GEOHYDROLOGY AND MATHEMATICAL SIMULATION OF THE PAJARO VALLEY AQUIFER SYSTEM, SANTA CRUZ AND MONTEREY COUNTIES, CALIFORNIA

By *Michael J. Johnson, Clark J. Londquist, Julie Laudon,* and *Hugh T. Mitten*

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

The inch-pound system of units is used in this report. For those readers who prefer to use metric (International System) of units rather than inch-pound units, the conversion factors for the units used in this report are listed below.

Multiply inch-pound unit	By	To obtain metric unit
in (inch)	25.4	millimeter
ft (foot)	0.3048	meter
mi (mile, statute)	1.609	kilometer
mi^2 (square mile)	2.590	square kilometer
ft/s (foot per second)	0.3048	meter per second
ft^3/s (cubic foot per second)	0.02832	cubic meter per second
(ft/s)/ft (foot per second per foot)	1.00	meter per second per foot
acre-ft (acre-foot)	0.001233	cubic hectometer
acre-ft/yr (acre-foot per year)	0.001233	cubic hectometer per annum
gallon per capita per day	0.003785	cubic meter per capita per day

Chemical concentrations in water are given in milligrams per liter (mg/L).

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

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ABSTRACT

The future economic growth of the Pajaro Valley will depend on the development of a reliable ground-water supply to meet most of its water needs. Ground-water resources are limited, and an increasing demand has resulted in lowered water levels and seawater intrusion near Monterey Bay. An investigation of the ground-water system of the Pajaro Valley was undertaken to describe the basic geology and hydrology of the system and to develop a better understanding of the system in response to pumping stresses. A mathematical model of the ground-water system was used to aid in the understanding of the system.

The geologic units that were studied in order to evaluate the major developed ground-water flow system of the Pajaro Valley area are of Quaternary age and consist principally of the Aromas Sand, terrace deposits, alluvium, and dune sand. These deposits extend westward from the San Andreas rift zone to a distance offshore beneath Monterey Bay and are bounded on the north, east, and southeast by outcrops of older consolidated and partly consolidated rocks. The Aromas Sand, terrace deposits, and alluvium contain lenticular beds of coarse gravels and sands that grade upward into lagoonal silts and clays. The Aromas Sand is divided into older fluvial deposits and younger eolian deposits. The terrace deposits and alluvium grade upward from a basal gravel bed into finer grained deposits. The basal gravel is underlain by the Aromas Sand and overlain by an extensive zone of numerous, intercalated clay beds. Above the clay beds, the terrace deposits and alluvium are heterogeneous mixtures of mostly fine-grained material.

The upper Tertiary Purisima Formation, which underlies the Quaternary deposits of the Pajaro Valley, has undergone very limited development in the study area due to its greater depth and generally lower permeability. However, the formation is a principal source of ground water for both the Soquel-Aptos and north-central Santa Cruz County areas and may have substantial water-bearing potential.

The presently developed aquifer system in the Pajaro Valley consists of three aquifers separated by two confining layers of fine-grained, less permeable material. The lower aquifer is in the lower part of the Aromas Sand. The most heavily developed aquifer of the three is the middle aquifer. This aquifer consists of a basal gravel bed in the alluvium and terrace deposits, and the upper fluvial and lower eolian parts of the Aromas Sand. The upper aquifer contains a number of discontinuous water-bearing zones, found locally in the upper eolian sequences of the Aromas Sand, upper terrace deposits, upper alluvium, and dune deposits. The lower confining layer consists of beds of clay and silty clay in the fluvial sequences of the Aromas Sand. The upper confining layer is a discontinuous composite of the clay beds above the basal gravels in the alluvium and terrace deposits, and the weathered soil zones in the upper eolian sequence of the Aromas Sand.

A simplified representation of the Pajaro Valley aquifer system was conceptualized so that the system could be simulated using mathematical techniques. The three aquifers of the system are represented by three model layers. The model layers are separated by two confining units that represent the lower confining layer in the lower Aromas Sand, and the upper confining layer in the terrace deposits, alluvium, and upper Aromas Sand. The uppermost model layer is considered to be an unconfined aquifer, the middle layer is either confined or unconfined, and the lower layer is considered to be entirely confined. Water-bearing units within the Tertiary rocks were not included in this model.

Owing to the availability of pumpage and water-level data, the model was calibrated in the lower and middle layers for transient conditions which occurred from spring 1970 to autumn 1981. Predevelopment conditions were not modeled for that period because of sparse data. At the end of calibration, the model reproduced, with acceptable accuracy, 366 spring and autumn water levels measured at 39 selected wells completed in the middle and lower aquifers. The standard error of estimate between measured and computed heads at the end of the calibration was 6.1 feet.

Model-generated water budgets for the 11-year simulation period show that the volume of water stored in the system decreased by approximately 23,000 acre-feet, and that most of this loss occurred during the 1976-77 drought years. Since then, water budgets indicate that the net volume of water in storage increased annually through the end of the simulation period. For the last year of the simulation (1981) water budgets show a net gain of approximately 2,200 acre-feet of water in storage.

The calibrated model can simulate with acceptable accuracy both semiannual fluctuations and long-term trends of potentiometric heads in specific areas in the lower and middle aquifers. In other parts of these aquifers, model-evaluated changes are considered as representing only general trends. The model is not intended to be used for predictive purposes in the upper aquifer. The reliability of the model can be improved with better definition of potentiometric heads within each model layer. Better estimates of pumpage distribution, both vertically and to a lesser extent areally, would also decrease error introduced into the model during calibration.

INTRODUCTION

The U.S. Geological Survey, in cooperation with the Santa Cruz County Flood Control and Water Conservation District, investigated the water resources of the Pajaro Valley. The Pajaro Valley area (fig. 1), the largest farming area in Santa Cruz County, has an economy that is dependent on a reliable water supply to meet its irrigation, agricultural, municipal, and domestic uses. About two-thirds of the area's municipal water needs are met by ground water. Many industrial users, such as food processing plants, rely on on-site wells for all or part of their water needs, whereas agricultural users are entirely dependent on ground water for irrigation needs.

Historically, with increasing demand for water and insufficient surface-water supply, ground-water use has increased and will probably continue to increase in the future. Ground-water resources, however, are limited, and pumping has already caused lowered water levels and seawater intrusion near Monterey Bay (Muir, 1974; H. Esmaili and Associates Inc., 1978; and Johnson, 1983). Careful management of the basin's ground-water supply is necessary to minimize these problems in the future. Management alternatives that have been suggested by local planning agencies include: (1) diversion or impoundment of local surface water, (2) augmenting ground-water supplies through increased natural recharge to the ground-water system or through use of imported water, (3) water conservation, and (4) restricted or redistributed use.

Purpose and Scope

The purposes of this report are to describe the basic geology and hydrology of the ground-water system in order to develop a better understanding of the system in response to pumping stresses. Reports by the California Department of Water Resources (1953), Muir (1972, 1974), and H. Esmaili and Associates Inc. (1978) were initially used to obtain general information on the geohydrologic system. Other sources of information include well tests, well logs, water-level measurements, geologic reports, and land- and water-use information. Principal geologic references are cited in the beginning of the section entitled "Geology." A mathematical model of the Pajaro Valley ground-water system was used to gain a better understanding of the system. The model was developed and calibrated using historical water-level data, pumpage, and a quantitative characterization of the physical properties of the aquifer system.

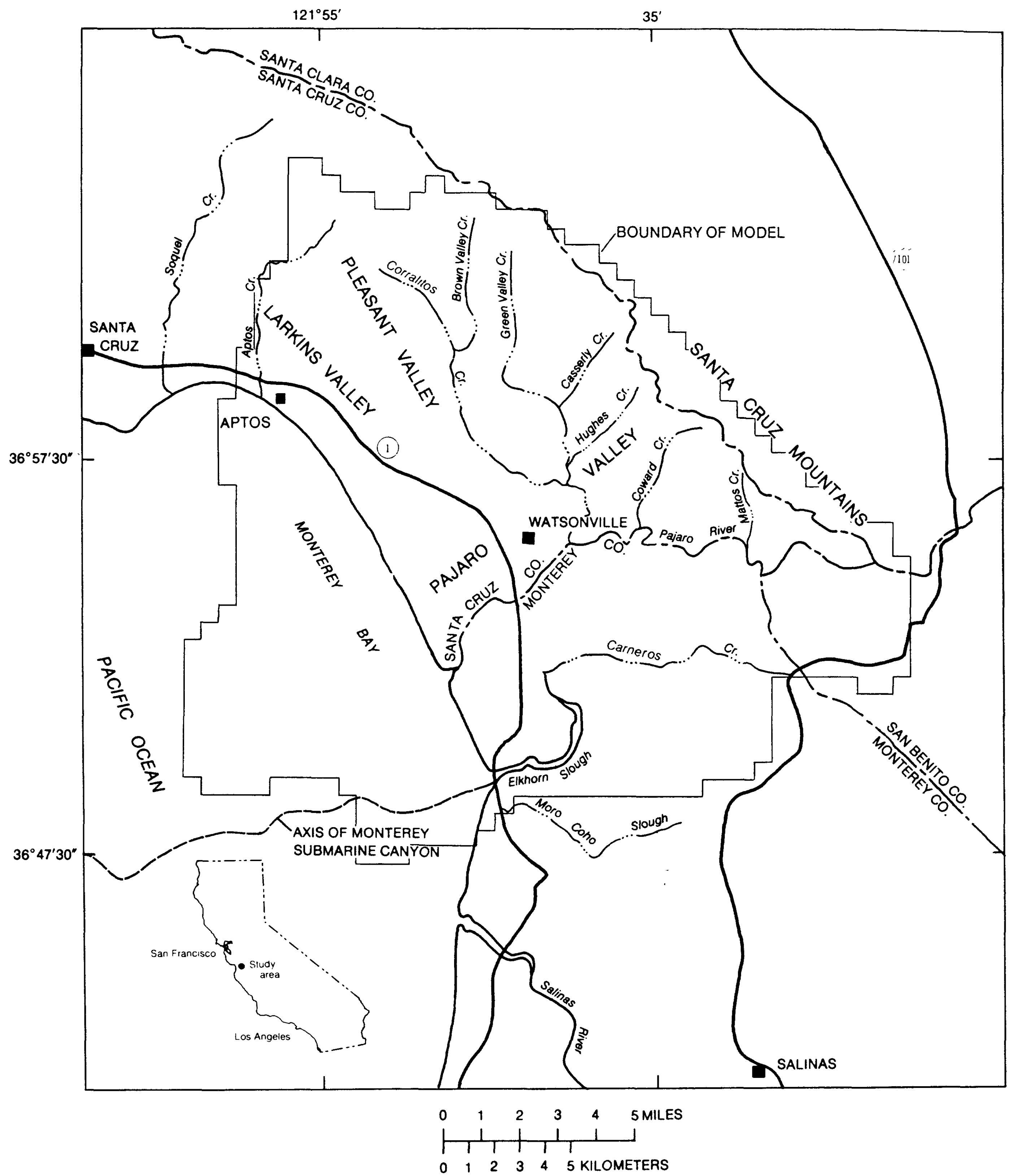


FIGURE 1. – Location of the Pajaro Valley area.

Location and General Features

The Pajaro Valley, about 160 square miles, consists of alluvial bottom lands, terraces, and foothills, and is located in southern Santa Cruz and northern Monterey Counties (fig. 1). The northern boundary of the valley is generally the drainage divide between Soquel and Aptos Creeks and the Pajaro River. The southern boundary is approximately the drainage divide between Elkhorn Slough and Moro Coho Slough. The Santa Cruz Mountains generally define the eastern boundary. The southwest and western boundaries are generally the Monterey Submarine Canyon in Monterey Bay.

The study area is that part of the valley lying below an altitude of 600 feet and is about 10 miles long and 8 miles wide. The study area slopes gently westward to the coast from the base of the Santa Cruz Mountains, which crest from 1,400 to 2,900 feet above sea level along the Santa Cruz-Santa Clara County line.

The Pajaro River, one of California's major coastal streams, flows westward through the study area transporting inland water through the Pajaro Valley bottom lands to the ocean. The river has an average annual flow of about 140 ft^3/s (U.S. Geological Survey, 1980) but ceases to flow at times in July and August. The Pajaro River's largest tributary within the study area is Corralitos Creek. It has one-tenth the average annual flow of the river (14 ft^3/s). The southern part of the study area is drained by Elkhorn Slough and its tributary valleys.

The area has a mild Mediterranean climate influenced by the coastal marine air. Summers are generally cool and dry, winters are mild and wet. Mean monthly temperatures for January and July in Watsonville are 48.4° F and 60.7° F, respectively (National Oceanographic and Atmospheric Administration, 1982). About 90 percent of the precipitation occurs from mid-October through mid-April, virtually all as rain. The average annual precipitation at Watsonville from 1880 through 1980 was 21.1 inches with a standard deviation of 6.5 inches. During an average year, annual precipitation (fig. 2) ranges from approximately 16 inches near the coast to more than 40 inches in the foothills of the Santa Cruz Mountains in the northeastern part of the study area (S.H. Hoffard, U.S. Geological Survey, written commun., 1981).

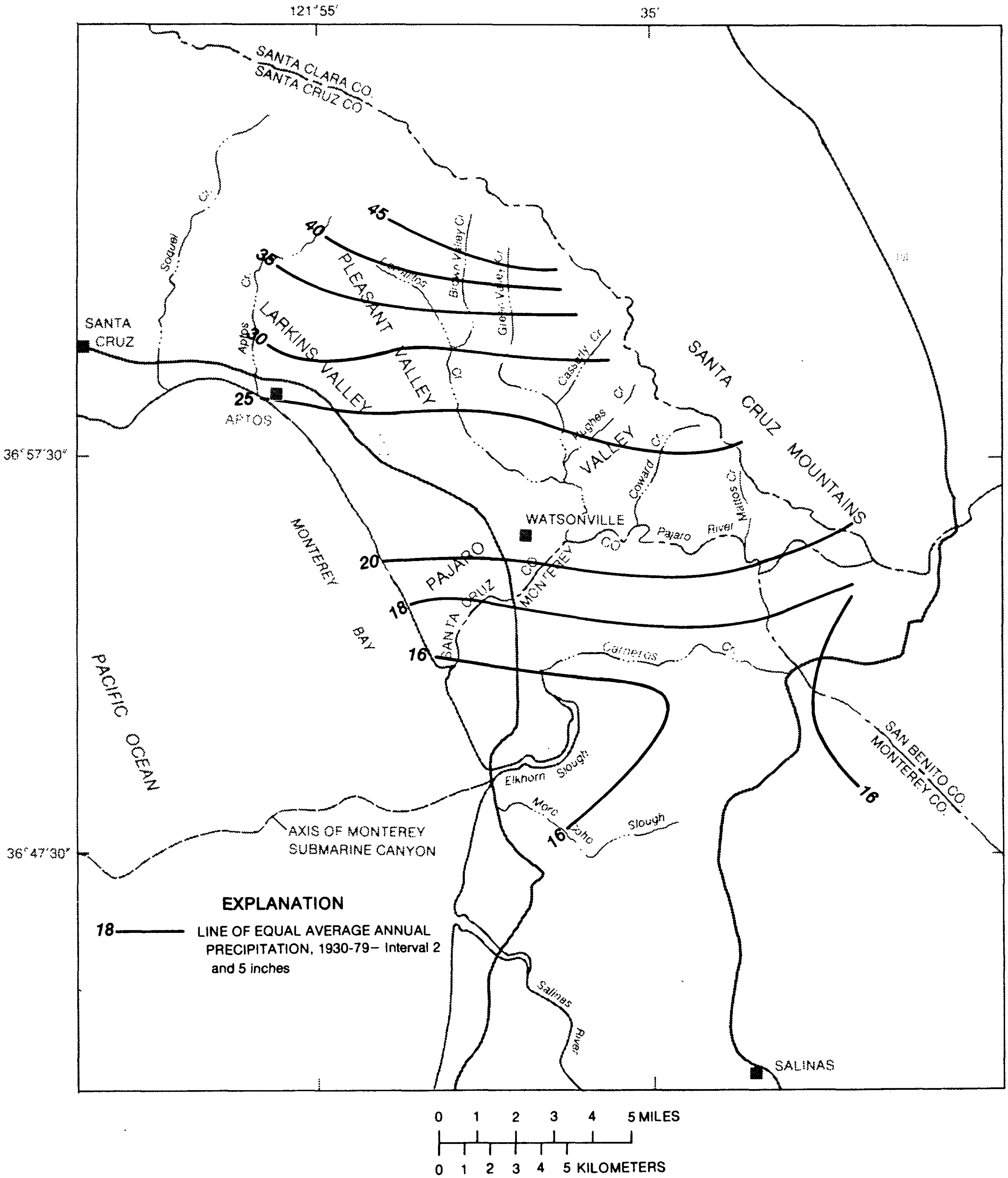
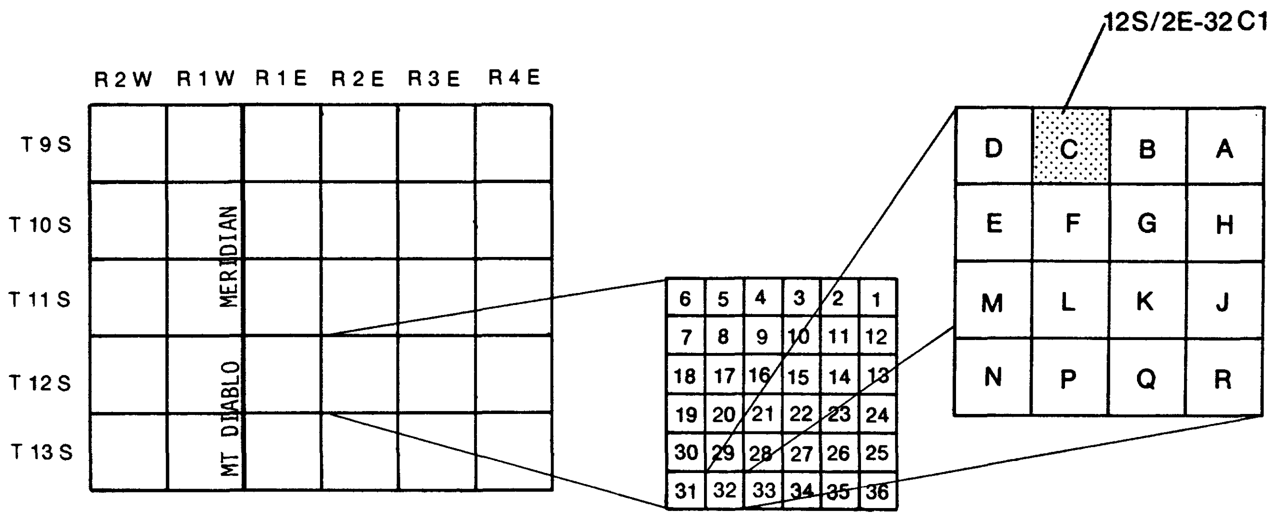


FIGURE 2. – Average annual precipitation, 1930-79.

Well-Numbering System

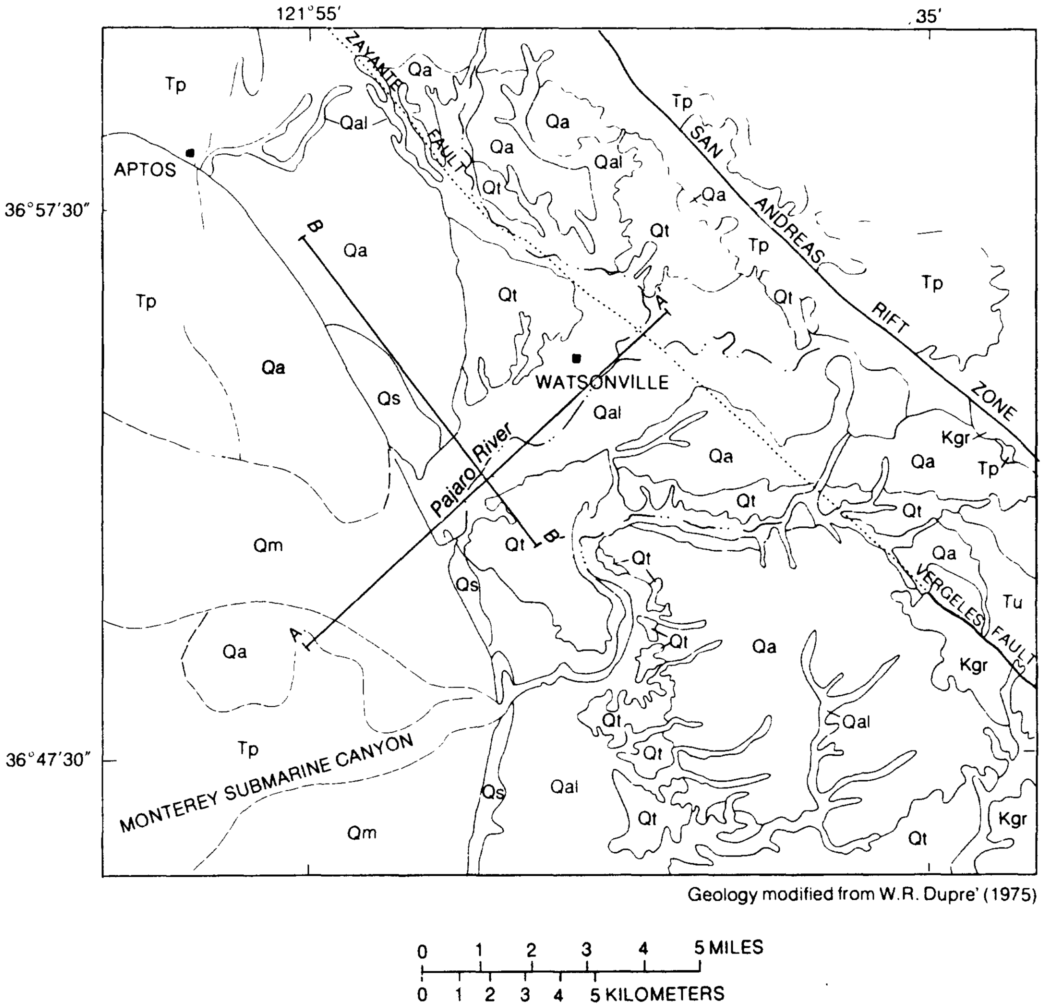
Wells are numbered according to their location in the rectangular system for subdivision of public land. For example, in the number shown in diagram 12S/2E-32C1, assigned to a well north of the city of Watsonville, that part of the number preceding the slash indicates the township (T. 12 S.); the part of the number following the slash indicates the range (R. 2 E.); the number following the hyphen indicates the section (sec. 32); the letter following the section number indicates the 40-acre subdivision according to the diagram below. The final digits are a serial number for wells in each 40-acre subdivision. All wells mentioned in this report are referenced to the Mount Diablo base line and meridian.



GEOLOGY

The regional geology of the Pajaro Valley area has been mapped and described by Greene (1970, 1977), Muir (1972), Clark and Rietman (1973), Dupré (1974, 1975), and Dupré and Tinsley (1980). The central part of the Pajaro Valley is basically an erosional and structural depression surrounded by areas of uplift and folding. The geometry of the depression is controlled by differential movement along the San Andreas, Zayante-Vergeles, and other less prominent fault zones (fig. 3).

West of the San Andreas rift zone, the Pajaro Valley area is underlain by a basement of Cretaceous granitic rocks. These granitic basement rocks are exposed in places along the rift zone but generally underlie sedimentary rocks at depths of 2,000 to 4,000 feet along the coast (fig. 3). Overlying the basement rocks are consolidated sequences of poorly permeable, mostly marine sedimentary rocks of Eocene to Miocene age consisting of shale, mudstone, clay, silt, fine sand, conglomerate, and minor deposits of volcanic rock.



CORRELATION OF MAP UNITS

Qs, Qm, Qal	Holocene	QUATERNARY
Qt	Pleistocene	QUATERNARY
unconformity		
Qa	Pleistocene	QUATERNARY
unconformity		
Tp	Pliocene	TERTIARY
unconformity		
Tu	Miocene to Eocene	TERTIARY
unconformity		
Kgr		CRETACEOUS

DESCRIPTION OF MAP UNITS

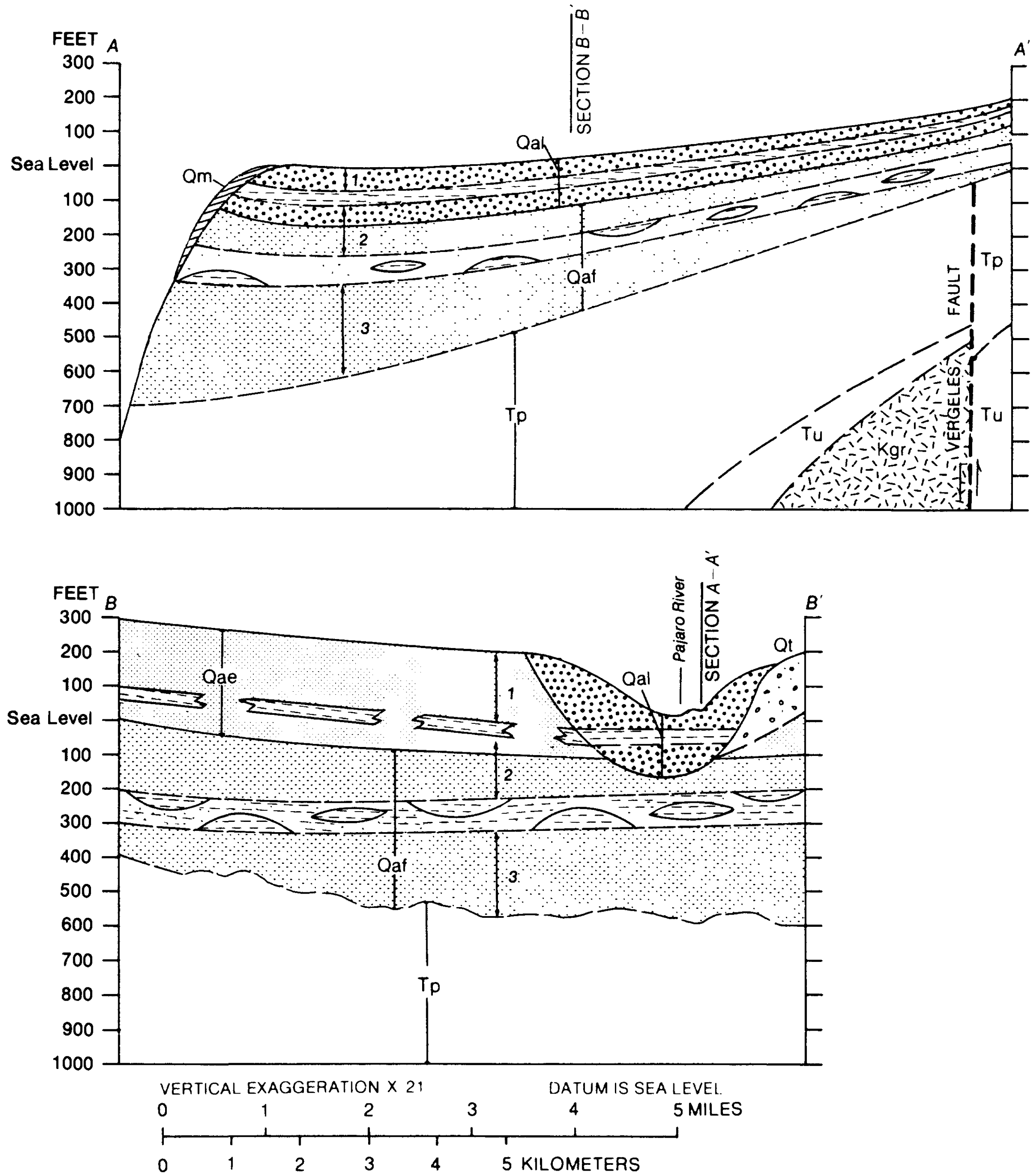
UNCONSOLIDATED DEPOSITS

- Qs — DUNE DEPOSITS (Holocene)
- Qm — YOUNG MARINE SEDIMENTS (Holocene)
- Qal — ALLUVIUM (Holocene)
- Qt — TERRACE DEPOSITS (Pleistocene)
- Qa — AROMAS SAND (Pleistocene) Shown as Qae and Qaf on sections
- Tp — PURISIMA FORMATION (Pliocene)

CONSOLIDATED ROCKS

- Tu — SEDIMENTARY ROCKS (Miocene to Eocene)—undifferentiated
- Kgr — GRANITIC ROCKS (Cretaceous)

FIGURE 3. — Generalized geology and diagrammatic sections of the Pajaro Valley area.



EXPLANATION

Qm — YOUNG MARINE SEDIMENTS

Qal — ALLUVIUM – Holocene dune deposits and alluvial deposits which includes layers of clay

Qt — TERRACE DEPOSITS – Gravels and cross-bedded sands

Qae / Qaf — AROMAS SAND – Eolian (Qae) and fluvial (Qaf) deposits of sand and clay (Pleistocene)

Tp / Tu — UNDIFFERENTIATED SEDIMENTS – Includes Upper Pliocene Purisima Formation (Tp) and undifferentiated Miocene to Eocene consolidated sedimentary rocks (Tu)

Kgr — GRANITIC ROCKS – Cretaceous basement rocks

CONTACT – Dashed where approximately located

FAULT – Approximate location; arrows indicate relative movement. Dashed where approximately located; dotted where concealed

1 Denotes vertical extent of upper aquifer

2 Denotes vertical extent of middle aquifer

3 Denotes vertical extent of lower aquifer

A —— A' Line of geologic section (sections are diagrammatic)

FIGURE 3. – Continued.

Overlying these consolidated, poorly permeable rocks are a series of westward-dipping, sedimentary rocks of late Tertiary and Quaternary age. These rocks include the poorly consolidated Purisima Formation (Miocene and Pliocene), the mostly unconsolidated Aromas Sand and terrace deposits (Pleistocene), unconsolidated alluvium, dune deposits, and younger marine sediments (Holocene). The Purisima Formation underlies the study area at depths ranging from at or near land surface along the northern and eastern boundaries of the study area, to as much as 800 or 900 feet near the mouth of the Pajaro River.

The geologic units that are of importance in the evaluation of the major developed ground-water-flow system of the Pajaro Valley area are of Quaternary age and consist principally of the Aromas Sand, terrace deposits, alluvium, and dune deposits (fig. 3). They extend westward from the San Andreas rift zone to some point offshore beneath Monterey Bay and are bounded on the north, east, and southeast by the outcropping Purisima Formation and older consolidated rocks. To the west, the Aromas Sand feathers out over the outcropping Purisima Formation under the northern part of Monterey Bay. The alluvial deposits extend out from the mouth of the Pajaro River, where they thin and grade into undifferentiated Holocene marine sediments. These marine sediments extend out under the bay in a west-northwest direction over the Aromas Sand and, in turn, over the Purisima Formation. Beneath Monterey Bay, the Monterey Submarine Canyon dissects both the alluvium and the Aromas Sand, whereas, onshore, the Aromas Sand extends continuously south into the Salinas Valley. The distribution of the Quaternary deposits, which are divided into 35 subunits, is described in greater detail by Dupré and Tinsley (1980).

The diagrammatic geologic sections in figure 3 show the simplified Quaternary geology. These sections do not show the complexities of the Quaternary deposits, each with its own depositional sequences of sediments. The alluvium, terrace deposits, and Aromas Sand each contain lenticular beds of coarse gravels and sands deposited by braided and meandering streams that grade upward into lagoonal silts and clays. Each sequence becomes finer grained in an upward direction and are described as "mega-fining upwards" sequences by Dupré (1975). The following is a detailed description of the major Quaternary units that are important hydrologically.

The Aromas Sand (Qa) (Pleistocene) consists of a heterogeneous sequence of mainly eolian and fluvial sand, silt, clay, and gravel. With a total thickness of more than 800 feet, most of the Quaternary Period in the Pajaro Valley is represented in the Aromas Sand. Locally, the Aromas Sand is divided into older fluvial deposits and younger eolian deposits that thin to the north and east (Dupré and Tinsley, 1980).

The fluvial deposits of the Aromas Sand (Qaf) are partly consolidated, moderately to poorly sorted, lenticular beds of silty clay, sand, and gravel deposited by meandering and braided streams and partly as alluvial fans. The alluvial fan sediments, deposited from the north and east, interfinger with eolian and marine deposits of Aromas Sand to the west (Dupré, 1975). Offshore, the fluvial deposits filled river channels entrenched in marine sedimentary rocks of the Purisima Formation (Greene, 1970; Environmental Research Consultants Inc., 1976). Numerous clay and silty clay beds as much as 2 feet thick, and soils as much as 14 feet thick separate the sands and relatively well-sorted gravel beds that range from 10 to 100 feet in thickness. Near the coast, unusually thick marine clays separate upper sequences of fluvial deposits from lower sequences of fluvial deposits (California Department of Water Resources, 1977). As shown in figure 3, the upper fluvial sand sequences in hydrologic contact with the Holocene alluvium are separated from the lower fluvial sequences by a composite of clay beds.

The eolian deposits of the Aromas Sand (Qae) are moderately well sorted and contain no intervening fluvial deposits to a depth of 200 feet (Dupré and Tinsley, 1980). These sands formed in the central part of the Monterey Bay area as a series of coastal dune fields. Eolian Aromas Sand is exposed along the coast in the northwestern foothills and extends outward over the Purisima Formation under Monterey Bay. Overlying the coastal parts of these deposits are Holocene dunes. The eolian deposits contain several depositional sequences, generally 20 to 60 feet thick, separated by highly weathered soil zones. As shown in figure 3, the weathered soil zones where locally present separate and confine the underlying fluvial deposits (Qaf) from the overlying uppermost eolian deposits (Qae).

The Pleistocene terrace deposits (Qt) consist of moderately to poorly sorted silt, sand, silty clay, and gravel. These materials also were deposited in upward-fining sequences as alluvial fan, fluvial, beach, and estuarine-tidal flat sediments during a period of rising sea level. Basal gravels grade upward into finer grained deposits (Dupré, 1974 and Dupré 1975). The terrace deposits are at least 120 feet thick, and may be as much as 230 feet thick in the vicinity of Watsonville.

Holocene alluvium (Qal) in the study area is a highly variable mixture of unconsolidated gravel, silt, and sand with lenses of clay and silty clay. The alluvium has filled an entrenched valley, at least 200 feet deep, that was cut by the Pajaro River and its tributaries during the last lowstand of the ocean. The valley was filled by an upwards-fining sequence of fluvial and estuarine deposits. At the base of the sequence is a continuous gravel bed that has an average thickness of about 50 feet and is in direct contact with the underlying Aromas Sand (Muir, 1972). Overlying the gravel bed throughout much of the region is an extensive zone of numerous, intercalated clay beds. An almost continuous blue clay marker bed is identified in drillers' logs. Above the clay beds, the upper alluvium is a heterogeneous mixture, composed mostly of fine-grained material.

Holocene dune deposits of eolian origin unconformably overlie the older deposits in some areas along the coast. These deposits consist of fine-to-medium grained, quartzose sand and in part are actively drifting (Muir, 1972, p. 12)

HYDROLOGY

The Pajaro Valley aquifer system consists mainly of the Quaternary Aromas Sand, terrace deposits, alluvium, and dune deposits (fig. 3). These deposits are hydraulically interconnected and range in thickness from zero in the eastern part of the area to at least 800 feet in the western part. The complex bedding and upward-grading sediments make evaluation of the hydrology complex, particularly in the western part of the valley where clay beds tend to be thicker and increasingly effective in separating and confining permeable zones.

The Pajaro Valley aquifer system is depicted as having three aquifers separated vertically by two confining layers of less permeable material (fig. 3). The lower aquifer occurs in the older fluvial part of the Aromas Sand, in the interval ranging from 300 to 600+ feet below sea level near the coast. Numerous interbedded clay and silty clay beds in the fluvial part of the Aromas Sand make up the lower confining layer that separates the lower and middle aquifers. This confining layer is thickest in the western part of the study area where marine clays are present, and thins to the east (fig. 3). The most intensely developed aquifer in the system is the middle aquifer. This aquifer is in the interval ranging from 100 to 200+ feet below sea level and consists of the basal gravel bed in the alluvium and terrace deposits, and the lower eolian and the upper fluvial part of the Aromas Sand. Extensive clay beds above the basal gravel bed in the alluvium and terrace deposits (fig. 4), and weathered soil zones in the eolian sequences of Aromas Sand compose the discontinuous upper confining layer. The upper aquifer of the system consists of a number of discontinuous water-bearing zones. These zones are found locally in the upper eolian sequence of Aromas Sand, the upper terrace deposits, upper alluvium, and Holocene dune deposits. the terrace deposits also contain cross-bedded sands and gravels as much as 50 feet thick that form local confined aquifers.

Pre-Quaternary rocks are not important as aquifers in the Pajaro Valley area. Granitic and lower Tertiary rocks do not contain appreciable quantities of readily recoverable water. Water derived from these rocks is obtained primarily from secondary storage in fractures and weathered zones, or from limited primary storage within sandstone lenses in the sedimentary rocks.

The upper Tertiary Purisima Formation, which underlies the Quaternary deposits of the Pajaro Valley, has not been developed in the study area. The formation is a principal source of ground water for both the Soquel-Aptos and north-central Santa Cruz County areas (Muir, 1980; Johnson, 1980) and may have some water-bearing potential for additional ground-water development (Johnson, 1983). In the Soquel-Aptos area, Hickey (1968) divided the formation (on the basis of drillers' logs) into three informal subunits that yield water to wells from sandstone layers. However, within the Pajaro Valley, few wells tap the Purisima Formation, which lies about 800 to 900 feet below the land surface near the mouth of the Pajaro River but crops out in the Soquel-Aptos area to the northwest and in the Santa Cruz Mountains to the northeast. Substantially lower water levels and greater drawdowns are reported for some wells completed in the upper part of the Purisima Formation than in the overlying, younger Quaternary deposits. This indicates a relatively lower rate of water transmission through the Purisima Formation to supply pumping wells, and a possibly lower recharge and storage potential for water within the formation.

Direct percolation of rainfall, irrigation return, and infiltration of surface water through beds and banks of channels are the principal sources of natural recharge to the Pajaro Valley aquifer system (H. Esmaili and Associates

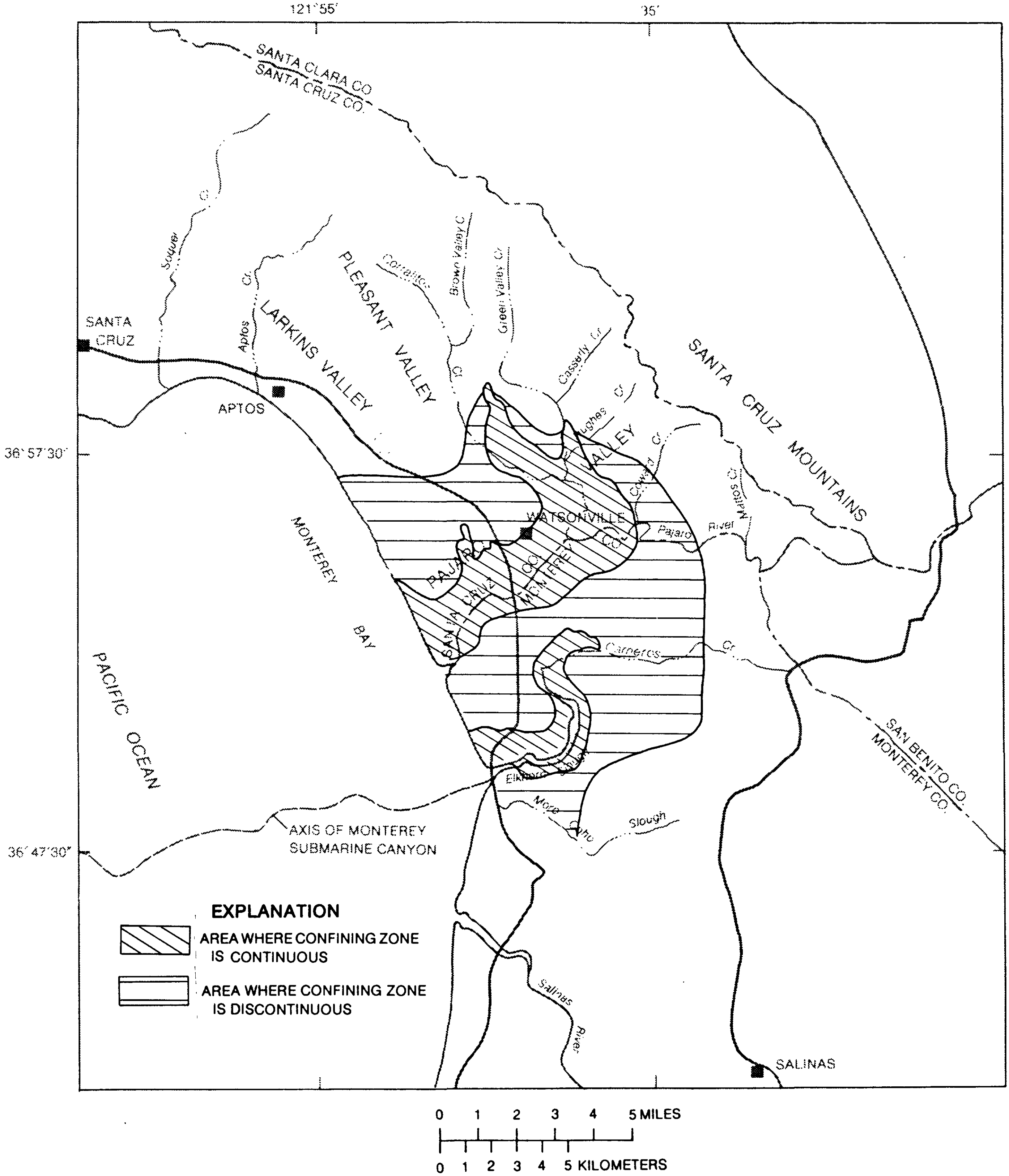


FIGURE 4. — Areal extent of the upper confining layer.

Inc., 1978). Clay layers tend to impede the downward movement of ground water. Those areas lying beyond the upper continuous confining layer (fig. 4) generally constitute areas where potentially high rates of recharge from precipitation to the aquifer system can occur (Muir, 1972). Additionally, H. Esmaili and Associates (1978) suggested that cultivation of land for agriculture increases the rate of recharge from precipitation. Where the extensive clay layers of the upper confining layer occur at shallow depths, precipitation results in little recharge. Most of this potential recharge eventually flows to the Pajaro River or undergoes evapotranspiration. Irrigation return is the excess applied irrigation water that percolates downward to the water table, helping to reduce salt buildup in the soils. Infiltration of surface water through beds and banks of channels occurs along Corralitos Creek and other smaller streams that drain the Santa Cruz Mountains. In these areas, surface water seeps directly into the Aromas Sand, terrace deposits, and alluvium. Seepage from the Pajaro River is an important source of recharge only in areas where the upper confining layer is discontinuous (fig. 4).

The granitic and Tertiary rocks may be a source of limited recharge to the Quaternary deposits through subsurface inflow from areas of outcrop in the Santa Cruz Mountains. Vertical movement of ground water between the Tertiary rocks and overlying Quaternary deposits is restricted by numerous siltstone and mudstone beds within the Purisima Formation. However, there is some lateral movement of ground water from the older rocks into the Quaternary deposits around the margins of the valley.

Ground-water movement within the Quaternary deposits is away from source areas of ground-water recharge (supplied by precipitation, stream channels, and interbasin underflow). Ground water moves toward the central axis of the valley and then generally from east to west down the valley to the ocean (fig. 5). In some of the coastal parts of the aquifer system, ground-water movement is away from the ocean, eastward toward local pumping depressions (fig. 5). In these areas, the potential exists for seawater to leak vertically down through or around confining layers from estuaries and sloughs onshore or to migrate horizontally from offshore through vertical leakage at ocean-bottom outcrops and through horizontal flow at the aquifers' Monterey Submarine Canyon exposures into the aquifer system.

As early as 1946, Simpson (1946) noted some evidence of seawater intrusion into the coastal parts of the Pajaro Valley aquifer system. In 1974, Muir (1974) observed that the most extensive inland intrusion of seawater into the Pajaro Valley aquifer system was in the middle aquifer, 100 to 200+ feet below sea level. He also observed that the lower aquifer in the Aromas Sand, 300 to 600+ feet below sea level, had been intruded but to a lesser extent. Since Muir's work, H. Esmaili and Associates (1978) noted increased chloride levels in wells and Johnson (1983) reported on an expanded coastal zone of seawater influence and its continuity from the Pajaro Valley through the Aromas Sand to the Salinas Valley with the potential for expansion to the zero-foot (sea level) potentiometric contours mapped farther inland and connecting both valleys. With the decline of potentiometric heads in coastal areas, poor-quality water may extend farther into estuaries, sloughs, or other channels beyond confining clay deposits where it can percolate more easily into freshwater aquifers. Unused wells with top to bottom gravel envelopes and wells with multiple perforation intervals also can provide conditions suitable for the interchange of water between different parts of the aquifer system. Fortunately, few poorly constructed or abandoned wells have been identified in the Pajaro Valley coastal area (Luhdorff and Scalmanini, 1983).

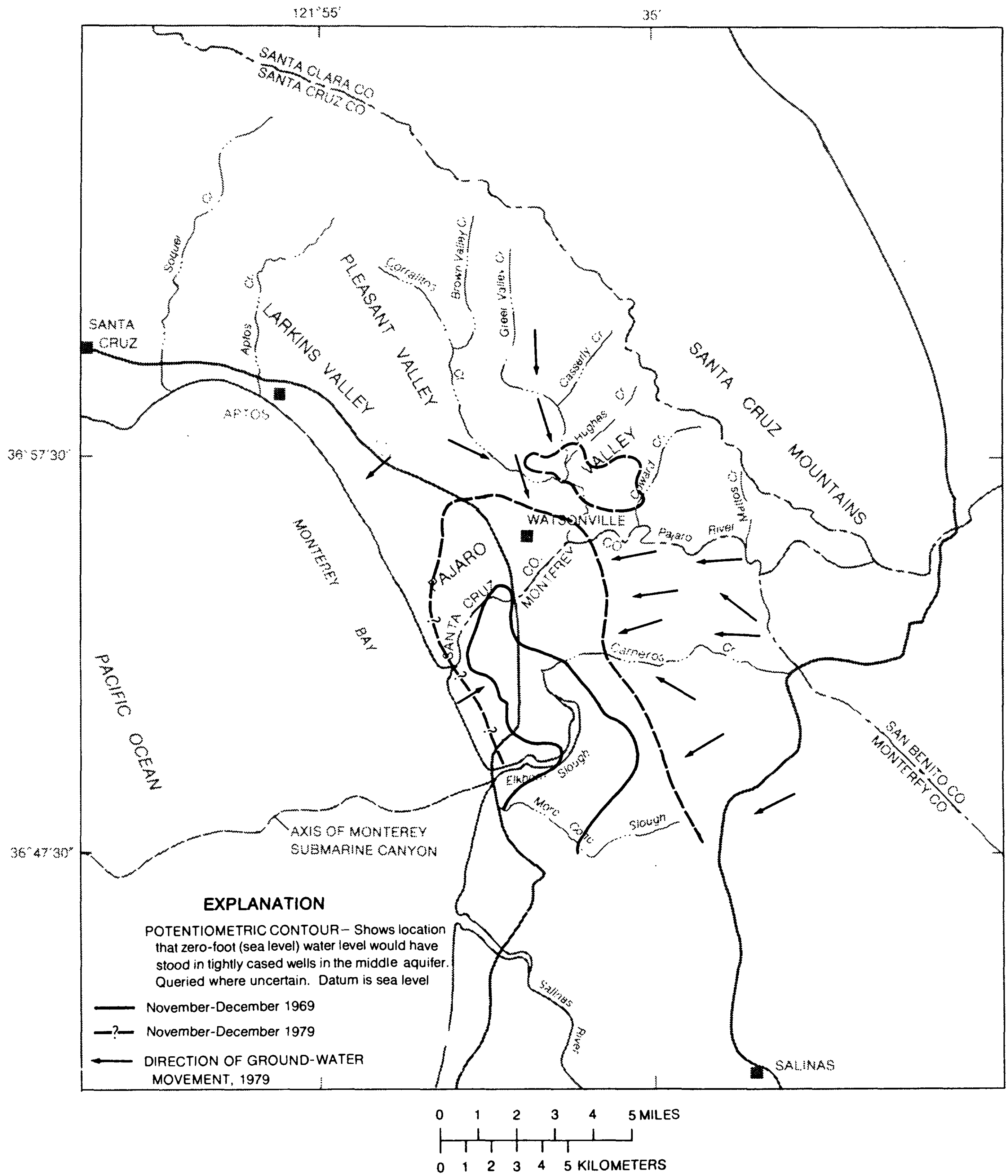


FIGURE 5. – Direction of ground-water movement, 1979 and location of the zero-foot (sea level) potentiometric contour in 1969 and 1979, in the middle aquifer. (Modified from Johnson, 1983.)

GROUND-WATER DEVELOPMENT AND ITS EFFECT ON POTENTIOMETRIC HEADS

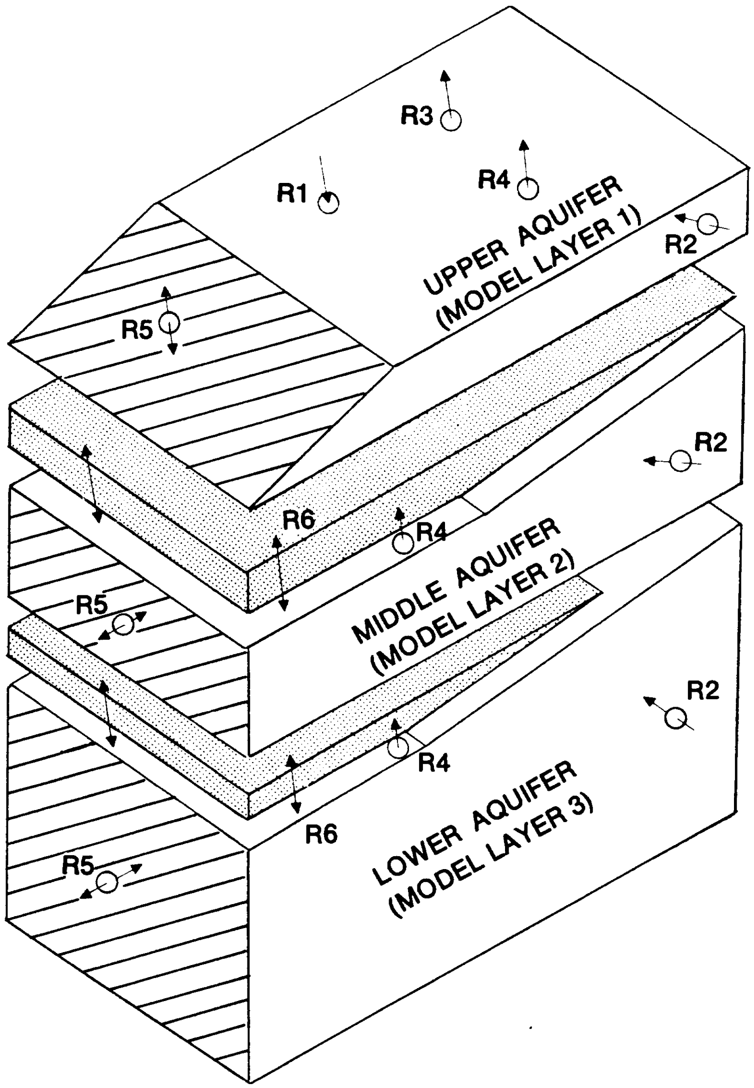
The first settlers who entered the valley to farm in 1851 relied on dry farming (Martin, 1892), but by the end of the 19th century, with a population of about 4,000 in the Watsonville area (Schuyler, 1902), ground-water development had started in the Pajaro Valley (Mackie, 1910). From 1940 to 1971, the Pajaro Valley aquifer system underwent substantial ground-water development to meet the irrigation needs of a growing agricultural industry. Muir (1974) calculated historical annual pumpage values for the Pajaro Valley area for the period 1963-71. Before 1963 no data were available. According to Muir (1974), total annual pumpage increased steadily from 40,900 acre-feet in 1963 to 61,700 acre-feet in 1971; a 51 percent increase. Estimates of annual pumpage for 1981 for this study, ranged from 65,700 to 77,700 acre-feet. This value suggests that total pumpage did not increase significantly from 1971 to 1981. Irrigation accounts for most of the water use in the Pajaro Valley area, however, municipal and commercial water use is expected to increase as the population continues to grow, while irrigation use is expected to remain stable or decline with land-use changes.

Accompanying ground-water development in the Pajaro Valley area was a steady decrease in the potentiometric heads in the Pajaro Valley aquifer system, particularly, the heavily pumped middle aquifer. Mackie (1910) noted a number of wells that tapped the gravel at the base of the alluvium, the middle aquifer, in the area between Watsonville and the coast. These wells maintained artesian heads sufficient to supply flowing water to tanks over 10 feet above ground. Although artesian heads dropped from the early 1900's, in the 1940's several wells in the same area were reported to flow at least during the winter months (Simpson, 1946). However, by 1970 pumping for irrigation had reduced the potentiometric heads in the area to the extent that there were no known flowing wells, (Muir, 1972). By the mid- to late 1970's, water levels in the middle aquifer west of Watsonville were consistently below sea level from at least May to December (Johnson, 1983). The November-December 1969 zero-foot potentiometric contour and the November-December 1979 zero-foot potentiometric contour for the middle aquifer (fig. 5) show that from 1969 to 1979 the area of the middle aquifer with heads below sea level increased significantly.

CONCEPTUAL MODEL

Actual field conditions are too complex to be simulated exactly using mathematical techniques. Therefore, a conceptual model of the aquifer system, which is a simplified representation of the actual system, is first developed. Simplifying assumptions are used in the conceptual model so that a mathematical approximation of the actual aquifer system is possible.

Figure 6 is a diagram of the conceptual model of the Pajaro Valley aquifer system. For mathematical modeling, the aquifer system has been divided into three model layers separated by two intervening confining layers. The confining layers are assumed to have no ground-water storage or horizontal flow within them. Therefore, they only affect the vertical movement of water between adjacent aquifers.



EXPLANATION

CONSTANT-HEAD BOUNDARY ALONG OCEAN-BOTTOM OUTCROPS

CONFINING LAYER

← DIRECTION OF GROUND-WATER MOVEMENT

R1 INFLOW FROM PRECIPITATION, STREAM-CHANNEL INFILTRATION, AND IRRIGATION RETURN FLOW

R2 INFLOW ACROSS CONSTANT-FLUX BOUNDARY

R3 OUTFLOW THROUGH NEAR-SURFACE DRAIN FUNCTION (DISCHARGE TO STREAMS)

R4 OUTFLOW THROUGH PUMPING WELLS

R5 SEAWATER INFLOW AND OUTFLOW ACROSS CONSTANT-HEAD BOUNDARY

R6 FLOW THROUGH CONFINING LAYER

FIGURE 6. — Conceptual model of the Pajaro Valley aquifer system.

Model layer 1 represents the upper aquifer, which is composed of the eolian sequences of Aromas Sand, terrace deposits, alluvium, and dune deposits above the upper confining layer (figs. 3 and 6). This layer extends from the water table down to about 120 feet below sea level along the coast and to about sea level farther inland. Layer 1 is assumed to be unconfined. All recharge to the aquifer system from precipitation, irrigation return, and seepage from streams is assumed to occur at the upper boundary of layer 1. Near the lateral onshore boundaries, the layer receives underflow from the surrounding sediments and along the coast freshwater is mixed with seawater from the ocean. In the model, layer 1 is hydrologically connected to the underlying layers where the upper confining layer is discontinuous (fig. 4). In the parts of the model where the upper confining layer is continuous, there is little interchange of water between layer 1 and the underlying layers.

Layer 2 of the model represents the middle aquifer, which is composed of the basal gravel bed of both the terrace deposits and alluvium, and the underlying and adjacent lower eolian and upper fluvial sequences of the Aromas Sand (fig. 3, sections A-A', B-B'). Model layers 1 and 2 are separated by a discontinuous confining unit. This confining unit corresponds to the upper confining layer, which is composed of the extensive clay beds in the upper terrace deposits and alluvium (fig. 4), and the discontinuous weathered soil zones in the lower eolian sequences of the Aromas Sand. Model layer 2 is considered to be confined where the upper confining layer is continuous and variably confined where the upper confining layer is discontinuous (fig. 4). This layer receives underflow from the surrounding material along the onshore lateral boundaries, and freshwater is exchanged with the ocean along its exposure in the Monterey Submarine Canyon.

Model layer 3 represents the lower aquifer, which is composed of lower fluvial deposits of Aromas Sand, which have varying degrees of vertical hydraulic conductivity. Numerous clay and silty clay beds interbedded with these fluvial deposits are conceptualized as reducing the hydraulic coupling between model layers 2 and 3. These clay beds make up the lower confining layer and are treated in the model as a composite confining unit at the boundary between model layers 2 and 3 (figs. 3 and 6). Layer 3 is assumed to be entirely confined and, as in layer 2, receives inflow across the onshore lateral boundaries, and water is exchanged with the ocean along its exposure in the Monterey Submarine Canyon. It is also assumed that there is no exchange of water between layer 3 and the underlying material.

In general, water entering the modeled aquifer system is from irrigation return, direct precipitation, stream leakage, and inflow across model boundaries. Ground water circulates through the three model layers in response to differences in hydraulic head. The water is discharged from the system by pumpage, near-surface loss to streams and evapotranspiration, and outflow across model boundaries.

MATHEMATICAL MODEL

A mathematical model consists of a set of differential equations that are known to represent ground-water flow (Wang and Anderson, 1982). Ground-water flow is simulated by simultaneously solving the differential equations with a computer. A mathematical model can be useful for gaining a better understanding of an aquifer system and also for evaluating aquifer responses to various applied stresses. However, models are to be used with care, and their results viewed with caution. A model is, at best, only an idealization of the actual aquifer system being simulated and cannot totally duplicate the real system. It is not possible for a model to include all the various conditions that are present within an aquifer. To do so would require a model as large and complex as the actual system itself. Therefore, it is necessary to use average conditions, to estimate conditions where sufficient data are not available, and to make simplifying assumptions.

The basic mathematical model used in this study uses a finite-difference solution technique and is commonly referred to as the "U.S. Geological Survey modular model" because of its input design. Users select from a number of major options, each requiring its own module of information. The advantage of this modular model format is that users have a greater flexibility in applying the mathematical model to varied and different aquifer conditions without needing to modify the computer code when a less comprehensive model is used or to pay higher computer-run costs for unwanted options permanently programmed in. The theoretical development of the model, numerical-solution techniques, computer code, and data requirements to run the program are discussed by McDonald and Harbaugh (1984).

In the model of the Pajaro Valley aquifer system, the three-dimensional aquifer system is approximated by horizontal layers separated by confining layers (fig. 6). The computer solves the two-dimensional ground-water-flow equation for each layer and couples the layers by terms that represent flow through the intersecting confining layers.

Grid Network

In the finite-difference method, a rectangular grid network is used to divide the study area into rows and columns. Each rectangle is termed a grid element or cell; the center point of each of these elements is a node. Values for aquifer properties are determined for each element by overlaying the grid network on data maps of the study area. In the finite-difference method, the aquifer properties within the grid element are assumed to be homogeneous. Therefore, each parameter value used is an average for the area of the grid element or for the domain of the node.

The grid network and its location in the Pajaro Valley area is shown in figure 7. The upper layer (model layer 1) has the greatest areal extent; the lower layer (model layer 3) has the least (fig. 7). The grid lines parallel the California grid coordinate system at intervals of 2,000 feet. An equal-area grid was used to facilitate the application of source-sink terms (recharge-discharge values), and to ensure equal interpretive weighting of hydraulic heads and of other computer-generated hydrologic values.

Data Requirements

For the mathematical model to function, the location and characteristics of the model boundaries, quantified aquifer properties for the model layers, initial or reference potentiometric head distribution, and rates and distribution of water inflows and outflows in the model layers must be specified. The accuracy of the model simulations is directly related to the accuracy of the input data. This information is supplied to the model in the form of the following properties:

- I. Boundary conditions for each model layer
- II. Initial potentiometric head distribution of each model layer
- III. Aquifer characteristics
  - A. Transmissivity for confined layers, and hydraulic conductivity and saturated thickness for unconfined layers
  - B. Storage coefficients for each model layer
  - C. Vertical leakance values between adjacent layers
- IV. Inflows and outflows of the aquifer system
  - A. Inflows
    1. Precipitation recharge into model layer 1
    2. Leakage from streams into model layer 1
    3. Pumpage return flow to model layer 1
    4. Boundary flow
  - B. Outflows
    1. Pumpage in all model layers
    2. Near-surface losses to streams and evapotranspiration in model layer 1
    3. Boundary flow

Boundary Conditions

Boundary conditions must be specified to simulate lateral flow at the edges of the modeled aquifer system. Two types of hydrologic boundaries were used in this model--constant-head boundaries and constant-flux boundaries. At a constant-head boundary, the heads in the grid elements designated as constant heads do not change with time, but the flux or amount of water coming into or leaving the grid element varies in response to head changes in adjacent grid elements. At a constant-flux boundary, the flux remains constant for the element, but the head varies in response to head changes in adjacent elements. When the constant flux is zero, the boundary is referred to as a no-flow boundary.

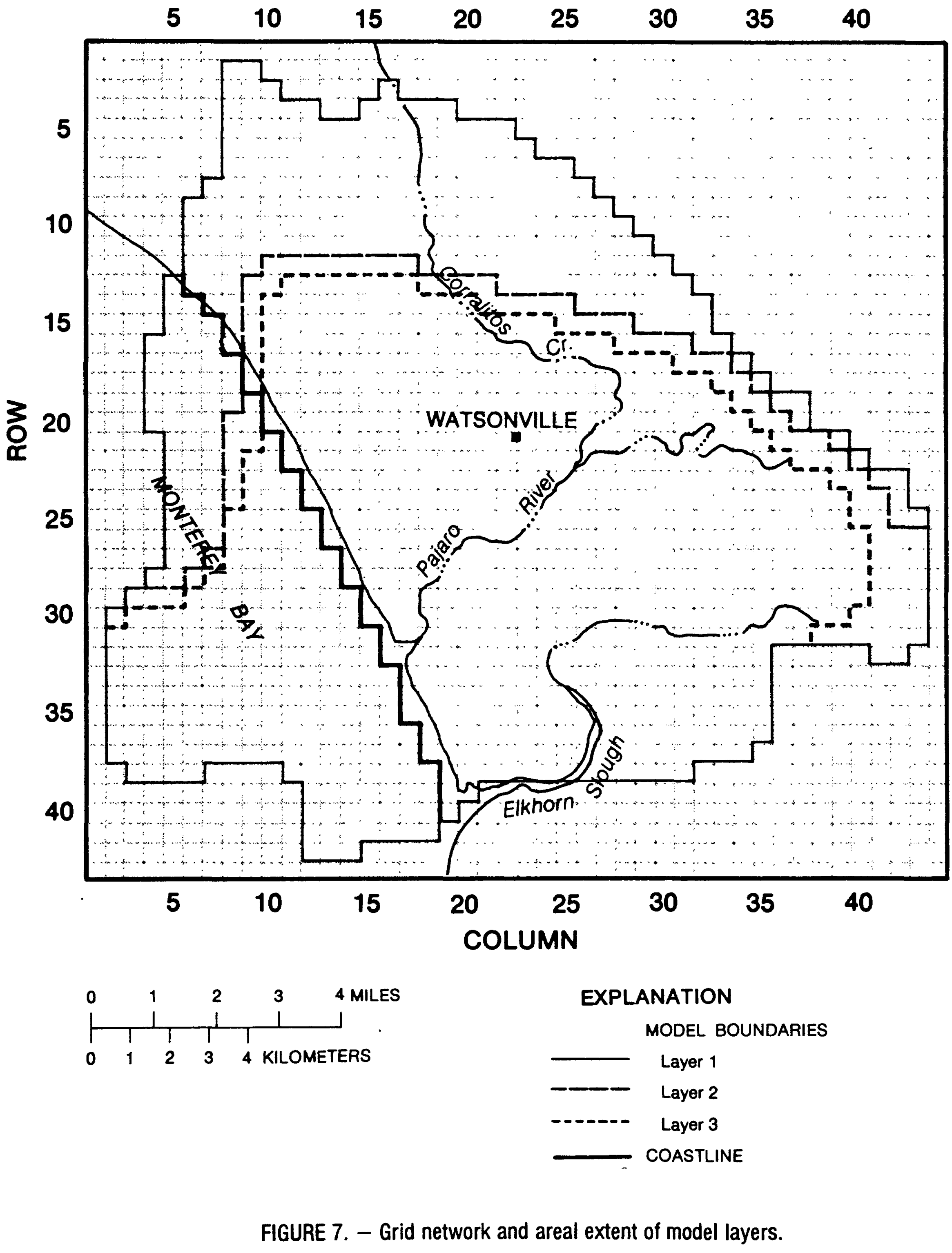


FIGURE 7. — Grid network and areal extent of model layers.

Constant-head boundaries were used in the model to simulate the interchange of water between the aquifer system and the ocean. Constant-head boundaries were specified where each of the three model layers are in contact with the ocean. Model layer 1 has an areal distribution of constant-head boundaries along the ocean floor (fig. 8), whereas, model layers 2 and 3 have constant-head boundaries only along the walls of the Monterey Submarine Canyon (figs. 9 and 10).

Constant-flux boundaries were used in the model to simulate the inflow across the onshore boundaries. The amount of subsurface flow and its distribution along the model boundaries is dependent on the hydraulic-head gradients across the boundary, the hydraulic conductivity at the boundary zone, and the size of the available cross-sectional area. Initially, it was estimated that 12,500 acre-ft/yr or 17.3 ft^3/s enters the model across the model boundaries. This inflow was distributed to the model layers as follows: 8.80 ft^3/s to layer 1, 4.65 ft^3/s to layer 2, and 3.85 ft^3/s to layer 3. The distributions of constant-flux boundaries for layers 1, 2, and 3 are shown in figures 8, 9, and 10.

The amount of boundary flow initially used in the model from pre-Quaternary formations was based on previous studies which identified geologic units with recharge potential (Muir and Johnson, 1979) and which estimated infiltration rates and quantities (Johnson, 1980, 1983). In general, areas of pre-Quaternary exposure were identified outside the model boundary where precipitation might infiltrate and move within the older rocks to the boundary of the model's Quaternary units or under the model area. The total subsurface flow available to the model's Quaternary units and to the underlying older Tertiary units was estimated at 19,600 acre-ft/yr, of which approximately one-third passes beneath the Quaternary units and eventually reaches the ocean. Principal areas of recharge for this subsurface flow included formations exposed in the trench between the San Andreas rift zone and the Zayante-Vergeles fault to the north and southeast of the study area, and the elevated pre-Quaternary formations to the northeast along the San Andreas rift zone. Recharge areas west of the trench include both the Soquel-Aptos area in the northwest and the granitic ridge area in north Monterey County to the southeast.

Initial Potentiometric Head Distribution

At the end of the 1960's, hydrographs from wells generally indicated only a small change in heads for the preceding period of record--an average decline of about 2 feet from 1950 to 1970 (Muir, 1972). Because this was a period of relative head stability, and because there were a substantial number of field measurements to document the head distribution, the potentiometric heads in spring 1970 were selected as the initial heads for the model calibration (fig. 11).

The same initial potentiometric heads were used for model layers 2 and 3, because differences in measured water levels between the upper and lower aquifers were not observed in the field during winter and early spring months, when pumpage stress is reduced. Water-level information for model layer 1 is generally inadequate for modeling purposes. Therefore, the initial potentiometric distribution for this layer was derived from both measured water levels and computed heads generated by the model at the beginning of the calibration.

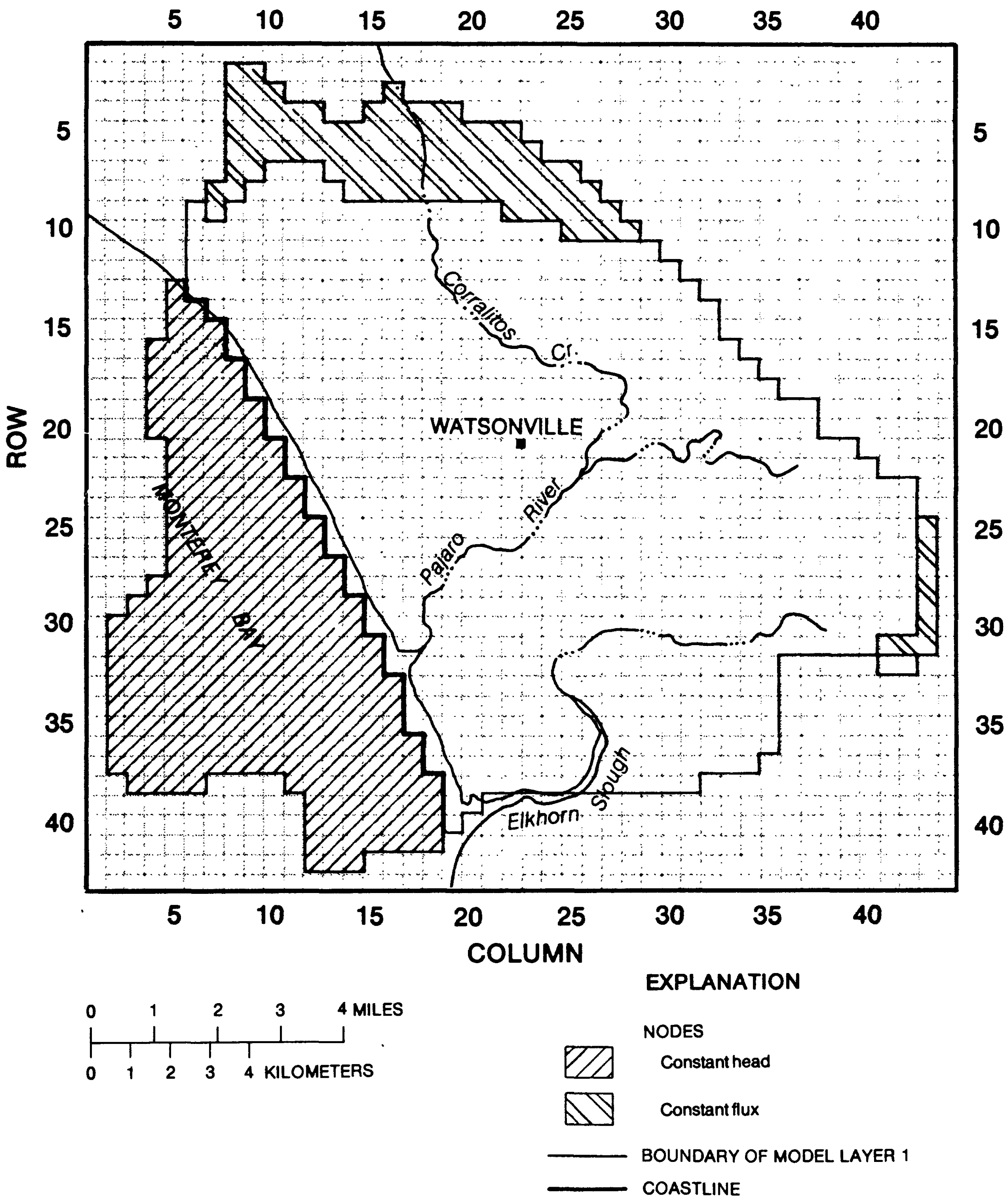


FIGURE 8. – Location of constant-head and constant-flux nodes, model layer 1.

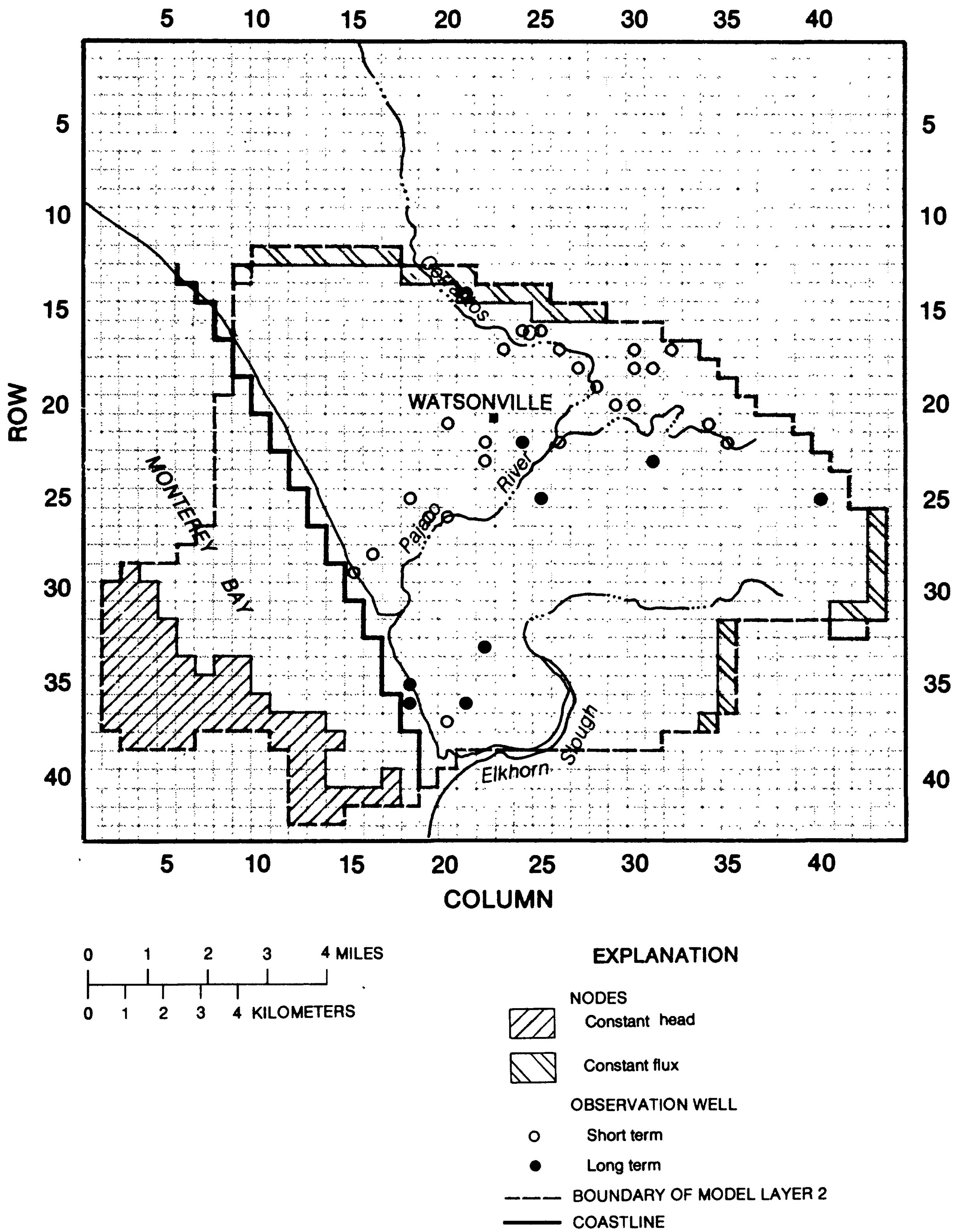


FIGURE 9. – Location of constant-head and constant-flux nodes, and observation wells, model layer 2.

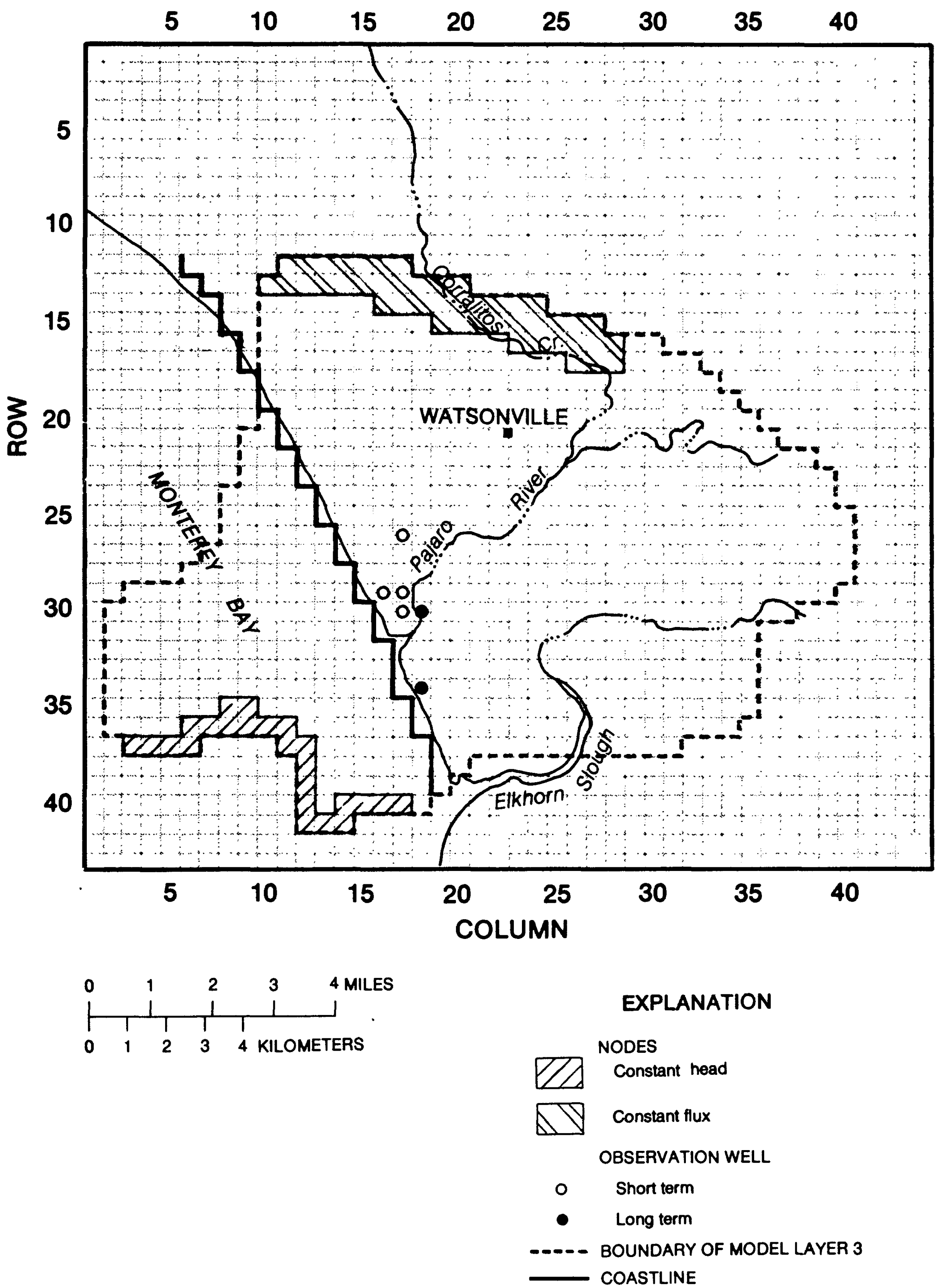


FIGURE 10. — Location of constant-head and constant-flux nodes, and observation wells, model layer 3.

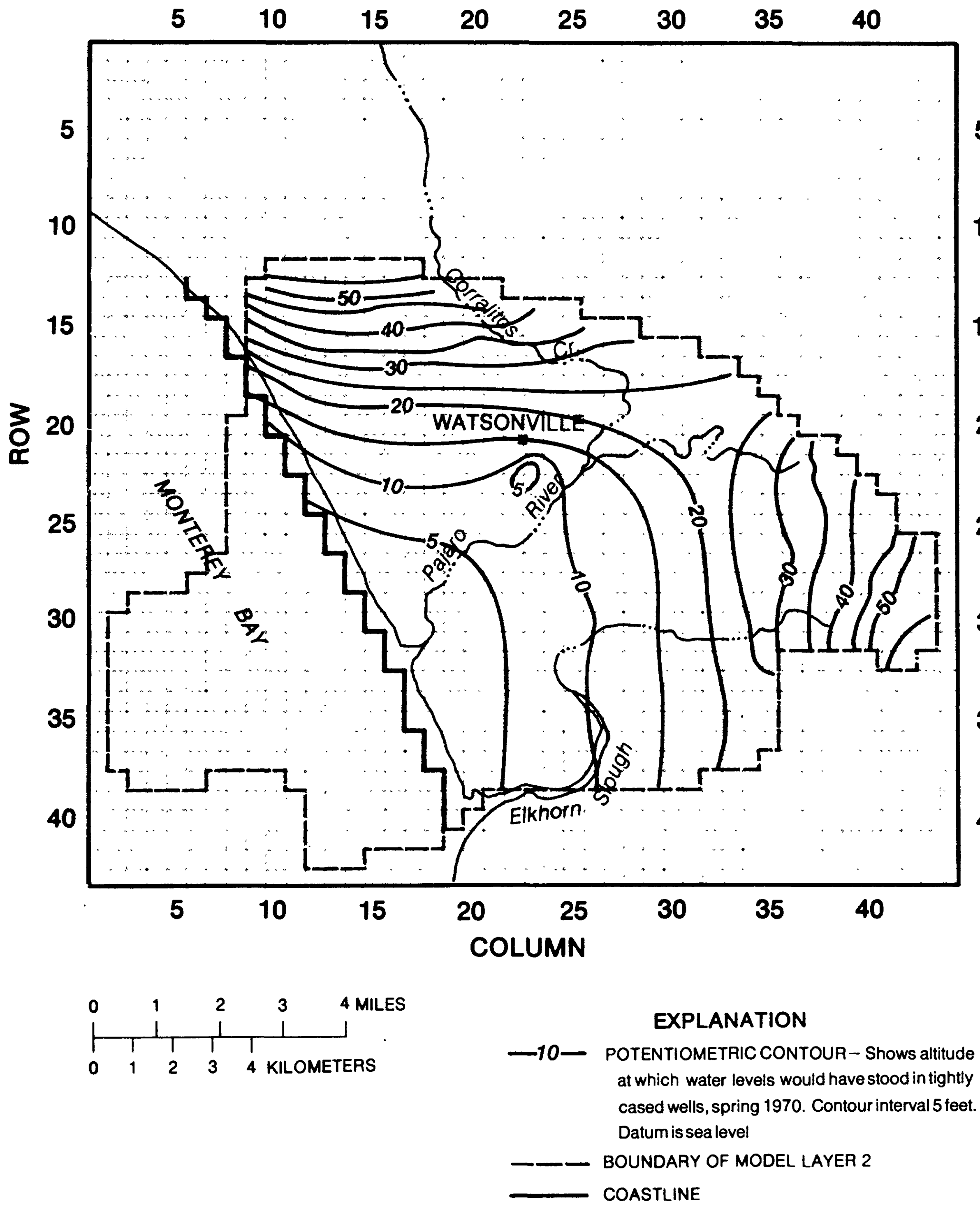


FIGURE 11. – Initial potentiometric surface, model layer 2, for spring 1970.

Aquifer Characteristics

The aquifer characteristics determine the transmissivity and storage of water within the model. Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a width of the aquifer under a hydraulic gradient (Lohman, 1972). In the unconfined upper aquifer (model layer 1, upper layer), the model calculates the transmissivity for each grid element of the layer from the hydraulic conductivity (flow through a area) times the thickness of the saturated material in the element. The thickness of the saturated material can vary with time as heads change. It is calculated by subtracting from each element the altitude at the bottom of the layer from the actual water altitude within the element. The initial hydraulic conductivity values assigned to elements of layer 1 ranged from 0.0009 ft/d in the bay mud to 22.5 ft/d in the alluvium. The hydraulic conductivity and transmissivity values were derived from specific capacity tests and driller's logs and then modified within limits during calibration of the model.

In the middle and lower layers, (model layers 2 and 3) the transmissivity values assigned to each grid element remain constant with time. For layer 2, the values ranged from 3,500 to 13,000 ft^2/d, and for layer 3, a single value of 3,700 ft^2/d was used.

The storage coefficient has been defined by Theis (1938) as the volume of water an aquifer releases from or takes into storage per surface area of the aquifer per change in head. According to Lohman (1972, p. 8), the storage coefficient of unconfined aquifers is virtually equal to the specific yield. Typical values for storage coefficients range from 0.01 to 0.35 for unconfined aquifers and from 0.00001 to 0.001 for confined aquifers (Johnson, 1972).

The initial storage coefficients for layer 1 were assigned on the basis of assumed distributions of specific-yield values as they relate to the local geology using correlations determined by Johnson (1967) and summarized by Todd (1980). Initial values for layer 1 ranged from 0.01 in clay to 0.15 in alluvium. In layer 2, initial values ranged from 0.015 in the east to 0.00018 in the west under the thick clay beds. The initial storage coefficient in layer 3 was assigned a uniform value of 0.00085 for the confined lower aquifer in the Aromas Sand, comparable to that of layer 2.

Vertical leakage from one layer to another occurs whenever there is a head difference between adjacent layers. Leakage is from the layer with higher potentiometric head to the layer with lower potentiometric head. The rate at which this leakage occurs is controlled by the thickness and vertical hydraulic conductivity of the clay in the confining layer and the head difference across the layer. In the model, the effective thickness of the two confining layers was assumed to be equal to the composite thickness of the discontinuous, interbedded clay layers. Depending on rock type, conductivities can range exponentially by more than 13 orders of magnitude (Freeze and Cherry, 1979). Initial values of the vertical hydraulic conductivity used in modeling the upper confining layer were on the order of 0.00009 to 0.000009 ft/d in the area of thick clay (fig. 4) and 0.9 in the other areas. In the lower confining layer, an initial value of 0.004 ft/d was used, indicating a greater hydraulic connection between model layers 2 and 3 than between layers 1 and 2.

Inflows and Outflows of the System

Inflows include all water entering the study area. In this model, all inflows except flow across model boundaries (discussed previously in the section on boundary conditions) are included in areal recharge and applied to model layer 1. All inflows to model layers 2 and 3 are assumed to be across model boundaries.

Areal recharge consists of infiltration of direct precipitation, irrigation return, and leakage from streams. The amount of rainfall percolation into ground-water storage is dependent on the quantity, distribution, and intensity of precipitation, climatic and evaporative effects, surface vegetation, surface condition, slope, soil type, and the ability of the underlying strata to absorb, transmit, and store water. Considering these factors, Muir (1972) and H. Esmaili and Associates Inc., (1978) identified the main areas of ground-water recharge by rainfall infiltration in the Pajaro Valley. From their work and the U.S. Geological Survey's studies of recharge for the Santa Cruz and Monterey County area, lines of equal precipitation were drawn onto the model's nodal grid. A percentage of the total precipitation was then assigned to individual nodes. The percentage of precipitation applied to the model as recharge ranged from 5 to 30 percent. An additional component of precipitation recharge is allowed for agricultural lands. This consideration was first suggested by H. Esmaili and Associates Inc., (1978). Generally, these are areas of level grade where natural vegetation is absent and which lie beyond the upper confining layer in the lower Pajaro Valley. Also, recharge from precipitation occurring just beyond the model boundary has been added to the adjacent boundary nodes to account for near-surface flow.

Irrigation return is that part of the applied irrigation water that percolates down to the water table. The application of this excess water is a necessary irrigation practice to help reduce salt buildup in the soils. The return flow for this area has been estimated to be as high as 30 percent of the total agricultural pumpage (Brown and Caldwell, 1976; H. Esmaili and Associates, 1978). A more conservative estimate of 20 percent is used in this model, all of which is assumed to return to the upper model layer.

Stream leakage is the water that passes through streambeds and percolates down to the water table. This recharge is dependent on the altitude of the water surface of the stream, the head in the underlying aquifer, and the altitude, vertical hydraulic conductivity, thickness, and area of the streambed. Recharge from stream leakage occurs where water levels in the underlying aquifer are below the water level of the overlying stream.

Recharge estimates for the drainage systems in the study area were calculated using flow records from gaging-stations monitored by the U.S. Geological Survey and Monterey County, and infiltration measurements (K.S. Muir, U.S. Geological Survey, written commun., 1980). These values compared favorably with previously published values of H. Esmaili and Associates Inc., (1978). Therefore, the published values were used with additional values for other small drainages in the study area (table 1). Stream leakage was simulated in the model as part of the areal recharge rather than using the stream parameter of the model so that stream leakage could be adjusted for seasons (fig. 12).

Table 1.--Estimated mean rates of annual channel recharge, Pajaro Valley area, 1957-72

[acre-ft/yr, acre-foot per year; ft^3/s, cubic feet per second]

Stream	Estimated mean recharge acre-ft/yr	Estimated mean recharge ft^3/s	Number of nodes applied
Pajaro River	[1]4,500	6.2	13
Corralitos and Brown Valley Creek	[1]2,880	4.0	12
Green Valley Creek	[1]1,200	1.7	7
Casserly and Hughes Creek	[1]655	.9	6
Coward Creek	[1]495	.7	4
Mattos Gulch Creek	[1]240	.3	2
Carneros Creek	[1]400	.6	9
Pleasant Valley drainage tributary	[1]870	1.2	8
Larkins Valley drainage tributary	[1]760	1.0	7
Total............................	12,000	16.6	

[1]H. Esmaili and Associates Inc., 1978

Outflows consist of all water leaving the study area and includes pumpage, near-surface water loss to streams, evapotranspiration, and flow across constant-head boundaries (discussed previously in the section on boundary conditions). Ground-water pumpage in the Pajaro Valley area is the principal discharge from the aquifers. Ground-water pumpage from the study area was divided into three different categories of use: (1) agricultural, which includes all water pumped for irrigation, (2) municipal and industrial, which includes all water pumped from within the city of Watsonville service area for use other than irrigation, and (3) other pumpage, which includes residential and associated commercial and industrial pumpage outside the city of Watsonville service area. Total pumpage was calculated for different uses (table 2) and distributed areally and vertically in the model (figs. 13, 14, and 15) on the basis of well logs and pumping information.

The quantity of agricultural pumpage from irrigation wells was determined from power-consumption records. Electrical energy consumption values were obtained from Pacific Gas and Electric Company's (P.G.& E.) metered agricultural accounts. The electrical energy required to pump a volume of water was computed from pump efficiency tests made by P.G.& E., (written commun., 1979). Interpretation is required in defining irrigation accounts, pump efficiencies, and lift. Both pump efficiencies and lift were field checked during the summer of 1981. Flow meters were inserted into mainline irrigation pipes in selected irrigation systems operating under normal conditions while directly monitoring P.G.& E. power meters. This allowed direct conversion factors (energy in kilowatt hours to equivalent acre-feet of water pumped) to be obtained within defined lift areas of the Pajaro Valley.

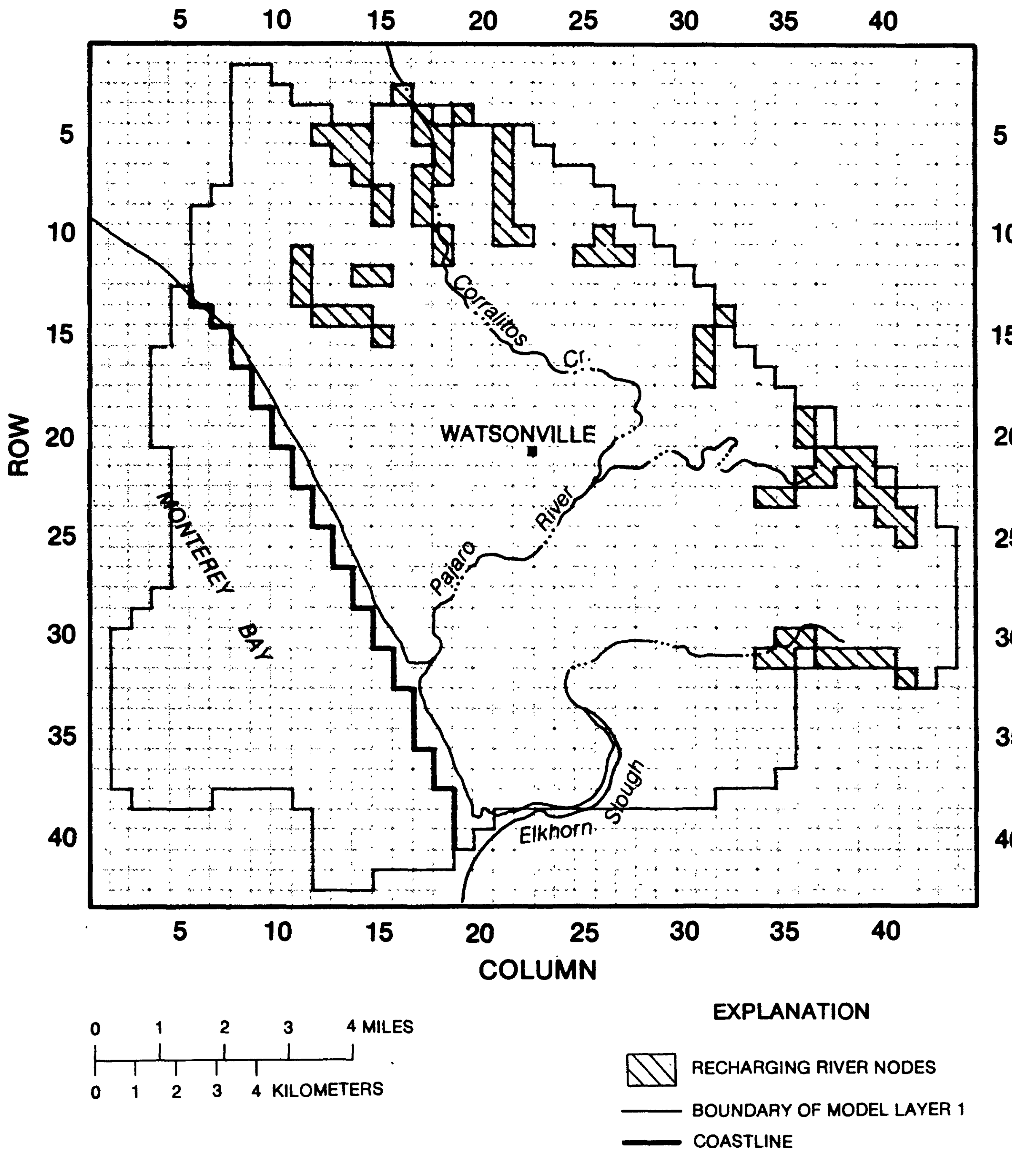


FIGURE 12. – Location of recharging river nodes, model layer 1.

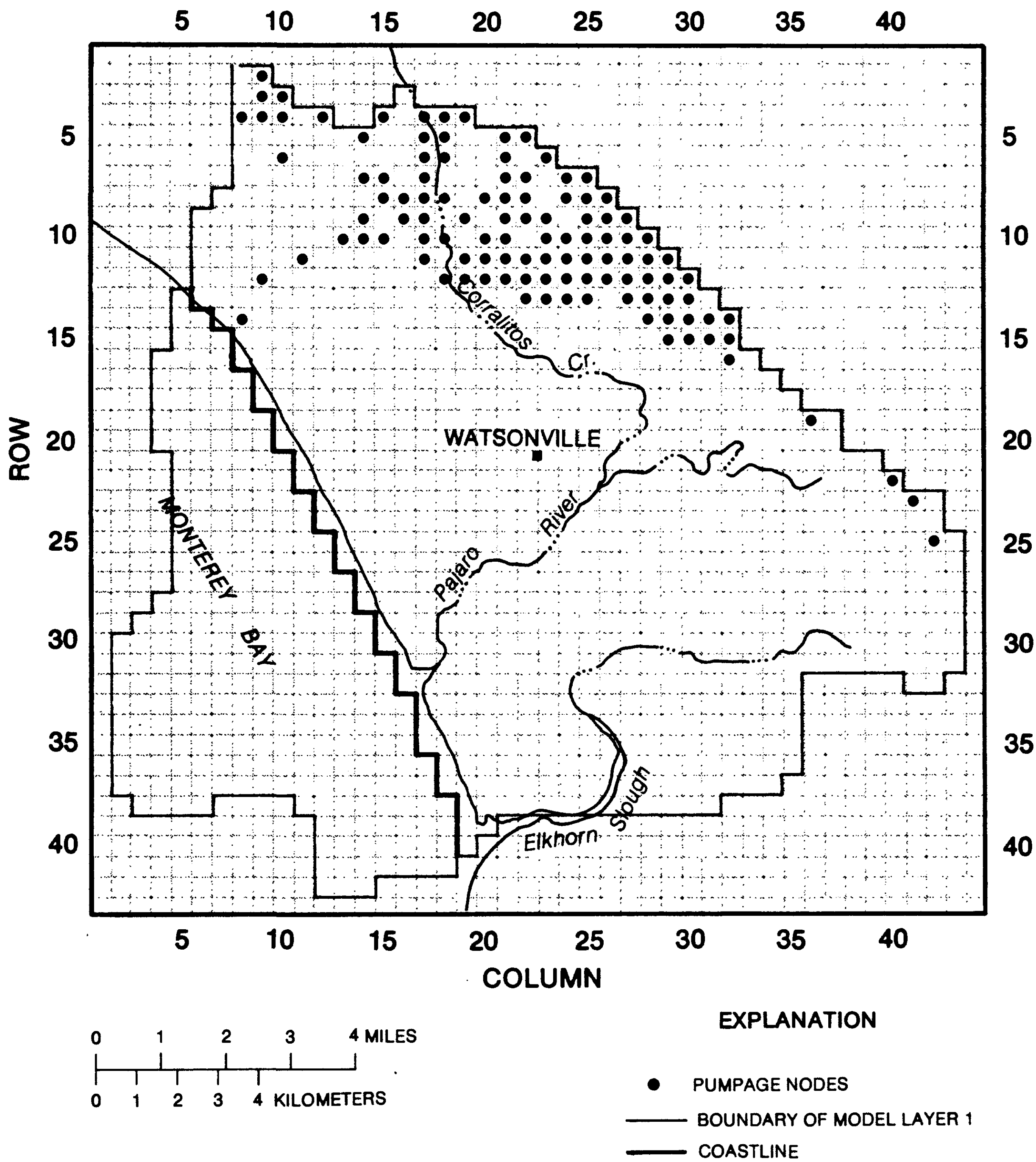


FIGURE 13. – Location of ground-water pumpage nodes, model layer 1, for 1976.

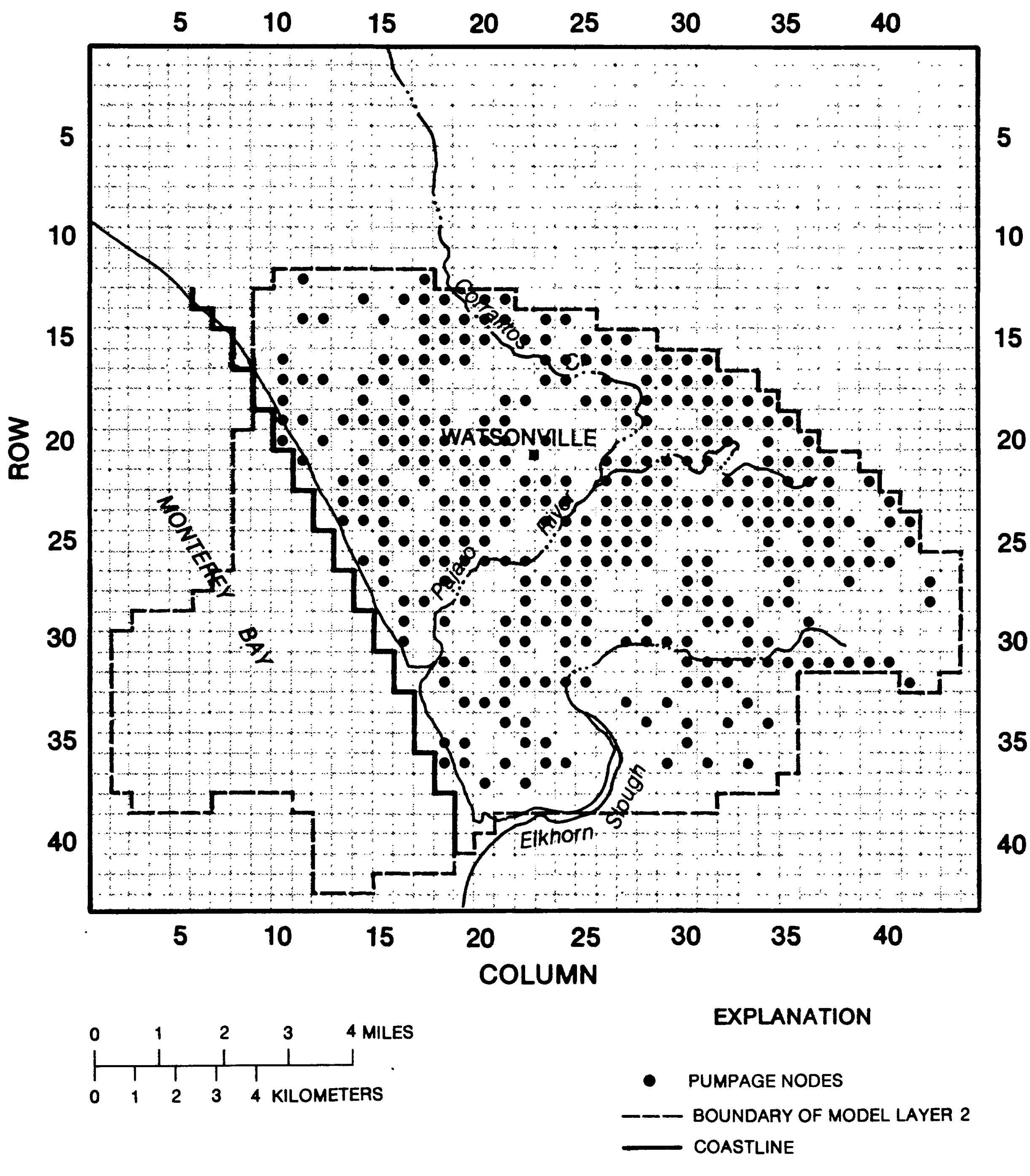


FIGURE 14. – Location of ground-water pumpage nodes, model layer 2, for 1976.

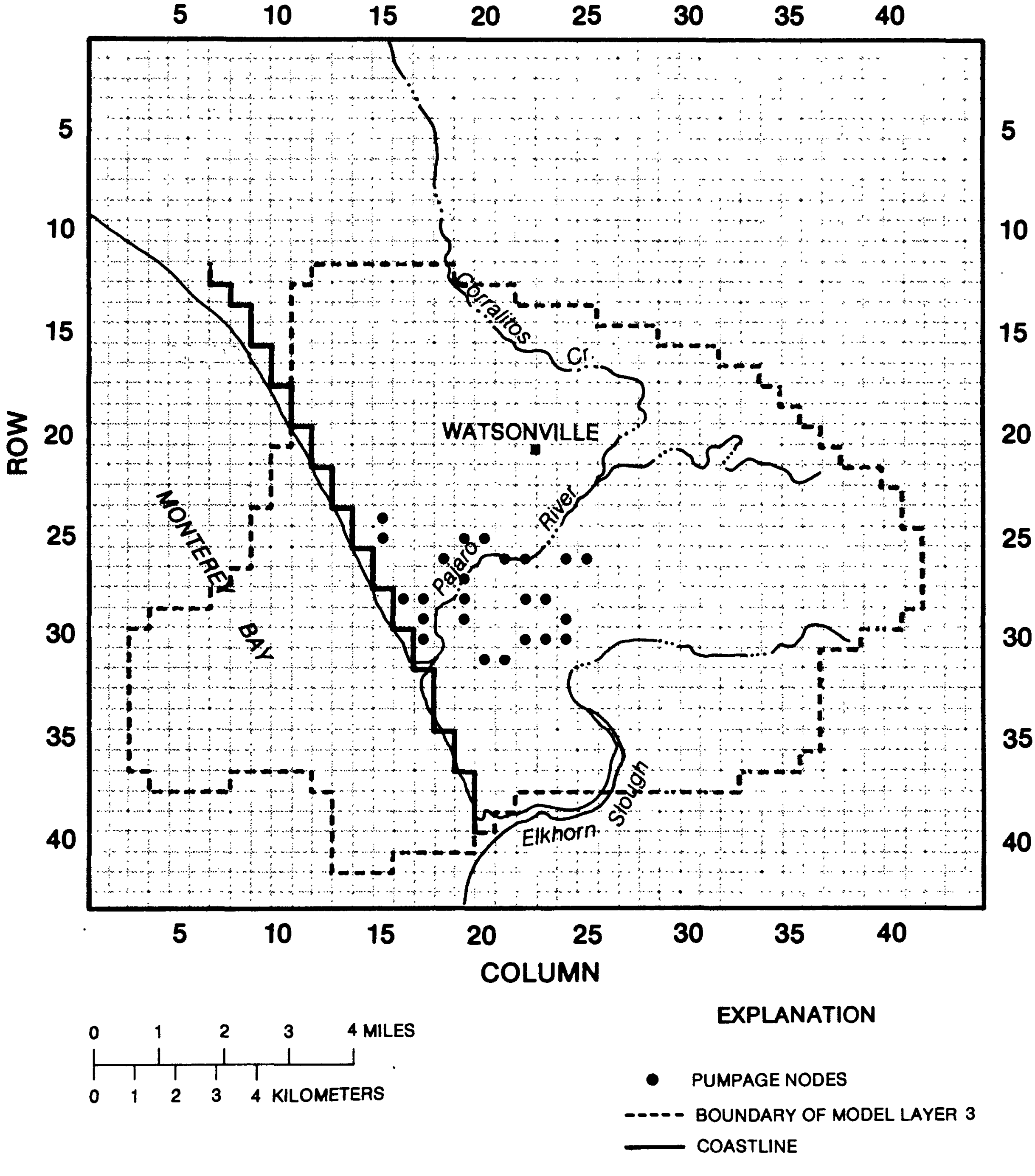


FIGURE 15. – Location of ground-water pumpage nodes, model layer 3, for 1976.

Table 2.--Estimated pumpage, in acre-feet, 1970-81

[Pumpage values for each category were obtained prior to modeling and adjustment in the calibration procedure as described in the text. The two values for irrigation pumpage relate to the maximum and minimum values discussed in the text and shown in figure 16. Total pumpage is for the end of the calibration process as shown in figure 24]

				Irrigation		Total	
Year	Other	Industrial	Municipal	Maximum	Minimum	Maximum	Minimum
1970	1,300	1,300	4,300	50,800	50,800	57,700	57,700
1971	1,300	1,500	3,200	56,000	56,000	62,000	62,000
1972	1,600	2,000	4,900	56,000	56,000	64,500	64,500
1973	2,000	1,800	3,800	48,000	43,000	55,600	50,600
1974	2,100	2,600	4,000	48,000	43,000	56,700	51,700
1975	2,300	2,400	3,300	53,200	47,000	61,200	55,000
1976	2,500	2,300	4,800	66,500	59,000	76,100	68,600
1977	2,700	2,500	4,700	70,700	63,000	80,600	72,900
1978	2,800	2,700	5,200	66,200	55,000	76,900	65,700
1979	3,100	2,500	5,600	66,200	54,000	77,400	65,200
1980	3,200	2,600	5,500	66,600	53,000	77,900	64,300
1981	3,300	2,600	5,800	66,000	54,000	77,700	65,700

A problem with this energy-use method is that P.G.& E.'s agricultural accounts do not distinguish between power used for irrigation pumpage and that used for other agricultural needs. Therefore, the nonirrigation power consumption must be estimated and removed from the total reported power consumption before calculating the irrigation pumpage. For this study, a detailed review was made of all agricultural accounts and nonirrigation electric power uses were identified and removed; remaining agricultural accounts were field checked by selected sampling. Then irrigation pumpage was calculated using what was estimated to be the maximum power that was used for irrigation and also the minimum power that was used for irrigation based on statistical error (fig. 16). Irrigation pumpage was also calculated by using the total reported agricultural power consumption to illustrate the error that could result if the nonirrigation power consumption is not removed before calculating pumpage. The divergence between the uncorrected and corrected pumpage curves (fig. 16) indicates that other energy uses (such as lighting and machinery) on the agricultural accounts, which must be identified and removed, are increasing.

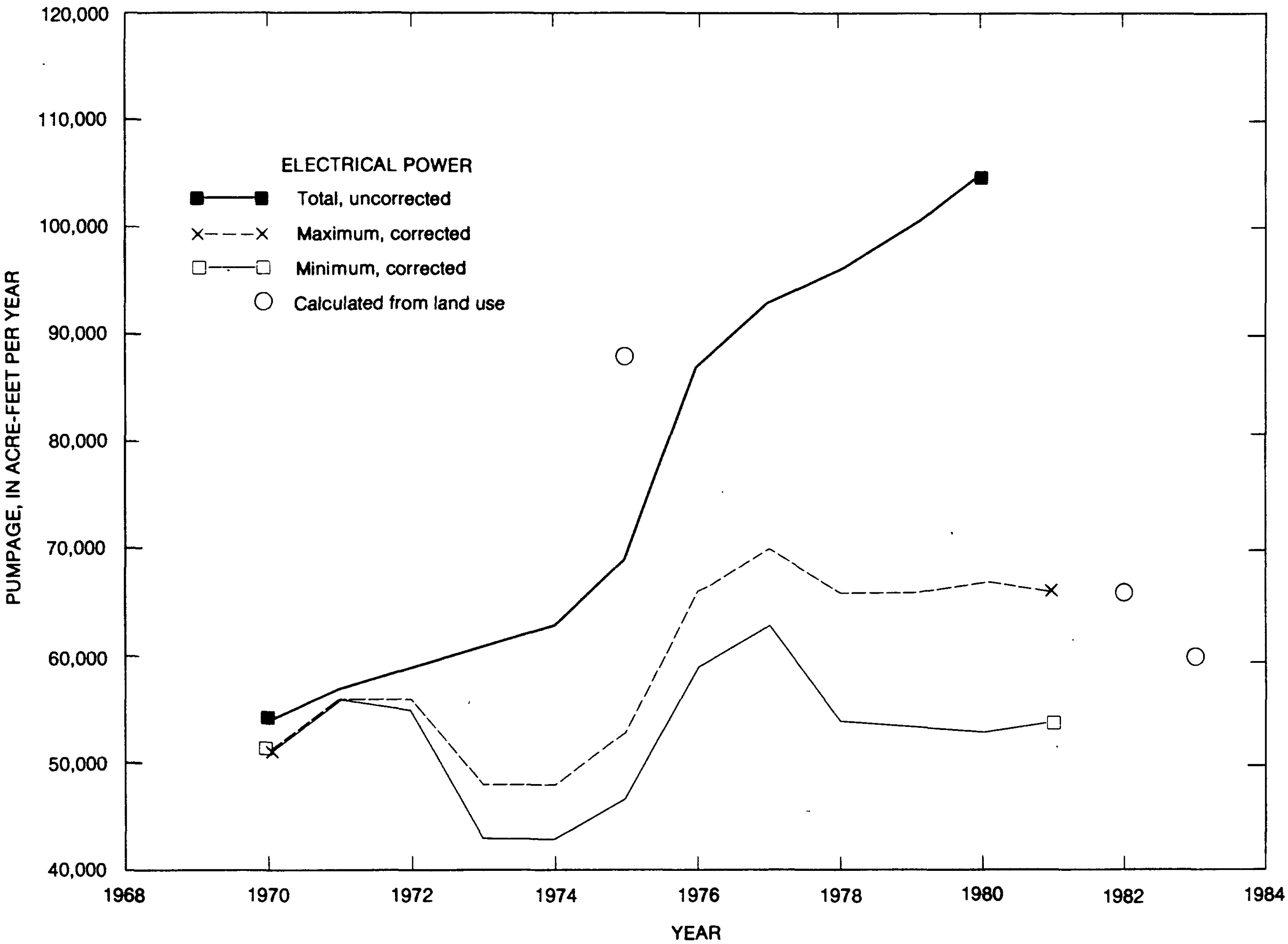


FIGURE 16. —Estimates of annual irrigation pumpage, 1970-83, based on electrical-power consumption and land use.

Another method for estimating agricultural pumpage is the land-use method. In this method, unit-applied water demands (crop application rates) for the different crops grown in the study area are estimated. These application rates and knowledge of the acreage in each crop category can be used to indirectly estimate the actual water pumped under average conditions of crop application. Three estimates of pumpage were made by H. Esmaili and Associates Inc. (1978, and oral commun., 1982 and 1983) using this method (fig. 16). The estimates for 1982 and 1983, which were made using more reliable crop application rates than were available in 1975, fall within the projected range of maximum and minimum pumpages using the energy-use method (fig. 16). This would indicate that the more convenient land-use method may be an equally reliable method for estimating irrigation pumpage, provided good estimates of crop application rates are maintained. The more current estimates of crop application rates for the Pajaro Valley were computed by the Santa Cruz County Agricultural Extension Service, University of California, Santa Cruz, and field checked during the 1980 and 1981 irrigation seasons for different crops by monitoring irrigation pumpage using flow meters supplied by the U.S. Geological Survey.

Pumpage for most municipal and industrial use within the city of Watsonville service area is metered and was determined from the records of the users. The Aromas County Water District and the Soquel Creek County Water District are also public suppliers of ground water within the study area. Their pumpage is considerably less than that of the city of Watsonville and is incorporated into estimates with "other pumpage."

Other pumpage in the study area includes residential, commercial, and industrial use outside the city of Watsonville service area. Residential water use was calculated indirectly by assuming a demand of 125 gal per person per day in the Monterey County part of the study area (Johnson, 1983). The Monterey County Planning Commission furnished estimates of the number and distribution of users in this area. Commercial and industrial water use was reported separately and added to the residential estimate. In the Santa Cruz part of the study area, residential, commercial, and industrial water use was estimated by assuming a demand of 150 gallons per person per day. Estimates of the number and distribution of users were determined by the Santa Cruz County Transportation Commission. Estimates of pumpage in Monterey and Santa Cruz Counties were calculated and summed for each year from 1970 to 1981 (table 2).

Ground water is lost to streams when the water table is higher than the altitude of the overlying stream surface and to evapotranspiration when the water table is within the root zone of the overlying plants. Within the study area these conditions generally are found principally in the lower Pajaro Valley, west of Watsonville and along Elkhorn Slough. In the lower Pajaro Valley a network of drain tiles and sump wells, that discharge directly to the river and sloughs, has been installed. These wells limit the maximum altitude of the water table and keep the upper soils from becoming saturated. Locally in other areas, faults and geologic boundaries impound and cause ground water to surface and be lost to streams, ponds, and evapotranspiration.

In the model, the loss of water to the streams, either naturally or through field drain tiles and loss to evapotranspiration, is simulated using a drain-well function (fig. 17). This function limits the maximum height of the water table to the altitude of the drain. Ground water rising above this level during simulation is "drained" or discharged from the system.

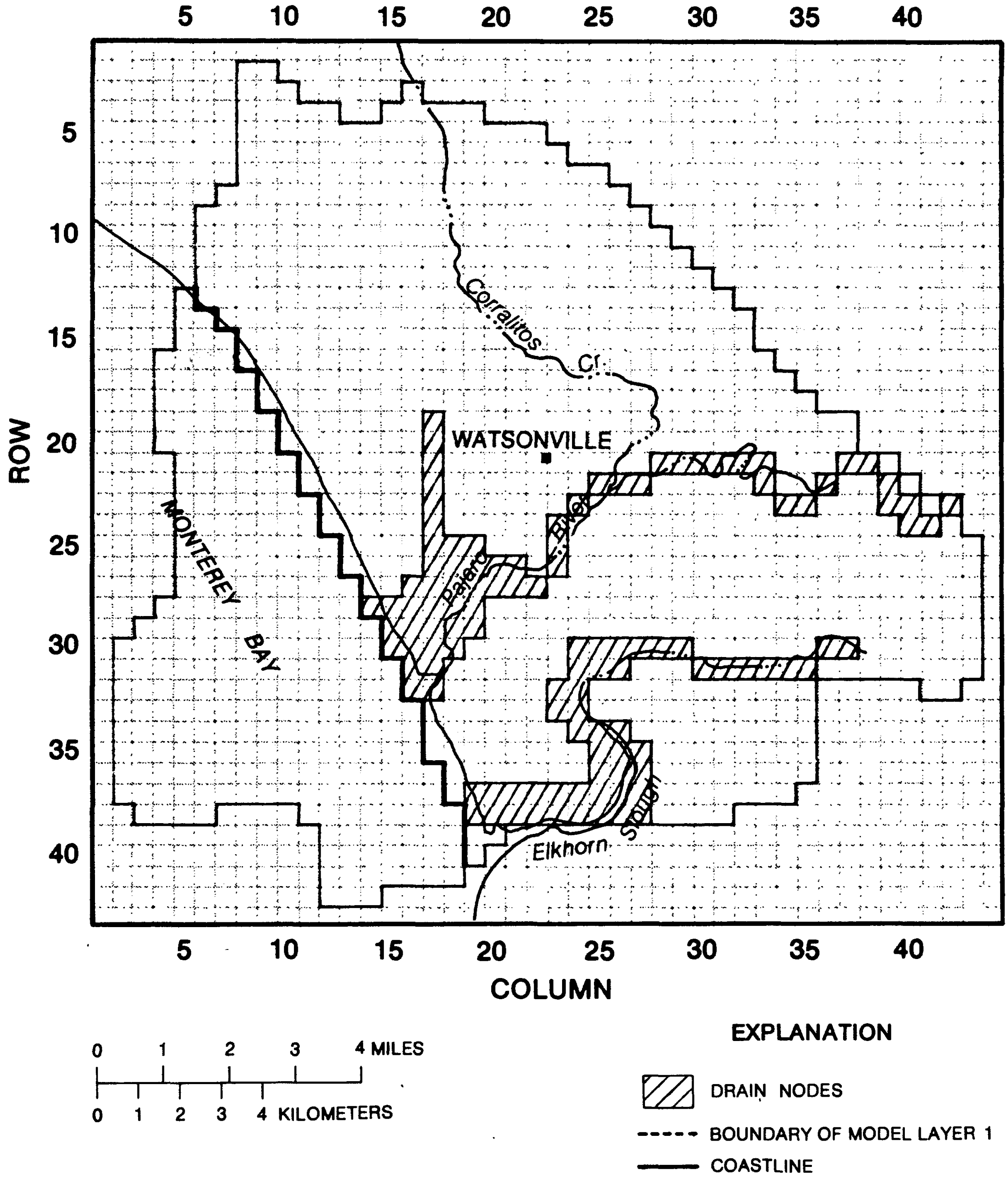


FIGURE 17. – Location of drain nodes, model layer 1.

Model Calibration

The calibration of a ground-water model is the trial-and-error process of adjusting the initial data estimates to obtain a better match between computed and measured potentiometric heads. The initial data estimates are adjusted within limits that are based on the geologic and hydrologic characteristics of the basin and the degree of confidence placed on the original data estimates. The standard error of estimate, which is a measure of the absolute difference between measured and computed heads, was used to determine the closeness of the match. The closeness of the final match is controlled by the complexity of the actual system as well as time constraints on the study (J.A. Skrivan, U.S. Geological Survey, written commun., 1980).

The simulation period for model calibration of transient conditions was spring 1970 to autumn 1981. This time interval was chosen because of the availability of pumpage and water-level data and also because it included a major ground-water stress period, the 1976-77 drought and subsequent recovery period. The interval was divided into twenty-three 6-month simulation periods representing alternating summer-autumn and winter-spring conditions. Typically during the 6-month winter-spring period (November 15-April 15) over 90 percent of the precipitation infiltration and 76 percent of the stream channel infiltration occurs when pumping stresses are low. In contrast, during the 6-month summer-autumn period when 80 percent of the irrigation pumpage and 60 percent of all other pumpage occurs, only 10 percent of the precipitation and 24 percent of the stream channel infiltration takes place. The model was calibrated to reproduce, reasonably well, 366 spring and autumn water levels measured at 39 selected wells completed in the middle and lower aquifers (well numbers are given in table 3 and well locations are shown in figures 9 and 10).

The first phase of the calibration process required adjusting the aquifer properties until the best combination of values for these properties was obtained. The calibrated hydraulic conductivity of model layer 1 ranges from 0.35 ft/d to 35 ft/d (fig. 18). The transmissivity of layer 2 ranges from 6,500 ft^2/d to 13,000 ft^2/d (fig. 19). Transmissivity of layer 3 is 7,800 ft^2/d. The storage coefficient for layer 1 ranges from 0.01 to 0.1 (fig. 20). The storage coefficient for layer 2 is 0.05 in the unconfined areas and ranges from 0.0001 to 0.001 in the confined areas (fig. 21). The storage coefficient for layer 3 is 0.0001. Leakance between layers 1 and 2 ranges from 0.00017 (ft/d)/ft to 0.00086 (ft/d)/ft in the areas of the confining clays and is 0.9 (ft/d)/ft for the remainder of the area (fig. 22). Leakance between layers 2 and 3 ranges from 0.0006 (ft/d)/ft to 0.0015 (ft/d)/ft (fig. 23).

Table 3.-- State well numbers and location of corresponding model nodes for observation wells used in the model calibration

Wells in layer 2 (see fig. 9)			Wells in layer 3 (see fig. 10)		
	Nodes			Nodes	
Well No.	Row	Column	Well No.	Row	Column
11S/2E-29F2	14	21	12S/1E-13R1	27	17
11S/2E-33C1	16	24	12S/1E-25F1	30	16
11S/2E-33A4	16	25	12S/1E-25B3	30	17
11S/2E-33E1	17	23	12S/1E-25G1	31	17
11S/2E-34D2	17	26	12S/2E-30M2	31	17
11S/2E-35H2	17	30	13S/2E-6E2	35	18
11S/2E-36F1	17	32			
11S/2E-34K1	18	27			
11S/2E-36M3	18	30			
11S/2E-36M1	18	31			
12S/2E-3A2	19	28			
12S/2E-2L1	20	29			
12S/2E-2H3	20	30			
12S/2E-5N1	21	20			
12S/3E-6N2	21	34			
12S/2E-8G3	22	22			
12S/2E-9C2	22	24			
12S/2E-10D1	22	26			
12S/3E-7B1	22	35			
12S/2E-8K2	23	22			
12S/2E-12E1	23	31			
12S/2E-18D1	25	18			
12S/2E-16H2	25	25			
12S/3E-16C2	25	40			
12S/2E-18L1	26	19			
12S/2E-18K3	26	20			
12S/1E-24G1	28	16			
12S/1E-24L1	29	15			
12S/2E-32C1	33	22			
13S/2E-6C1	35	18			
13S/2E-6E3	36	18			
13S/2E-5M1	36	21			
13S/2E-6R1	37	20			

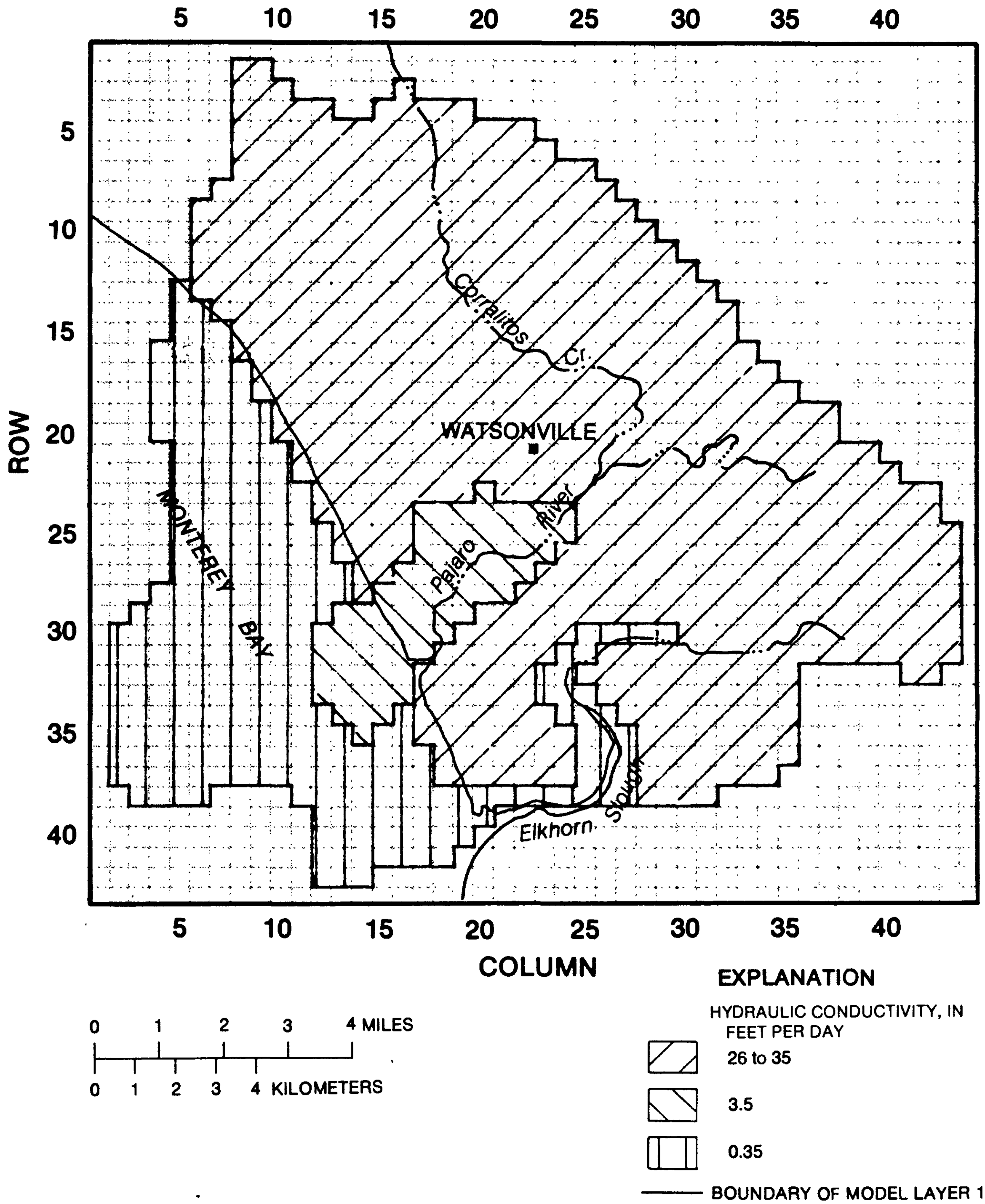


FIGURE 18. – Hydraulic conductivity, model layer 1.

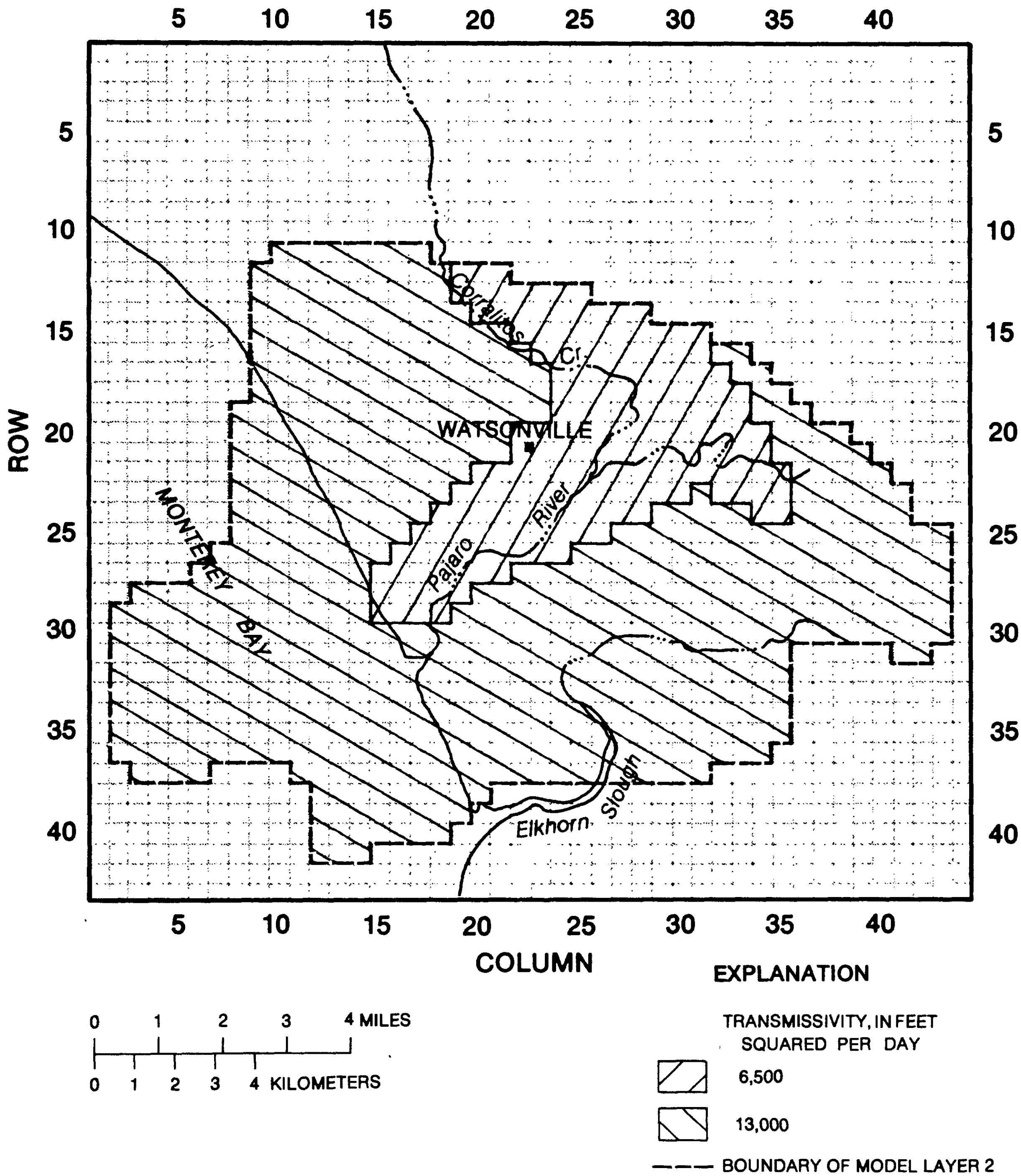


FIGURE 19. – Transmissivity, model layer 2.

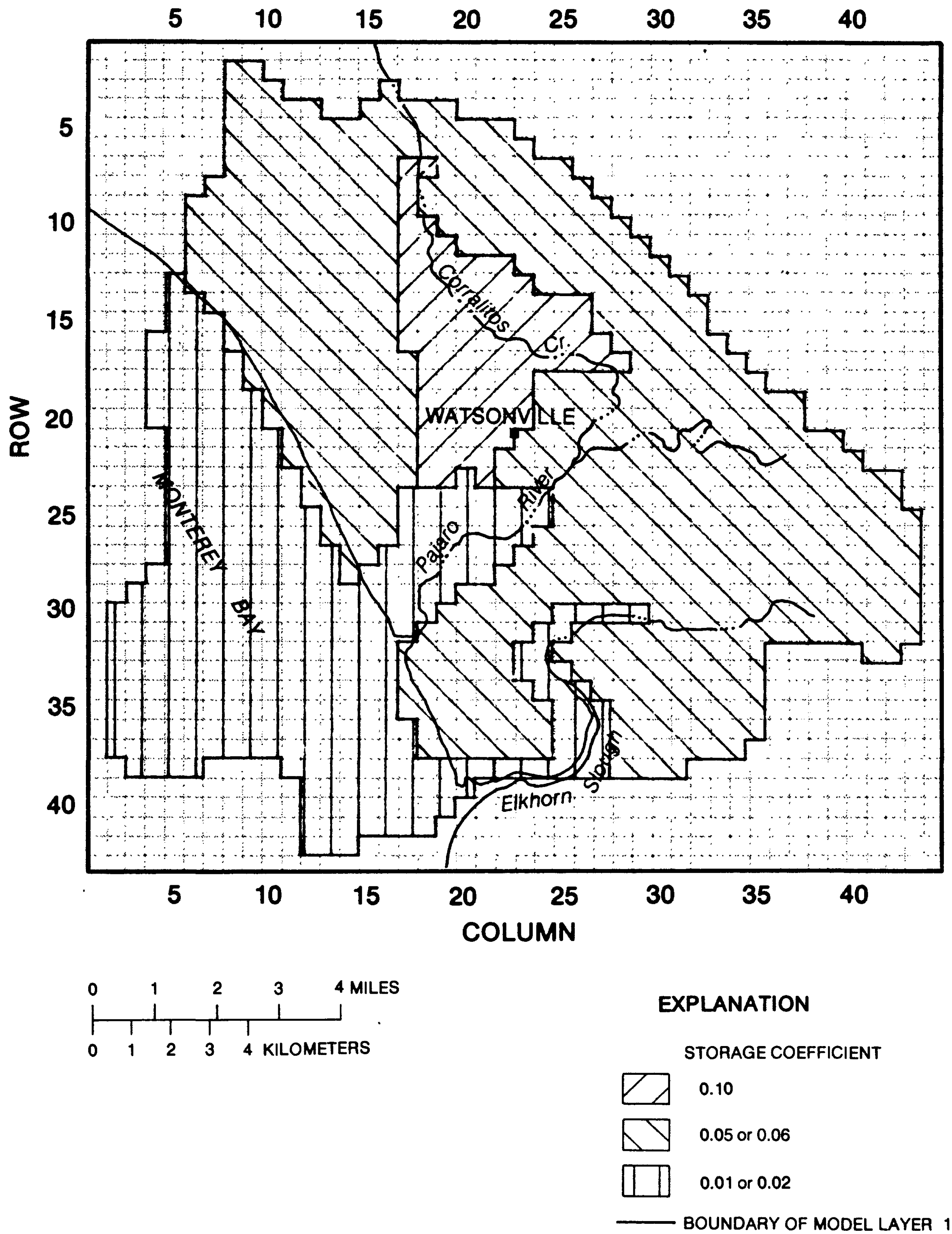


FIGURE 20. – Storage coefficient, model layer 1.

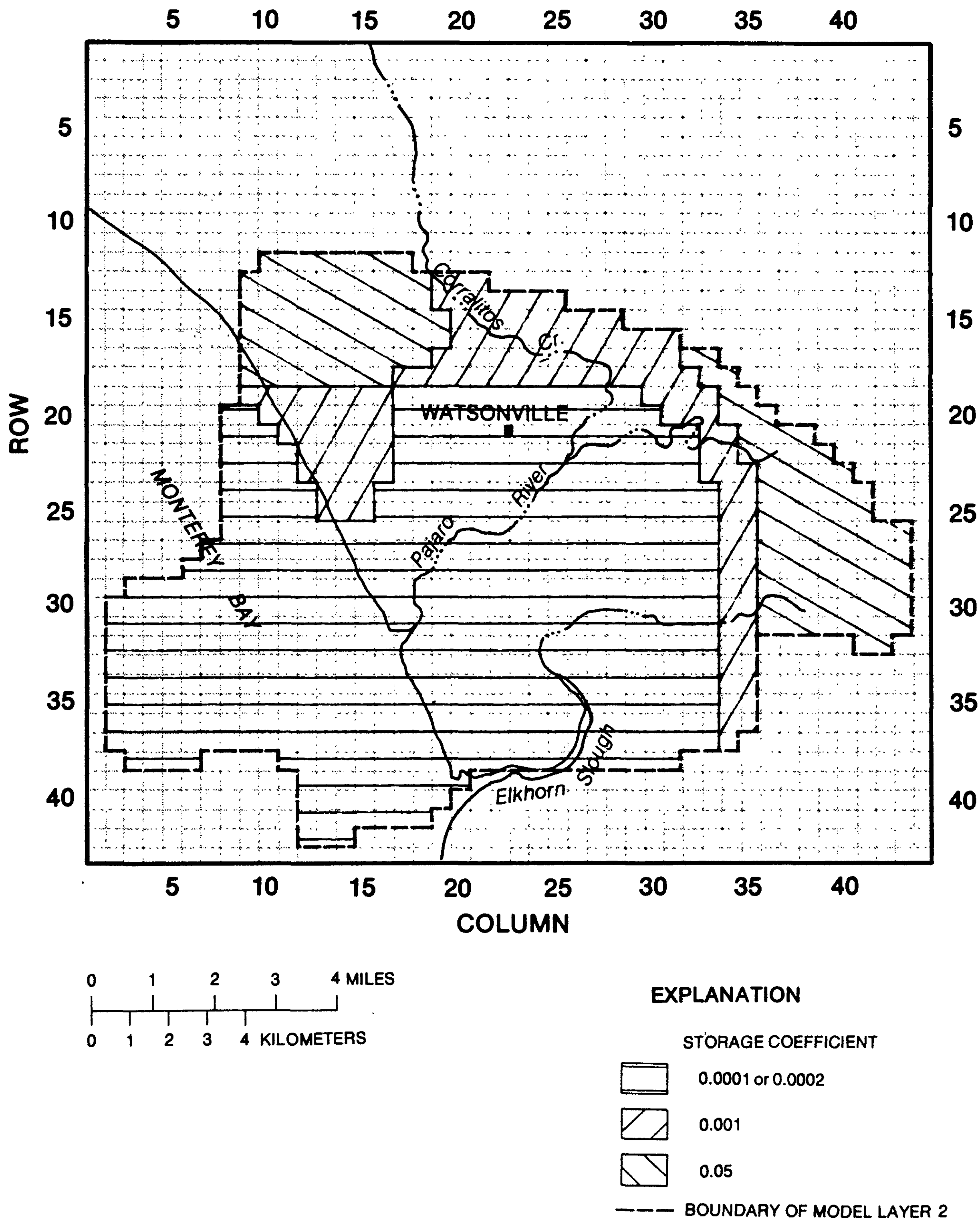


FIGURE 21.– Storage coefficient, model layer 2.

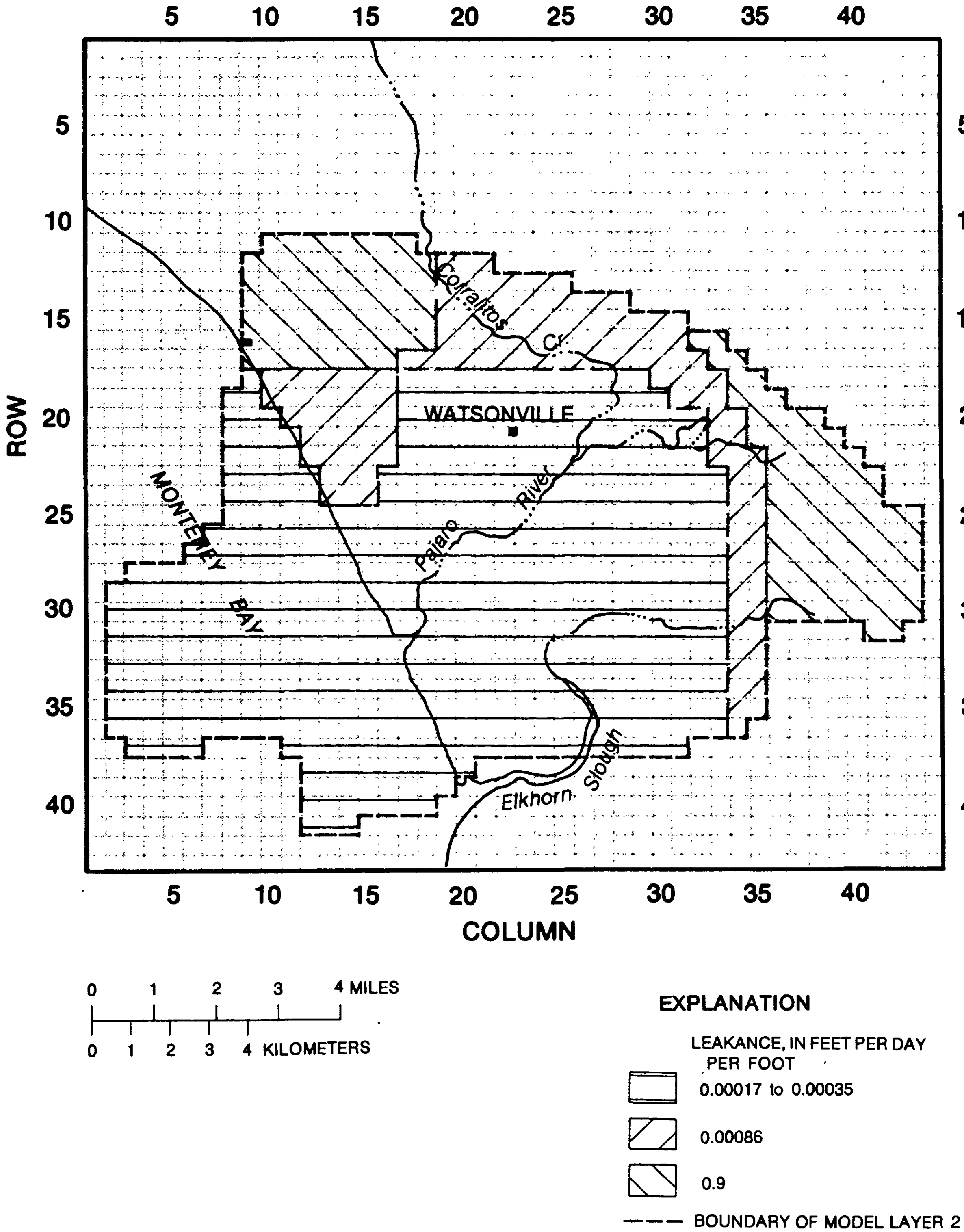


FIGURE 22. — Leakance between model layers 1 and 2.

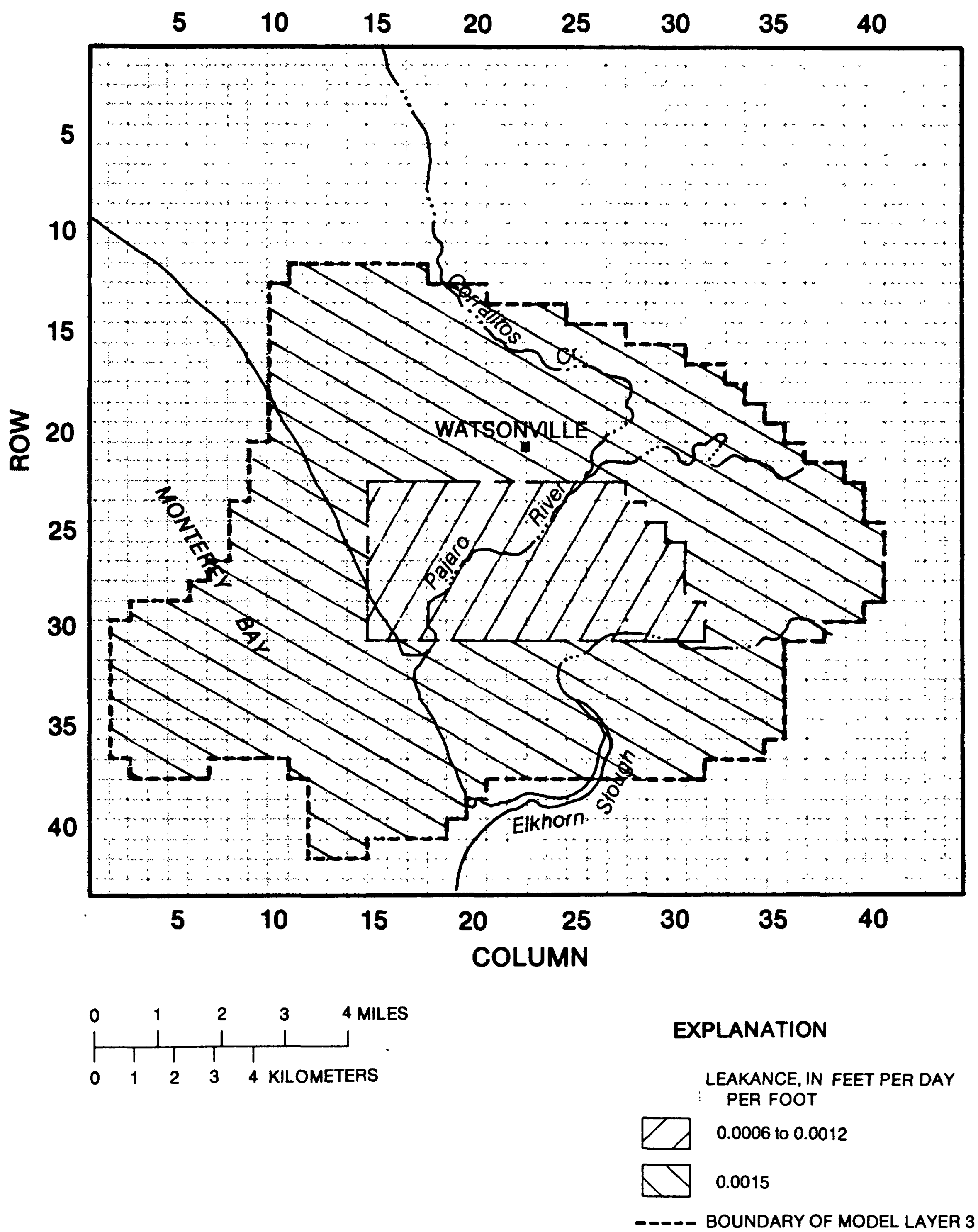


FIGURE 23. — Leakance between model layers 2 and 3.

The second phase of the calibration process required adjusting of the inflows and outflows of the ground-water system. During model calibration, the irrigation part of the pumpage data was reduced by a uniform 10 percent for each simulation period through 1977. For simulation periods after 1977, calibration resulted in a reduction of about 18 percent from the initial estimates. In effect, the model suggests that the maximum corrected irrigation pumpage values shown in figure 16 and used initially in the model (table 2) are less desirable than the minimum values shown in figure 16. There is an 18-percent difference between the maximum and minimum curves in figure 16 after 1977. Figure 24 shows the total pumpage for each simulation period at the end of the calibration process. Areal recharge was decreased about one percent and total underflow across the model boundaries was increased by about 3 percent uniformly for the twenty-three simulation periods. The final calibrated underflow across the boundaries was 12,870 acre-ft/yr or 17.78 ft^3/s and was distributed to the model layers as follows: 8.08 ft^3/s to layer 1, 5.85 ft^3/s to layer 2, and 3.85 ft^3/s to layer 3.

The model could not actually be calibrated in areas where there were no head measurements (figs. 9 and 10). In these areas input data were adjusted to produce the best match in the areas where there were head measurements. These values may not necessarily be the best ones to use in simulating the potentiometric surface within the areas where there were no data with which to calibrate.

Figure 25 shows hydrographs that compare measured heads in wells with long-term water-level records, and computed heads at the corresponding model nodes using the final calibrated input data. These hydrographs show a good correlation between measured and computed heads for both the annual fluctuations and long-term trends. The standard error of estimate between measured and computed heads at the end of the calibration process was 6.1 feet. Model-generated potentiometric surfaces for layer 2 for spring 1981 and autumn 1981, using the final calibrated input data, are shown in figures 26 and 27.

During the 11-year simulation period from the autumn of 1970 through the autumn of 1981 there was a net loss of water from storage within the aquifer system of about 23,000 acre-feet (table 4). Model-generated budgets show that most of this loss occurred during the 1976-77 drought (table 5). From the end of the drought through 1981, the budgets indicate that the net volume of water in storage was increasing annually.

Model-generated water budgets for the 1981 winter-spring and summer-autumn simulation periods (table 4) indicate that at the end of the winter-spring period about 83 percent of the water entering the system was from areal recharge, about 16 percent enters the system as inflow across the constant-flux boundaries, and about 1 percent enters the system as inflow across the constant-head boundary. The outflows from the system at the end of this period were: 84 percent to pumpage, 9 percent out across the constant-head boundaries, and 7 percent to the drains.

At the end of the 1981 summer-autumn simulation period about 72 percent of the water coming into the system was from recharge, 23 percent across the constant-flux boundaries, and 5 percent across the contant-head boundaries. Outflows at the end of this simulation period consisted of 96 percent to pumpage, 2 percent out across constant-head boundaries, and 1 percent to drains. During those two simulation periods there was a net gain of about 2,200 acre-feet of water in storage.

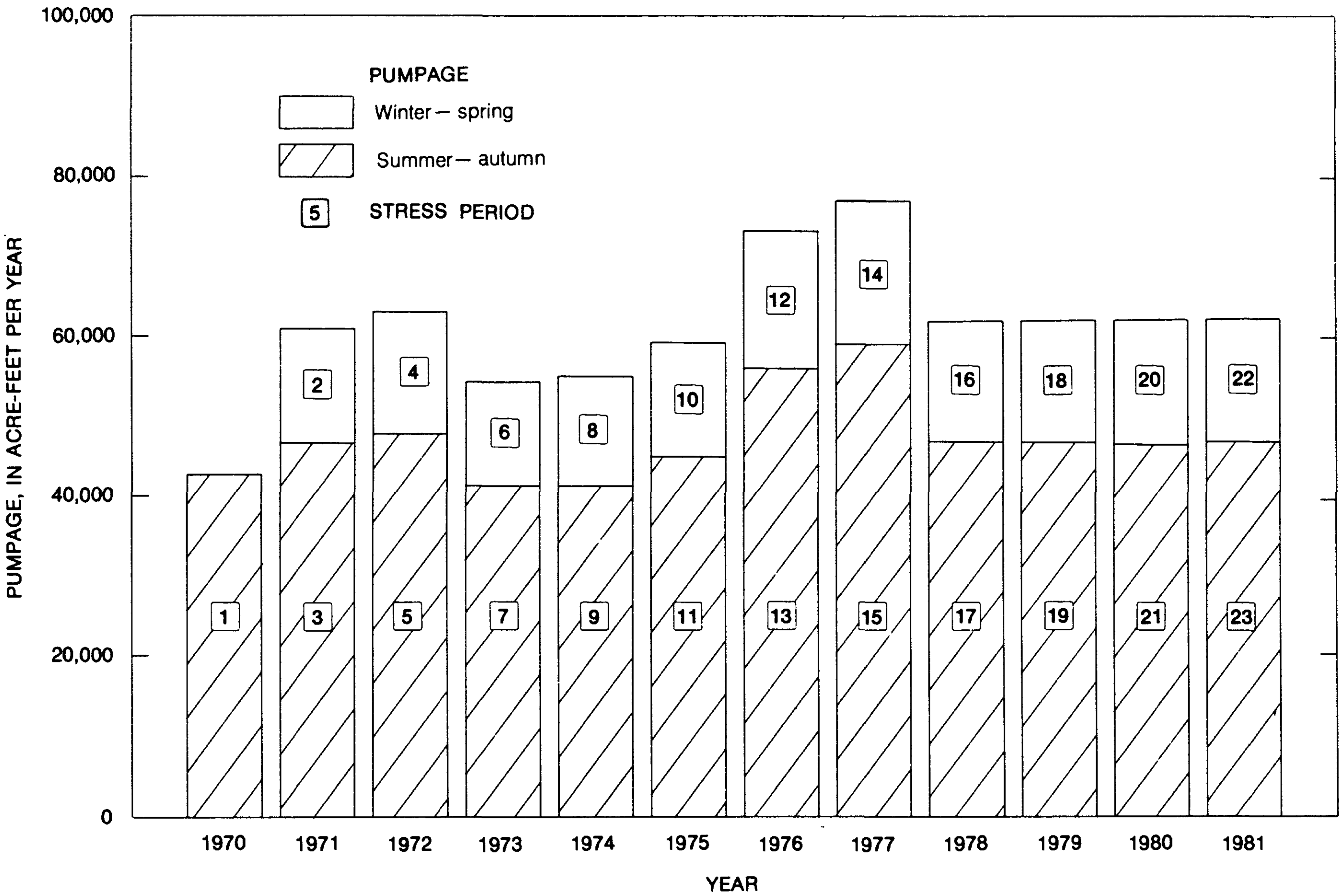


FIGURE 24.—Estimated calibrated total pumpage for each model stress period.

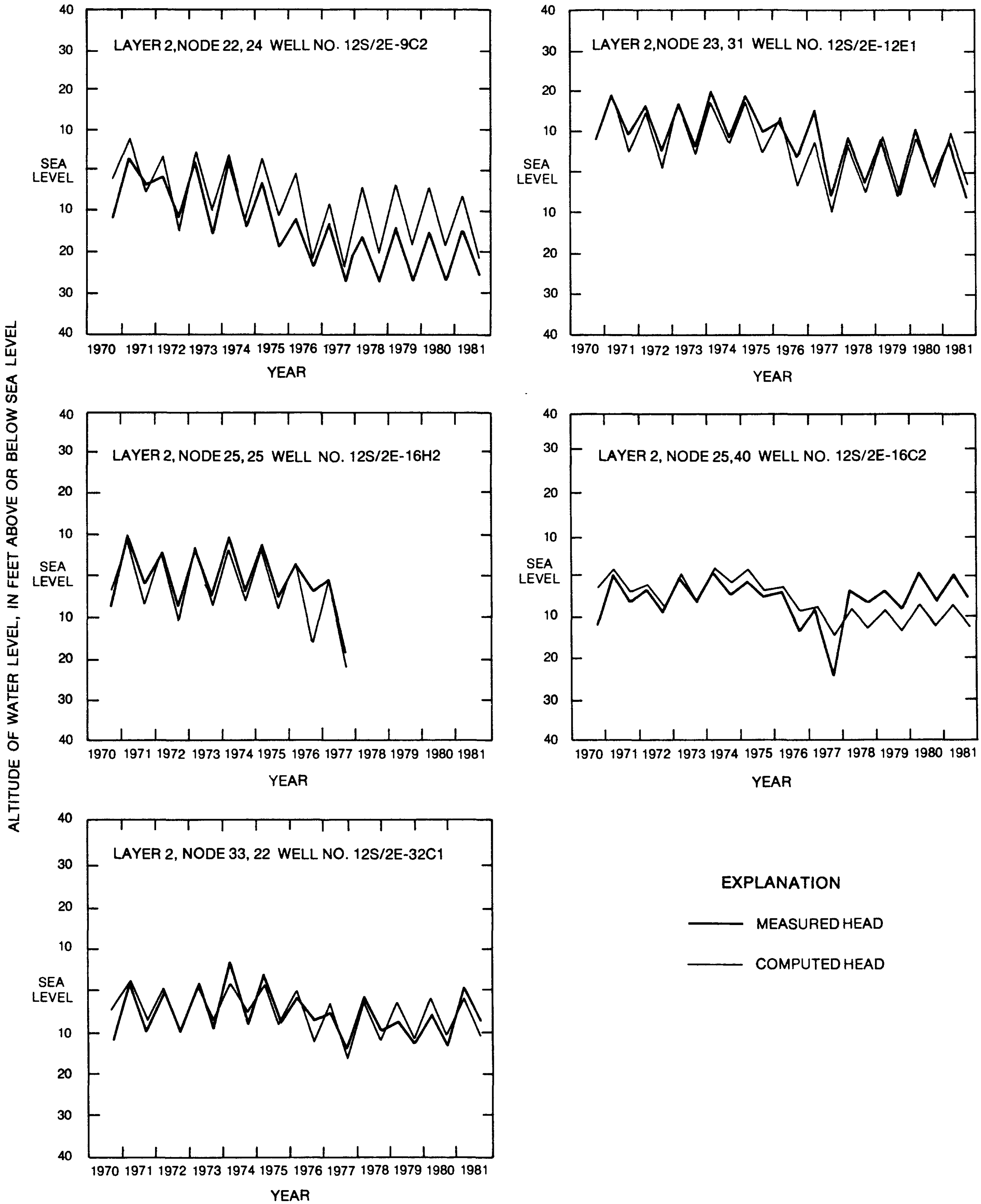


FIGURE 25. – Hydrographs of measured and computed potentiometric heads for observation wells and corresponding model nodes, model layers 2 and 3.

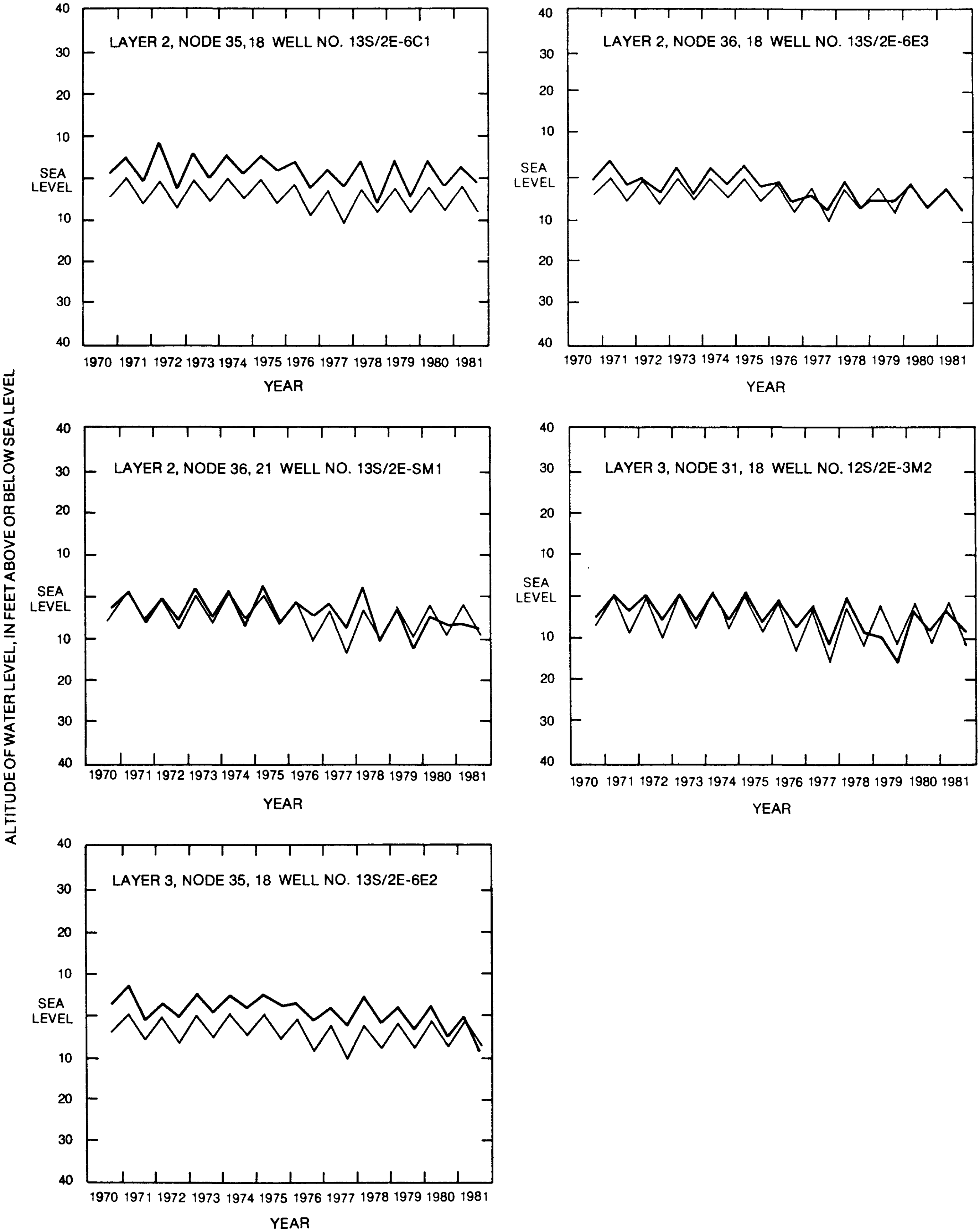
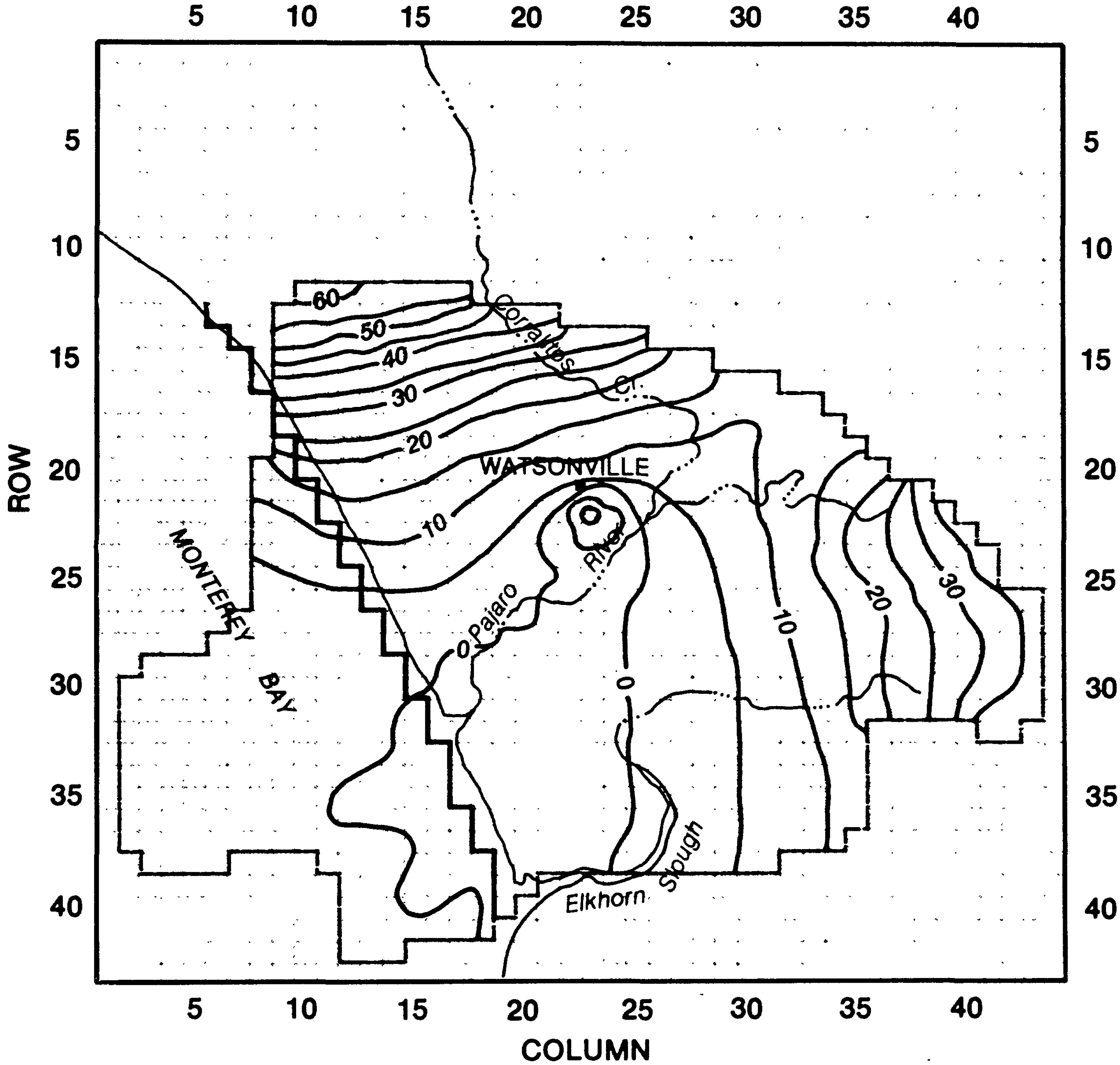


FIGURE 25. — Continued.



0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

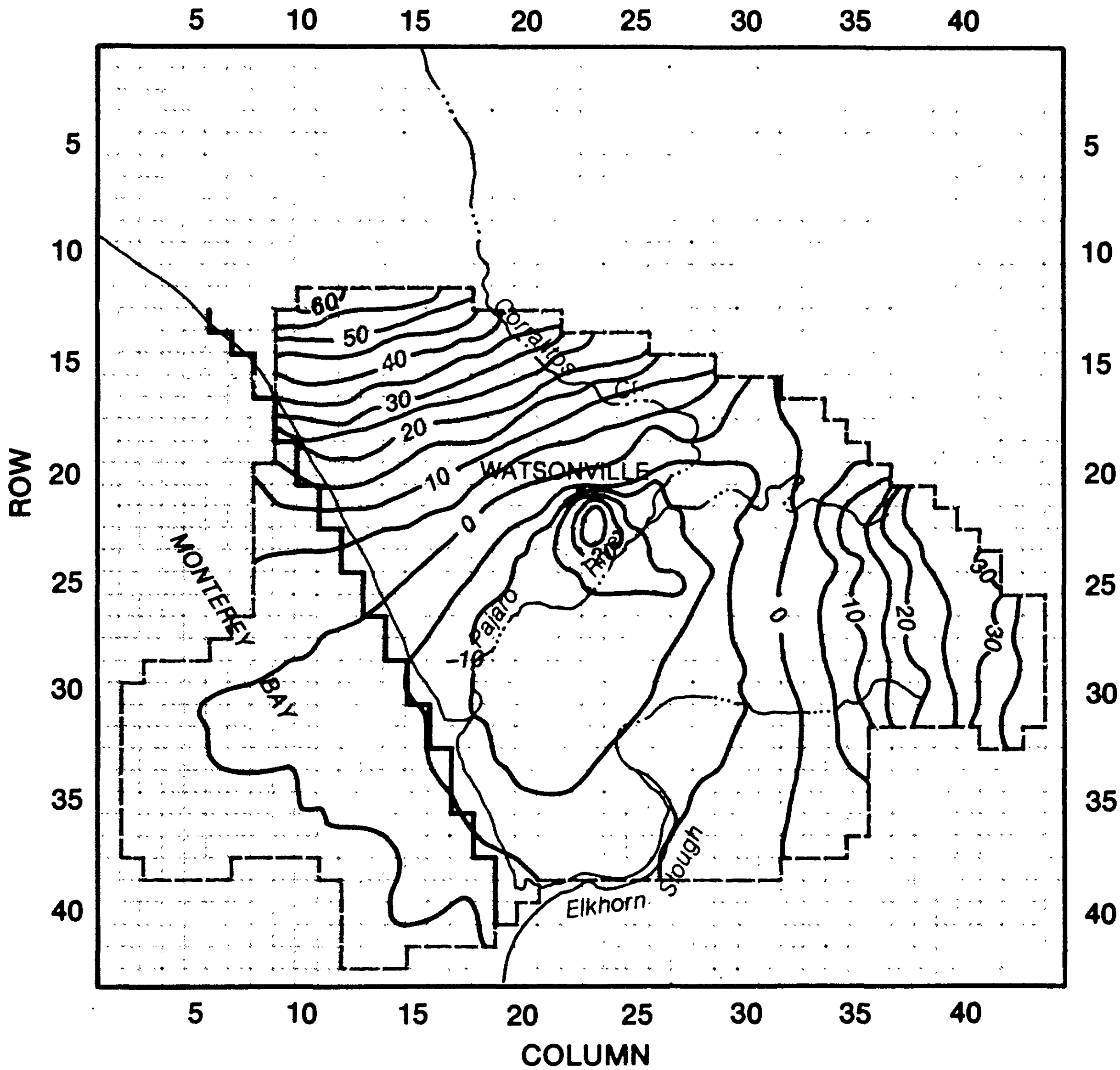
EXPLANATION

—*10*— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells, spring 1981 Contour interval 5 feet. Datum is sea level

– – – – BOUNDARY OF MODEL LAYER 2

———— COASTLINE

FIGURE 26. – Simulated potentiometric surface, model layer 2, for spring 1981.



0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

—*10*— POTENTIOMETRIC CONTOUR – Shows altitude at which water level would have stood in tightly cased wells, autumn 1981 Contour interval 5 feet. Datum is sea level

– – – – BOUNDARY OF MODEL LAYER 2

——— COASTLINE

FIGURE 27. – Simulated potentiometric surface, model layer 2, for autumn 1981.

Table 4.--Water budgets for the 11-year model simulation period from autumn 1970 through autumn 1981, the winter-spring period of 1981, and the summer-autumn period of 1981

[Some percent totals do not equal 100 because of rounding of the data]

	Autumn 1970 through autumn 1981		Winter-spring 1981		Summer-autumn 1981	
	Acre-feet	Per-cent	Acre-feet	Per-cent	Acre-feet	Per-cent
Inflow recharge	566,000	78	34,300	83	20,100	72
Constant-flux boundaries	141,600	19	6,600	16	6,300	23
Constant-head boundaries	18,200	3	400	1	1,400	5
Total-In..........	726,200		41,300		27,800	
Outflow pumpage	689,100	92	15,300	84	46,800	96
Drains	27,400	4	1,300	7	600	1
Constant-head boundaries	32,000	4	1,700	9	1,200	2
Total-Out.........	749,100		18,300		48,600	
Change in storage	-22,900		+23,000		-20,800	

Table 5.--Model simulated annual net change in volume of water in storage, 1971 through 1981

[Values in thousands of acre-feet; the total of these annual net changes does not equal the total shown in table 4 because of rounding of data]

	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981
Net change in storage	-7	-13	10	15	-5	-21	-22	10	1	7	2

No attempt was made to calibrate measured water levels in layer 1. This layer represents several discontinuous water-bearing zones which cannot be accurately simulated with the available data or with a model of this type. The model treats this layer as one homogeneous aquifer and computes a composite water level for each node. The computed water levels were, however, compared to land-surface elevations to ensure that all water levels were below land surface and within reason.

The model was not calibrated to reproduce steady-state conditions because of the very limited data available before significant development took place in the valley. However, after the transient calibration was completed, a model run was made in which pumpage and recharge from irrigation return were removed from the model and the potentiometric heads were allowed to decay from the spring 1971 heads to a steady-state condition. The water levels at the end of this run, when compared to land surface, appeared to be reasonable. The computed heads in the confined parts of layer 2, west of Watsonville, compared favorably with early reported heads in some of the older wells in the area.

Model Sensitivity

By varying one parameter and holding all others constant, it is possible to observe the relative sensitivity of the model to the various input properties. Separate model simulations are made with varied individual properties for a wide range of values. The effects of each change in a parameter is determined by computing the standard error of estimate after each model run.

Plots of the standard error of estimate versus the factor of change of the parameter for each of the input properties are shown in figure 28. When the factor of change is 1.0, the parameter is unchanged from the final calibration value. In model layer 2, separate analyses were done for the sensitivities of the model for storage and leakage properties for the confined and unconfined areas.

These sensitivity analyses indicate that the model is most sensitive to pumpage, recharge, leakance of the upper confining layer, transmissivity in layer 2, and storage in the unconfined parts of the model. Small errors in estimating these properties can have a significant effect on the computed heads, while other properties can be varied over several orders of magnitude without significantly affecting the standard error. These analyses also indicate that the standard error might be reduced slightly by further calibration of the model. However, this was not attempted because it was thought that the slight improvement that might be obtained did not warrant the additional time and effort that would be required.

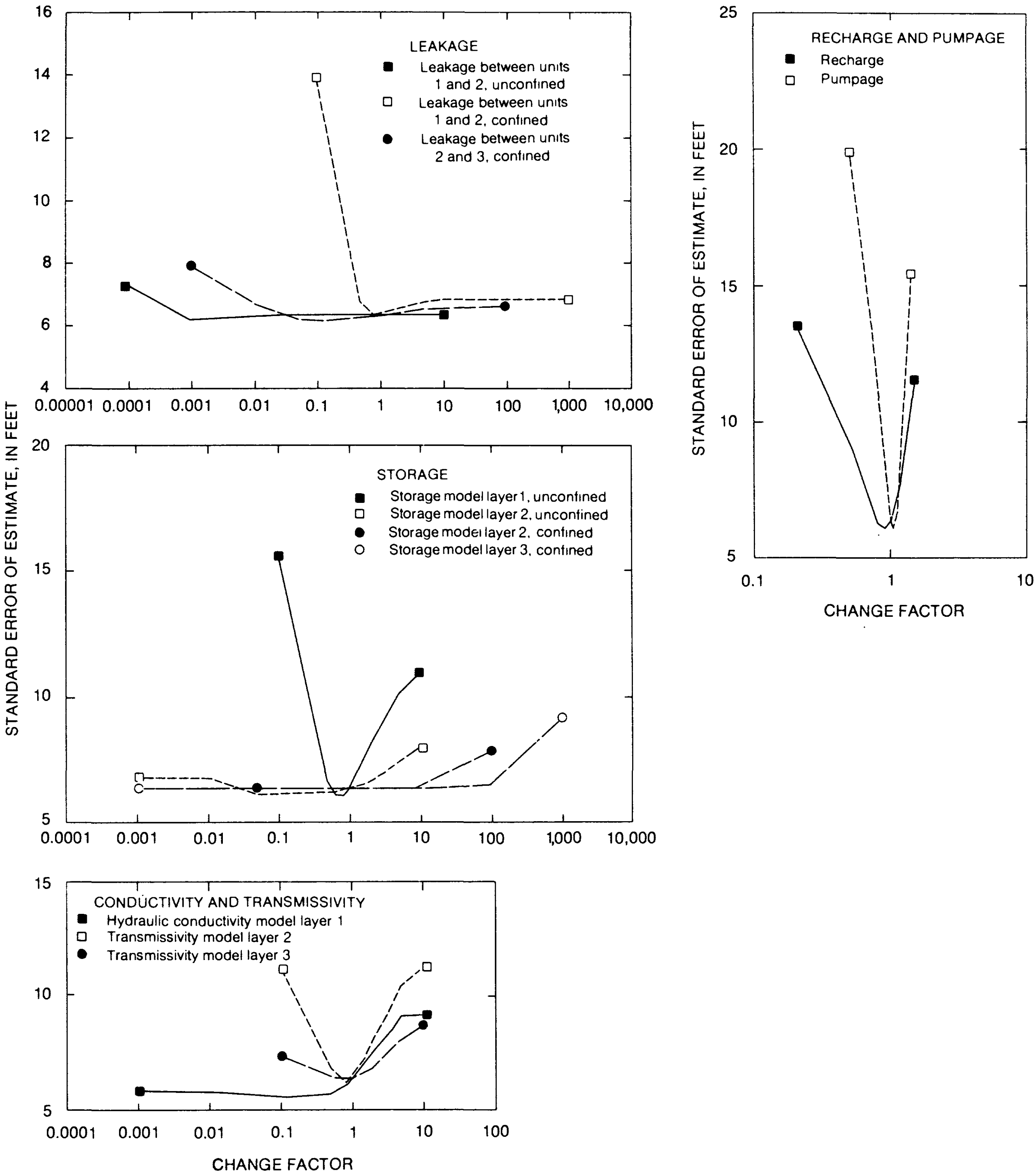


FIGURE 28. — Model sensitivity to changes in aquifer properties, recharge, and pumpage.

Limitations of the Model

Within specified limits, a mathematical model can be useful for evaluating aquifer responses to various changes in aquifer stresses. However, a model is only a simplified approximation of the actual system based on average and estimated conditions. The accuracy with which a model can evaluate aquifer responses is directly related to the accuracy and adequacy of the input data.

This model has been calibrated to simulate both semiannual fluctuations and long-term trends of potentiometric heads in specific areas of model layers 2 and 3 where historic water-level data are available (table 3, figs. 9 and 10). Within these areas the model can be useful for evaluating the effects of proposed changes in aquifer stresses. To test for the effects of a specific water-management plan, good estimates of the quantity and distribution of inflow and outflow associated with the plan must be calculated and input to the model. For other areas within layers 2 and 3 and when making simulation runs longer than the calibration period or when testing proposed aquifer stresses that do not fall within the range of those encountered during the calibration process, the results of the simulation should be considered as only representing general trends. The model was not calibrated in layer 1; therefore, this part of the model should not be used for any evaluation purposes.

Owing to the mathematical approximations associated with simulating boundary flow, the impact of change in stresses may not be accurately simulated near the model boundaries. Also, because of the large size of the model's grid elements, the localized impact of small change in aquifer stresses cannot be accurately simulated.

This model does not simulate seawater intrusion into the aquifer system. It has no provisions for calculating the movement of the freshwater-seawater interface and the resultant displacement of one fluid with another. It can, at best, be used only to indicate areas where there is potential for seawater intrusion to occur. A model and report on the origin and mechanisms of seawater intrusion in the Pajaro Valley area is described in greater detail by Bond and Bredehoeft (1987).

Improving the Model

Water-Level Measurements

When modeling annual changes in potentiometric heads, the computed heads ideally should be calibrated to real heads that were measured at consistent points in the annual cycle. These points are the end of the winter recharge period (winter high), and the end of the summer discharge period (summer low). Generally, these are the most stable reference points for comparing the effects of each year's changes in the water budget. Conditions of climate and water use in the Pajaro Valley can make these events difficult to predict for monitoring purposes. The variable climate in the study area can cause the winter high to occur at different times in different years. Similarly, periods of heaviest pumpage occur at different times each year, causing the summer low to shift in time from year to year. Also, daily fluctuations in water levels as much as 6 feet have occurred when irrigation pumps were turned on and off daily. These daily fluctuations further mask long-term trends in the annual cycle.

The installation and maintenance of several continuous water-level recorders for a number of years would: (1) define the amplitude of daily water-level fluctuations due to water-use practices; (2) define the magnitude and time of the winter high and summer low in the annual cycle; and (3) allow comparison of annual highs and lows for several years to identify long-term trends in the water budget. With this information, investigators would be able to determine at what point in the annual and daily cycles the water levels in other wells were measured, and also whether changes in water levels are caused by long-term changes in the water budget, or are simply the effect of the timing of the measurement relative to climate and water use. Initially, two recording wells could be drilled and constructed. One well could be located in Santa Cruz County, northeast of the city of Watsonville where potentiometric heads are near sea level, and the other well could be located in Monterey County between the city of Watsonville and the coast but inland from the potentially intruded zone of higher chloride concentration. Consideration should also be given to monitoring different depth intervals and setting these observation wells at a reasonable distance from existing or future pumping wells.

Better calibration of the mathematical model of the Pajaro Valley aquifer system would require additional water-level data from fewer than 20 wells. These wells would adequately define the aquifer being modeled if they were properly distributed and indeed representative of the aquifer. Each of these wells or their replacements need to be located and monitored for a continuous period of years, with at least an annual sampling interval during the winter high, and with all wells monitored within the shortest time interval during a given well round. Ideally, these wells would be monitored a number of times (for example, at three different times) during the week to identify and remove background fluctuations owing to short-term stress, and referenced to a few select continuous recording wells (mentioned previously) to define when in the annual cycle they were actually monitored.

Pumpage Estimates

Improving the quality of ground-water-pumpage estimates would help to further refine the model calibration in future years. For modeling purposes, it is crucial to know the volume of ground water pumped, when it is pumped, and its areal and vertical distribution within the different model layers.

Agricultural pumpage is estimated to be 80 percent of the total pumpage in the Pajaro Valley. Therefore, continued and improved knowledge of changing agricultural practices is important for accurate pumpage estimates. As discussed in the section on outflow, the land-use method of estimating agricultural pumpage volume and timing is improving through increased knowledge of field conditions. In comparison, the use of power-account records for estimating pumpage is becoming a more complex problem that requires defining and removing increasing amounts of nonpumping energy use.

Neither method identifies vertically (and to a lesser extent areally) where water is removed without extensive field location of wells correlated with well-log information. In this model, power-account coordinates identified field locations, but, for the most part, individual wells were not uniquely identified to individual logs. Irrigation pumpage was distributed vertically, on the basis of available well-log information indicating general pumpage depth zones in different areas of the model. For the model to accurately simulate relative head differences vertically between layers, it would be necessary to define individual pumping zones and their contributions to the total pumpage for at least each of the major irrigation wells in the area.

SUMMARY

The Pajaro Valley is the largest farming area in Santa Cruz County and is dependent on the development of a reliable ground-water supply to meet most of its water needs. The ground-water resources of the area are limited, however, an increasing demand has already resulted in lowered water levels and seawater intrusion near Monterey Bay. The U.S. Geological Survey entered into a cooperative agreement with the Santa Cruz County Flood and Water Conservation District to investigate the water resources of the Pajaro Valley. The purposes of this study were to describe the basic geology and hydrology of the ground-water system in the Pajaro Valley area and to develop a better understanding of the system in response to pumping stresses. A mathematical model of the ground-water flow system was used to aid in the understanding of the system.

The Pajaro Valley is located in southern Santa Cruz and northern Monterey Counties, along Monterey Bay, and consists of about 160 square miles of alluvial bottom lands, terraces, and foothills. The study area is that part of the valley lying below an altitude of 600 feet and is about 10 miles long and 8 miles wide.

The Pajaro Valley is an erosional and structural depression surrounded by areas of uplift and folding. The geometry of the depression is controlled by differential movement along the San Andreas, Zayante-Vergeles, and other less prominent fault zones. The area is underlain by a Cretaceous basement complex. Overlying the basement complex are consolidated sequences of poorly permeable, sedimentary deposits of Eocene to Miocene age. Overlying these consolidated, poorly permeable deposits and filling the basin are a series of westward-dipping and thickening sedimentary rocks of late Tertiary and Quaternary age. These rocks include the Purisima Formation, the Aromas Sand, and the overlying terrace deposits, alluvium, dune deposits, and younger marine sediments. An entrenched valley cut by the ancestral Pajaro River through terrace deposits and into the Aromas Sand has been filled by alluvium and forms the present valley floor.

The significant geologic units used in the evaluation of the ground-water flow system of the Pajaro Valley are part of the Quaternary deposits and consist principally of the Aromas Sand, terrace deposits, alluvium, and dune sand. They extend westward from the San Andreas rift zone to some point offshore beneath Monterey Bay and are bounded on the north, east, and southeast by outcrops of the Purisima Formation and older consolidated rocks. The Aromas Sand, terrace deposits, and alluvium each contain lenticular beds of coarse gravels and sands that grade upward into lagoonal silts and clays. The Aromas Sand has a total thickness of more that 800 feet at the mouth of the Pajaro River and consists of a heterogeneous sequence of mainly eolian and fluvial sand, silt, clay, and gravel.

The Aromas Sand is divided into older fluvial deposits and younger eolian deposits. The fluvial deposits are partly consolidated, moderately to poorly sorted, lenticular beds of silty clay, sand, and gravel. Numerous clay and silty clay beds and soils separate the sands and relatively well-sorted gravel beds that range from 10 to 100 feet in thickness. Near the coast, thick marine clays separate upper sequences of fluvial deposits from lowered sequences of fluvial deposits. The eolian deposits are moderately well sorted and contain no intervening fluvial deposits to a depth of 200 feet. These eolian deposits, however, do contain several depositional sequences, generally 20 to 60 feet thick, separated by highly weathered soil zones.

The terrace deposits consist of moderately to poorly sorted silt, sand, silty clay, and gravel. These deposits are at least 120 feet thick, and may be as much as 230 feet thick in the vicinity of Watsonville. The terrace deposits grade upward from basal gravels into finer grained deposits.

The alluvium in the study area is a highly variable mixture of unconsolidated gravel, silt, and sand that contain lenses of clay and silty clay. At the base of the sequence is a continuous gravel bed which has an average thickness of about 50 feet and is in direct contact with the underlying Aromas Sand. Overlying the basal gravel bed throughout much of the region is an extensive zone of numerous, intercalated clay beds. Above the clay beds, the upper alluvium is a heterogeneous mixture of mostly fine-grained material.

The presently developed aquifer system in the Pajaro Valley consists of three aquifers separated by two confining layers of finer grained, less permeable material. The lower aquifer is in the older fluvial part of the Aromas Sand. The most heavily developed aquifer in the system is the middle aquifer, which consists of the basal gravel bed in the alluvium and terrace deposits, and the lower eolian and upper fluvial parts of the Aromas Sand. The upper aquifer actually consists of a number of discontinuous water-bearing zones. These zones are found locally in the upper eolian sequences of Aromas Sand, upper terrace deposits, upper alluvium, and dune deposits. The lower confining layer consists of beds of clay and silty clay in the fluvial sequences of Aromas Sand. The upper confining layer is a discontinuous composite of the clay beds above the basal gravel bed in the alluvium and terrace deposits, and the weathered soil zones in the upper eolian sequences of Aromas Sand.

Pre-Quaternary rocks are not important as aquifers in the Pajaro Valley area. The Purisima Formation, which underlies the Quaternary deposits and is a principal source of ground water in other adjacent areas, has not been developed in the study area. The few wells completed in these deposits have substantially lower water levels and greater drawdowns than are reported for wells completed in the overlying Quaternary deposits.

Direct percolation of rainfall, irrigation return, and infiltration of surface water through the beds and banks of channels are the principal sources of recharge to the aquifer system. This recharge generally occurs in those areas beyond the extent of the upper confining clay layer. In the area underlain by this clay layer, the upper aquifer is partly saturated and the potential recharge flows to the Pajaro River. Vertical movement of ground water between the aquifer system and the underlying material is restricted by numerous siltstone and mudstone beds within the Purisima Formation. There is some lateral movement of ground water, however, from the older rocks into the aquifer system around the margins of the valley.

Ground-water movement within the Pajaro Valley aquifer system is away from source areas of ground-water recharge toward the central axis of the valley and then generally from east to west down the valley to the ocean. In some of the coastal parts of the aquifer system, the movement is from the ocean eastward toward local pumping depressions. The most extensive inland intrusion of seawater has occurred in the middle aquifer.

A simplified representation of the Pajaro Valley aquifer system was conceptualized in order to simulate the system using mathematical techniques. For modeling purposes the system is divided into three model layers representing the three aquifers. The three model layers are separated by two confining units. The uppermost layer is considered to be an unconfined aquifer, the middle layer is either confined or unconfined, and the lower layer is considered to be entirely confined.

Inflows to the ground-water system result from precipitation, irrigation return, stream leakage, and underflow across model boundaries. Irrigation return was estimated to be 20 percent of total agricultural pumpage. Estimates of stream leakage were taken from previously published values.

Outflows from the ground-water system consist of pumpage, near-surface losses to streams and evapotranspiration, and underflow across model boundaries. Agricultural pumpage was determined from power consumption records, municipal and industrial pumpage was reported by the users, and other pumpage was calculated on the basis of a per capita water demand. Ground-water loss to streams and evapotranspiration was simulated in the model using a drain-well function.

The model was calibrated in the lower and middle layers for transient conditions that occurred from spring 1970 to autumn 1981 because of the availability of pumpage and water-level data. The model was calibrated to reproduce, with acceptable accuracy, 366 spring and autumn water levels measured at 39 selected wells completed in the middle and lower aquifers. Both the initial aquifer characteristics and inflows and outflows were adjusted during calibration. The model was not calibrated to reproduce measured water levels in model layer 1 because of sparse data and the discontinuous characteristics of that upper aquifer. Predevelopment conditions were not modeled for that period because of sparse data. Hydrographs and water budgets generated with the final calibrated input data reasonably reflect known conditions. Hydrographs show a close correlation between measured water levels in selected wells that have long-term records in the middle and lower aquifers, and computed heads at corresponding nodes in model layer 2 and 3 for both annual fluctuations and long-term trends. The standard error of estimate between measured and computed heads at the end of the calibration was 6.1 feet.

For the 11-year simulation period from the autumn of 1970 to the autumn of 1981, the volume of water stored in the system decreased by about 23,000 acre-feet. The model-generated budgets for the simulation period indicated that most of this loss occurred during the 1976-77 drought. From the end of the drought through 1981, the budgets indicate that the net volume of water in storage was increasing annually.

Model-generated water budgets for the 1981 winter-spring and summer-autumn simulation periods indicate that for the winter-spring period 83 percent of the inflow to the system was from areal recharge, 16 percent from flow across constant-flux boundaries, and 1 percent from flow across constant-head boundaries. Outflow for this period was 84 percent to pumpage, 9 percent across constant-head boundaries, and 7 percent to the drain-wells. For the summer-autumn period inflow was 72 percent from areal recharge, 23 percent across constant flux-boundaries, and 5 percent across constant-head boundaries. Outflow for this period was 96 percent to pumpage, 2 percent to constant-head boundaries and 1 percent to the drain wells. For these two simulation periods there was a net gain of 2,200 acre-feet of water in storage.

Within layers 2 and 3, where historical water-level data are available, the model can be useful for evaluating the effects of proposed changes in aquifer stresses, but certain limitations exist. When model simulations are longer than the period to which the model was calibrated, or when testing stresses outside the range of those encountered during the calibration process, results should be considered as only representing general trends. Owing to the design of the model, the effect of aquifer stress changes near model boundaries and the localized effect of small stress changes cannot be accurately simulated. The model was not designed to simulate the movement of the freshwater-saltwater interface. At best, the model can only indicate where there is potential for seawater intrusion.

Analyses of the model's sensitivity to the various input properties indicate that it is most sensitive to pumpage and areal recharge. Of the aquifer characteristics, the model is most sensitive to storage in model layer 1, transmissivity in model layer 2, and leakage between model layers 1 and 2.

The reliability of model evaluations can be increased with improved definition of potentiometric heads to which the model is calibrated, and improved pumpage estimates. One or several continuous water-level recording wells would improve the value of monitoring wells by (1) defining the amplitude of daily water-level fluctuations (2) defining magnitude and time of the winter high and summer low in the annual cycle, and (3) allowing comparisons of annual highs and lows for several years to identify long-term trends in the water budget. Improved estimates of pumpage, particularly agricultural pumpage, and improved definition vertically and areally of pumpage distribution also would increase the reliability of model evaluations.

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