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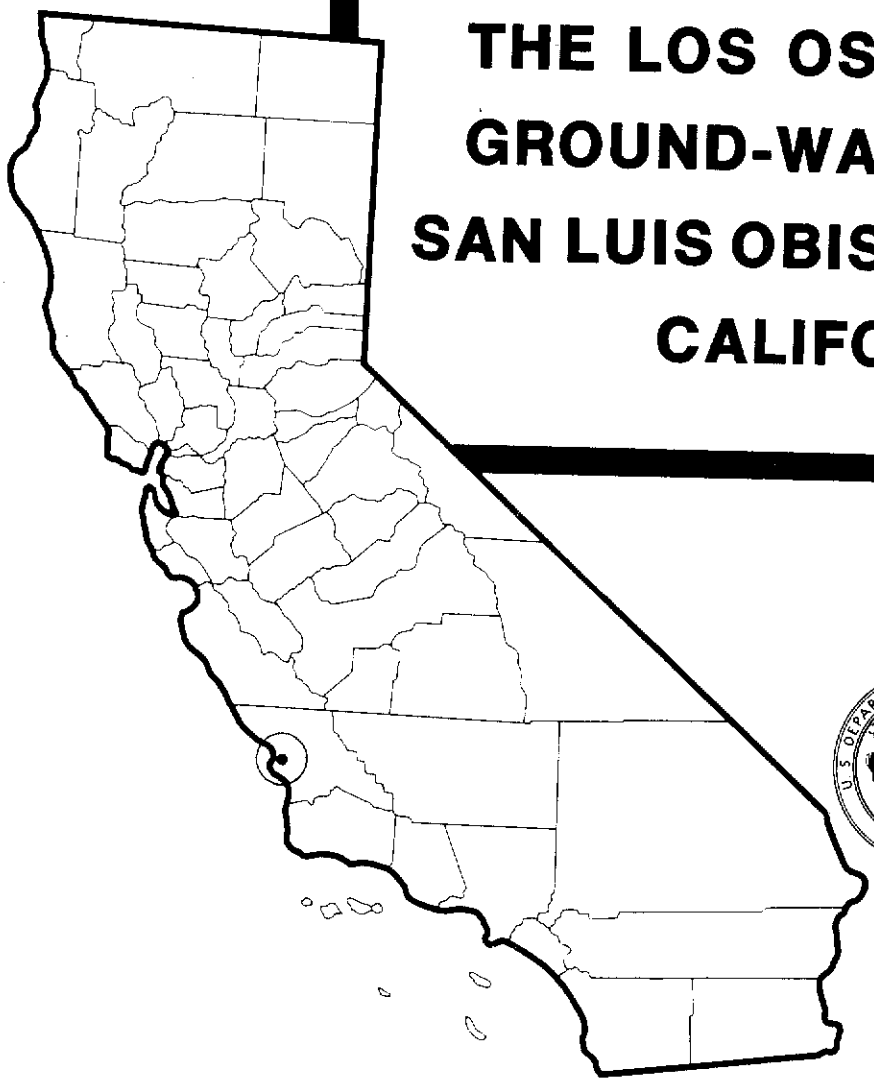
HYDROGEOLOGY AND WATER RESOURCES OF THE LOS OSOS VALLEY GROUND-WATER BASIN SAN LUIS OBISPO COUNTY CALIFORNIA



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 88-4081

Prepared in cooperation with the
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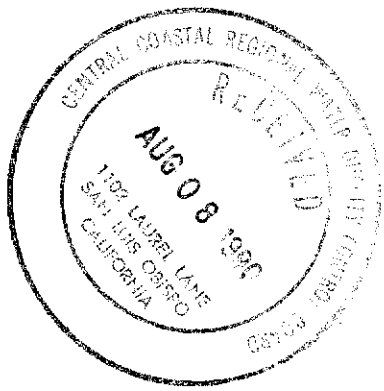

HYDROGEOLOGY AND WATER RESOURCES OF THE LOS OSOS VALLEY GROUND-WATER BASIN, SAN LUIS OBISPO COUNTY, CALIFORNIA

By *Eugene B. Yates* and *John H. Wiese*

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Water-Resources Investigations Report 88-4081

Prepared in cooperation with the
SAN LUIS OBISPO COUNTY FLOOD CONTROL AND
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4023-08

Sacramento, California
1988

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For readers who prefer to use metric and International System (SI) units rather than inch-pound units, the conversion factors for the terms used in this report are as follows:

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per annum
cubic foot per day (ft^3/d)	0.2832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	0.3048	meter per meter
gallon per minute (gal/min)	0.06308	liter per second
inch	25.4	millimeter
inch per foot (in/ft)	0.0833	meter per meter
inch per month (in/mo)	25.4	millimeter per month
inch per year (in/yr)	25.4	millimeter per annum
mile	1.609	kilometer
square mile (mi^2)	2.59	square kilometer

Degree Fahrenheit (^{o}F) is converted to degree Celsius (^{o}C) by using the formula:

$$\text{Temp } ^{o}C = (\text{temp } ^{o}F - 32)/1.8$$

DEFINITION OF TERMS

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.

Water year: A water year is a 12-month period, October 1 through September 30, designated by the calendar year in which it ends. In this report, years are water years unless otherwise noted.

HYDROGEOLOGY AND WATER RESOURCES OF THE LOS OSOS VALLEY GROUND-WATER BASIN SAN LUIS OBISPO COUNTY, CALIFORNIA

By *Eugene B. Yates* and *John H. Wiese* [1]

ABSTRACT

The Los Osos Valley ground-water basin is located on the coast of central California. It extends about 3 miles inland and an unknown distance offshore, where it is in hydraulic connection with the Pacific Ocean. Its maximum onshore depth is about 1,000 feet. Ground-water flow in the basin was investigated using existing data, geologic mapping, drilling, and measurements of potentiometric head, water quality, and streamflow.

The basin is underlain largely by relatively impermeable rocks of the Franciscan Complex. Basin fill consists of unconsolidated, complexly layered sediments of Miocene age or younger. Individual beds are generally thin and discontinuous.

A three-dimensional digital model of the basin was developed and calibrated to match potentiometric heads and head-dependent flows during water years 1970-77 and 1986. The model simulated poorly the steep vertical potentiometric heads, and it could not simulate perched water tables. In other respects, model results were good and not highly sensitive to likely errors in input data.

Infiltrated rainfall contributes about 80 percent of annual recharge to the ground-water basin, and ground-water inflow accounts for almost all the remainder. Net recharge from Los Osos Creek is small. In water year 1986, outflow from the basin consisted of net municipal pumpage (24 percent), net agricultural pumpage (25 percent), net outflow across the ocean boundary (26 percent), perched-water runoff (16 percent), and phreatophyte transpiration (9 percent). During water years 1970-77 net municipal pumpage and net agricultural pumpage accounted for only 10 and 22 percent of total outflow, respectively.

The population of Los Osos Valley is expected to increase by about 20,000 people by the year 2010, and municipal water use is expected to increase by about 1,700 acre-feet per year. The model was used to simulate the effects of various future water-supply and wastewater-disposal alternatives on the ground-water system. Results indicated that if wastewater is centrally treated and recharged to the ground-water basin, the entire projected municipal water demand can be met with locally pumped ground water without inducing seawater intrusion, even during droughts lasting 1 to 3 years. If wastewater is exported from the basin, however, large amounts of seawater intrusion are likely to occur even if nearly half of the municipal water demand is met with imported water.

INTRODUCTION

Within a period of 15 years, Los Osos Valley (fig. 1) changed from a sparsely settled agricultural area to a heavily developed residential community. The population of the valley, which nearly quadrupled between 1970 and 1985, relies exclusively on local ground water to meet its water needs. Continued increases in ground-water withdrawals, the exclusive use of septic systems for wastewater disposal, and the proximity of the ocean threaten the ground-water basin with overdraft, nitrate contamination, and seawater intrusion. By 1983, nitrate concentrations in shallow ground water in most residential areas exceeded 45 mg/L (milligrams per liter), which is the maximum level allowed for public water supplies (Brown and Caldwell, Inc., 1983). Ground-water levels in the vicinity of several large municipal wells are frequently below sea level, and salinity has increased in some wells near the coast. Furthermore, if nitrate contamination is mitigated by collecting and exporting wastewater from the basin, total withdrawals of ground water might greatly exceed the rate of ground-water recharge and increase the likelihood of seawater intrusion. This complex management dilemma underscores the need to develop a comprehensive and accurate understanding of the ground-water basin and the geologic and climatic factors affecting the rates and directions of ground-water flow.

[1] *Consulting geologist registered with State of California.*

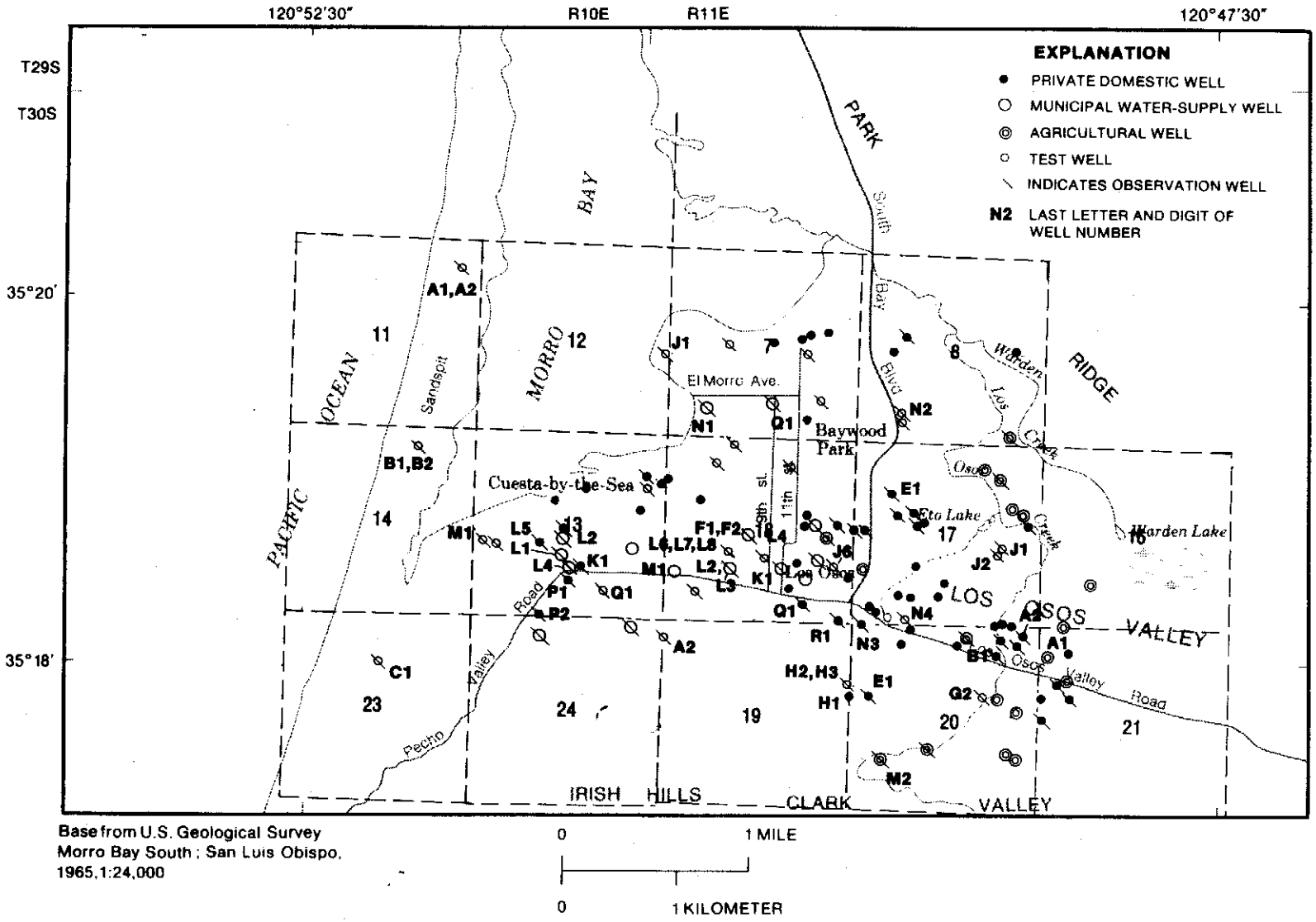


FIGURE 2.– Locations of private domestic, municipal, and agricultural wells used in this study.

subdivision. Forty-acre subdivisions are lettered in the following order:

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

GEOLOGY OF THE GROUND-WATER BASIN

REGIONAL GEOLOGY AND GEOLOGIC HISTORY

The Los Osos Valley ground-water basin is a small, shallow basin, about 8.6 mi^2 in area, occupying the central and western parts of Los Osos Valley. Seafloor acoustic reflection data and gravity data suggest that the valley may continue offshore another 5 miles with a width of at least 6 miles (Wagner, 1974; Burch and others, 1968). The basin is filled with permeable, unconsolidated sediments and underlain by relatively impermeable basement rocks. The surficial geology of the onshore ground-water basin and vicinity is shown in figure 3, which includes details and revisions not included on previous maps by Hall (1973) and Hall and others (1980).

The structure of the basin consists of an asymmetric downfold, the axis of which is parallel to and less than a mile from the southern edge of the basin. The northern limb of the syncline rises at 4 to 5 degrees over a basement of the Cretaceous and Jurassic Franciscan Complex. The northern boundary of the basin occurs at the foot of Park Ridge, which separates the basin from the valley of Chorro Creek. The southern limb rises at 20 to 25 degrees over Tertiary sediments and Franciscan basement rocks and terminates at the northern flank of the Irish Hills. The axis of the syncline plunges about 3 degrees to the west. A geologic section along the axis of the basin is shown in figure 4. Figures 5 and 6 show geologic sections perpendicular to the axis at two locations.

Thickness of the basin along its axis ranges from a few feet about 1 mile east of Los Osos Creek to about 1,000 feet near well 24A2. The principal municipal water wells are located near Los Osos Valley Road, between South Bay Boulevard and Pecho Valley Road. Altitude of the base of the ground-water basin is shown in figure 7. Because the data used to draw the contours were sparse and in some cases unreliable, the contours are approximate. The occurrence of Careaga Sandstone at depth in the ground-water basin was not recognized prior to this study. The exact thickness of the occurrence is unknown, except that it exceeds 450 feet in places. The approximate subsurface extent of the Careaga Sandstone in the ground-water basin is indicated on figure 7. In general, however, the basin shape and thickness shown in figure 7 are consistent with the results of an earlier gravity survey (Grannell, 1969).

Basin fill consists primarily of the Paso Robles Formation and the Careaga Sandstone. Smaller volumes are contributed by windblown sand deposits and Holocene alluvium. Basement rocks around the basin are largely Franciscan graywackes and metavolcanics, the Miguelito shale of the Pismo Formation, and dacite intrusives.

Geologic development of the Los Osos ground-water basin began in the Tertiary Period when faulting created separate blocks of Franciscan basement rock. Basement blocks in this part of the Coast Ranges have each had somewhat different geologic histories, and much of the geologic record has been lost to erosion. Beneath the basin may be a block that stood fairly high during much of Neogene time and that accumulated only a thin column of Tertiary sediments.

In the Los Osos area, Franciscan rocks were deformed, faulted, and eroded—possibly several times—before deposition of the Miguelito shale during the Miocene and Pliocene. The shale may have lapped onto only the south edge of the basin block. Deposition of the Careaga Sandstone, also during the Pliocene, followed a minor period of erosion of the shale. Faulting along the Los Osos fault (fig. 3) and the Edna fault zone 3 miles south of Los Osos Valley dropped the Tertiary rocks on the south side into a fault-bounded basin and allowed complete erosion of any northward continuation of the sediments. Similar tectonic activity resulted in formation of the San Luis Valley, which adjoins Los Osos Valley to the east.

The pre-Paso Robles rocks were eroded to a nearly flat topography, then downfolded along an axis nearly coincident with the westward projection of the Los Osos fault to form the Los Osos basin. During the Pliocene and Pleistocene, the basin was filled with sediments of the Paso Robles Formation. Dips of individual beds in

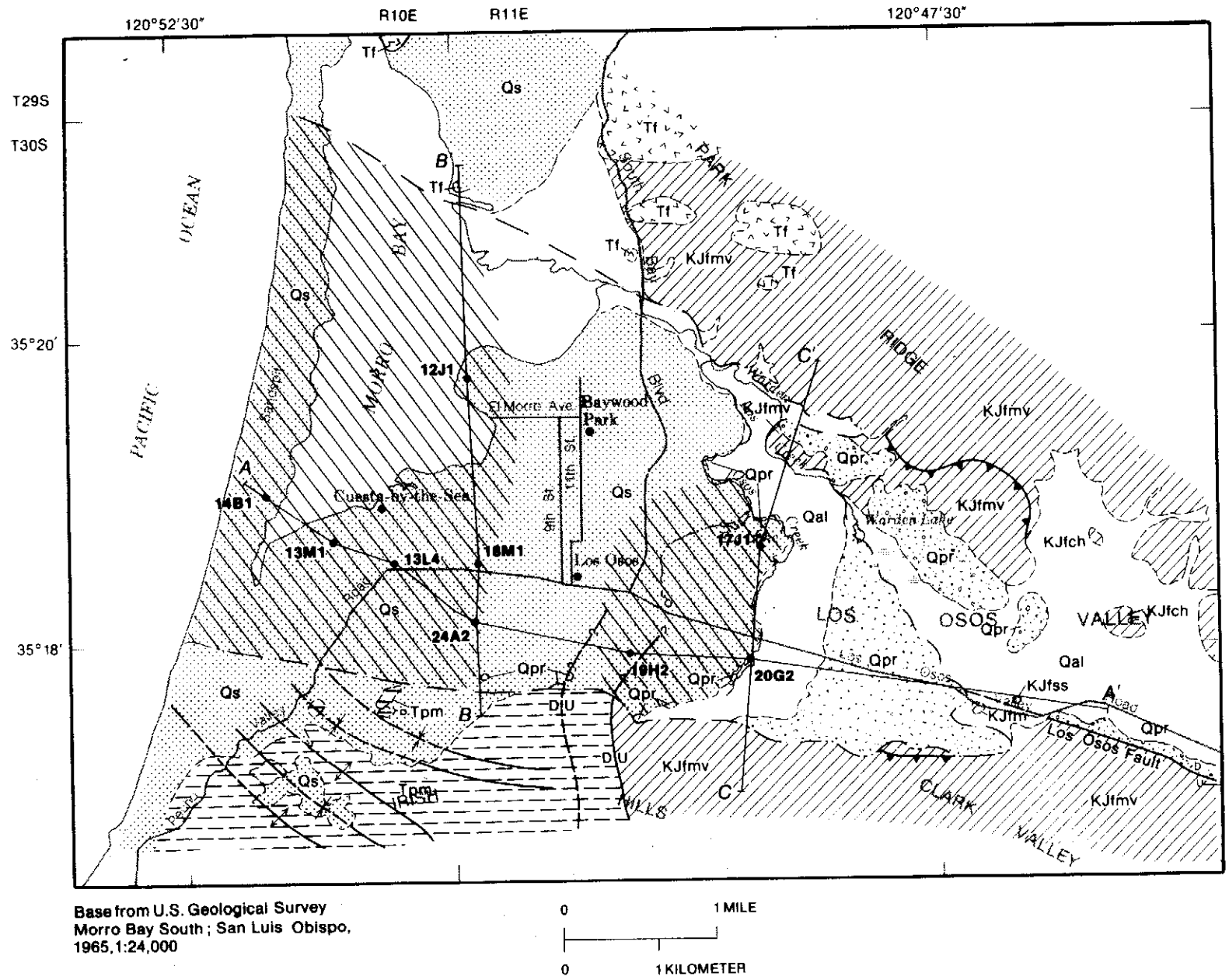


FIGURE 3.– Geology and structure of the onshore part of Los Osos Valley ground-water basin.

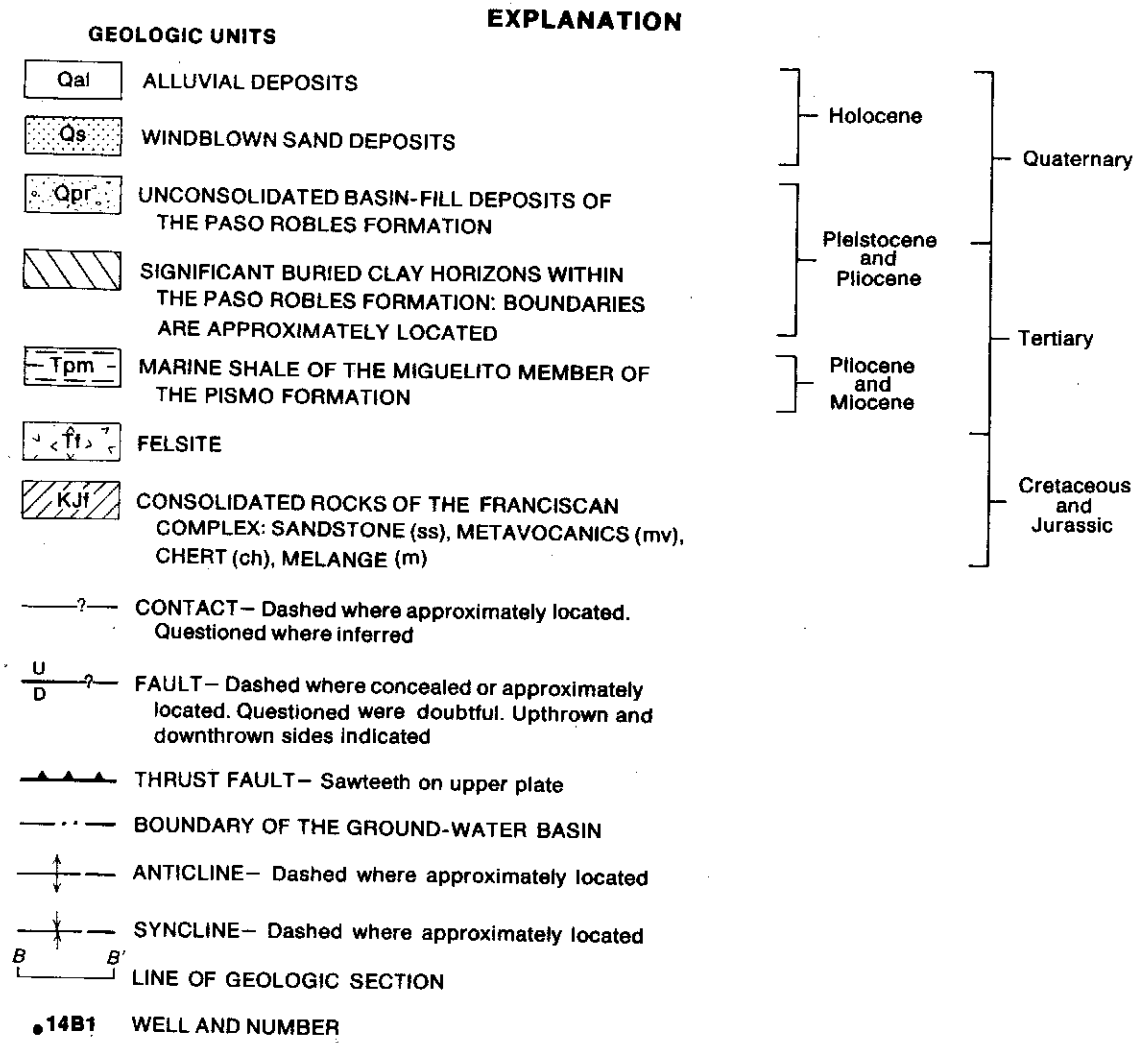
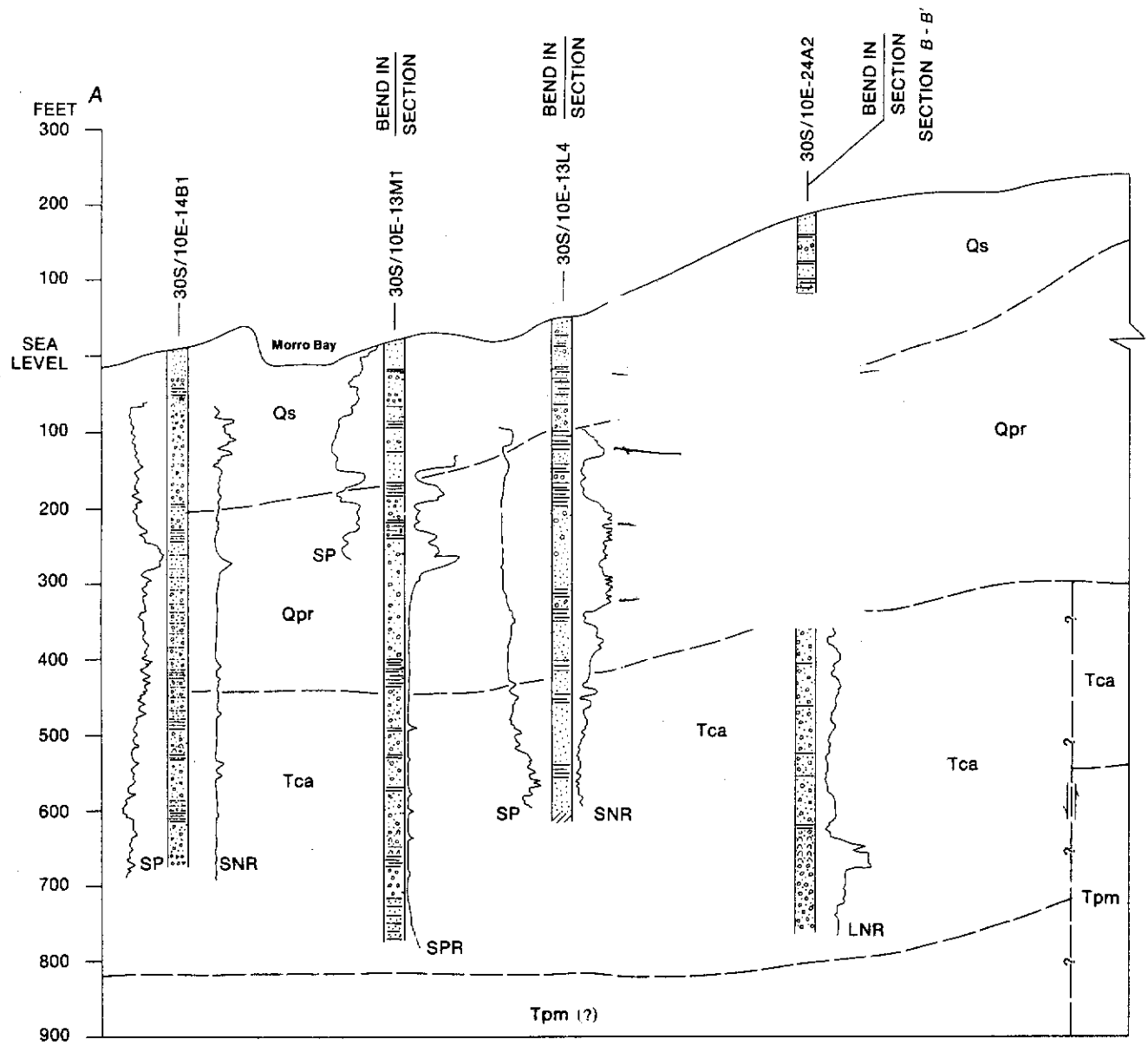


FIGURE 3.– Geology and structure of the onshore part of Los Osos Valley ground-water basin – Continued.



EXPLANATION

GEOLOGIC UNITS

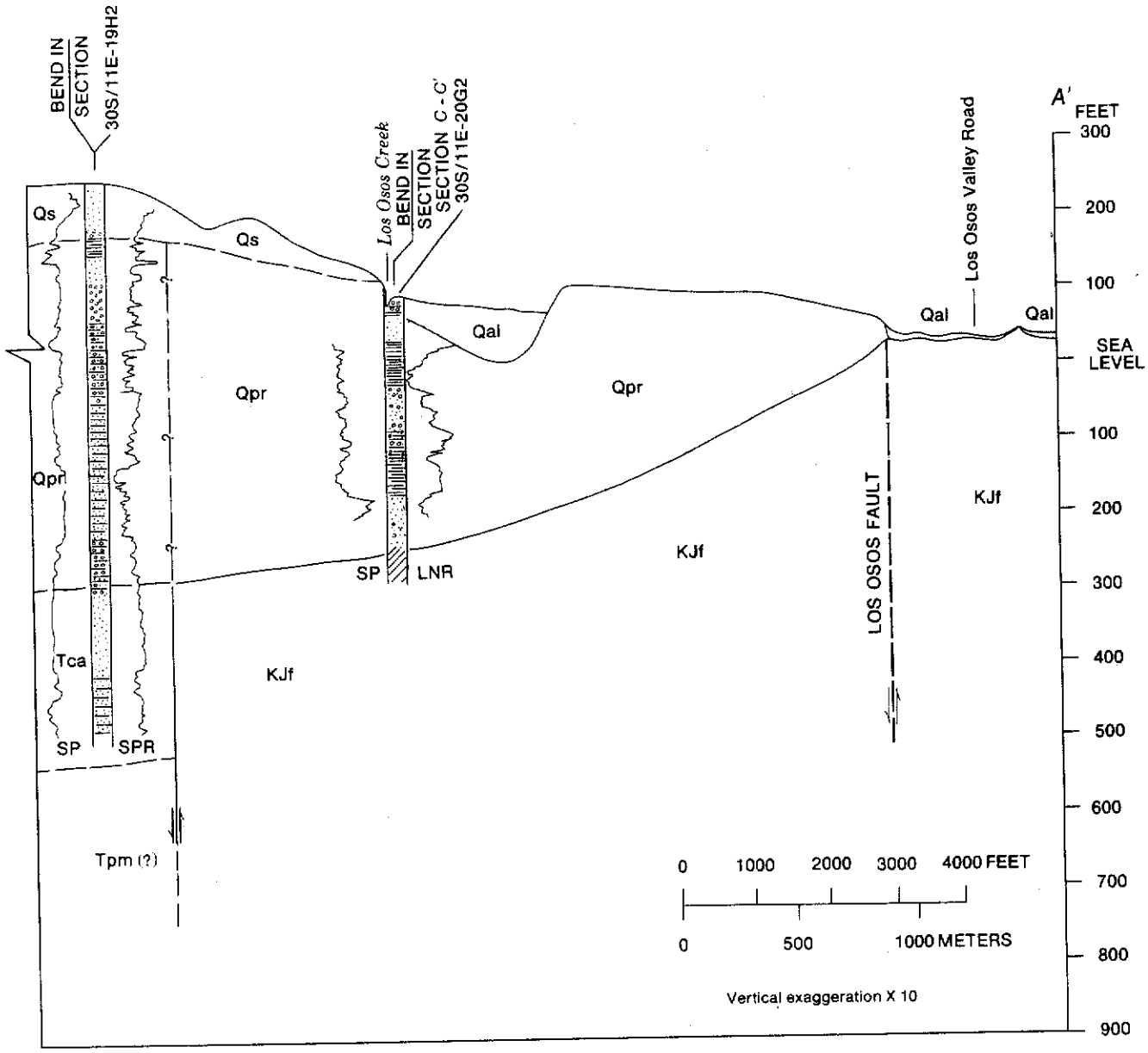
- Qal — ALLUVIAL DEPOSITS OF HOLOCENE AGE
- Qs — WINDBLOWN SAND DEPOSITS OF HOLOCENE AGE
- Qpr — UNCONSOLIDATED BASIN-FILL DEPOSITS OF THE PASO ROBLES FORMATION OF PLEISTOCENE AND PLIOCENE AGE
- Tca — UNCONSOLIDATED BASIN-FILL DEPOSITS OF THE CAREAGA SANDSTONE OF PLIOCENE AGE
- Tpm — MARINE SHALE OF THE MIGUELITO MEMBER OF THE PISMO FORMATION OF TERTIARY AGE
- KJf — CONSOLIDATED ROCKS OF THE FRANCISCAN COMPLEX (UNDIFFERENTIATED) OF CRETACEOUS AND JURASSIC AGE

—?— CONTACT– Dashed where approximately located. Questioned where inferred

—?— FAULT– Dashed where concealed or approximately located. Questioned were doubtful. Arrows indicate relative movement

30S/11E-19H2 — WELL BOREHOLE AND NUMBER-Electric log shown to left and (or) right of borehole

FIGURE 4.– Geologic section *A-A'* along the east-west axis of the ground-water basin.



EXPLANATION —Continued

BOREHOLE LITHOLOGY

- GRAVEL
- SAND
- SILT
- CLAY
- SHELLS
- BEDROCK

BOREHOLE ELECTRIC LOGS—
scales increase to the right

LNR	LONG-NORMAL RESISTIVITY
SNR	SHORT-NORMAL RESISTIVITY
SP	SPONTANEOUS POTENTIAL
SPR	SINGLE-POINT RESISTANCE

FIGURE 4.— Geologic section *A-A'* along the east-west axis of the ground-water basin —Continued.

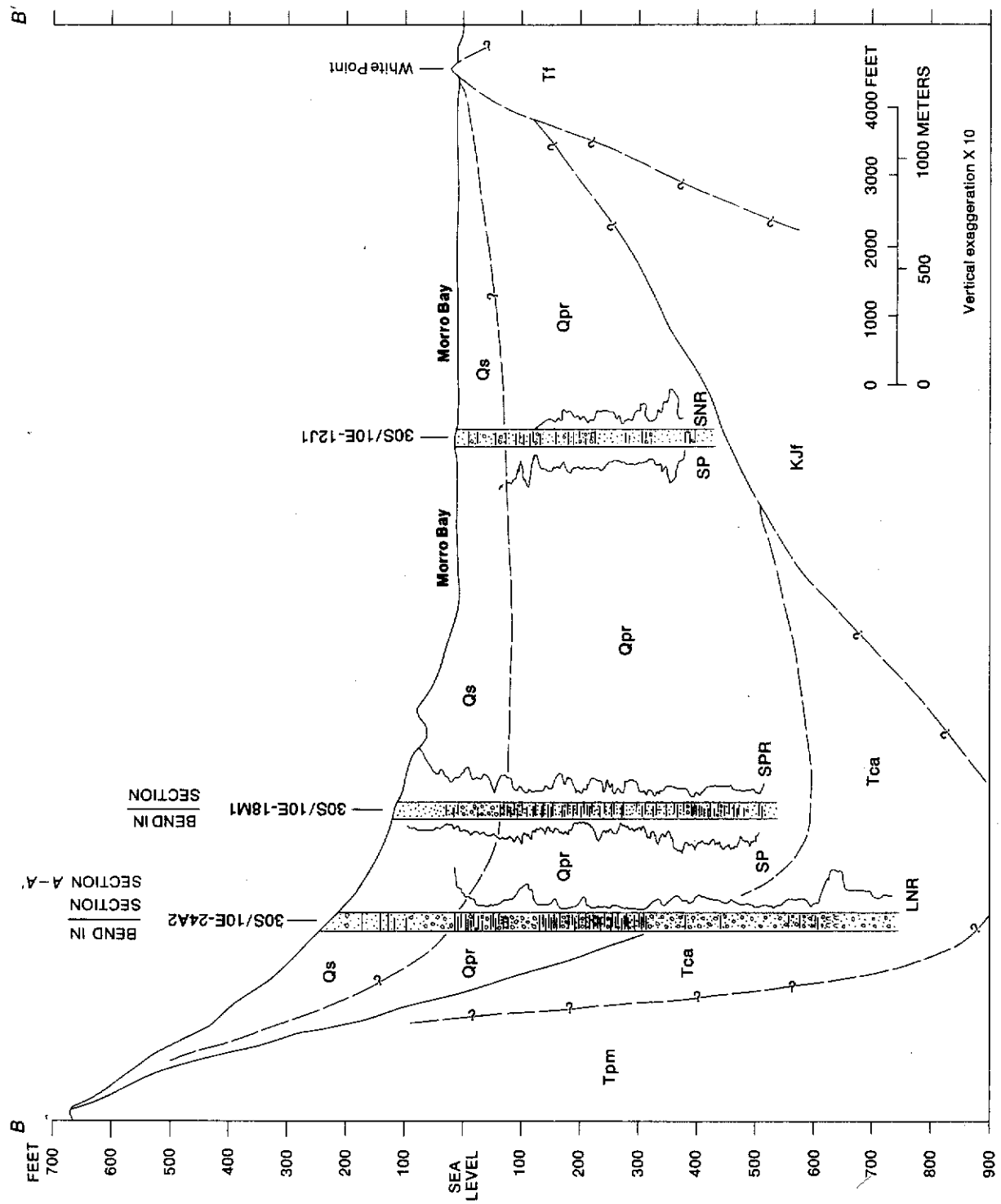


FIGURE 5.– Geologic section *B–B'* along a north-south line near the eastern shore of Morro Bay.

EXPLANATION

GEOLOGIC UNITS

Qs	WINDBLOWN SAND DEPOSITS OF HOLOCENE AGE
Qpr	UNCONSOLIDATED BASIN-FILL DEPOSITS OF THE PASO ROBLES FORMATION OF PLEISTOCENE AND PLIOCENE AGE
Tca	UNCONSOLIDATED BASIN-FILL DEPOSITS OF THE CAREAGA SANDSTONE OF PLIOCENE AGE
Tpm	MARINE SHALE OF THE MIGUELITO MEMBER OF THE PISMO FORMATION OF TERTIARY AGE
Tf	FELSITE
KJf	CONSOLIDATED ROCKS OF THE FRANCISCAN COMPLEX (UNDIFFERENTIATED) OF CRETACEOUS AND JURASSIC AGE

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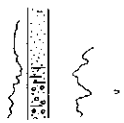


WELL BOREHOLE AND NUMBER- Electric log shown to left and (or) right of borehole

BOREHOLE LITHOLOGY

GRAVEL

SAND

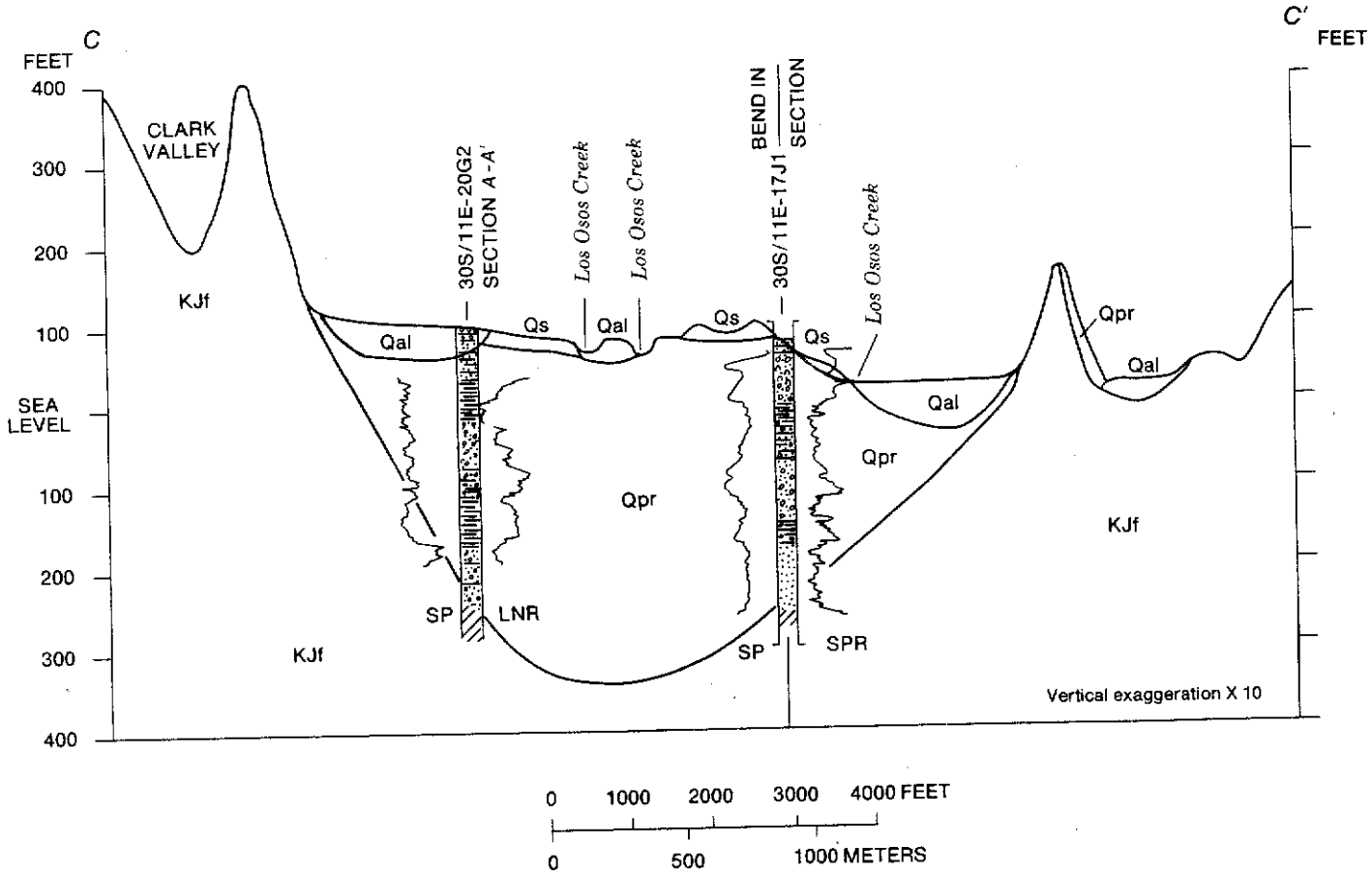
CLAY

SHELLS

BOREHOLE ELECTRIC LOGS — scales increase to the right

LNR	LONG-NORMAL RESISTIVITY
SNR	SHORT-NORMAL RESISTIVITY
SP	SPONTANEOUS POTENTIAL
SPR	SINGLE-POINT RESISTANCE

FIGURE 5.— Geologic section *B*–*B*′ along a north-south line near the eastern shore of Morro Bay –Continued.



EXPLANATION

GEOLOGIC UNITS

- Qal — ALLUVIAL DEPOSITS OF HOLOCENE AGE
- Qs — WINDBLOWN SAND DEPOSITS OF HOLOCENE AGE
- Qpr — UNCONSOLIDATED BASIN-FILL DEPOSITS OF THE PASO ROBLES FORMATION OF PLEISTOCENE AND PLIOCENE AGE
- KJf — CONSOLIDATED ROCKS OF THE FRANCISCAN COMPLEX (UNDIFFERENTIATED) OF CRETACEOUS AND JURASSIC AGE
- ——?—— CONTACT – Dashed where approximately located. Questioned where inferred
- 30S/11E-20G2 — **WELL BOREHOLE AND NUMBER**- Electric log shown to left and (or) right of borehole

BOREHOLE LITHOLOGY

- GRAVEL
- SAND
- CLAY
- SHELLS
- BEDROCK

BOREHOLE ELECTRIC LOGS -- scales increase to the right

- LNR — LONG-NORMAL RESISTIVITY
- SP — SPONTANEOUS POTENTIAL
- SPR — SINGLE-POINT RESISTANCE

FIGURE 6.– Geologic section *C*–*C'* along a north-south line near Los Osos Creek.

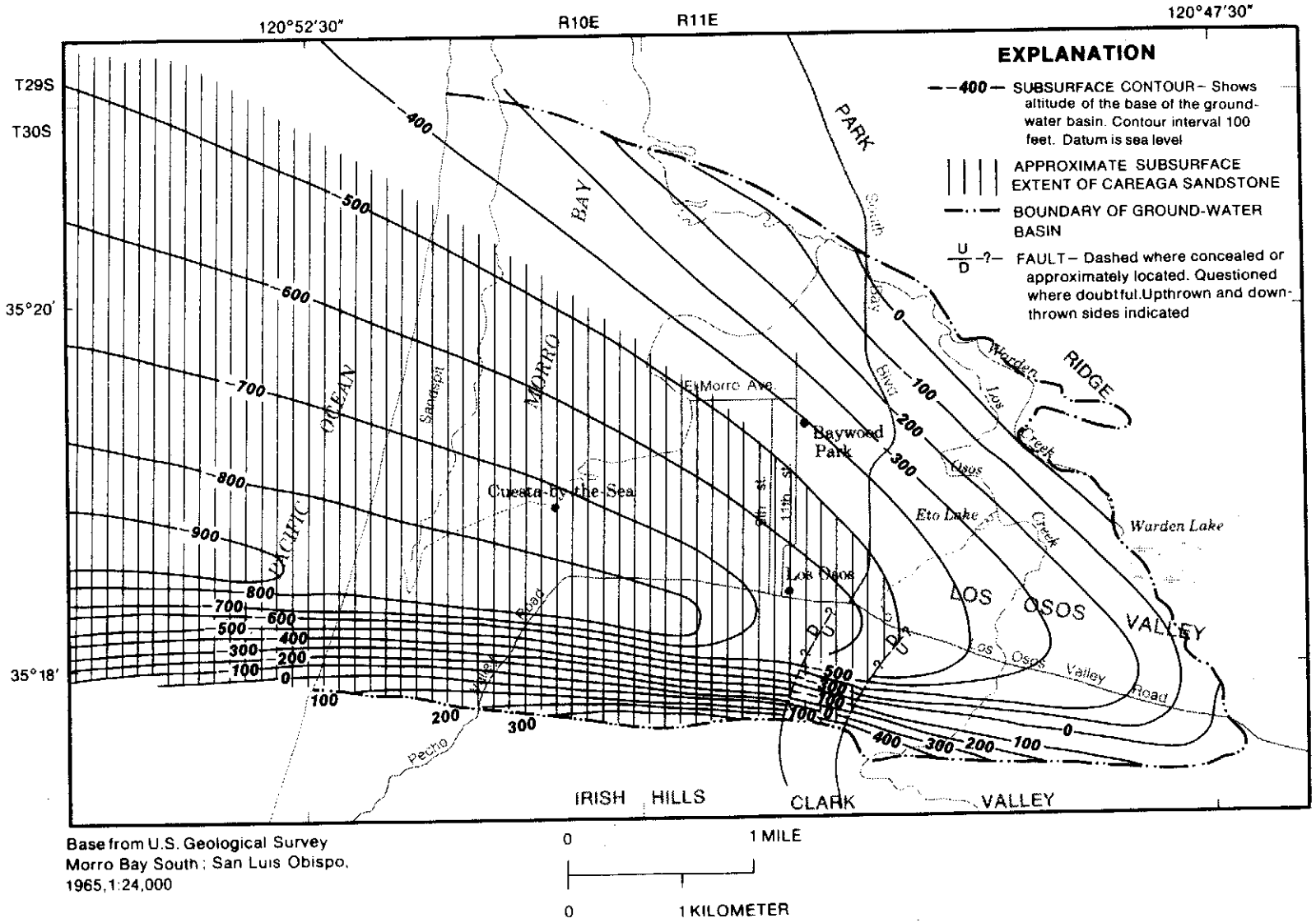


FIGURE 7.– Approximate altitude of the base of the ground-water basin and approximate subsurface extent of the Careaga Sandstone.

the Paso Robles Formation indicate that downfolding and deposition were concurrent. Coarser sediments seem to make up a larger fraction of the section near the center of the basin, possibly because of stream gravel deposition. Subsequent erosion during the late Pleistocene planed off these downwarped beds, leaving a topography that may have included gently rolling hills near the center of the basin and steep coastal bluffs along the former coastline. The low, dissected, flat-topped mesa of exposed Paso Robles Formation east of Los Osos Creek was formed during this period of erosion. Thin erosional remnants of the Paso Robles Formation occur locally along the flanks of the hills surrounding the basin.

Pleistocene erosion was followed by windblown spreading of sand dunes from the shore eastward to Los Osos Creek. Holocene erosion of the dunes has not progressed far enough to integrate completely the surface drainage on them; several undrained hollows remain.

The regional pattern of folds and faults trends northwestward in most parts of the Coast Ranges. In Los Osos basin, the trend of Los Osos fault is nearly east-west. The Edna fault zone south of Los Osos Valley also trends nearly east-west.

The Los Osos fault (fig. 3) is exposed along the eastern end of the southern edge of Los Osos Valley, where it appears to offset Paso Robles sediments by about 100 feet. The fault is not evident at the surface farther west in the valley, but a subsurface extension may exist. An extension of the fault could have caused the asymmetrical steepness of the southern limb of the basin syncline, and it could also explain the striking dissimilarity between the logs of well 30S/10E-23C1 and those of wells farther north along the sandspit (California Department of Water Resources, 1979, p. 30). Additional evidence of Holocene uplift to the south can be seen in wave-cut terraces in the Irish Hills. The terraces occur at elevations as high as 800 feet, which is higher than any previous interglacial stand of sea level. Vertical movement along the Los Osos fault could have been the mechanism for the uplift.

The western end of the Edna fault zone terminates in two parallel unnamed north-south faults, which extend northward into the basin west of the point where Los Osos Creek enters the valley (fig. 3). South of the basin, these unnamed faults have caused vertical offsets of at least 160 feet in Tertiary and older rocks. Within the basin, the bottom of the basin fill deposits at well 30S/11E-19H2 is anomalously low with respect to a trend projected westward from deep well 30S/11E -20G2 (fig. 4). The low base suggests that the easternmost fault extends into the basin and offsets the Careaga Sandstone and possibly the basal part of the Paso Robles Formation. Steep water-level gradients between well 19H2 and wells along Los Osos Creek suggest that the easternmost fault has offset the Paso Robles Formation and created a barrier to ground-water flow. The extent to which the westernmost fault affects basin-fill deposits is less clear. Although the western edge of a shallow clay layer in the Paso Robles Formation occurs in the vicinity of this fault, the edge could be due to erosion of the Paso Robles Formation prior to deposition of the windblown sands. In figure 4, the westernmost fault is shown offsetting the Careaga but not the Paso Robles Formation. However, even the offset of the Careaga Sandstone is somewhat conjectural. The faults may meet a subsurface extension of the Los Osos fault beneath the Pleistocene basin fill. No other faults have been recognized at the edges of the basin or beneath it.

GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS

BASEMENT ROCKS

In this report, basement rocks refer to consolidated rocks that neither contain nor transmit significant quantities of water. Basement rocks north of the basin are primarily metavolcanics of the Franciscan Complex. Hard sandstone and shale also occur, but the metavolcanics (known locally as "redrock") are more commonly found at the contact with Paso Robles sediments in outcrops and drill holes. The metavolcanics are largely pillow basalt, in most places massive, reddish brown, deeply weathered, clayey, and highly fractured. In several places, rocks of this unit are fine-grained, greenish-brown and clayey, weathering to soft, angular chips about 0.1 inch in size. The latter lithology probably represents altered tuff, whereas the former represents lavas. Where the lavas are brittle, fractures can store and transmit ground water. A few wells completed in basement rocks in the eastern part of the valley have capacities up to 150 gal/min, although most wells have much smaller capacities. The tuffs contain little water.

Along the crest of Park Ridge, numerous Tertiary dacite plugs and sills of various sizes have intruded the Franciscan metavolcanics. Morro Rock, a prominent local landmark, is a dacite dome rising 578 feet from the northern end of Morro Bay (outside the study area). Rock of the dacite intrusives ranges from massive coarse porphyry to slightly porphyritic felsite. Dark blue-gray when fresh, the rock weathers to yellowish-white; in most places it is highly resistant to erosion and forms a line of peaks and ridges. There are many small intrusives, and nearly all appear to have steep to moderate dips at their margins, in many places concordant with dips of bedding in the surrounding rock. No baking or other alteration of the Franciscan wallrock is evident.

All the dacite bodies are moderately to highly fractured, and some good-quality domestic water has been obtained from springs and near-horizontal holes drilled to intersect the fractures. Potassium-argon data indicates that the intrusives were emplaced during the Oligocene Epoch (Turner and others, 1970).

South of the basin, the Paso Robles Formation lies above Franciscan metavolcanics and graywacke, as well as above diatomaceous shale of the Miguelito Member of the Pismo Formation. The metavolcanics are similar to those exposed north of the basin. The graywacke sandstone is greenish or brownish gray at the surface and bluish gray as seen in well cuttings. Its poorly sorted, coarse- to medium-angular grains are rechrystallized to a hard and brittle rock, which characteristically includes small angular chips of black shale. Interbedded with the graywacke is hard black silky shale, locally highly sheared to gray gouge. Both shale and graywacke are unfossiliferous. A few shallow domestic wells produce as much as 70 gal/min from fractures in the weathered graywacke in the area east of Los Osos Creek, but yields are generally much smaller. In all outcrops, the Franciscan is highly deformed, and its bedding planes and shears are nearly vertical.

The Miguelito Member of the Pismo Formation is of Pliocene to late Miocene age. In the Los Osos area, the Miguelito consists of thinly bedded, soft, low-density diatomaceous shale. Layers are typically 1 to 2 inches thick. The shale is silicified and flinty in some areas and grades to porcellanite in other areas. The rock is white where weathered, greenish-black where fresh. Permeability of the shale is low even though porosity is high. The only fossils observed during this study were unidentified microfossils. The shales are highly fractured and dip 40 to 70 degrees northward at the southern edge of the ground-water basin. Farther south, they are complexly deformed into many steep-sided folds, which plunge northwest and continue offshore for at least several miles.

BASIN FILL

In this study, "basin fill" refers to unconsolidated sedimentary deposits that fill the Los Osos Valley ground-water basin and can be distinguished from basement rocks by their significantly higher porosities and permeabilities. These deposits are less indurated than sedimentary basement rocks. Although ground water may move through fractures in the basement rocks, this movement is much more limited than the flow of water through the porous basin sediments. The Careaga Sandstone is the oldest and deepest basin-fill unit, occupying the bottom of the center of the basin. Overlying the Careaga is the Paso Robles Formation. In most areas, the Paso Robles is overlain by a thin surficial layer of either windblown sand or Holocene alluvial deposits associated with Los Osos Creek. Within the basin, surface exposures of Paso Robles are limited almost entirely to areas east of the Los Osos Creek floodplain.

The Careaga Sandstone lies beneath the Paso Robles Formation throughout much of the western and central parts of the ground-water basin (fig. 7). Thicknesses up to 450 feet were encountered at wells 30S/10E-13M1, -24A2, and 30S/11E-19H2, but the formation was not completely penetrated. The top of the Careaga Sandstone is difficult to distinguish from the lower part of the Paso Robles Formation on the basis of borehole lithologic logs from the Los Osos area. Prior to this study the upper 200 to 300 feet of the Careaga Sandstone shown in figure 4 were assigned to the Paso Robles Formation (California Department of Water Resources, 1979; Brown and Caldwell, Inc., 1983; Morro Group, Inc., 1986).

In the Los Osos area, both formations are missing key characteristics that facilitate identification in other areas. The Paso Robles Formation is missing its usual well-developed basal clay layer, at least in the western part of the basin, and the Careaga Sandstone does not contain sand dollar fossils (*Dendraster*, sp.) and white porcelaneous sands as it typically does in occurrences south of the study area (Dibblee, 1950; Woodring and Bramlette, 1950). However, the lithology of drill cuttings in 30S/10E-13M1 is otherwise nearly identical to that of Careaga outcrops at Garey in the Santa Maria Valley, 40 miles to the southeast, and at the beach in the San Simeon fault zone, 31 miles to the northwest. There are no Careaga outcrops in the study area, and it may be bounded locally on the north by a subsurface extension of the Los Osos fault.

In drill cuttings, the Careaga is a massive, light- to dark-green, fine-grained micaceous quartz sandstone, weakly to moderately cemented, locally carrying fossil mollusks. The hydraulic properties of the Careaga Sandstone were not measured directly, but lithologic and electric logs indicate that its porosity and hydraulic conductivity are probably moderate to high.

The Paso Robles Formation was deposited under a variety of conditions ranging from fluvial and lagoonal in the eastern part of the basin to near-shore marine at the sandspit. Consequently, it exhibits a wide range of lithologic types. Deep strata in the eastern part of the basin consist mainly of yellow-white clayey sand and brown clay. Along the southern edge of the basin it contains material from adjacent bedrock. Outcrops east of Los Osos Creek consist of brown clayey sand with abundant well-rounded cobbles and pebbles of Franciscan and Tertiary rock. In boreholes west of Los Osos Creek, the formation consists of moderately

rounded and subangular cherty diatomite pebbles in a coarse sand matrix. Marine fossils were found in test wells near the base of the formation as far east as Los Osos Creek, but the fossils may have been wind transported. In-place marine fossils were found near the base of the formation in wells near Ninth Street. In general, Paso Robles sediments seem to be coarser near the center of the basin, possibly because streams and their associated gravel deposits were historically more common along the axis of the syncline.

The bulk of the Paso Robles Formation typically consists of unconsolidated, interbedded reddish-brown clay and clayey, pebbly sand in discontinuous beds and lenses ranging in thickness from 1 foot to perhaps 50 feet. In general, gravel layers in the eastern half of the basin are finer grained and more angular, with a clay matrix of low permeability. These layers may have been deposited as mudflows. In the western half, gravels are coarser (up to 6 inches in diameter), more rounded and better sorted, with a sand matrix. They are gray-brown to blue-gray and locally appear marine, although no fossils have been found. Yields from these cleaner sands and gravels are high, and municipal wells for Los Osos and Baywood Park are all located in this area. The top of the formation is taken as the uppermost reddish-brown clay layer, but this layer is not everywhere the same bed. Where windblown sand directly overlies sand of the Paso Robles Formation, the Paso Robles sand is usually slightly redder.

Individual layers in the Paso Robles Formation are laterally discontinuous and difficult to correlate between wells. For example, electric logs from four wells, all of which are more than 500 feet deep and within 1,000 feet of each other (wells 30S/11E-18L6, -18L2, -18F2, and an unnumbered test well 50 feet east of 18L2), indicate that distinctive clay or sand layers can be correlated confidently between only two or three of the wells. The abrupt lateral discontinuity of beds within the Paso Robles Formation is typical of sediments deposited in a coastal environment under conditions of rising and falling sea level (Swift and Palmer, 1978).

Fairly continuous clay layers can be identified in at least two areas. One layer extends 3,000 to 4,000 feet westward from Los Osos Creek between the south edge of the ground-water basin and the vicinity of Eto Lake (fig. 3). This layer is typically 2 to 20 feet thick and is the uppermost part of the Paso Robles Formation. It is buried beneath 20 to 70 feet of windblown sand deposits. Perched ground water on the layer occasionally emerges as seepage near the foot of the Irish Hills, and it is the source of flow in two springs near Los Osos Valley Road. A second clay layer 50 to 80 feet in thickness at depths ranging from 100 to 250 feet can be correlated fairly well among lithologic logs of numerous wells west of the north-south extension of Ninth Street (fig. 3).

The hydraulic conductivity of the lower half of the Paso Robles Formation near the center of the basin was measured by an aquifer test in March 1986. Recovery data for well 30S/11E-18L2 indicated a horizontal hydraulic conductivity of 4 ft/d (± 2 ft/d). This result is similar to that of 5.6 ft/d determined from recovery data for well 30S/11E-18M1 by Brown and Caldwell, Inc. (1974, p. 20).

Aquifer-test results also indicated lateral discontinuity of individual Paso Robles beds and great variation in hydraulic properties. The response of water levels at observation well 30S/11E-18L6 to pumping at well 30S/11E-18L2 were compared with the response to pumping at well 30S/11E-18F2. Discharge rates were within 10 percent of each other, and no other deep wells were operating in the vicinity. Even though 18F2 is farther away (590 feet versus 500 feet), it produced about six times as much drawdown at the observation well. When 18F2 and 18L6 were used as observation wells for pumping at well 18L2, drawdown was greater at 18F2 even though it is twice as far away as 18L6. The screened intervals of the three wells are similar but not identical. A likely explanation of the test results is that the local configuration of permeable beds results in more highly conductive flow paths between well 18F2 and wells 18L2 and 18L6 than between 18L2 and 18L6.

The apparent heterogeneity of Paso Robles sediments in the vicinity of the test site precluded measurement of the storage coefficient, but the specific storage of confined alluvial aquifers is commonly about 0.000001 per foot (Heath, 1983, p. 28; Lohman, 1972, p. 53). Vertical hydraulic conductivity was not measured either, but in layered alluvial aquifer systems it is commonly 0.1 to 0.01 times the horizontal hydraulic conductivity (Freeze and Cherry, 1979, p. 34).

The surficial windblown sand deposits are a composite of the older stabilized dunes between Morro Bay and Los Osos Creek, the climbing dunes that lap across onto the Pismo Formation along the southern boundary of the basin, and the dunes that make up the sandspit west of Morro Bay. The thickness of the sands varies considerably, in part because of erosional irregularities in the upper surface of the underlying Paso Robles Formation, and in part because of the natural topography of the present-day dunes. On the floor of the valley, the sands typically range in thickness from 30 to 80 feet; however, the thickness is probably greater than 100 feet under a prominent hill in the eastern part of Baywood Park. Thicknesses in excess of 150 feet also occur locally in the vicinity of Pecho Valley Road (fig. 1). These great thicknesses may have resulted from infilling of ero-

sional sea notches formed along the Pleistocene coastline. The sand deposits become progressively thinner farther up the slopes of the Irish Hills and pinch out entirely near the first ridgecrest south of the basin. Their highest occurrence is about 950 feet above sea level.

The windblown sands are unconsolidated and fine grained, and they have few visible bedding planes. The sands consist of dominantly well-rounded quartz and have minor amounts of magnetite and white chert. In some areas, a weak iron oxide cement has slightly consolidated irregular zones a few feet thick, beneath what are probably former swales where runoff concentrated. Ponding in swales probably also resulted in scattered local silty layers 1 to 2 feet in thickness which have been found at depths of 10 to 40 feet. Ponding continues to occur, resulting in local flooding and perched ground water. Specific capacities of wells screened in the sand deposits indicate hydraulic conductivities of 25 to 50 ft/d (California Department of Water Resources, 1972, p. 22), while sediment lithology suggests a range of 0.5 to 20 ft/d (Heath, 1983, p. 13; Lohman, 1972, p. 53). Specific yield probably is between 0.1 and 0.3.

Holocene alluvial deposits cover the Los Osos Creek floodplain, a band of flat ground about 2,000 feet wide adjacent to the east bank of the creek between Clark Valley and Morro Bay. The thickness of the alluvium ranges from 20 feet along the west side of the floodplain to possibly 65 feet at points along the east side. Los Osos Creek formerly flowed along the east edge of the floodplain. In the late 1800's, the creek was rerouted to flow along the higher western edge in order to expedite flow of irrigation water from the creek eastward to row crops on the valley floor (Stratton, 1868). The creek has incised a channel 10 to 15 feet deep along its present course.

The alluvial deposits consist of clayey gravel and sand. Lithologic logs of closely spaced wells near Los Osos Valley Road indicate that layering is generally discontinuous. However, a continuous band of gravel occurs along the eastern edge of the deposits. The gravel was probably deposited as stream-channel sediment along Los Osos Creek before it was rerouted.

In the alluvial area are several dozen domestic and irrigation wells. Domestic wells produce small amounts of ground water from Paso Robles clayey gravels beneath the alluvial deposits. Irrigation wells extract water from basal gravels of the alluvial deposits as well as from the Paso Robles Formation.

Hydraulic conductivity of the alluvial deposits has not been measured, but it is probably low. Even large-bore wells have yields less than 200 gal/min, and surface penetration of irrigation water is slow. Some wells as deep as 100 feet have been unproductive. The range of lithology indicates that hydraulic conductivity is probably between 0.01 and 15 ft/d, and specific yield is between 0.02 and 0.2 (Heath, 1983, p. 13; Lohman, 1972, p. 53).

BOUNDARIES OF THE GROUND-WATER BASIN

The onshore boundary of the ground-water basin is shown in figure 3. This boundary lies where the Paso Robles Formation and windblown sand deposits taper to a negligible thickness (less than about 40 feet) or pinch out entirely against basement rocks. Basement rocks also form the bottom boundary of the basin. Areas indicated as Paso Robles Formation outside the basin boundary consist of thin erosional remnants.

From a hydraulic standpoint, the offshore boundary of the ground-water basin is the interface between the aquifer system and the ocean. From a water-supply standpoint, the more important boundary is the interface between fresh and saline ground water within the aquifer system. The presence of brackish ground-water beneath the sandspit indicates that the ground-water basin is hydraulically connected with the ocean. This study assumed that seepage occurs through the ocean floor and the bottom of Morro Bay.

In coastal aquifers containing both freshwater and seawater, the two tend not to mix. Seawater is denser, and it tends to underlie the freshwater and extend inland as a "toe" or "wedge" near the bottom of the basin. Freshwater is less dense and tends to float on top of the seawater, flowing seaward and then rising as seepage through the ocean floor. Although some mixing does occur, the interface between the two types of water is commonly distinct, so that it constitutes a boundary to the flow of fresh ground water. In a complexly layered aquifer system like the Los Osos Valley ground-water basin, the interface can be at different locations in different layers, depending on their relative hydraulic connection to pumping wells and the ocean or bay.

Because seawater is 2.5 percent denser than freshwater, the potentiometric head on the freshwater side of the interface must be 2.5 percent greater than the depth of the interface below sea level, if the interface is to remain stationary. For example, in order to balance the interface in an unconfined aquifer at a depth of 400 feet below sea level, a freshwater head of 10 feet above sea level would be needed. In this steady-state situation, the seawater remains stationary while freshwater flows seaward above the interface at a constant rate. Seawater intrudes when the freshwater head is insufficient to counterbalance the greater density of seawater, even when the freshwater head is above sea level.

HYDROLOGY

SURFACE RUNOFF

The ultimate source of inflow to the Los Osos Valley ground-water basin is rainfall on the surface-water hydrologic unit surrounding the basin. The boundaries of surface-water subbasins that make up the hydrologic unit are shown in figure 8. Rain falling on areas outside the ground-water basin but within the hydrologic unit can reach the ground-water basin either as ground-water inflow or as surface runoff into Los Osos Creek and its tributaries. Where they overlie the ground-water basin, Los Osos and Warden Creeks interact directly with ground water through seepage processes.

Flow in Los Osos Creek is highly seasonal. In winter, large but brief flows occur in direct response to rainstorms. These flows, sometimes peaking at over 1,000 ft^3/s, generally subside to less than 40 ft^3/s within a few days. In spring and summer, baseflow is supported by seepage from soil and ground water. Baseflow gradually recedes, and Los Osos Creek usually dries up in late summer along most or all of the reach between the southern edge of the ground-water basin and Eto Lake. Winter flows in Warden Creek are about the same size as flows in Los Osos Creek. Baseflow in summer tends to be larger, however, because Warden Creek serves as a drain for shallow ground water at the north end of the Los Osos Creek floodplain.

Flow in Los Osos Creek at the Los Osos Valley Road bridge has been recorded since 1976, when a permanent gage was installed by the San Luis Obispo County Flood Control and Water Conservation District. Periodic manual measurements of flow in Los Osos Creek where it first crosses onto the ground-water basin were made during the spring and summer of 1986. No measurements prior to 1976 are available at either site. Also, no measurements are available for Warden Creek or other tributary streams at the points where they cross the basin boundary. Surface- and ground-water inflow from drainage areas surrounding the basin was estimated by analyzing rainfall-runoff relations by using the Precipitation-Runoff Modeling System (PRMS), a rainfall-runoff simulator developed by the U.S. Geological Survey (Leavesley and others, 1983). PRMS simulates daily mean streamflow on the basis of numerous climatic variables and physical characteristics of a given drainage area. Rainfall, interception, depression storage, surface runoff, infiltration, soil-moisture storage, evaporation, transpiration, and deep percolation are all analyzed using numerous empirical and theoretical equations.

Climate data used for PRMS simulations in this study were daily temperature and rainfall at the Morro Bay Fire Department (Carol Romerein, Morro Bay Fire Department, written commun., 1986). The physical characteristics of the eight surface-water subbasins surrounding the ground-water basin were estimated from geologic, topographic, and soil maps. Coefficients of the flow equations used by PRMS were calibrated for Los Osos Creek (subbasin 6, fig. 8) by comparing PRMS results with measured monthly flow and estimated average deep percolation for calendar years 1978-81 and 1986. Measured and calculated discharge in Los Osos Creek at the Los Osos Valley Road bridge for these two periods are shown in figure 9. The measured data from 1978-81 are from the permanent gage at the road bridge. Because the streambed is sandy and unstable at that site, the gage frequently fails to record low flows; it also fails to account for seepage losses in the reach between the basin boundary and the gage site. Low flows and the seepage correction were estimated using the manual measurements made at the basin boundary in 1986. The 1978-81 data were used to calibrate simulation of a broad range of flows over a longer period of time. Average annual deep percolation of soil moisture in the drainage area was calibrated to equal 1.3 in/yr, which was the measured value in the Lompoc area 50 miles to the south (Blaney and others, 1963, p. 43).

After making appropriate changes to reflect differences in drainage area, rainfall, slope, aspect, and vegetative cover, PRMS was used to simulate runoff from subbasins 1, 2, 3, 4, 5, and 8. Estimated average annual surface runoff during 1970-77 is given in table 1 for all streams at the points where they enter the

Table 1.—*Estimated average annual surface runoff and ground-water underflow from surface-water subbasins around the ground-water basin during water years 1970-77*

[Acre-ft/yr, acre-feet per year]

Surface-water subbasins (fig. 8)	Area (acres)	Surface runoff to creeks (acre-ft/yr)	Underflow to ground-water basin (acre-ft/yr)
1	678	10	74
2	425	27	47
3	962	67	105
4	261	17	28
5	5,799	870	0
6	4,484	2,400	0
7	385	0	46
8	223	27	24
Total	13,217	3,418	324

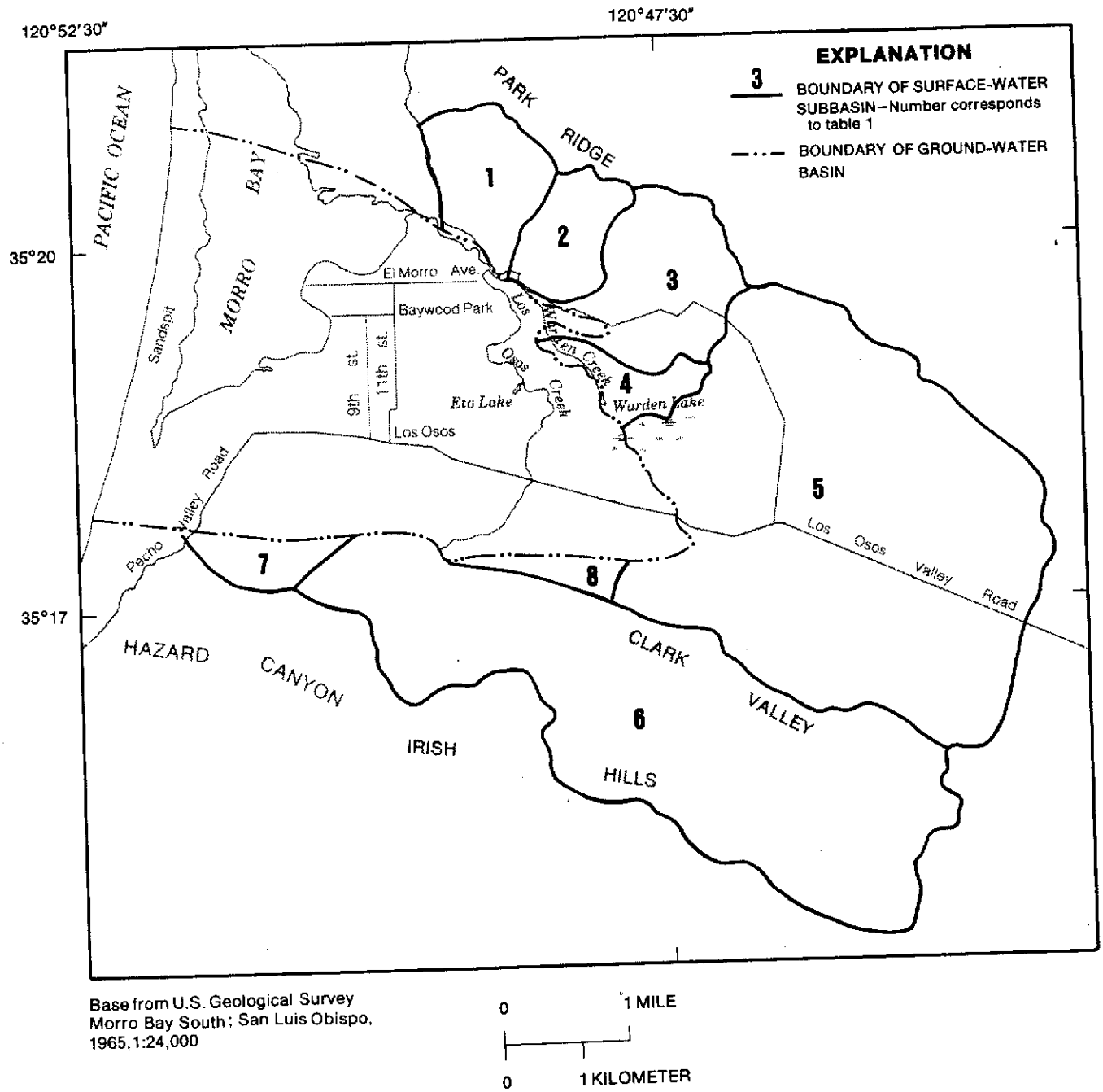


FIGURE 8.— Boundaries of surface-water subbasins surrounding the ground-water basin.

ground-water basin. The accuracy of the runoff estimates for streams other than Los Osos Creek is unknown, because measured streamflow data are not available.

GROUND-WATER FLOW SYSTEM

CONCEPTUALIZATION

The occurrence and movement of water in the Los Osos Valley ground-water basin are complex and variable, and so they cannot be measured or described in minute detail. At a larger scale, however, general flow patterns can be identified and used to develop a simplified conceptualization of the flow system. This conceptualization may not be correct in detail, but it is sufficiently accurate to serve as the basis for basinwide hydrologic interpretation and water-resources management. In this study, the conceptual flow system also serves as a blueprint for development of a mathematical model of the flow system.

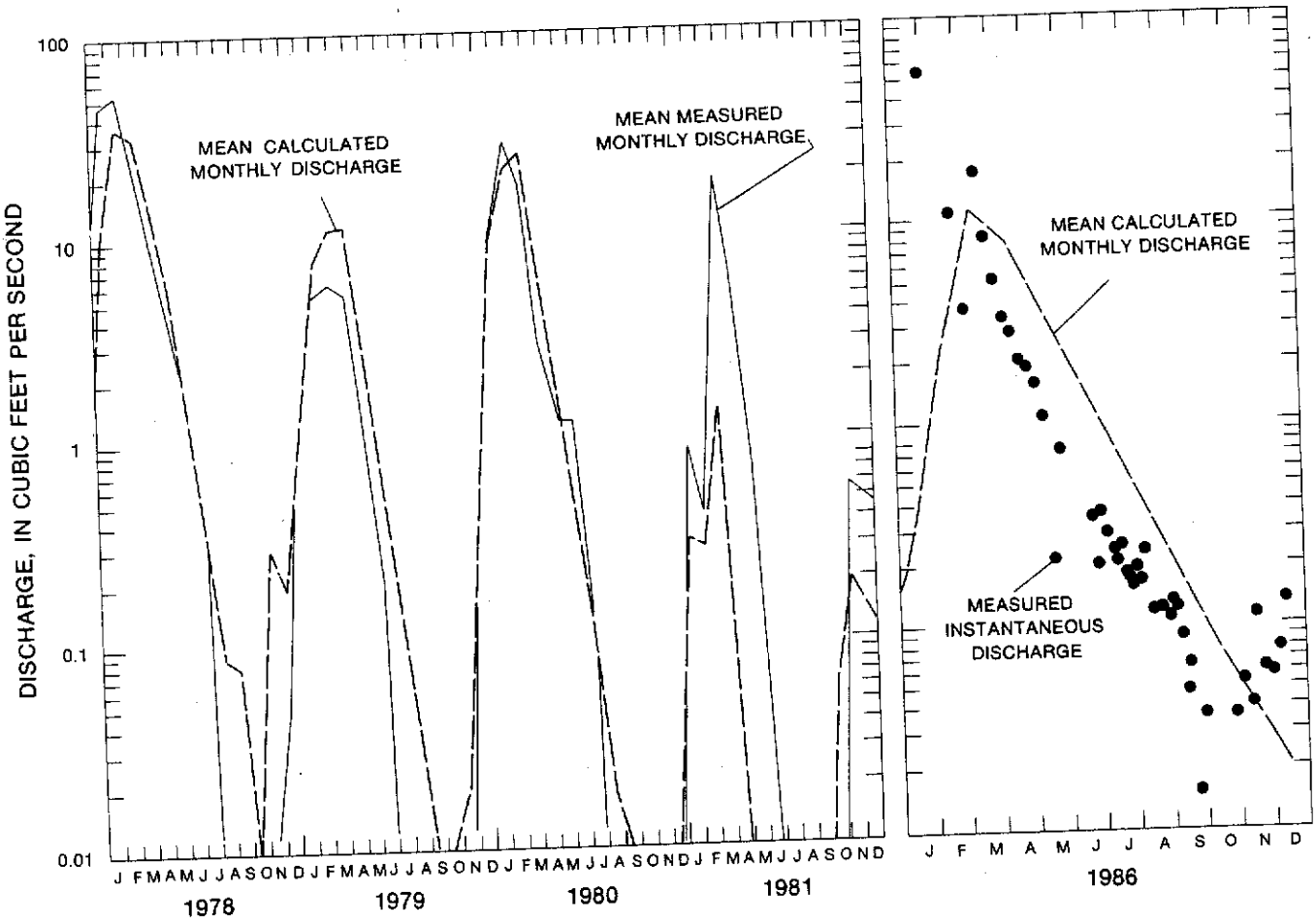


FIGURE 9.— Measured and calculated discharge in Los Osos Creek at Los Osos Valley Road bridge during calender years 1978-81 and 1986. Calculated discharge determined by the Precipitation-Runoff Modeling System.

In general, ground water in the study area moves downward from sources of recharge at the land surface and then flows horizontally to wells and to the ocean. Smaller amounts enter the basin as underflow from surrounding areas and leave the basin as seepage to streams or phreatophyte transpiration. With two exceptions, fine-grained beds and layers in the basin fill are laterally discontinuous and do not separate the basin into well-defined aquifers and confining beds. Instead, the beds impede but do not entirely block vertical ground-water flow. The overall effect of numerous local confining beds is equivalent to that of an aquifer system which is homogeneous but has vertically anisotropic hydraulic conductivity.

The two exceptions are (1) the continuous clay layer west of Los Osos Creek near the southern edge of the ground-water basin and (2) the clay layer that occupies most of the western part of the basin (fig. 3). The former layer is shallow and results in perched ground water in the windblown sand deposits. The latter is deeper, and it contributes to vertical gradients in salinity and potentiometric head within the Paso Robles Formation.

Saturated ground-water flow occurs primarily in the Paso Robles and Careaga Formations. Although the basement rocks of the Franciscan Complex and the Miguelito Member of the Pismo Formation are at least locally fractured and may allow inflow of some ground water from areas south of the basin, they are probably much less permeable than the basin-fill sediments. The basement rocks are considered impermeable for this study. The windblown sand deposits are highly permeable but are largely unsaturated. They play an important role in recharge processes but not in the horizontal flow of ground water.

Aquifers of the ground-water basin extend an unknown distance offshore. There are no apparent flow barriers separating the ocean from the ground-water basin, and flow between the two probably occurs through the sea floor and the bottom of Morro Bay.

The largest natural sources of ground-water recharge are from infiltration of rainfall, ground-water inflow, and seepage from Los Osos Creek. Other important sources of recharge include return flow from applied irrigation water and deep percolation of septic-system effluent. Most of the discharge from the ground-water basin is to wells. Smaller amounts flow to the ocean or are lost to phreatophyte transpiration.

POTENTIOMETRIC HEADS AND TRENDS

Long-term trends in potentiometric head are a good indicator of changes in the hydrologic system. However, the basinwide distribution of potentiometric head is difficult to determine because of local and transient factors affecting measurements made at individual wells. Nearly all the wells used in this study are active production wells at which residual pumping drawdowns may be large. In one municipal well (30S/11E-18L2), for example, the water level rose 10 feet between 1 and 6 hours after a 12-hour pumping period. The water level rose an additional 3 feet during the period 6 to 12 hours after pumping. Residual drawdowns at private domestic wells are probably smaller. Diurnal and lunar tidal fluctuations were measured at wells 30S/10E-13M1 and 30S/11E-7Q1. The maximum amplitudes of the diurnal fluctuations were 1.1 feet and 0.3 foot, respectively. The amplitude of the lunar tidal fluctuation was 1.4 feet at 13M1. Reference-point altitudes were surveyed at most wells. The magnitude of transient barometric effects on water levels is not known.

Vertical potentiometric head gradients also complicate the process of measuring and describing the basinwide head distribution. Vertical head gradients probably occur throughout the ground-water basin; they have been measured at all locations where adjacent or nested wells are perforated at separate depth intervals. At wells 30S/11E-8N2, 30S/11E-17J1, and 30S/10E-13M1, measurements at two depths indicated downward head gradients ranging from 0.036 to 0.66 ft/ft. Gradients during 1985-86 were lowest in spring and greatest in late summer. These data do not imply that two distinct aquifers exist. Vertical head gradients may vary considerably throughout the vertical section in response to the vertical distribution of pumping and recharge. For example, wells 30S/11E-18L6, -18L7, and -18L8 are completed at three different depths at the same location. The lowest head occurs at the deepest depth and the highest head occurs at the shallowest depth, indicating a continuously downward gradient throughout the upper 500 feet of vertical section.

Perched ground-water conditions produce an extremely steep vertical head gradient. These conditions occur in the area of the shallow clay layer west of Los Osos Creek. For example, well 30S/11E-19H1 is screened at a depth of 50 to 70 feet, which is just above the clay layer. The well intercepts perched ground water year-round. A nearby well (30S/11E-19H2) intercepts a deep water table at 250 feet below land surface; this well is screened at a depth of 280 to 380 feet. Well 30S/11E-19H3 is screened at a depth of 200 to 220 feet and is always dry, indicating unsaturated conditions below the clay layer.

In spite of the aforementioned difficulties, potentiometric-head data were analyzed for cumulative trends during a baseline period representative of long-term average climatic conditions. The baseline period was chosen on the basis of long-term trends

evident in the 110-year record for the rainfall station at California Polytechnical Institute in San Luis Obispo, California. Water years 1970-77 were selected for this study to represent long-term average hydrologic conditions. This period also includes years significantly wetter and drier than normal. Average annual rainfall at the Bender station in Los Osos (fig. 1) was 15.9 inches during that period. Correlation with the San Luis Obispo data indicates that long-term average rainfall at the Bender station is probably about 16.3 inches.

Hydrologic conditions during June 1985 through December 1986 were also investigated in this study. More complete potentiometric-head data were available for that period, and it serves as a recent reference period for analysis of prospective water-resources management actions.

Potentiometric heads at 37 wells were analyzed for cumulative trends during 1970-77. Data at 12 of the wells were too erratic or too few in number to determine a meaningful trend. Of the remaining 25 wells, data at only 7 showed long-term trends significantly different from zero at a 95 percent confidence level (fig. 10). Six of the seven wells showed long-term declines. The trends evident at these wells indicate that the ground-water system was not in a condition of steady state because it was adjusting to the significant changes in land and water use that occurred during the early 1970's.

INFLOW AND OUTFLOW

NONPOINT RECHARGE

Nonpoint recharge to the Los Osos Valley ground-water system occurs when rainfall, irrigation water, or septic-system effluent percolates past the root zone of plants growing at the land surface. Recharge flow can be estimated by calculating a water budget for moisture in the root zone. Changes in soil moisture storage are the net result of inflows from rainfall and irrigation minus outflows to surface runoff, evapotranspiration, and deep percolation. All plants transpire soil moisture, but phreatophytes are also able to transpire ground water directly from the water table or capillary fringe. The amount of ground water transpired by phreatophytes was calculated separately because it depends on the depth of the water table.

For this study, land in Los Osos Valley was divided into 19 soil-moisture zones. Each zone represented an area of reasonably uniform rainfall, soil type, and soil cover or land use. Land use was determined from surveys done by the California Department of Water Resources in 1968, 1977, and 1984 (Mark van Vlack, California Department of Water Resources, written commun., 1986). Changes in land use in intervening years were assumed to be gradual. A map of the zones as they appeared in 1984 is shown in figure 11, and the characteristics of each zone are summarized in table 2.

Soils on the windblown-sand deposits are porous and highly permeable. In contrast, soils on exposed Paso Robles Formation east of the floodplain have a high clay content and are relatively impermeable; soils on the flood plain alluvial deposits have intermediate properties. Water-retention characteristics of each soil type were obtained from the U.S. Soil Conservation Service (1984). Available water capacity was calculated as the product of root depth, in feet, and the difference between field capacity and wilting point, both in inches per foot (Dunne and Leopold, 1978, p. 142). For the purposes of this report, field capacity and wilting point were assumed to be constant and equal to the amounts of water in storage at values of soil-moisture tension of 30 and 1,000 kPa (kilopascals), respectively. Assumed root depths ranged from 1.5 feet for crop and lawn areas to 18 feet for native vegetation on sandy soils. Available water capacity ranged from 1.1 inches for shallow-rooted plants on sandy soils to 14 inches for deep-rooted plants on clay soils.

A one-dimensional water budget was calculated for each zone on a monthly basis. Soil-moisture storage at the end of each month was used as initial soil-moisture storage for the following month.

Rainfall was calculated as the average of rainfall at two local measurement stations (Bender and Baywood Park), adjusted for individual zone locations according to long-term distribution patterns. Rainfall on impervious surfaces such as roads and rooftops was assumed to accrue to adjacent soil areas, because there are no municipal stormdrains.

Surface runoff within the ground-water basin occurs only infrequently during periods of heavy rainfall. On the basis of soil permeability and rainfall frequency-duration data (California Department of Water Resources, 1976), it was estimated that significant amounts of runoff occur when monthly rainfall exceeds 20 inches on sandy soils, 7 inches on the alluvial clay loam, and 3 inches on clay soils derived from the Paso Robles Formation. Other factors such as slope and vegetation were not considered. It was assumed that all rainfall in excess of these threshold amounts becomes surface runoff.

Two methods were used to calculate evapotranspiration of soil moisture. In irrigated areas, average monthly evapotranspiration rates for specific crops were determined on the basis of field studies of evapotranspiration in coastal valleys of central California

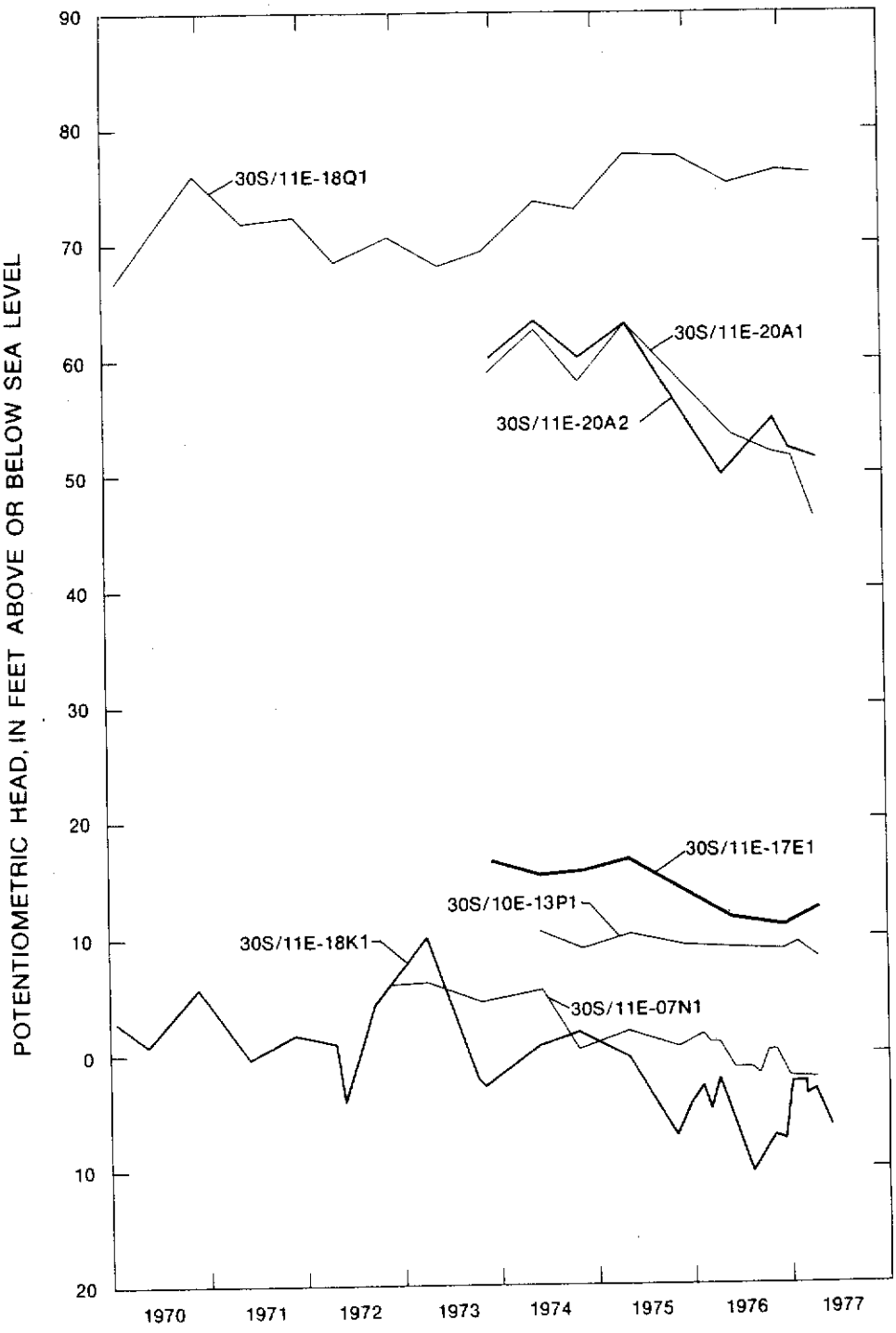


FIGURE 10.— Potentiometric heads at seven wells, water years 1970-77.

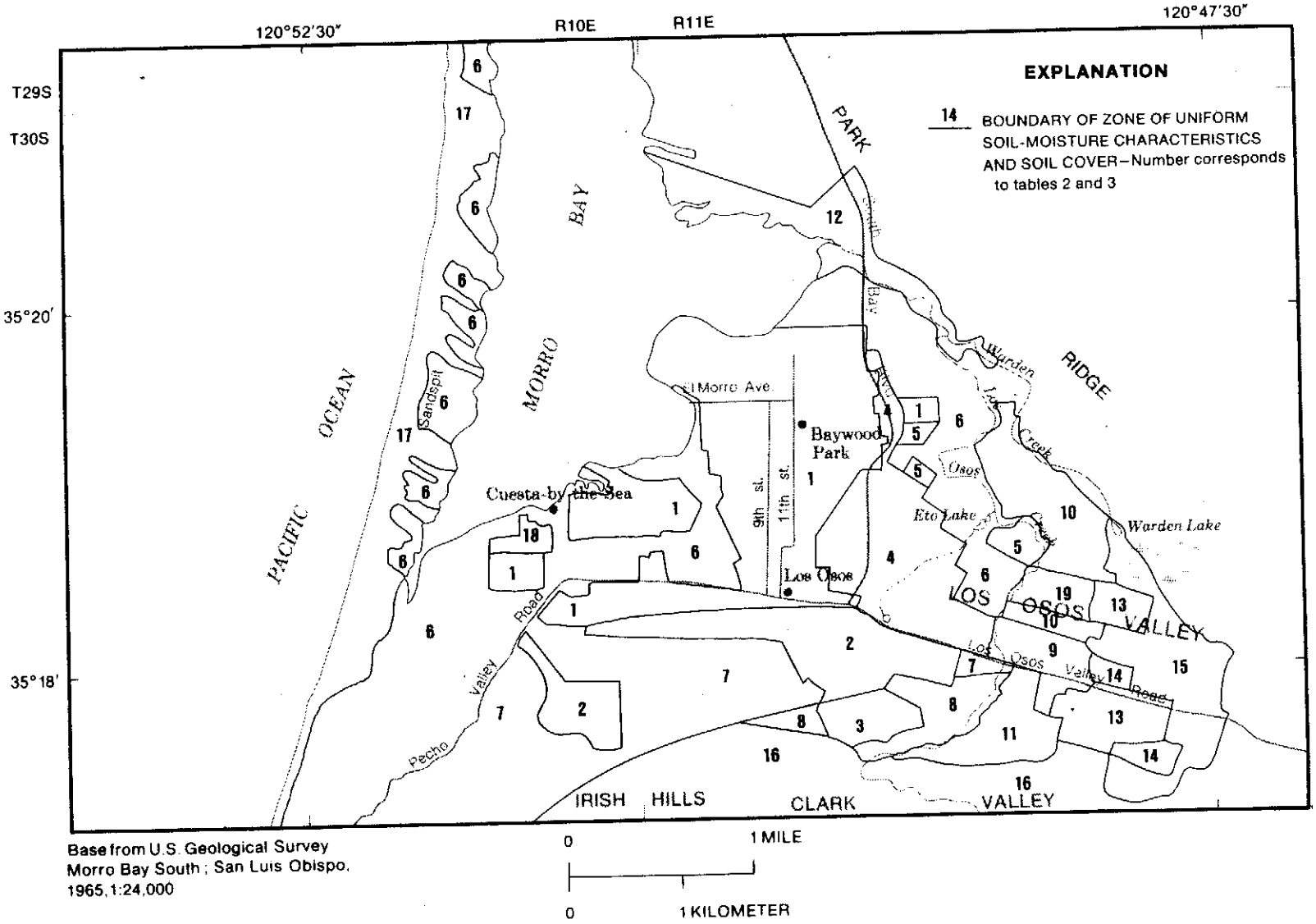


FIGURE 11.—Zones of uniform soil-moisture characteristics and soil cover in 1984. (modified from Mark van Vlack, California Department of Water Resources, written commun.,1986)

Table 2.—*Characteristics of soil-moisture zones in 1984*

[Only areas within boundaries of ground-water basin are included. Do., ditto; in/yr, inches per year]

Zone (fig. 11)	Area (acres)	Soil type	Average rainfall[1] (in/yr)	Soil cover (percent of area)								
				Impervious	Irrigated ornamentals	Native vegetation			Crops		Wetlands	Beach
						Brush	Trees	Grass	Irrigated	Nonirrigated		
1	1,162	Sand	15.2	30	20	20	30	0	0	0	0	0
2	271	do.	16.0	30	25	45	0	0	0	0	0	0
3	73	do.	17.0	30	25	45	0	0	0	0	0	0
4	367	do.	15.5	15	10	45	30	0	0	0	0	0
5	51	do.	15.2	0	0	0	0	0	100	0	0	0
6	1,142	do.	15.2	0	0	100	0	0	0	0	0	0
7	384	do.	16.0	0	0	100	0	0	0	0	0	0
8	92	do.	17.0	0	0	100	0	0	0	0	0	0
9	77	Loam	16.0	30	20	20	30	0	0	0	0	0
10	225	do.	15.5	0	0	0	0	0	100	0	0	0
11	135	do.	16.5	0	0	0	0	0	100	0	0	0
12	131	do.	15.0	0	0	0	0	0	0	0	100	0
13	186	Clay	17.0	0	0	0	0	0	0	100	0	0
14	45	do.	17.0	0	0	0	0	0	100	0	0	0
15	286	do.	17.0	0	0	0	0	100	0	0	0	0
16	0	do.	17.0	0	0	100	0	0	0	0	0	0
17	427	Sand	15.0	0	0	0	0	0	0	0	0	100
18	35	do.	15.0	0	100	0	0	0	0	0	0	0
19	126	Loam	16.0	0	0	0	0	0	0	100	0	0

[1]During water years 1979-77.

(California Department of Water Resources, 1975; Blaney and others, 1963). Irrigated ornamental plants in urban areas were assumed to be equivalent to a mix of deciduous orchard, subtropical orchard, and lawn. Crops were assumed to consist of a mix of lettuce, broccoli, carrots, cauliflower and "other field crops." Regional evapotranspiration rates were adjusted downward by about 30 percent to account for the frequent occurrence of fog in the immediate vicinity of the coastline (California Department of Water Resources, 1975, p. 16).

Evapotranspiration in irrigated areas was assumed not to be limited by soil moisture content, because irrigation assures an ample water supply. Furthermore, monthly evapotranspiration rates were assumed to be the same in all years. This assumption reflects the climatic influence of the ocean, which tends to maintain air temperature within a narrow range. Air temperature is highly correlated with potential evaporation.

A different method was used to estimate evapotranspiration by native vegetation. For plants relying on naturally occurring soil moisture, evapotranspiration is generally a function of both potential evaporation and available soil moisture. Potential evaporation was calculated for each month using the Blaney-Criddle formula, as modified by the U.S. Soil Conservation Service (1967, p. 6, units converted):

$$E = (0.01724T^2 - 0.3128T)\, k\, d, \qquad (1)$$

where

E is potential evaporation, in inches;

T is average air temperature, in degrees Fahrenheit;

k is empirical "crop factor" for the native vegetative type; and

d is fraction of annual hours of daylight occurring during the month.

When soil moisture was greater than or equal to field capacity, actual evapotranspiration was assumed to equal potential evaporation. When soil moisture was less than the wilting point, evapotranspiration was

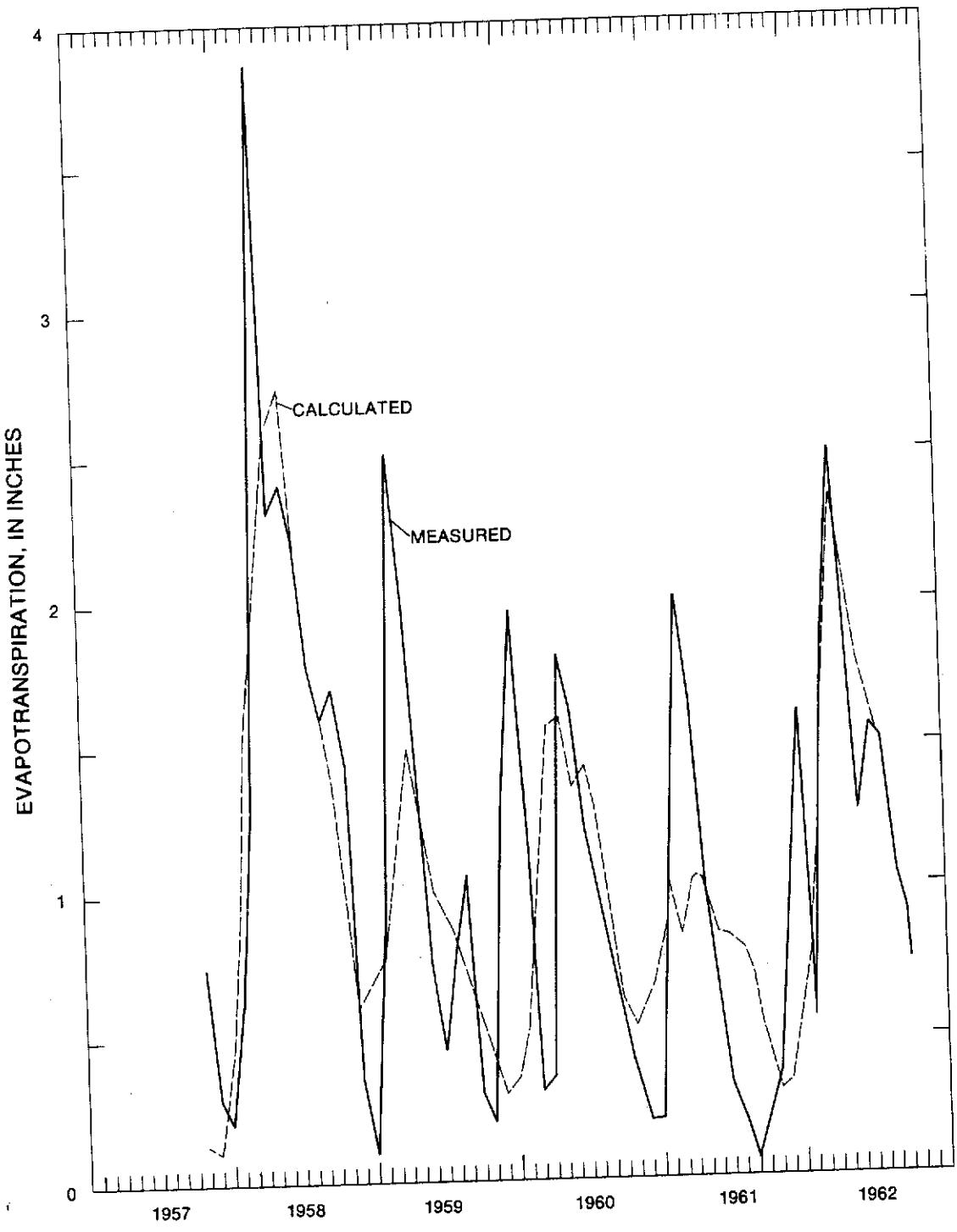


FIGURE 12.– Measured and calculated evapotranspiration at Lompoc, California, calendar years 1957-62.

assumed not to occur. For intermediate amounts of soil moisture, actual evapotranspiration was calculated using a power function:

$$AET = E\,(a\,S^b);\ W<S<F, \qquad (2)$$

where

AET is actual evapotranspiration, in inches;

E is potential evaporation;

a is coefficient of power function;

b is exponent of power function;

S is soil moisture, in inches;

W is soil moisture corresponding to wilting point, in inches; and

F is soil moisture corresponding to field capacity, in inches.

The crop factor (*k*) and the exponent (*b*) of the power function were selected by comparing measured and calculated rates of evapotranspiration and deep percolation. Measured values were from a 5-year field investigation of evapotranspiration and soil moisture on the Lompoc Plain, 50 miles south of Los Osos (Blaney and others, 1963). The variables *k* and *b* were adjusted to obtain the best possible agreement between measured and calculated evapotranspiration. For a specified value of *b*, coefficient *a* was automatically set to maintain the assumption that actual evapotranspiration equals zero at the wilting point and equals potential evapotranspiration at field capacity. Separate values of *k* and *b* were chosen for bare soil, chaparral (brush), oak trees, and native grass. Best results were obtained when *k* was varied seasonally between a maximum in winter and a minimum in late summer; this reflects the growing season for native vegetation in the study area. All *k* values were between 0.40 and 1.05, which are within the range measured for a variety of other plant types (Dunne and Leopold, 1978, p. 140). Values of *b* ranged from 0.8 to 2.0. Measured and calculated evapotranspiration for chaparral in the Lompoc area are shown in figure 12. Climate, vegetation, and soil type of the Lompoc and Los Osos areas are similar, so that coefficients and relations determined from Lompoc data probably approximate those of Los Osos.

The evapotranspiration function for native vegetation was applied to the Los Osos study area using the values of *k* and *b* corresponding to the vegetation type in each zone. Evapotranspiration was calculated using average monthly temperatures at the Morro Bay Fire Department (Carol Romerein, Morro Bay Fire Department, written commun., 1986). Distribution of nonpoint ground-water recharge from each zone during 1970-77 (average annual rates) and 1986 are shown in table 3. During 1970-77, average annual rainfall on the ground-water basin was 6,100 acre-ft/yr, and evapotranspiration of soil moisture (including irrigation water) was 5,720 acre-ft/yr. In water year 1986, rainfall and evapotranspiration were 8,530 and 6,430 acre-ft, respectively.

Ground-water recharge from septic-system effluent was also assumed to constitute a source of nonpoint recharge in urban areas. Because seepage from individual septic tanks is highly localized and quickly moves below the root zone, it is not significantly diminished by evapotranspiration. For this reason, it was not included in the soil-moisture budget calculations described in this section. Less than 10 percent of water used indoors is lost to evaporation and other consumptive uses; the remainder is collected in drains

Table 3.—*Distribution of nonpoint ground-water recharge in soil-moisture zones during water years 1970-77 and 1986*

[All values are in acre-feet per year and include recharge from rainfall, urban and agricultural irrigation return flow, septic-system return flow, and effects due to shallow perching layers. Values for 1970-77 are averages for those years]

Zone (fig. 11)	1970-77	1986
1	760	2,000
2	110	270
3	0	0
4	240	110
5	20	90
6	150	100
7	100	180
8	10	60
9	0	160
10	350	440
11	170	320
12	0	0
13	0	0
14	60	60
15	0	0
16	0	0
17	350	530
18	50	80
19	30	50
Total	2,400	4,450

as wastewater (California Department of Water Resources, 1983). For this study, septic-tank effluent was assumed to equal 90 percent of water used indoors in urban areas. Indoor water use was distinguished from outdoor water use by a curve-separation procedure using a graph of the average monthly distribution of municipal pumpage (fig. 13). Indoor water use was assumed to be constant in all months and to equal total urban water use in December, the month of least total use. Outdoor water use was assumed to account for the difference between indoor water use and total urban water use in all other months. By this method, outdoor water use equals about 27 percent of annual urban water use. The proportion averages 30 percent for all areas within about 50 miles of the central California coast (California Department of Water Resources, 1983). The slightly lower value for the Los Osos area is probably due to fog and cool summer temperatures that occur in the immediate vicinity of the ocean. Applying this proportion to historic water-use data indicates that septic-system effluent averaged 740 acre-ft/yr during 1970-77 and amounted to 1,590 acre-ft in water year 1986. In 1986, about 3 percent of the septic-system effluent occurred in subbasin 7 (fig. 8) and entered the ground-water basin as underflow.

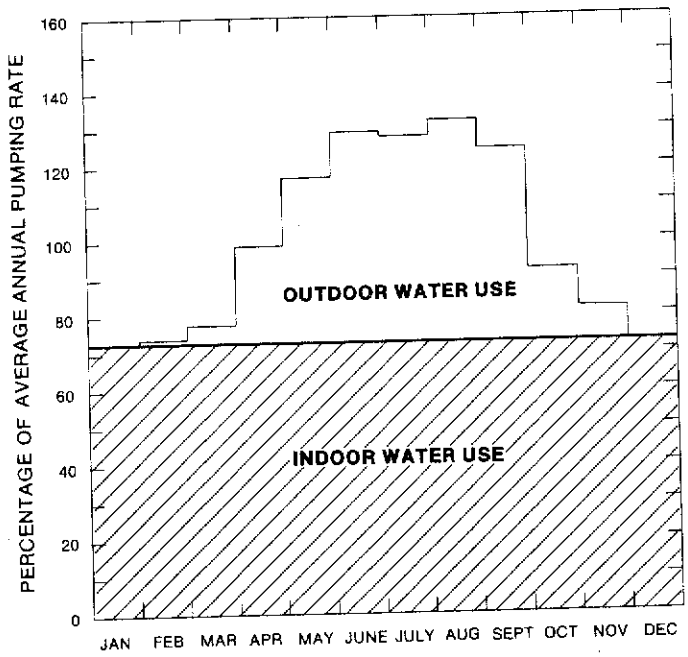


FIGURE 13.– Average monthly distribution of municipal pumping rates during water years 1970-77.

PHREATOPHYTE TRANSPIRATION

In addition to evapotranspiration of soil moisture, transpiration occurs directly from ground water in areas where the water table is shallow or plants have deep roots. Where the water table is particularly shallow, soil moisture is no longer a limiting factor, and actual evapotranspiration approximately equals potential evapotranspiration. No direct measurements of evapotranspiration are available for the Los Osos area, but the soil-moisture budget calculations indicate that potential evapotranspiration from the surface of the ground-water basin was about 8,600 acre-ft in water year 1986. Of this total, about 3,100 acre-ft (36 percent) failed to occur because of soil-moisture limitations. The latter amount represents the maximum amount of ground water that plants could have transpired if the water table were shallow in all areas. The actual amount of transpiration by phreatophytes was about 200 acre-ft because shallow water tables occurred only around the perimeter of Morro Bay, along the lower reaches of Los Osos and Warden Creeks, and in the area of shallow perched ground water near Los Osos Valley Road between South Bay Boulevard and Los Osos Creek.

STREAM GAINS AND LOSSES

Seepage from Los Osos Creek during water year 1986 was estimated by measuring changes in flow in two reaches. A temporary gage was installed at the entry point of Los Osos Creek into Los Osos Valley (fig. 1). The gage was in operation for 6 weeks starting in December 1985. Manual discharge measurements were made every 1-2 weeks from March through November 1986 at that site, as well as at Los Osos Creek near Los Osos, a permanent gaging station operated by the San Luis Obispo County Flood Control and Water Conservation District, and at the confluence with the outlet of Eto Lake (fig. 1).

During baseflow recession in spring and summer 1986, measured seepage loss between the temporary gage site and the permanent gage site ranged from 0.09 to 2.77 ft^3/s and was typically about 0.6 ft^3/s. The larger apparent seepage losses, which were measured during periods of high flow associated with storms, may have been due to transient bank-storage effects. Seepage loss between the permanent gage site and the Eto Lake site was measured only twice, in May 1986. In both cases the streamflow was less than 0.3 ft^3/s and the seepage loss was less than 5 percent of the streamflow.

As baseflow receded during the summer of 1986, flow in Los Osos Creek became discontinuous, disappearing for short reaches and reemerging farther downstream. Between August and December 1986, flow generally extended less than 0.25 mile from the mouth of Clark Valley before disappearing into the streambed. Reemergence occurred continuously in two short reaches located 600 to 1,400 and 3,200 to 5,000 feet downstream of the Los Osos Valley Road bridge. In July, reemergence also occurred in short reaches upstream of the bridge where steep hillslopes occur along

the west bank of the creek. The reemergent flow probably results from ground water draining from the hills. Ground-water drainage sometimes forms numerous small springs along the west bank of the creek, as was observed, for example, during a survey in 1974.

UNDERFLOW

Ground-water underflow across basin boundaries occurs along the onshore and offshore portions of the perimeter of the basin. Along Park Ridge and the Irish Hills east of Los Osos Creek (in subbasins 1-4 and 8, fig. 8), weathered shallow Franciscan bedrock and thin veneers of Paso Robles Formation store a small amount of infiltrated rain and release it gradually to the ground-water basin. Average annual ground-water underflow from these five subbasins to the ground-water basin (table 1) was estimated by multiplying drainage area times the average long-term deep percolation rate in the Lompoc area of 1.3 in/yr (Blaney and others, 1963), and equalled 278 acre-ft/yr. This amount of deep percolation was also accounted for in the rainfall-runoff analyses used to estimate surface-water inflow to the basin from the same subbasins.

Little or no ground water enters the basin from the east end of Los Osos Valley (subbasin 5) for two reasons. First, shallow slopes and thin, clayey soils greatly hinder the horizontal movement of water. Second, the mesalike terrace just inside the east end of the basin probably creates a local ground-water mound, which would tend to prevent inflow from the east. Deeply percolated soil moisture in the east end of the valley was assumed to emerge at a constant rate as flow in Warden Creek. This flow was estimated to be 0.17 ft^3/s.

Subbasin 6 discharges to the ground-water basin through the narrow lower end of Clark Valley, where shallow Franciscan basement rocks force underflow to reemerge as surface flow in Los Osos Creek. Fractures in the Franciscan rocks, however, conceivably could allow underflow beneath the ridge separating Clark Valley from Los Osos Valley. Although Franciscan rocks were assumed to be impermeable beneath the basin, they are commonly highly fractured in outcrop. It was assumed that at depth the fractures are not sufficiently open and interconnected to transmit large quantities of water. When well 30S/11E-20G2 was drilled for this study, however, water from the uppermost Franciscan basement rocks flowed into the borehole. If basement fractures are continuous, underflow might occur. This underflow might come from deep percolation of rainwater on the ridge and seepage losses from Los Osos Creek as it flows through Clark Valley. The underflow might amount to several hundred acre-ft per year, but it was assumed to be negligible for this study.

Windblown sand deposits on the Irish Hills occur upslope of the basin boundary (subbasin 7, fig. 8). The soil-moisture accounting algorithm indicated that these deposits transmit an average of about 50 acre-ft/yr of infiltrated rainfall to the ground-water basin.,

Underflow across the offshore boundary of the ground-water basin can be inferred from changes in salinity of water in observation wells along the sandspit. Increasing salinity indicates that seawater is intruding into the basin, whereas stable or decreasing salinity indicates a net outflow of fresh ground water. Table 4 shows the quality of seawater and ground water at the sandspit at wells 30S/10E-11A1, -11A2, and 30S/10E-14B1 in June 1977; well 14B1 in December 1985; and wells 11A1 and 11A2 in March 1986. The concentration of chloride ions is generally a good indicator of salinity. Chloride concentration increased at all three wells by amounts ranging from 5.3 percent in 11A1 to 38 percent in 11A2. The large percentage increase in 11A2 is due to the low concentrations of all ions in the sample. The increases in chloride concentration indicate that there may have been a net inflow of seawater during 1977-86. However, there are not enough data to draw firm conclusions. The small changes in salinity could have resulted from slight shifts in the location of the interface, such as shifts resulting from normal seasonal and annual variations in recharge.

Other water-quality measurements at the sandspit indicate that changes in that area may be more complex than simple intrusion. In samples from well 30S/10E-11A1, concentrations of dissolved solids and four of the seven measured individual ion species decreased (table 4). The other three species, including chloride, showed increases. The relative amounts of various ion species also indicated a shift away from the sodium-chloride character of seawater and toward the calcium-magnesium-bicarbonate character of deep onshore ground water (fig. 14).

Potentiometric heads in deep wells near the south end of Morro Bay also suggest that seawater has been intruding at least intermittently in recent years. With one exception in 1983, potentiometric heads since 1979 at well 13S/10E-13P2 have been below sea level. Similar levels were measured at well 30S/10E-13L4. Some of the low measurements can be ascribed to residual pumping drawdown. However, potentiometric heads at observation well 30S/10E-13M1 have also been continuously between 1 and 8 feet below sea level since the well was drilled in 1985. In contrast, potentiometric heads in wells perforated at shallower depths

(30S/10E-13L5, -13K1, -13L1, -13L2, -13Q1, and -13P1) have been above sea level in recent years.

Between 1963 and 1970, the specific conductance of water in well 30S/10E-24C1 increased to a level of about 1,200 µS/cm at 25 °C (microsiemens per centimeter at 25 degrees Celsius). The source of the poor- quality water was near the bottom of the well, and in 1970 the well was plugged from a depth of 600 feet back up to a depth of 400 feet. The source of the poor-quality water was never identified, although at the time it was thought to be brines leaking from an abandoned oil well 2,500 feet to the south (Joel Spates, California Cities Water Co., oral commun., 1988). Given that well 24C1 originally penetrated to a depth of about 400 feet below sea level, the poor-quality water might also have resulted from seawater intrusion caused by pumping at the well.

Electric logs from another nearby deep well, 30S/10E-13L4, indicate poor-quality water below about 530 feet below sea level (fig. 4). This well was drilled in 1977, and the perforated interval is between 170 and 310 feet below sea level. However, water quality has reportedly not deteriorated over time (Joel Spates, California Cities Water Co., oral commun., 1988).

The water-quality and potentiometric-head data for wells near the south end of Morro Bay indicate that the direction and rate of underflow across the ocean boundary probably varies with depth in the basin fill. Deep aquifers (more than about 200 feet below land surface) are heavily stressed by pumpage at large municipal wells. Deep aquifers have potentiometric heads generally slightly below sea level, and they are becoming more saline at the sandspit. Shallow aquifers, which are less heavily stressed, have potentiometric heads above sea level, and they are not becoming significantly more saline at the sandspit.

Table 4.—*Quality of seawater and ground water at the Morro Bay sandspit in water years 1977 and 1986*

[Data for 1977 are from California Department of Water Resources (1979). Site numbers from California Department of Water Resources (1979) samples are retained for consistency. Values are in milligrams per liter unless otherwise noted. µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; —, not measured]

Well No.	Date	Specific conductance (µS/cm)	pH (standard units)	Calcium, dissolved, as Ca	Magnesium, dissolved, as Mg	Sodium dissolved, as Na
30S/10E-11A1	6-29-77	38,700	8.2	446	1,030	8,450
(site 1, shallow) ...	3-5-86	41,400	7.3	150	940	8,300
30S/10E-11A2	6-29-77	8,680	7.9	403	309	910
(site 1, deep)	3-5-86	10,400	7.6	500	450	1,000
30S/10E-14B1	6-22-77	31,400	7.9	512	815	6,350
(site 3, shallow) ...	12-4-85	36,500	7.2	—	—	—
Seawater	6-29-77	72,800	—	451	1,301	10,630

Well No.	Date	Potassium, dissolved, as K	Bicarbonate[1] as HCO_3	Sulfate, dissolved, as SO_4	Chloride, dissolved, as Cl	Solids, residue at 180°C, dissolved
30S/10E-11A1	6-29-77	328	145	2,130	15,200	30,800
(site 1, shallow)	3- 5-86	310	148	2,300	16,000	29,700
30S/10E-11A2	6-29-77	15	79	320	2,670	5,600
(site 1, deep)	3- 5-86	15	207	420	3,700	6,100
30S/10E-14B1	6-22-77	220	154	1,780	11,700	24,000
(site 3, shallow)	12- 4-85	—	—	—	14,000	24,600
Seawater	6-29-77	383	159	2,603	18,565	36,300

[1]Incremental titration was done in field when sample was collected.

Table 5.—*Pumpage from municipal and private domestic wells during water years 1970-86*

[Values are in acre-feet per year]

Water year	Municipal wells	Private domestic wells
1970	620	140
1971	700	170
1972	830	160
1973	720	130
1974	910	170
1975	1,150	250
1976	1,260	280
1977	1,330	190
1978	1,470	170
1979	1,640	200
1980	1,650	240
1981	1,890	270
1982	1,780	210
1983	1,820	200
1984	2,050	210
1985	2,040	200
1986	2,220	210

PUMPAGE

Municipal.—More than 80 percent of households in the study area receive water from three large community water suppliers. These suppliers obtain their water from 13 large-capacity wells. Monthly production amounts for these wells from 1970-86 were made available for this study (Mark van Vlack, California Department of Water Resources, written commun., 1986). The remaining households are supplied by private domestic wells. Pumpage from these wells was estimated by assuming that household water consumption was the same as that of households supplied by the community systems.

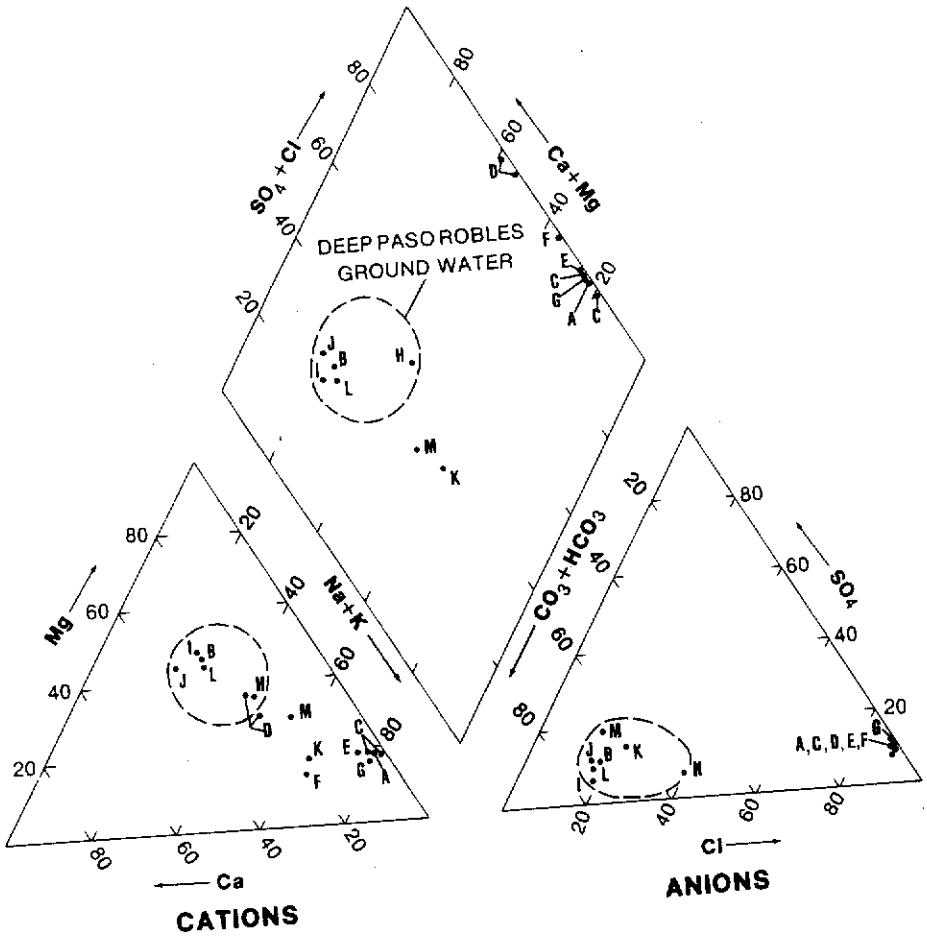
The community-supply wells are located in the central and western parts of the study area. Most of them are 250 to 500 feet deep. Private domestic wells are scattered throughout the study area but are concentrated in the eastern parts of Los Osos and Baywood Park and in outlying residential areas. Fifty-one private domestic wells were identified for this study, and estimated total private pumpage was assumed to be distributed evenly among them. Pumpage from municipal and private domestic wells for water years 1970-86 is given in table 5. Average monthly distribution of municipal pumpage during water years 1970-77 is shown in figure 13.

Agricultural.—Estimates of agricultural water use were developed using the soil-moisture accounting algorithm described earlier. In each irrigated agricultural zone, irrigation was assumed to occur whenever soil moisture fell below a "depletion limit" corresponding to a specified fraction of available water capacity. The amount of applied water was assumed to equal the amount required to bring soil moisture back up to field capacity, plus an excess amount to account for irrigation inefficiency. Depletion limits ranged from 54 to 77 percent of available water capacity and were chosen such that the algorithm calculated realistic irrigation frequencies. Irrigation efficiency was assumed to be 60 percent per application for all crops on all soils. An advantage of using the soil-moisture accounting algorithm is that it accounts for the effects of irregular climatic fluctuations on crop water use. Another advantage is that it calculates simultaneous and mutually consistent estimates of pumpage and recharge. The soil-moisture accounting algorithm indicated that annual agricultural pumpage in the ground-water basin averaged about 800 acre-ft/yr during 1970-77 and was 970 acre-ft in 1986.

DIGITAL SIMULATION OF GROUND-WATER FLOW

A digital model was developed to provide an integrated analysis of the ground-water-flow system in the Los Osos Valley ground-water basin. The model helped to account for spatial variations in aquifer properties and interactions among inflows, outflows, and potentiometric heads. The model was also used to estimate flows and basin characteristics for which direct measurements were unavailable. Once a satisfactory simulation of the ground-water basin under present-day pumping stresses was obtained, the model was used to simulate the basin under hypothesized future stresses. In this way, the model served as an experimental tool to investigate the potential effects of water-resources management alternatives.

The digital model is a mathematical representation of the conceptualized flow system. In order to solve the equations in the model, it was necessary to make simplifying assumptions about basin characteristics and the physical processes governing ground-water flow. The model is not as detailed and complex as the real system. The accuracy and precision of model results are limited by the validity of the simplifying assumptions and the accuracy and detail of the input data.



Site letter	Location	Depth of perforations (feet)	Date	Dissolved solids (mg/L)
A	Seawater	—	6-29-77	36,300
B	Los Osos Creek	—	1983	395
C	30S/10E-11A1	234-244	6-29-77	30,800
			3-5-86	29,700
D	30S/10E-11A2	150-160	6-29-77	5,600
			3-5-86	6,100
E	30S/10E-14B1	275-285	6-22-77	24,000
			[1]12-4-85	24,600
F	30S/10E-14B2	190-200	6-22-77	16,600
G	30S/10E-13M1	477-537	8-7-85	33,700
H	30S/10E-13M2	197-227	8-7-85	142
I	30S/11E-17J1	160-190	8-6-85	264
J	30S/11E-18L6	[2]355-600	8-6-85	402
K	30S/11E-18L8	100-140	8-7-85	146
L	30S/11E-19H2	280-380	8-6-85	315
M	30S/11E-20G2	300-360	8-7-85	446

[1]Not shown on plot. Only dissolved solids and chloride were measured.

[2]Perforations are intermittent; total of perforations is 120 feet.

Sources: Samples dated 1977 were collected by the California Department of Water Resources (1979); the sample dated 1983 and the water-quality region for deep Paso Robles ground water were reported by Brown and Caldwell, Inc., (1983); all other samples were collected for this study.

FIGURE 14.— Trilinear diagram showing quality of seawater and of water at selected well and stream locations.

MODEL DESIGN

Ground-water flow was simulated using the modular three-dimensional finite-difference model developed by McDonald and Harbaugh (1984). For details of the flow equations and numerical solution methods used in the model, the reader is referred to their report. The discussion here is limited to important assumptions made in the process of applying the model to the Los Osos Valley study area.

A plan view of the model grid is shown in figure 15. The grid has 26 rows and 40 columns of individual cells with widths and lengths ranging from 600 to 1,000 feet. The point at the center of each cell is called a node. A node is the point at which certain model data such as pumpage are input and for which the model calculates potentiometric head. Only cells inside the boundary of the ground-water basin are used actively in the model. The model has three layers. Layer 1, the uppermost layer, is 160 feet thick except along the onshore boundaries of the basin, where it tapers to 100 feet. Layer 2 is 200 feet thick, tapering to 100 feet along the onshore boundaries. Layer 3 is the bottom layer and includes all remaining basin fill between the bottom of layer 2 and the basement rocks. It ranges in thickness from 100 to 509 feet. Model layers 1, 2, and 3 have 637, 558, and 233 active cells, respectively.

Aquifer properties were specified for each cell in the grid, and inflows and outflows from the ground-water basin were allocated to nodes at appropriate locations. In many cases, it was possible to obtain quantitative estimates of properties and flows from existing information. In other cases, existing data were incomplete or unreliable, and so values were obtained by model calibration.

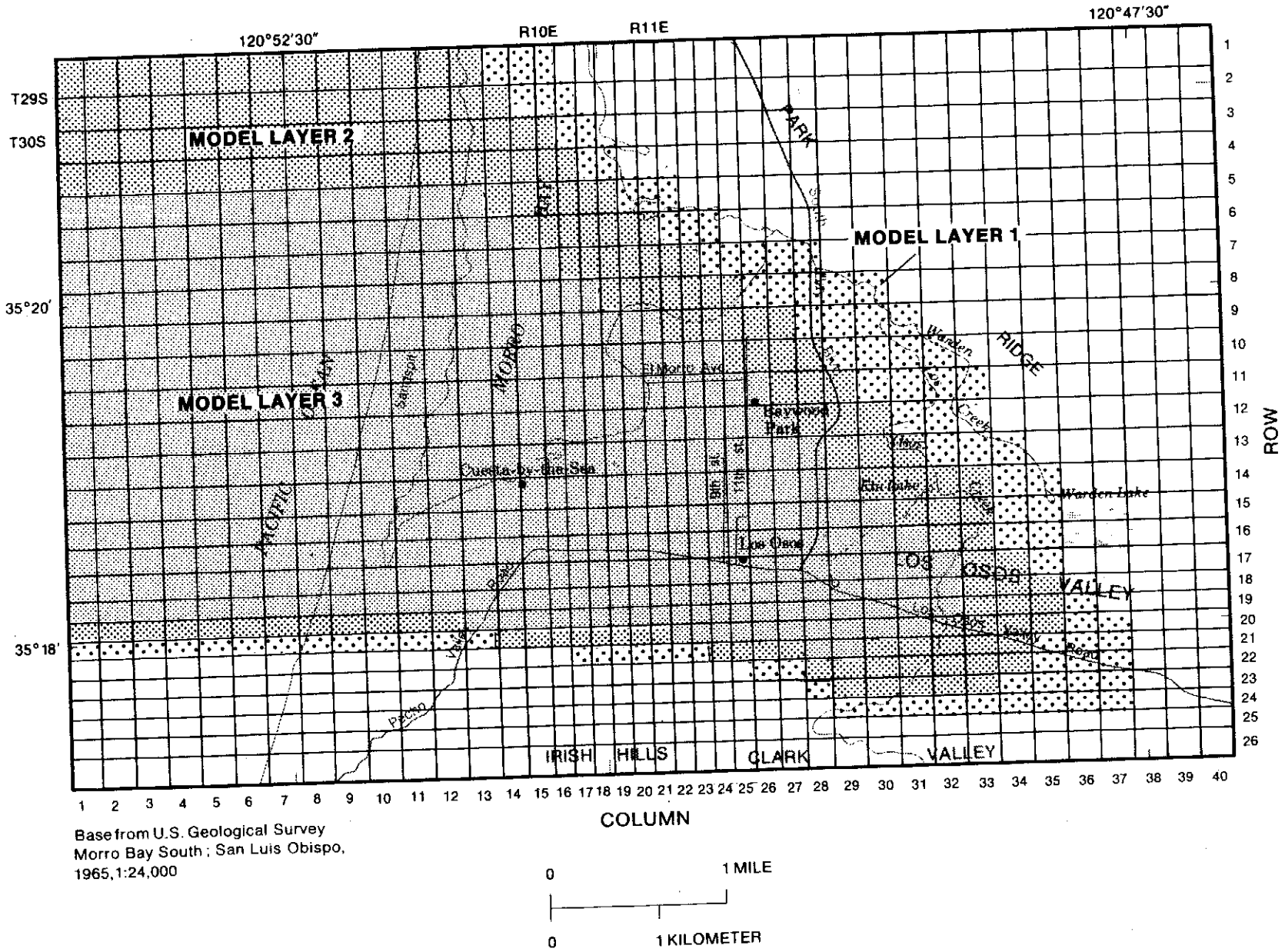
Aquifer characteristics.—The model is designed to simulate flow in the Paso Robles and Careaga Formations. Although these formations consist of numerous layers with widely varying hydraulic properties, individual layers are too thin and discontinuous to simulate individually throughout the basin. Instead, it was assumed that for basin-scale analysis the combined effect of all the layers would be equivalent to that of a homogeneous, vertically anisotropic porous medium. Model layers therefore generally do not correspond to specific strata; their primary purpose is to provide mathematical definition of vertical flow and potentiometric head gradients within the basin. One exception occurs west of Los Osos town center, where the interface between model layers 1 and 2 corresponds to an extensive clay layer. Flow through the surficial deposits of windblown sand was not simulated, because the model can simulate only saturated ground-water flow, and the sand deposits are largely unsaturated.

Horizontal and vertical hydraulic conductivity of the model layers are shown in figure 16. The zonation of hydraulic conductivity within each layer reflects the general tendency for basin fill to be coarser and more permeable near the axis of the basin. The clay layer between model layers 1 and 2 appears as zones of low vertical hydraulic conductivity in the western part of layer 1. The two faults crossing the southern boundary of the basin are barriers to ground-water flow and were represented as lines of nodes with low horizontal hydraulic conductivities.

Ground water is unconfined in model layer 1. Specific yield follows the same zones of uniformity as hydraulic conductivity (fig. 16). Where the water table is generally in the lower part of the windblown sand deposits, specific yield is 0.18. Values ranging from 0.10 to 0.15 are used where the water table is in the floodplain deposits or the Paso Robles Formation. These values were obtained in part by model calibration, and they are appropriate for the geologic materials in each zone.

Gravity drainage does not occur in layers 2 and 3, and so storage responses are similar to those of confined aquifers. Specific storage, which is the storage coefficient divided by aquifer thickness, was determined by calibration to equal 0.00003 per foot for all zones in layer 2 and 0.00002 per foot for all zones in layer 3. These values are larger than would be expected for an ideal confined aquifer in response to a short-term stress such as an aquifer test. The geology of the ground-water basin indicates, however, that the aquifer system is leaky rather than strictly confined. The large storage response could be due in part to a "delayed yield" effect caused by slow vertical leakage of water into the pumped aquifers from overlying and underlying strata. In a study of the Santa Barbara ground-water basin on the coast about 90 miles south of Los Osos, for example, calibrated storage coefficients ranged over four orders of magnitude, depending on degree of confinement (Martin and Berenbrock, 1986, p. 29). Another explanation of the large specific storage values in this study is that the calibration procedure matched potentiometric-head changes that occurred over periods of months and years, whereas aquifer tests generally measure changes over hours and days. In complexly layered alluvial ground-water basins, storage responses to long-term stresses are large compared to those for short-term stresses (Yates, 1988).

Boundary conditions.—The area of each model layer is indicated in figure 15. The onshore boundary of each layer follows the contact between basin fill and basement rocks for the average depth of that layer. No flow was assumed for these boundaries except where shallow inflow from adjacent surface-water subbasins



Base from U.S. Geological Survey
Morro Bay South; San Luis Obispo,
1965, 1:24,000

FIGURE 15.— Model grid and active cells for layers 1, 2, and 3 of the digital model.
Model layers overlap. Patterned areas show farthest extent of each layer.

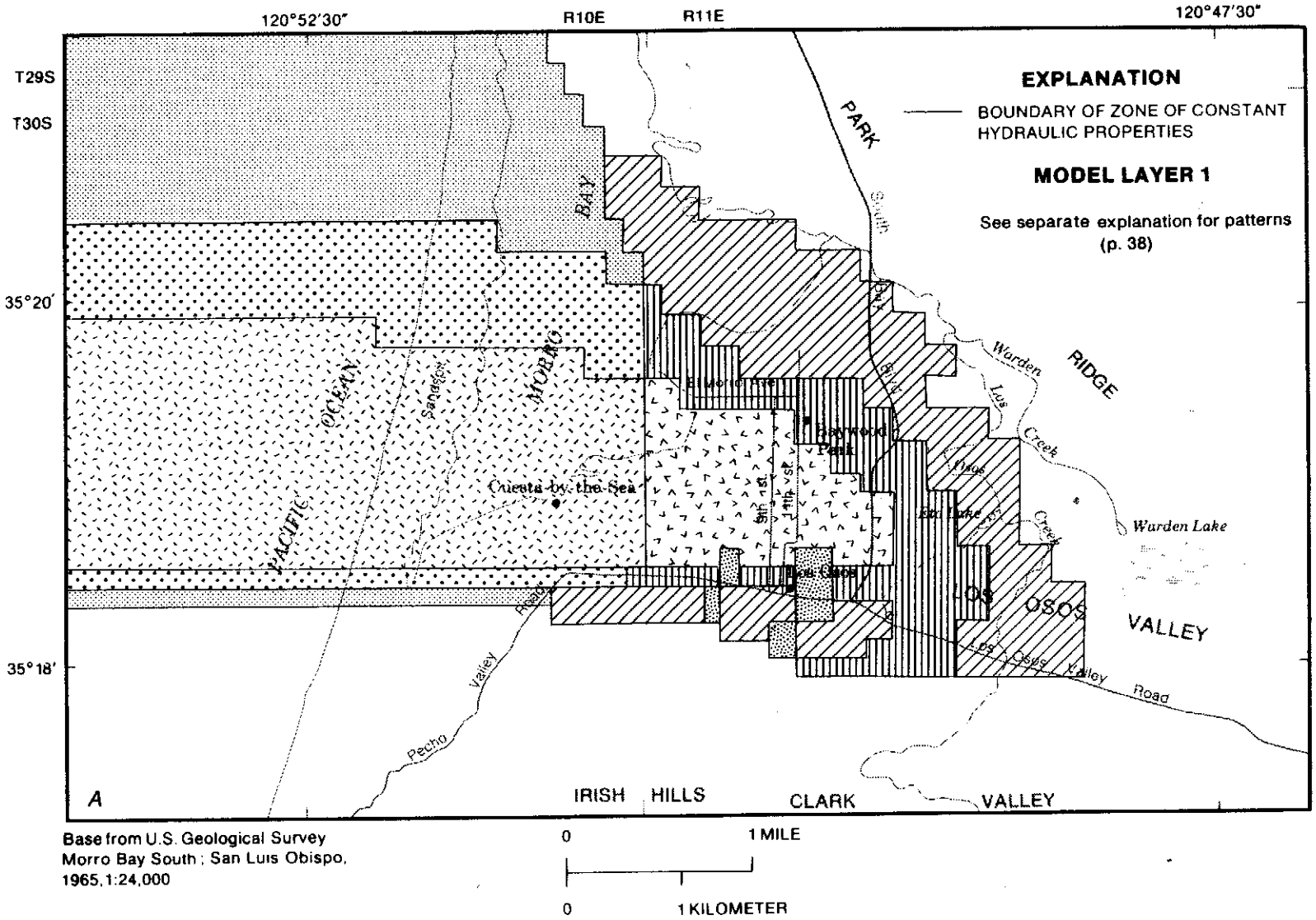


FIGURE 16.— Calibrated hydraulic properties of model layers 1, 2, and 3. *A*, Model layer 1.

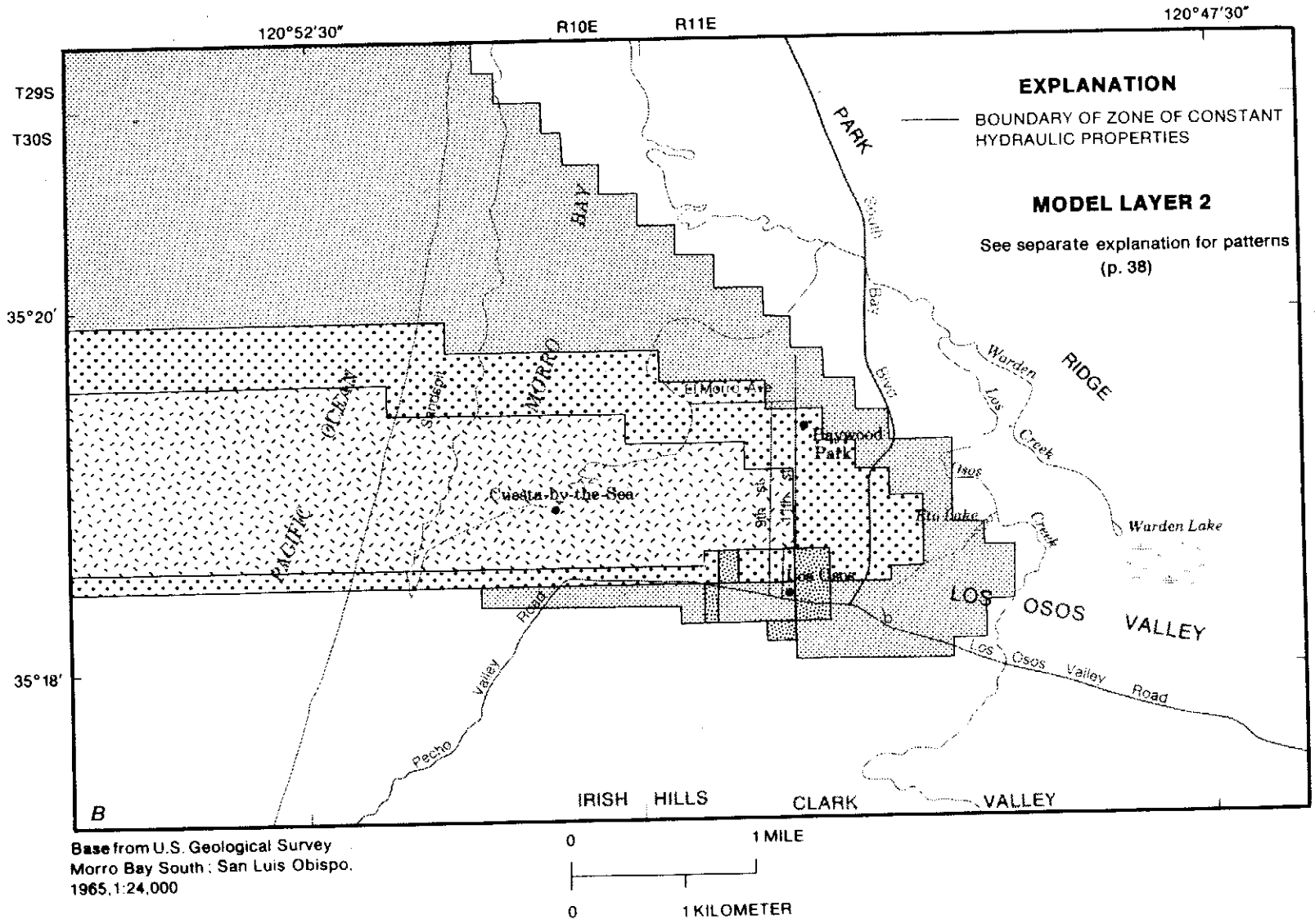


FIGURE 16.— Calibrated hydraulic properties of model layers 1, 2, and 3—Continued. *B*, Model layer 2.

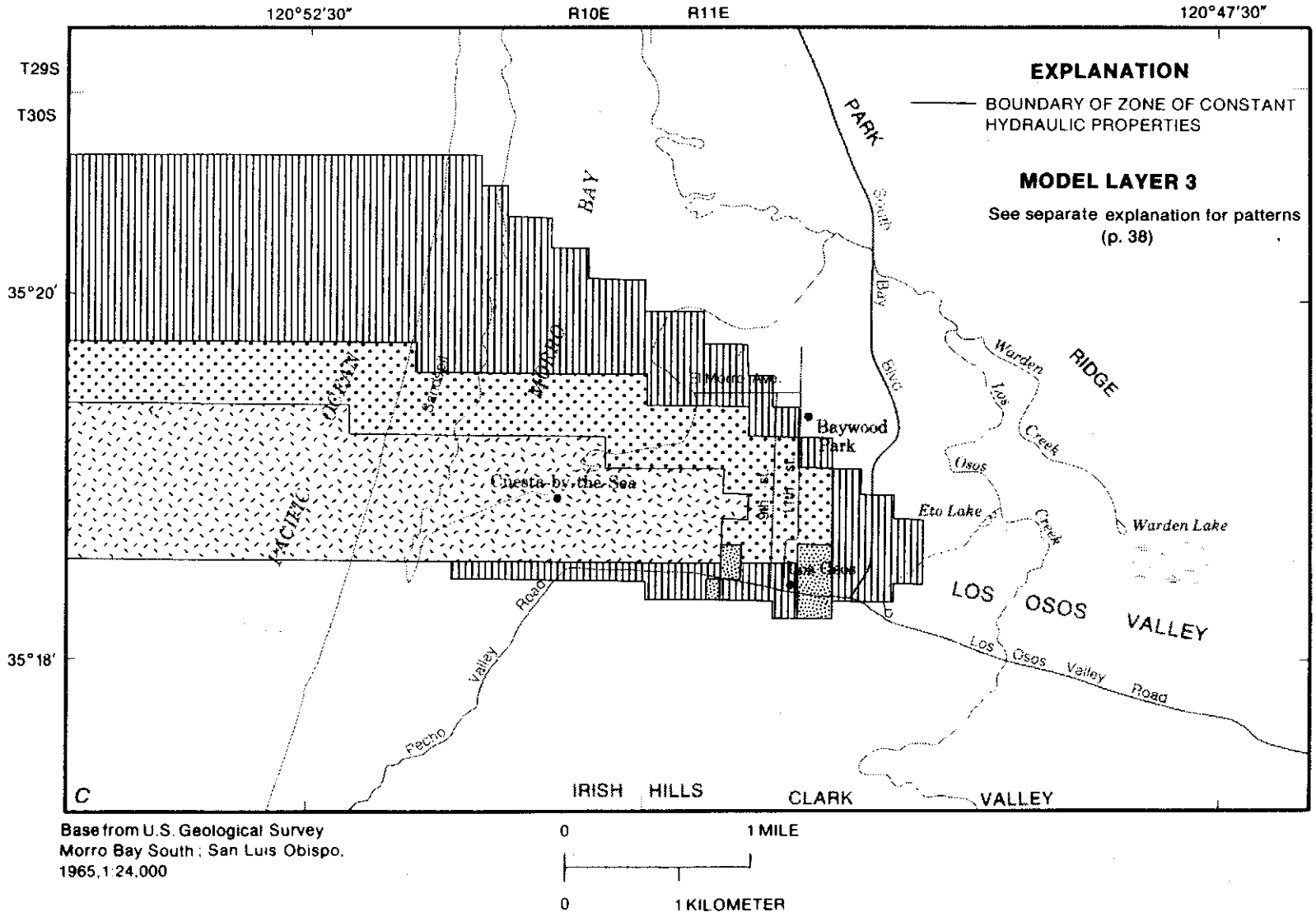


FIGURE 16.— Calibrated hydraulic properties of model layers 1, 2, and 3—Continued. *C*, Model layer 3.

EXPLANATION FOR FIGURE 16

	PATTERN	HORIZONTAL HYDRAULIC CONDUCTIVITY (FEET PER DAY)	VERTICAL HYDRAULIC CONDUCTIVITY (FEET PER DAY)	SPECIFIC YIELD (DIMENSIONLESS)	SPECIFIC STORAGE (PER FOOT)
LAYER 1 (fig. 16 *A*)		6	0.03	0.18	— —
		5	0.03	0.18	— —
		4	0.03	0.15	— —
		6	0.06	0.18	— —
		5	0.05	0.15	— —
		4	0.04	0.12	— —
		0.001	0.04	0.10	— —
LAYER 2 (fig. 16 *B*)		6	0.06	— —	0.00003
		5	0.05	— —	0.00003
		4	0.04	— —	0.00003
		0.001	0.04	— —	0.00003
LAYER 3 (fig. 16 *C*)		5	0.04	— —	0.00002
		4	0.04	— —	0.00002
		3	0.03	— —	0.00002
		0.001	0.04	— —	0.00002

was assumed to occur. For surface-water subbasins 1, 2, 3, 4, and 8 (fig. 8), inflow was allocated to boundary nodes in layer 1. Inflow from subbasin 7 was allocated to layer 2.

Hydraulic connection between ground water and the ocean was simulated by a head-dependent boundary including nodes along the ocean floor, the bottom of Morro Bay, and the vertical plane defining the west end of the model grid. The potentiometric head on the ocean side of the boundary was assumed to equal zero. In other words, no correction was made to account for the difference in density between seawater and fresh ground water. Sensitivity analysis of the model indicated that any errors due to this assumption would be small. As a consequence of this assumption, however, the model was unable to simulate the location or movement of the interface between saltwater and freshwater in the aquifers.

In the model system, vertical flow between the ocean and the aquifers is regulated by the coefficient of leakance of a hypothetical boundary layer representing seafloor sediments. This coefficient equals the hydraulic conductivity across the layer divided by the layer thickness. In the horizontal direction, a similar hypothetical layer represents aquifer materials beyond the western edge of the model grid. In the model, a coefficient of leakance of 0.01 per day was used at both the horizontal and vertical interfaces with the ocean. The western edge of the model boundary was placed about 2 miles offshore because this distance is large enough that errors in the offshore boundary conditions have a negligible effect on onshore potentiometric heads.

Inflow and outflow.—Some flows into and out of the ground-water system are not influenced by potentiometric heads. Examples include nonpoint recharge, pumpage, and ground-water inflow. These flows were calculated prior to each simulation and were included in the model as specified flows at appropriate nodes. Recharge from septic systems and deep percolation of soil moisture was assigned to nodes in layer 1. Nonpoint recharge near the center of the shallow clay perching layer west of Los Osos Creek (fig. 3) was assumed to emerge as flow in springs and be lost as surface runoff. Recharge near the edge of the perching layer was assumed to be displaced laterally to nodes in layer 1 adjacent to the perimeter of the layer. Pumpage from individual wells was distributed among the model layers according to the depths of the well screens.

Ground-water inflow from surface-water subbasins around the ground-water basin (fig. 8) was assumed to be approximately constant with time because low subsurface permeability and long travel times tend to diminish annual variations in flow. This inflow was allocated to nodes along the perimeter of layer 1. Inflow from subbasin 7 consists mainly of septic-system leachate and deep percolation from landscape irrigation. Monthly variations in this inflow were included in the model.

Other flows into and out of the ground-water basin are influenced by potentiometric heads and are referred to as head-dependent flows. Examples include seepage to and from Los Osos Creek, phreatophyte transpiration, flow across the ocean boundary, and flow to and from aquifer storage. These flows are calculated by the model during the course of each simulation to ensure that flows and potentiometric heads are mutually consistent.

Seepage from Los Osos and Warden Creeks was calculated using a discontinuous function of the difference in potentiometric head between the stream and adjacent ground water (McDonald and Harbaugh, 1984, p. 217). When ground-water heads near the stream were above the altitude of the bottom of the streambed, seepage was proportional to the wetted area of the streambed, the coefficient of leakage of the streambed, and the difference in altitude between the surface of the stream and the adjacent water table. The direction of seepage was out of or into the stream, depending on whether the stream surface was above or below the adjacent water table. When ground-water heads were below the bottom of the streambed, seepage occurred only when the stream was flowing and was always out of the stream and independent of the altitude of the water table.

The altitude of the surface of the stream is equal to the altitude of the streambed plus stream stage, and wetted area equals the length of the stream channel times the average wetted perimeter. Stream stage and wetted perimeter were calculated from stream discharge using two functions developed from manual discharge measurements and stream-channel geometry. The functions were fitted to emphasize accuracy at low flows. Because of their longer duration, low flows probably contribute a considerably larger volume of recharge than do brief peak flows. The following functions were assumed to be the same at all points along the stream channel:

$$S = 0.0164Q^{0.273} \tag{3}$$

$$W = \begin{bmatrix} 0.306Q^{0.249}, Q \le 3.5 \times 10^6 \\ 13.0 + 2S, Q > 3.5 \times 10^6 \end{bmatrix} \tag{4}$$

where

S is stream stage, in feet;

W is wetted perimeter, in feet; and

Q is stream discharge, in cubic feet per day.

Because of the nonlinear interdependence of streamflow and ground-water heads, these values were calculated simultaneously during model simulations using a modification of the method developed by Prudic and others (David Prudic, U.S. Geological Survey, written commun., 1986). The nonlinearity occurs because stream discharge and hence stream stage and wetted area change significantly along Los Osos and Warden Creeks as a result of seepage gains and losses. In order to maintain correct mass balance in the stream and calculate an appropriate stage and wetted perimeter for any point along its length, the creeks were divided into a series of reaches. Starting with the uppermost reach at the basin boundary and proceeding reach-by-reach in the downstream direction, mutually consistent values of ground-water head, seepage, and reach outflow were iteratively calculated.

Twenty-nine stream reaches were used in the model, each associated with a particular model node. Reach lengths ranged from 400 to 1,960 feet. The reaches were grouped into four segments reflecting the tributary relations among Los Osos Creek, Warden Creek, and streams entering from surface-water subbasins around the perimeter of the ground-water basin. Streambed thickness was assumed to be 1 foot. Vertical hydraulic conductivity of the streambed decreased from 3.0 ft/d where Los Osos Creek enters the valley to 0.12 ft/d at Morro Bay. This distribution is consistent with the observation that the clay content of the streambed increases markedly downstream of Los Osos Valley Road (fig. 1).

Phreatophyte transpiration was calculated by the model during each simulation according to the water-table altitude in model layer 1. At nodes where the water table was less than 10 feet below land surface, the transpiration rate was to equal the difference between potential evapotranspiration and actual evapotranspiration of soil moisture. Below 10 feet, the rate decreased linearly with water-table depth, reaching a value of zero at a depth of 18 feet. The latter depth corresponds approximately to the bottom of the root zone for native plants in the study area (Blaney and others, 1963, p. 30).

MODEL CALIBRATION

Procedure.—Calibration is a procedure in which selected variables in the model are individually adjusted within a range of reasonable values in order to improve the accuracy of model results. Variables calibrated in this model include horizontal and vertical hydraulic conductivity, storage coefficient, and coefficients of leakance of the ocean boundary and the streambed of Los Osos Creek. Model accuracy was evaluated by comparing simulated and measured potentiometric heads for water years 1970-77 and 1986. Measured data for 37 wells were used for 1970-77, and data for 60 wells were used for 1986. Simulated and measured seepage from Los Osos Creek during 1986 was also used as a basis for comparison.

Transient rather than steady-state simulations were used for model calibration because the recent rapid increases in water use probably mean that the ground-water basin was not in a steady state during either calibration period. Steady-state conditions probably also did not exist immediately prior to the start of the calibration periods. Instead of using simulated steady-state potentiometric heads at the start of each transient simulation—as is commonly done—measured heads from the period just before the start of the simulation were used. The model calculated potentiometric heads and head-dependent flows for each month of the two calibration periods. Simulated potentiometric heads at model nodes were interpolated in time and space to coincide exactly with the dates and locations of measured potentiometric heads, so that direct comparisons could be made between them.

Results.—Hydrographs of measured and simulated potentiometric heads at four wells during water years 1970-77 are shown in figure 17 and during the period from June 1985 to December 1986 in figure 18. Measured and simulated potentiometric heads are shown separately in figure 19 for the three model layers in September 1986; in figure 20, they are shown for layer 1 in March 1986.

Seasonal variations in potentiometric heads are generally greatest in the south-central part of the basin. In layer 1, potentiometric heads between the southern end of the sandspit and the southern end of South Bay Boulevard were 2 to 3 feet higher in March 1986 than in September 1986. Along the upper part of Los Osos Creek, potentiometric heads were 5 to 10 feet higher in March than in September. There were few or no seasonal changes in potentiometric heads along the lower part of Los Osos Creek and in the southeast corner of the basin. Seasonal variations in potentiometric heads in model layers 2 and 3 followed similar patterns, except that their magnitude was slightly greater in layer 3 than in layers 1 and 2.

Simulated annual water budgets for the ground-water basin during the two calibration periods are summarized in table 6. Some of the items in the water budgets warrant further clarification. Rainfall recharge is the remaining amount of nonpoint recharge calculated by the soil-moisture accounting algorithm after subtracting contributions from agricultural and urban irrigation return flow. Underflow of ground water across the ocean boundary into the basin is seawater intrusion.

Perched-water runoff is nonpoint recharge that is intercepted by the shallow clay layer west of Los Osos Creek and lost as surface runoff.

The sizes of individual items in the water budgets range over three orders of magnitude. Budget entries are rounded to the nearest 10 acre-ft/yr. Although the larger items are probably not accurate to three significant figures, this level of rounding was needed to retain the small items. Sensitivity analysis of the model demonstrated that small items varied predictably in response to changes in input data, and so their magnitudes were not simply the result of random errors in the large items.

Mass-balance error is the residual imbalance in the water budget after inflows, outflows, and storage changes are accounted for; it is the result of the numerical method used to solve the equations in the digital model. Head-dependent flows are calculated from simulated heads, which the model determines only to a specified level of precision. Increased precision requires more computer time. Heads were determined to within 0.01 foot in this model, and the mass-balance

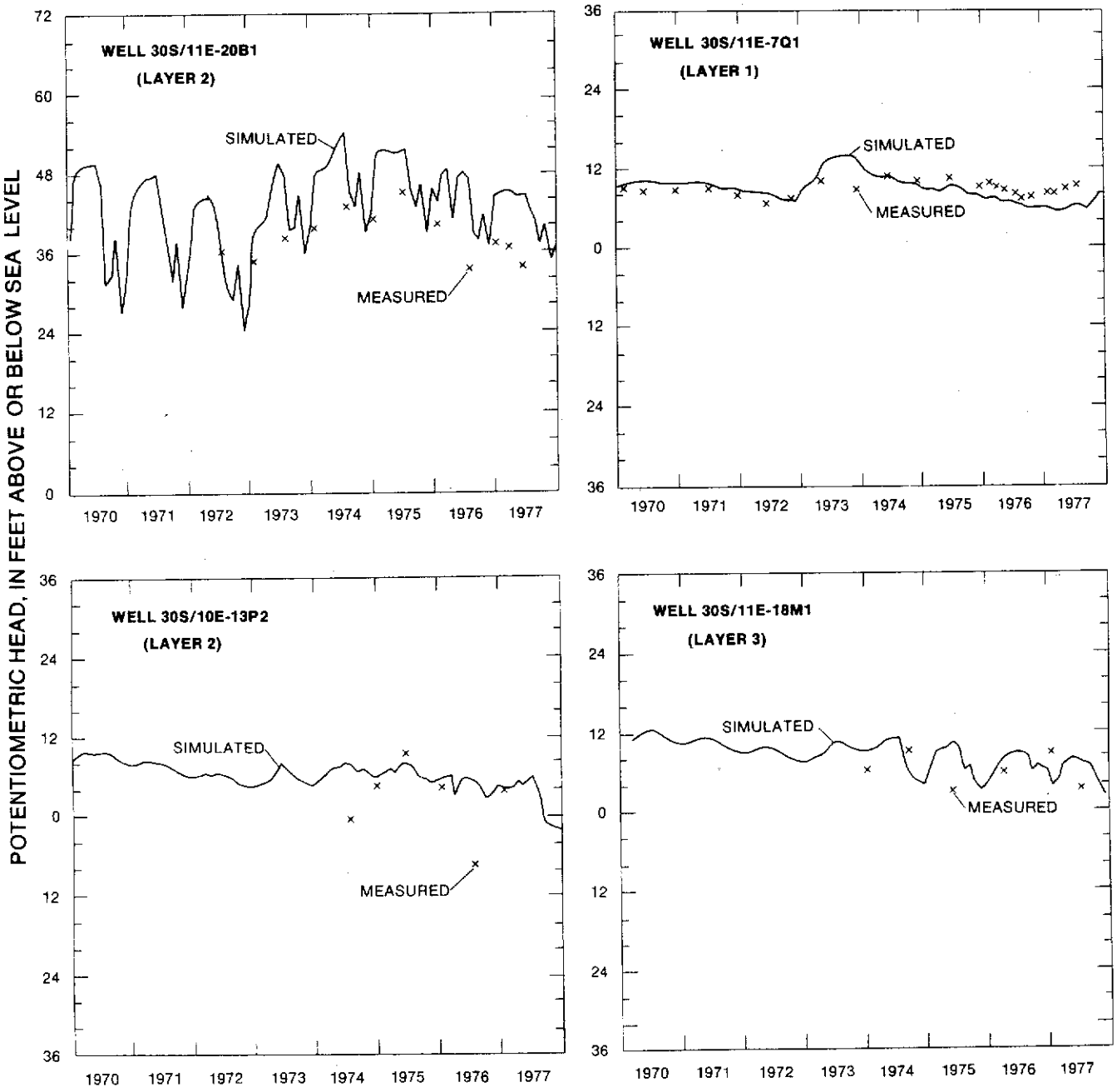


FIGURE 17.– Measured and simulated potentiometric heads at four wells, water years 1970-77.

error was less than 1 percent of the total budget for both calibration periods.

SENSITIVITY ANALYSIS

The accuracy of model results cannot be fully described with a single quantitative value. For historic periods, simulated heads can be compared quantitatively with measured heads only at well locations, and for simulations of hypothetical or future conditions even this is not possible. Sensitivity analysis, however, is a procedure similar to calibration that provides a quantitative estimate of the likely magnitudes of errors associated with individual variables in the model. For this study, data for individual variables in the model were changed one at a time by amounts roughly equal to the uncertainties in their values, and the corresponding changes in simulation results indicated the types and magnitudes of errors associated with the values of those variables.

Results of the sensitivity analysis of the model (table 7) include changes in heads as well as changes in head-dependent flows calculated by the model. Several

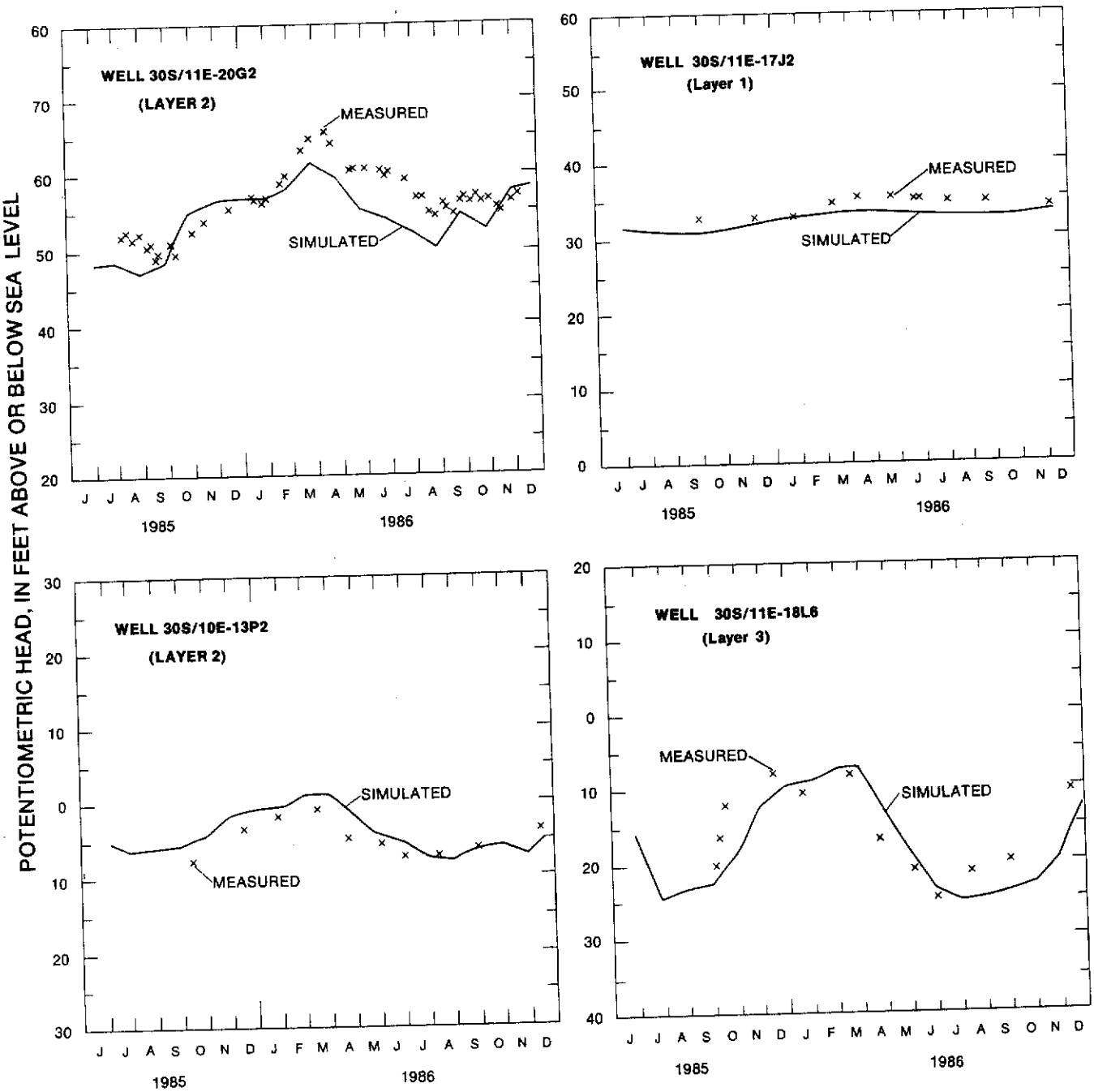


FIGURE 18.– Measured and simulated potentiometric heads at four wells, June 1985 to December 1986.

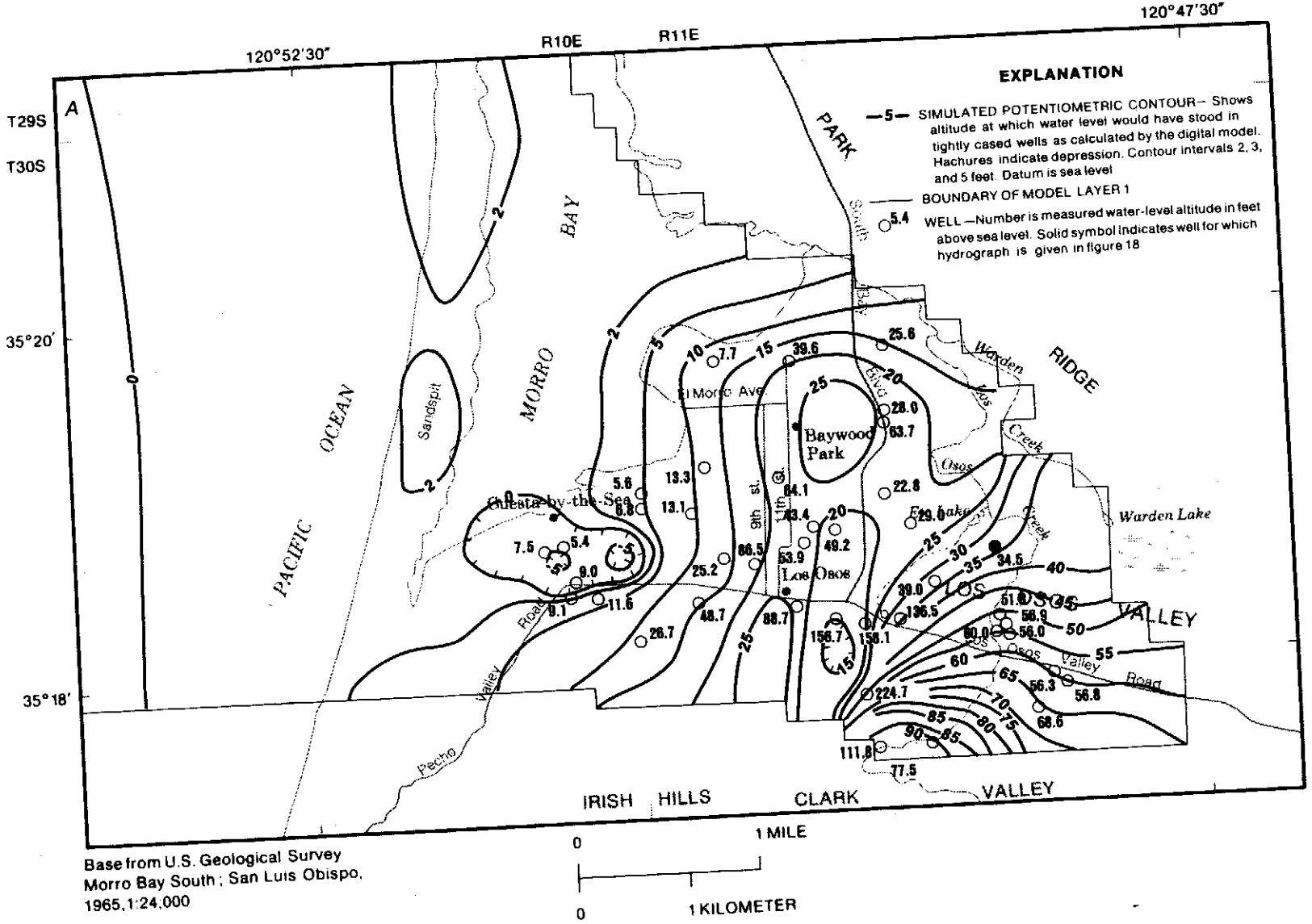


FIGURE 19.— Measured and simulated potentiometric heads for model layers 1, 2, and 3, September 1986.
A, Model layer 1.

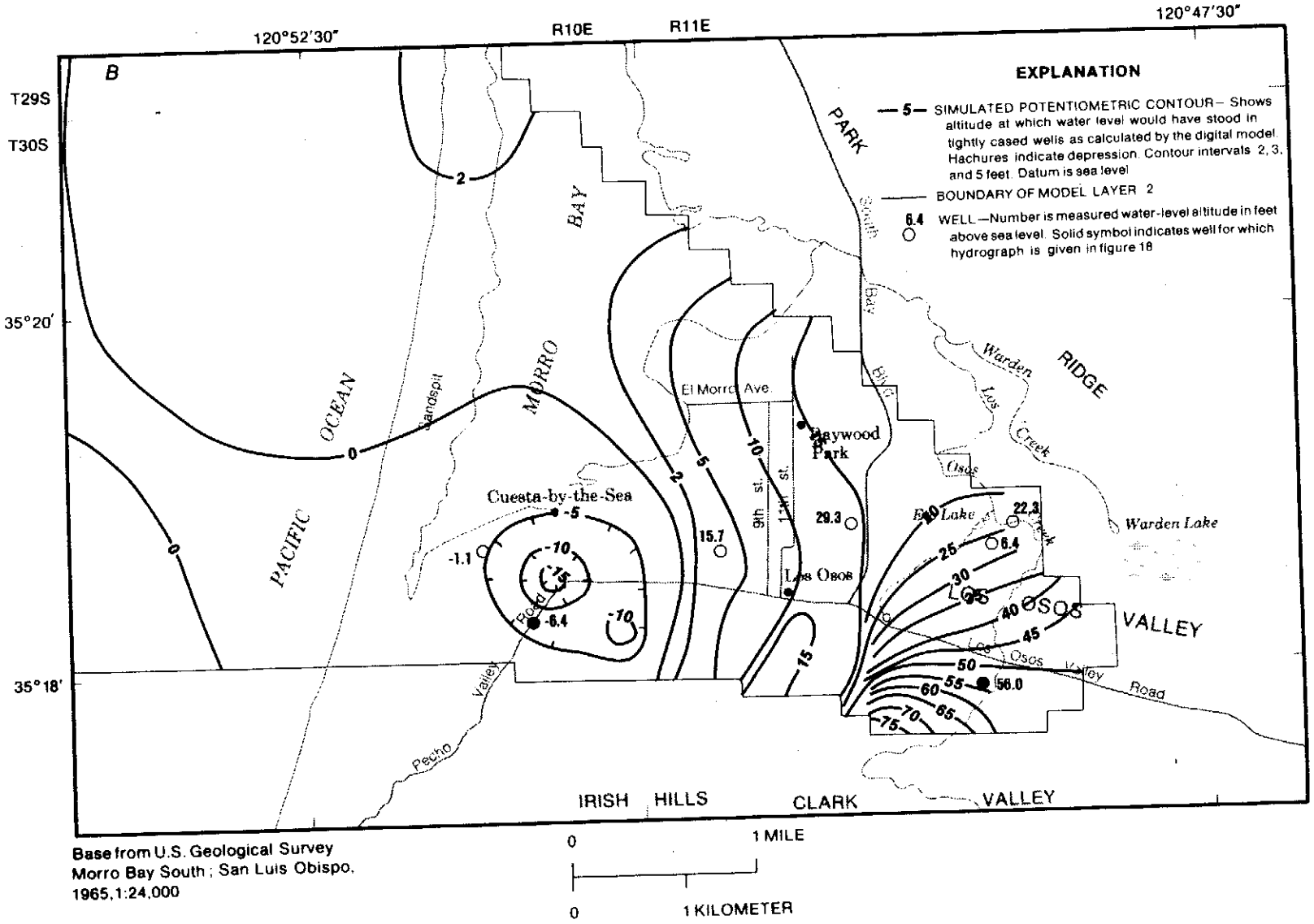
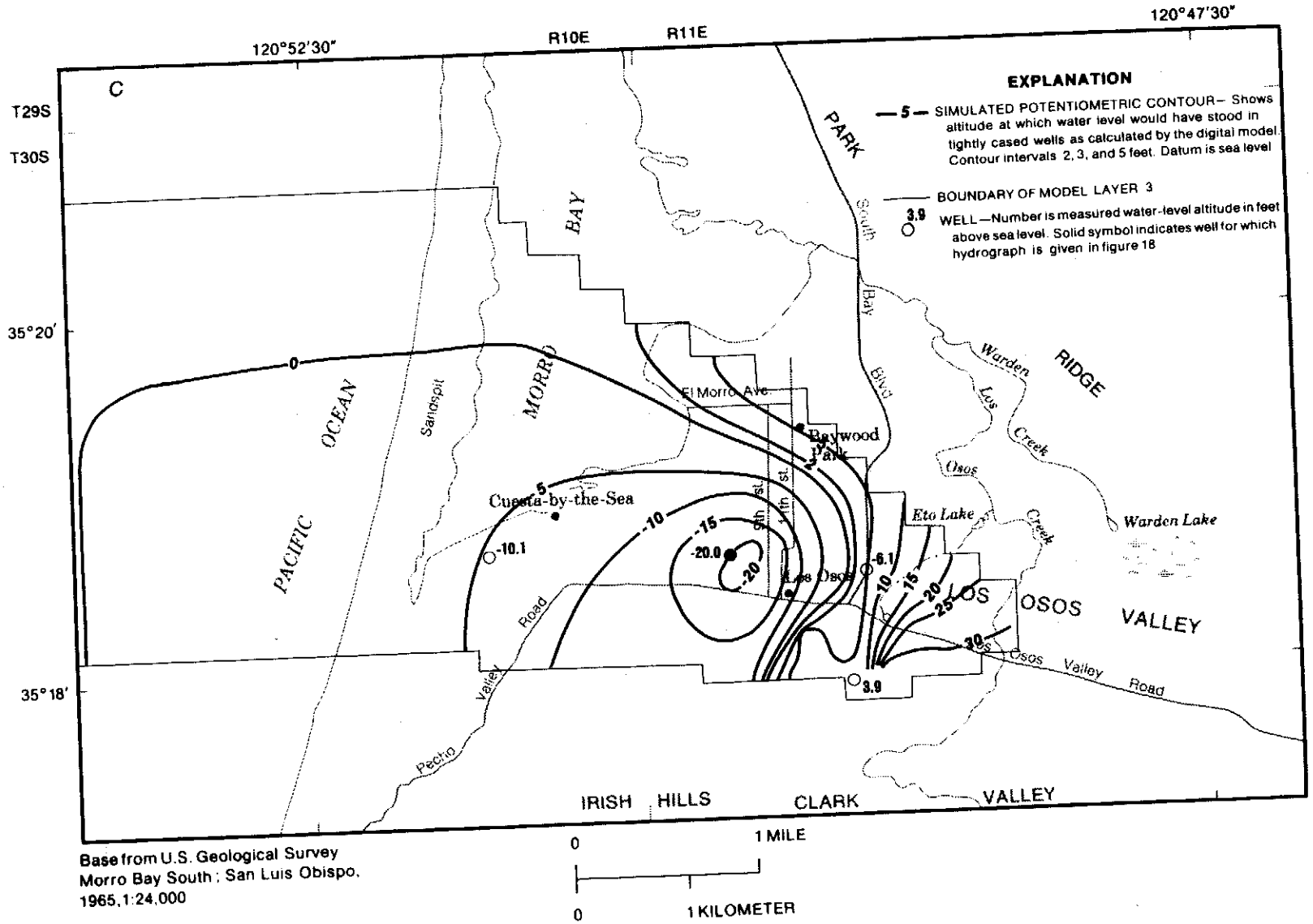


FIGURE 19.– Measured and simulated potentiometric heads for model layers 1, 2, and 3, September 1986 – Continued.
B, Model layer 2.



Base from U.S. Geological Survey
Morro Bay South; San Luis Obispo, 1965, 1:24,000

FIGURE 19.– Measured and simulated potentiometric heads for model layers 1, 2, and 3, September 1986 –Continued.
C, Model layer 3.

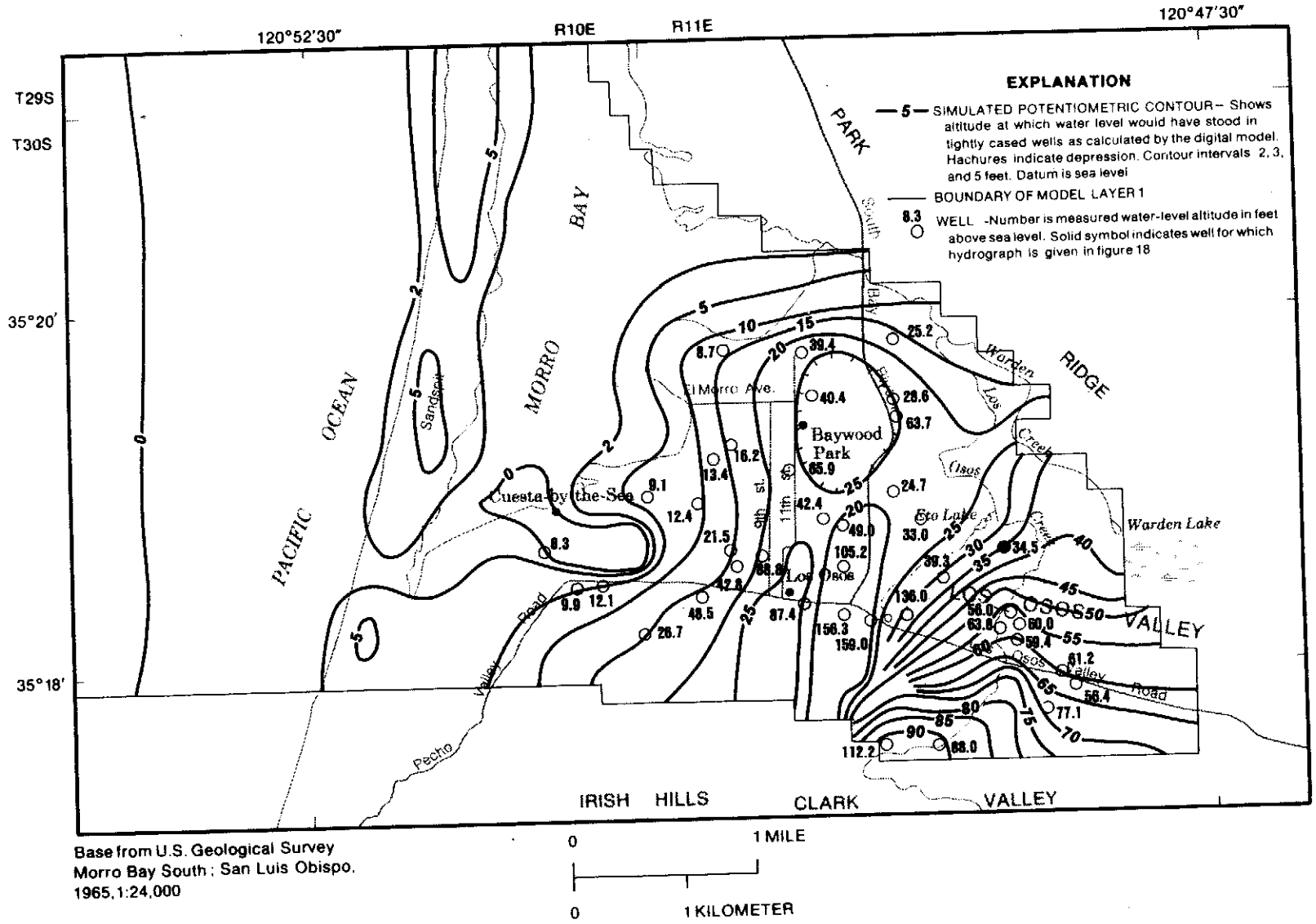


FIGURE 20.– Measured and simulated potentiometric heads for model layer 1, March 1986.

Table 6.—*Simulated annual water budgets for Los Osos Valley ground-water basin during water years 1970-77 and 1986*

[All values are in acre-feet per year. Values for 1970-77 are averages for that period. Positive net flow indicates flow into basin; negative net flow indicates flow out of the basin. <, less than]

Budget item	1970-77			1986		
	Inflow	Outflow	Net flow	Inflow	Outflow	Net flow
Rainfall recharge	1,300	0	1,300	2,530	0	2,530
Los Osos Creek seepage	390	440	-50	690	640	50
Ground-water underflow:						
Onshore boundaries	320	0	320	420	0	420
Ocean boundary	0	1,030	-1,030	<10	590	-590
Municipal water use:						
Community well pumpage	0	940	-230	0	2,220	-550
Private well pumpage	0	180		0	210	
Septic percolation	740	0		1,550	0	
Irrigation return flow	150	0		330	0	
Agricultural water use:						
Pumpage	0	800	-480	0	970	-570
Irrigation return flow	320	0		400	0	
Phreatophyte transpiration	0	310	-310	0	200	-200
Perched-water runoff	0	110	-110	0	360	-360
Total inflows and outflows			-590			730
Net storage change			-620			690
Mass-balance error			30			40

assumptions about the ocean boundary were tested in addition to initial heads and variables involved in aquifer flow, stream seepage, nonpoint recharge, septic-system return flow, and pumpage. Except for the tests of the ocean boundary, the reference simulation for each test was similar if not identical to the final calibrated simulation of water year 1986. It was assumed that the flow system was linear; that is, it was assumed that increases and decreases in the test variables would have equal and opposite effects.

In table 7, effects of variables on stream seepage are indicated by net stream recharge, which equals seepage from Los Osos Creek minus seepage to the creek. Changes in streambed hydraulic conductivity affect both directions of seepage approximately equally and consequently do not affect net recharge as much as might be expected. Variables that affect ground-water levels adjacent to the creek have opposite influences on stream gains and losses and consequently have a large effect on net stream recharge. These variables include horizontal hydraulic conductivity, specific yield, agricultural irrigation efficiency, septic-system return flow, and initial potentiometric head.

Initial potentiometric head has a large effect on water budgets for short simulations such as the 1985-86 calibration simulation. Initial head at each model node for this simulation was estimated by spatial interpolation of potentiometric heads measured in spring 1985. The effects of measurement errors and errors in the interpolation process were tested by comparing simulation results with a simulation in which initial heads were 3 feet higher at all nodes. The higher heads were clearly inaccurate in offshore areas. In water year 1986, they resulted in an increase of 1,310 acre-ft (220 percent) in calculated outflow to the ocean. Onshore, higher water levels caused a decrease in net stream recharge from +50 to -180 acre-ft. Ground-water levels and flows also tended to shift back toward the values originally determined during calibration. In some locations, the initial 3-foot difference in potentiometric head decreased continuously throughout the simulation. There was also a net decrease in aquifer storage of 930 acre-ft during water year 1986. In contrast, the calibration simulation indicated a net increase in aquifer storage of 683 acre-ft, which is more consistent with the wetter-than-average climatic conditions during water year 1986.

During model development, effects due to the density difference between seawater and freshwater were assumed to be negligible. The validity of this assumption was qualitatively indicated by implementing alternative assumptions in several simulations. Under the alternative assumptions, the hydraulic head of seawater on the ocean side of the boundary was increased to the equivalent freshwater

Table 7.—*Results of sensitivity analysis of the digital model*

[Net stream recharge is seepage from Los Osos Creek minus seepage to Los Osos Creek. Use of aquifer storage is average of annual sums of monthly flows to and from storage. Simulations were of the 1985-86 period unless otherwise noted. Values are in acre-feet per year unless otherwise noted. ET, evapotranspiration. ft/d, feet per day]

Variable changed	Amount of change	Effect			
		Net stream recharge	Outflow to ocean	Seawater intrusion	Potentiometric head
Horizontal hydraulic conductivity.	-1 ft/d in all layers and zones	-57	-44	0	Recharge mounds higher and pumping depressions deeper by 2 to 5 feet
Vertical hydraulic conductivity.	-50 percent in all layers and zones	-11	-69	0	Higher by as much as 3 feet near creek in layer 1. Lower by 1 to 4 feet in layer 2 and 2 to 6 feet in layer 3
Specific yield.	-0.05 in all zones of layer 1	-72	-2	2	Seasonal fluctuations as much as 8 feet greater near creek in layer 1, and 1 to 2 feet greater in layers 2 and 3
Specific storage.	-90 percent in layers 2 and 3	-5	5	3	No change in layer 1. Total amplitude of seasonal fluctuations greater by up to 6 feet in layer 2 and 10 feet in layer 3
Streambed hydraulic conductivity.	-20 percent	-43	0	0	Lower by 2 to 4 feet in layer 1 near creek during winter and spring flow season
ET by native and nonirrigated plants.	-20 percent	-7	3	0	Higher by less than 1 foot in layer 1 near urban areas
ET by crops.	-22 percent	-22	1	0	Generally higher by 1 to 3 feet throughout floodplain in layer 1, and by 2 to 5 feet in summer near agricultural wells
Agricultural irrigation efficiency.[1]	-0.2 (from 0.6 to 0.4)	-88	0	0	In summer, lower by 10 to 20 feet near agricultural wells and lower by 1 to 3 feet throughout the floodplain
Municipal pumpage.	-20 percent	15	8	-6	Higher near urban areas by 1 foot in layer 1 and 2 to 7 feet in layers 2 and 3
Septic return flow.	11 percent	-10	6	0	Higher by up to 1 foot in layer 1 near urban areas.
Initial potentiometric head.	3 feet at all nodes	-230	1,310	-4	Higher by up to 3 feet in offshore areas in all layers. Tendency in most areas to converge to same heads as in calibration simulation
Ground-water inflow.	294 acre-feet per year	-28	6	-2	Higher by 1 to 3 feet in layers 1 and 2 along southern edge of basin. Little change north of Los Osos Valley Road

[1]Irrigation efficiency is the fraction of applied water actually consumed by crop evapotranspiration. For this test, the decrease in efficiency was achieved by increasing applied water (pumpage), rather than by decreasing consumptive use.

head. Also, the interface between saltwater and freshwater was assumed to be a no-flow boundary of the fresh ground-water basin. The interface was assumed to be located near the sandspit. Similar assumptions have been used in ground-water models of other coastal areas (Guswa and LeBlanc, 1985; Ryder, 1985). To incorporate these assumptions accurately in this model, the position of the interface would have to be adjusted until simulated head in the adjacent active nodes equalled the freshwater-equivalent head of seawater at the node altitudes. This trial-and-error adjustment process would have to be done for each row of nodes in each model layer in every time step of every simulation, because the interface can be at different locations in different aquifers and can move with time. The cursory sensitivity analysis indicated that the alternative boundary assumptions had little effect on the overall water budget or on simulated potentiometric head in onshore areas. Simulated heads in the immediate vicinity of the assumed interface location may be strongly affected, however.

In other sensitivity tests, the percentage change in every head-dependent flow was almost always less than the percentage change in the input variable. The one exception was the test of specific yield in layer 1. Specific yield was decreased by 0.05 in all zones, corresponding to percentage decreases ranging from 28 to 50 percent. The result was a 144 percent decrease in net stream recharge and a 50 percent increase in seawater intrusion. However, these large percentage changes are primarily a consequence of the small magnitude of the reference flows (50 acre-ft/yr of net stream recharge, and 4 acre-ft/yr of intrusion).

In general, the results of the simulation of the 1985-86 period were not highly sensitive to errors in data for individual variables. Sensitivity to simultaneous errors in combinations of variables was not investigated. The reliability of any particular aspect of model results should be evaluated according to the uncertainties of the variables that most strongly affect it. For example, the 50 acre-ft of net stream recharge calculated for water year 1986 may not be significantly greater than zero, given that relatively small errors in the estimates of horizontal hydraulic conductivity, specific yield, or agricultural irrigation efficiency could cause errors in net stream recharge of about that magnitude.

ANALYSIS OF HYDROLOGIC SYSTEM

Measured potentiometric heads for layer 1 (figs. 19-20) show a high degree of spatial variability. This variability may result partly from random errors in measurement, but probably it results chiefly from local perched water-table conditions and vertical head gradients in the upper part of the ground-water basin. The model simulates vertically averaged heads for the entire 160-foot thickness of layer 1 and cannot simulate perched water tables. This limitation is particularly evident in the vicinity of the perching clay layer west of Los Osos Creek (fig. 3), where measured heads are especially variable and often considerably higher than the simulated heads. The model also does not account for local variations in aquifer properties, which contribute additional variation to the measured heads. These limitations restrict the ability of the model to accurately simulate measured heads at every well.

Simulated potentiometric heads were compared with 596 head measurements from 59 wells during the 1985-86 calibration period. The median error (measured head minus simulated head) was 4.4 feet. The mean error was larger (17.3 feet), indicating a positively skewed distribution. The skew was primarily the result of seven "outlier" wells at which simulated heads were consistently much lower than measured heads. The seven wells are 30S/11E-17N3, -17N4, -18J6, -18L4, -18Q1, -18R1, and -20E1. These are all shallow wells in the vicinity of the intersection of South Bay Boulevard and Los Osos Valley Road, where perching clay layers and lenses are known to occur. The deepest well is only 86 feet deep, and four of the wells are less than 50 feet deep. These wells probably draw from perched ground water, which the model is unable to simulate.

These seven "outlier" wells accounted for most of the scatter in the data. A total of 65 measurements were made at these wells. Omitting them from the error analysis decreased the standard deviation of the errors from 37.2 feet to 13.0 feet. The revised median and mean were 3.4 and 5.9 feet, respectively. The median error is still greater than zero, and the distribution is still slightly positively skewed, apparently indicating that the model generally tends to underestimate potentiometric head. Even the largely revised statistics may be biased, however, because measured heads were not distributed uniformly throughout the basin fill but were predominantly from shallow wells where perching and steep vertical head gradients are likely to occur. In general, simulation of head in the lower part of layer 1 was reasonably good.

The cumulative distribution of absolute errors, with and without the seven "outlier" wells, is shown in figure 21. When all measurements are included, 90 percent of the errors are less than 67 feet; when measurements from the seven wells are omitted, 90 percent of the errors are less than 27 feet.

Fewer measured heads are available for model layers 2 and 3. Many of them are from large-capacity

production wells and may reflect significant errors due to residual drawdowns. Nevertheless, general patterns are evident, which the model simulated reasonably well. Vertical head gradients are almost always downward and tend to be smallest near the lower end of Los Osos Creek and greatest near large-capacity municipal wells and the upper end of Los Osos Creek. Although small downward gradients might have occurred under natural conditions, present-day gradients are steep because most pumpage comes from deep strata while all recharge and return flow occurs near the land surface. In September 1986, the difference in heads between layers 1 and 3 was about 2 feet near the mouth of Los Osos Creek, 25 to 35 feet near wells 30S/10E-13P2 and 30S/11E-18L2, and 10 to 20 feet between South Bay Boulevard and Los Osos Creek. A 15-foot difference between layers 1 and 2 occurred where Los Osos Creek first enters the valley. Near large municipal wells, vertical head gradients in March 1986 were smaller than those in September because seasonal decreases in water use resulted in smaller pumping depressions in deep strata.

The downward head gradients have important long-range water-quality implications. Even in the western part of the basin, where there is an apparently continuous clay layer, model results indicated that a significant amount of recharge to deep strata must come from downward percolation of return flow. Seepage from Los Osos Creek is insufficient to supply present pumping rates, and the absence of widespread seawater intrusion indicates that the ocean is also not the principal source of supply. The most likely source is downward percolation of return flow. Although at present only shallow wells have been affected by poor-quality return flow, it is likely that deep wells eventually also would be affected.

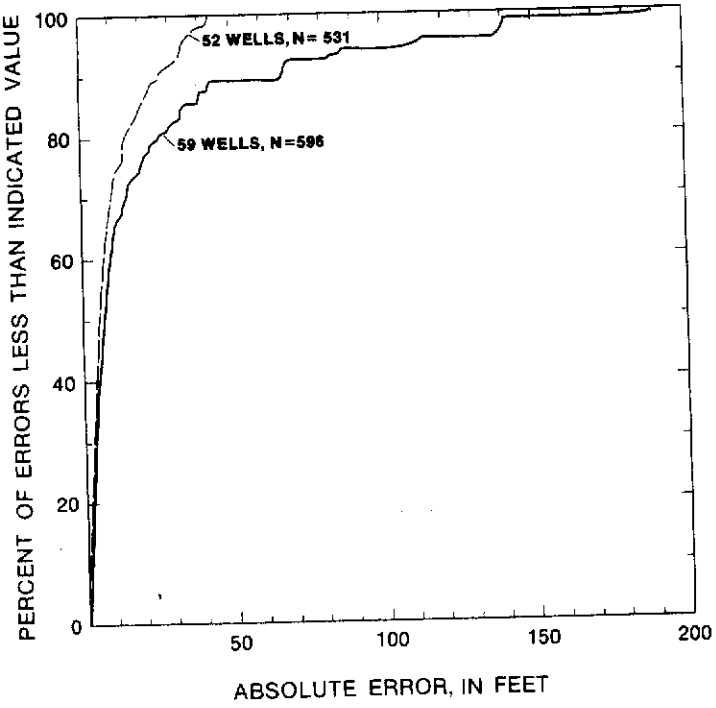


FIGURE 21.—Cumulative distribution of errors in the calibrated simulation of the period from June 1985 to December 1986. N, number of measurements.

Measured heads at well 30S/11E-19H2 near the southern boundary of the basin during 1986 clearly demonstrate that the easternmost of the two faults entering the basin from the south acts as a flow barrier. Heads at the well were less than 10 feet above sea level throughout the year. The well is a deep observation well, and there are no nearby deep pumping wells. Heads at well 30S/11E-20M2, which is only 2,000 feet away but on the opposite side of the eastern fault, were consistently between 111 and 114 feet above sea level. Well 20M2 is a pumping well, but the water level in it is closely related to flow in nearby Los Osos Creek. The stream-bed altitude near the well is about 120 feet above sea level. The steep head gradient between the wells indicates a low transmissivity, presumably because of the fault. The westernmost of the two faults also was assumed to act as a flow barrier.

Upstream of the Los Osos Valley Road bridge, ground-water levels are generally below the streambed of Los Osos Creek. Except for seasonal inflow of perched water from the shallow clay layer west of the creek, seepage is mostly out of the creek and independent of ground-water levels. Along Warden Creek and Los Osos Creek downstream of Eto Lake, ground-water levels are generally above the level of the streambed. In those areas, seepage is mostly head dependent and into the creek.

A comparison of the simulations of the 1970-77 and 1986 calibration periods illustrates the complex but predictable interaction of various components of the hydrologic system. All differences between the potentiometric heads and budgets for the two calibration periods can be explained by differences in rainfall and urbanization. Rainfall in 1986 was 37 percent greater than average annual rainfall during 1970-77. Predictably, seepage was greater from the upper part of Los Osos Creek because of larger and more prolonged flow. Rainfall recharge was also greater, and there was a net increase in aquifer storage (table 6).

The amount of urban development in the ground-water basin increased from about 880 acres during 1970-77 to about 1,430 acres in 1986. Net pumpage, which is the sum of all types of pumpage minus the sum of all types of return flow, increased from 710 to 1,120 acre-ft/yr. This increase in net pumpage

was offset by decreases in other outflows, mainly phreatophyte transpiration and outflow to the ocean. Seepage to Los Osos Creek also increased because adjacent ground-water levels along the lower reaches were higher, principally because of septic-system return flow. In fact, increased pumpage associated with urbanization has generally increased vertical head gradients, because of increased pumpage from the bottom part of the basin and additional return flow at the land surface. For example, in September 1977 the head differences between model layers 1 and 3 were typically 5 to 10 feet near South Bay Boulevard, 10 to 15 feet in the southern part of the Los Osos Creek floodplain, and up to 25 feet near Ninth Street. In September 1986, the differences had increased to 15 to 20 feet near South Bay Boulevard, 15 to 25 feet in the southern part of the floodplain, and up to 35 feet near Ninth Street.

The possibility that fractured basement rocks might allow a significant amount of ground-water inflow from Clark Valley or Hazard Canyon (fig. 8) still cannot be ruled out. During sensitivity analysis of the model, the effects of this ground-water inflow appeared similar to the effects of a decrease in net agricultural pumpage. Net agricultural pumpage could be estimated only approximately because of uncertainties in the amount of irrigation return flow and the effects of coastal fog on crop water use. Ground-water inflow from basement rocks was not included in the final calibrated model because measured and simulated heads can be matched acceptably by using reasonable values of irrigation return flow and crop water use. An equally acceptable match, however, could have been obtained by assuming several hundred acre-ft per year each of ground-water inflow and additional net pumpage.

The ultimate sources and fates of ground water in the basin become more evident when related inflows and outflows are combined as indicated by the net flows (table 6). For example, seepage from Los Osos Creek is largely offset by seepage to Los Osos Creek, and pumpage is largely offset by septic percolation and irrigation return flow. Several important conclusions can be drawn from the net-flow data. Rainfall recharge is clearly the main source of recharge, accounting for 2,530 acre-ft (84 percent) of net inflow to the basin in water year 1986. Net ground-water inflow across onshore boundaries accounted for most of the remaining 16 percent (420 acre-ft), and net recharge from Los Osos Creek was almost negligible (50 acre-ft). The amount of net pumpage for municipal use increased from 230 to 550 acre-ft/yr between 1970-77 and 1986. Net agricultural pumpage increased from 480 to 570 acre-ft/yr. A decrease in net outflow to the ocean from 1,030 to 590 acre-ft/yr compensated for the pumpage increases. Net pumpage accounted for 49 percent of net outflow from the basin in 1986, up from 33 percent during 1970-77.

A comparison of annual inflow and outflow rates with the total amount of water in storage indicates the extent to which basin storage capacity is utilized. In April 1986, the total volume of fresh ground water in the ground-water basin was about 270,000 acre-ft. This number was obtained by multiplying the saturated volume of each basin-fill formation by its estimated specific yield. Because of the large amount of clay in the Paso Robles Formation, specific yield throughout model layers 2 and 3 was assumed to equal 0.10. The western limit of fresh ground water was assumed to be located just east of the sandspit. Of the total volume of fresh ground water, about 14,000 acre-ft is above sea level. Inflow and outflow during water year 1986 were both between 5,000 and 6,000 acre-ft, roughly 40 percent of the amount of fresh water stored above sea level.

Several characteristics of rainfall recharge are not evident from the water-budget data. In areas of native vegetation, deep percolation occurs only during wet years. The soil-moisture accounting algorithm indicated that deep percolation (ground-water recharge) occurred during only 4 to 6 of the 96 months in the 1970-77 period. This time distribution is similar to that of recharge observed by Blaney and others (1963, p. 36). Recharge from rainfall is increased by urbanization, as long as storm drains are not installed. Rainfall on impervious surfaces runs off and becomes concentrated on adjoining soil areas, where it quickly saturates the soil and initiates deep percolation. Rainfall recharge is also increased by irrigation in agricultural and urban areas. Irrigated soils usually contain much more water at the end of summer than do nonirrigated soils. During the following winter, less rainfall is required to saturate the soil and initiate deep percolation.

SIMULATION OF WATER-RESOURCES MANAGEMENT ALTERNATIVES

In 1983, nitrate concentrations in shallow ground water throughout most of Los Osos and Baywood Park were greater than 45 mg/L (Brown and Caldwell, 1983, fig. 5-3). These concentrations exceeded the maximum contaminant level for drinking water set by the State of California (1985). In 1983, the California Regional Water Quality Control Board, Central Coast Region, imposed a prohibition on septic-system discharges after November 1, 1988. In response to the prohibition, San Luis Obispo County initiated plans to construct centralized wastewater collection and treatment facilities for the Los Osos area. The facilities might increase the risk of seawater intrusion if the treated

wastewater is exported from the basin, and so the county also began considering plans to recharge reclaimed wastewater and to import surface water from outside the basin.

Any major changes in water demand, source of supply, and wastewater disposal are likely to have significant local and basinwide effects on ground-water levels and flow. The ground-water flow model described in this report was used to simulate the hydrologic effects of various water-resources management alternatives for the Los Osos area.

DESCRIPTION OF ALTERNATIVES

The seven water-resources management alternatives evaluated for this report represent combinations of various options for water supply, wastewater treatment, and wastewater disposal. The options for each alternative are indicated in table 8. The alternatives were evaluated for conditions expected to occur around the year 2010. According to projections by the San Luis Obispo County Planning Department, the population of the Los Osos area is expected to increase from 14,660 in 1985 to about 35,000 in 2010. Annual municipal water use during the same period is expected to increase from 2,430 to 4,130 acre-ft/yr (Mark van Vlack, California Department of Water Resources, written commun., 1987). Housing density in existing residential areas was assumed to increase slightly during that period, and new residential development was assumed to fill in around existing residential areas to form the urban area shown in figure 22. Agricultural land use and irrigation practices in 2010 were assumed to be the same as in 1986.

All alternatives were evaluated under normal climatic conditions. In addition, several alternatives were simulated under wet and (or) dry climatic conditions (table 8), including those most likely to cause undesirable hydrologic effects during periods of

Table 8.—*Simulated annual water budgets for the Los Osos Valley ground-water basin in the year 2010 for alternatives 1 through 7 under various climatic conditions*

[Values are in acre-feet. <, less than]

Budget item	Alternative 1: All ground water with septic systems					Alternative 2: Ground water and imported water with septic systems		
		Wet		Dry			Wet	
	Normal	First year	Third year	First year	Third year	Normal	First year	Third year
INFLOW								
Ground-water inflow	400	600	600	350	350	400	600	600
Seepage from Los Osos Creek	600	640	420	40	40	340	290	220
Septic percolation	2,660	2,660	2,660	2,660	2,660	2,660	2,660	2,660
Wastewater recharge	0	0	0	0	0	0	0	0
Irrigation return flow:								
Agricultural	400	370	370	440	440	400	370	370
Urban	540	580	580	610	610	540	580	580
Rainfall recharge	2,180	8,950	8,950	1,250	1,250	2,180	8,950	8,950
Seawater intrusion	30	20	0	30	90	0	0	0
OUTFLOW								
Pumpage:								
Agricultural wells	980	920	920	1,080	1,080	980	920	920
Community wells	3,920	3,920	3,920	3,920	3,920	2,220	2,220	2,220
Private domestic wells	210	210	210	210	210	210	210	210
Phreatophyte transpiration	200	220	330	370	240	330	310	390
Perched-water runoff	490	1,000	1,000	520	520	490	1,000	1,000
Seepage to Los Osos Creek	630	1,390	1,850	450	450	1,080	2,230	2,710
Ground-water outflow to ocean	500	720	1,800	380	220	1,080	1,360	2,490
Total inflows and outflows	-120	5,440	3,550	-1,550	-1,200	130	5,200	3,440
Net storage change	-70	5,350	3,480	-1,500	-1,140	150	5,120	3,370
Mass-balance error	50	-90	-70	50	60	20	-80	70

abnormal climate. Normal conditions were represented by average conditions during water years 1970-77, wet conditions by water year 1983, and dry conditions by water year 1977. Rainfall was 239 percent of normal in 1983 and 57 percent of normal in 1977. Rainfall and temperature data for each of these periods were used in conjunction with the soil-moisture accounting algorithm and PRMS to develop estimates of areal recharge, streamflow at the model boundary, and ground-water inflow from subbasin 7 (fig. 8). Ground-water inflow from all other subbasins was assumed to equal the long-term average inflow of 278 acre-ft/yr.

WATER SUPPLY

Three options were considered for municipal water supply. The first option was to continue pumping from existing municipal wells at the 1986 rate and meet future increases in water demand with new wells. This option was assumed in alternatives 1, 4, and 5. Six new wells, each producing 240 to 270 acre-ft/yr, were hypothesized. Their proposed locations (fig. 22) were selected after considering basin depth, aquifer properties, patterns of projected residential development, and potential well-interference effects.

The second and third options involved the importation of surface water via the proposed Coastal Aqueduct of the California State Water Project (SWP). In 1963, San Luis Obispo County contracted for 25,000 acre-ft/yr of SWP water (California Department of Water Resources, 1987, p. 1). Under the second water-supply option, SWP water would be used to meet future increases in water demand, but existing municipal wells would continue pumping at their present rates; this option was assumed for alternatives 2, 6, and 7. Under the third option, municipal pumping would be eliminated and replaced entirely with SWP water; this option was assumed for alternative 3. Under all three

Table 8.—*Simulated annual water budgets for the Los Osos Valley ground-water basin in the year 2010 for alternatives 1 through 7 under various climatic conditions*—Continued

Budget item	Alternative 3: All imported water with recharged wastewater	Alternative 4: All ground water with recharged wastewater					Alternative 5: All ground water with exported wastewater
			Wet		Dry		
	Normal	Normal	First year	Third year	First year	Third year	Normal
INFLOW							
Ground-water inflow	360	360	560	560	310	310	360
Seepage from Los Osos Creek	490	970	750	540	770	780	810
Septic percolation	0	0	0	0	0	0	0
Wastewater recharge	2,340	2,340	2,710	2,710	1,980	1,980	
Irrigation return flow:							
Agricultural	400	400	370	370	440	440	400
Urban	540	540	580	580	610	610	540
Rainfall recharge	2,180	2,180	8,950	8,950	1,250	1,250	2,180
Seawater intrusion	0	0	0	0	0	<10	1,100
OUTFLOW							
Pumpage:							
Agricultural wells	980	980	920	920	1,080	1,080	980
Community wells	0	3,920	3,920	3,920	3,920	3,920	3,920
Private domestic wells	210	210	210	210	210	210	210
Phreatophyte transpiration	450	150	170	310	250	200	40
Perched-water runoff	190	190	710	710	220	220	190
Seepage to Los Osos Creek	1,270	420	1,040	1,470	320	280	190
Ground-water outflow to ocean	3,260	900	1,180	2,340	810	550	100
Total inflows and outflows	-50	20	5,770	3,850	-1,450	-1,090	-240
Net storage change	-30	40	5,720	3,780	-1,390	-1,030	-200
Mass-balance error	20	20	-50	-50	60	60	40

water-supply options, existing private domestic wells were assumed to continue pumping at their present rates.

WASTEWATER TREATMENT

Two options were considered for wastewater treatment. Under the first option, septic systems were assumed to continue as the principal means of treating and disposing of wastewater. This option was assumed for alternatives 1 and 2. Implementation of this option is unlikely, because it would allow nitrate contamination of ground water to continue. This option was included primarily as a reference condition for evaluating the effects of the second option.

The second option would be to collect all municipal wastewater and treat it at a central facility. This option was selected for alternatives 3 through 7. Preliminary engineering designs for the collection line and treatment facility have been developed (Morro Group, Inc., 1986). The treatment plant would be located near the confluence of Los Osos and Warden Creeks (fig. 22) and would be capable of tertiary-level treatment. Under this option, the facility would treat all municipal wastewater in the year 2010, which would amount to an annual volume of about 2,700 acre-ft.

WASTEWATER DISPOSAL

If wastewater were collected and treated (alternatives 3-7), there would be two options for disposing of it. The first option is to export wastewater from the basin, for example by discharging it directly to the ocean. This option was assumed for alternatives 5 and 7. The second option is to recharge wastewater into the ground-water basin, either by allowing it to percolate from holding ponds or by discharging it to Los Osos Creek during periods of low flow. This option was assumed for alternatives 3, 4, and 6. A plan currently under consideration by San Luis Obispo County calls for a combination of pond percolation and discharge to the creek (Morro Group, Inc., 1986). Ponds covering a total of about 18 acres would be constructed near the foot of the Irish Hills, and a pipeline would allow discharge to Los Osos Creek near the point where it enters Los Osos Valley (fig. 22). Discharge to the creek would occur

Table 8.—*Simulated annual water budgets for the Los Osos Valley ground-water basin in the year 2010 for alternatives 1 through 7 under various climatic conditions*—Continued

Budget item	Alternative 6: Ground water and imported water with recharged wastewater					Alternative 7: Ground water and imported water with exported wastewater		
		Wet		Dry			Dry	
	Normal	First year	Third year	First year	Third year	Normal	First year	Third year
INFLOW								
Ground-water inflow	360	560	560	310	310	360	310	310
Seepage from Los Osos Creek	600	350	300	660	690	600	50	50
Septic percolation	0	0	0	0	0	0	0	0
Wastewater recharge	2,340	2,710	2,710	1,980	1,980	0	0	0
Irrigation return flow:								
Agricultural	400	370	370	440	440	400	440	440
Urban	540	580	580	610	610	540	610	610
Rainfall recharge	2,180	8,950	8,950	1,250	1,250	2,180	1,250	1,250
Seawater intrusion	0	0	0	0	0	380	430	560
OUTFLOW								
Pumpage:								
Agricultural wells	980	920	920	1,080	1,080	980	1,080	1,080
Community wells	2,220	2,220	2,220	2,220	2,220	2,220	2,220	2,220
Private domestic wells	210	210	210	210	210	210	210	210
Phreatophyte transpiration	270	290	420	450	360	120	180	120
Perched-water runoff	190	700	700	220	220	190	220	220
Seepage to Los Osos Creek	880	1,760	2,210	700	630	530	350	330
Ground-water outflow to ocean	1,600	1,880	3,060	1,500	1,250	160	120	50
Total inflows and outflows	70	5,540	3,730	-1,130	-690	50	-1,290	-1,010
Net storage change	110	5,470	3,660	-1,080	-640	70	-1,260	-970
Mass-balance error	40	-70	-70	50	50	20	30	40

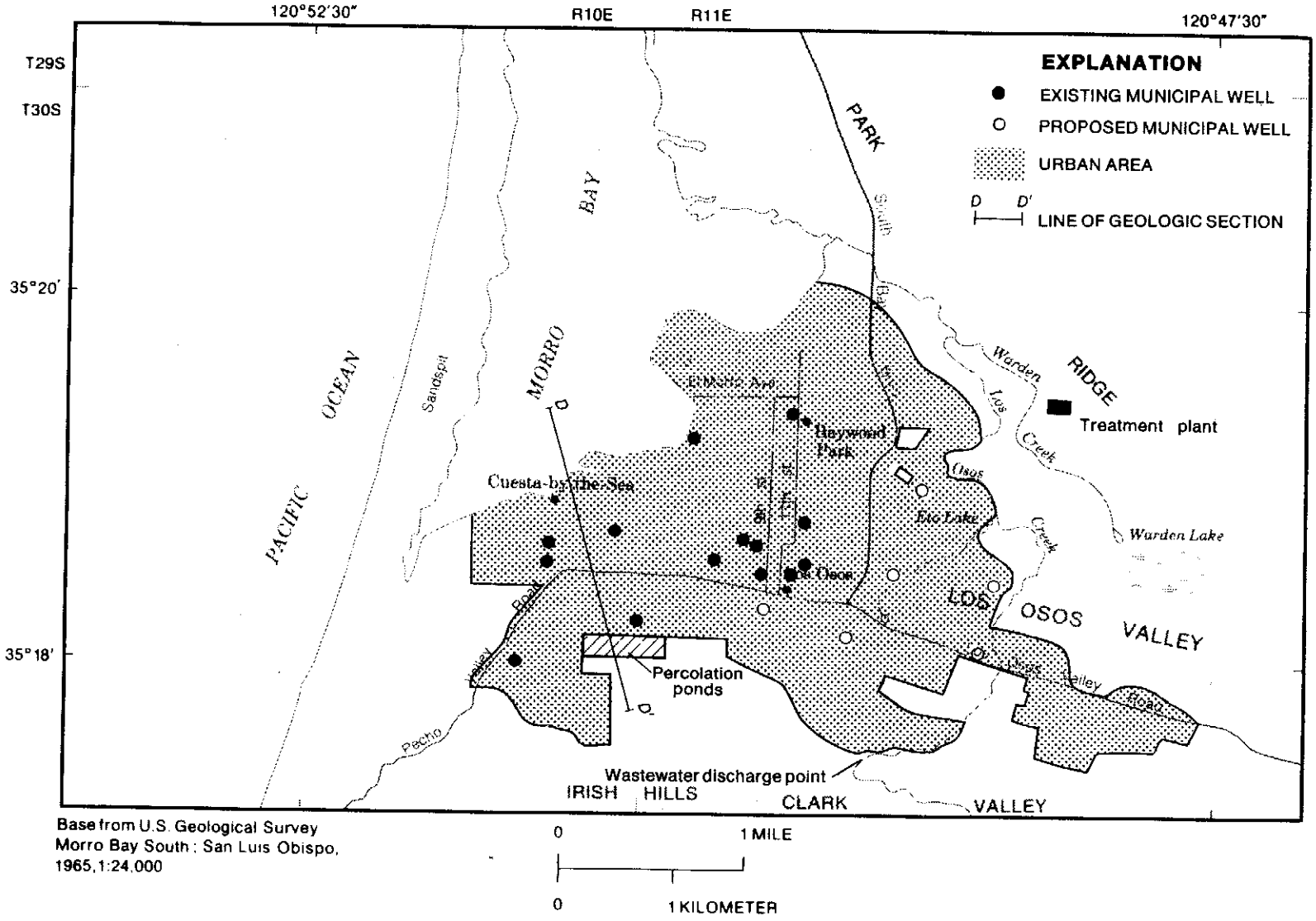


FIGURE 22.-- Projected extent of urban areas, locations of existing and proposed municipal wells, and locations of proposed wastewater treatment plant, percolation ponds, and discharge point in the year 2010.

only during periods when natural streamflow percolates entirely and does not flow through to Morro Bay. In most years, this condition exists in summer and fall. The rate of discharge would be limited to the maximum rate of seepage from the streambed; throughflow of wastewater to Morro Bay would not be allowed.

The percolation ponds would be used year-round to recharge any wastewater that could not be recharged by the creek. In most years, the ponds would need to handle all the flow in winter and spring and some of the flow in summer and fall.

Under normal climatic conditions, it was assumed that 1 ft^3/s of wastewater would be diverted to the creek during July through December. This amount corresponds to an annual volume of 362 acre-ft, about 13 percent of the total wastewater volume in 2010. Under wet conditions, it was assumed that no discharges to the creek would occur in any month. Under dry conditions, a discharge of 1 ft^3/s was assumed to be possible in all months. This amount corresponds to an annual volume of 724 acre-ft, or about 26 percent of the total wastewater volume. These rates and seasons approximate those that would maximize the amount of percolation through the streambed without causing throughflow to Morro Bay. The rates and seasons were selected on the basis of seepage measurements in 1986, streamflow in 1970-77 (average), 1977, and 1983, and simulations of seepage under 2010 water-use conditions. Results of the simulations indicated that the assumed rates and seasons occasionally allowed small amounts of throughflow to the bay or underestimated the maximum potential rate of infiltration. However, these slight inaccuracies were not large enough to bias significantly the evaluation of the alternatives.

EFFECTS OF SIMULATED ALTERNATIVES

To simulate each alternative, model input data were developed for the year 2010 assuming normal climatic conditions. These data were replicated to create input data for a series of identical years. Simulation using the repeated annual input data was continued until simulated output also began repeating on an annual cycle, indicating that the ground-water flow system had reached an "equilibrium" with the new regime of inflows and outflows. Depending on the assumed initial potentiometric heads, several years of simulation were required before aquifer storage changes and head-dependent flows reached this new equilibrium. Using September 1986 heads as initial heads, 10 to 20 years of simulation were typically required to reach a new equilibrium with the conditions represented by the alternatives. Less simulation time was required when the final heads for one alternative were used as the initial heads for simulation of a similar alternative. The results obtained by this method are virtually the same as the results that would have been obtained by gradually increasing pumpage and wastewater-treatment capacity in a detailed simulation of the entire 24-year period from 1986 to 2010. Once equilibrium was achieved, simulations were continued for 8 additional years. The alternatives were compared on the basis of the 8 equilibrium years, which do not correspond to specific future years but rather represent an arbitrary 8-year period under conditions expected to exist in the year 2010.

Wet or dry climatic conditions were then simulated for selected alternatives by repeating the 8-year simulation and introducing 4 identical years of appropriate streamflow, pumpage, and recharge data starting in the fifth year.

Hydrographs of simulated potentiometric heads at selected locations are shown for alternative 4 in figure 23. Heads under normal climatic conditions exhibited seasonal cycles but were level in the long term. Heads under wet or dry conditions also fluctuate seasonally but progressively increased or decreased with respect to normal conditions.

Contours of simulated potentiometric heads in model layer 1 for each alternative in September of an equilibrium year under normal climatic conditions are shown in figure 24. Water budgets under normal climatic conditions for each of the alternatives are shown in table 8. Water budgets for the first and third wet and (or) dry years are also shown for selected alternatives.

Most of the items in the water budgets were specified as model input and reflect the assumptions discussed in this report. The other items—stream seepage, phreatophyte transpiration, seawater intrusion, storage changes, and outflow to the ocean—are all head-dependent flows calculated by the model during the course of each simulation. These latter budget items are of particular interest in evaluating the effects of management alternatives.

Alternative 1 represents continuation of present water-supply and wastewater-disposal practices. A comparison of the simulation of alternative 1 (fig. 24 and table 8) with the simulation of 1986 (fig. 19 and table 6) indicates the general magnitude of changes likely to occur in the intervening 24 years if present practices continue. Some of the differences between the simulations can be attributed, however, to greater-than-average rainfall in 1986. Figures 19 and 24 show that heads in layer 1 would not change in the western part of the basin but would drop as much as 10 feet in the vicinity of South Bay Boulevard by the year 2010.

Slight increases in heads in the southeast corner of the basin in 2010 were due to septic return flow from new residential development in that area. Similar differences occurred in heads for model layers 2 and 3. When climatic differences are taken into consideration, the water budget for alternative 1 (table 8) indicates that the 1,700 acre-ft of additional municipal pumpage in 2010 was largely offset by an increase in septic-system return flow. The remaining difference was due to a decrease in ocean outflow, an increase in return flow from urban landscape irrigation, and a slight increase in seawater intrusion.

The effects of different wastewater treatment and disposal options in the year 2010 can be determined by comparing the simulation of alternative 1 with simulations of alternatives 4 and 5 (fig. 24). With wastewater recharge (alternative 4, fig. 24), potentiometric heads in layer 1 were 5 to 10 feet lower beneath urban areas in the north-central and eastern parts of the basin because septic-system return flow no longer occurred. In the south-central part of the basin, a prominent water-table mound was created by recharge from the wastewater-percolation ponds. The mound was up to 95 feet higher than heads under alternative 1

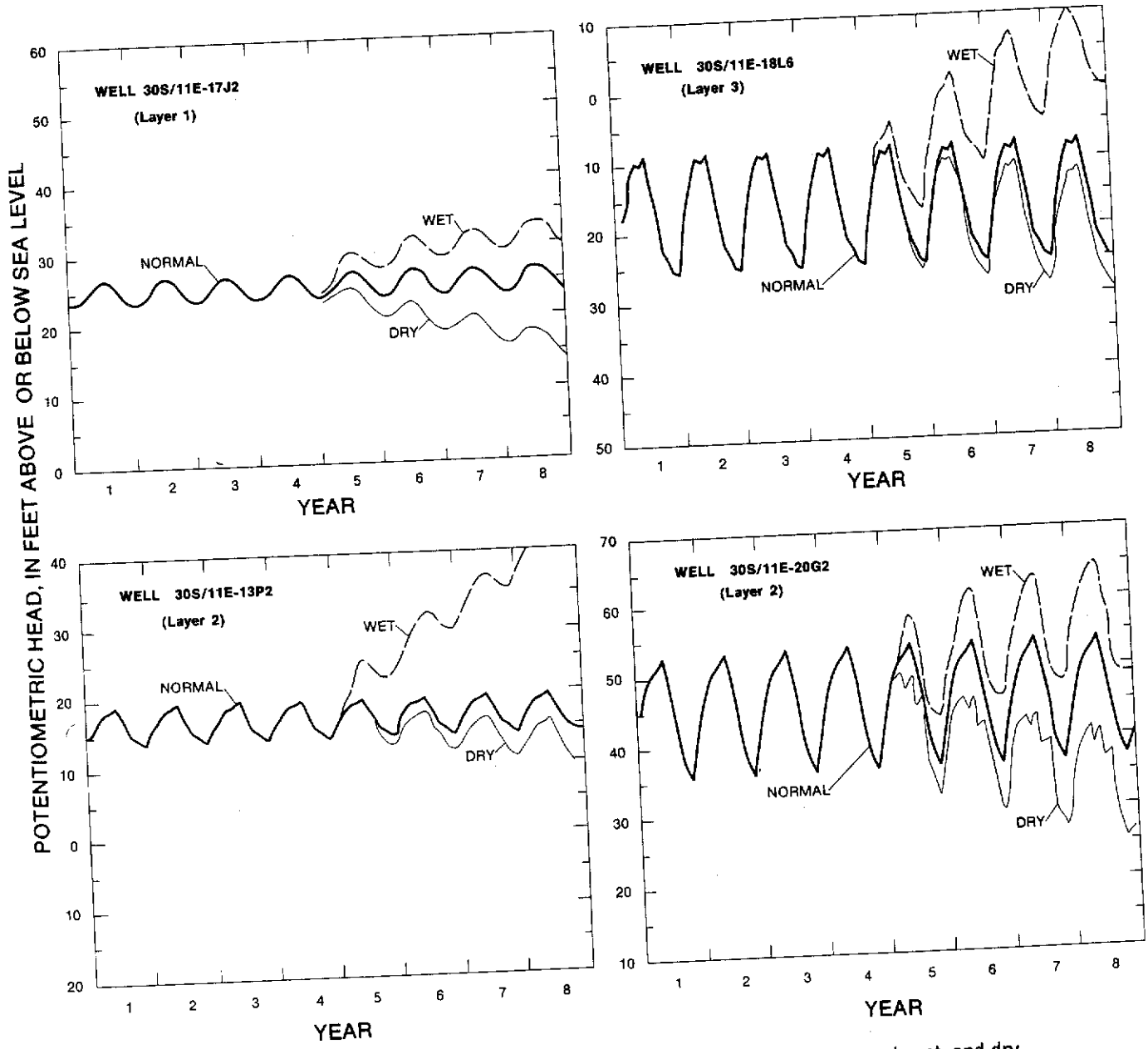


FIGURE 23.— Simulated potentiometric heads for alternative 4 under normal, wet, and dry climatic conditions at four well locations

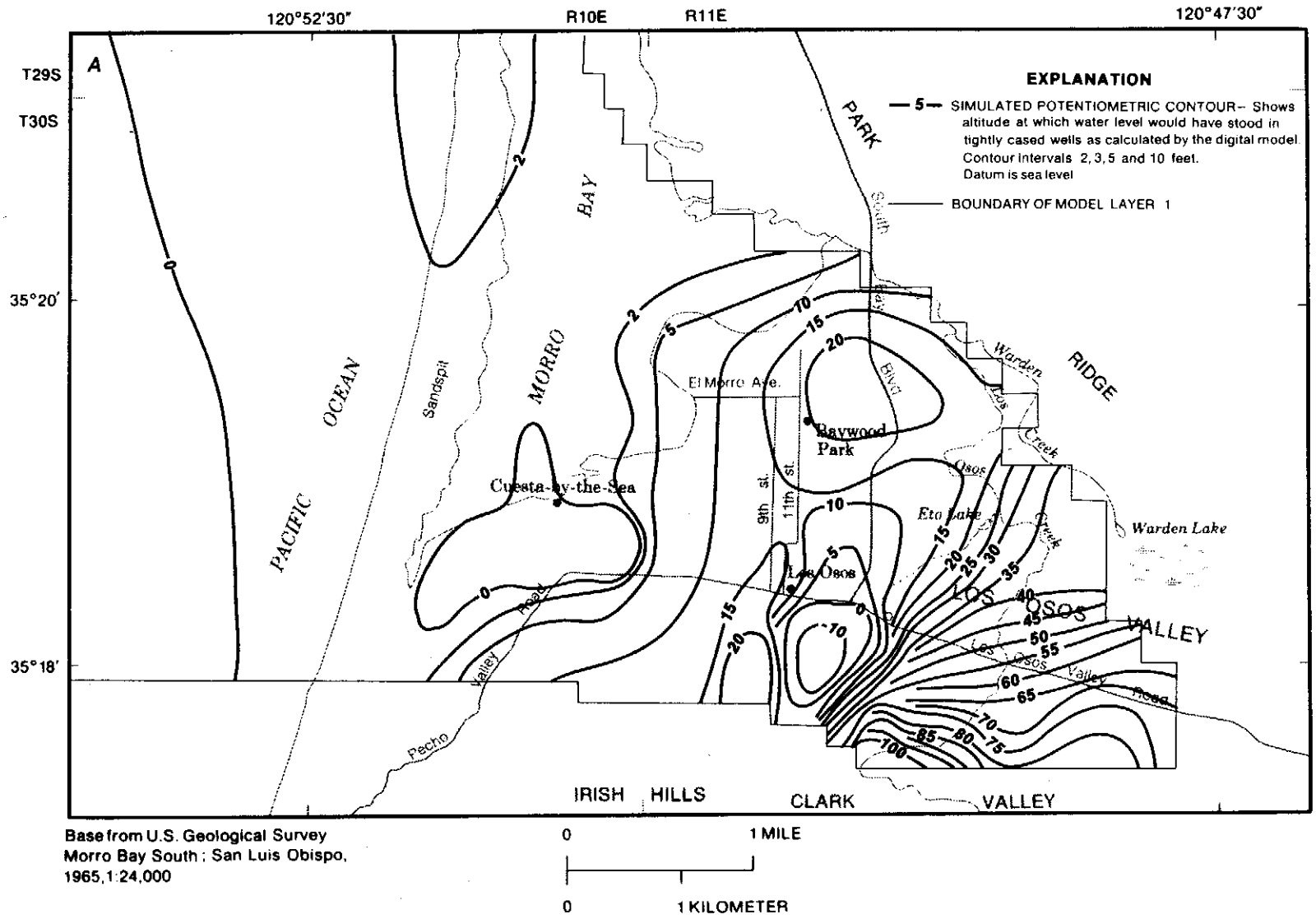


FIGURE 24. – Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7. *A*, Alternative 1.

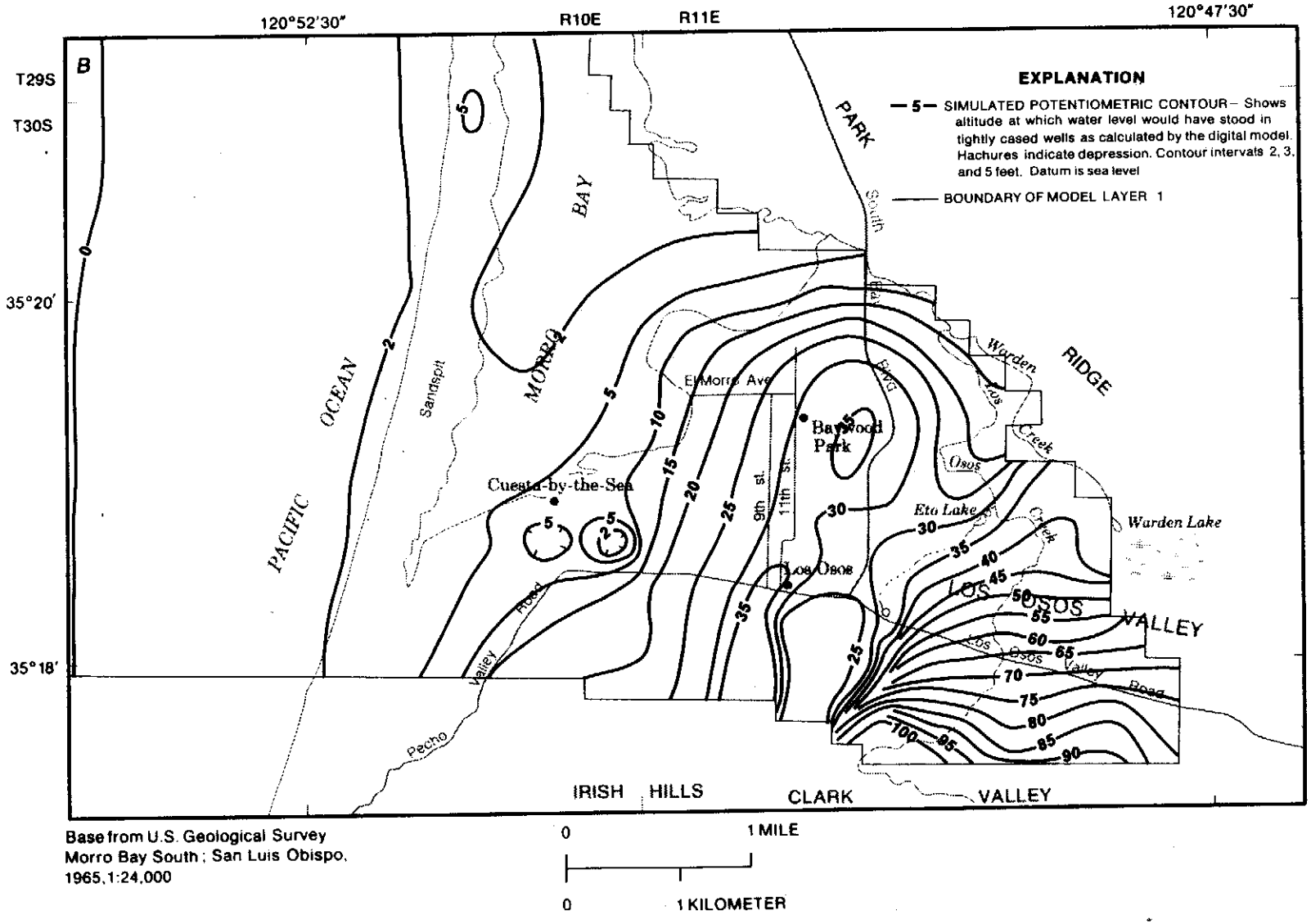


FIGURE 24.—Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7 —Continued. *B*, Alternative 2.

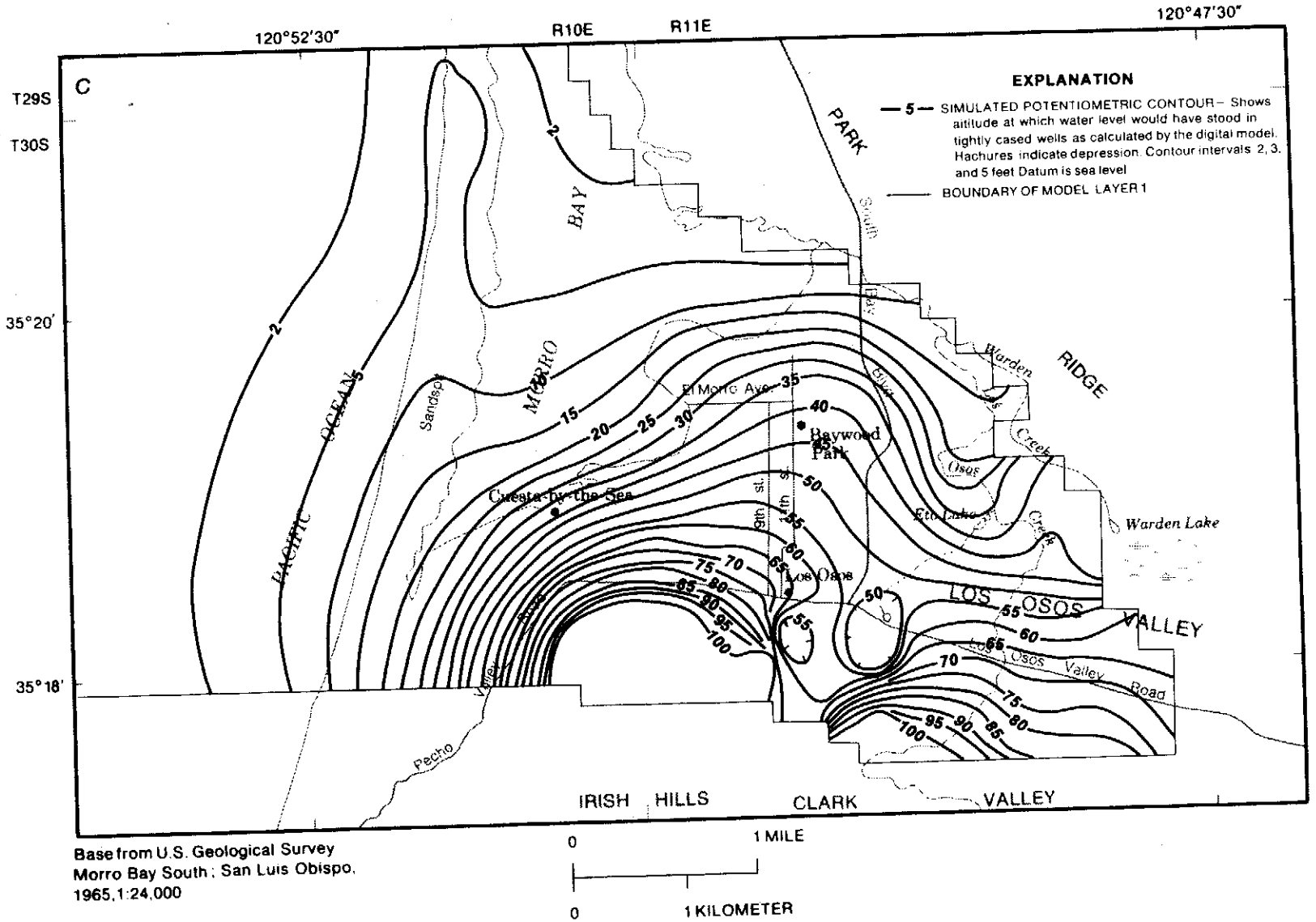


FIGURE 24. – Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7 – Continued. *C*, Alternative 3.

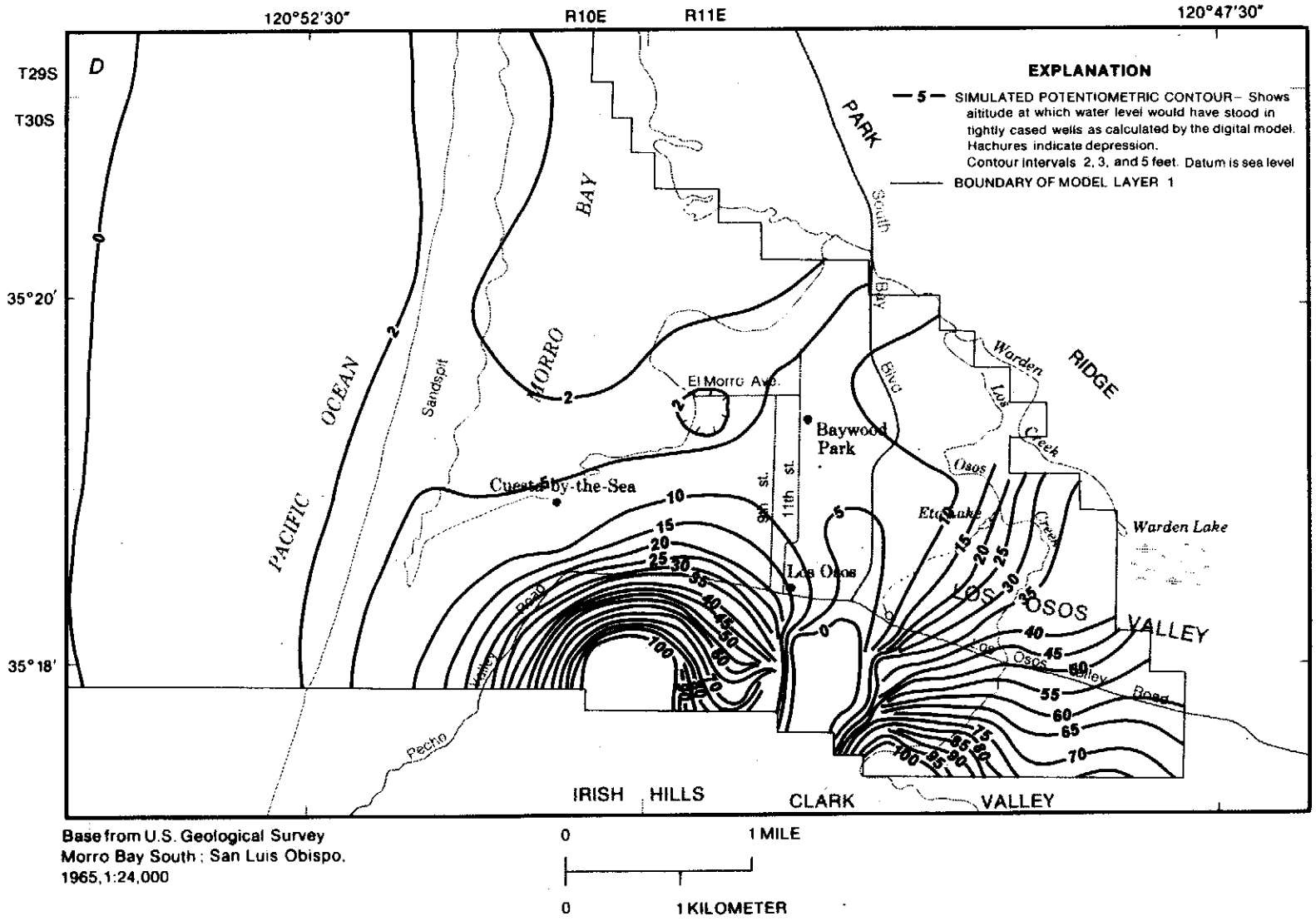


FIGURE 24.— Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7—Continued. *D*, Alternative 4.

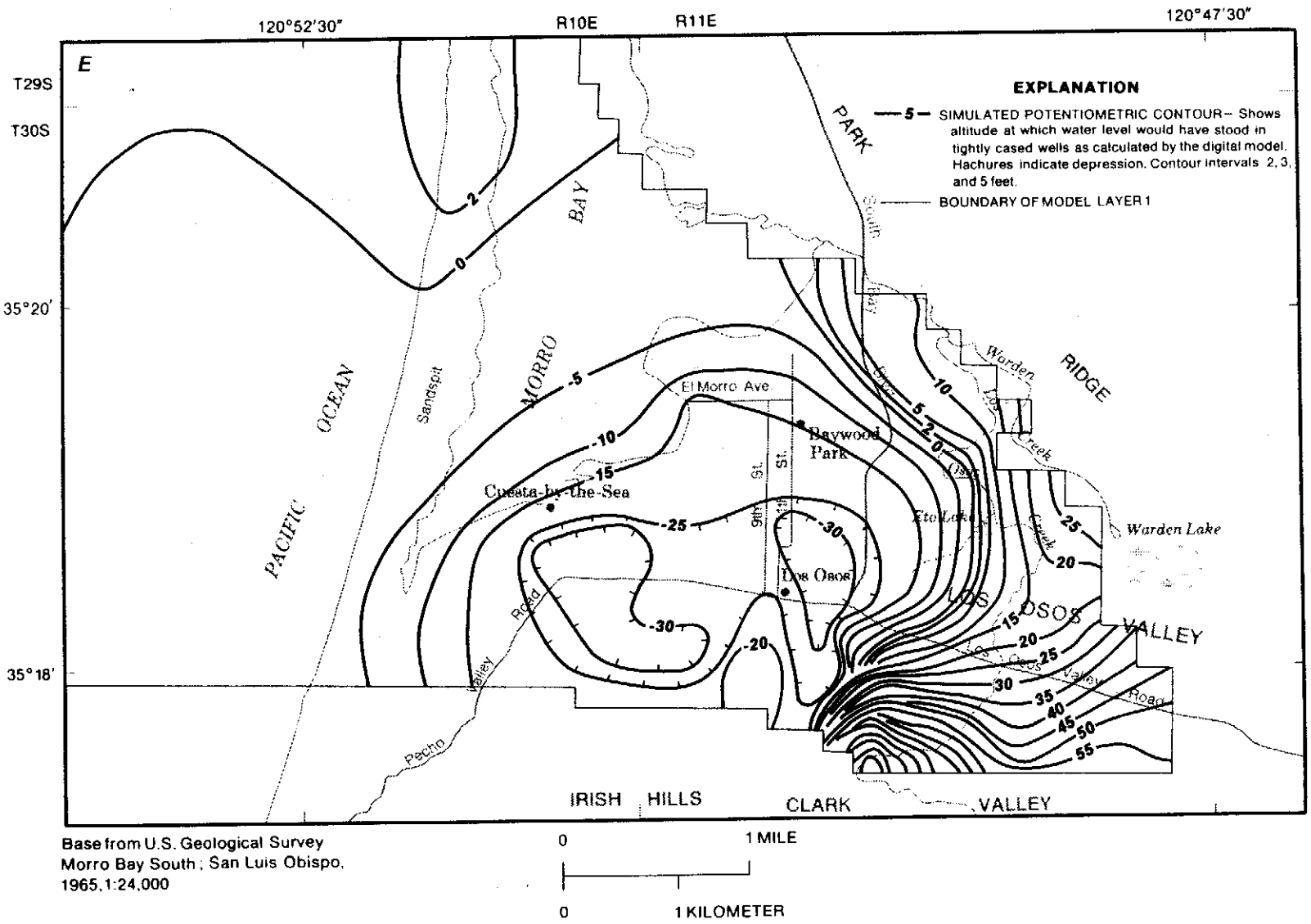


FIGURE 24. – Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7 –Continued. *E*, Alternative 5.

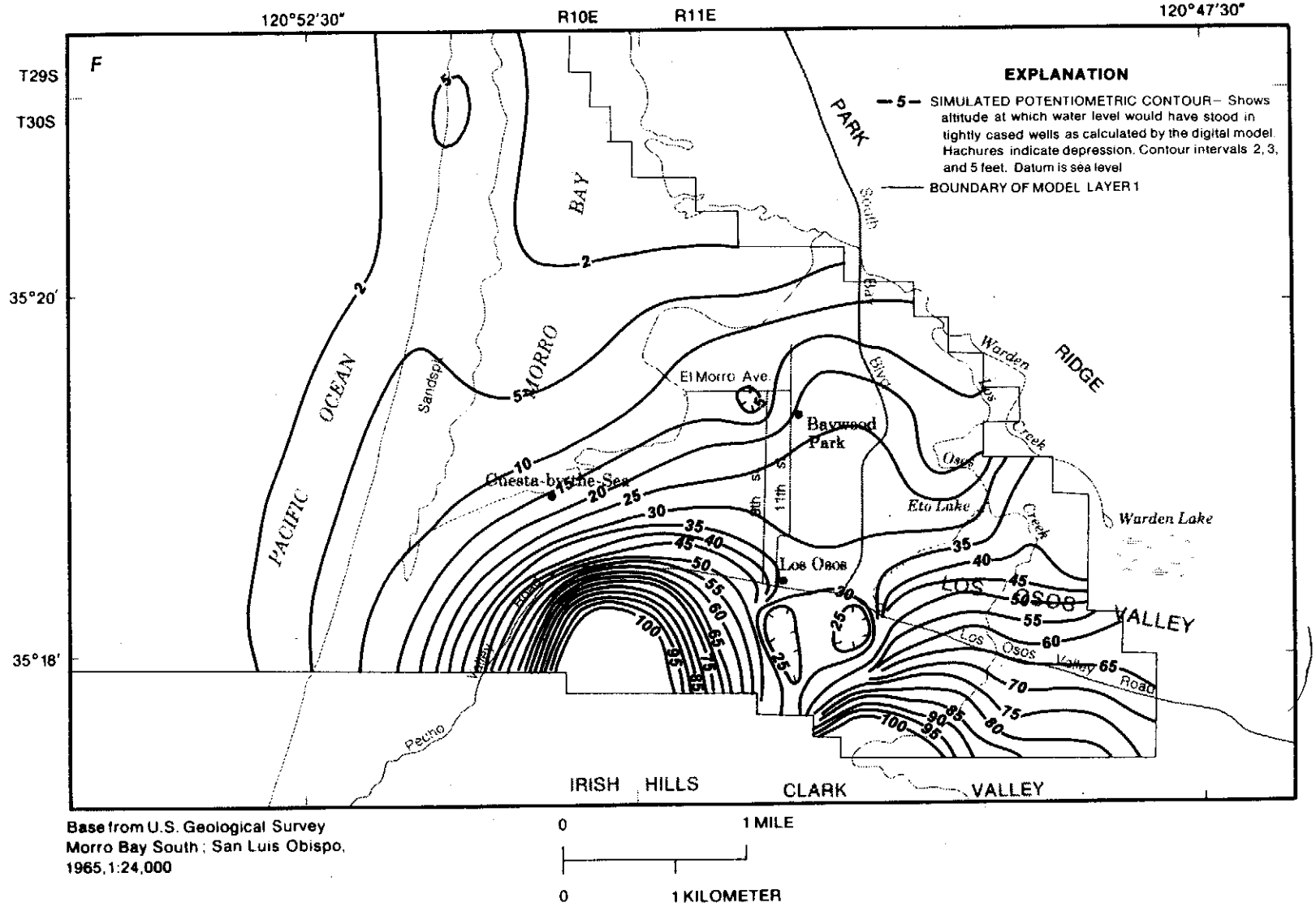


FIGURE 24. — Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7—Continued. *F*, Alternative 6.

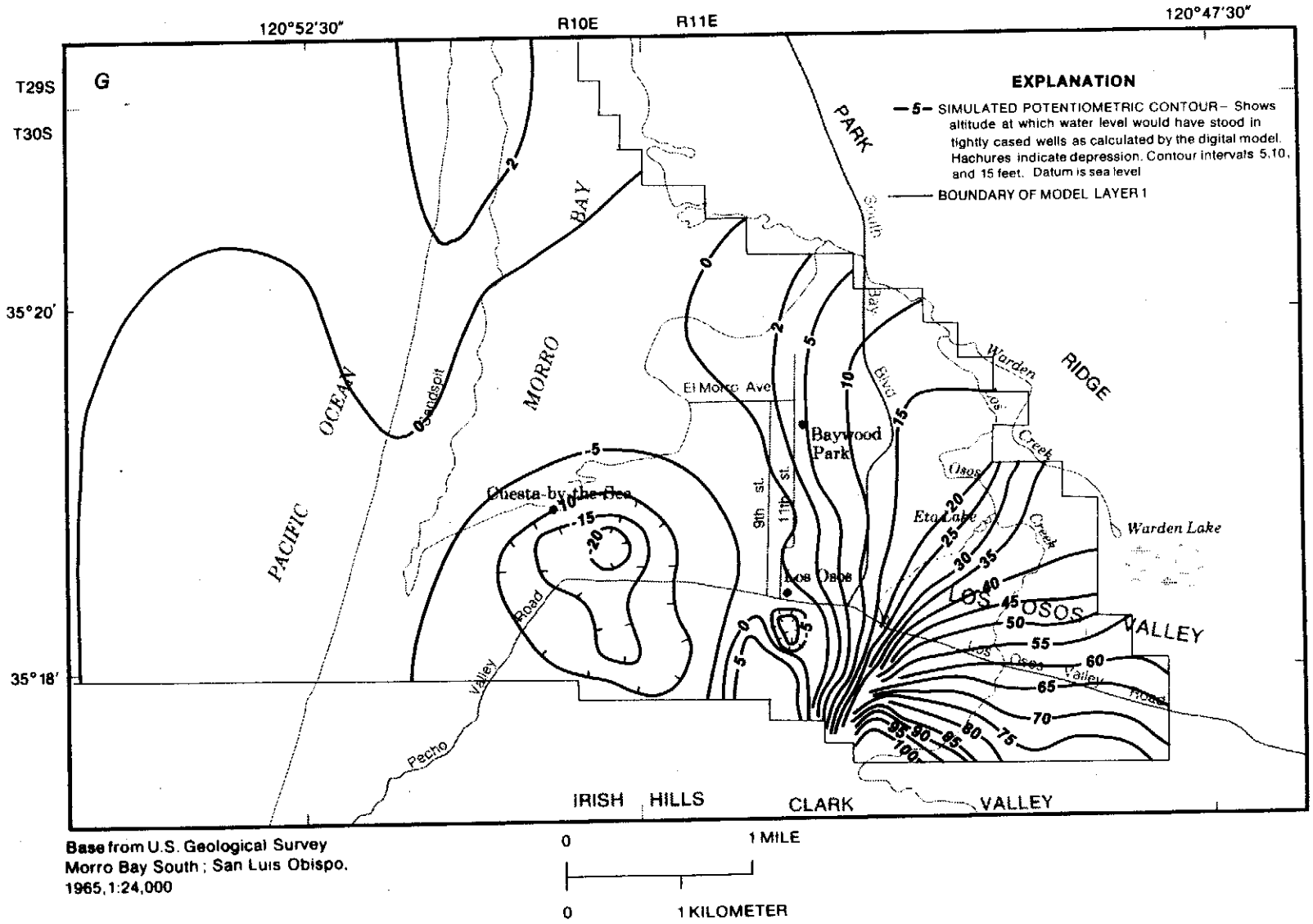


FIGURE 24.— Simulated potentiometric heads in model layer 1 in September under normal climatic conditions for management alternatives 1–7 —Continued. *G*, Alternative 7.

(fig. 24). Export of wastewater (alternative 5) resulted in lower heads in all areas. Heads in layer 1 were as much as 40 feet lower than under alternative 1 near Ninth Street, and they were below sea level as far inland as Eto Lake.

Heads in model layer 3 showed similar relative differences. With septic systems (alternative 1), heads decreased inland to 30 feet below sea level near Ninth Street. With export of wastewater, equally low heads also occurred in the eastern part of the basin. With wastewater recharge (alternative 4), a head depression as low as 30 feet below sea level occurred near the south end of Ninth Street, but it was separated from the ocean boundary by a low potentiometric-head ridge in the vicinity of the sandspit as shown in figure 25.

Differences in model-calculated budget items for alternatives 1, 4, and 5 (table 8) were related to the differences in heads. Recharge and export of wastewater (alternatives 4 and 5) both resulted in a lower water table along the lower reaches of Los Osos Creek and near the shore of Morro Bay. As a result, seepage to Los Osos Creek and phreatophyte transpiration both decreased relative to alternative 1, although the decrease under alternative 5 was greater. When wastewater was exported, recharge from Los Osos Creek increased by about 200 acre-ft/yr because of a lower water table near the creek. An additional increase of about 160 acre-ft/yr resulted when wastewater was discharged to the creek in summer, even though the water table was higher. Export of wastewater increased seawater intrusion from 30 to 1,100 acre-ft/yr and decreased ocean outflow from 500 to 100 acre-ft/yr. In contrast, wastewater recharge eliminated intrusion and increased ocean outflow to 900 acre-ft/yr.

A comparison of simulations of alternatives 2, 6, and 7 under normal climatic conditions (table 8) also reveals effects associated with the wastewater-disposal options. These alternatives are identical to alternatives 1, 4, and 5, except that in alternatives 2, 6, and 7, imported surface water meets some of the municipal water demand. Again, differences in model-calculated budget items were closely related to differences in heads (fig. 24 and table 8). Patterns and magnitudes of differences in heads were similar to those described for alternatives 1, 4, and 5. Phreatophyte transpiration and seepage to Los Osos Creek were both greatest with septic systems (330 and 1,080 acre-ft/yr, alternative 2) and least with wastewater export (120 and 530 acre-ft/yr, alternative 7). Recharge from Los Osos Creek was least with septic systems (340 acre-ft/yr) and greatest with recharge or export of wastewater (600 acre-ft/yr, alternatives 6 and 7). Ocean outflow increased from 1,080 to 1,600 acre-ft/yr with wastewater recharge and decreased to 160 acre-ft/yr with export. Export also introduced 380 acre-ft/yr of seawater intrusion.

The effects of the different water-supply options are best revealed by a comparison of alternatives 3, 4, and 6. A major effect of replacing municipal pumpage with imported water was to raise heads throughout the central and eastern part of the basin. Partial replacement (alternative 6, fig. 24) increased heads 10 to 20 feet in layer 1, and full replacement (alternative 3) increased heads 30 to 50 feet. The largest increases for both alternatives were slightly east of Ninth Street. Offshore heads increased only slightly.

In model layer 3, partial replacement of municipal water (alternative 6) increased heads by about 10 feet near the eastern shore of Morro Bay and by as much as 50 feet between Ninth Street and Los Osos Creek. Heads were still slightly below sea level in a local depression near the south end of Ninth Street, however. Full replacement (alternative 3) raised heads in layer 3 by up to 75 feet and established a seaward head gradient throughout the onshore part of the basin.

Differences in water budgets among alternatives 3, 4, and 6 (table 8) were related to the differences in heads. Seepage from Los Osos Creek decreased with increasing use of imported water because ground-water levels were increasingly high. Seepage from the creek was 490, 970, and 600 acre-ft/yr for alternatives 3, 4, and 6, respectively. Seepage to Los Osos Creek increased for the same reason to 1,270, 420, and 880 acre-ft/yr, respectively. Phreatophyte transpiration also increased with increasing use of imported water. Seasonal use of aquifer storage, calculated as the average of winter storage gains and summer storage losses, decreased with increasing use of imported surface water. Seasonal use (not shown in table 8) decreased from about 2,000 to about 1,700 acre-ft/yr with partial use of imported water (alternative 6) and decreased to about 1,500 acre-ft/yr with full use (alternative 3). Net annual storage change, however, was about zero under normal climatic conditions.

Flow across the ocean boundary is strongly affected by the choice of water supply. Ground-water outflow to the ocean increased with increasing use of imported water to 3,260, 900, and 1,600 acre-ft/yr for alternatives 3, 4, and 6, respectively. The increase also occurred when wastewater disposal was by septic systems (alternatives 1 and 2) or export (alternatives 5 and 7). Export of wastewater increased seawater intrusion, and seawater intrusion decreases with increasing use of imported water. For example, a decrease of intrusion from 1,100 to 380 acre-ft/yr was associated with changing from full use of ground water (alternative 5) to partial use of imported water (alternative 7). Partial

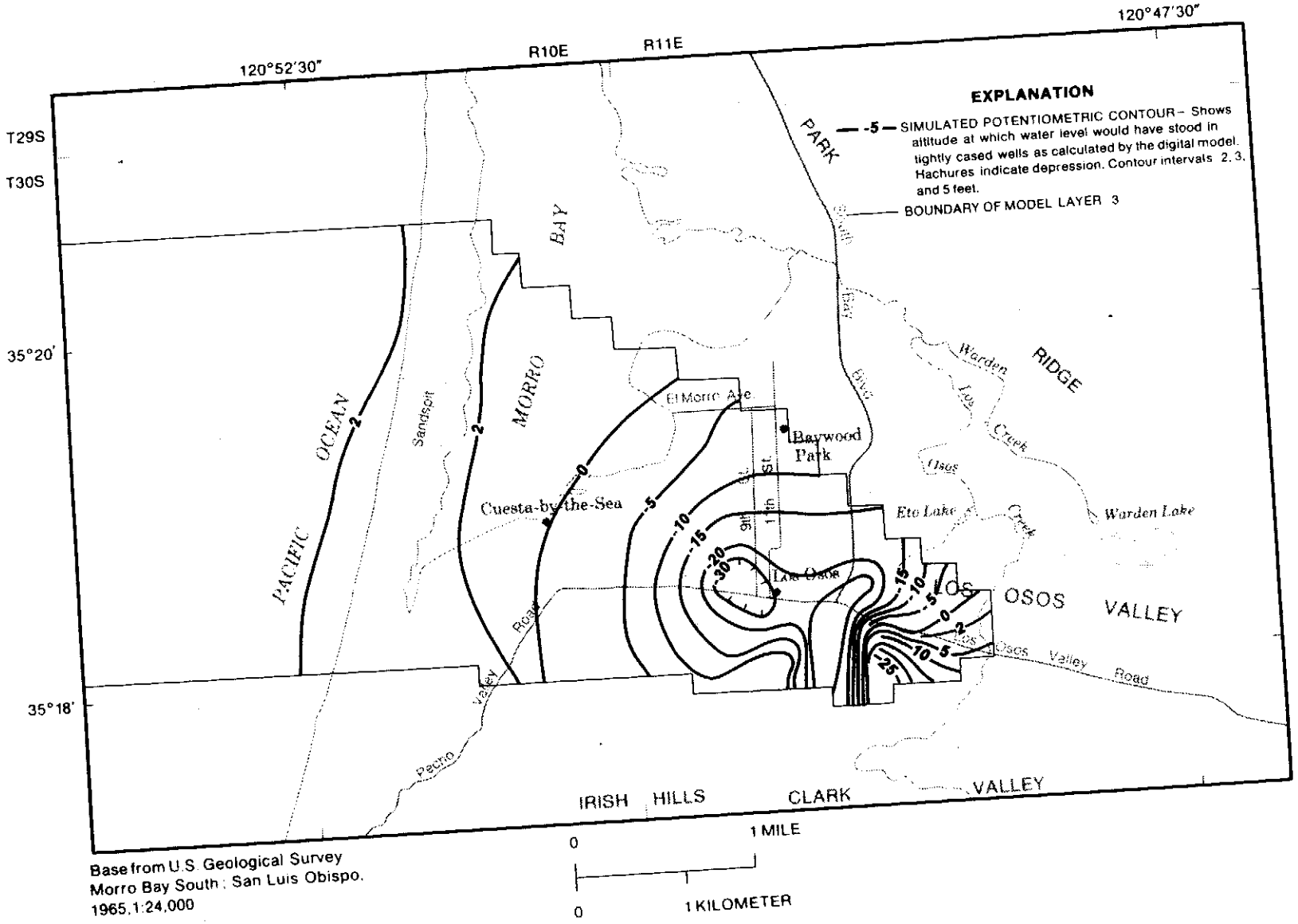


FIGURE 25.– Simulated potentiometric heads in model layer 3 in September under normal climatic conditions for management alternative 4.

use of imported water was not sufficient to preclude seawater intrusion when wastewater was exported (alternative 7).

In all simulations of abnormal climatic conditions, a series of wet years resulted in rising heads, and a series of dry years resulted in declining heads (fig. 23). Water budgets for the first and third consecutive wet or dry year are shown for selected alternatives in table 8. Water budgets for the second year are not shown, but they reflect changes of the same kind. Changes in seepage to and from Los Osos Creek were greatest in the first wet or dry year and became progressively smaller in subsequent years. For example, seepage from the creek under alternative 6 decreased from 600 acre-ft/yr under normal climatic conditions to 350, 320, and 300 acre-ft/yr in the first, second, and third wet years, respectively. Year-to-year changes in outflow to the ocean and phreatophyte transpiration tended to be greatest between the first and second wet or dry years, probably because of delays in release of water from aquifer storage. For example, outflow to the ocean under alternative 6 increased from 1,600 acre-ft/yr under normal climatic conditions to 1,880, 2,500, and 3,060 acre-ft/yr in the first, second, and third wet years, respectively.

A major management concern during wet periods is that under alternatives 3, 4, and 6 the water table downslope of the percolation ponds might rise to the land surface and damage structures or cause local flooding. Such flooding is most likely to occur in spring, and it is also more likely to occur if imported water is used to replace some or all municipal pumpage. The likelihood of local flooding was investigated through the use of analytical flow equations. The digital flow model is suitable for simulating general flow patterns throughout the basin, but the vertical and horizontal grid spacing is too coarse to simulate accurately the local water-table mounding in detail.

Contours of simulated potentiometric heads for alternatives 3, 4, and 6 (fig. 24) indicated that shallow ground water was most likely to be a problem along flow paths from the percolation ponds directly to Morro Bay. Line *D-D'* (fig. 22) approximates such a flow path. A schematic vertical section along this line is shown in figure 26. The southern end of the shallow ground-water flow system along this section is impermeable bedrock. The northern end is Morro Bay, which is assumed to be a fully penetrating constant-head boundary located at the shoreline of the bay. The base of the flow system along the section is the extensive clay layer that occurs throughout the western part of the ground-water basin at a depth of about 150 to 200 feet. The flow system is unconfined, and it receives nonpoint recharge from rainfall and landscape irrigation return flow along the entire length of the section. In addition, recharge would occur from the proposed percolation ponds.

The water-table profile along section *D-D'* was calculated by superimposing the effects of nonpoint recharge, boundary conditions, and the percolation ponds. The principle of superposition (Bear, 1979, p. 152) is not valid in unconfined flow analysis unless drawdowns or water-table mounds are small compared to total aquifer thickness. Although calculated mounds were often large in this case, sensitivity analysis indicated that the results were not highly sensitive to total aquifer thickness. Also, any error introduced by superposition is conservative from a management standpoint in that it tends to overestimate the height of the water-table mound.

The recharge ponds were represented in this analysis by a point-source recharge well. In reality, pond percolation would be spread out over a narrow rectangular area measuring 400 by 2,000 feet. The ponds might be represented more accurately by a line

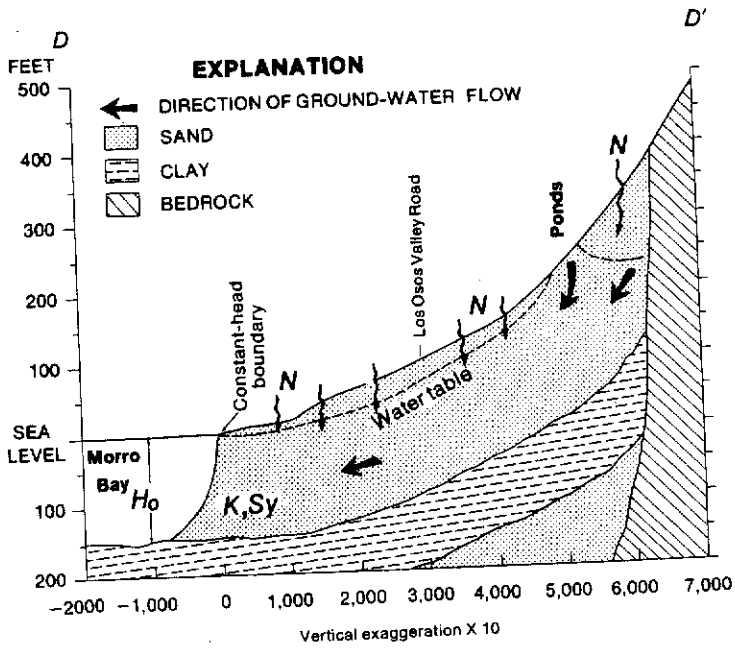


FIGURE 26.– Schematic section along line *D–D'* showing simplified concepualization of geology and shallow ground-water flow near the proposed wastewater-percolation ponds. The indicated variables are aquifer thickness (*Ho*), horizontal hydraulic conductivity (*K*), specific yield (*Sy*), and nonpoint recharge rate (*N*). Variable *L* (not shown) is the horizontal distance from bedrock to Morro Bay. Location of section in figure 22.

source at locations close to the ponds. Farther away, the effects of the actual ponds and those of an equivalent recharge well become indistinguishable. Because shallow ground water is more likely to be a problem near the bay than near the ponds, a point-source analysis is reasonable. However, this approximation may cause considerable overestimation of mound height in the immediate vicinity of the ponds. The exact amount of overestimation was not determined.

The method of images (Freeze and Cherry, 1979, p. 330) was used to include the impermeable basin boundary in the analysis. The effects of the boundary were assumed to equal those of a hypothetical recharge "image" well across the boundary from the ponds.

Calculated water table profiles after 1 year of recharging all municipal wastewater (2,710 acre-ft) through the ponds are shown in figure 27. Profiles are shown for different assumed values of hydraulic conductivity, nonpoint recharge rate, and constant-head boundary location. These variables strongly affected the calculated profile. The profile was not strongly influenced by specific yield or aquifer thickness, and so multiple curves are not shown for those variables. Altitude of the land surface is also shown in the figure; the vertical axis scale is exaggerated by a factor of ten. Areas where the calculated water table is above the land surface are areas where waterlogging and seepage are likely to occur for the simulated conditions.

Figure 27*A* shows that the water-table profile is strongly dependent on the value of hydraulic conductivity. Given reasonable values of aquifer thickness and specific yield, and nonpoint recharge rates that might occur during wet winters, seepage and waterlogging near Morro Bay are likely if hydraulic conductivity is less than about 15 ft/d. Although a calibrated value of 4 to 6 ft/d was used in layer 1 of the digital model, that value represents conditions in the Paso Robles Formation, which is generally less permeable than the overlying sand deposits. Much of the shallow ground-water flow near the ponds would occur in the sand deposits, which could easily have a hydraulic conductivity greater than 15 ft/d.

Figure 27*B* shows that the profile is strongly dependent on the rate of nonpoint recharge. The profiles shown are for steady-state recharge at rates equivalent to 1, 2, and 4 in/mo ($N = 0.0027, 0.0055$, and 0.0110 ft/d, respectively). The soil-moisture accounting algorithm described earlier in this report indicated that recharge rates in zone 1 (fig. 11) during a wet year averaged about 4.5 in/mo November through March and 2.3 in/mo for the year. The profiles indicate that seepage might occur for nonpoint recharge rates greater than about 2 in/mo, assuming the recharge ponds are operating year-round at a rate of 2,710 acre-ft/yr.

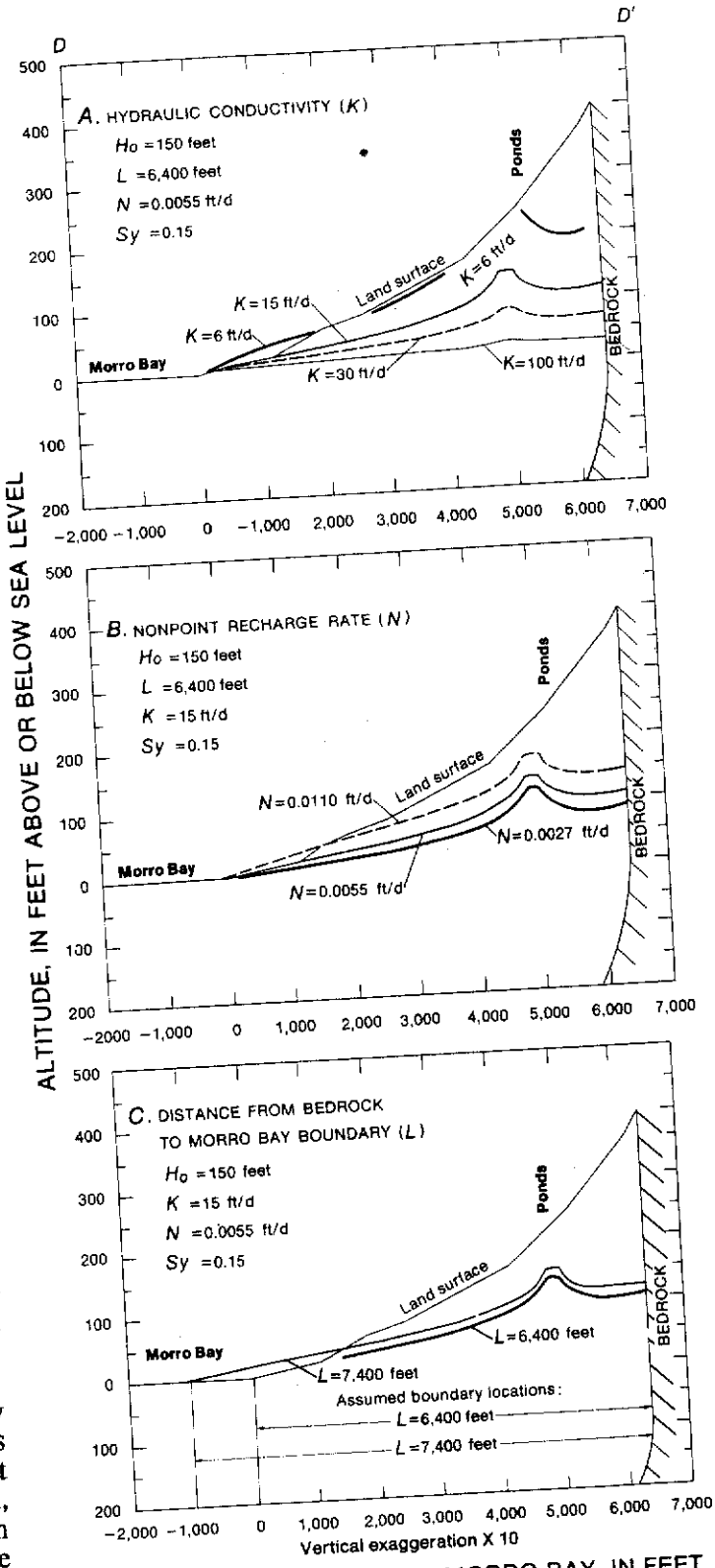


FIGURE 27.– Schematic sections along line *D*–*D'* showing sensitivity of calculated water-table profile to (*A*) hydraulic conductivity, (*B*) nonpoint recharge rate, and (*C*) distance from bedrock to Morro Bay boundary.

Figure 27C shows that the profile is sensitive to the assumed effective location of the constant-head boundary at Morro Bay. The assumption that Morro Bay fully penetrates the aquifer at the shoreline is a considerable simplification of the actual flow geometry at the boundary. In reality, flow probably occurs through a strip of bay floor adjacent to the shore, and ground-water flow may be largely upward in that vicinity. If the width of the outflow strip is represented approximately by a fully penetrating, constant-head boundary 1,000 feet offshore, the onshore water-table profile is much higher than under the original assumption.

In general, the analytical flow calculations indicate that seepage and waterlogging might be a problem, especially near the shore of Morro Bay. The calculations were sensitive to estimates of hydraulic conductivity, nonpoint recharge rates, and the flow characteristics of the bottom of Morro Bay. The likelihood of seepage problems could be determined from more accurate estimates of these variables.

A major management concern for dry periods is that lowered ground-water levels would increase seawater intrusion. Intrusion also is more likely if ground water is the sole source of municipal supply (alternatives 1, 4, and 5) or if wastewater is exported (alternatives 5 and 7). Heads in layer 1 after 3 dry years under alternative 1 (fig. 28) were lower than heads under normal climatic conditions (fig. 24) by 1 to 2 feet in the central and western parts of the basin and by as much as 15 feet in the southeast corner of the basin. Heads were below sea level only in a localized depression near Ninth Street. Heads in layer 3 after 3 dry years (fig. 29) were below sea level everywhere except at the extreme eastern and western ends of the basin. Under alternative 1, intrusion increased from 30 acre-ft/yr in normal climatic conditions to 90 acre-ft/yr in the third dry year (table 8). Under alternative 7, the corresponding increase was from 380 to 560 acre-ft/yr. Head changes under alternative 7 were similar to those described for alternative 1. No intrusion occurred even after 3 dry years under alternative 6, and intrusion was just beginning at the end of the third dry year under alternative 4.

Long-term salt build-up in the ground-water basin is another management concern. Proposed wastewater-treatment facilities principally would remove nitrates; other dissolved ions would remain in the wastewater and be recharged to the ground-water basin. Analyses of water supply and wastewater in the Los Osos area indicate that 100 to 200 mg/L of dissolved solids are added during municipal use (Brown and Caldwell, Inc., 1983; George Gibson, San Luis Obispo County Engineering Department, written commun., 1987). This salt load is added each time the water is used and would tend to accumulate in the ground-water basin unless it is diluted by freshwater recharge or removed by outflow to the ocean.

A detailed, distributed-parameter salt budget analysis of the basin was beyond the scope of this study. A water budget for the part of the basin directly affected by recharge from the proposed wastewater-percolation ponds indicates the magnitude of the problem. Contours of simulated potentiometric head for alternative 4 (fig. 24) indicate that the recharge mound principally lies west of South Bay Boulevard and south of El Morro Avenue (fig. 1). In layer 1, about 66 percent of the inflow to this area under alternative 4 was recharged wastewater. About 66 percent of the outflow was downward to layer 2, and only 12 percent was outflow to the ocean. In layer 2, 95 percent of the inflow to the same area was downward percolation from layer 1. As in layer 1, only 1 percent of the outflow was to the ocean, and 58 percent was downward to layer 3. These figures indicate that a large proportion of the recharged wastewater would percolate downward to the principal pumping aquifers and a small amount would flow out to the ocean. In this case, long-term salt build-up is likely to be a problem, at least in the area directly influenced by the recharge mounds. Areas north of El Morro Avenue and east of South Bay Boulevard may or may not be strongly affected, depending on the locations of future municipal supply wells and whether or not Los Osos Creek is used for supplemental wastewater recharge. Even in the year 2010, however, the annual volume of recharged wastewater would be only about 1 percent of the total volume of fresh ground water in the basin, so that salinity increases are likely to be slow.

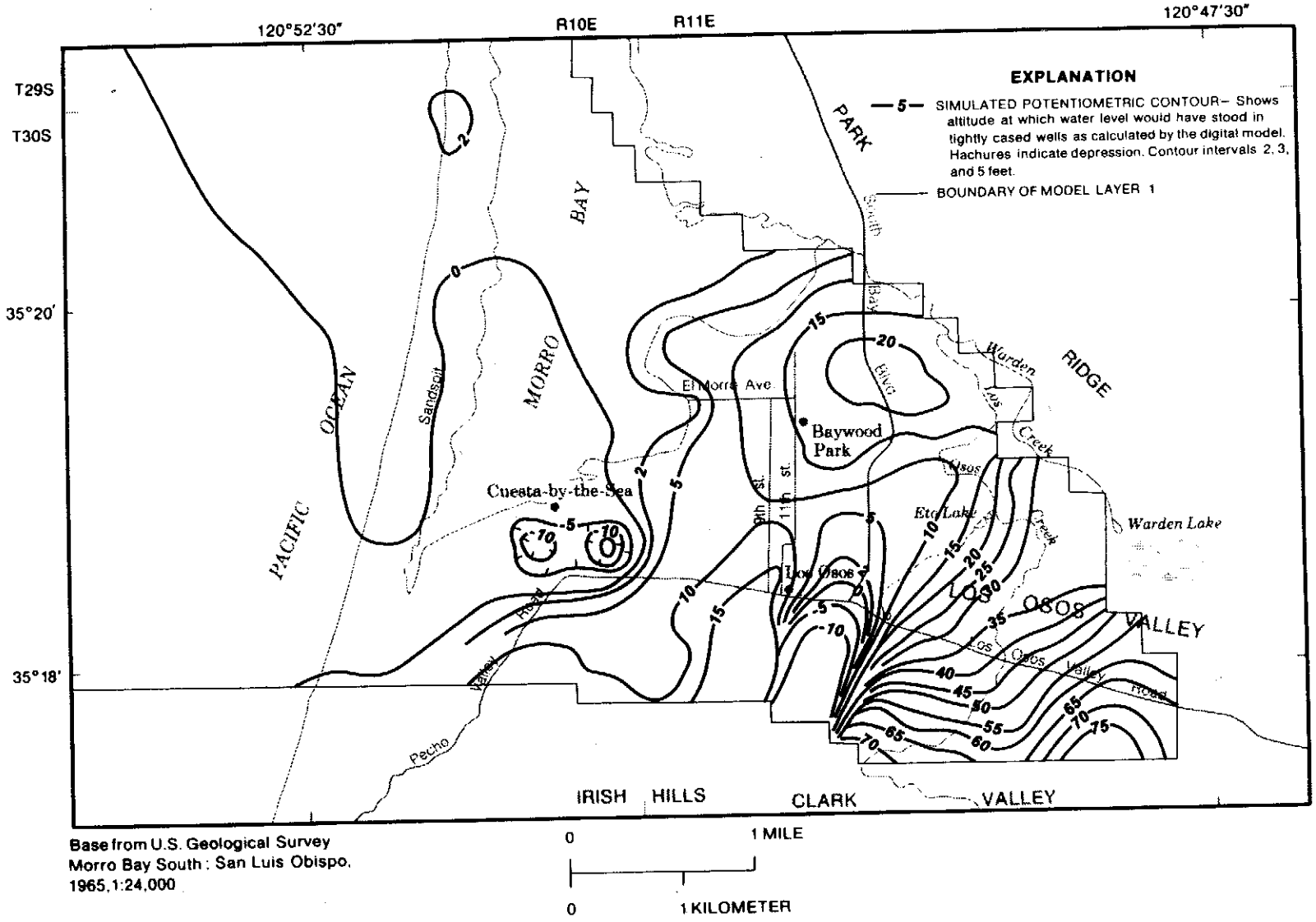


FIGURE 28. – Simulated potentiometric heads in model layer 1 in September after three dry years under management alternative 1.

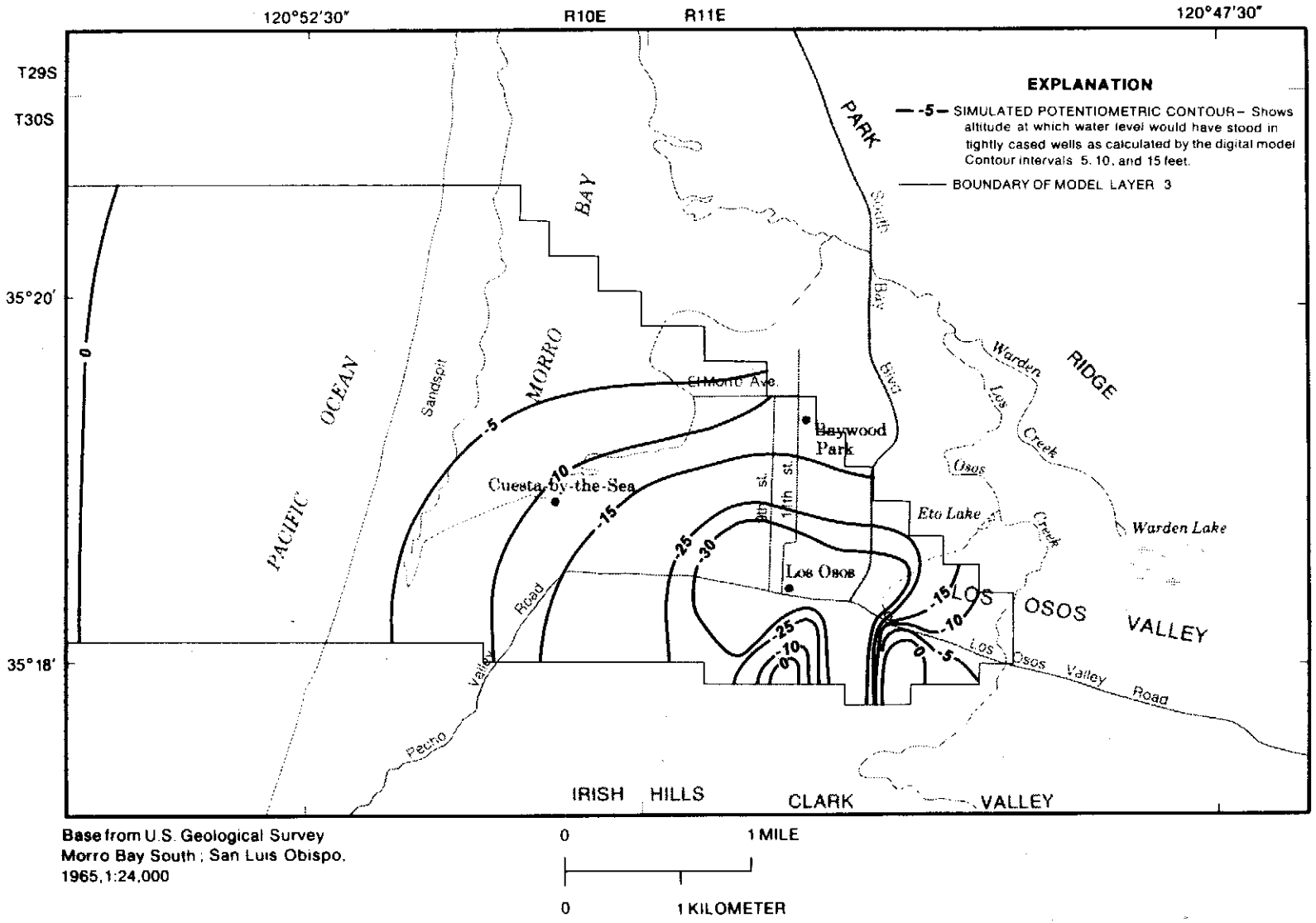


FIGURE 29. Simulated potentiometric heads in model layer 3 in September after three dry years under management alternative 1.

SUMMARY

Los Osos Valley is a small valley on the coast of central California. A ground-water basin occupies the western part of the valley and extends an unknown distance offshore. The basin is 1,000 feet deep in places and mainly filled with unconsolidated sediments of the Careaga Sandstone and Paso Robles Formation. The sediments consist of complexly layered beds of gravel, sand, silt, and clay. Individual layers are generally too thin and discontinuous to form major aquifers and confining beds. The layering does impede vertical flow of water, however, and significant vertical head gradients are common.

The surface of the basin is covered in most areas by thin layers of windblown sand deposits or by Holocene alluvial deposits associated with Los Osos Creek. The sand deposits are highly permeable but for the most part unsaturated.

Basement rocks underlying the basin include the Pismo Formation and metavolcanics and metasediments of the Franciscan Complex. These rocks are generally much less permeable than the basin-fill sediments, but they may transmit some ground water through fractures. Offshore, the ground-water basin is in hydraulic connection with the ocean, as is evidenced by brackish ground water in wells near the coastline.

A three-dimensional finite-difference model was developed to simulate flow in the ground-water basin. The model grid consisted of three layers, each containing 1,040 cells. The number of active cells ranged from 233 in layer 3 to 637 in layer 1. The model simulated potentiometric heads and head-dependent inflows and outflows, including seepage to and from Los Osos Creek, flow across the ocean boundary, and changes in storage. Transient simulations of 1970-77 and 1986 were used to obtain calibrated estimates of aquifer properties and coefficients of leakance of the ocean boundary and the Los Osos Creek streambed.

The model was unable to simulate perched water tables, vertical potentiometric-head gradients within model layers, and the location of the saltwater-freshwater interface. These shortcomings, however, do not significantly affect the ability of the model to simulate horizontal ground-water flow in onshore areas and calculate a basinwide water budget. Results of the calibration simulations were stable and reasonably insensitive to errors in input data. Sensitivity analysis demonstrated that in terms of percent change, errors in individual input variables resulted in smaller errors in calculated head-dependent flows.

The largest source of recharge to the ground-water basin in water year 1986 was deep percolation of rainfall. This recharge flow was estimated by calculating monthly soil-moisture budgets for 19 soil-moisture zones in the study area. Each zone represented an area of uniform soil cover, soil type, and rainfall. Soil-moisture budgets accounted for rainfall, irrigation, runoff, evapotranspiration, deep percolation, and changes in soil moisture storage. Recharge from rainfall was 2,530 acre-ft in 1986.

Municipal and agricultural pumpage in 1986 was largely offset by return flow from septic systems and from urban and agricultural irrigation. Net municipal pumpage was 550 acre-ft, and net agricultural pumpage was 570 acre-ft.

Other inflows in 1986 included ground-water underflow (420 acre-ft) and net seepage from Los Osos Creek (50 acre-ft). Other outflows included net outflow to the ocean (590 acre-ft), perched-water runoff (360 acre-ft), and phreatophyte transpiration (200 acre-ft). There was an increase of 690 acre-ft in aquifer storage.

Shallow ground water in the urbanized part of the basin is contaminated with nitrates. The contamination apparently has resulted from recent large increases in the number of residents in the Los Osos area and the exclusive use of septic systems for disposal of urban wastewater. In response to this problem, local agencies are considering several options for management of water supply and wastewater disposal. Water-supply options include continued exclusive use of ground water, import of water to meet future increases in demand, and import of water to meet present as well as future demand. Wastewater disposal options include continued use of septic systems, centralized treatment and recharge, and export.

The ground-water flow model was used to simulate the effects of various combinations of water-supply and wastewater-disposal options on the ground-water basin. Simulations were done for assumed conditions in the year 2010, when population and municipal water use are expected to be about twice as large as in 1986. Normal, wet, and dry climatic conditions were evaluated separately.

Continued exclusive use of ground water and septic systems would result in a small increase in seawater intrusion, but, in general, increases in municipal pumpage would be offset by increases in return flow from septic systems and urban landscape irrigation. Centralized treatment and recharge of wastewater would result in lower heads in most urban areas but much higher heads near the wastewater percolation ponds. Increased recharge from Los Osos Creek would

also result, as well as increased outflow to the ocean and elimination of seawater intrusion. In contrast, export of wastewater would result in a smaller increase in recharge from the creek, a decrease in outflow to the ocean, and a large increase in seawater intrusion.

Import of water to meet future increases in demand would raise potentiometric heads throughout the basin; it would also decrease net seepage from Los Osos Creek and increase greatly outflow to the ocean. If wastewater is exported, however, partial use of imported water would not eliminate seawater intrusion completely. It was not determined whether importing water to meet all future demand would eliminate intrusion caused by exporting wastewater.

Waterlogging of soils downhill from proposed wastewater-percolation ponds might be a problem near the shore of Morro Bay during wet winters. Seawater intrusion would tend to increase during a series of dry years similar to 1977. For example, exclusive use of ground water in conjunction with centralized treatment and recharge of wastewater would not cause seawater intrusion under normal climatic conditions, but it would cause a small amount of intrusion after 3 dry years.

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