SIMULATION OF FRESHWATER AND SALTWATER FLOW IN THE COASTAL AQUIFER SYSTEM OF THE PURISIMA FORMATION IN THE SOQUEL-APTOS BASIN, SANTA CRUZ COUNTY, CALIFORNIA

By Hedeff I. Essaid

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4148

Menlo Park, California
1992

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

For sale by the Books and
Open-File Reports Section,
U.S. Geological Survey
Federal Center, Box 25425
Denver, Co 80225

For additional information write to:
Regional Hydrologist
U.S. Geological Survey
345 Middlefield Rd., MS 466
Menlo Park, CA 94025

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Conversion Factors

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6215	mile
square kilometer (km^2)	0.3861	square mile
millimeter per year (mm/yr)	0.03937	inch per year
meter per second (m/s)	3.281	foot per second
cubic meter per second (m^3/s)	35.32	cubic foot per second
cubic meter per year (m^3/yr)	35.32	cubic foot per year

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation:

$$°C = (°F)-32/1.8.$$

Vertical Datum

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

SIMULATION OF FRESHWATER AND SALTWATER FLOW IN THE COASTAL AQUIFER SYSTEM OF THE PURISIMA FORMATION IN THE SOQUEL-APTOS BASIN, SANTA CRUZ COUNTY, CALIFORNIA

by Hedeff I. Essaid

Abstract

A quasi-three-dimensional, finite-difference model that simulates freshwater and saltwater flow separated by a sharp interface has been used to study the layered coastal aquifer system of the Purisima Formation in the Soquel-Aptos basin, Santa Cruz County, California. The model has been used to evaluate the potential for seawater intrusion in the Soquel-Aptos basin. Ground water extracted from the system has come mainly from capture of stream baseflow, rather than from reduction of offshore freshwater discharge. Simulation suggests that the interface today is still responding to long-term Pleistocene sea-level fluctuations and has not achieved equilibrium with present-day sea-level conditions. The rate of movement of the interface in response to increased ground-water pumpage that has occurred over the past 50 years is probably of the same order of magnitude as the longer term responses. These results have implications for understanding the long-term development of the Soquel-Aptos system.

INTRODUCTION

The Soquel-Aptos area lies between latitudes 36°55' N. and 37°10' N. and longitudes 121°45' W. and 122°05' W. (fig. 1). It extends from the Scotts Valley area on the west to Watsonville on the east, and from the San Andreas Fault on the north to the Monterey Bay on the south. This study concentrates on the part of the Soquel-Aptos basin that is southwest of the Zayante Fault. The study area includes the eastern part of the city of Santa Cruz, as well as the towns of Soquel, Aptos, and Capitola, and covers about 150 km^2. Physiographically, the area varies from very steep valley slopes and angular landforms in the Santa Cruz Mountains, to nearly flat marine terraces, sea cliffs, and narrow beaches at the coast of the Monterey Bay. The area is drained mainly by Branciforte, Soquel, and Aptos Creeks (fig. 1). Offshore, in the Monterey Bay, the Monterey Canyon trends southwesterly about 65 km from its head at Elkhorn Slough to the base of the continental slope (fig. 2). It is one of the largest submarine canyon complexes in the eastern Pacific Ocean and is similar in dimensions to the Grand Canyon of the Colorado River.

The development of the Santa Cruz-Monterey area began with the establishment of a Franciscan mission in Santa Cruz in 1791. Both the population and agriculture increased gradually during the early 19th century but increased rapidly in the 1850's owing to migration of settlers from the mining counties that led to the accelerated development of homes, resorts, and irrigated agriculture. Today the Soquel-Aptos region is mainly an urban area with very little active agriculture or industry. Land use is primarily residential, commercial, recreational, and open space. The results of land use surveys for 1948-49 (California State Water Resources Board, 1953) and 1976 (Montgomery Consulting Engineers, 1976) are summarized in table 1 and show that the area has undergone considerable development. Urban growth in the Soquel-Aptos area has led to an increased demand for water. In 1950, the draft from the system was estimated at 0.7 million m^3/yr (California State Water Resources Board, 1953). In 1984, the Soquel Creek Water District delivered about 6.0 million m^3/yr, with 4 million m^3/yr pumped from the Purisima Formation (Luhdorff and Scalmanini, Consulting Engineers, 1985). Projected water requirements for the year 2020 are 14 to 15 million m^3 (Montgomery Consulting Engineers, 1976).

The Soquel Creek Water District encompasses about 30 km^2 along the Santa Cruz coastline (fig. 3) and initially represented the combination of facilities originally owned and operated by the Monterey Bay

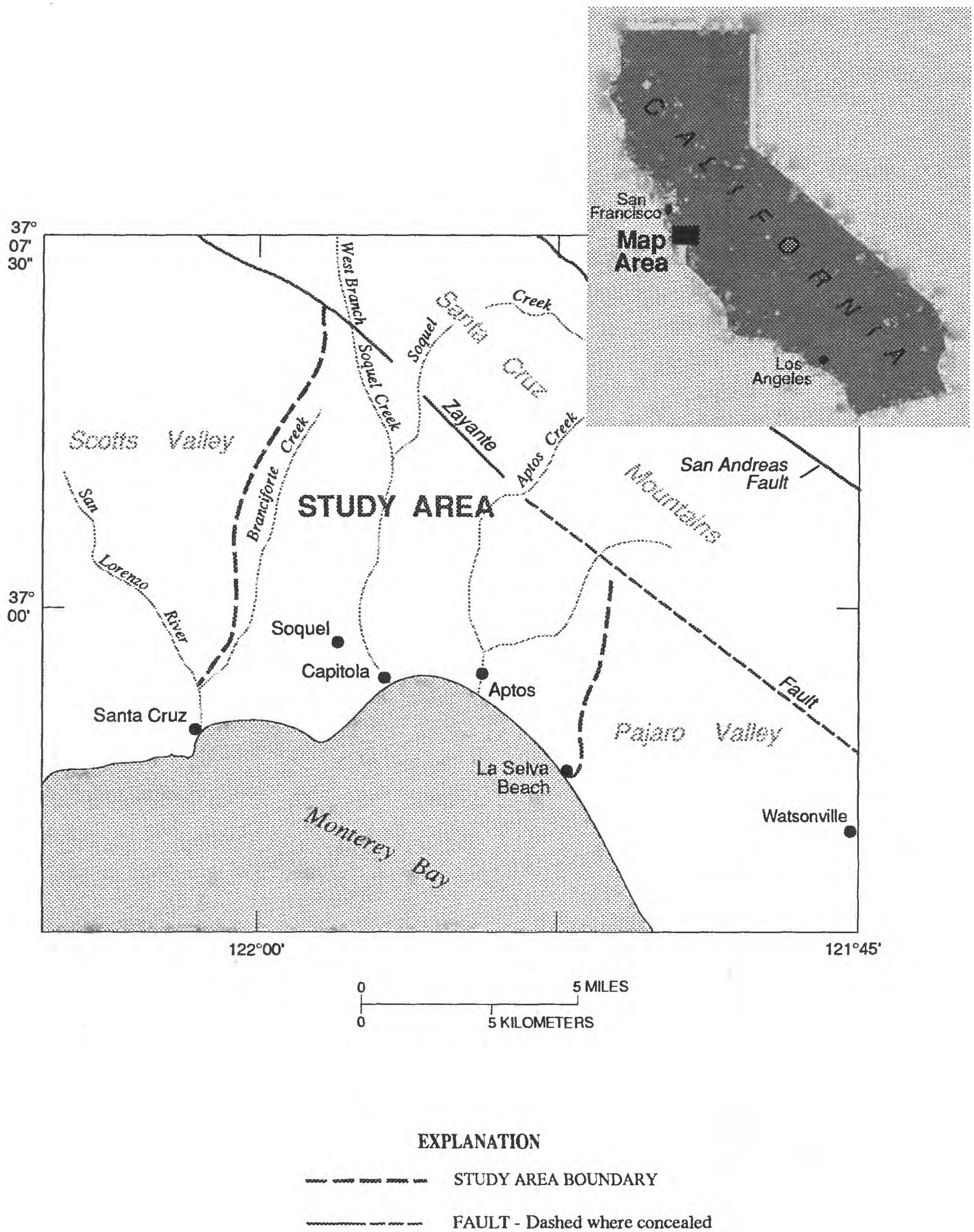
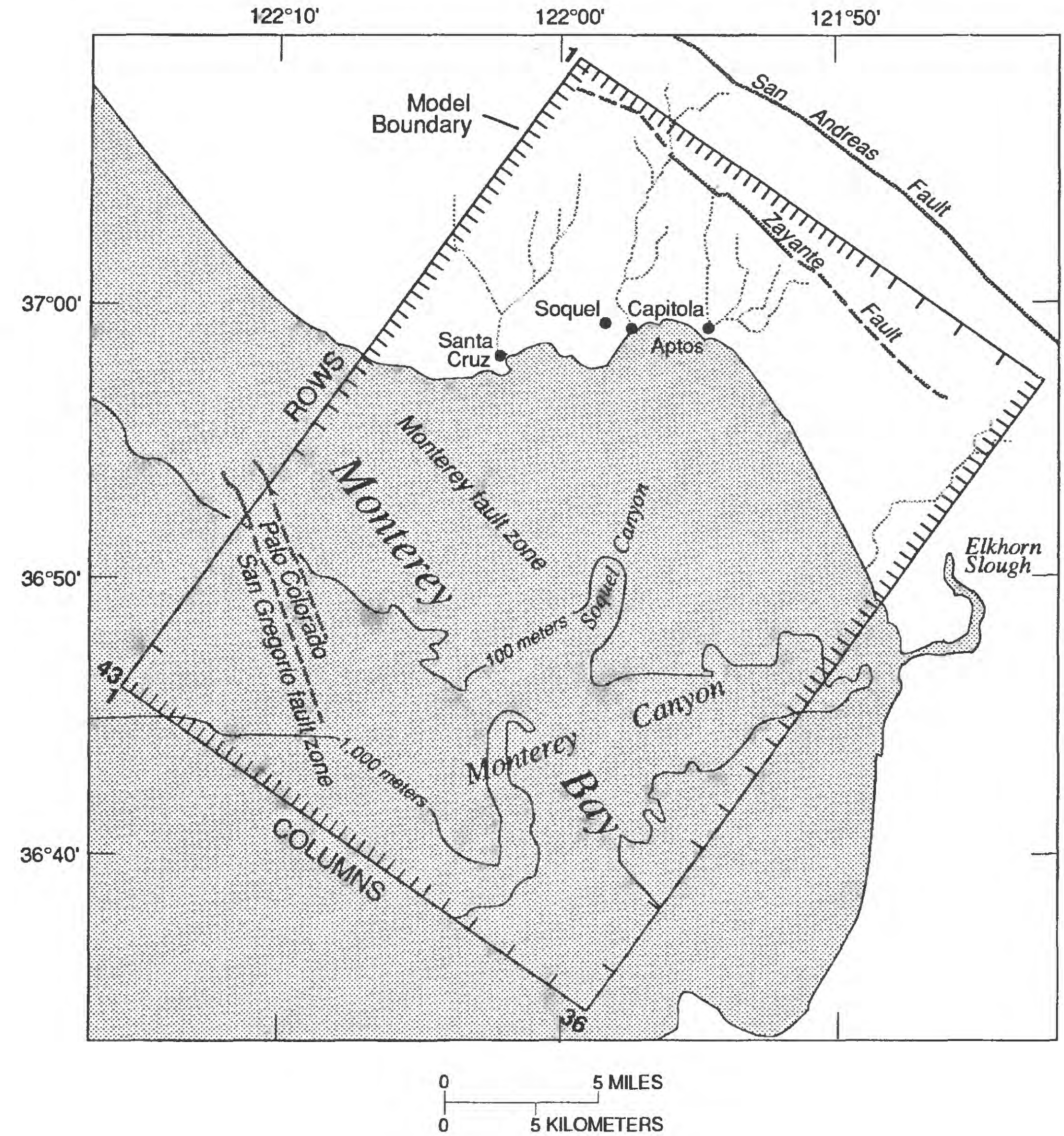


Figure 1. Location of the Soquel-Aptos basin.



EXPLANATION

FAULT - Dashed where concealed

Figure 2. General onshore and offshore features of the study area and the modeled area.

and La Selva Beach Water Companies, which were acquired by the District in 1964. Since then, as the principal water-supply agency in the Soquel-Aptos area, the District has depended exclusively on ground water as its source of supply, but it has significantly expanded and updated the supply (wells), storage, and transmission system for municipal water supply in the area. It now operates a total of 17 wells, 12 of which are completed in the Purisima Formation and 5 of which are completed in the Aromas Sand. In addition to its role as a water-supply agency, the District is the principal agency responsible for ground-water and water-resource management in the area. In that role, and as a result of the projected growth and increase in water demand, the District is assessing the ground-water resources in the basin as well as potential water-quality problems. Studies of the Soquel-Aptos area have been undertaken to determine the location,

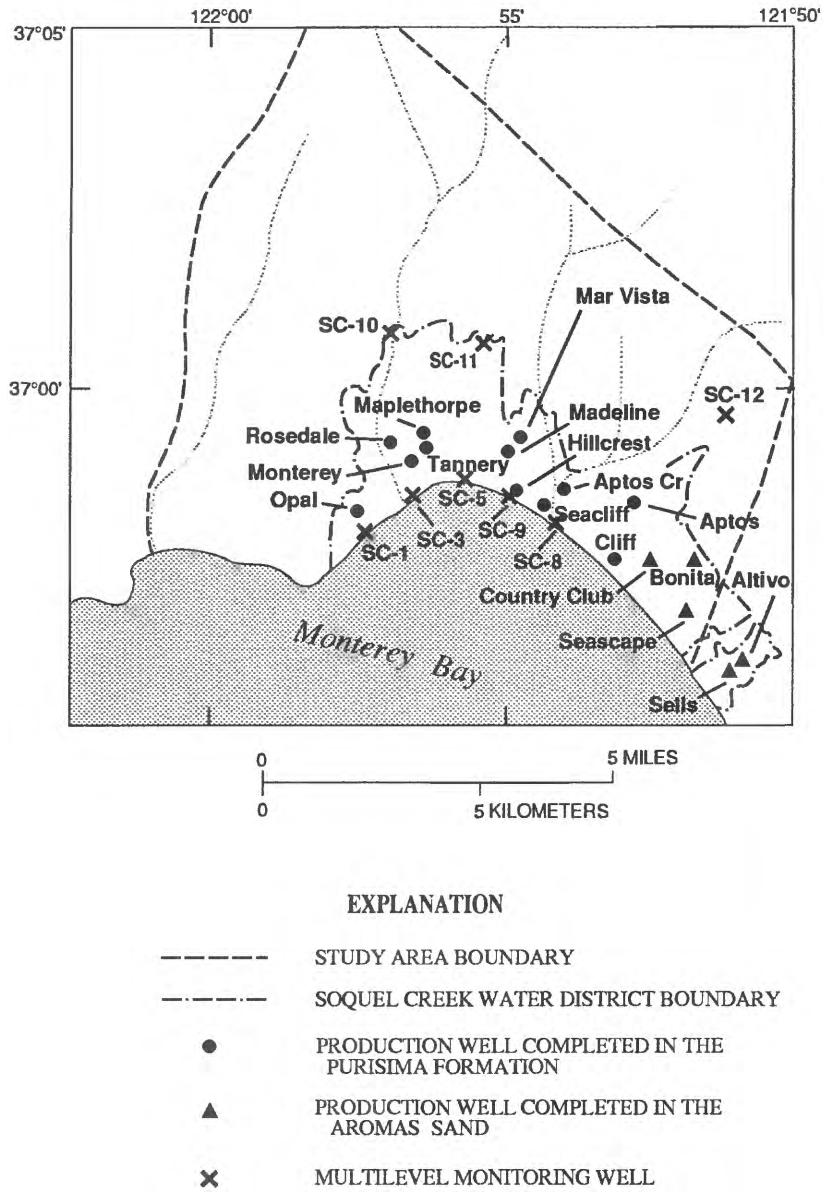


Figure 3. Soquel Creek Water District area and location of production and monitoring wells.

extent, and characteristics of the aquifers, quantity of water flowing through the aquifers, and the potential for seawater intrusion. There is considerable uncertainty regarding the amount of development that the ground-water system can sustain without inducing seawater intrusion. Previous studies have given values for either through-flow or potential yield for the Purisima Formation that range from 5.4 to 16 million m^3/yr.

The disparity in the through-flow and potential yield estimates of the previous work is a reflection of the differing methods of analysis applied to the Soquel-Aptos basin. Previous studies did not consider the offshore boundary conditions. To determine the quantity of water that can be developed safely without inducing significant ground-water quality degradation due to seawater intrusion, several issues must be addressed: the quantity of freshwater flow through the system; the quantity of freshwater discharge to the sea; the undisturbed position of the interface offshore; and the rate at which the interface would move due to onshore development. A multilayer freshwater-saltwater flow model of the Soquel-Aptos basin has been developed to examine these issues.

Table 1. Land use in the Soquel-Aptos basin for 1948-49 and 1976

[km², square kilometer]

Land use	1948-49[1] Area (km²)	1948-49[1] Percentage of total area	1976[2] Area (km²)	1976[2] Percentage of total area
Urban (residential, commercial, industrial)	4.5	12	28	83
Recreational	2.8	8	4.2	13
Agricultural and open space	29	80	1.3	4
Total	36.3	100	33.5	100

[1]California State Water Resources Board (1953).
[2]Montgomery Consulting Engineers (1976).

PURPOSE AND SCOPE

This report presents the results of simulation of the ground-water flow system of the Soquel-Aptos basin using a digital model of coupled freshwater and saltwater flow. Model simulations are used to estimate the freshwater flow through the aquifer system, and the response of the offshore freshwater-saltwater interface to ground-water development and postglacial sea-level rise. Results presented in this report reflect knowledge of the system and ground-water conditions as of 1985. Work in the basin is continuing and includes updated monitoring and interpretation of both the Purisima Formation ground-water levels and Aromas Sand ground-water conditions (Luhdorff and Scalmanini, Consulting Engineers, 1987, 1988, and 1990).

PREVIOUS STUDIES

Akers and Hickey (1967) did a preliminary reconnaissance study of the hydrogeology of the Soquel-Aptos area. This was followed by a more detailed study by Hickey (1968), in which he delineated the framework of the water-bearing units and their characteristics. By applying Darcy's law (an equation that relates the factors controlling ground-water flow) at the coast, Hickey estimated the discharge from the primary-water-bearing units to the sea, prior to development, as being 12 million m³/yr. He also estimated that the recharge necessary to balance this natural discharge was 100 mm/yr, or about 13 percent of the 760 to 810 mm average annual precipitation. Hickey's analysis of chemical data for the Soquel-Aptos area indicated that seawater had not yet intruded inland, but he believed that the hydraulic gradients suggested that the interface could be fairly close to the shoreline.

Muir (1980) did another study of the Soquel-Aptos area; his conclusions differed substantially from those of the earlier studies. Muir believed that increased chloride concentrations in shallow wells near the coast indicated that seawater had already intruded the upper part of the Purisima Formation. However, water pumped from the deeper intervals of the Purisima Formation showed no significant changes in chloride concentration, even though heads had been lowered below sea level in some areas.

Muir estimated the potential yield of the Purisima Formation by examining the relation between average annual pumpage and corresponding average annual net change of ground water in storage for a base period in which the climatic conditions approximated the long-term average. He chose the period from 1962 to 1975 for analysis because it represented average basin recharge conditions, and ground-water storage was the same at the end of the period as at the beginning. Muir (1980, p. 21) concluded that the "safe yield" for the basin was equal to the average annual pumpage for this period, which was 5.4 million m³/yr. He then checked this value, using a second method of analysis (Todd, 1964), by plotting annual average change in ground-water levels in all wells against annual pumpage. The pumpage that corresponds to a zero change in water levels on such a plot is taken as being the potential yield. The value he obtained was 5.0 million m³/yr, which corresponded closely with his first estimate. Muir's conclusion was that the average ground-water pumpage since 1970 was already in excess of the potential yield of the Purisima Formation and that pumping at this rate had caused a decline in water levels, leading to seawater intrusion in the upper part of the Purisima Formation.

On the basis of these conclusions, the Soquel Creek Water District and the Santa Cruz County Board of Supervisors restricted water connections, well construction, and building construction. In December 1980, the District adopted an ordinance that prohibited certain uses of water and prescribed a moratorium on future water service connections; the County adopted a moratorium on new well construction in the affected area. Consequently, investigations were begun to address the questions raised concerning water availability and potential seawater intrusion problems in the area.

Bloyd (1981) prepared a contour map of ground-water levels for the area (fig. 4). The data used to construct the map were obtained by measuring water levels in all accessible wells without distinguishing between aquifer units. This map showed cones of depression that were significantly below sea level in areas of pumping near the coast.

Thorup (1981) used an inventory of surface water to estimate the annual ground-water recharge to the basin as 16 million m^3/yr. He suggested that from 1.5 to 3.0 million m^3/yr of this recharge must be reserved for outflow to the sea in order to prevent seawater intrusion, and concluded that the yield of the aquifer was on the order of 13 to 14 million m^3/yr. Comparing his values with those of Hickey (1968) and Muir (1980), Thorup concluded that 10 million m^3/yr was a reasonable average value for "safe yield".

Following Thorup's study, the Soquel Creek Water District hired Luhdorff and Scalmanini, Consulting Engineers, to review the previous work, to examine the current conditions in the basin, and to develop and implement a coastal monitoring system. Luhdorff and Scalmanini, Consulting Engineers (1981), presented a review and analysis of previous work in which they concluded that there was no evidence of aquifer overdraft or seawater intrusion, and that there was a definite need for a ground-water

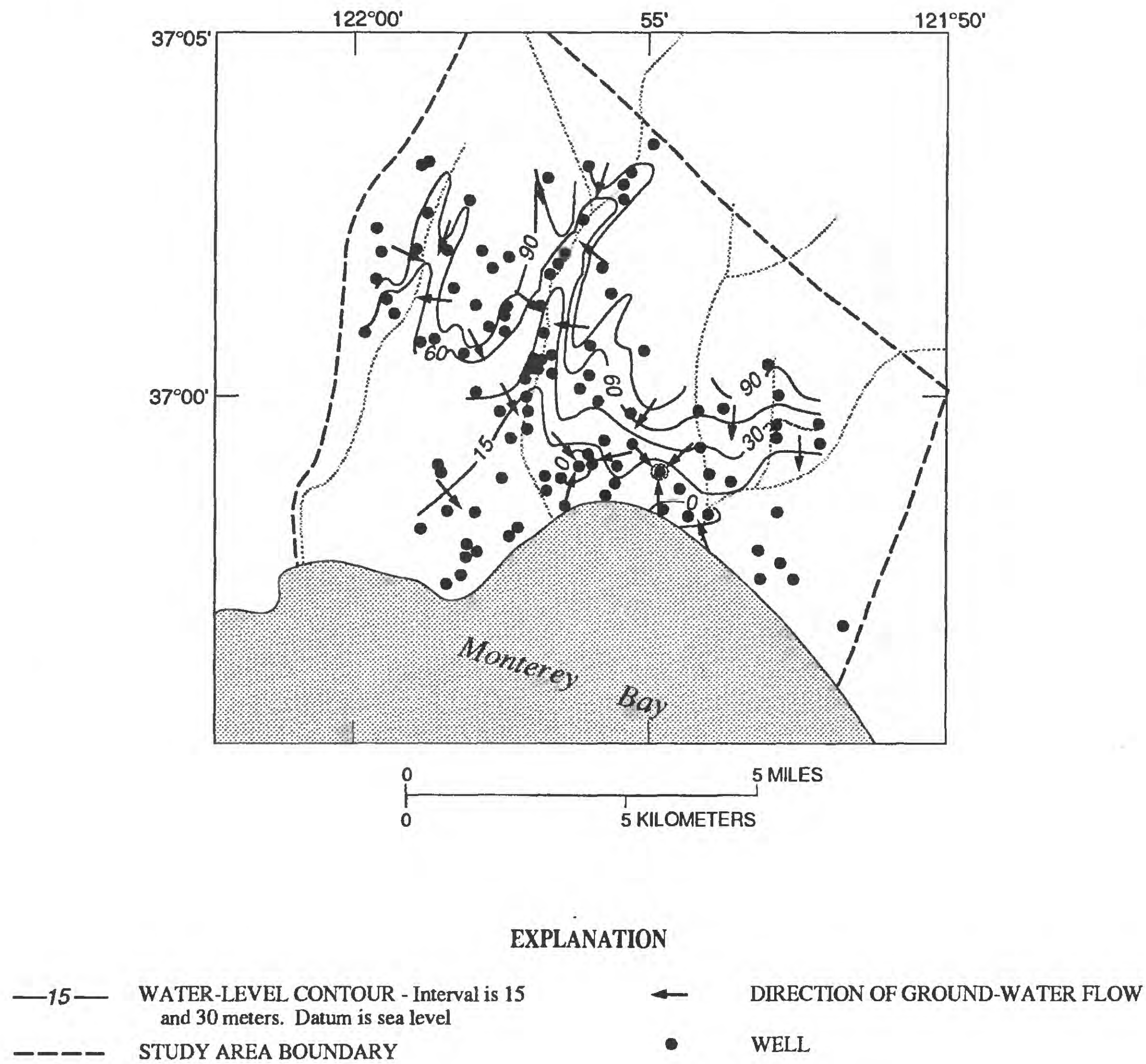


Figure 4. Approximate water-level contours, April 1981, for the Soquel-Aptos area (from Bloyd, 1981).

monitoring program. They suggested that the best method to manage the system was by continual monitoring and analysis of basin response to pumping. On the basis of these conclusions, the District lifted its moratorium on new water connections in autumn 1981 and hired Luhdorff and Scalmanini, Consulting Engineers, to implement an ongoing basinwide monitoring and analysis program (Luhdorff and Scalmanini, Consulting Engineers, 1984).

A network of test holes was drilled and logged along the coast and at selected inland sites to better delineate the geology and lithology of the aquifer system. Seven of those test holes were completed into multilevel monitoring wells, five along the coast and two inland, to allow ongoing measurement of ground-water levels and quality (fig. 3). Luhdorff and Scalmanini, Consulting Engineers (1984), presented a general description of the onshore geology and water-bearing units as well as water-level maps. They concluded that there had been no permanent reversal of ground-water gradient at the coast and that there were only isolated temporary cones of depression below sea level. They estimated that the outflow from the Purisima Formation to the sea was about 12 million m^3/yr when pumpage from the basin was approximately 3.7 million m^3/yr and, therefore, that the total flow through the aquifer was on the order of 15 to 16 million m^3/yr. Their conclusion was that there were no significant ground-water quality problems that might affect the District's water supply capability. They also concluded that the few observed instances of poor-quality water at shallow depths were not a result of inland pumping because they occurred in locations with water levels above sea level. They postulated that these shallow, near-coast areas might be recharged with poorer quality water at the coastline. These observations led them to conclude that there was no evidence of seawater intrusion.

ACKNOWLEDGMENTS

The author would like to thank the Soquel Creek Water District for their cooperation during this study. Without the monitoring well data and pumpage records provided by the Water District, this study would not have been possible.

HYDROGEOLOGIC SETTING

CLIMATE

The Soquel-Aptos area has a mild Mediterranean climate, similar to that of other central California coastal valleys and plains. The area is influenced by the coastal marine air, and during winter months storms sweep inland from the northern Pacific Ocean.

Historical records of temperature and precipitation are available for Santa Cruz, and the trends observed at this station are characteristic of the basin as a whole. Mean monthly temperatures and precipitation are given in table 2. The climate is seasonal and has summers that are generally dry and relatively

Table 2. Mean monthly temperature and precipitation at Santa Cruz

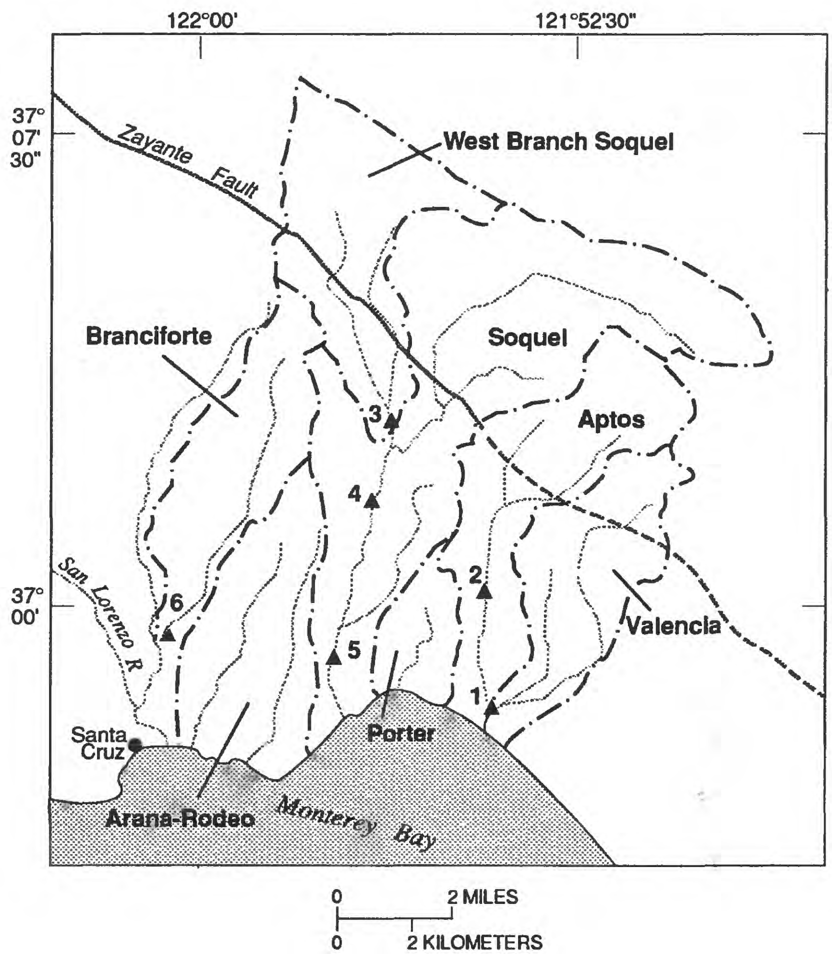
[Period of temperature record, 1951-80, National Oceanic and Atmospheric Administration (1984); period of precipitation record, 1867-1980, California Department of Water Resources (1981). °F, degree Fahrenheit; mm, millimeter]

Month	Mean monthly temperature (°F)			Mean monthly precipitation (mm)	
	Daily maximum	Daily minimum	Monthly	Precipitation	Percentage of annual
January	59.5	38.4	49.0	34.3	4.8
February	62.3	40.4	51.4	75.9	10.7
March	64.1	40.7	52.4	138	19.3
April	67.0	41.9	54.5	150	21.0
May	70.8	45.3	58.1	127	17.8
June	74.0	48.4	61.2	98.3	13.8
July	75.0	50.5	62.8	50.3	7.1
August	75.4	50.9	63.2	19.6	2.7
September	77.0	49.9	63.4	5.08	.7
October	73.7	46.5	60.1	1.52	.2
November	66.1	41.9	54.0	1.52	.2
December	60.5	38.6	49.6	10.7	1.5
Annual	68.8	44.5	56.6	711	99.8

cool and winters that are characterized by precipitation and mild temperatures. Precipitation is mainly rainfall, and about 90 percent of the annual rainfall occurs from November through April. The mean annual precipitation for the Soquel area at the coast is about 500 mm and increases rapidly inland with rise in altitude to about 1,300 mm at the crest of the Santa Cruz Mountains (S.H. Hoffard, U.S. Geological Survey, written commun., 1984). Mean annual rainfall also increases northward along the coast from about 500 mm south of Watsonville to about 710 mm north of Santa Cruz. Recharge from this precipitation is the source of the ground water in the area.

SURFACE WATER

The major creeks that drain the Soquel-Aptos area are: Branciforte Creek, a tributary of the San Lorenzo River; Soquel Creek and its tributary West Branch Soquel Creek; and Aptos Creek (fig. 5).



EXPLANATION

Aptos — DRAINAGE BASIN BOUNDARY AND BASIN NAME

STREAM

▲ GAGING STATION

1 Aptos Creek at Aptos
2 Aptos Creek near Aptos
3 West Branch Soquel Creek near Soquel
4 Soquel Creek near Soquel
5 Soquel Creek at Soquel
6 Branciforte Creek at Santa Cruz

Figure 5. Drainage basins of the Soquel-Aptos area.

Other minor gulches exist in the area. The drainage pattern is generally dendritic, with the creeks flowing to the Monterey Bay perpendicular to the coastline. Table 3 summarizes the locations, drainage areas, and periods of record for the stream-gaging stations in the area.

Branciforte, Soquel, and Aptos Creeks are perennial streams; ground-water discharge sustains baseflow throughout the year. As can be observed from hydrographs of Soquel and Aptos Creeks (fig. 6), in dry years (such as 1975) most of the stream discharge is baseflow. In wet years (such as 1981) there is a component of surface runoff and interflow to the streams, and an increase in baseflow. The increase in baseflow is caused by more ground-water discharge in wet years.

GEOHYDROLOGIC FRAMEWORK

The geology and stratigraphy of the Santa Cruz Mountains in the vicinity of the Soquel-Aptos area has been studied by Allen (1946), Cummings and others (1962), Clark (1966), and Clark and Rietman (1973). More detailed studies of the geology of the Soquel-Aptos area have been done by Hickey (1968) and Luhdorff and Scalmanini, Consulting Engineers (1984). Johnson (1980) studied the north-central part of Santa Cruz County, and Muir (1972) studied the geology of the Pajaro Valley to the southeast. The offshore geology of the Monterey Bay has been

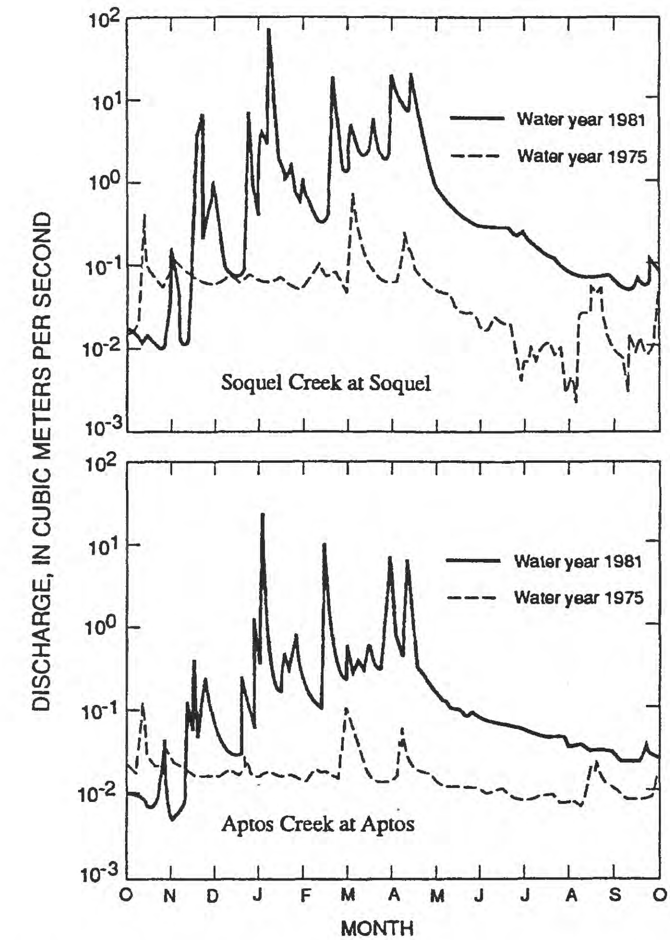


Figure 6. Discharge of Soquel and Aptos Creeks for water years 1975 (a dry year) and 1981 (a wet year).

Table 3. Gaging stations and average discharges for period of record

[Data from U.S. Geological Survey and California Department of Water Resources records. km^2, square kilometer; m^3/yr, cubic meter per year; --, no data. See figure 5 for location of stations]

Station	Location	Drainage area (km^2)	Period of record (water year)	Average discharge (m^3/yr)
Aptos Creek at Aptos	36°58'33"N 121°54'05"W	31.9	1959-72	0.22
Aptos Creek near Aptos	37°00'06"N 121°54'18"W	26.4	1972 to present	.31
West Branch Soquel Creek near Soquel	37°03'03"N 121°56'17"W	31.6	1959-72	.35
Soquel Creek near Soquel	37°02'02"N 121°56'35"W	82.9	1969-70, 1972	--
Soquel Creek at Soquel	36°59'29"N 121°57'17"W	104	1952 to present	1.3
Branciforte Creek at Santa Cruz	36°59'10"N 122°00'48"W	44.8	1940-43, 1953-68	.59

investigated by Martin (1964) and Greene (1970, 1977). The reader is referred to these previous reports for detailed descriptions of the geology of the area. This report discusses only the principal water-bearing units in the study area.

The principal hydrogeologic units of interest in the Soquel-Aptos basin are the Purisima Formation of late Miocene and Pliocene age and the Aromas Sand of Pleistocene age. The Purisima Formation, which has historically been of greater importance than the Aromas Sand as a source of municipal water supply, consists of marine, silty to clean, fine- to medium-grained sandstone containing siltstone and claystone interbeds. Figure 7 is a generalized geologic map of the area showing the areal extent of the Purisima Formation and the boundaries of the modeled area where the unit is present. Hickey (1968) divided the Purisima into three informal subunits based on lithologic and hydrologic characteristics. Luhdorff and Scalmanini, Consulting Engineers (1984) drilled eight exploratory wells and from their examination of geophysical logs and other geologic evidence they were able to delineate seven distinct Purisima subunits throughout the basin that are separated by claystone interbeds (fig. 8). Because this work represents the most detailed interpretation of the system, Luhdorff and Scalmanini's framework was adopted for this study. However, in order to simplify the analysis for simulation purposes, the system was reduced to five subunits by combining the AA and A subunits and E and F subunits.

The Purisima Formation is exposed at the land surface over most of the Soquel-Aptos area, and offshore it crops out on the ocean floor and along the walls of the Monterey Canyon. It is very thin at the northwestern border of the area, but increases in thickness towards the southeast, where it reaches a thickness of greater than 600 m. Onshore, it lies directly on the granitic basement, whereas offshore, it overlies the Monterey Formation. Both the granitic basement and the Monterey Formation are considered non-water-bearing for the purposes of this report.

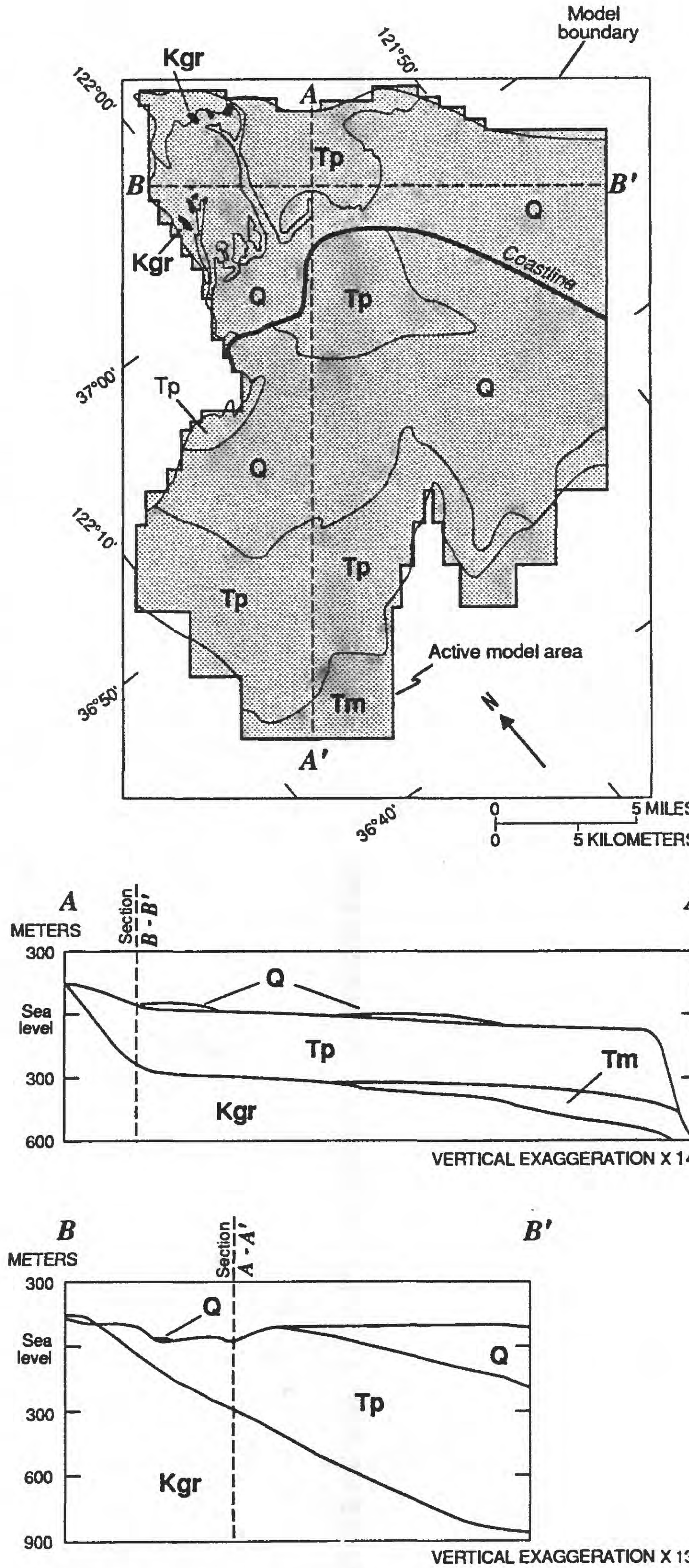


Figure 7. Generalized geologic map showing onshore and offshore surficial geology, and geologic sections. (Q, Quaternary deposits; Tp, Purisima Formation; Tm, Monterey Formation; Kgr, Cretaceous granitic basement. Modified from Greene, 1977.)

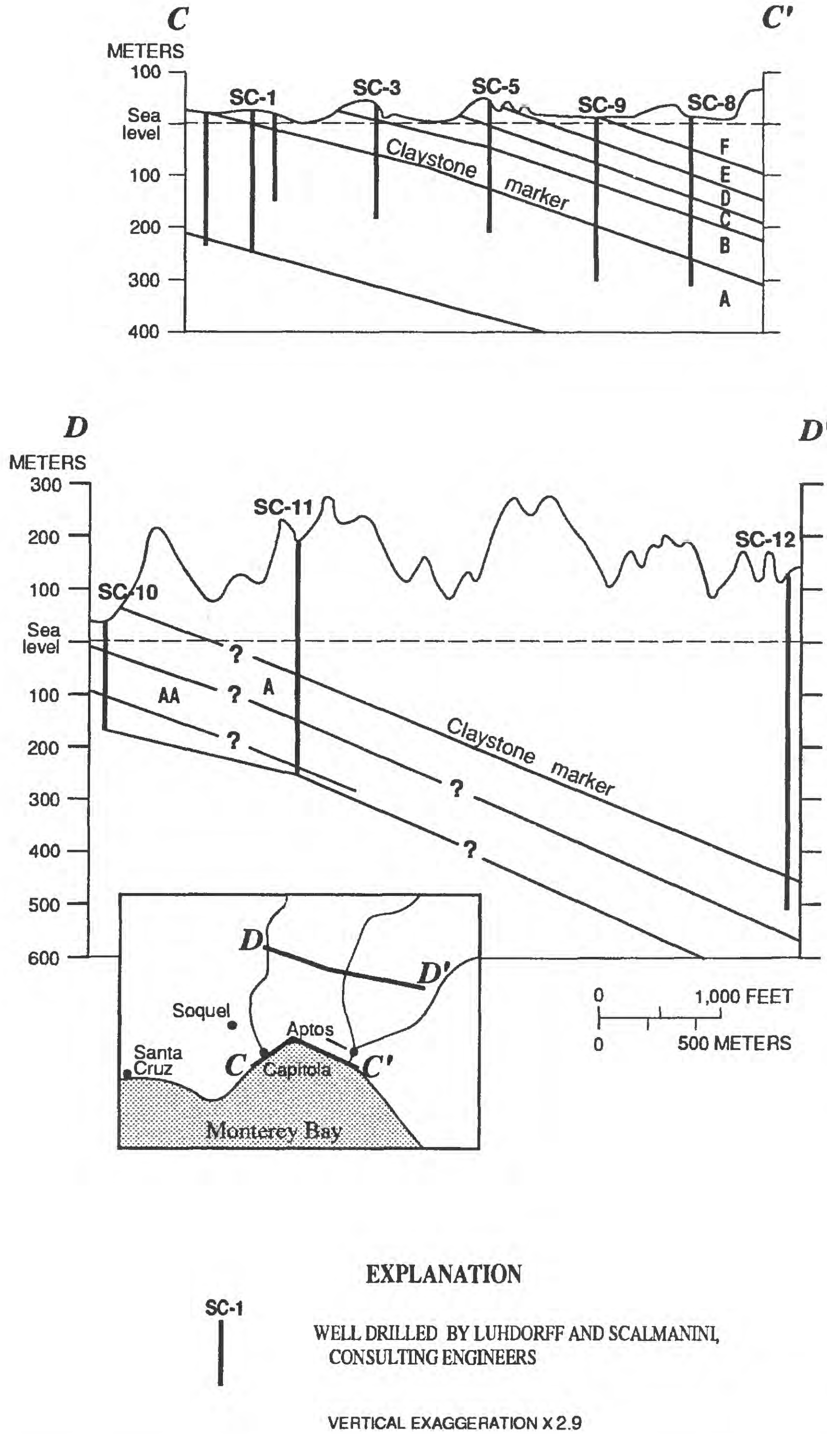
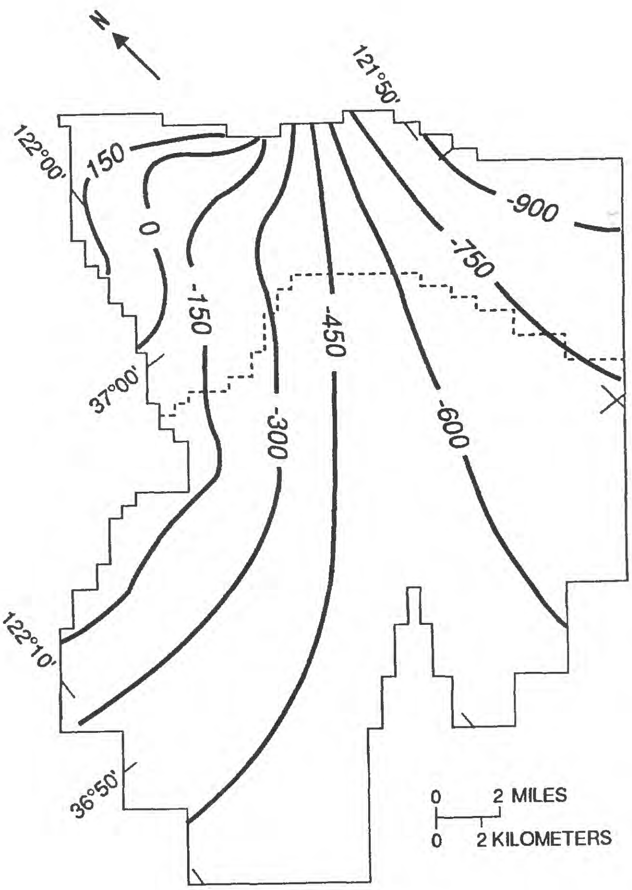


Figure 8. Geologic sections showing Purisima subunits (modified from Luhdorff and Scalmanini, Consulting Engineers, 1984).

Basinwide structure contour and thickness maps were constructed by integrating the onshore geologic information of Luhdorff and Scalmanini, Consulting Engineers (1984), and Hickey (1968) with the offshore work of Greene (1977). The base of the flow system was taken to be the Cretaceous granitic basement onshore and the relatively impermeable Monterey Formation offshore. By incorporating outcrop data (Hickey, 1968), well logs (Luhdorff and Scalmanini, Consulting Engineers, 1984), and seismic stratigraphic sections (Greene, 1977), it was possible to delineate the system geometry. A basement topography map was constructed (fig. 9), as well as structural contour maps for the top of the Purisima subunits. The structural contours for subunit A are shown in figure 10. The thickness of subunit A ranges from 0 m to 150 m because the basement was originally a surface of erosion that was later buried by the overlying Purisima deposits (fig. 11). Overlying subunits (B, C, D, and E) had uniform thicknesses throughout the basin, except in the outcrop areas where the original thickness has been reduced by erosion. Subunit B has a thickness of 76 m, subunit C of 37 m, and subunit D of 30 m. The thickness of subunit E increases from less than 60 m on the west to 183 m on the east (fig. 11). Because these subunits have relatively uniform thicknesses over the basin, they have a similar structure to subunit A.

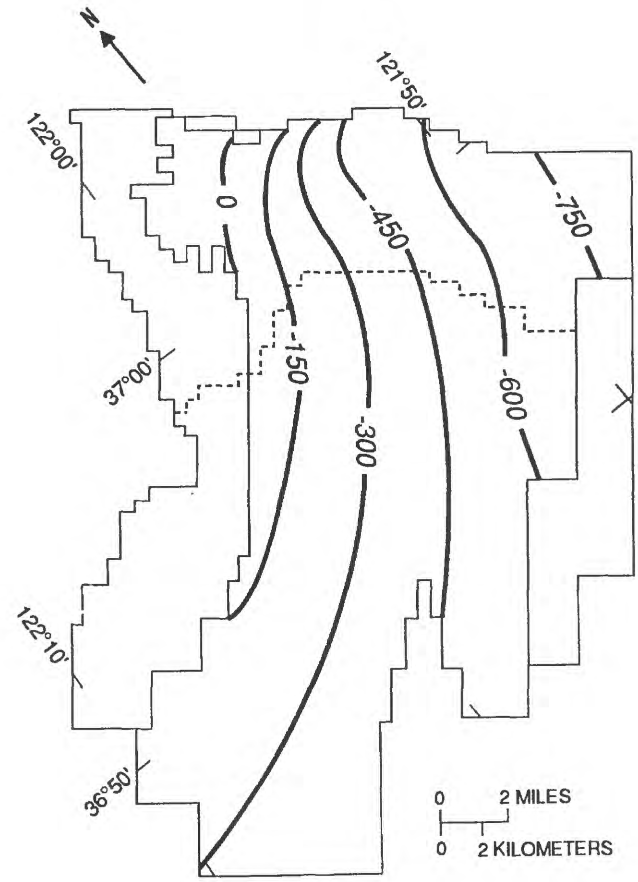
The Quaternary sequence in the area is represented by the Aromas Sand, terrace deposits, and alluvium (Dupre, 1975). The Aromas, which is made up of interbedded fluvial, marine, and eolian deposits of Pleistocene age, is a brown to red, poorly consolidated, clayey, fine to coarse grained sandstone containing lenses of silt and clay. It overlies the Purisima Formation in the eastern part of the area, both onshore and offshore, and increases in thickness toward the southeast. The terrace deposits of late Pleistocene age consist of interbedded silt, clay, sand, gravel, and conglomerate and rest unconformably on the Purisima Formation. They occur at two levels along the coast; the younger terraces are at 6 to 30 m altitude and the older terraces are at 60 to 90 m altitude. The thicknesses of the terrace deposits range from a few meters to as much as 30 m. Unconsolidated silt, clay, sand, and gravel alluvial deposits of Holocene age occur in the valleys of the major creeks in the area.



EXPLANATION

---------- COASTLINE

Figure 9. Basement topography. Values on contour lines are altitude (in meters) relative to sea level.



EXPLANATION

--------- COASTLINE

Figure 10. Structural contours for top of subunit A. Values on contour lines are altitude (in meters) relative to sea level.

RECHARGE AND BASEFLOW ESTIMATES

The quantity of recharge to the Soquel-Aptos basin was determined by estimating a basin water budget. Estimates of average annual precipitation and runoff for Branciforte, West Branch Soquel, Soquel, and Aptos Creeks were taken from Rantz (1974). Evapotranspiration was initially calculated using the estimates of Blaney and Ewing (1953) for normal consumptive use of natural vegetation on the Pajaro Valley floor, which is adjacent to the Soquel-Aptos area. Table 4 summarizes the estimated recharge values for these calculations and indicates that the total recharge to the basin is 0.30 m^3/s.

There is considerable uncertainty associated with the estimate of evapotranspiration from the basin, but it is a critical parameter for evaluating the amount of ground-water recharge. Johnson (1980) estimated that the evapotranspiration in the northern part of the Soquel-Aptos basin (north of the Zayante Fault) was from 52 to 59 percent of mean annual precipitation. Using a mean value of 55 percent to calculate evapotranspiration, the total recharge to the basin is 0.66 m^3/s (table 4), more than twice the first estimate (0.30 m^3/s). This water balance approach can only give an order of magnitude estimate of ground-water recharge. These recharge values represent the water entering the northern and southern areas of the basin.

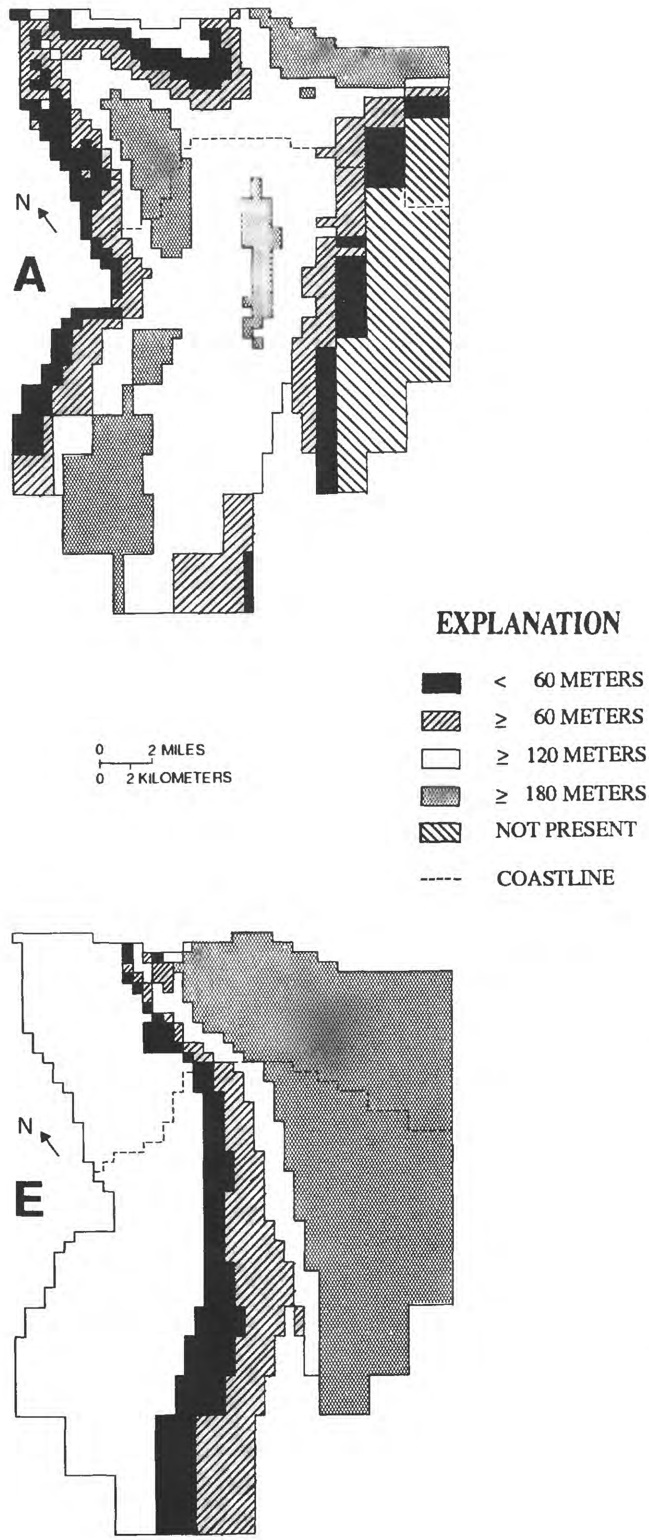


Figure 11. Discretized thickness maps for subunits A and E.

North of the Zayante Fault, water flows southeastward, parallel to the fault, and it is believed that some of this water enters the southern part of the basin by flowing across the fault in the vicinity of the Aptos Creek basin (Johnson, 1980). However, because there are no estimates of how much water flows across this boundary, it is difficult to accurately estimate how much of the recharge enters the basin south of the Zayante Fault.

To obtain additional information about the groundwater flow through the system, stream hydrographs were analyzed to estimate baseflow. For Branciforte, West Branch Soquel, Soquel, and Aptos Creeks, estimates of annual baseflow were made by simple straight-line hydrograph separation. Soquel Creek has the longest record (1953-84), and using available data, annual baseflow records of equal length were generated for the other creeks. This was done by correlating the logarithm of the baseflow at each creek with the logarithm of the baseflow at Soquel Creek and the annual precipitation at Santa Cruz. The regression equations are given in table 5. From these estimates of annual baseflow for 1953-84, the mean annual baseflow was calculated for each drainage basin and also for the proportion of the drainage basin within the model area (table 5).

Table 6 summarizes the estimates of freshwater flux that have been made for the Soquel-Aptos basin and the methods used. There is a wide range in the values; however, the estimates tend to be within 0.2 to 0.6 m^3/s.

HISTORICAL PUMPAGE

Table 7 lists the Soquel Creek Water District production wells that tap the Purisima Formation, their perforated intervals, subunits, and years in operation. From 1967 to present, actual pumpage values were available; however, earlier pumpage had to be estimated. The California State Water Resources Board (1953) estimated the draft from the Soquel-Aptos basin in 1949 to be about 0.024 m^3/s. An exponential function was fit to the known values to obtain estimates of the total annual pumpage for the undocumented years (1920-48 and 1950-66) (fig. 12).

Table 4. Water balance estimates for the Soquel-Aptos area

[mm, millimeter; m^3/s, cubic meter per second]

Basin	Mean precipitation[1] (mm)	Mean runoff[1] (mm)	Evapotranspiration[2] (mm)	Recharge[2] (m^3/s)	Evapotranspiration[3] (mm)	Recharge[3] (m^3/s)
Soquel	1,020	340	620	0.13	559	0.27
West Branch Soquel	1,120	394	650	.074	615	.11
Aptos	914	240	589	.086	503	.17
Branciforte	991	371	612	.011	546	.11
Total				0.30		0.66

[1]Rantz (1974).
[2]Based on normal consumptive use of natural vegetation on Pajaro Valley floor, Blaney and Ewing (1953).
[3]55 percent of mean precipitation.

Table 5. Estimated mean annual baseflow for the main drainage basins of the Soquel-Aptos area

[km^2, square kilometer; m^3/s, cubic meter per second]

Basin	Total drainage area (km^2)	Area within model (km^2)	Mean annual baseflow (m^3/s)	Proportioned baseflow (m^3/s)
Soquel	104	35.2	0.37	0.12
West Branch Soquel	31.6	11.7	.09	.03
Aptos	31.6	16.8	.10	.05
Branciforte	44.8	26.7	.07	.04
Total	212	90.4	0.63	0.24

Regression equations used to estimate mean annual baseflow for years without record (baseflow in cubic millimeters per second, precipitation in millimeters):

West Branch Soquel baseflow = exp (-2.007 + 1.17 log (Soquel baseflow) - 0.406 (Santa Cruz precipitation))
R^2=90.5 percent

Aptos baseflow = exp (-1.764 + 0.881 log (Soquel baseflow) - 0.0132 (Santa Cruz precipitation))
R^2=92.2 percent

Branciforte baseflow = exp (-0.629 + 0.391 log (Soquel baseflow) - 0.0099 (Santa Cruz precipitation))
R^2=64.0 percent

Table 6. Estimates of flux through the Soquel-Aptos basin

[m^3/s, cubic meter per second]

Study	Flux (m^3/s)	Method of estimation
Hickey, 1968	0.40	Application of Darcy's law to the primary water-bearing units
Muir, 1980	0.18	Method by Todd (1964)
Thorup, 1981	0.50	Based on a water balance for the basin
Luhdorff and Scalmanini, 1984	0.49	Application of Darcy's law at the coast
Present study	[1]0.30-0.66	Based on a water balance for the system
	[2]0.24-0.63	Based on estimates of mean annual baseflow

[1]Lower value calculated using evapotranspiration by Blaney and Ewing (1953); upper value calculated with evapotranspiration as 55 percent of mean precipitation.

[2]Lower value is baseflow proportioned to area within model; upper value is total baseflow.

Table 7. Production wells in the Soquel-Aptos basin

[Data from Luhdorff and Scalmanini, Consulting Engineers, 1984. m, meter; m/s, meter per second; --, no data. See figure 3 for location of wells]

Well	Perforated interval (m)	Subunits	Online	Grid location (row, column, layer)	Estimated hydraulic conductivity (m/s)
Opal #1	? to -39	A	1930 to present	18,17,1	1×10^{-4}
Opal #4	-39 to -64	A	1980 to present	18,17,1	1×10^{-4}
Hillcrest	-17 to -56	E	1923 to present	14,21,5	2×10^{-5}
Aptos	3 to -76	E	1930 to present	11,24,5	3×10^{-5}
Seacliff	? to -58	E	1935 to present	13,22,5	2×10^{-5}
Monterey	? to -88	A	1950 to present	15,17,1	8×10^{-5}
Mar Vista	--	ABCD	1950-68	13,20,1	--
Cliff	-40 to -101	E	1961 to present	14,26,5	1×10^{-5}
Maplethorpe	-71 to -150	A	1965 to present	14,17,1	8×10^{-5}
Aptos Creek	-66 to -209	BCDE	1965 to present	13,22,5	8×10^{-6}
Tannery	-66 to -145	A	1971 to present	14,17,1	8×10^{-5}
Madeline	-82 to -152, -191 to -246	ABCD	1973 to present	13,20,1	8×10^{-6}
Rosedale	-24 to -130	ABC	1984 to present	15,16,1	1×10^{-4}

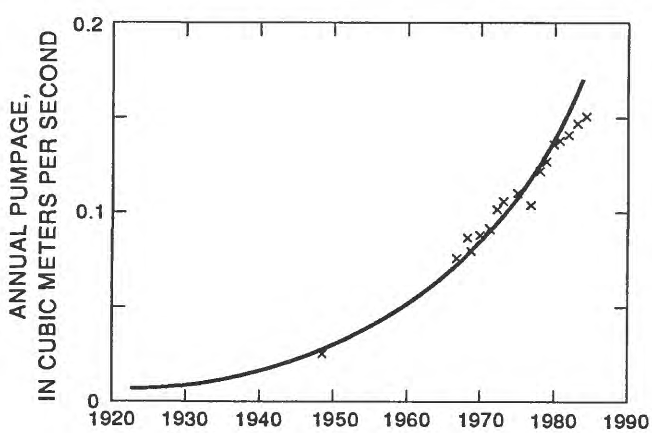


Figure 12. Annual pumpage from the Purisima Formation. × represents measured values, the dashed line is the fitted function (pumpage = exp (0.0503 (year) -98.1), R^2 = 0.93).

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

A numerical model of the layered coastal ground-water system of the Soquel-Aptos basin was developed to aid analysis of the effect of development in the basin on the potential for seawater intrusion. The model was used to estimate freshwater fluxes through the system, to study movement of the freshwater-saltwater interface in response to development and Pleistocene sea-level rise, and to estimate the current (1985) position of the interface.

MODEL DESCRIPTION

The model SHARP (Essaid, 1990) is a quasi-three-dimensional, numerical finite-difference model that simulates freshwater and saltwater flow separated by a sharp interface in layered coastal aquifer systems. The model SHARP was used to simulate the Soquel-Aptos basin. It facilitates regional simulation of coastal ground-water conditions in layered systems and includes the dynamics of both saltwater and freshwater. The model accommodates multiple aquifers, separated by confining units, with spatially variable porous media properties. The uppermost aquifer of the system may be confined, unconfined, or semiconfined with an areally distributed recharge. Temporal variations in recharge and pumping are accounted for by multiple pumping periods. The boundary conditions that can be simulated in the model include no-flow boundaries, constant freshwater head and/or constant saltwater head boundaries, and leaky head-dependent boundaries.

For each aquifer, the vertically integrated freshwater and saltwater flow equations are solved:

$$\underbrace{S_f B_f \frac{\partial \phi_f}{\partial t}}_{(1)} + \underbrace{n\alpha \frac{\partial \phi_f}{\partial t}}_{(2)} + \underbrace{\left[n\delta \frac{\partial \phi_f}{\partial t} - n(1+\delta)\frac{\partial \phi_s}{\partial t} \right]}_{(3)}$$

$$= \underbrace{\frac{\partial}{\partial x}\left(B_f K_{fx} \frac{\partial \phi_f}{\partial x} \right)}_{(4)} + \underbrace{\frac{\partial}{\partial y}\left(B_f K_{fy} \frac{\partial \phi_f}{\partial y} \right)}_{(4)} + \underbrace{Q_f}_{(5)} + \underbrace{Q_{lf}}_{(6)} \qquad \text{(1a)}$$

$$\underbrace{S_s B_s \frac{\partial \phi_s}{\partial t}}_{(1)} + \underbrace{\left[n(1+\delta)\frac{\partial \phi_s}{\partial t} - n\partial \frac{\partial \phi_f}{\partial t} \right]}_{(3)}$$

$$= \underbrace{\frac{\partial}{\partial x}\left(B_s K_{sx} \frac{\partial \phi_s}{\partial x} \right)}_{(4)} + \underbrace{\frac{\partial}{\partial y}\left(B_s K_{sy} \frac{\partial \phi_s}{\partial y} \right)}_{(4)} + \underbrace{Q_s}_{(5)} + \underbrace{Q_{ls}}_{(6)} \qquad \text{(1b)}$$

where

- ϕ_f, ϕ_s = the vertically averaged fresh and saltwater heads, respectively (L, length);
- S_f, S_s = the fresh and saltwater specific storages (L^{-1});
- B_f, B_s = thickness of the fresh and saltwater zones (L);
- n = porosity;
- δ = $\gamma_f/(\gamma_s-\gamma_f)$ and γ_f, γ_s;
- γ_f, γ_s = the fresh and saltwater specific weights ($ML^{-2}T^{-2}$; M, mass; T, time);
- K_{fx}, K_{sx} = fresh and saltwater hydraulic conductivities in the x-direction (LT^{-1});
- K_{fy}, K_{sy} = fresh and saltwater hydraulic conductivities in the y-direction (LT^{-1});
- Q_f, Q_s = fresh and saltwater source/sink terms (LT^{-1});
- Q_{lf}, Q_{ls} = fresh and saltwater leakage terms (LT^{-1});
- α = 1 for an unconfined aquifer, = 0 for a confined aquifer; and,

(1) through (6) are terms explained below.

Leakage between aquifers is calculated by applying Darcy's law. Equations 1a and 1b represent coupled, parabolic partial differential equations that must be solved simultaneously for the freshwater head (ϕ_f) and the saltwater head (ϕ_s). Once these values are obtained, the interface elevation (ς_1) can be calculated from:

$$\varsigma_1 = (1+\delta)\phi_s - \delta\phi_f \qquad (2)$$

This system of coupled, nonlinear partial differential equations is discretized using an implicit finite-difference scheme. The discretized system of equations is solved using the strongly implicit procedure (SIP) (Stone, 1968). The positions of the interface tip and toe, within the discretized finite-difference grid blocks, are tracked using linear extrapolation of the interface elevations calculated at grid points.

In equations 1a and 1b, the type 1 terms represent the change in elastic storage within each domain. The type 2 term represents the change in freshwater storage due to drainage at the water table, the type 3 terms represent the change in storage within each domain due to movement of the interface, the type 4 terms represent the divergence of the fluxes in the x and y directions, the type 5 terms (recharge, pumpage) and type 6 terms (leakage) represent the sources and sinks to the aquifer. In regions distant from the interface, only one type of fluid (freshwater or saltwater) is present in the aquifer and the flow is described by the appropriate single equation without the interface (type 3) storage terms.

SYSTEM GEOMETRY

In order to implement a numerical model, it is necessary to translate the hydrogeologic conditions of the area into a framework that can be simulated by the model. This is accomplished by defining the geometry, boundary conditions, and physical parameters of the basin, in a manner that will reproduce the system's behavior, over a discrete grid. Figure 2 shows the extent of the model grid area (43 rows by 36 columns). In the area of interest, the grid blocks have dimensions of 610 by 610 m, and the spacing increases toward the southeast and southwest boundaries to a maximum of 2,500 by 3,500 m.

The numerical model consists of five layers that represent the five subunits of the Purisima Formation described in the Geohydrologic Framework section of this report. Layer 1, the lowermost layer, represents the AA and A subunits, layers 2, 3, and 4 represent the B, C, and D subunits, respectively, and layer 5 represents the E and F subunits. Layer 5 is overlain by the Quaternary Aromas Sand, which is not simulated in the model but is used as a boundary condition. The thickness, altitude, and areal extent of each layer were discretized over the 43 by 36 grid. The model outcrop areas and areal extent of each subunit are shown in figures 13 and 14, respectively.

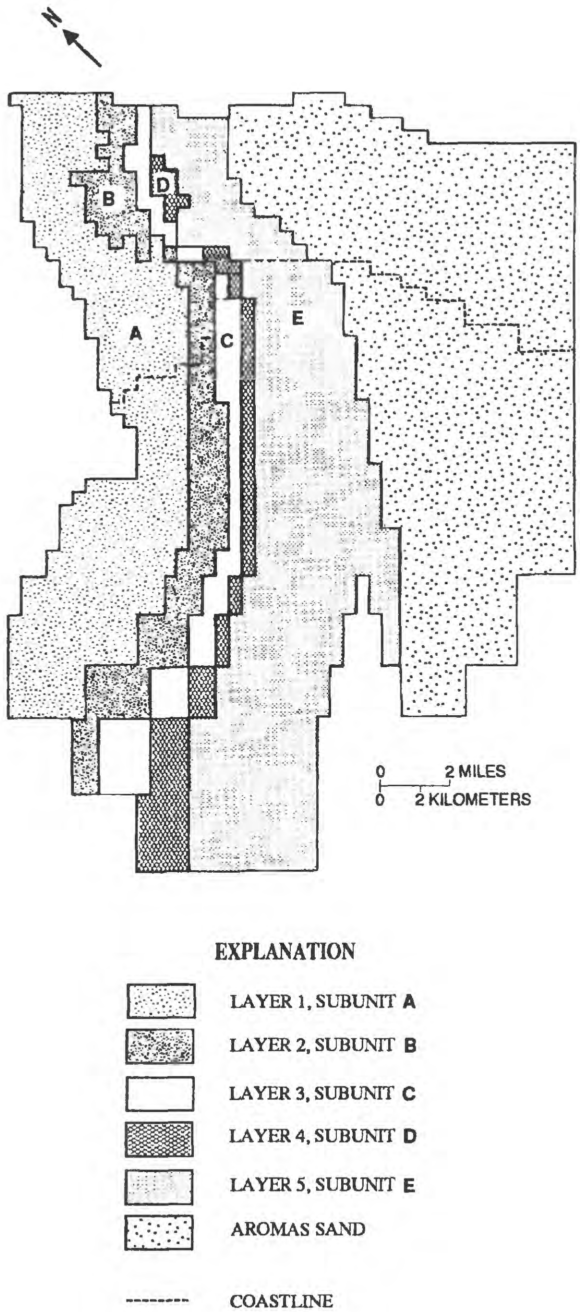


Figure 13. Discretized outcrop areas of model subunits A through E.

BOUNDARY CONDITIONS

The lateral boundaries of the system were delineated on the basis of the physical features affecting the hydrogeologic conditions in the basin (fig. 15). The Purisima Formation decreases in thickness westward and pinches out along the northwestern border of the area; this boundary was prescribed as a no-flow boundary for all layers. The Zayante Fault was set as a no-flow boundary, as was the offshore Palo Colorado-San Gregorio Fault zone. At the southeastern edge of the Soquel-Aptos area there is no clear physical boundary; therefore, the model boundary was extended about 8 km toward the southeast and an estimated flow line was assumed to be a no-flow boundary. The southeast boundary was placed far enough away from the area of interest so as not to affect the solution there. The Monterey Canyon outcrop was represented by constant head nodes. Saltwater heads were fixed at zero along the canyon boundary. To fix the values of freshwater head at the equivalent freshwater heads representing the thickness of the column of saltwater above the canyon outcrop of each subunit, the leakance of these nodes was made sufficiently large. Thus, both freshwater and saltwater heads were fixed at the canyon, yet the interface was free to move.

The base of the system is relatively impermeable and is considered a no-flow boundary. However, water can enter or leave the system across the top, making it a critical boundary over the top of the system. Recharge enters each layer on the area of onshore outcrop; ground water also discharges to the surface-water system as stream baseflow. If these fluxes were known, they could be used to specify the outcrop boundary condition for each layer, but it is very difficult to accurately determine the distribution of these fluxes; instead, another means of representing this boundary was used. Toth (1963) showed that topography influences ground-water flow, and the water table is generally a subdued replica of the land surface. The onshore outcrops of each subunit were accounted for by fixing the water table altitude above the aquifer, and introducing a leakance factor to represent the vertical connection between the aquifer and water table (fig. 16). Onshore, the altitude of the water table was taken to be the average topography. Offshore, the head in the overlying layer was fixed at the freshwater head equivalent to the overlying column of saltwater. By specifying the boundary condition in this manner, water can leak into and out of each layer. In this manner, the model calculates the amount of recharge to and discharge from the system. The amount of leakage will vary as heads in the aquifer vary. Recharge to the system occurs in the areas of highest altitude and ground-water discharge occurs to streams in the valleys. In the southeastern area, subunit E is overlain by the Aromas Sand, which has experienced considerable drawdown in some areas of the Pajaro Valley (Bond and Bredehoeft, 1987; Johnson and others, 1988). To accommodate these areas, a time-dependent water-table altitude was used to represent this boundary

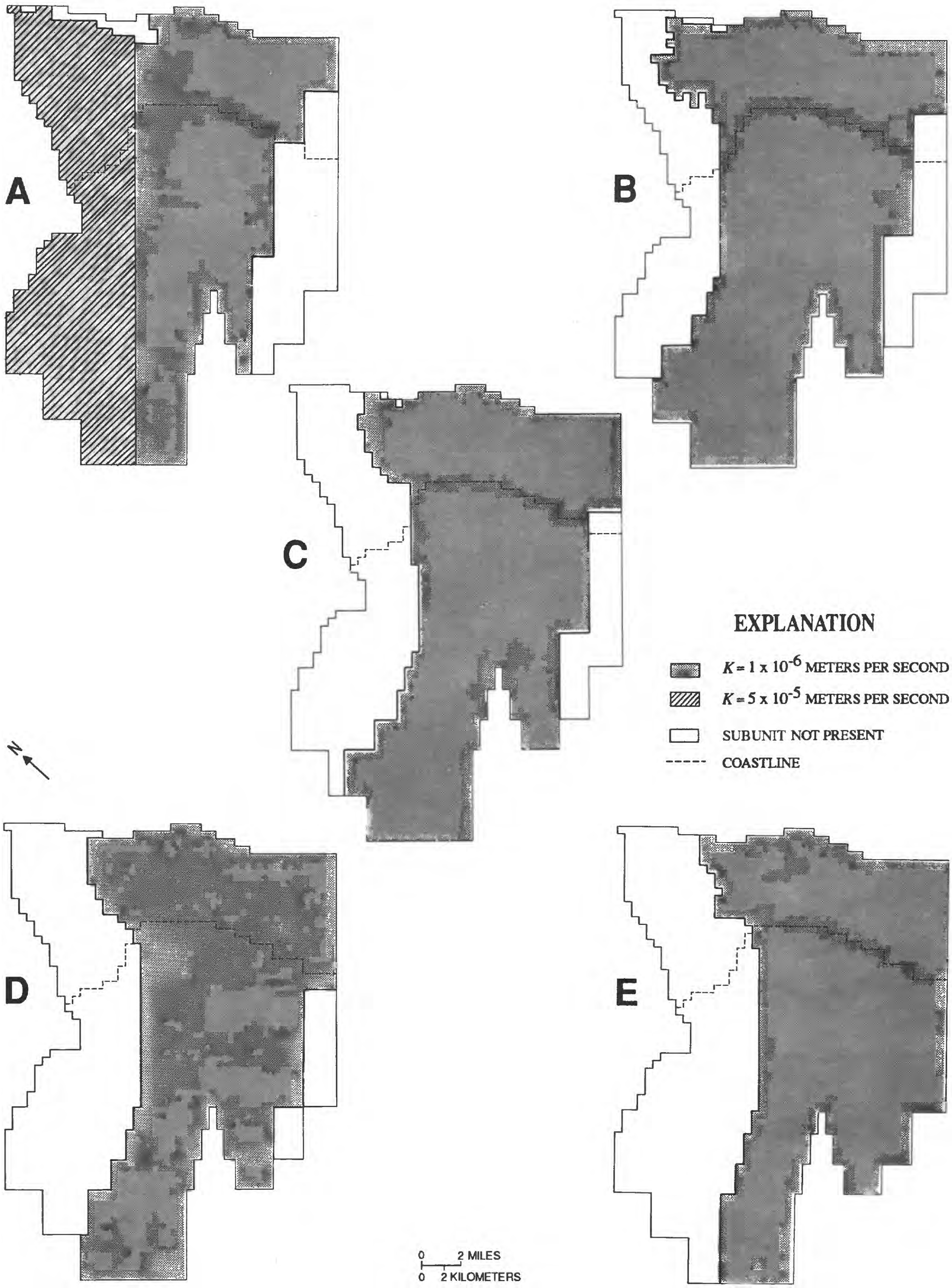


Figure 14. Areal extent and hydraulic conductivity (K) distribution of each model subunit.

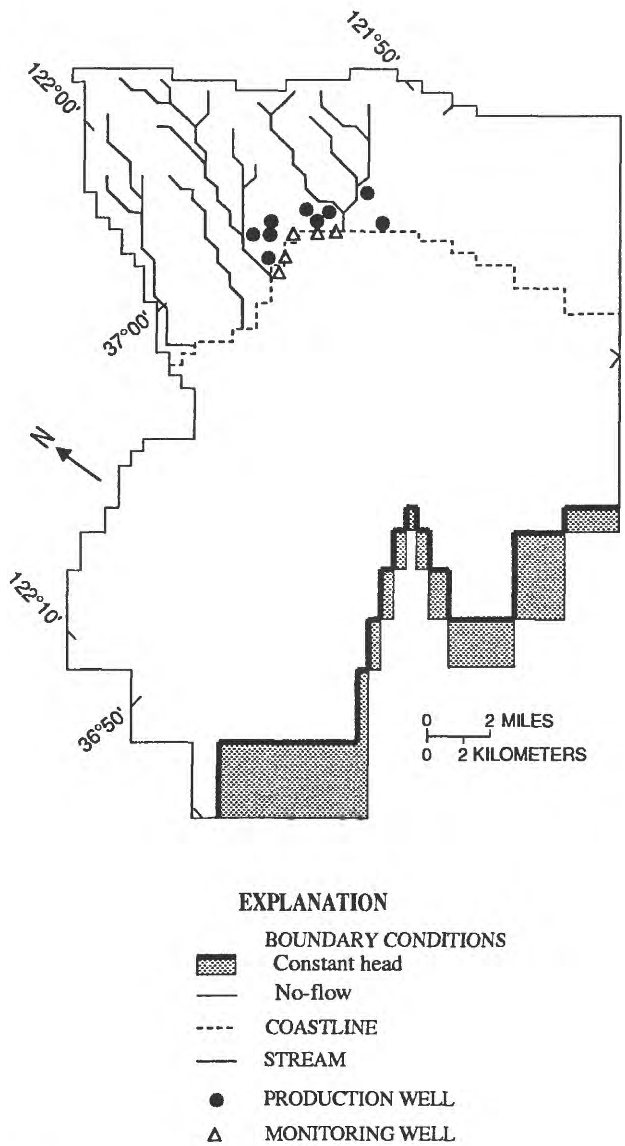


Figure 15. Boundary conditions and major features of the model area.

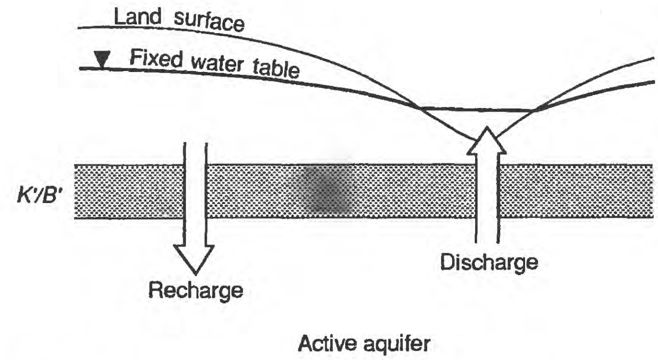


Figure 16. Fixed water-table boundary condition. (*K'*, conductivity of confining layer; *B'*, thickness of confining layer).

condition with a linear decrease in heads from predevelopment conditions to reported present-day water levels.

MODEL CALIBRATION

After formulating the conceptual framework of the hydrogeologic system (geometry and boundary conditions), it is then necessary to determine the values of aquifer parameters (conductivity, specific storage, leakance, and effective porosity). These values are initially chosen on the basis of available data and then adjusted by trial and error to obtain simulated water levels that match observed water levels. The parameter values obtained by this trial and error process of model calibration are not unique. The calibration, however, can be constrained on the basis of available hydrologic information. The process also leads to an understanding of the factors determining the system's response and behavior, that is, the parameters and boundary conditions to which the system is most sensitive.

Bloyd (1981) compiled water-level measurements for about 150 wells in the Soquel-Aptos area in April 1981 and constructed a ground-water-level map representing the near-surface flow system (fig. 4). These wells represented water levels in the shallow Purisima subunits, except near the coast where the production wells tap the deeper units. Bloyd observed that the general direction of ground-water movement in the area was from the higher altitudes in the northern part of the area toward the stream valleys and the coast. Comparison of this map with the measurements of Hickey (1968) indicates that significant drawdowns of as much as 12 to 15 m have occurred from 1968 to 1981 in the cones of depression caused by the high capacity wells near the coast. However, ground-water levels in the northern part of the area have remained more or less the same, and, for the most part, are close to the land surface.

Bloyd's (1981) map represents the most comprehensive measurement of water levels in the basin and therefore, was used for model calibration. In addition, estimates of recharge to the system and baseflow to the streams were made and used to constrain the calibration process (tables 4 and 5). Conditions were simulated for the period from 1930 to April 1981, using annual time steps through 1980, and then monthly time steps through April 1981, in order to maintain comparability with Bloyd's map of observed heads. Estimated values of pumpage were apportioned to the individual wells as they went into production on the basis of the present-day distribution of pumpage within the basin. Table 8 gives the annual pumpage rates for the model blocks containing wells. Many production wells penetrate several layers and the individual flow contribution of each layer to the total pumpage from the wells is unknown. For this reason, wells penetrating several layers were simulated by introducing pumpage into one layer and by increasing the leakance between it and the other layers penetrated by the well, thereby allowing the model to calculate the flow contribution of each layer. The leakance at the well blocks was adjusted so that simulated heads in each layer matched observed heads in nearby monitoring wells. These leakance values were increased only slightly over the values in adjacent blocks because the block size is considerably larger than the well diameter, thus, the model layers continued to behave as individual units. In the Aptos Creek well, it was necessary to apportion 20 percent of the total pumpage to subunit A in order to match heads, although this well is not thought to reach subunit A. This may be an indication that subunit A has considerable hydraulic connection to the overlying unit and that the claystone interbeds may not be as continuous near this well.

AQUIFER PARAMETERS

The aquifer parameters for which the model has been calibrated are hydraulic conductivity, leakance (effective vertical hydraulic conductivity divided by the distance between the midplanes of model layers), and specific storage. Early simulations showed that conductivity and leakance were the critical properties that control the behavior of the system. Changes in conductivity affect the gradients in the basin and the drawdowns at the wells. Leakance values control the quantity of water that moves through the system (recharge and discharge) and the areal extent of the cones of depression (amount of vertical leakage to the wells). It also became apparent that the freshwater flow system achieved a nearly steady-state freshwater head distribution within the annual time step, and therefore, specific storage was not a critical parameter. The effective porosity of all units was estimated as a constant value of 0.1.

Specific capacity measurements (discharge/drawdown) are made on a regular basis at the production wells. Table 7 lists the mean hydraulic conductivities at each well estimated from specific capacity measurements. The values were estimated by multiplying the mean specific capacity, in gallons per minute per foot of drawdown, by 2,000 to convert to transmissivity, in gallons per day per foot squared (Theis and others, 1963). Transmissivity was then divided by the thickness of the perforated interval of the well to obtain conductivity and the value was converted to metric units. A trend (also observed by Hickey, 1968) of decreasing conductivities towards the east and in the younger subunits is noticeable in these data.

The hydraulic conductivities of all layers were initially set at 3×10^{-5} m/s and the leakance at 10^{-10} s^{-1}, representing a ratio of horizontal to vertical hydraulic conductivity of 100:1 to 1,000:1. Simulation showed, however, that the values had to be reduced by roughly an order of magnitude to obtain both a head distribution and flux through the system resembling observed conditions. This discrepancy between measured values and calibrated values can be attributed to the fact that the specific capacity tests measure the conductivity of the more permeable units and also include the effects of vertical leakage. Both of these would lead to an overestimation of the bulk (averaged) effective conductivity of the units. Table 9 summarizes the aquifer parameters used in the model. The high ratio of horizontal to vertical hydraulic conductivity is consistent with the presence of siltstone and claystone interbeds. Maps of subunit hydraulic conductivities and leakance values are given in figures 14 and 17, respectively.

RESULTS OF 1930-81 SIMULATIONS

The initial conditions were obtained by simulating predevelopment conditions; the system was allowed to achieve steady state both onshore and offshore. The simulated onshore predevelopment water levels are shown in figure 18*A*. This is a composite water-level map constructed by taking the water levels from the unit outcropping in each area (for example, unit A in the west, unit E in the east). As can be observed from this map, the near-surface ground-water system is influenced by the topography and water flows mainly to the streams and toward the coast. Early reports of conditions in the area indicate that wells in the Capitola area (where the marine terraces have a land-surface altitude of approximately 25 m) were free flowing (California State Water Resources Board, 1953) when first drilled. The simulated water levels of approximately 30 m at the coast in the Capitola area would reflect free-flowing conditions.

Table 8. Annual pumpage at model blocks

[row, column, layer; values shown are in cubic meters per second; --, no data]

Year	18,17,1	14,21,4	13,22,5	11,24,5	14,26,5	15,17,1	14,17,1	13,20,1	15,16,1
1930	0.0065	0.0014	--	0.0025	--	--	--	--	--
1931	.0068	.0014	--	.0025	--	--	--	--	--
1932	.0071	.0014	--	.0028	--	--	--	--	--
1933	.0074	.0017	--	.0028	--	--	--	--	--
1934	.0079	.0017	--	.0031	--	--	--	--	--
1935	.0071	.0014	0.0017	.0028	--	--	--	--	--
1936	.0076	.0017	.0017	.0028	--	--	--	--	--
1937	.0079	.0017	.0017	.0031	--	--	--	--	--
1938	.0085	.0017	.0020	.0031	--	--	--	--	--
1939	.0088	.0020	.0020	.0034	--	--	--	--	--
1940	.0093	.0020	.0020	.0037	--	--	--	--	--
1941	.0096	.0020	.0023	.0037	--	--	--	--	--
1942	.0102	.0023	.0023	.0040	--	--	--	--	--
1943	.0108	.0023	.0025	.0042	--	--	--	--	--
1944	.0113	.0025	.0025	.0042	--	--	--	--	--
1945	.0119	.0025	.0025	.0045	--	--	--	--	--
1946	.0125	.0025	.0028	.0048	--	--	--	--	--
1947	.0133	.0028	.0028	.0051	--	--	--	--	--
1948	.0139	.0028	.0031	.0054	--	--	--	--	--
1949	.0144	.0031	.0034	.0057	--	--	--	--	--
1950	.0085	.0020	.0020	.0034	--	0.0059	--	0.0059	--
1951	.0091	.0020	.0020	.0034	--	.0065	--	.0065	--
1952	.0096	.0020	.0023	.0037	--	.0068	--	.0068	--
1953	.0099	.0023	.0023	.0040	--	.0071	--	.0071	--
1954	.0105	.0023	.0023	.0040	--	.0074	--	.0074	--
1955	.0110	.0023	.0025	.0042	--	.0079	--	.0079	--
1956	.0116	.0025	.0025	.0045	--	.0082	--	.0082	--
1957	.0122	.0025	.0028	.0048	--	.0088	--	.0088	--
1958	.0127	.0028	.0028	.0051	--	.0091	--	.0091	--
1959	.0136	.0028	.0031	.0051	--	.0096	--	.0096	--
1960	.0142	.0031	.0031	.0054	--	.0102	--	.0102	--
1961	.0144	.0031	.0031	.0057	0.0020	.0102	--	.0102	--
1962	.0150	.0031	.0034	.0059	.0023	.0108	--	.0108	--
1963	.0159	.0034	.0037	.0062	.0023	.0113	--	.0113	--
1964	.0167	.0037	.0037	.0065	.0023	.0119	--	.0119	--
1965	.0102	.0023	.0125	.0040	.0014	.0074	0.0147	.0074	--
1966	.0108	.0023	.0130	.0042	.0017	.0076	.0153	.0076	--
1967	.0122	.0017	.0150	.0045	.0014	.0023	.0218	.0093	--
1968	.0105	.0034	.0167	.0068	.0025	.0048	.0283	.0074	--
1969	.0139	.0031	.0170	.0054	.0020	.0099	.0198	--	--
1970	.0201	.0037	.0190	.0059	.0017	.0122	.0178	--	--
1971	.0161	.0048	.0198	.0062	.0020	.0105	.0241	--	--
1972	.0184	.0054	.0232	.0054	.0014	.0051	.0340	--	--
1973	.0093	.0048	.0212	.0051	.0011	.0076	.0453	.0040	--
1974	.0091	.0045	.0204	.0048	.0011	.0074	.0425	.0037	--
1975	.0136	.0051	.0218	.0057	.0011	.0076	.0396	.0068	--
1976	.0161	.0054	.0207	.0065	.0014	.0079	.0433	.0065	--
1977	.0144	.0017	.0167	.0054	.0011	.0051	.0425	.0085	--
1978	.0159	.0020	.0193	.0079	.0014	.0091	.0481	.0091	--
1979	.0221	.0034	.0198	.0079	.0001	.0091	.0425	.0125	--
1980	.0210	.0017	.0144	.0071	.0028	.0119	.0453	.0207	--
1981	.0215	.0014	.0173	.0091	.0037	.0116	.0425	.0195	--
1982	.0241	.0020	.0195	.0079	.0042	.0139	.0396	.0173	--
1983	.0218	.0028	.0232	.0105	.0037	.0184	.0453	.0108	--
1984	.0150	.0045	.0221	.0082	.0054	.0184	.0311	.0074	0.0269

Table 9. Summary of aquifer parameters used in the model

[m, meter; m/s, meter per second; s^{-1}, $second^{-1}$]

Subunit	Hydraulic conductivity (m/s)	Maximum thickness (m)	Specific storage (m)	Leakance (s^{-1})
A	10^{-6} to 10^{-5}	250	10^{-6} to 10^{-7}	10^{-9} to 10^{-13}
B	10^{-6}	76	10^{-7} to 10^{-6}	10^{-9} to 10^{-11}
C	10^{-6}	37	10^{-6}	10^{-9} to 10^{-10}
D	10^{-6}	30	10^{-7} to 10^{-6}	10^{-9} to 10^{-10}
E	10^{-6}	183	10^{-5}	10^{-9} to 10^{-11}

The simulated composite water levels for April 1981 and the observed water levels by Bloyd (1981) are shown in figure 18*B*. The cones of depression at the coast, which are below sea level, reflect the heads in the lower subunits tapped by the deep production wells. Water levels in the northern part of the area have remained relatively stable over time. At the coast, however, pumping has modified the predevelopment flow field. The cones of depression now capture some of the water that previously flowed to the streams and offshore. Table 10 shows the predevelopment and 1981 baseflows to the creeks, which compare favorably to the estimates made in the previous section.

In order to understand how development has modified the fluxes through the system, the annual recharge, discharge, and pumpage relations for the period from 1930 to 1985, as calculated by the model, are shown in figure 19. Prior to development, the recharge to the system was 0.50 m^3/s; 0.47 m^3/s discharged onshore to the creeks and the overlying Aromas Sand. Only 0.03 m^3/s of the water flowed to the sea offshore, yet this was sufficient to maintain the freshwater-saltwater interface position offshore. With development and an increase in pumpage in the basin, the 1981 onshore and offshore discharges had decreased to 0.43 m^3/s and 0.01 m^3/s, respectively. The decrease in ground-water discharge to the streams is illustrated in figure 19 by the decrease in baseflow to Soquel Creek with increased ground-water pumpage.

These results demonstrate that most of the water entering the Soquel-Aptos basin is being discharged to the streams onshore, and only a small component of the recharge is flowing offshore. The freshwater flow system is most active onshore where there is strong topographic relief driving the flow towards the streams. Water that is not discharged to the streams flows offshore. Because of the gentle slope of the continental shelf, low conductivity, and increase in the overlying equivalent freshwater head, this flow is small, but has been sufficient to prevent seawater intrusion. Most of the water that has been withdrawn from the basin is derived from captured baseflow and additional induced recharge (fig. 19).

HISTORY MATCHING AND SENSITIVITY TO AQUIFER PARAMETERS

In order to check and "fine tune" the calibrated model, calculated monthly water levels were compared with those measured at the coastal multilevel monitoring wells from 1983 to 1985 (Luhdorff and Scalmanini, Consulting Engineers, 1985). Simulations were initiated in 1982 in an attempt to include the transient effects due to conditions prior to 1983. The results are given in figure 20, and show that the match between simulated and measured heads is relatively good.

A simple exercise to examine the sensitivity of the model to aquifer parameter values was carried out by systematically varying the parameters in each individual layer and comparing the computed values of head to the observed values (273 measurements). The standard error of estimate was calculated for each case, and figure 21 shows the result of these runs. The stress (pumpage) on the system is the dominant controlling factor. However, changes in hydraulic conductivity affect the magnitude of drawdown caused by pumping at the production wells, and leakance affects the amount of flux through the system. The system is most sensitive to changes in subunits A and E, with the behavior of the other subunits being a reflection of the conditions in A and E.

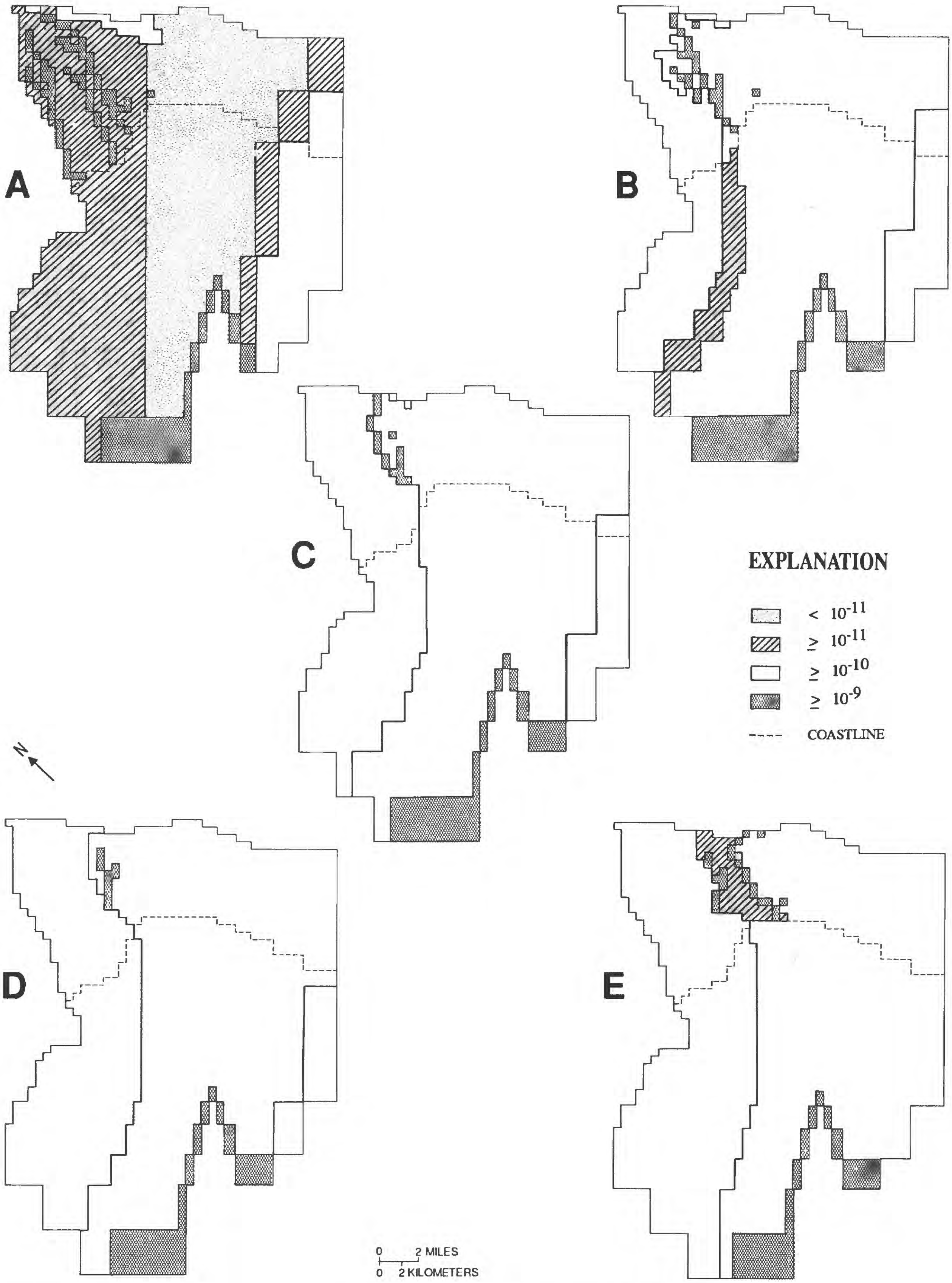


Figure 17. Distribution of leakance (in seconds $^{-1}$) for the model subunits.

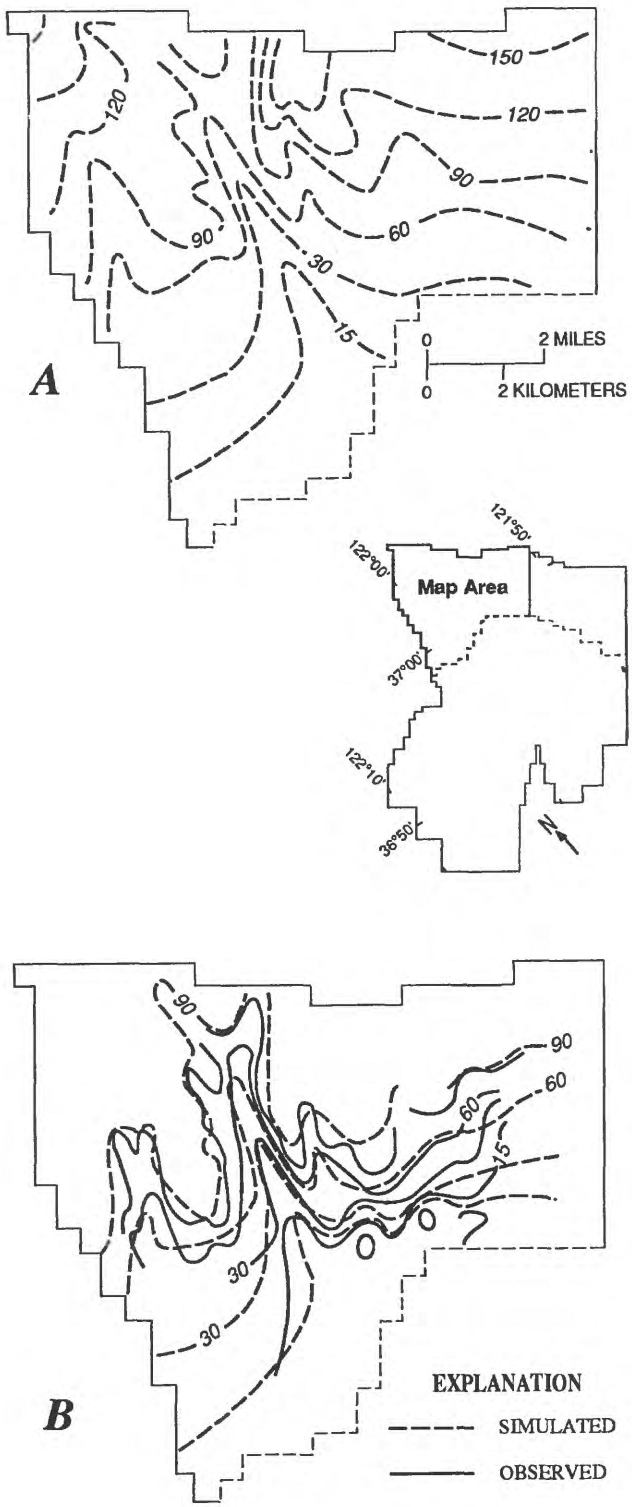


Figure 18. Composite onshore water-level maps. *A.* Simulated predevelopment water levels. *B.* Simulated and observed water levels for April 1981. Water levels are in meters relative to sea level.

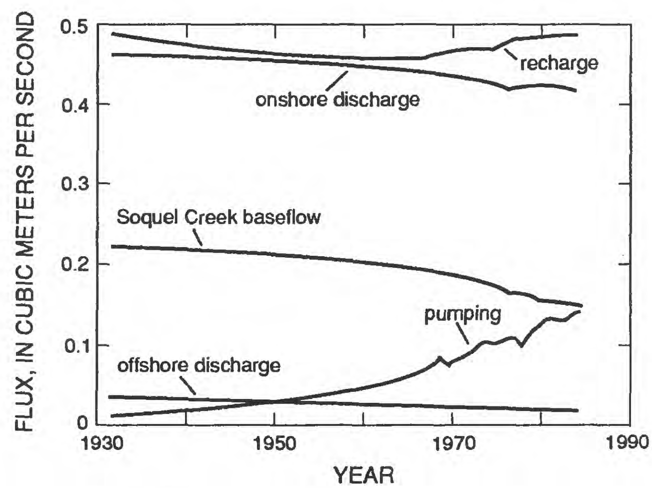


Figure 19. Ground-water flow rates through the Soquel-Aptos basin, 1930-85.

Table 10. Ground-water discharges to streams as calculated from the model

[m^3/s, cubic meter per second]

Basin	Predevelopment (m^3/s)	April 1981 (m^3/s)	1985 (m^3/s)
Soquel	0.23	0.16	0.14
West Branch Soquel	.03	.03	.03
Aptos	.07	.05	.04
Branciforte	.03	.03	.03
Total	.36	.27	.24

FUTURE GROUND-WATER DEVELOPMENT AND THE POTENTIAL FOR SEAWATER INTRUSION

The simulation of conditions from 1930 to 1985 showed almost no movement of the saltwater interface offshore, although significant changes occurred in the flow system. The initial (1930) and 1985 freshwater heads, saltwater heads, and interface tip and toe positions for the five Purisima subunits are shown in figures 22 and 23. This simulation suggests that interface response is quite slow and takes place over long timeframes. Pumpage has led to the development of cones of depression near the coast that have modified the flow patterns in the basin. Ground water that flowed to the streams under natural conditions has been diverted to the production wells.

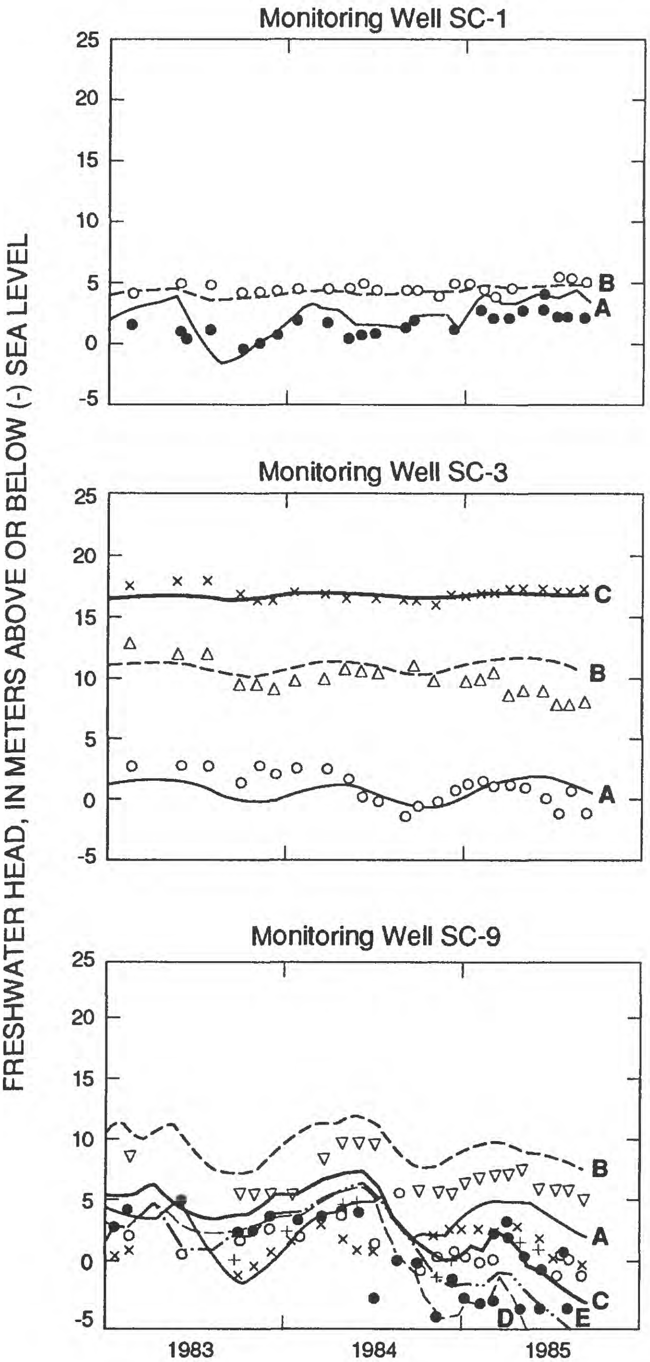


Figure 20. Simulated and measured monthly water levels at three of the coastal monitoring wells (points are observed levels; lines are simulated levels; letters refer to subunits).

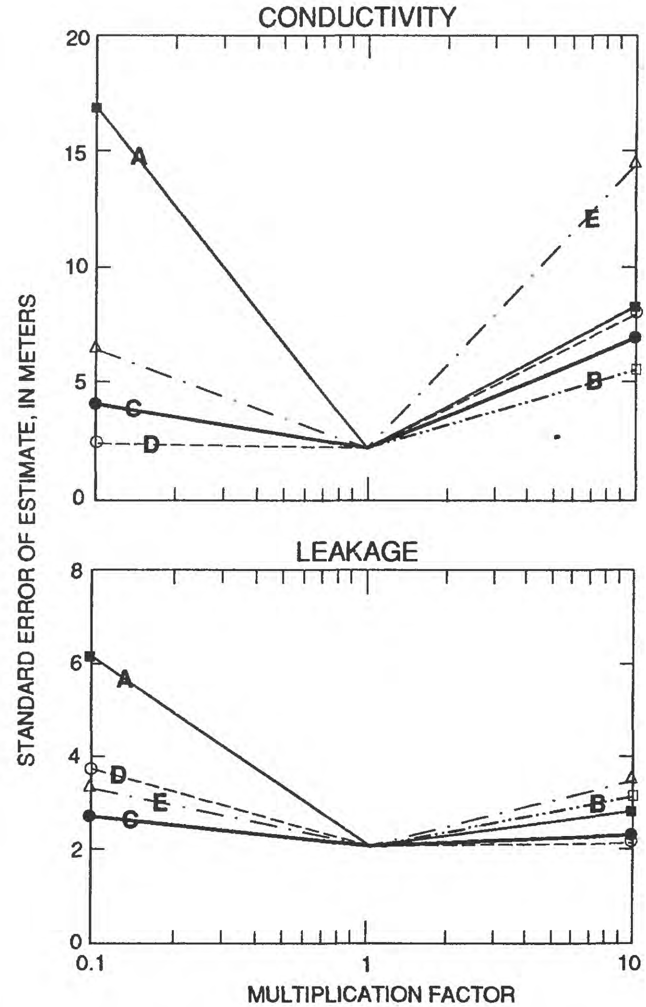


Figure 21. Sensitivity of model to aquifer parameters in 1983-85 simulations. Lines represent model subunits A through E.

The amount of development that the Soquel-Aptos basin can sustain is dependent on the amount of baseflow that can be captured by proper location of wells; the resulting decrease in surface-water flow that is acceptable; and the potential for seawater intrusion as a result of ground-water pumpage. Seawater may enter the aquifer by migration of the interface, or by vertical leakage of seawater into the freshwater through the ocean floor. As mentioned above, interface movement is very slow and takes place over very long timeframes. Leakage of saltwater into the shallow aquifers, however, is possible over the short term. For 1985 conditions, freshwater is flowing offshore from all layers, and there is no simulated leakage of saltwater into the aquifer (see figure 23).

To examine the possible consequences of increased pumpage in the basin, a simulation was carried out with pumpage twice the 1985 rates at all wells. The 1985 heads were used as initial conditions, and a period of 10 years was simulated (using annual time steps). The results are shown in figure 24. Increased pumpage had little effect on the rate of movement of the interface. It did, however, cause the

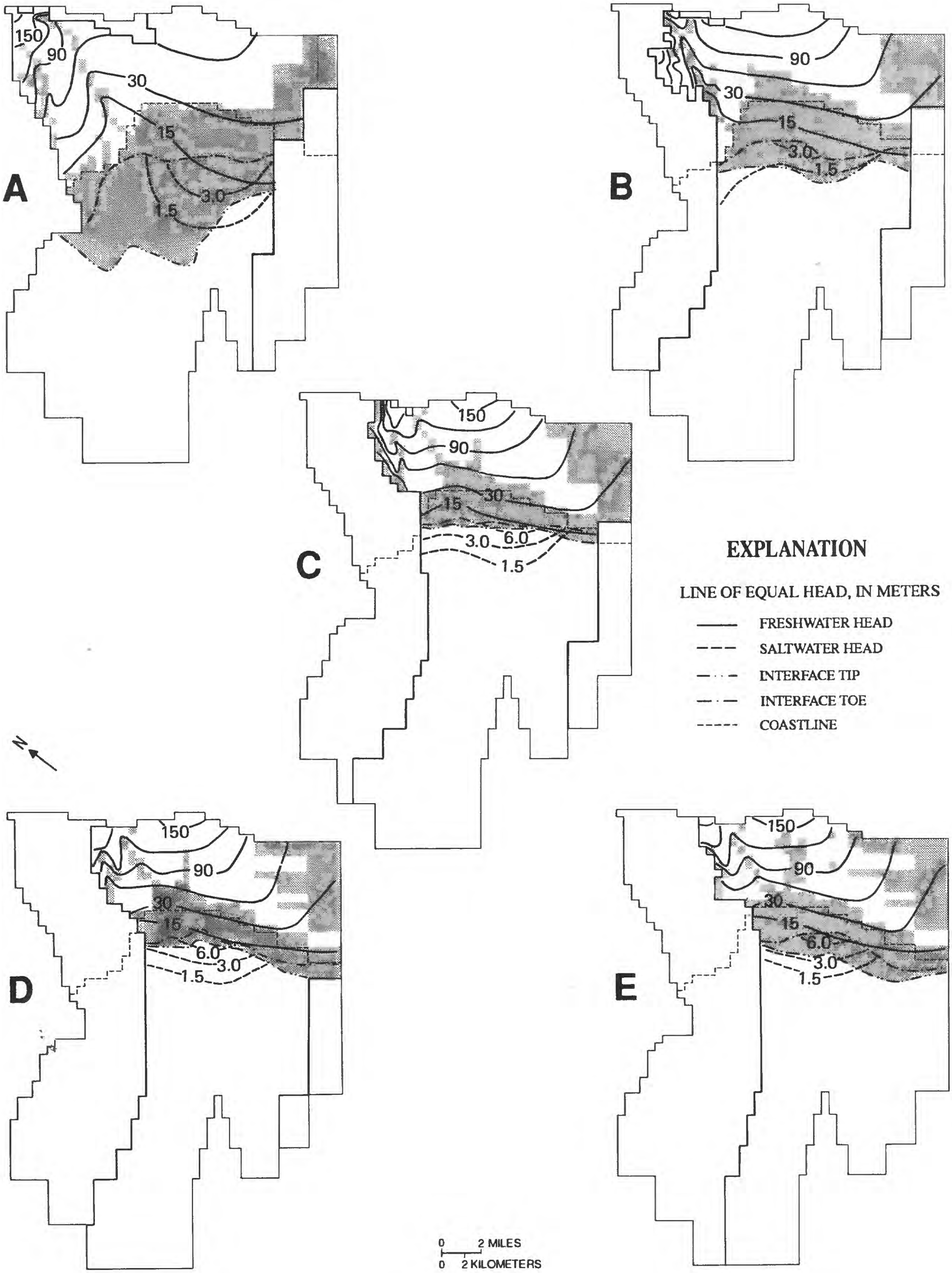


Figure 22. Simulated freshwater and saltwater heads (in meters relative to sea level) and interface tip and toe positions in subunits A through E for predevelopment (1930) conditions. Shading represents areas of freshwater discharge from top of aquifer.

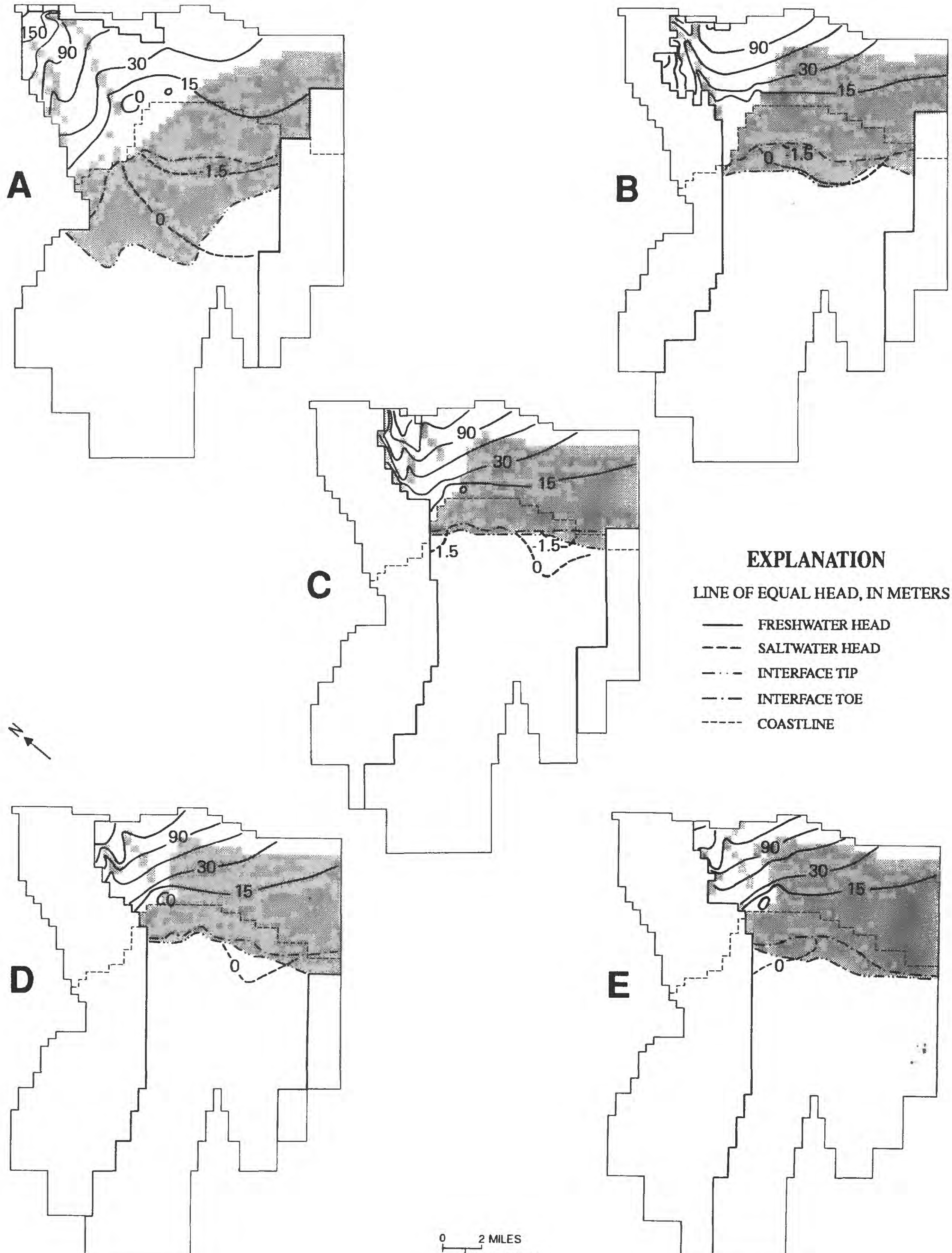


Figure 23. Simulated freshwater and saltwater heads (in meters relative to sea level) and interface tip and toe positions in subunits A through E for 1985 pumping rates. Shading represents areas of freshwater discharge from top of aquifer.

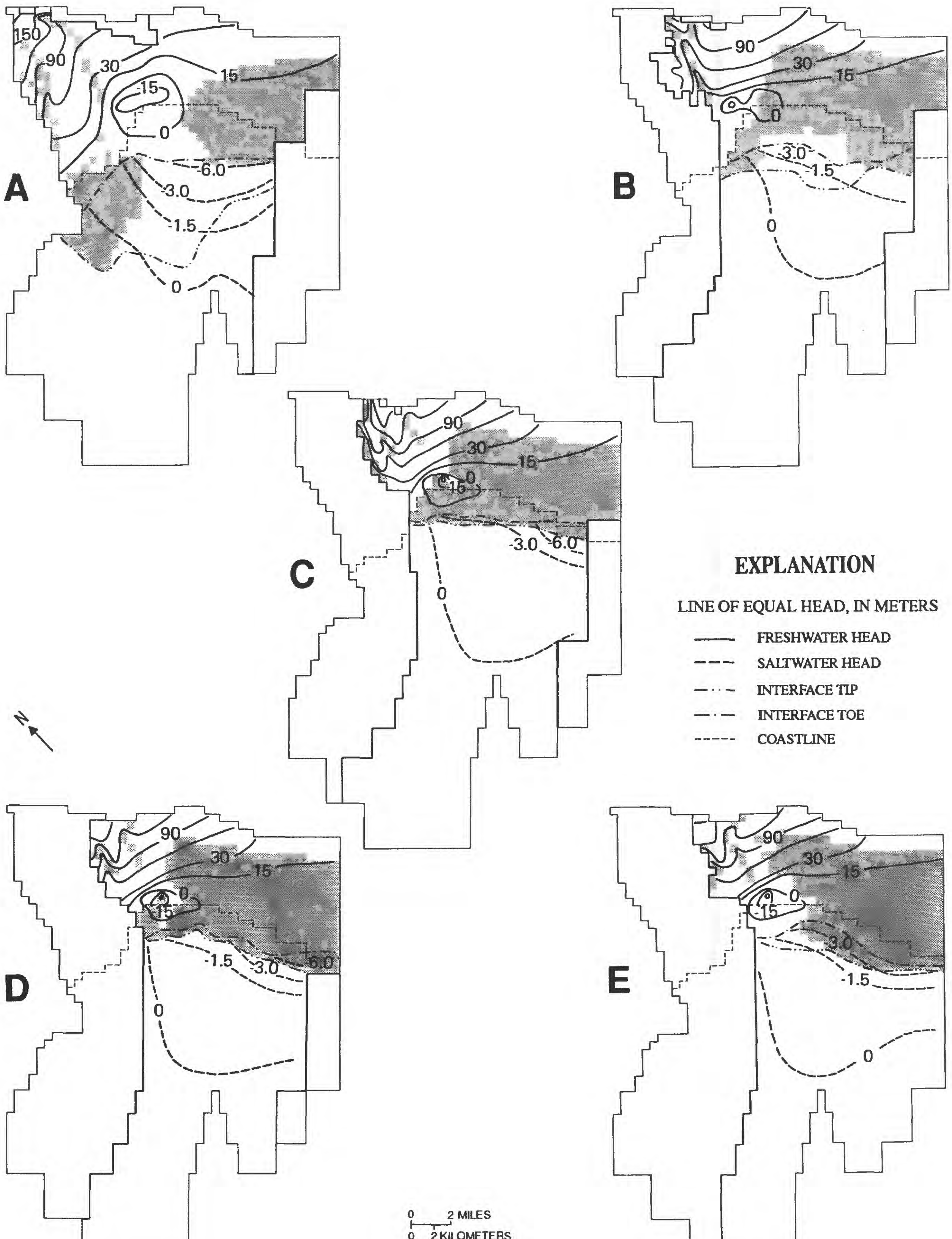


Figure 24. Simulated freshwater and saltwater heads (in meters relative to sea level) and interface tip and toe positions in subunits A through E for twice 1985 pumping rates. Shading represents areas of freshwater discharge from top of aquifer.

development of larger cones of depression, which, in the upper units, extended offshore. As a result, leakage of seawater into subunit E has been induced. Also, the freshwater discharge onshore has been reduced to 0.34 m^3/s. Thus, the most immediate potential cause for seawater intrusion is pumping in the shallow Purisima subunits near the coast that could induce downward leakage of seawater through ocean floor outcrops.

INTERFACE MOVEMENT AND SEA-LEVEL CHANGE

The previous simulations have shown that the response of the saltwater-freshwater interface is slow and takes place over long timeframes. This slow response suggests that the offshore interface position in the Soquel-Aptos basin may not be in equilibrium with present-day sea level and could still be responding to Pleistocene sea-level changes. This hypothesis has been tested using a long-term simulation incorporating sea-level change.

The Monterey Bay region has undergone a complex Quaternary history of sea-level changes accompanied by tectonic downbowing in the lowland areas of the Pajaro Valley and uplift of Pleistocene terraces in the northern area (greatest in the Aptos-Capitola area) (Dupre, 1975; Bradley and Griggs, 1976; Greene and Clark, 1979). Dupre and others (1980) examined the vertical sequence of sedimentary structures preserved in marine terrace deposits in the northern Monterey Bay region. Their analysis showed that the Quaternary deposits in the Watsonville region reflect at least 11 cycles of glacio-eustatic sea-level change. The last major low-stand of sea level occurred about 18,000 years before present during the Wisconsinan glacial maximum, and sea level has been rising since then (Schwartz and others, 1986). Fossil molluscs collected from Quaternary sediments on the outer continental shelf in southern Monterey Bay at a depth of 100 to 109 m were dated at 17,000 years (Powell and Chin, 1984). Analysis of the molluscan assemblages indicated that they were representative of the deep inner sublittoral zone (18 to 46 m depth) and cooler water conditions thought to reflect the low sea level associated with the late Wisconsinan glacial maximum. Thus, it can be concluded that about 18,000 years ago, relative sea level was approximately 76 m lower than at present.

In order to investigate the rate of interface movement in response to sea-level changes, the period of post-Wisconsinan glacial maximum sea-level rise was simulated. To simplify the analysis, a constant rate of sea-level rise was used, and no changes in onshore and offshore topography, onshore boundary conditions, or aquifer properties were made. It was assumed that most of the compaction and diagenesis of these Pliocene sediments had occurred before this period. A steady-state simulation for a sea level 76 m below present sea level was used as the initial condition (fig. 25). A constant rate of sea-level rise of 4.2 mm/yr over 18,000 years then was simulated. The simulation was repeated using 500-, 100-, and 50-year time-step sizes, and virtually the same solution resulted in each case. Figure 26 shows the freshwater heads, saltwater heads, and interface tip and toe position after 18,000 years of sea-level rise.

Initially, in the simulations with sea level 76 m below present-day sea level, there was a gentle seaward freshwater gradient in the shelf area, which reflected the smooth topography, and freshwater extended to Soquel Canyon. Gradients in the inland areas were steeper than in the shelf area owing to the more rugged topography. After 18,000 years of sea-level rise, the heads in the offshore area have risen in response to the change in the offshore boundary condition. The offshore freshwater gradient has become very flat, and saltwater is flowing landward as the interface moves.

Shown in the section in figure 27 are the steady-state positions of the interface for sea level at 0 and -76 m, and the transient interface position after 18,000 years of sea-level rise to 0 m. The simulation of rising sea level shows that the interface has not yet reached its equilibrium position. The unshaded zone in the section of figure 27 shows the difference between the transient position of the interface after 18,000 years of sea-level rise (2) and the steady-state interface position in equilibrium with current sea level (1). The equilibrium interface is significantly landward of the transient interface. This is because of the relatively low vertical and horizontal conductivities and the slow response of the system to changes in the boundary condition at the ocean floor and canyon outcrop during sea-level rise. Initially, at steady state, there is a more or less static wedge of saltwater beneath the freshwater. After 18,000 years, however, saltwater heads have risen and shoreward seawater flow has been induced (see figure 26). Given sufficient time, the interface would move to a position in equilibrium with present-day sea level.

In spite of the simplifications involved in this analysis, it appears that the interface is currently responding to the Pleistocene sea-level fluctuations in Monterey Bay, as well as to recent development in

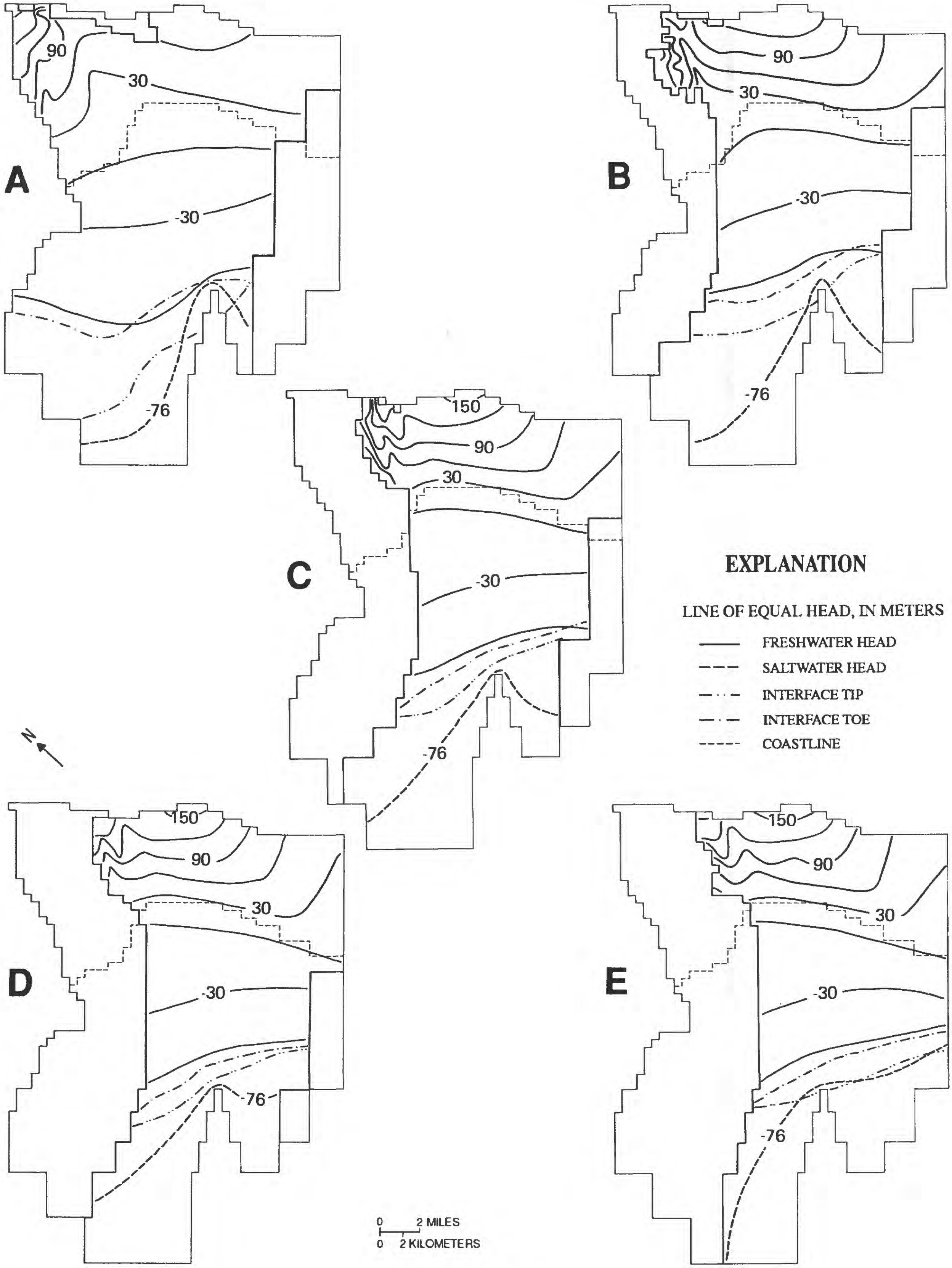


Figure 25. Simulated freshwater and saltwater heads (in meters relative to sea level) and interface tip and toe positions in subunits A through E for conditions in equilibrium with sea level at 76 meters below current sea level.

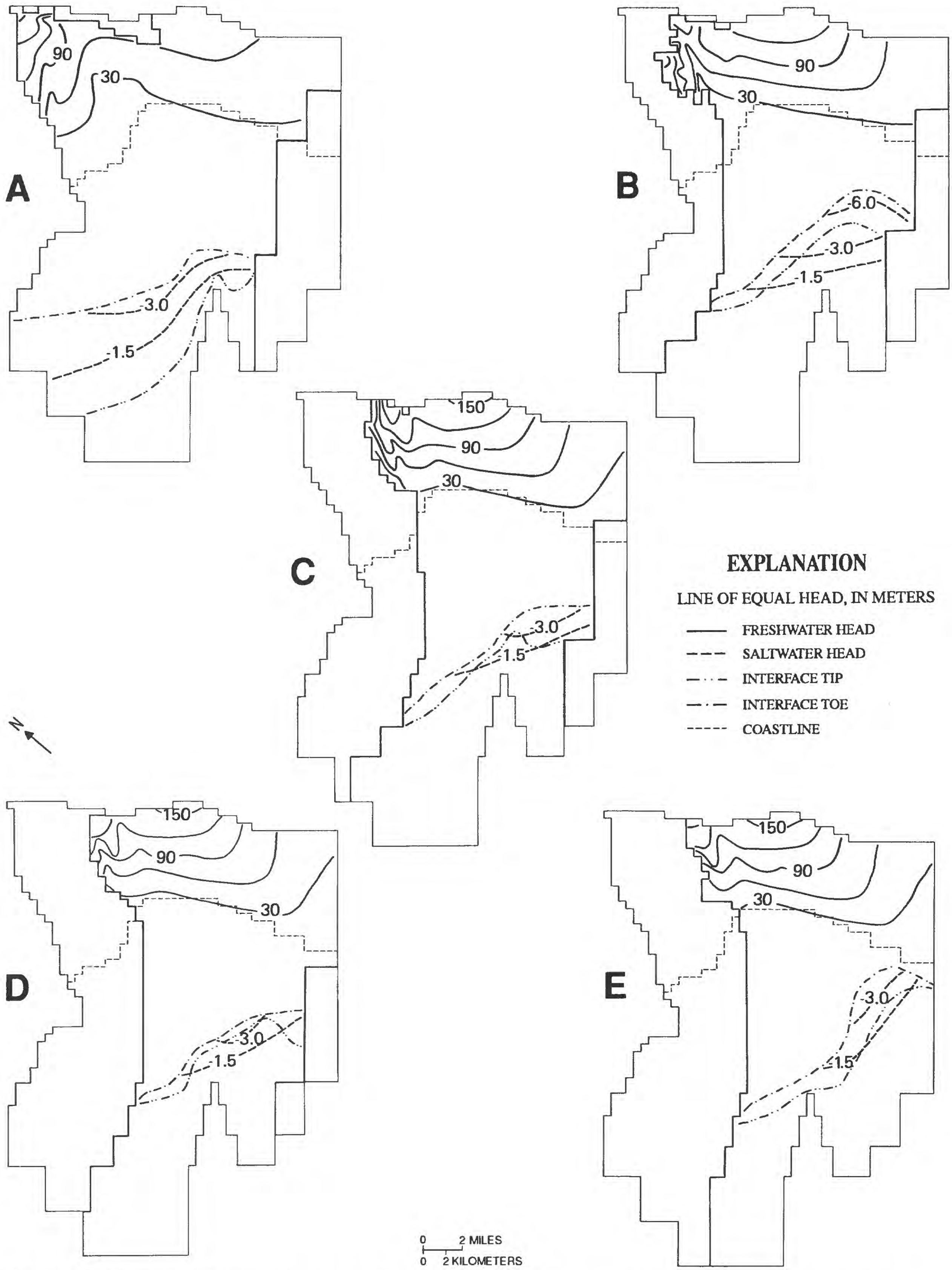
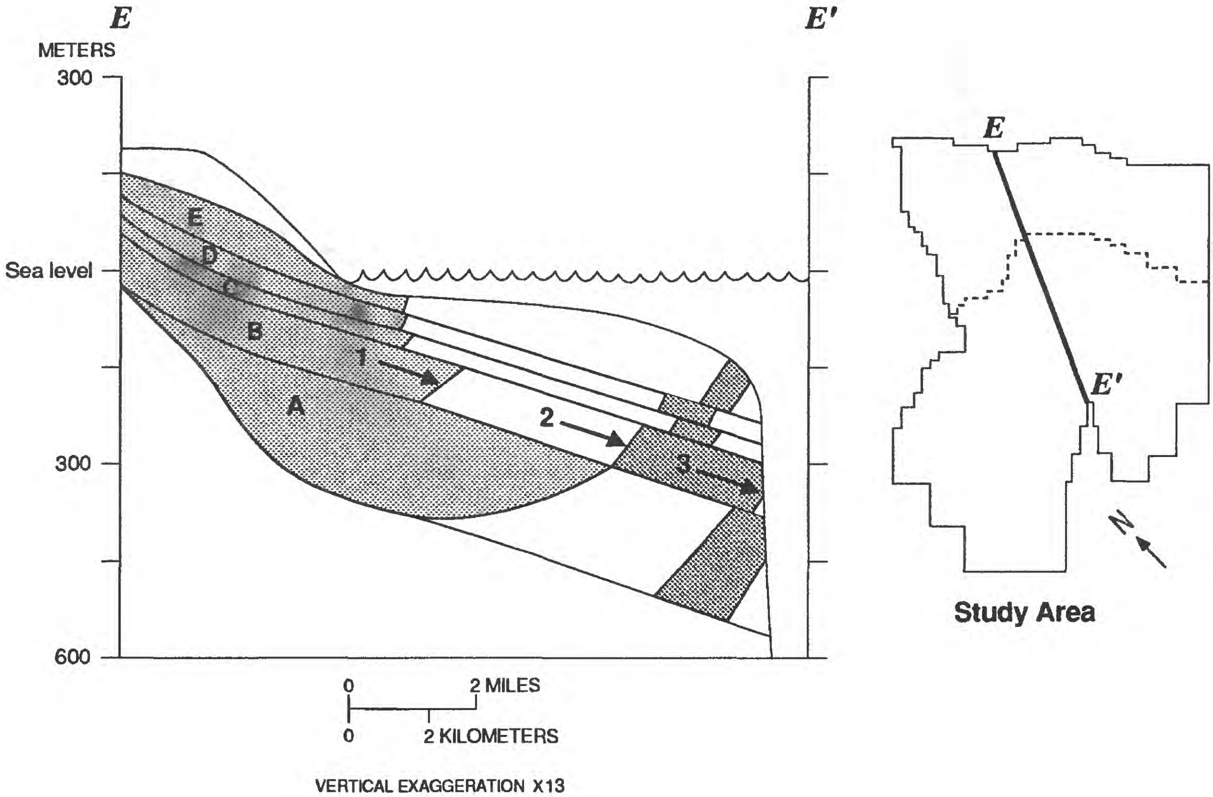


Figure 26. Simulated freshwater and saltwater heads (in meters relative to sea level) and interface tip and toe positions in subunits A through E after 18,000 years of sea-level rise.



EXPLANATION

1 STEADY STATE WITH SEA LEVEL AT 0 METER

2 TRANSIENT WITH SEA LEVEL AT 0 METER

3 STEADY STATE WITH SEA LEVEL AT -76 METERS

Figure 27. Simulated interface along section *E-E′* for steady-state positions with sea level at 0 and -76 meters, and transient position with sea level at 0 meter. Unshaded area represents the region through which the interface has not yet moved in response to sea-level change. Letters refer to subunits.

the Soquel-Aptos basin. The rate of movement of the interface in response to the increased ground-water pumpage of the past 50 years is probably of the same order of magnitude as the longer term response to sea-level changes.

The interface probably did not achieve equilibrium with the maximum high-stands or minimum low-stands of sea level; rather, it oscillated about a position in equilibrium with the mean of the Quaternary sea-level stands. The interface probably was not in equilibrium with the Wisconsinan low-stand of sea level but was still responding to earlier sea-level changes. Today, it is likely that the interface is in an intermediate position between that of the 18,000-year simulation and the simulation in equilibrium with present-day sea level. Similar conditions have been observed in the northern Atlantic coastal plain, where the transition zone between freshwater and saltwater is about 100 km offshore. This situation is believed to reflect a long-term average sea level between 15 and 30 m below present sea level (Meisler and others, 1984). This northern Atlantic coastal plain is similar to the Soquel-Aptos basin in that it also is a layered system with comparable horizontal and vertical conductivities.

SUMMARY AND CONCLUSIONS

A quasi-three-dimensional, finite-difference model that simulates freshwater and saltwater flow separated by a sharp interface was used to study the layered coastal aquifer system of the Purisima Formation in the Soquel-Aptos basin, Santa Cruz County, California. The model was used to evaluate the potential for seawater intrusion in the Soquel-Aptos basin. Predevelopment steady-state conditions and 1930-81 transient conditions were simulated. Results of these simulations suggest that ground water extracted from the system has come mainly from capture of stream baseflow, rather than from reduction of offshore freshwater discharge. The potential for future seawater intrusion was investigated by simulating conditions with twice the 1985 pumping rates. The results of this simulation indicate that the most immediate potential cause for seawater intrusion is pumping from the shallow Purisima subunits near the coast that could induce downward leakage of saltwater into the aquifers through ocean floor outcrops. Long-term simulation incorporating the sea-level rise of the past 18,000 years suggests that the interface today is still responding to long-term Pleistocene sea-level fluctuations and has not achieved equilibrium with present-day sea-level conditions. The rate of movement of the interface in response to increased ground-water pumpage occurring over the past 50 years is probably of the same order of magnitude as the longer term responses.

As Bredehoeft and others (1982) state, the magnitude of pumpage from a basin that can be sustained depends on the quantity of natural discharge that can be captured, and to a lesser degree, the quantity of additional recharge that can be induced. The acceptable magnitude of development depends on the hydrologic consequences that can be tolerated, and in many cases it takes long periods of time before a new equilibrium is achieved. Simulation of the Soquel-Aptos basin has shown this to be the case. As we interpret the simulation results, it is important to bear in mind the limitations of the model. There is considerable uncertainty in the model input values of hydraulic conductivity, leakance, and specific storage because of the limited data available. Also, effective hydraulic conductivities of the layers were used, although there may be some more conductive layers in which the saltwater interface may respond more quickly to onshore pumping. Little is known regarding water levels prior to development of the basin, which introduces uncertainty into the initial conditions used for the 1930-81 simulations. Within the constraints of these uncertainties, however, it is possible to draw conclusions regarding the principal features of the Purisima Formation aquifer system in the Soquel-Aptos area.

Simulation of the Soquel-Aptos basin has led to an increased understanding of the ground water-surface water interaction, as well as the offshore freshwater-saltwater flow system. Under natural predevelopment conditions, about 90 percent of the freshwater recharge is discharged through baseflow to the streams. The remaining water flows offshore and is discharged to the sea by leakage through the ocean floor. The most active part of the flow system is onshore, where there is strong topographic relief. Offshore, however, the continental shelf has a relatively uniform, gentle slope, and the head at the top of the system is controlled by the sea surface, which is flat (there are no head gradients at the top of the system). Therefore, ground-water flow in this part of the system is sluggish. These findings concur with the observations of Toth (1963) for ground-water flow in small basins.

Ground-water development in the basin has led to some decrease in the natural freshwater flow offshore. The predominant source for the water withdrawn, however, has been the capture of natural baseflow. The cones of depression near the coast have modified the flow patterns in the basin, diverting to the production wells ground water that flowed under natural conditions to the streams. Thus, the amount of development that this basin can sustain is dependent on the quantity of baseflow that can be captured by proper location of wells, and the resulting decrease in surface-water flow that is acceptable.

Another limitation on development is the potential for seawater intrusion as a result of ground-water withdrawals. Simulation indicates that in the short term the interface movement is negligible; that is, the interface behaves more or less as an immovable impermeable boundary. This is because of the slow flow response in the saltwater zone. This slow response is a result of the low horizontal and vertical conductivities, which impede the flow of saltwater into the interface zone, hindering the interface movement. Bond and Bredehoeft (1987) investigated the pathways of seawater intrusion into the primary confined aquifer in the Pajaro Valley using an areal two-dimensional solute-transport model. Their analysis showed that although lateral flow of saltwater through the offshore outcrop contaminates the aquifer at a higher rate, this water has not moved onshore yet, and vertical leakage has been the main pathway for seawater intrusion into the onshore portion of the aquifer. This leakage has occurred primarily beneath the estuaries and sloughs, as well as through the near-shore ocean floor. In the Soquel-Aptos basin, water levels in the deep Purisima subunits have been lowered below sea level near the coast. In the shallow Purisima subunits, however, this is not the case, and freshwater is still flowing to the sea. If, however, water levels near the coast in the shallow subunits were to be drawn down below sea level, vertical leakage of saltwater into these subunits through ocean floor outcrops would be induced. This would lead to degradation of ground-water quality. To avoid drawdown at the coast, it is beneficial to pump from the lower aquifers near the coast, and/or to place shallow wells inland.

Simulation of the post-Wisconsinan glacial maximum sea-level rise suggests that the interface is still responding to long-term Pleistocene sea-level fluctuations and has not achieved equilibrium with present-day conditions. The rate of movement of the interface in response to the increased ground-water pumpage that has occurred over the past 50 years is of the same order of magnitude as the longer term responses.

REFERENCES

Akers, J.P., and Hickey, J.J., 1967, Geohydrologic reconnaissance of the Soquel-Aptos area, Santa Cruz County, California: U.S. Geological Survey open-file report, 58 p.

Allen, J.E., 1946, Geology of the San Juan Bautista quadrangle, California: California Division of Mines Bulletin 133, 112 p.

Blaney, H.F., and Ewing, P.A., 1953, Irrigation practices and consumptive use of water in Pajaro Valley, CA, in Santa Cruz - Monterey Counties Investigation: State Water Resources Board, Bull. 5, p. 159-190.

Bloyd, R.M., 1981, Approximate ground-water-level contours, April 1981, for the Soquel-Aptos area, Santa Cruz County, California: U.S. Geological Survey Open-File Report 81-680, 3 p.

Bond, L.D., and Bredehoeft, J.D., 1987, Origins of seawater intrusion in a coastal aquifer--A case study of the Pajaro Valley: Journal of Hydrology, v. 92, no. 3-4, p. 363-388.

Bradley, W.C., and Griggs, G.B., 1976, Form genesis, and deformation of central California wave-cut platforms: Geological Society of America Bulletin, 87, p. 433-449.

Bredehoeft, J.D., Papadopulos, S.S., and Cooper, H.H., 1982, Groundwater--The water budget myth, *in* Scientific Basis of Water Resource Management: National Research Council, Washington, D.C., p. 51-57.

California Department of Water Resources, 1981, California rainfall summary, 1849-1980: Sacramento, California.

California State Water Resources Board, 1953, Santa Cruz-Monterey Counties investigation: Bulletin No. 5, State of California, Sacramento, California, 230 p.

Clark, J.C., 1966, Tertiary stratigraphy of the Felton-Santa Cruz area, Santa Cruz Mountains, California: Stanford, California, Stanford University, Ph.D. dissertation.

Clark, J.C., and Rietman, J.D., 1973, Oligocene stratigraphy, tectonics, and paleogeography southwest of the San Andreas fault, Santa Cruz Mountains and Gabilan Range, California Coast Ranges: U.S. Geological Survey Professional Paper 783, 18 p.

Cummings, J.C., Touring, R.M., and Brabb, E.E., 1962, Geology of the northern Santa Cruz Mountains, California, *in* Bowen, O.E., ed., Geologic guide to the gas and oil fields of northern California: California Division of Mines Bulletin 181, p. 179-220.

Dupre, W.R., 1975, Quaternary history of the Watsonville lowlands, north-central Monterey Bay region, California: Stanford, California, Stanford University, Ph.D. dissertation.

Dupre, W.R., Clifton, H.E., and Hunter, R.E., 1980, Modern sedimentary facies of the open Pacific coast and Pleistocene analogs from Monterey Bay, California, *in* Field, M.E., Bouma, A.H., Colburn, I.P., Douglas, R.G., and Ingle, J.C., eds., Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium, 4, p. 105-119.

Essaid, H.I., 1990, The computer model SHARP, a quasi-three-dimensional finite-difference model to simulate freshwater and saltwater flow in layered coastal aquifer systems: U.S. Geological Survey Water-Resources Investigations Report 90-4130, 181 p.

Greene, H.G., 1970, Geology of southern Monterey Bay and its relationship to the ground-water basin and salt-water intrusion: U.S. Geological Survey open-file report, 50 p.

-----1977, Geology of the Monterey Bay region, California: U.S. Geological Survey Open-File Report 77-718, 343 p.

Greene, H.G., and Clark, J.C., 1979, Neogene paleogeography of the Monterey Bay Area, California, *in* Armentrout, J.M., Cole, M.R., and Terbest, H., eds., Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium, 3, p. 277-298.

Hickey, J.J., 1968, Hydrogeologic study of the Soquel-Aptos area, Santa Cruz County, California: U.S. Geological Survey open-file report, 48 p.

Johnson, M.J., 1980, Geology and ground water in north-central Santa Cruz County, California: U.S. Geological Survey Water-Resources Investigations Report 80-26, 33 p.

Johnson, M.J., Londquist, C.J., Laudon, Julie, and Mitten, H.T., 1988, Geohydrology and mathematical simulation of the Pajaro Valley aquifer system, Santa Cruz and Monterey Counties, California: U.S. Geological Survey Water-Resources Investigations Report 87-4281, 62 p.

Luhdorff and Scalmanini, Consulting Engineers, 1981, Review and analysis of reports relating to groundwater resources in the Soquel-Aptos area, Santa Cruz County, California: Woodland, California, 77 p.

-----1984, Groundwater resources and management report, 1983, Soquel Creek Water District, Soquel, California: Woodland, California, 52 p.

-----1985, Groundwater resources and management report, 1984, Soquel Creek Water District, Soquel, California: Woodland, California, 48 p.

-----1987, Ground-water monitoring and management, Aromas Red Sands, Soquel Creek Water District: Woodland, California, 54 p.

-----1988, Ground-water resources and management report, Soquel Creek Water District: Woodland, California, 85 p.

-----1990, Ground-water monitoring and management, 1990 update, Aromas Red Sands, Soquel Creek Water District: Woodland, California, 42 p.

Martin, B.D., 1964, Monterey submarine canyon, California--genesis and relationship to continental geology: Los Angeles, California, University of Southern California, Ph.D. dissertation.

Meisler, Harold, Leahy, P.P., and Knobel, L.L., 1984, Effect of eustatic sea-level changes on saltwater-freshwater relations in the Northern Atlantic Coastal Plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.

Montgomery Consulting Engineers, 1976, Soquel Creek Water District, comprehensive plan for water system development: Walnut Creek, California.

Muir, K.S., 1972, Geology and ground water of the Pajaro Valley area, Santa Cruz and Monterey Counties, California: U.S. Geological Survey open-file report, 33 p.

-----1980, Seawater intrusion and potential yield of aquifers in the Soquel-Aptos area, Santa Cruz County, California: U.S. Geological Survey Water-Resources Investigations Report 80-84, 29 p.

National Oceanic and Atmospheric Administration, 1984, Climatological data, annual summary: National Oceanic and Atmospheric Administration, v. 88, no. 13, Asheville, North Carolina.

Powell, C.L., and Chin, J.L., 1984, Faunal evidence for a late Wisconsin sea-level low stand, Monterey Bay outer shelf, Central California (abstract): Society of Economic Paleontologists and Mineralogists, First Annual Midyear Meeting, p. 66.

Rantz, S.E., 1974, Mean annual runoff in the San Francisco Bay region, California, 1931-70: U.S. Geological Survey Miscellaneous Field Studies Map MF-613, scale 1:500,000, 2 sheets.

Schwartz, D.L., Mullins, H.T., and Belknap, D.F., 1986, Holocene geologic history of a transform margin estuary--Elkhorn Slough, Central California: Estuarine, Coastal and Shelf Science, v. 22, p. 285-302.

Stone, H., 1968, Iterative solution of implicit approximations of multidimensional partial differential equations: Society for Industrial and Applied Mathematics, Journal of Applied Mathematics, v. 5, no. 3, p. 530-559.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, *in* Bentall, Ray, compiler, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331-340.

Thorup, R.R., 1981, Groundwater review of the Soquel-Aptos area, Santa Cruz County, California: Santa Cruz, California, Santa Cruz County Builders Exchange, 89 p.

Todd, D.K., 1964, Ground water hydrology: New York, John Wiley, 336 p.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, no. 16, p. 4795-4812.

GPO 688-401/79228