Plant: Monterey, Calif., Draft environmental impact report, 90 p.

California Department of Water Resources, 1969, Carmel River basin water quality investigation: San Joaquin District, A water-quality investigations memorandum report prepared for the Central Coastal Regional Water Quality Control Board, 46 p.

______1974, Zone 11 Investigation - Carmel Valley and seaside ground water basins, Monterey County: San Joaquin District, 25 p.

______1977, Carmel Valley - thickness of alluvium: San Joaquin District, letter to Monterey County Flood Control and Water Conservation District, December 16, 1977, plates 2A and 2B.

California State Public Utilities Commission, 1974, A summary report of facts, analysis and conclusions relating to the Monterey Peninsula water supply problems: California State Public Utilities Commission Case 9530.

Carlson, F. R., and Rozelle, K. D., 1978, Carmel Valley vegetation study: San Francisco, Calif., CH2M Hill, Inc., Report to the Monterey County Flood Control and Water Conservation District, 52 p.

Carmel Valley Master Plan Study Committee, 1978, Technical analysis planning recommendations for the Carmel Valley Master Plan: Carmel Valley, Calif., 25 p.

Clark, J. C., Dibblee, T. W., Jr., Greene, H. G., and Bowen, O. E., Jr., 1974, Preliminary geologic map of the Monterey and Seaside 7.5-minute quadrangles, Monterey County, California, with emphasis on active faults: U.S. Geological Survey Miscellaneous Field Studies Map MF-577, scale 1:24,000, 2 sheets.

Clayton, C. J., 1978, Zone 11 Monterey County Flood Control and Water Conservation District--Review of studies and reports for supplemental water supply for Zone 11 compiled: various pagination.

Corey, A. T., 1969, Flow in porous media: Fort Collins, Colorado State University, Agricultural Engineering Department Pub. AEP68-69ATC42, 259 p.

Dames and Moore, Consulting Engineers, 1973, Yield of alluvial aquifer in Carmel Valley near Carmel-by-the-Sea, California: Los Angeles, Report to California American Water Co., 37 p.

Davis, S. N., and DeWiest, R. J. M., 1966, Hydrogeology: New York, John Wiley, 463 p.

Dibblee, T. W., 1974, Geologic map of the Jamesburg quadrangle, California: U.S. Geological Survey open-file map, scale 1:62,500.

Durbin, T. J., 1978, Calibration of a mathematical model of the Antelope Valley ground-water basin, California: U.S. Geological Survey Water-Supply Paper 2046, 51 p.

Durbin, T. J., Kapple, G. W., and Freckleton, J. R., 1978, Two-dimensional and three-dimensional digital flow models for the Salinas Valley ground-water basin, California: U.S. Geological Survey Water-Resources Investigations 78-113, 134 p.

Earth Metrics, Inc., Consulting Engineers, 1977, Aquifer recharge case study technical report: Report for the Association of Monterey Bay Area Governments, 68 p.

Esmaili and Associates, Inc., 1978, Nonpoint sources of ground-water pollution in Santa Cruz and Monterey Counties, California: Berkeley, Calif., various pagination.

Fiedler, W. M., 1944, Geology of the Jamesburg quadrangle, Monterey County, California: California Division of Mines Report 40, p. 177-250, pl. 9: Geologic map of the Jamesburg quadrangle, Monterey County, California, scale 1:62,500.

Graham, S. A, 1976, Tertiary sedimentary tectonics of the central Salinian Block of California: Stanford, Calif., Stanford University Geology Department, Doctoral dissertation, 443 p.

Greene, H. G., 1977, Geology of the Monterey Bay Region: U.S. Geological Survey Open-File Report 77-718, 347 p.

Greene, H. G., and Clark, J. C., 1979, Neozene paleogeography of the Monterey Bay Area, California, in Cenezoic paleography of the western United States: Pacific Coast Paleography Symposium, 3d, San Francisco, 1979, 335 p.

Greene, H. G., Lee, W. H., McCulloch, D. S., and Brabb, E. E., 1973, Fault map of the Monterey Bay Region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-518, scale 1:200,000, 4 sheets.

Greenwood, R., 1978, Water supply for Carmel Valley Master Plan Study Commission: Monterey, Calif., 15 p.

Hood, A. G., 1973, Sanitary engineering investigation of water quality, Carmel River and Carmel Valley ground water, Monterey County, Water Sanitary Section, California State Department of Health: Monterey, Calif., 3 p.

Kennedy Engineers, 1979, Carmel Valley/Highlands study, Carmel Sanitary District areawide facilities plan: San Francisco, Project report, various pagination.

Krumbein, W. C., and Monk, G. D., 1942, Permeability as a function of the size parameters of unconsolidated sand, in Transactions of the American Institute of Mining and Metallurgical Engineers: v. 151, p. 153-163.

Lawson, A. C., 1893, The geology of Carmelo Bay: University of California Publications in Geological Sciences, v. 1, no. 1, p. 1-59.

Lee, E. B., 1978, Background for consideration of expanding water extraction from the Carmel Valley aquifer: Report prepared for Monterey County Board of Supervisors, 6 p.

Monterey County Flood Control and Water Conservation District, 1968-75, Ground water and climatology: Monterey, Calif., annual issue.

Monterey Peninsula Water Management District, 1979, Report to the California Coastal Commission: Monterey, Calif., various pagination.

Muir, K. S., 1964, Geology and ground water of San Antonio Creek Valley, Santa Barbara County, California: U.S. Geological Survey Water-Supply Paper 1664, 53 p.

Neill Engineers and Hahn, Wise and Associates, Inc., Consulting Engineers, 1969, Public service and facilities element of the General Plan -- Carmel Valley-Carmel Highlands study area: Carmel, Calif., various pagination.

Pinder, G. F., and Frind, E. O., 1972, Application of Galerkin's procedure to aquifer analysis: Water Resources Research, v. 8, no. 1, p. 108-120.

Planning Collaborative, Inc., Consulting Engineers, 1978, Recommended management guidelines--Aquifer recharge protection, AMBAG 208 Program: Report for the Association of Monterey Bay Area Governments, 26 p.

Rantz, S. E., 1969, Mean annual precipitation in the California region: U.S. Geological Survey open-file map, scale 1:1,000,000.

Simpson, J. P., III, 1972, The geology of Carmel Bay, California: Monterey, Calif., Naval Postgraduate School thesis, 74 p.

Thorup, R. R., 1976, Ground-water study of the Carmel Valley Ranch and Carmel River watershed, Monterey Peninsula, Monterey County, California: Monterey, Calif., Consultant's report for the Monterey County Planning Commission hearing on Carmel Valley Ranch, March 31, 1976, 24 p.

______1979, Ground-water report on the Carmel Valley Ranch and Carmel River watershed, Monterey County, California: Monterey, Calif., Consultant's report for the Carmel Valley Ranch, 22 p.

Trask, P. D., 1926, Geology of Point Sur quadrangle, California: University of California Publications in Geological Sciences, v. 16, M.S. thesis, 74 p.

U.S. Army Corps of Engineers, 1977, Carmel River, Monterey County, California, Progress report for water resources development: Monterey, Calif., various pagination.

______1979, Feasibility report for water resources development for Carmel River, Monterey County, California: Monterey, Calif., 111 p.

U.S. Department of Agriculture, 1977, Soil survey of Monterey County: Monterey, Calif., Soil Conservation Service, 90 p.

Waananen, A. O., and Crippen, J. R., 1977, Magnitude and frequency of floods in California: U.S. Geological Survey Water-Resources Investigations 77-21, 96 p.

Kapple and others--CARMEL VALLEY ALLUVIAL GROUND-WATER BASIN, CALIFORNIA--WRIR 83-4280