GEOHYDROLOGIC FRAMEWORK, HISTORICAL DEVELOPMENT OF THE GROUND-WATER SYSTEM, AND GENERAL HYDROLOGIC AND WATER-QUALITY CONDITIONS IN 1990, SOUTH SAN FRANCISCO BAY AND PENINSULA AREA, CALIFORNIA

By John L. Fio *and* David A. Leighton

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CONVERSION FACTORS, VERTICAL DATUM, WATER-QUALITY INFORMATION, AND WELL-NUMBERING SYSTEM

CONVERSION FACTORS

Multiply	By	To obtain
cubic meter (m^3)	0.0008107	acre-foot
cubic meter per year (m^3/y)	0.0008107	acre-foot per year
gram (g)	0.03527	ounce, avoirdupois
kilometer (km)	0.6214	mile
liter (L)	0.2642	gallon
meter (m)	3.281	foot
milligram (mg)	35.27	ounce, avoirdupois
milligram per liter (mg/L)	133.5	ounce per gallon
millimeter (mm)	0.03937	inch
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot
square meter per year (m^2/y)	10.76	square foot per year

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

$$°F=1.8(°C)+32$$

VERTICAL DATUM

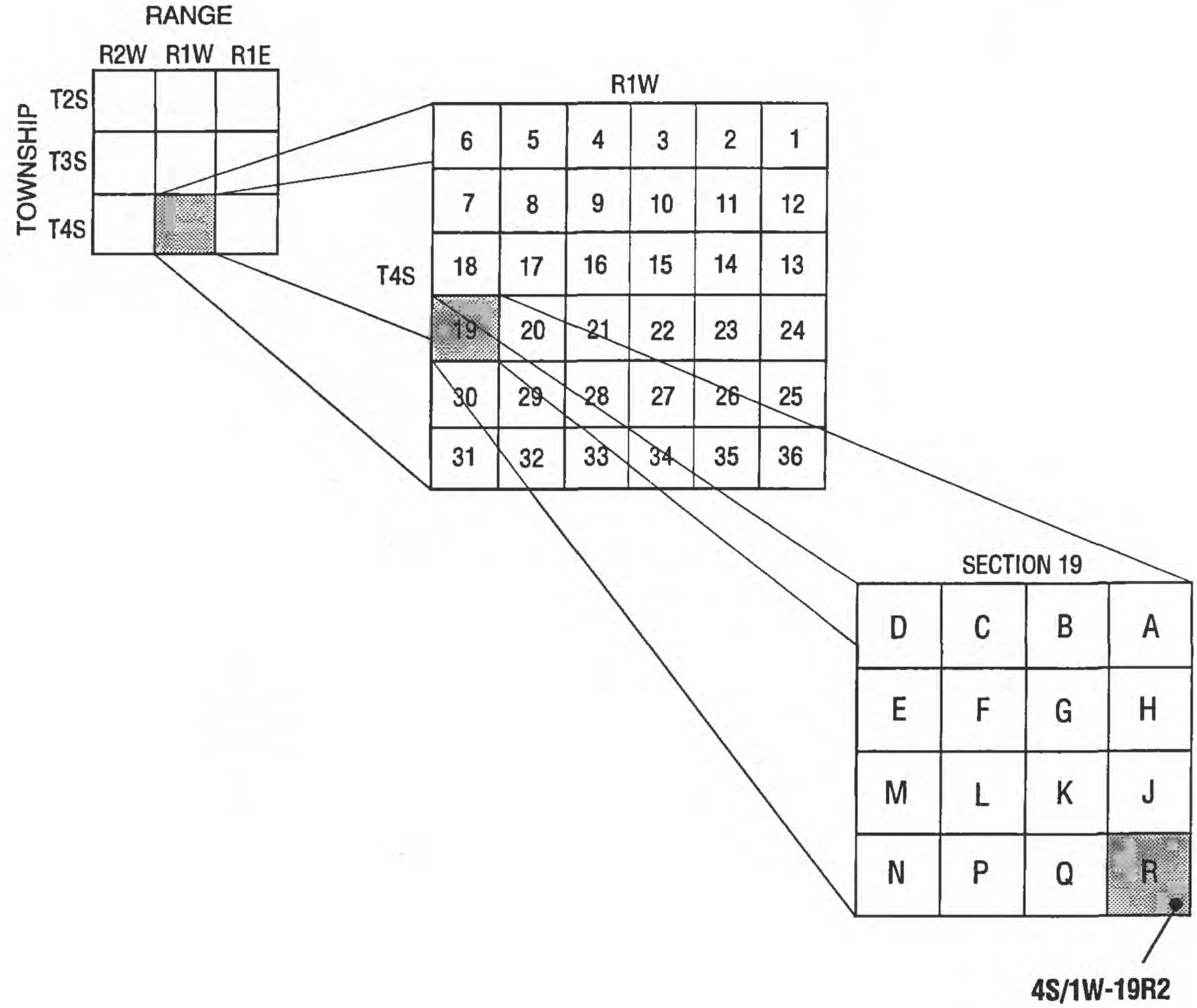
Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

WATER-QUALITY INFORMATION

Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

WELL-NUMBERING SYSTEM

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. The identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is further divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the Mount Diablo base line and meridian (M). Well numbers consist of 15 characters and follow the format 004S001W19R002M. In this report, well numbers are abbreviated and written 4S/1W-19R2. Wells in the same township and range are referred to only by their section designation, 19R2. The following diagram shows how the number for well 4S/1W-19R2 is derived.



GEOHYDROLOGIC FRAMEWORK, HISTORICAL DEVELOPMENT OF THE GROUND-WATER SYSTEM, AND GENERAL HYDROLOGIC AND WATER-QUALITY CONDITIONS IN 1990, SOUTH SAN FRANCISCO BAY AND PENINSULA AREA, CALIFORNIA

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Abstract

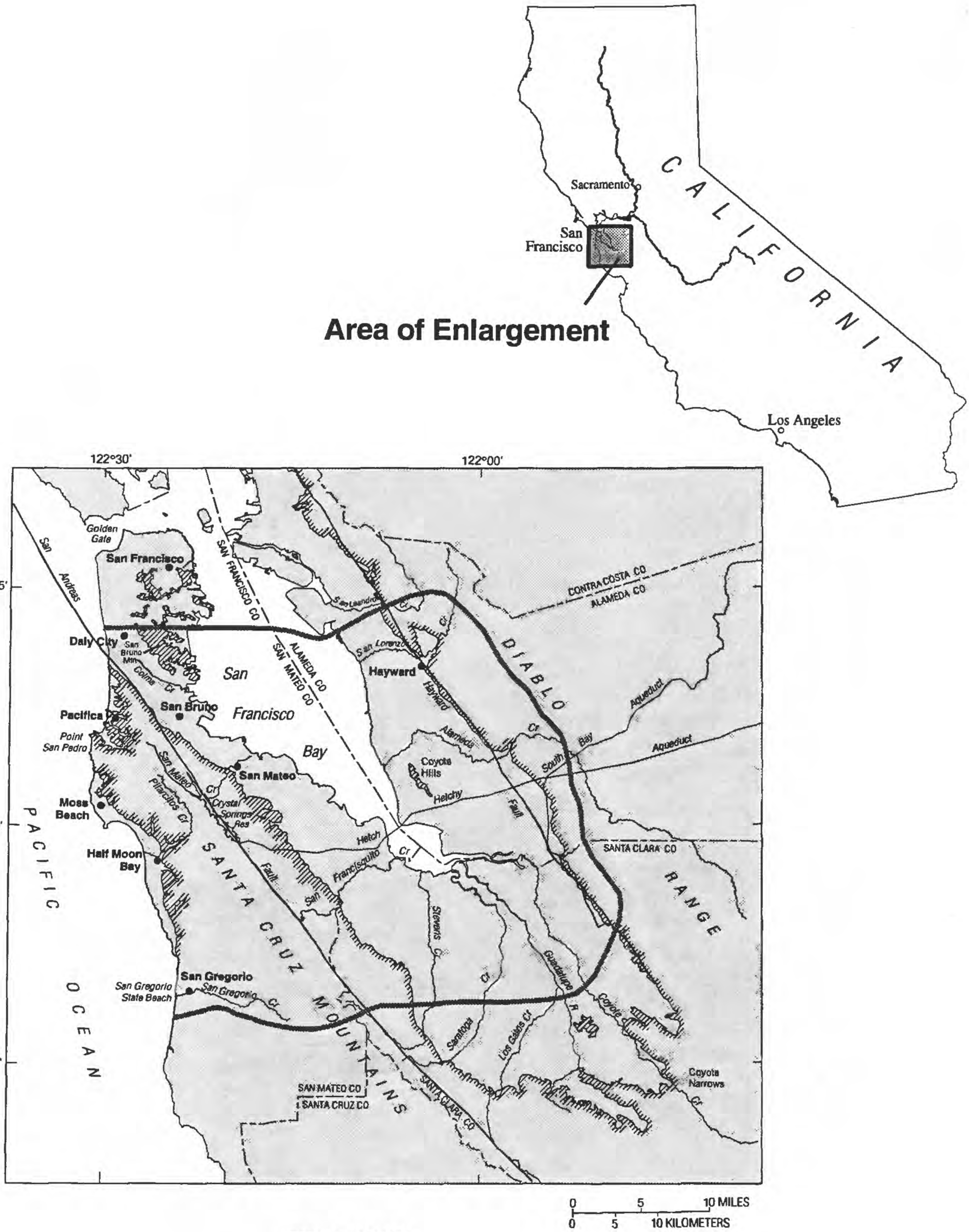
Existing data are used for a regional assessment of geohydrologic and water-quality conditions in the south San Francisco Bay and Peninsula area. Semiconsolidated and unconsolidated sediments form productive aquifers along the coast of the Pacific Ocean and in the large interior valley and plains associated with south San Francisco Bay. These sediments are a heterogeneous mixture of fine- and coarse-grained alluvium; therefore, distinct aquifers and aquifer boundaries are difficult to delineate in much of the study area.

Coarse-grained sediment associated with old stream channels forms the primary aquifers in the study area. Reported transmissivity calculated from pumping tests indicates that the depth-averaged fraction of coarse-grained sediment determined from well-driller reports explains 24 percent of the variability in reported aquifer transmissivity. The capacity of sediments to store ground water also is related to the mixture of fine- and coarse-grained sediment, and most of the pore-space available for storage is in Santa Clara and Alameda Counties.

Historical pumping of ground water resulted in overdraft conditions, and maximum overdrafts prior to 1965 were accompanied by subsidence of the land surface and saltwater contamination. Large quantities of imported surface water delivered after 1965 have restored water levels in many parts of the study area. Reported well pumpage for water supply represents a minimum estimate of total withdrawals, and most of the 179,500,000 cubic meters withdrawn in 1990 was pumped in Santa Clara and Alameda Counties. The concentrations and character of dissolved constituents in ground water in 1990 reflect the regional geohydrology and historical overdraft conditions.

INTRODUCTION

The south San Francisco Bay area includes communities that surround south San Francisco Bay and that are adjacent to the Pacific Ocean along the Peninsula (fig. 1). This area is part of the larger San Francisco Bay region, the largest urban and industrial center in northern California. The population of the area is growing and presently exceeds 3 million people. Water needed to support this large population is supplied by a combination of surface and ground water. The State of California and city of San Francisco supplement the water supply for this area by importing substantial quantities of surface water from distant drainage basins. The capacity of these surface-water supplies to meet future demand is limited and can vary annually as a result of climatic conditions. Furthermore, deliveries of imported surface water are susceptible to short-term interruptions by natural disasters, such as fires and earthquakes. An assessment of the ground-water system in the south San Francisco Bay area is needed to provide managers and other planners comprehensive information for making decisions and plans



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 1. South San Francisco Bay and Peninsula area and study-area boundary, California.

to augment water supplies during emergency situations, meet increased demands associated with future growth, and improve the allocation of available water resources in the region.

This report describes the results of an investigation of geohydrologic and water-quality conditions in the south San Francisco Bay and Peninsula area. Although there have been previous investigations in the area and data-collection activities continue at various locations, the data for the region have not been compiled, evaluated, or analyzed systematically for more than 25 years. Furthermore, importation of substantial quantities of surface water to the region since 1965 has drastically altered hydrologic conditions. For these reasons, the U.S. Geological Survey, in cooperation with the Bay Area Water Users Association (BAWUA), conducted an assessment of the regional ground-water system.

Purpose and Scope

This report provides geohydrologic and water-quality information for historical and current conditions (1990) in the south San Francisco Bay and Peninsula area. The report was written on the basis of an evaluation of data from published reports, maps, digital databases, and other paper records maintained by local, State, and Federal agencies. The data were compiled into a geographic information system (GIS) database, and the database was used to assess the historical development of the ground-water system from 1915 to 1990. During this period, the area underwent a transition from a primarily agricultural economy to the largest urban and industrial center in northern California. Evaluation of the changes in hydrologic and water-quality conditions during the past 75 years provides useful insight into ground-water system response to potential future changes in the management of water resources.

Study Area

The study area encompasses most of San Mateo County, part of northern Santa Clara County, and the southwestern part of Alameda County (fig. 1). The study area includes coastal areas that consist of marine terraces and small alluvial valleys adjacent to the Pacific Ocean, and a large interior valley that drains into San Francisco Bay. The inland valley is flanked by the Diablo Range to the east and Santa Cruz Mountains to the west. Most water purveyors within the study area purchase surface water from the city of San Francisco, which imports water by way of the Hetch-Hetchy Aqueduct from drainage basins more than 200 km to the east. The coalition of water purveyors that purchase water from the city of San Francisco form the Bay Area Water Users Association, which is the cooperator for this study.

Water is used in the study area for various municipal, agricultural, industrial, and domestic purposes. Before 1965, ground water supplied the water needs in most of the area. Imported surface water to supplement water supplies was first delivered to the area by the city of San Francisco in 1940, whereas the State of California did not start significant deliveries of imported surface water until 1965. Since 1965, increasing supplies of imported surface water have supplied most water requirements in the south bay area.

Data-collection and management activities within the study area range from sophisticated programs using numerical models, recharge facilities, and monitoring networks that facilitate the conjunctive use of surface- and ground-water supplies in parts of the area, to minimal information on the density and distribution of wells, pumpage, and water quality in other parts. For example, Alameda and Santa Clara Valley water districts have programs that supplement natural recharge with temporary and permanent facilities to store and spread imported surface water for percolation into the ground-water system. In contrast, conjunctive-use efforts in other parts of the study area are minimal to nonexistent, and ground-water management is from a relatively local perspective.

Previous Investigations

Previous studies have been done to assess the quantity and quality of ground water in the south San Francisco Bay and Peninsula area, and several are cited in this report. The purpose of this section is to provide general information on selected studies that describe conditions before and after the delivery of substantial quantities of imported surface water to the region in 1965.

The earliest published account of regional ground-water conditions is provided by the U.S. Geological Survey for a study in Santa Clara County and parts of San Mateo and Alameda Counties in the early 1900's (Clark, 1924). The report provides geohydrologic and land-use information on conditions as early as 1915. Included in the report are a compilation of geohydrologic data from nearly 3,000 wells and estimated annual recharge, pumpage, and consumptive-use data for the period 1912-20.

The next study of similar regional extent was done in the 1960's by the California Department of Water Resources (1967). This study compiled massive quantities of geohydrologic and water-quality data for the area bounded in the north by the cities of San Mateo and Hayward and in the south by the Coyote Narrows. The results provide information on hydrologic conditions before the State of California delivered imported surface water. Subsequent studies done in Alameda and Santa Clara Counties document the early response of the ground-water system to increased surface-water supplies (California Department of Water Resources, 1967, 1973, and 1975).

Since the early 1970's, the frequency of ground-water studies generally has increased because of greater reliance on ground water during the drought conditions of 1977-78 and 1987-92 and a general increase in public concern over issues related to ground-water quantity and quality. These studies have focused on issues of relatively local concern. Examples of such recent geohydrologic and ground-water modeling investigations are studies in northern San Mateo County (Applied Consultants, 1991), in Santa Clara County (CH2M Hill, 1992), and in Alameda County (Montgomery, 1991). The results of these and other local studies provide information on geohydrologic conditions within subareas of the study area during the late 1980's and early 1990's.

METHODS

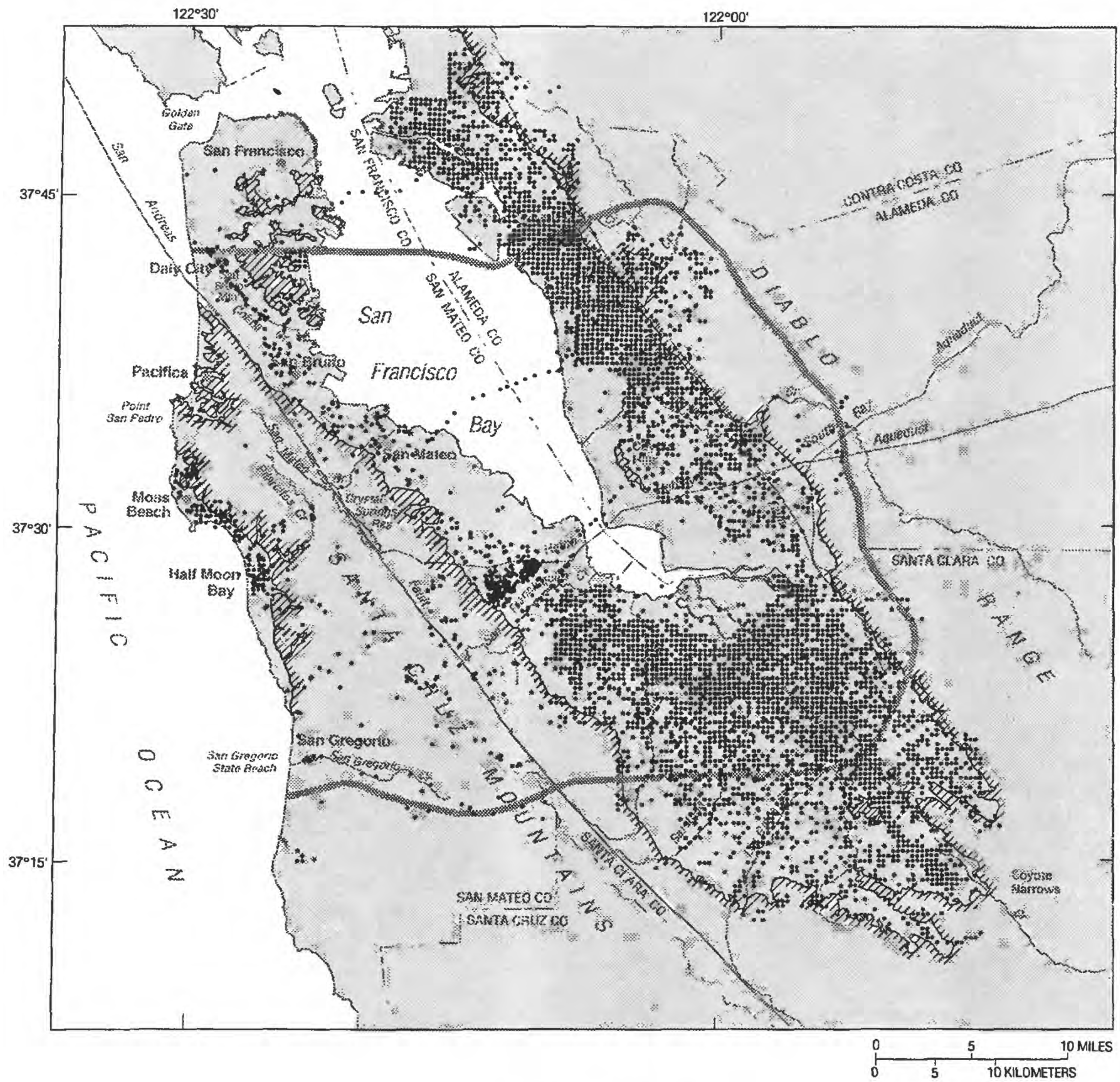
Description of Database

Geohydrologic, water-quality, water-use, and land-use data were obtained from numerous local, State, and Federal agencies. The form of the data ranged from published reports and maps to records maintained in paper and digital files. A geographic information system (GIS) database was used to compile and organize the data into different thematic coverages. Each of these coverages, or data layers, contain features based on themes such as wells, political boundaries, transportation networks, and land use. The features are referenced to a common coordinate system; thus, data layers can be combined or intersected for spatial analyses of the data. Leighton and others (1994) provide a detailed description of the data layers used in this study.

Data-compilation efforts focused on areas within the boundaries of the study area, but some data were compiled for areas outside the study area to ensure a smooth distribution of data across the study area boundaries. More than 25,000 wells or boreholes were identified for which one or more of the following types of data are available: lithology, water level, or water quality. For the purpose of this study, wells and boreholes will be referred to collectively as wells for the remainder of this report. These wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. The approximate locations of the wells, based on well-identification number, are plotted in figure 2. Field validation of these locations was beyond the scope of this study, and many well records were considered incomplete in their present form because the well-construction information necessary for proper interpretation of the data was lacking. Therefore, a subset of this data set was developed for compilation in the GIS database by the selection of wells with adequate information on well depth, top and bottom of well perforations, use of the well, and location (Leighton and others, 1994).

The GIS database contains data on 1,014 wells with information on (1) location and well construction (1,014 sites), (2) subsurface lithology (762 sites), (3) ground-water levels (293 sites), and (4) ground-water quality (394 sites). The wells were located with reasonable accuracy on U.S. Geological Survey 7.5-minute topographic quadrangles prior to their compilation into the database and include observation wells that are not used to produce water, domestic wells used to supply water for private consumption, and large production wells that supply water for municipal, industrial, institutional, and irrigation water uses. The sites are plotted in figure 3 and show that the density of data points is different from that shown on figure 2, but the general coverage of data locations is similar.

It is noteworthy that, because resources were limited, this subset of wells does not represent all of the sites in the study area for which there are useful geohydrologic and water-quality data. Additional work would be necessary if greater data density was needed for smaller, subregional analyses or to improve data coverage in areas that are currently lacking information. Because most of the data are site



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

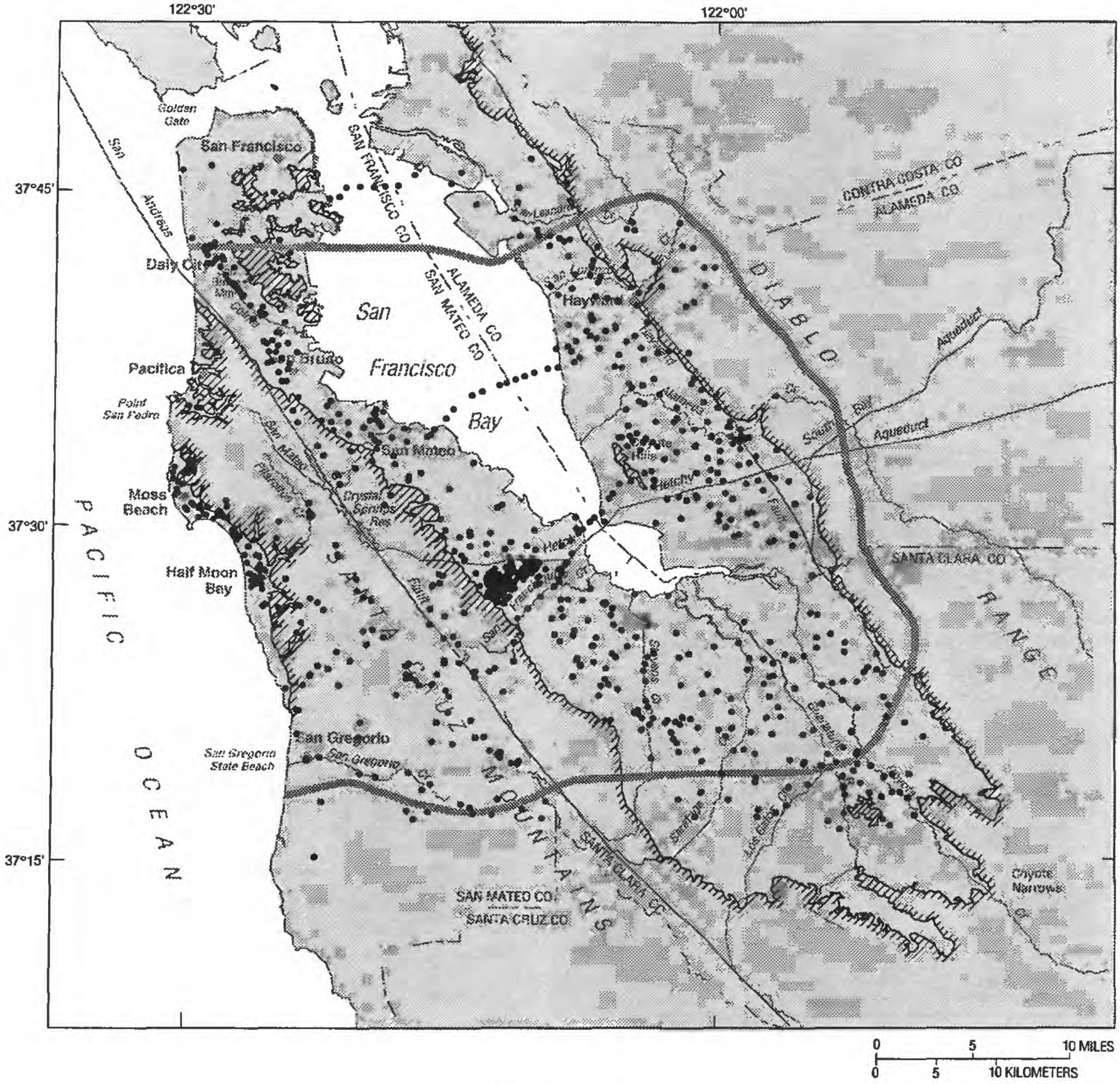
Location of well and borehole data identified for this study

Figure 2. Location of well and borehole data used to develop database, south San Francisco Bay and Peninsula area, California.

specific, extrapolation between sites was necessary to evaluate spatial trends. In most circumstances, extrapolation consisted of constructing maps by contouring the data between sites with either automated procedures or manual procedures and incorporating the results into the database.

Texture Maps and Estimating Storage Capacity

Texture, as defined in this study, refers to the depth-averaged fraction of coarse-grained sediment determined from lithologic data in well-driller logs.



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

• Location of well and borehole data in the database used for this study

Figure 3. Location of well and borehole data in the database, south San Francisco Bay and Peninsula area, California.

Sediment deposits that consist mostly of gravel and sand were assumed to be entirely coarse grained (100-percent coarse grained). Similarly, sediment deposits that consist of mostly silt and clay were assumed to be entirely fine grained (0-percent coarse grained). Hence, coarse-grained sediment was defined in this study as unconsolidated clayey or silty sand, sand, gravelly sand, clayey or silty gravel, gravel, and sandy gravel; fine-grained sediment was defined as unconsolidated mud, clay, silt, silty clay, peat, clayey silt, sandy or gravelly clay, sandy silt, or top soil (table 1). For the purposes of this study, rock, stone, shale, fractured shale, hard or cemented clay, tight, hard, or cemented sand, sandstone, and

Table 1. List of common lithologic descriptions in well-driller reports, corresponding fraction of coarse-grained sediment, and estimated specific yield, south San Francisco Bay and Peninsula area, California

General description in well-driller report	Fraction of coarse-grained sediment (percent)	Specific yield
Rock, stone, shale, fractured shale	0	0.00
Hard or cemented clay, hardpan	0	.01
Mud, clay, silt, silty clay, peat, clayey silt	0	.05
Sandy or gravelly clay, sandy silt, top soil	0	.05
Tight, hard, or cemented sand, sandstone, tight, hard, or cemented gravel	0	.10
Clayey or silty sand, clayey or silty gravel	100	.05
Sand, gravelly sand	100	.20
Gravel, sandy gravel	100	.20

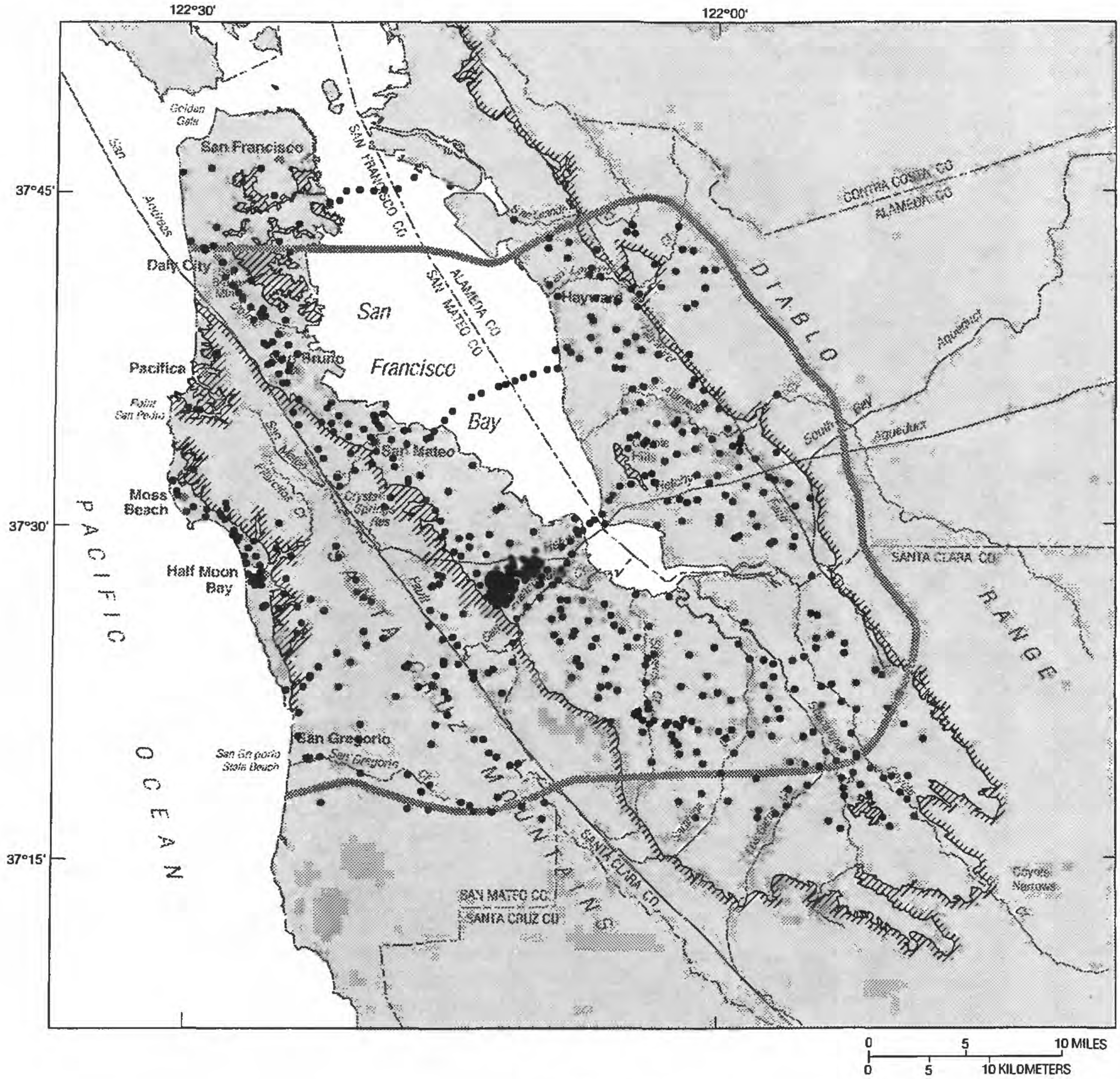
tight, hard, or cemented gravel are considered fine grained. The combination of coarse- and fine-grained sediments form the aquifer matrix in the study area.

The total volume of pore space between the sediment grains is one factor that influences the aquifer's storage capacity. Storage capacity, as defined in this study, is the quantity of water that could potentially be released from the aquifer under gravity drainage. Thus, the storage capacity of the aquifer was estimated from values of the specific yield inferred from lithologic data. In this report, the values of specific yield represent a compilation of values used in previous studies that related lithologic data from well-driller reports to the specific yield of sediment deposits (Davis and others, 1959; California Department of Water Resources, 1975).

The distribution of sediment texture and storage capacity was mapped by contouring the depth-averaged fraction of coarse-grained sediment and specific yield with the use of the Surface III mapping package (Sampson, 1988). Well-driller reports for 762 wells (fig. 4) were discretized in 0.3-m intervals, and the depth-averaged fraction of coarse-grained sediment and specific yield was calculated for several depth intervals. A similar approach was used by Laudon and Belitz (1991) to construct maps of sediment texture for areas of the western San Joaquin Valley in California, and additional details of the mapping method are given by Laudon and Belitz (1991). The storage capacity was estimated by integrating the two-dimensional surface of depth-averaged specific yield over the depth interval of unconsolidated sediment.

Calculating Hydraulic Heads

Hydraulic heads at 293 wells (fig. 5) were calculated from water-level data as the difference between land-surface altitude and depth to water. Water-level data compiled for this study were often reported as both depth to water and calculated head, but in some circumstances were reported only as depth to water. Where the altitude of the measuring point was not available, a digital model was used to estimate the altitude of land surface to calculate hydraulic head at sites where data were reported as only depth to water (Leighton and others, 1994). Water levels generally were measured semiannually, but some agencies have collected water levels on a quarterly, monthly, or even weekly basis. For the purpose of this study, the water levels were averaged on an annual basis. Time-series plots were made to show changes in average annual hydraulic head during 1936-92, and contour maps of the hydraulic-head surface in 1965 and 1990 were prepared manually for two depth intervals to infer changes in hydraulic-head gradients. The hydraulic-head surface for the shallow zone less than 45 m below land surface was approximated in areas where data were lacking using the few data points available and a map of the shallow water table (Webster, 1973). This was done because the water table in a large part of the inland valley is reportedly insensitive to pumping from deeper zones. The assumption that hydraulic heads in the shallow aquifer zone are the same as the altitude of the water table is questionable, and contours in areas of uncertainty are intended only to show estimated changes from historic conditions determined from limited data. Application of the maps in these areas for determining absolute hydraulic heads and hydraulic-head gradients is not warranted. The hydraulic-head surface for the deep zone (greater than 45 m below land surface) was not contoured in areas with inadequate data coverage.



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Well or borehole location

Figure 4. Location of wells and boreholes used to construct texture maps, south San Francisco Bay and Peninsula area, *California*.

Water Quality

Water quality in the study area was assessed with reported results from analyses of water samples from 394 wells (fig. 6). The computer program SNORM (Bodine and Jones, 1986) was used to calculate the normative salt assemblage, or salt norm, of a water sample from the reported concentration of major cations (sodium, calcium, and magnesium) and anions (chloride, carbonate, and sulfate) in the water samples. The salt norm represents an estimate of the equilibrium salt assemblage expected when a

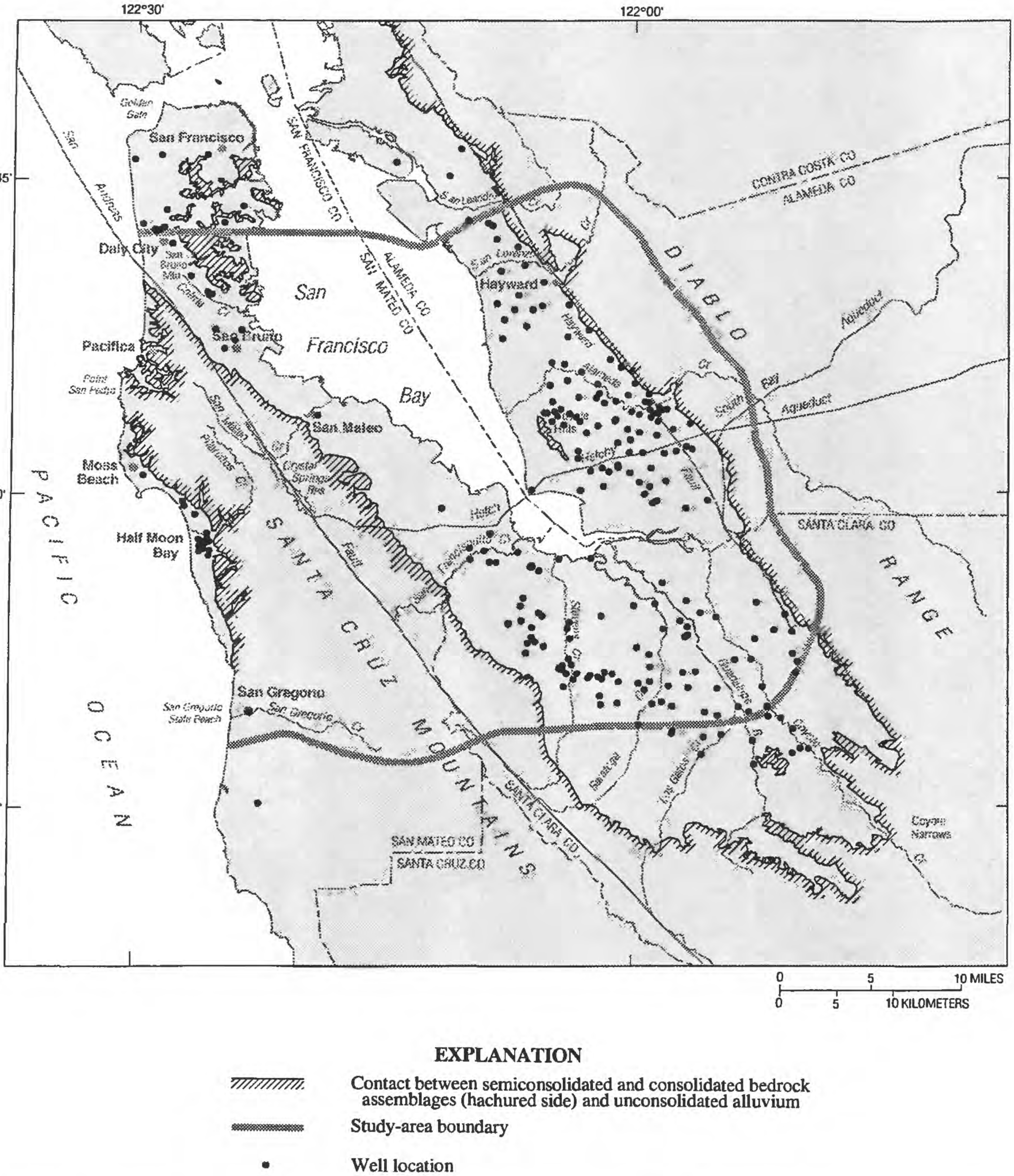
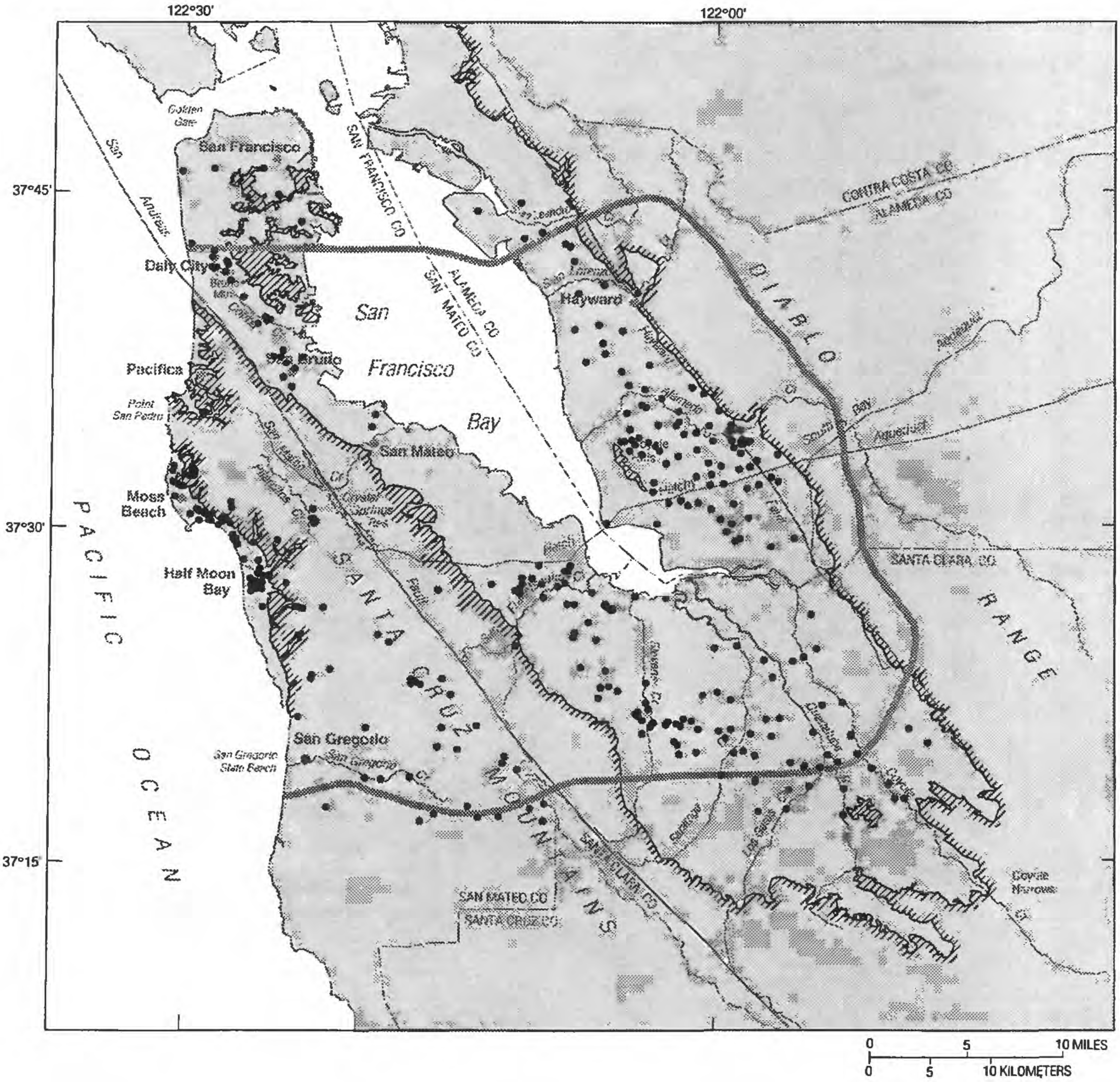


Figure 5. Location of wells used to calculate hydraulic heads, south San Francisco Bay and Peninsula area, California.

water sample is evaporated to dryness under land-surface conditions (Bodine and Jones, 1986) and can be used to classify different types of water.

The database also contains information for other constituents of concern and was used to assess the distribution and concentration of these constituents. For example, the spatial distribution of dissolved solids in ground water was assessed by constructing a map showing areas where reported well-water samples have dissolved-solids concentrations consistently greater than 500 mg/L and consistently



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

• Well location

Figure 6. Location of wells for which water-quality data are available, south San Francisco Bay and Peninsula area, California.

greater than 1,000 mg/L. This map was constructed in two steps. First, the average reported concentration of dissolved solids from 1980-90 was calculated for each well. This 10-year interval was selected in order to obtain an acceptable number and distribution of data points for the most recent representation possible. Second, these average concentrations were used to modify similar boundary intervals previously reported by Webster (1972) in order to obtain a map for the entire study area; in areas where data were lacking, the boundaries of Webster (1972) were not altered.

GEOHYDROLOGIC FRAMEWORK

Regional Geohydrology

In the inland valley, the ground-water system generally is unconfined in the upslope areas, whereas in the lowlands, a relatively shallow water table aquifer overlays confined and semiconfined aquifers (California Department of Water Resources, 1967). The ground-water system associated with the marine terraces along the coast of the Pacific Ocean reportedly is unconfined (Earth Science Associates, 1986). Most wells in the inland valley withdraw ground water from deeper semiconfined and confined zones, and water levels in these wells show hydraulic response to short- and long-term pumping cycles. In the valley lowlands, water levels measured in wells perforated exclusively within the shallow water-table aquifer are reportedly insensitive to pumping cycles in deeper wells because of the low permeability of the clay beds that confine ground water at greater depth.

Percolation of precipitation, infiltration of runoff through stream beds, and artificial recharge of imported surface water are the primary mechanisms through which the ground-water system is replenished. Most precipitation and runoff occurs during the winter and early spring months, and mean precipitation can vary spatially from about 300 mm in the inland valley to greater than 500 mm in the surrounding highlands and along the coast (Rantz, 1971). Numerous streams collect the runoff generated in the highlands and discharge it into south San Francisco Bay and the Pacific Ocean. The drainage basins for Alameda Creek, Coyote Creek, and Guadalupe River have the greatest area of drainage (table 2). Water-conservation efforts and imported surface water are used to increase ground-water recharge from Alameda Creek and several streams in northern Santa Clara County. Other mechanisms such as leakage from buried sewer and water-supply lines and irrigation return flows from urban and agricultural areas can contribute recharge to the ground-water system, but they are difficult to quantify.

Table 2. Major streams and drainage areas, south San Francisco Bay and Peninsula area, California

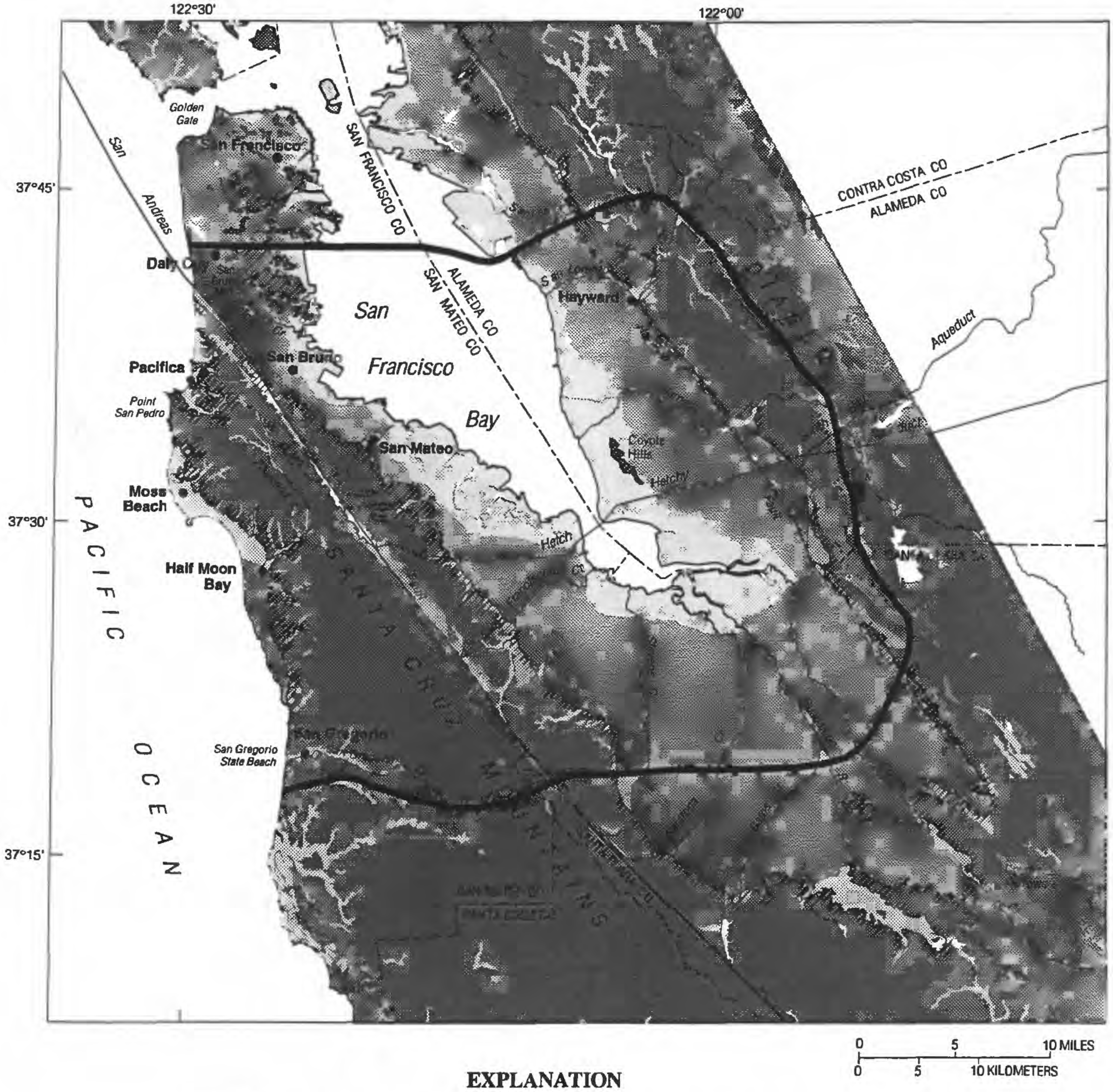
[km^2, square kilometer]

Stream name	Area drained (km^2)
San Leandro Creek	120
San Lorenzo Creek	120
Alameda Creek	1,700
Coyote Creek	910
Guadalupe River	380
Saratoga Creek	110
Stevens Creek	61
San Francisquito Creek	100
San Mateo Creek	88
Colma Creek	41
Pilarcitos Creek	74
San Gregorio Creek	130

Rocks and sediments in the study area can be grouped by age to assess their relative significance to ground-water resources (California Department of Water Resources, 1967). The younger, water-bearing sediments are found in valleys along the coast of the Pacific Ocean and in the large inland valley and alluvial fans that surround south San Francisco Bay (fig. 7). Rocks of Tertiary age and the older Franciscan assemblage of Jurassic and Cretaceous age form bedrock in the study area because they generally are consolidated and of relatively low permeability. Wells that intersect secondary openings formed by fractures in the bedrock can yield water, but the quantity generally is relatively small and variable, depending on local conditions. In contrast, semiconsolidated and unconsolidated gravel and sand deposited during the Pliocene, Pleistocene, and Holocene age typically form important aquifers in the study area; substantial deposits of silt and clay form confining beds in the study area.

The San Francisco Bay depression is a relatively recent occurrence in geologic history and was first inundated by the Pacific Ocean during the late Pleistocene epoch (Helley and Lajoie, 1979). The late Pleistocene epoch was marked by four worldwide glacial events that altered historical sea levels (California Department of Water Resources, 1967). A rise in the altitude of the sea increased the base level of streams and rivers, resulting in low hydraulic gradients and deposition of thick layers of silt and clay in the estuarine environment associated with the bay, its surrounding marshlands, and slow moving channels that enter the bay. As the sea retreated, streams that drained across the older bay bottom eroded and reworked these older deposits and contributed extensive layers of sand and gravel (Helley and Lajoie, 1979). The net result is a heterogeneous mixture of fine- and coarse-grained sediment, and in many areas it is not possible to delineate distinct aquifers or aquifer boundaries.

The thickness of unconsolidated and semiconsolidated alluvium (fig. 8) was calculated from



EXPLANATION

Marine deposits of Holocene Age--Modified from Wentworth (1993)

Alluvium of Pleistocene and Holocene Age--Modified from Wentworth (1993)

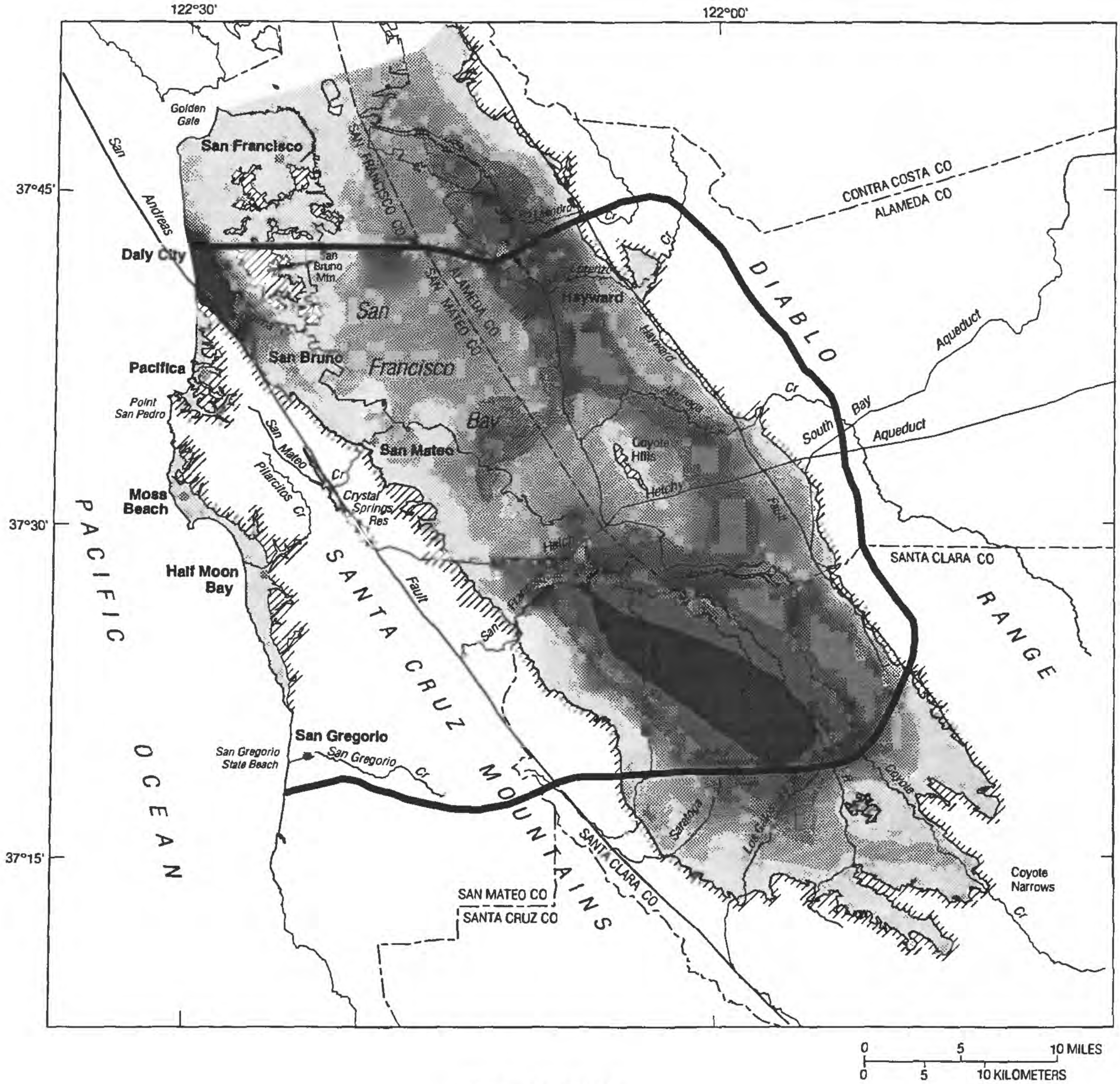
Alluvium of Pliocene and Pleistocene Age--Modified from Wentworth (1993)

Franciscan Complex of Jurassic and Cretaceous Age and rocks of Tertiary Age--Modified from Wentworth (1993)

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 7. Surficial geology in the south San Francisco Bay and Peninsula area, California.



EXPLANATION

Thickness of alluvium, in meters

0 to 100

101 to 200

201 to 300

301 to 400

greater than 400

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 8. Thickness of alluvium in the south San Francisco Bay and Peninsula area, California.

maps of land-surface altitude and elevation of the bedrock surface. The bedrock surface consists of local highs and lows mostly due to nonuniform tectonic subsidence between the San Andreas Fault in the west and related Hayward Fault in the east (California Department of Water Resources, 1967). This differential movement is manifested by deep valleys filled with more than 400 m of sedimentary deposits in the northwestern, northeastern, and southern areas that surround south San Francisco Bay.

Description of Physiographic Subareas

For this study, physiographic subareas were identified to focus analysis in parts of the study area. The subareas defined are of substantial size and were selected on the basis of relatively large-scale trends; thus, these subareas do not necessarily conform to discrete hydrologic units or ground-water basins. For example, it is possible for recharge in one subarea to discharge from pumping wells in a downslope subarea. The boundaries of the subareas are shown in figure 9 and are defined as follows: (a) the Exposed Bedrock subarea comprises surficial exposures of the oldest consolidated rock formations; (b) the Uplands subarea comprises surficial exposures of continental sediments deposited during the late-Pliocene and early-Pleistocene ages; (c) the East and West Side Alluvial Apron subareas comprise surficial exposures of continental sediment deposited during the Pleistocene and Holocene ages; (d) the Niles Cone subarea comprises part of the East Side Alluvial Apron subarea demarcated by the boundaries of the Niles Cone; (e) the Coastal subarea comprises the semiconsolidated and unconsolidated sediment in exterior areas adjacent to the Pacific Ocean; (f) the Merced subarea comprises a 3- to 5-km-wide valley between the Santa Cruz and San Bruno Mountains, underlain by predominantly marine sediments deposited during the Pliocene and Pleistocene age and extends northward beyond the boundaries of the study area; (g) the San Jose Plain subarea comprises distal parts of alluvial fans deposited by Coyote Creek, Guadalupe River, and Los Gatos Creek; and (h) the Bay Plain subarea comprises the tidal flats, marshlands, and bay-fill areas adjacent to San Francisco Bay.

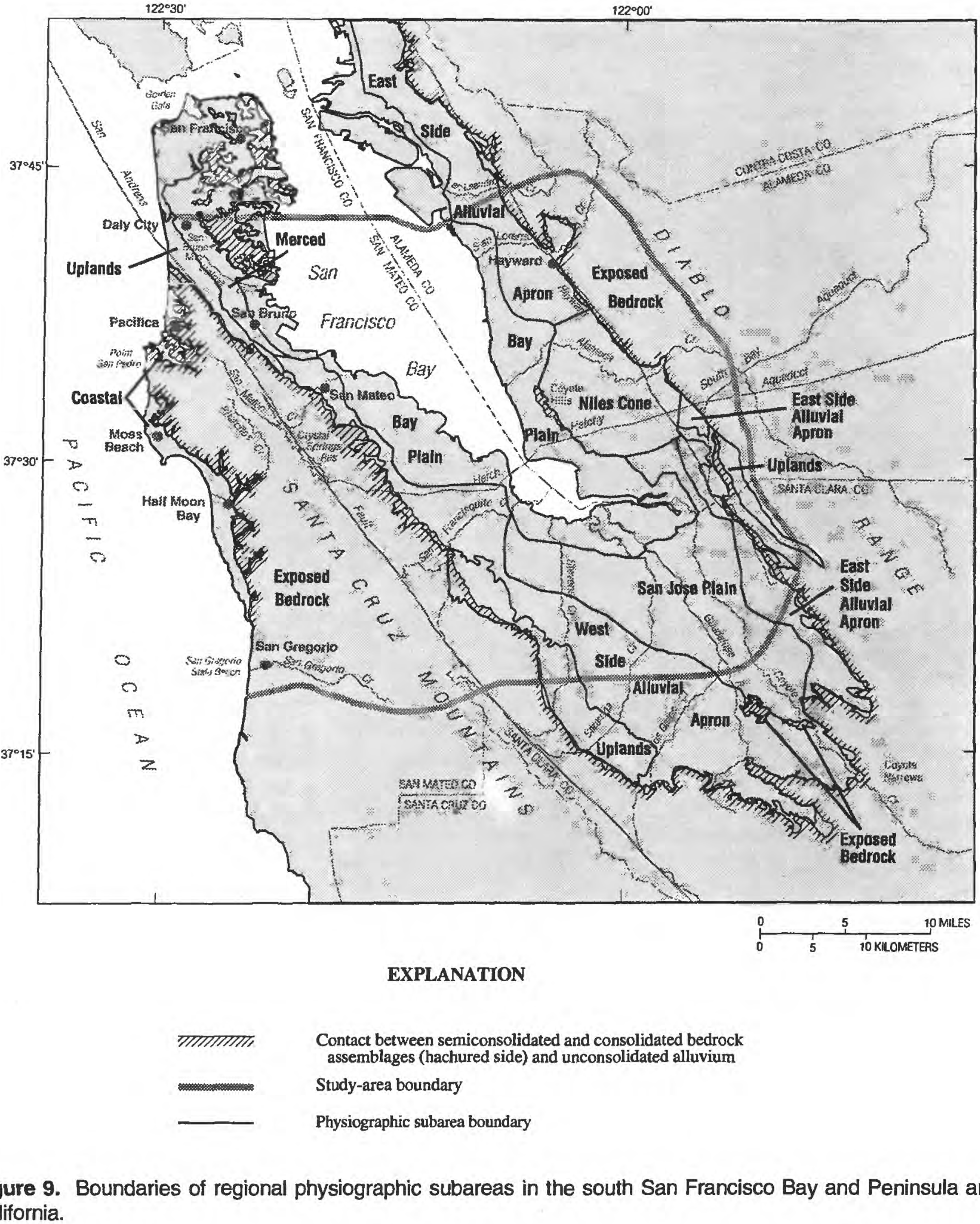
Exposed Bedrock

This study defines bedrock as semiconsolidated and consolidated rock assemblages older than Pliocene age. In the study area, this definition includes sedimentary and volcanic rocks of Tertiary age, and the sandstone, shale, and greenstone of the Franciscan assemblage (Jurassic and Cretaceous age). These rocks form the bedrock subarea where they are exposed at land surface and are the underlying basement complex for younger alluvium. Wells in this subarea typically withdraw water from fractures. These wells have variable yields and primarily are used as private sources of water; thus, this subarea is not very significant to regional water resources. The database contains 168 wells in the Exposed Bedrock subarea, and these wells have completion depths that range from 5 to 180 m below land surface. Recharge to the more expansive alluvial aquifers downslope of this subarea, by way of subsurface flow, may be significant but presently is not well understood. It should be noted that relatively small alluvial valleys are present within the Exposed Bedrock subarea, but these valleys are not delineated in this report because of the regional scope of the physiographic subareas.

Uplands

The Uplands subarea consists of three areas having surficial deposits of unconsolidated and semiconsolidated alluvium of Pliocene and Pleistocene age. The Upland subareas are demarcated by the boundaries of the Exposed Bedrock subarea and younger alluvium of Pleistocene and Holocene age. The northwestern part of the Uplands subarea consists of marine deposits of the Merced Formation of Pliocene and Pleistocene age, and the southwestern and southeastern parts consist of continental deposits of the Santa Clara Formation of Pliocene and Pleistocene age; in the northeastern part of the study area, continental sediments of Pleistocene age have been referred to as the Alameda Formation. These sediments lie unconformably on bedrock and are overlain by younger alluvium in downslope areas.

The total number of wells in the Uplands subarea is relatively small (only eight wells are identified in the database having completion depths that range from 18 to 244 m below land surface). Although the potential for ground-water production in the Uplands is limited, these formations are productive aquifers when tapped by deep wells at lower altitudes in downslope valley areas. Furthermore, the Uplands in the western part of the study area can be important as a source area for recharge to deeper aquifers in downslope valley areas. In the southeast, the combination of eastward dip of formations forming the Uplands (10 to 30°) and low permeability



EXPLANATION

Figure 9. Boundaries of regional physiographic subareas in the south San Francisco Bay and Peninsula area, California.

zones associated with the Hayward Fault reportedly prevent significant westward movement of ground water to downslope valley areas (California Department of Water Resources, 1967).

East and West Side Alluvial Aprons

Streams draining the Exposed Bedrock and Upland subareas have formed numerous alluvial fans on the eastern and western slopes of the study area. The database contains 381 wells in the East and West Side Alluvial Apron subareas, and the wells have completed depths that range from 8 to 389 m below land surface. The areal extent and relative significance of the alluvial aprons to ground-water production varies, but this subarea is very important for ground-water recharge. In southern Alameda and northern Santa Clara Counties, the streams, rivers, and adjacent flood plains are used as spreading grounds for artificial recharge by imported surface water. The sediments associated with the East and West Side Alluvial Apron subareas form multiple aquifer systems, and because sediments at the lower margins of alluvial aprons are typically fine grained, the exchange of ground water between aquifers of adjacent aprons is presumably small (California Department of Water Resources, 1967).

Niles Cone

The Niles Cone is an important aquifer system of the East Side Alluvial Apron subarea and consists of two ground-water basins effectively separated by the Hayward Fault. Alluvium east of the fault generally is coarse grained, and ground water east of the fault reportedly does not move westward across the fault in significant quantities to recharge downslope aquifers. West of the fault, the alluvium is unlike most other sedimentary deposits within the study area in that the coarse- and fine-grained deposits form distinct and areally extensive aquifers and confining beds.

The database contains 97 wells in the Niles Cone subarea that have completed depths that range from 20 to 198 m below land surface. Alluvium west of the Hayward Fault and beneath the Niles Cone are separated generally into the following four groups: the Newark aquifer (approximately 20 to 40 m below land surface), Centerville aquifer (approximately 55 to 60 m below land surface), Fremont aquifer (approximately 90 to 120 m below land surface), and deeper aquifers (greater than 120 m below land surface). These aquifers consist of unsorted deposits of sand and gravel separated by thick layers of clay. Ground-water contours for shallow depth intervals generally show water movement toward the northwestern and southwestern boundaries of the Niles Cone, but because the permeability of sediments is typically low at the lower margins of alluvial fans, the quantity of water exchanged presumably is small (California Department of Water Resources, 1967). In contrast, the deeper aquifers penetrate older alluvium of late Pliocene to early Pleistocene age and seem to have greater lateral continuity. The areal extent of these aquifers may extend beyond the Niles Cone subarea. The quantity of water moving between these areas, and the general nature of the deeper aquifers in the Niles Cone subarea, is not well understood.

Coastal

The Coastal subarea includes the exterior areas in San Mateo County adjacent to the Pacific Ocean. This subarea is characterized by valleys and marine terraces filled with a combination of marine and nonmarine sediments. The database contains 73 wells in the Coastal subarea that have completed depths that range from 14 to 146 m below land surface. The aquifers generally are small in areal extent, and the most significant aquifer is in a 1- to 2-km-wide strip adjacent to Half Moon Bay. This aquifer provides a source of water to the local community. Smaller valley areas also exist near Pacifica, Point San Pedro, and San Gregorio, but the number of wells and quantity of water pumped is relatively small.

Merced

In the northern part of the study area, there is a 3- to 5-km-wide valley between the Santa Cruz and San Bruno Mountains. This valley was once ancestral arm of the Pacific Ocean that existed before the present Golden Gate and consists of a continuous body of permeable marine and nonmarine sediments. The boundaries of the Merced subarea were determined by surficial exposures of the Colma Formation of Pleistocene age, which is underlain by the Merced Formation of Pliocene and Pleistocene age. The Merced Formation forms aquifers that are a significant water supply to the cities of San Francisco, South San Francisco (not shown in fig. 9), Daly City, and San Bruno; 63 wells are in the database for the Merced subarea and indicate completed depths that range from 16 to 210 m below land surface. The aquifer extends northward from the study area into San Francisco and westward beneath the Pacific Ocean at least as far as the San Andreas Fault (not shown in fig. 9); the eastward extent of the aquifer beneath south San Francisco Bay is uncertain.

The ground-water system in the Merced subarea is generalized as an upper unconfined aquifer within the Colma Formation and deeper semiconfined or confined aquifer within the underlying Merced Formation. The Colma Formation consists of fine-grained sand and silty sand with occasional thin beds of clay, whereas the Merced Formation consists of nearly 2 km of predominantly shallow marine and estuarine deposits with thin interbedded muds and peats. Thick fine-grained layers (3 to 18 m) typically occur every 90 to 180 m (Clifton and Hunter, 1987). When continuous, these fine-grained layers can confine ground water in more permeable underlying sediment, and when tilted, these fine-grained layers can impede horizontal movement of ground water. The Merced Formation dips to the northeast, with bedding planes that decrease from more than 40° in the strata between San Bruno and Daly City to 10 or 15° in strata exposed north of the study area (Bonilla, 1971).

San Jose Plain

The boundaries of the San Jose Plain subarea were defined by the California Department of Water Resources (1967) and generally coincide with the boundary of artesian head reported by Clark (1924) and the boundary of 0.3-m subsidence reported by Poland and Ireland (1988). This area consists of Quaternary alluvium deposited at distal parts of the fans formed by Coyote Creek, Guadalupe River, and Los Gatos Creek. The Quaternary deposits are in turn underlain by the older Santa Clara Formation of Pliocene and Pleistocene age, which rests unconformably on bedrock of Jurassic and Cretaceous age.

The response of hydraulic heads to annual pumping cycles in the San Jose Plain subarea varies with depth, and analyses of water levels collected in 1963 by the California Department of Water Resources (1967) identified independent hydraulic-head responses within the 0- to 50-m, 50- to 110-m, 110- to 170-m, and greater than 170-m depth intervals. Heads were found to decrease with depth, but horizontal hydraulic-head gradients generally were similar at all depths (California Department of Water Resources, 1967). Hence, upslope recharge that enters the coarse-grained deposits moves preferentially in the horizontal direction to pumping centers in the San Jose Plain because of the low permeability of the fine-grained confining beds. Wells that penetrate the coarse-grained deposits usually are productive and have provided a significant supply of water to northern Santa Clara County for the past century. The database contains 100 wells in the San Jose Plain subarea; the wells have completed depths that range from 14 to 302 m below land surface.

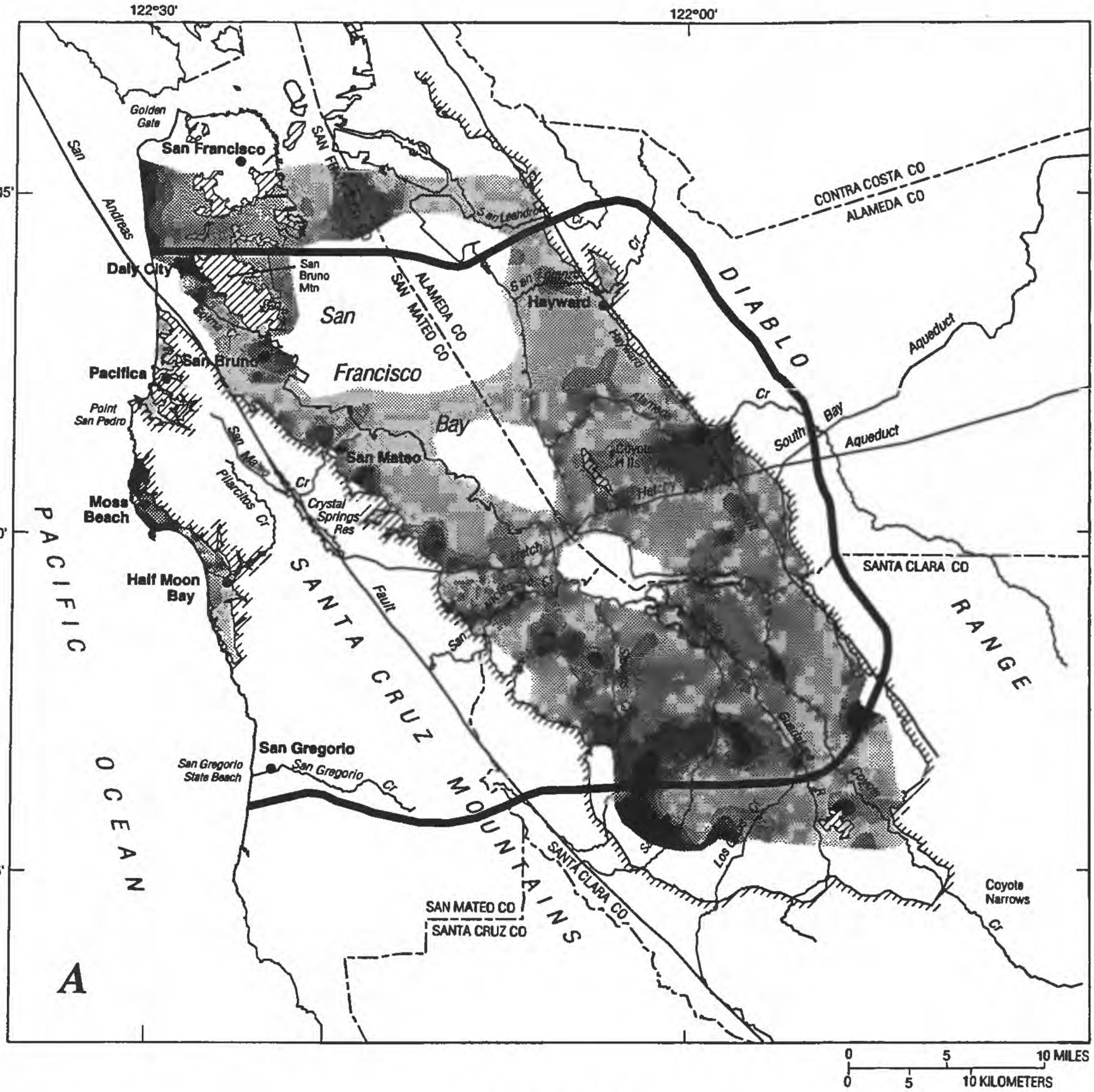
Bay Plain

The Bay Plain subarea is delineated by the most recent marine sediments deposited by San Francisco Bay and includes clay and silty-clay materials ranging in thickness from as much as 37 m beneath the bay to less than 0.3 m at the margins of the bay (Atwater and others, 1977). Because these deposits are relatively fine grained and continuous, ground water beneath the bay and in the Bay Plain subarea typically is confined. Lithologic data are available for areas adjacent and beneath south San Francisco Bay (fig. 4), but hydraulic-head and water-quality data for areas beneath the bay were not available for this study (figs. 5 and 6). Therefore, the Bay Plain subarea was identified as the tidelands, marshlands, and bay-fill areas that surround south San Francisco Bay, and hydrologic and water-quality conditions beneath the bay are not specifically considered in this study. The database contains 91 wells with completed depths that range from 6 to 216 m below land surface in the Bay Plain subarea.

Distribution of Coarse-Grained Sediment

Ground-water flow is affected by the distribution of coarse- and fine-grained sediment. The distribution of coarse- and fine-grained sediment in the study area has been affected by variable uplift and subsidence caused by tectonic forces, changes in sea level due to periodic glacial episodes, and climatic changes that altered patterns of stream discharge and deposition (Helley and Lajoie, 1979). Maps showing the depth-averaged fraction of coarse-grained sediment in the 0- to 15-m, 15- to 35-m, 35- to 60-m, and greater than 60-m depth intervals are shown in figures 10*A-D*. The most areally extensive deposits of coarse-grained sediment are found in the interior alluvial valley.

Coarse-grained sediment generally is associated with stream channels that drained into the Pacific Ocean and south San Francisco Bay, and the depth-averaged fraction of coarse-grained sediment generally increases with distance inland from the bay. In



EXPLANATION

Average fraction of coarse-grain sediment expressed as a percent--Fraction unknown in blank areas

0 - 25

26 - 50

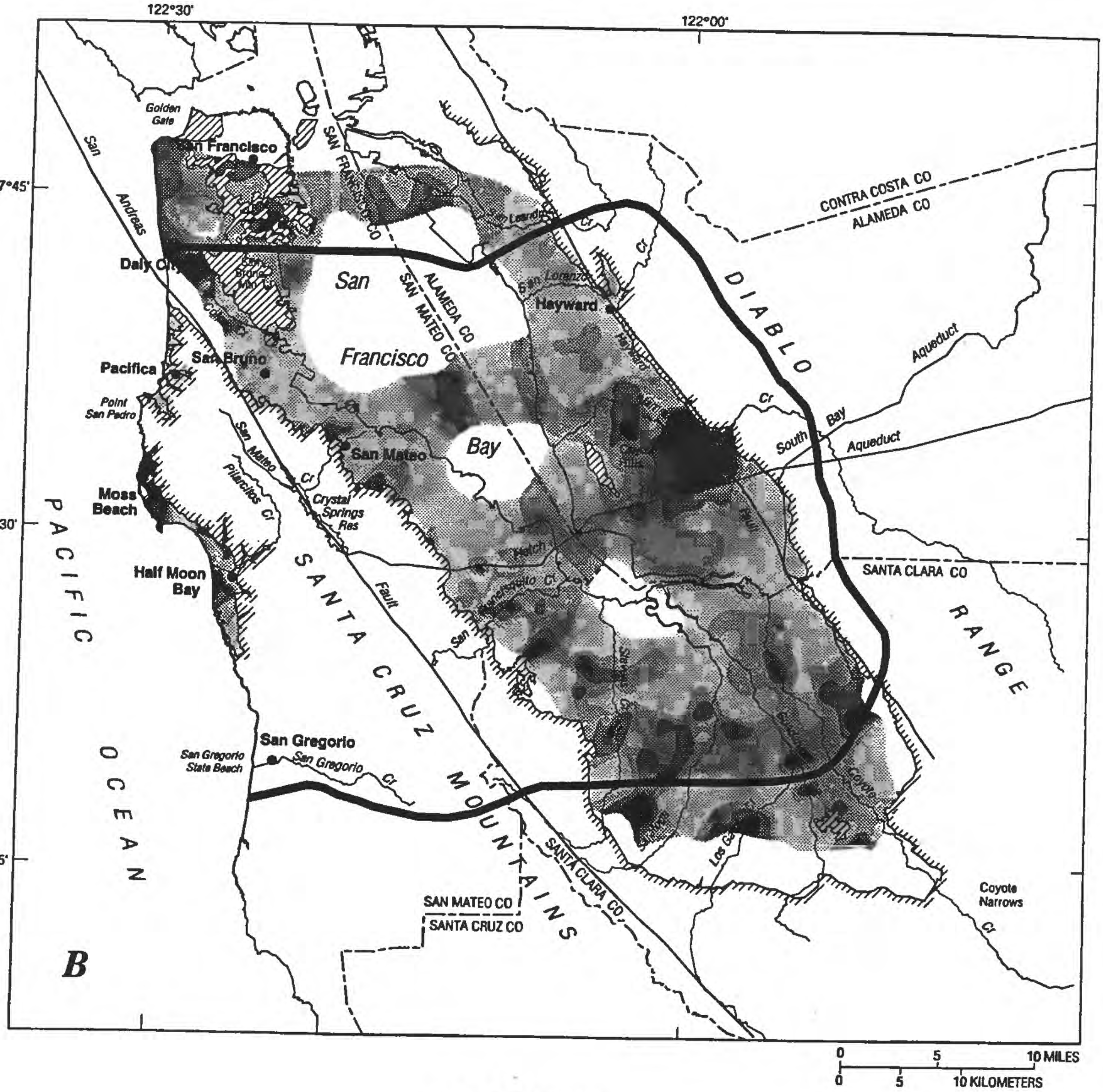
51 - 75

76 - 100

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 10. Fraction of coarse-grained sediment in selected depth intervals, south San Francisco Bay and Peninsula area, California. *A*, 0 to 15 meters. *B*, 15 to 35 meters. *C*, 35 to 60 meters. *D*, greater than 60 meters.



EXPLANATION

Average fraction of coarse-grain sediment expressed as a percent--Fraction unknown in blank areas

- 0 - 25
- 26 - 50
- 51 - 75
- 76 - 100

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 10. *Continued.*

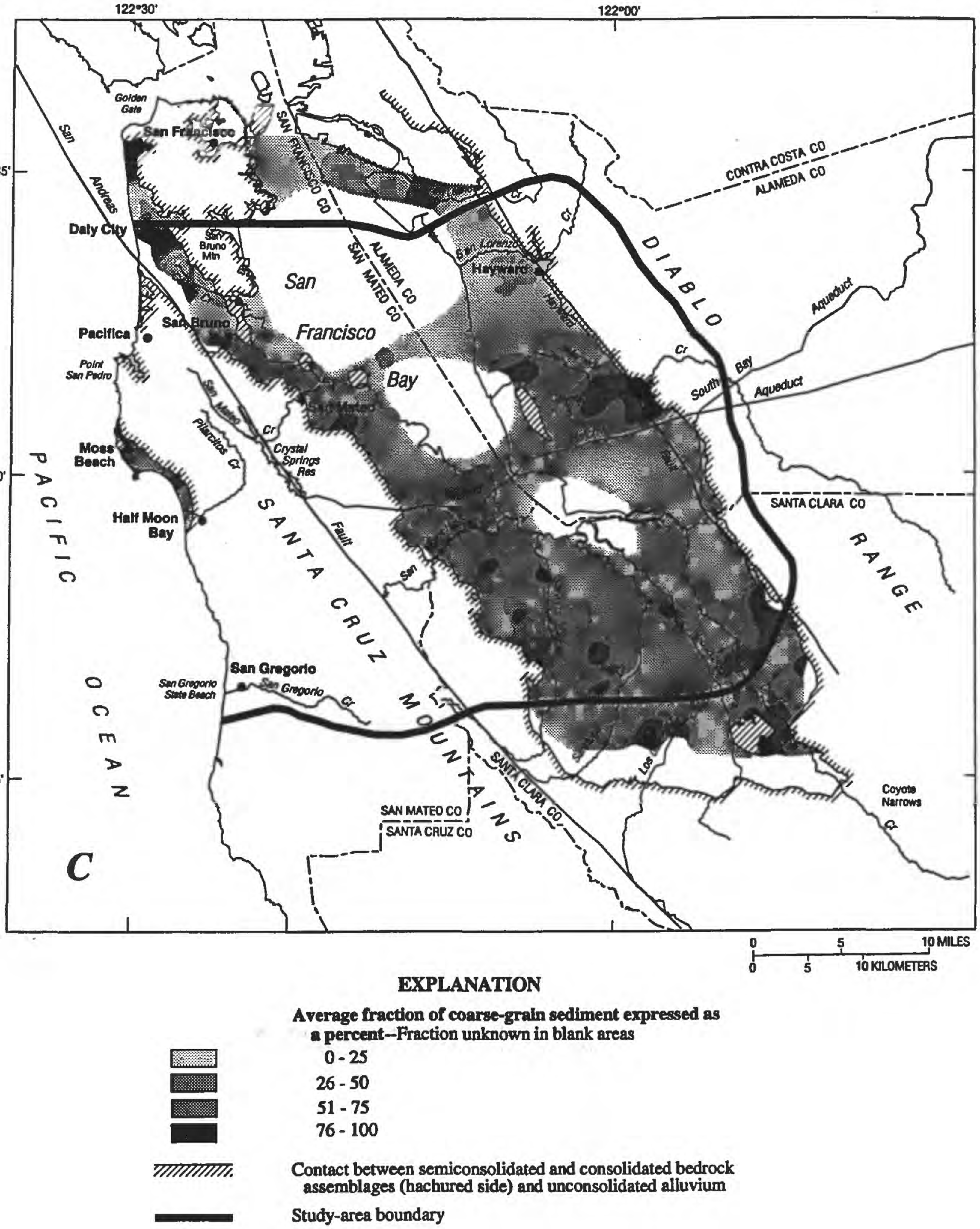
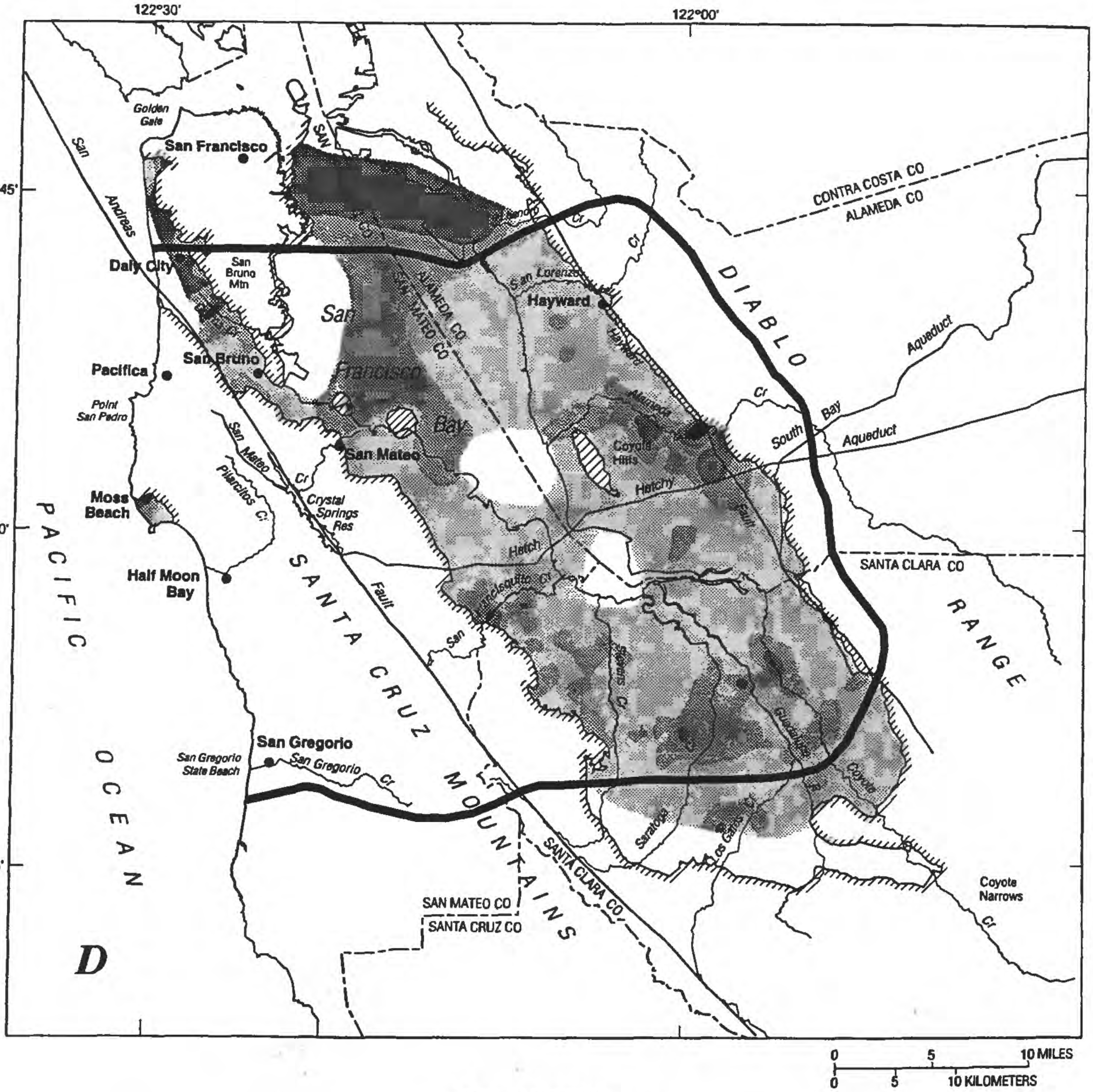


Figure 10. *Continued.*



EXPLANATION

Average fraction of coarse-grain sediment expressed as a percent--Fraction unknown in blank areas

0 - 25

26 - 50

51 - 75

76 - 100

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 10. *Continued.*

the 0- to 15-m depth interval, upslope areas have substantial deposits of coarse-grained sediment and form sites of ground-water recharge for deeper aquifers. In the downslope areas of the interior valley, substantial deposits of fine-grained sediment form what generally is referred to as the overlaying "clay-cap." The depth-averaged fraction of coarse-grained sediment in the interior valley increases in the 15- to 35-m depth interval (fig. 10*B*) forming a major shallow aquifer system. The shallow aquifers are underlain by substantial deposits of fine-grained sediment in the 35- to 60-m depth interval (fig. 10*C*) forming a major confining bed for aquifers below the 60-m depth (fig. 10*D*). The quantity of coarse-grained sediment is fairly small at most depths in areas north of the Hetch Hetchy Aqueduct in San Mateo County and south of the San Bruno Mountains; probably because local streams drain relatively small areas and thus have a small capacity for transporting sediment. In contrast, the drainage basin of Alameda Creek is substantial (1,700 km^2), which resulted in large quantities of coarse-grained sediment deposited in the Niles Cone subarea.

The maps of coarse-grained sediment represent smoothed estimates of numerous well logs and are not intended to provide quantitative simulation of distinct aquifer units. The assumption that texture at a point is related to values several kilometers away is probably not valid, and specific lithologic conditions at a well may deviate from the regional trends shown in the maps. Also, mapping uncertainty increases with depth because the number of data points available for interpolation between sites decreases as the depth of the mapping interval increases. The shaded areas of depth-averaged fraction of coarse-grained sediment may therefore imply greater lateral continuity of individual coarse-grained beds than actually exist between wells. For example, the shaded areas in figure 10*B* imply general continuity of coarse-grained sediment in the San Jose Plain subarea (see fig. 9 for subarea boundaries), but previous investigations in this area have shown that it is difficult to correlate lithologic data between wells that are just a few kilometers apart (Poland and Ireland, 1988). Although nearby wells may have similar quantities of sand and gravel, the thickness and vertical stratification of individual sediment layers may be quite different. In contrast, continuity of coarse-grained sediment at the distal ends of Alameda and San Francisquito Creeks is consistent with water-level measurements and pumping test data reported by California Department of Water Resources (1967). These characteristics, taken together, indicate a hydraulic connection between shallow aquifers on the east and west sides of south San Francisco Bay.

Although the texture maps do not necessarily delineate continuous aquifers or confining beds, they do show that wells in areas near stream channels will penetrate a greater cumulative thickness of sand and gravel than wells at the midpoint between stream channels. Similarly, wells in upslope areas of the alluvial aprons generally penetrate greater quantities of sand and gravel than in areas adjacent to and beneath south San Francisco Bay. Ground-water flow within these sediments is determined by the hydraulic conductivity of individual lithologic layers and the potential field described by the three-dimensional distribution of hydraulic head. The transmissivity of an aquifer is related to the hydraulic conductivity and thickness of individual lithologic layers, and thus represents the ability of the aquifer to transmit water. It will therefore be useful to assess the relation between measured transmissivity and fraction of coarse-grained sediment used to construct the texture maps.

Table 3 shows transmissivity values from reported pumping tests and the corresponding depth-averaged fraction of coarse-grained sediment calculated from well-driller reports. When the driller report for a well used in the reported pumping test was not available, a report from a well less than 570 m from the test well was used to estimate the depth-averaged fraction of coarse-grained sediment at the test point. The transmissivity values in table 3 generally increase with increasing fraction of coarse-grained sediment. It is noteworthy that two wells in exclusively fine-grained sediment apparently withdraw water from aquifers with significant transmissivities (354,000 to 363,000 m^2/y). The well drillers reported large depth intervals of sandy and gravely clay and sandy and gravelly silt at these two sites. The significant permeability of sediments penetrated by the wells may indicate greater quantities of sand and gravel than implied by the descriptions recorded by the well drillers.

Linear regression of the six reported transmissivity values resulting from pumping tests in wells with well logs in the database indicates that 61 percent of the variability in transmissivity is explained by the average fraction of coarse-grained sediment (p-value of 0.07); linear regression of all data in table 3 indicates that 24 percent of the variability in transmissivity is explained by the average fraction of coarse-grained sediment (p-value of 0.02). Variability in the terminology used by different well drillers to describe the lithology, differences in geologic source materials and depositional history that affect the permeability of the aquifer matrix, and variability in construction characteristics, satu-

Table 3. Reported values of transmissivity and fraction of coarse-grained sediment from well-driller reports, south San Francisco Bay and Peninsula area, California

[m, meter; m^2/y, meter squared per year; --, no data. Fraction of coarse-grained sediment: Number in bold designates wells less than 570 meters from the test well]

State well No.	Depth to bottom of well casing (m)	Transmissivity (m^2/y)	Fraction of coarse-grained sediment (percent)	Source of data
2S/6W - 11R1	110	2,120,000	**78**	Yates and others, 1990
3S/5W - 20M2	--	[1]72,900	**42**	Applied Consultants, 1991
3S/6W - 1K1	--	[2]108,500	**74**	Applied Consultants, 1991
4S/1W - 7G3	--	214,000	**14**	California Department of Water Resources, 1968
4S/1W - 21P6	--	16,700,000	**79**	California Department of Water Resources, 1968
4S/1W - 28D9	--	4,330,000	**79**	California Department of Water Resources, 1968
5S/1W - 6H1	--	789,000	**42**	California Department of Water Resources, 1968
5S/2W - 12B2	--	757,000	**30**	California Department of Water Resources, 1968
6S/1E - 31K2	229	907,000	14	CH2M Hill, 1992
6S/3W - 1B2	330	156,000	20	CH2M Hill, 1992
6S/3W - 1D1	--	33,500	**48**	CH2M Hill, 1992
6S/3W - 1M1	131	12,200	25	CH2M Hill, 1992
7S/1E - 2J6	--	354,000	**0**	CH2M Hill, 1992
7S/1E - 7R5	253	943,000	48	CH2M Hill, 1992
7S/1E - 16C6	--	671,000	**3**	CH2M Hill, 1992
7S/1E - 22H4	238	780,000	13	CH2M Hill, 1992
7S/1W - 13E4	--	626,000	**20**	CH2M Hill, 1992
7S/1W - 22E11	--	544,000	**0**	CH2M Hill, 1992
7S/1W - 23R1	--	771,000	**10**	CH2M Hill, 1992
7S/1W - 24J2	--	363,000	**0**	CH2M Hill, 1992
7S/1W - 26R4	--	317,000	**46**	CH2M Hill, 1992

[1]Average of reported tests conducted 9-10-88 and 9-13-88
[2]Recovery data

rated thickness, and physical conditions of the pumping tests could explain much of the remaining variability. Hence, figure 10 may be used to infer general trends in aquifer permeability and related well yields, but additional factors limit the usefulness of these maps to quantify the distribution of transmissivity in the study area.

Estimated Storage Capacity

The volume of water that can be released from an aquifer under gravity drainage is defined in this study as the storage capacity. Storage capacity was estimated from the specific yield of sediments in the depth interval between land and bedrock surfaces with lithologic data from well-driller reports. The results parallel regional trends in sediment texture and thickness and, therefore, are useful for relative comparisons of estimated ground-water storage within the physiographic subareas (table 4). For example, the thickest deposits of unconsolidated and semiconsolidated sediments are found in northern Santa Clara County (fig. 8); thus, almost half of the estimated storage capacity in the study area is in the San Jose Plain and West Side Alluvial Apron subareas ($7,460\times10^6$ m^3). These subareas are the location of major users of ground water within the regional ground-water system and, when combined with the East Side Alluvial Apron and Niles Cone subareas (storage capacity of $3,250\times10^6$ m^3), contain almost 70 percent of the storage capacity for the entire study area. In contrast, the area and vertical extent of unconsolidated and semiconsolidated sediment in the Coastal subarea represent a minimal contribution to storage capacity in the study area (83×10^6 m^3).

Storage capacity is an estimate of the maximum volume of subsurface storage potentially available for pumping. Operational values may be considerably less than reported in table 4 because of geohydrologic conditions and water-quality constraints. For example, the depth to the saturated zone can be substantial in many parts of the study area; thus, storage capacity reported in table 4 probably is greater than the volume of water that would be released by gravity drainage. Also, coarse-

Table 4. Estimated ground-water storage capacity of sediments beneath physiographic subareas of the south San Francisco Bay and Peninsula area, California

[m, meter; m^3, cubic meter; --, assumed zero]

Physiographic subarea	Storage capacity (1,000,000 m^3)			
	Land surface to sea level	Sea level to 20 m below sea level	Depths greater than 20 m below sea level	Total
Exposed Bedrock . .	--	--	--	--
Uplands	307	43	600	950
East Side Alluvial Apron	220	150	900	1,270
West Side Alluvial Apron	390	220	1,700	2,310
Niles Cone	140	240	1,600	1,980
Coastal	37	43	3	83
Merced	92	38	350	480
San Jose Plain	220	330	4,600	5,150
Bay Plain	36	354	2,700	3,090
Total	1,442	1,418	12,453	15,313

grained sand and gravel deposits have significant volumes of pore space and readily store and transmit water to wells. In contrast, the volume of pore space within fine-grained sediment beds also can be significant, but the relatively low permeability of these deposits limit their use as temporary reservoirs and efficient conduits of ground water. Thus, the contribution of coarse- and fine-grained deposits to storage capacity may not be adequately weighted to reflect relative differences in permeability that affect the time required to transmit water in and out of storage. Finally, the volume of water available for pumping can be limited by potential subsidence of the land surface and saltwater contamination.

The term subsidence, in this report, refers to downward vertical movement of the land surface resulting from compaction of unconsolidated and semiconsolidated sediments that form the aquifer matrix (Poland and others, 1988). As discussed later in this report, maximum drawdowns in areas historically affected by subsidence were about 20 m below sea level, and thus drawdowns below this depth may cause renewed subsidence in some areas. As a result, the storage capacity at depths greater than 20 m below sea level may not be available in areas susceptible to subsidence. Similarly, storage capacity may not be fully available in areas adjacent to the Pacific Ocean and south San Francisco Bay because drawdowns below sea level may induce the inland movement of saltwater.

Relative reductions in storage capacity because of potential subsidence and saltwater intrusion can be approximated on a regional basis with the results in table 4. For example, the storage capacity of sediments between land surface and a depth of 20 m below sea level is $2{,}860 \times 10^6$ m^3. If regional pumping levels are restricted to maximum drawdowns of 20 m below sea level, the potential for subsidence represents a regional reduction in storage capacity of more than 80 percent. Similarly, the storage capacity within the depth interval between land surface and sea level is $1{,}442 \times 10^6$ m^3, and the potential for saltwater intrusion can represent a regional reduction in storage capacity of more than 90 percent. These reductions in storage capacity represent maximum estimates because not all parts of the study area are at equal risk of subsidence and saltwater intrusion. For example, some areas consist of fairly shallow and (or) predominantly coarse-grained sediment and are at minimal risk of compaction when drawdown occurs. Similarly, inland aquifers and some aquifers adjacent to and beneath the bay may be hydraulically separated by thick deposits of fine-grained sediment, which limits the exchange of saltwater with ground water. Operational values of storage capacity for subareas of the study area require study at the subregional and local scale of observation.

HISTORICAL DEVELOPMENT OF THE GROUND-WATER SYSTEM

During the past century, water demand and supply has changed dramatically in the south San Francisco Bay and Peninsula area. Reported ground-water production and surface-water deliveries to northern Santa Clara County and southern Alameda County for the years 1915, 1955, 1966, 1977, and 1990 are shown in figure 11. Before 1966, ground water supplied most of the water required by agriculture and early urban development; total pumpage

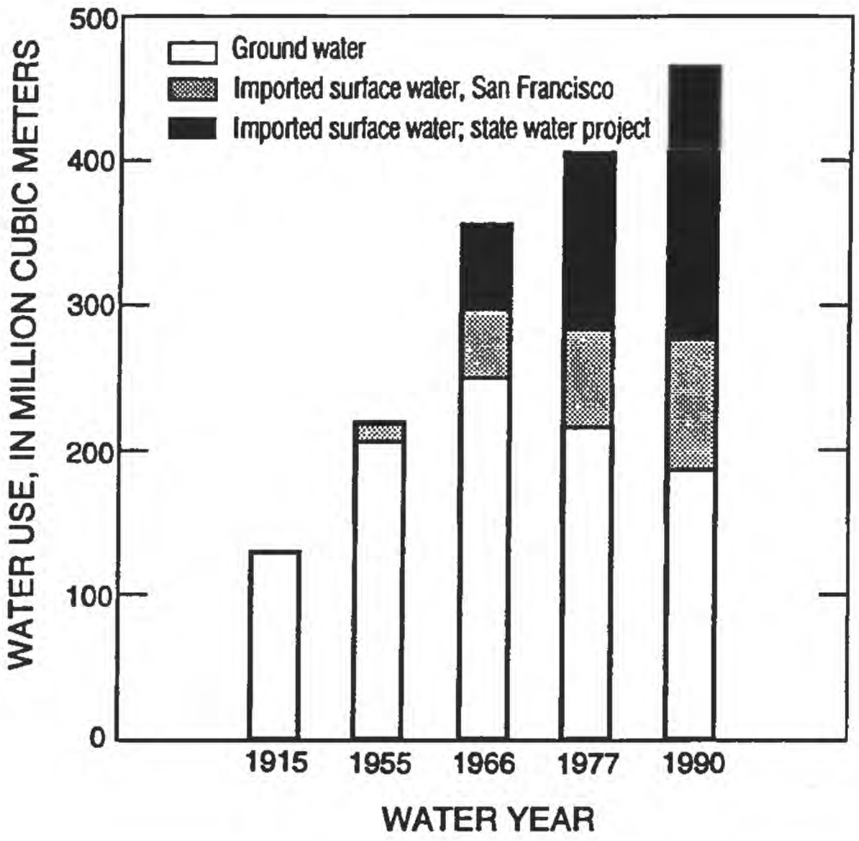


Figure 11. Water use and source of supply in northern Santa Clara and southern Alameda Counties (1915, 1955, 1966, 1977, 1990). Sources of data are from Clark (1924), California Department of Water Resources (1968, 1975), Poland and Ireland (1988), Leighton and others (1994), and Scott Seely, Hilton, Farnkopf, and Hobson, written commun., (1992).

in the study area in 1915 was about 128×10^6 m^3/y (Clark, 1924). Rapid urban growth resulted in greater demands for water and large increases in ground-water pumpage, which continued until surface water was imported to meet increasing demands for water. Water deliveries by the city of San Francisco began in 1940, and the State of California first delivered surface water in 1965 (not shown in fig. 11). By 1990, the combined supply of surface- and ground-water resources used in northern Santa Clara and southern Alameda Counties was about 470×10^6 m^3/y. The reported 1990 water supply to the entire study area (not shown in fig. 11) consisted of about 468×10^6 m^3 of delivered surface water (Scott Seely, Hilton, Farnkopf, and Hobson, written commun., 1992) and about 179.5×10^6 m^3 of reported well pumpage for water supply.

The water-supply data identify two general periods in the historical development of water resources in the study area. The first period includes the interval from the early 1900's to 1965, when ground-water pumpage supplied most needs for water. The second period includes conditions after 1965 to 1990, when substantial quantities of surface water were imported to supplement water supplies. Maximum ground-water overdrafts generally occurred in 1965, which represents a pivotal year between these two periods. A greater understanding of the ground-water system can be gained by evaluating early development conditions and the changes that occurred in response to historical pumpage and recharge.

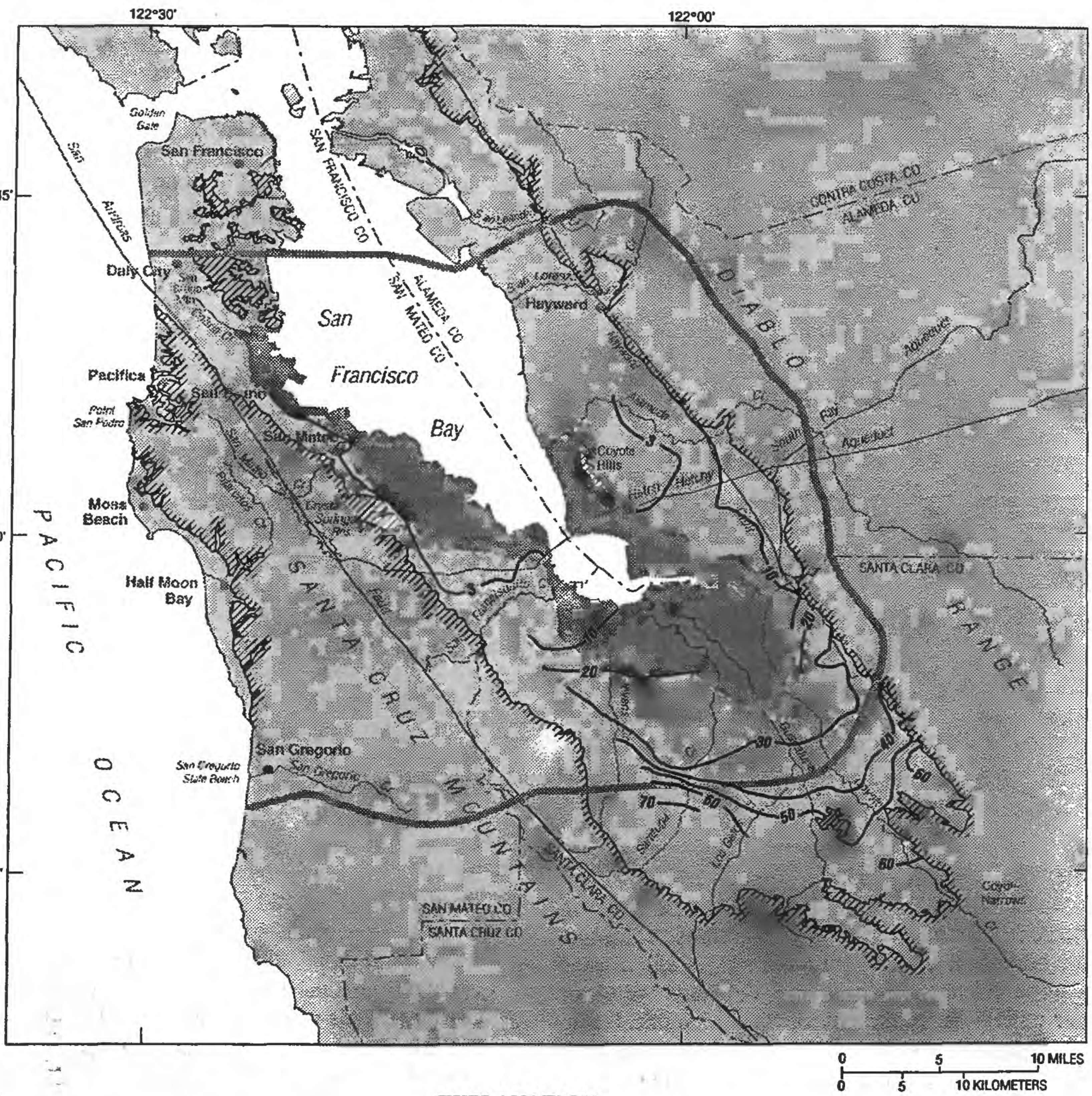
Early Development

Early development of ground water was in response to irrigation requirements. Because little rain falls during the summer growing season, most areas were dependent upon ground water for irrigation. Clark (1924) estimated that water requirements for irrigation were about 100×10^6 m^3/y in 1915 and increased to about 150×10^6 m^3/y by 1919. Water requirements for municipal and industrial supplies were substantially less—about 30×10^6 m^3/y during 1912-18 (Clark, 1924).

The pumping of ground water had begun to alter hydrologic conditions as early as the 1920's, when Clark (1924) reported that Alameda Creek flowed continuously before the 1920's but was dry for considerable parts of the year by 1924. Similarly, the flow in other streams also was intermittent by 1924. Natural recharge during this period ranged from 110×10^6 to 120×10^6 m^3/y, leading Clark (1924) to conclude that recharge and withdrawals were about equal. He supported his conclusion with observations that water levels in wells decreased during periods of rainfall deficits (droughts), but the levels returned to normal relatively quickly once rainfall returned. Maps of water-level altitudes in wells reported by Clark (1924) for the early 1900's show that horizontal hydraulic-head gradients were toward San Francisco Bay (fig. 12), and ground water beneath a substantial part of the alluvial valley was under pressure and characterized by free-flowing wells.

Historical Response to Pumping and Recharge Conditions

The hydraulic response of the ground-water system to pumping and recharge conditions resulting from historical changes in water supply and demand has been recorded by water-level measurements in wells. Measured depth to water in selected wells in the Coastal, Bay Plain, East Side Alluvial



EXPLANATION

Area of free-flowing wells--Modified from Clark (1924)

— *70* — **Hydraulic-head contour**--Shows altitude of water-level surface. Contour interval, in meters, is variable. Datum is sea level. Modified from Clark (1924)

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 12. Altitude of water levels measured in wells during the early 1900's, south San Francisco Bay and Peninsula area, California.

Apron, San Jose Plain, Merced, Niles Cone, and West Side Alluvial Apron subareas during 1936-92 is shown in figure 13. Water levels rose in the East Side Alluvial Apron and San Jose Plain subareas during 1936-43, which indicates an increase in hydraulic head and the quantity of water stored in the aquifer. The corresponding increase in hydraulic head and ground-water storage was a direct result of conservation efforts by the Santa Clara Water Conservation District, which was formed to provide re-

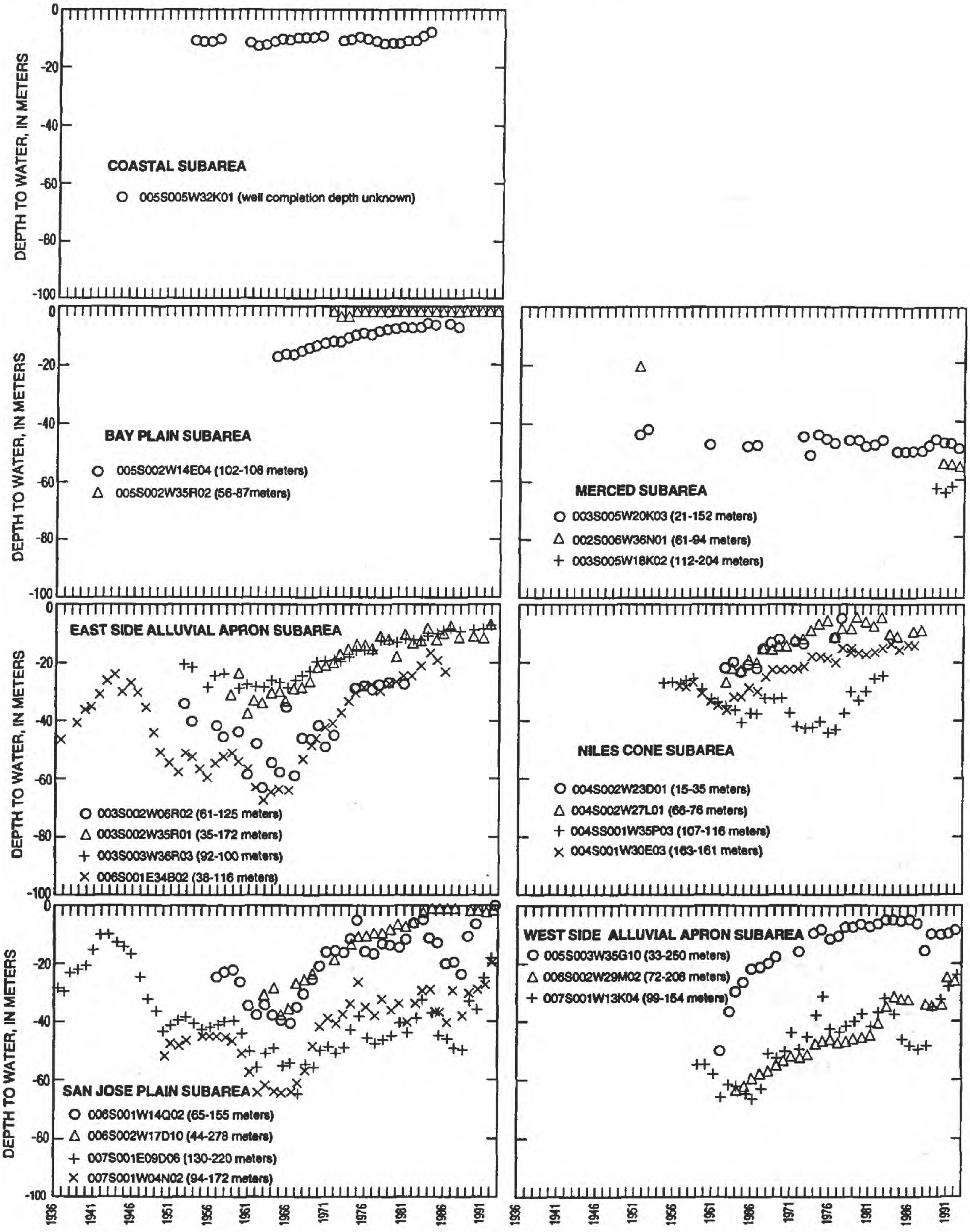


Figure 13. Depth to water in wells in physiographic subareas of the south San Francisco Bay and Peninsula area, California, 1936-92. Well number and well-completion interval (in meters below land surface) shown following symbols in each graph.

lief to ground-water overdraft by constructing retention facilities designed to increase natural recharge from storm runoff. The delivery of imported surface water to these subareas by the city of San Francisco also probably helped to reduce demand for ground water.

Increased pumpage and general precipitation deficits during the period 1944 to 1965 resulted in greater depths to water in most wells (Poland and Ireland, 1988). A map showing hydraulic-head contours calculated from 1965 water levels in wells perforated in the shallow and deep zones is shown in figure 14. Increased pumpage resulted in a decrease in hydraulic heads when compared with hydraulic conditions in the early 1900's (fig. 12). Associated drawdowns resulted in large cones of depression in northern Santa Clara and southern Alameda Counties, and ground-water gradients in some areas reversed from a bayward direction to a landward direction. These conditions resulted in subsidence of the land surface and saltwater contamination in some parts of the study area.

Although data are sparse, reported water levels in wells from the Coastal and Merced subareas show varied response to hydrologic conditions during the past 30 to 40 years. One well in the Merced subarea (2S/6W-36N1) shows a nearly 40-m increase in depth to water between the 1950's and 1992. It is uncertain what the rate and magnitude of drawdown was in this well because only one measurement was collected before 1990. Similarly, static water levels reported by Applied Consultants (1991) indicate an average drawdown of 23 m during the period 1959 to 1988 in three other wells in the Merced subarea (drawdown in the three wells ranged from 22 to 24 m). In contrast, depth to water in one well in the Coastal subarea (5S/5W-32K1) and one well in the Merced subarea (3S/5W-20K3) has been steady since the 1950's. Rising demands for water in most of San Mateo County have been met with imported surface water, which represented more than 90 percent of the total water supply to San Mateo County in 1990 (Scott Seely, Hilton, Farnkopf, and Hobson, written commun., 1992).

After 1965, the rapid increase in surface-water deliveries by the city of San Francisco and State of California was used to reduce demands for ground water and supplement natural ground-water recharge, thereby restoring water levels to pre-1960 conditions. This brought a temporary halt to subsidence and saltwater contamination, but problems could resume if overdraft conditions return. An evaluation of historical subsidence and saltwater contamination in greater detail would help to improve our understanding of limitations in the supply of ground water in the study area.

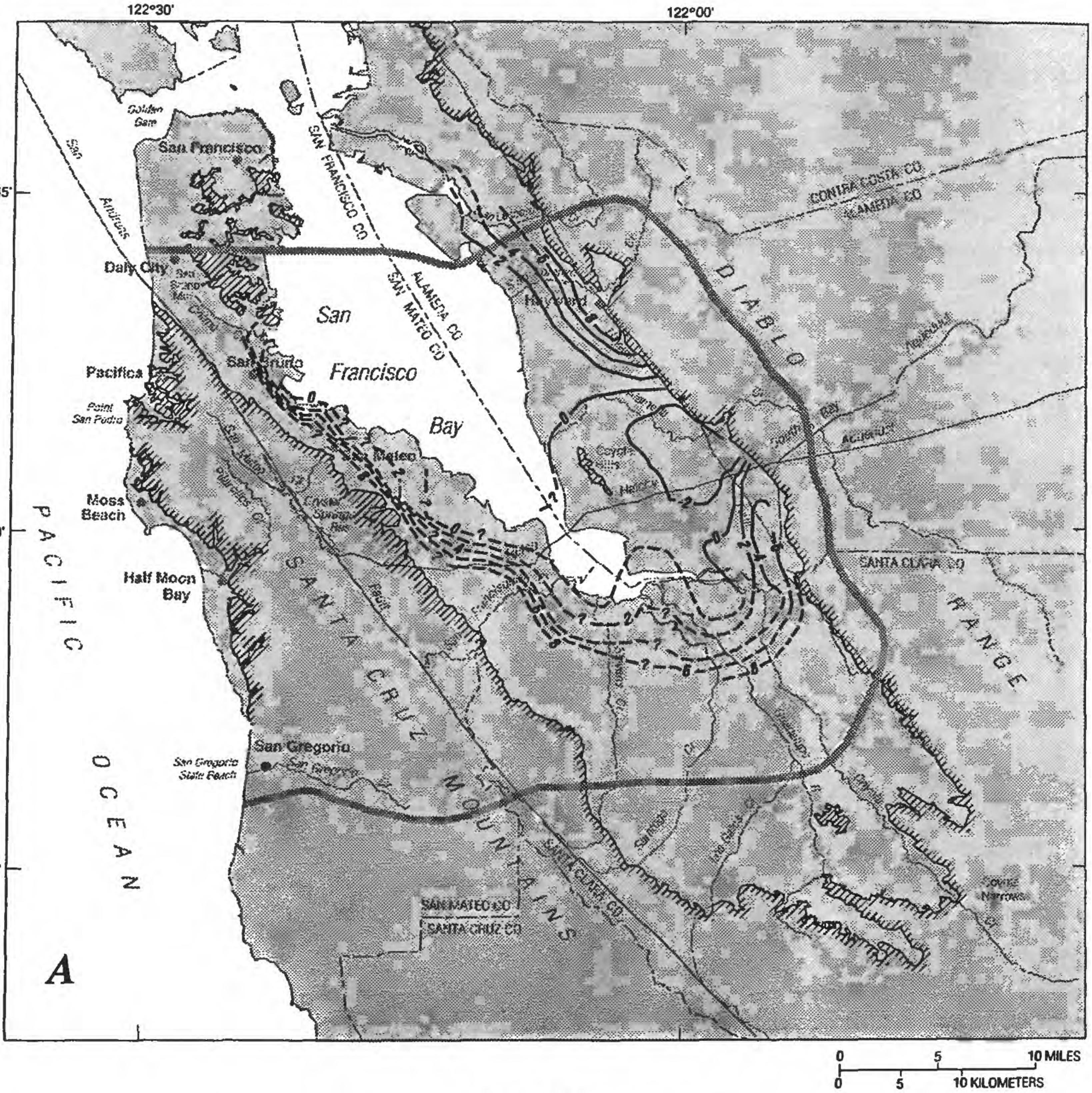
Changes to the Aquifer System due to Excessive Pumping

Subsidence of Land Surface

Pumping initially removes ground water from the permeable coarse-grained sediment matrix, thereby lowering the water table or pressure head in the aquifer. The reduction in hydraulic head increases the effective stress borne by the sediment grains and can induce the release of water by the compaction of compressible fine-grained sediment beds. The total reduction in the volume of fine-grained sediment can cause subsidence of the land surface.

Water-level fluctuations in wells reflect a change in effective stress, and extensive investigations by Poland and Ireland (1988) showed a correlation between reductions in hydraulic heads and subsidence of the land surface. Their study indicated that total subsidence during 1934-67 was more than 2 m in some areas of northern Santa Clara County (fig. 15), and maximum compaction occurred in areas that coincided with large depressions in the hydraulic-head surface within the former zone of pressure identified by Clark (1924). The ratio of subsidence and compaction measured with an extensometer indicated that the vertical movement of land surface resulted from the compaction of sediments at depths greater than 60 m below land surface (Poland and Ireland, 1988); fine-grained sediment beds in the upper 35- to 60-m depth interval form an areally extensive confining bed in the study area.

The historical rate and magnitude of subsidence was dependent in part on variability in the decline of hydraulic head. For example, subsidence slowed dramatically in northern Santa Clara County from 1938 to 1947 due to a temporary recovery in hydraulic heads (Poland and Ireland, 1988). When overdraft and head declines resumed, subsidence continued until delivery of surface water by the State of California in 1965 supplemented water supplies and eventually brought an end to continued subsidence. Should overdraft conditions resume, renewed subsidence also could resume. Poland and Ireland (1988) reported that estimated costs for the



EXPLANATION

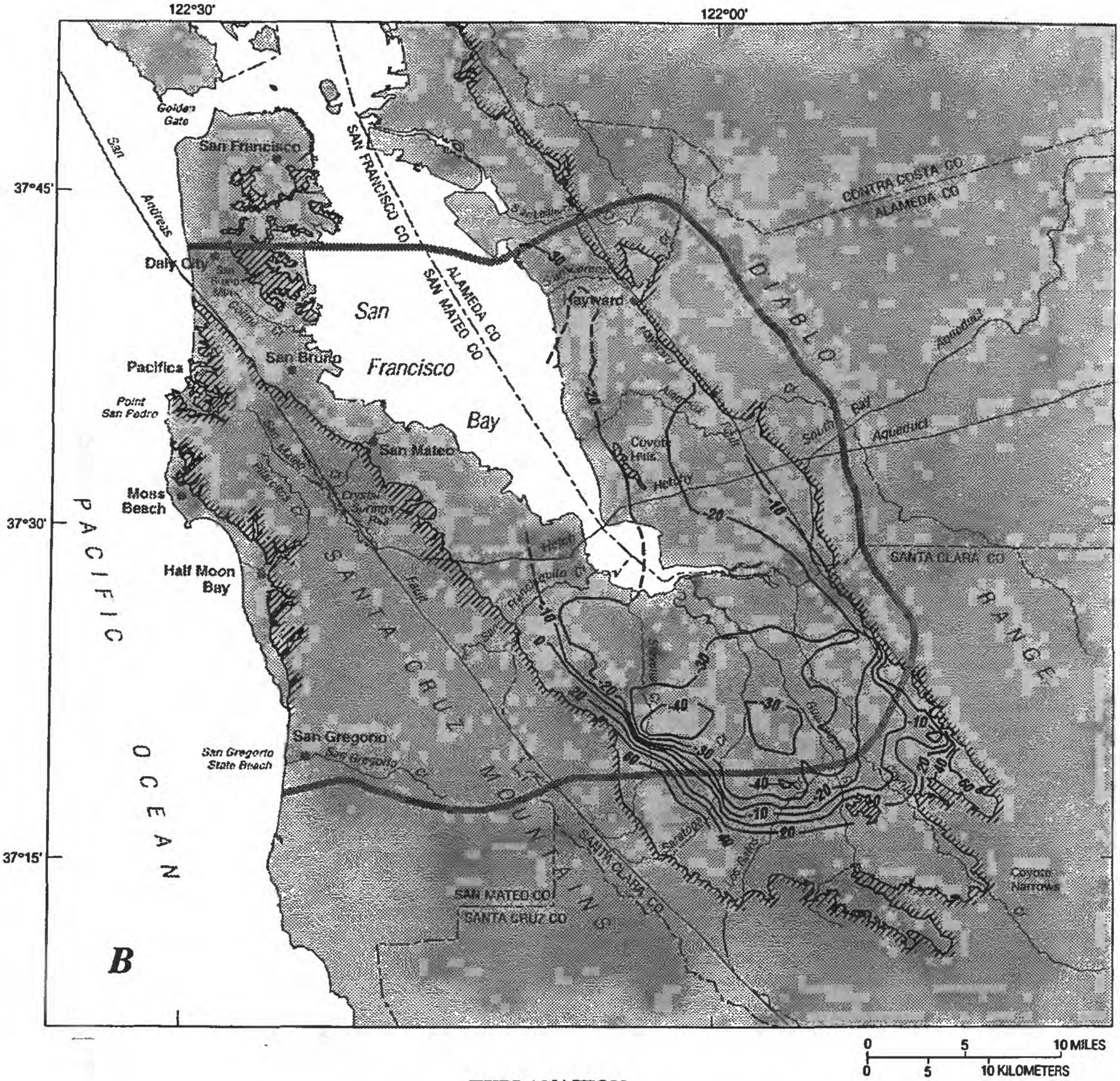
—2 – – – **Hydraulic head contour**--Shows the altitude of water-level surface. Dashed lines are approximate locations of contours using the few data points available and a modified regional map of the water table from Webster (1973). Queried in areas of greatest uncertainty. Contour interval, in meters, is variable. Datum is sea level

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 14. Hydraulic-head surface in 1965, south San Francisco Bay and Peninsula area, California. *A*, shallow zone. *B*, deep zone.

repair and maintenance of levees, damaged wells, railroads, roads, bridges, and sewers as a result of subsidence in northern Santa Clara County exceeded $100 million in 1979 dollars. For these reasons, water levels are measured at key index wells for comparison with subsidence thresholds (CH2M Hill,



EXPLANATION

—2 - - - **Hydraulic head contour**--Shows the altitude of water-level surface. Dashed lines are approximate locations of contours using the few data points available and a modified regional map of the water table from Webster (1973). Queried in areas of greatest uncertainty. Contour interval, in meters, is variable. Datum is sea level

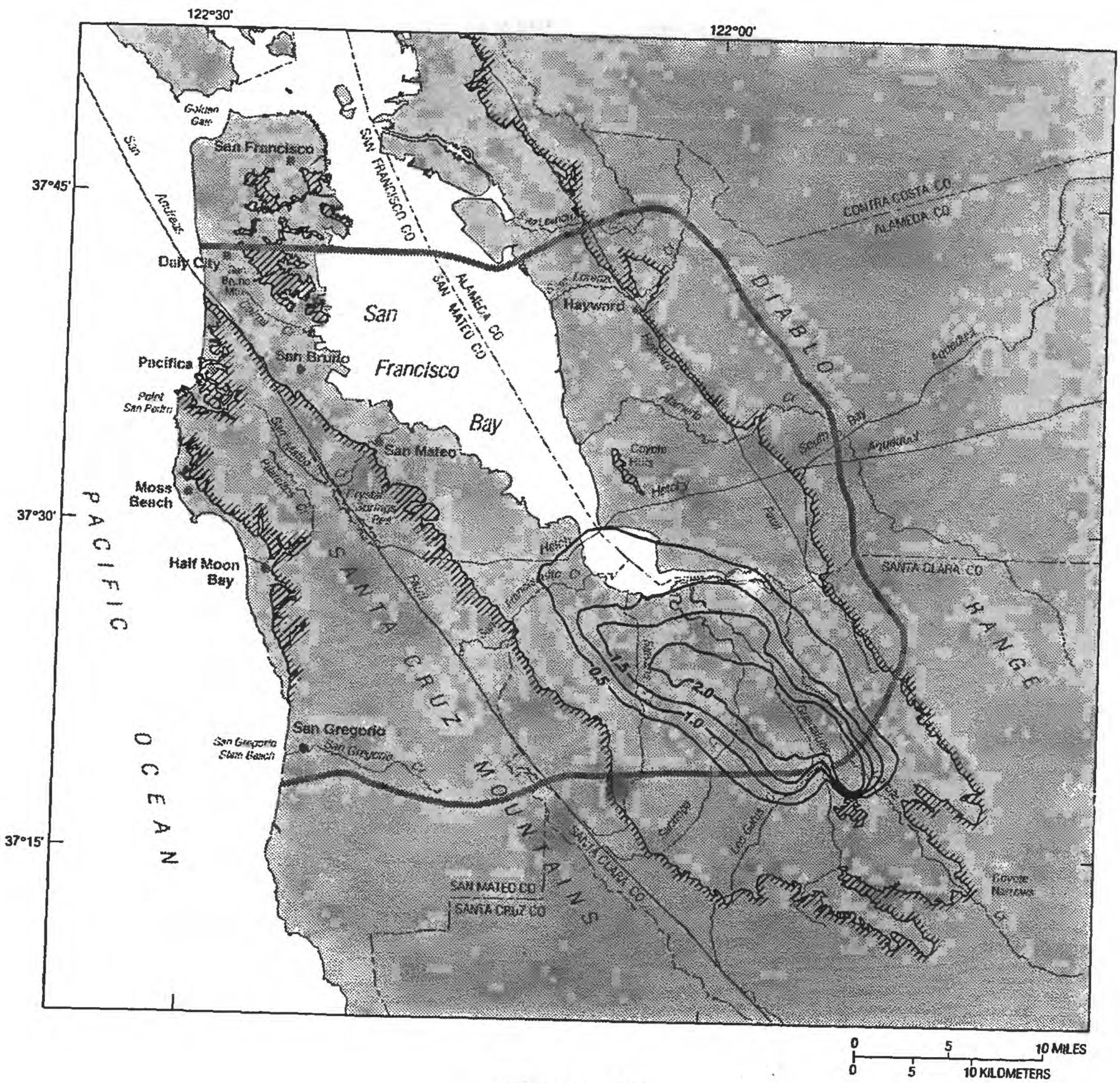
Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 14. *Continued.*

1992) and used to limit drawdowns and prevent renewed subsidence in northern Santa Clara County.

Little information is available to assess historical subsidence in other parts of the study area. His-



EXPLANATION

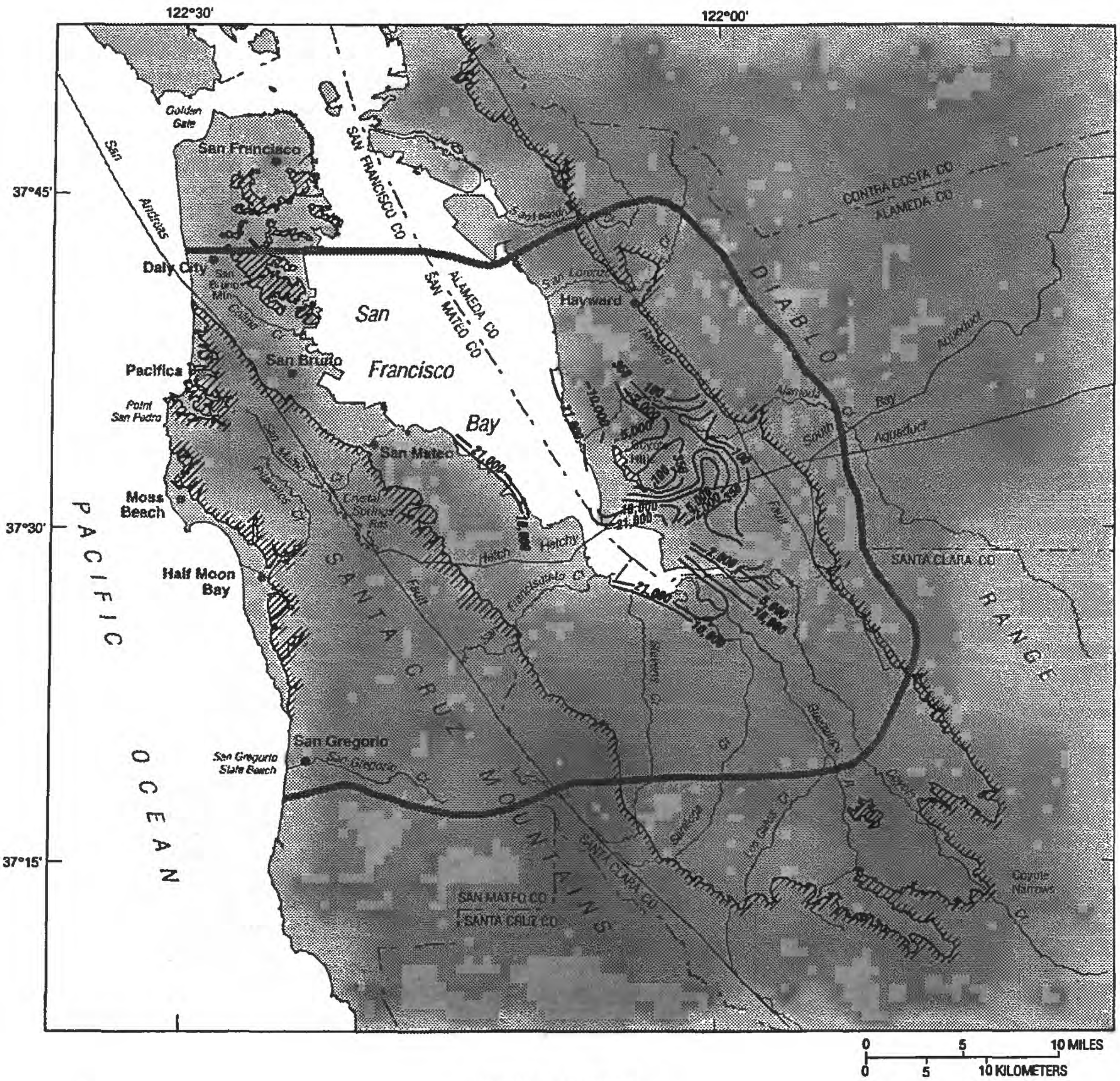
— 0.5 — **Line of Equal Subsidence**--Interval 0.5 meter. Modified from Poland and Ireland (1988)

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 15. Total subsidence measured during 1934-67, south San Francisco Bay and Peninsula area, California.

torical subsidence in southern Alameda and San Mateo Counties reported by Poland and Ireland (1988) was less than about 0.3 m. Monitoring of water levels and land-surface altitude in these areas may be necessary for assessing the occurrence and extent of subsidence in the future.



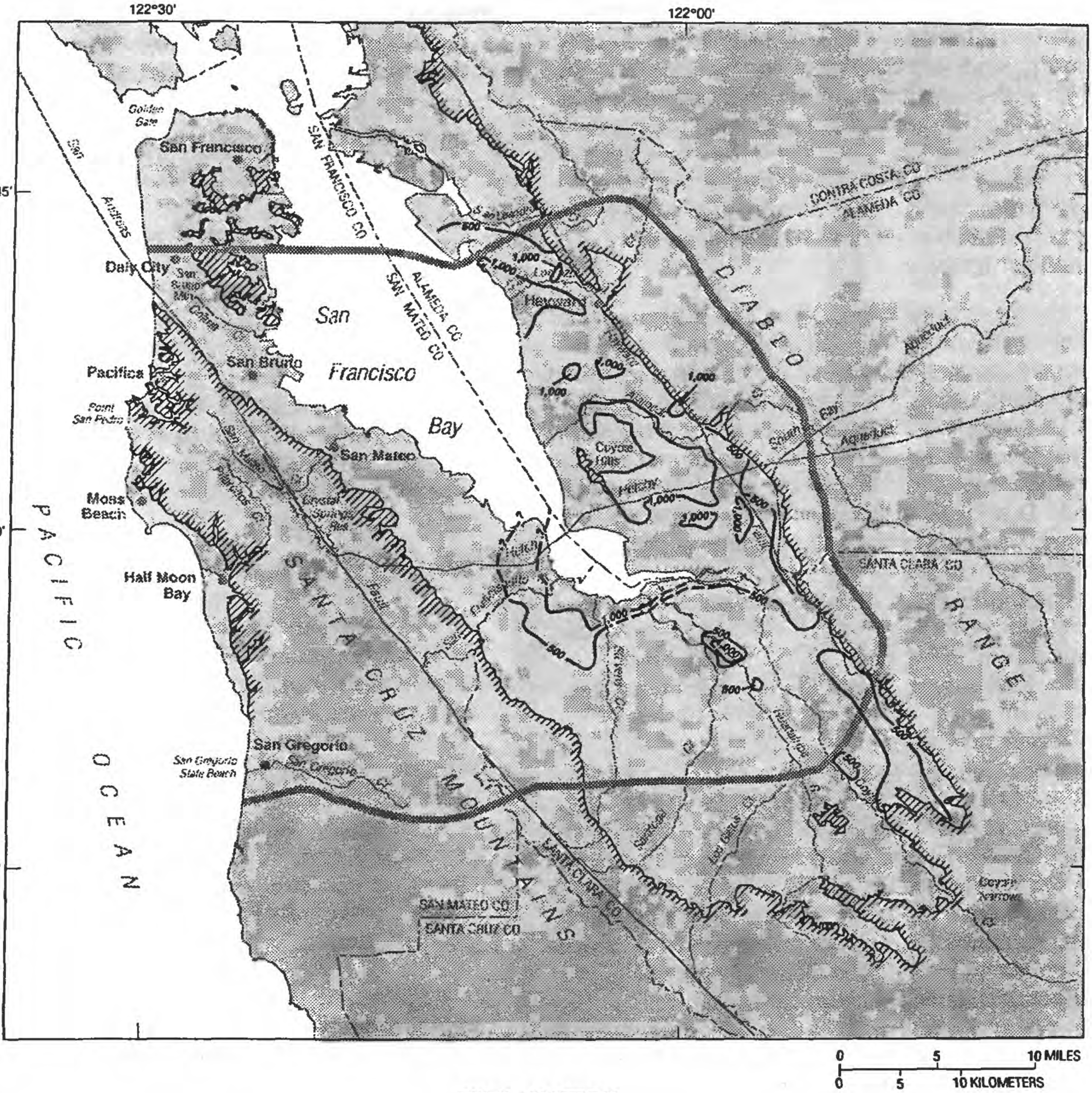
EXPLANATION

—100—	**Line of equal chloride ion concentration**--Interval, in milligrams per liter, is variable. Modified from California Department of Water Resources (1968)
(hachured line)	Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium
(heavy line)	Study-area boundary

Figure 16. Chloride-ion concentrations in the shallow aquifer in southern Alameda and northern Santa Clara Counties, California, 1965-66.

Saltwater Contamination

Saline water represents a potential source of contamination to ground-water resources in areas adjacent to the Pacific Ocean, San Francisco Bay, and the associated tidal flats, marshlands, and salt evaporators. The lowering of hydraulic heads in aquifers beneath and adjacent to the bay in the past has induced the seepage of saltwater across the bay muds and toward inland pumping centers. Breaks in



EXPLANATION

— 500 — ? — Line of equal dissolved-solids concentration in areas where consistently greater than 500 milligrams per liter (or 1,000 milligrams per liter). Dashed where approximately located. Query (?) indicates areas of greatest uncertainty. Modified from Webster (1972)

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 17. Areas in which dissolved-solids concentrations in ground water were consistently greater than 500 milligrams per liter, south San Francisco Bay and Peninsula area, California, 1945-70.

the bay muds, areas where the bay muds had been thinned by dredging of ship channels, and abandoned or improperly sealed wells greatly increased the rate of salt-water intrusion (California Department of Water Resources, 1973). The inland movement of saltwater was fairly rapid, and by 1967 a substantial part of the shallow aquifer was affected by high concentrations of salt, as indicated by lines of equal chloride-ion concentration (fig. 16). Near the bay, aquifers are separated vertically by substantial deposits of fine-grained sediment, and the movement of saltwater in the shallow zone was, therefore, mostly horizontal. The contaminated water then moved downward into underlying aquifers in the inland areas where the vertical hydraulic continuity increases.

Water-quality data indicate that the quantity of usable water in the Niles Cone subarea decreased from a maximum rate of 11×10^6 m^3/y in 1961-62 to a minimum rate of 1×10^6 m^3/y in 1967-68 (California Department of Water Resources, 1973). Artificial recharge of imported surface water and conservation measures taken by the Alameda County Water District have increased ground-water recharge, which has increased hydraulic heads and reduced the volume of saltwater intrusion. In 1973, the water district began an aquifer-reclamation program that pumped contaminated water into surface channels that empty into the bay (Montgomery, 1991). Reclamation pumping has ranged from less than 4×10^6 m^3 in 1975, to more than 14×10^6 m^3 in 1982; reclamation pumping in 1990 was 7.8×10^6 m^3 (Alameda County Water District, written commun., 1992). Monitoring of water levels and pumpage volumes enables managers in Alameda County Water District to ensure that hydraulic-head gradients are bayward in the shallow aquifer system, and 0 to slightly landward in the deeper aquifers. These measures are intended to remediate saltwater-contamination in the Niles Cone subarea and prevent contamination problems in the future.

Evidence of saltwater contamination exists for other parts of the study area adjacent to south San Francisco Bay. Saltwater contamination identified in northern Santa Clara County generally is limited to the shallow aquifer system in the Bay Plain subarea, and the greatest extent of contamination is associated with aquifers beneath present-day stream beds (Iwamura, 1980). Webster (1972) mapped areas where dissolved-solids concentrations in well-water samples (collected during the period 1945 to 1970) were consistently between 500 and 1,000 mg/L, or consistently greater than 1,000 mg/L (fig. 17). Dissolved-solids concentrations were consistently greater in areas associated with Alameda and San Lorenzo Creeks of the Niles Cone and East Side Alluvial Apron subareas and areas in northern Santa Clara County where stream channels empty into the bay; many of the samples collected within the 1,000-mg/L boundaries had dissolved-solids concentrations that exceeded 2,000 mg/L (Webster, 1972).

GENERAL HYDROLOGIC AND WATER-QUALITY CONDITIONS IN 1990

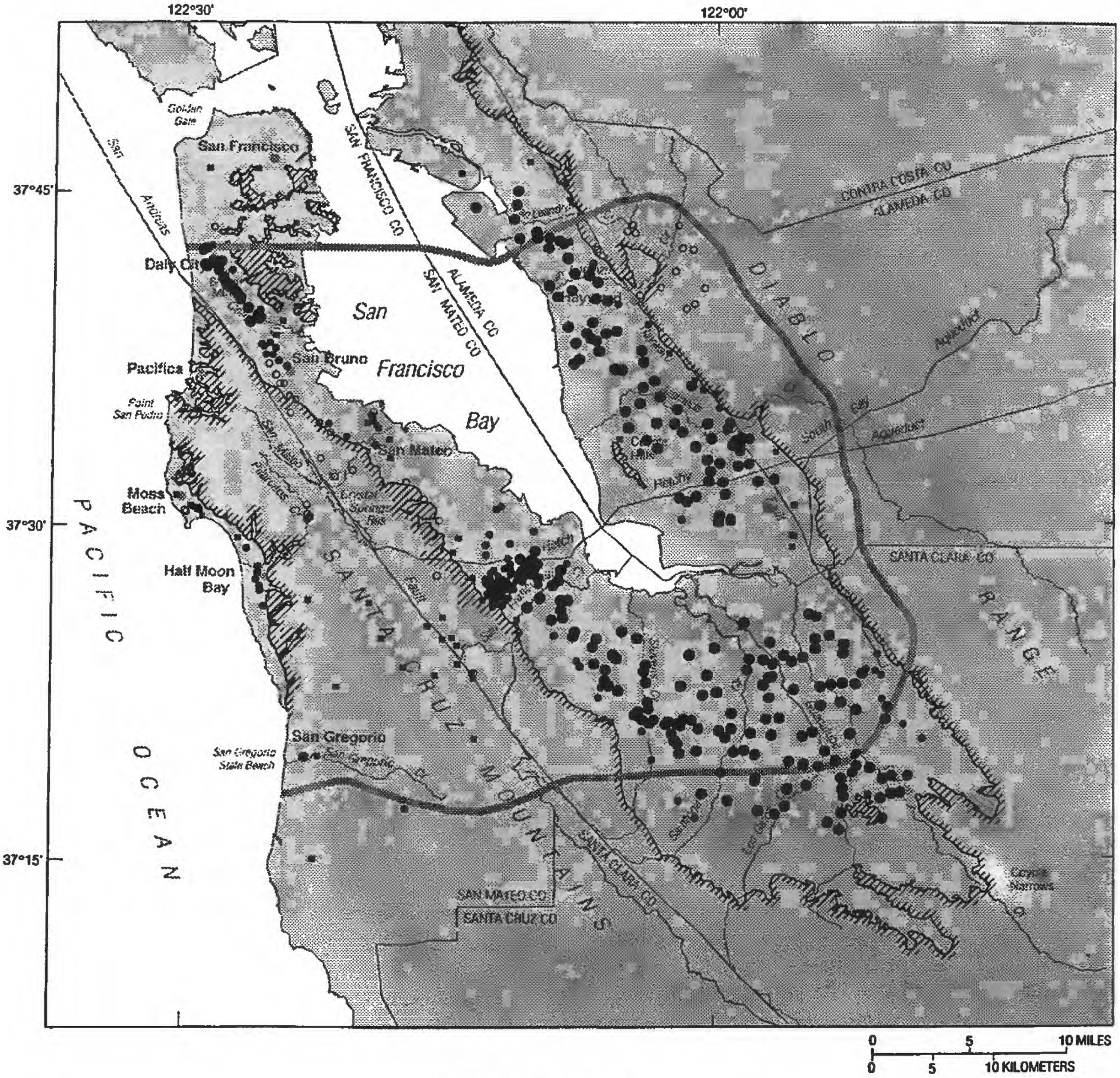
Future development of ground-water resources to increase pumping yields and water supplies for the study area is limited by current development levels and other hydrologic and water-quality constraints. A description of 1990 hydrologic and water-quality conditions provides a description of base conditions for evaluation of possible future changes that could result from greater pumpage or increased conjunctive use of ground- and surface-water supplies.

Existing Wells and Reported Pumpage

Water-supply wells are typically located in areas where demands for water are greater than surface-water supplies and where geohydrologic conditions are favorable for ground-water pumping; few wells are typically found in areas with unfavorable geohydrologic conditions or where surface-water supplies meet water demand. The distribution of water-supply wells, the depth distribution of well perforations, and reported pumpage are described in this section to assess the general magnitude and spatial distribution of ground-water development in the study area.

Major water-supply wells, herein referred to as production wells, were defined in this study as wells used to supply irrigation, industrial or municipal water needs, or wells with well-casing diameters greater than 200 mm. A total of 505 wells in the database supply water for irrigation, industrial, or municipal water requirements. A total of 95 additional wells have casing diameters greater than 200 mm, and these wells were about evenly distributed between domestic and institutional uses (47 wells) and other unknown uses (48 wells).

The distribution of production wells in the database are plotted in figure 18 relative to subareas of variable maximum probable well yield (68 percent confidence interval) reported by Webster (1972). As noted by Webster (1972), his subareas were determined from available geohydrologic information and are defined using the concept of



EXPLANATION

Well location and probable maxium well yield (68 percent confience interval). Modified from Webster (1972)

- ○ 1,000 to 10,000 cubic meters per year
- ▪ 10,000 to 100,000 cubic meters per year
- • 100,000 to 1,000,000 cubic meters per year
- ● 1,000,000 to 3,000,000 cubic meters per year

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 18. Location of production wells in the database and maximum probable well yields, south San Francisco Bay and Peninsula area, California.

normal probability. Thus, the expected maximum well yield for a well located in the 10,000 to 100,000 m^3/y subarea is smaller than the expected maximum well yield for a well in the adjacent 100,000 to 1,000,000 m^3/y subarea. It is possible that some wells in either subarea may have maximum well yields of 100,000 m^3/y, but most wells in the former subarea will have yields that are less than 100,000 m^3/y, and many wells in the latter subarea will have yields greater than 100,000 m^3/y. Most production wells in the database are located within subareas where maximum probable well yields are marginal-to-adequate for irrigation, heavy industry, and municipal use (68-percent chance of maximum yields ranging from 1,000,000 to 3,000,000 m^3/y), indicating that from a regional perspective the most productive aquifers have been tapped by production wells. The pumping levels for many of these wells, however, are uncertain, and additional study with the intent of maximizing yield within these areas and improving the conjunctive use of both local and regional surface- and ground-water resources may be warranted.

The depth distribution of productive zones in the physiographic subareas is assessed with the reported perforation depths of production wells (fig. 19). Two relative maximums in the number of perforated wells occur at about 30 m and 125 m below land surface in the West Side Alluvial Apron subarea because of a bias in the database. A substantial number of the wells in this subarea were found and located in a relatively small area north of San Francisquito Creek (fig. 18) as part of an ongoing and related study. These wells are used to irrigate private residential estates and are perforated in the shallow aquifer zone. Similar wells probably exist in many other parts of the study area, but these wells have not been located and the data have not been compiled into the database to the same extent as was done for this area. The large number of perforated wells at the 20-m depth reflects the substantial number of residential wells in the database for this area, whereas the maximum number of perforated wells at the 125-m depth probably reflects the production wells in the West Side Alluvial Apron subarea that traverse both shallow and deep aquifer zones. In contrast, relative minimums in the Niles Cone subarea occur at depths of about 50 m, 100 m, and 130 m below land surface. These depths coincide with confining beds that separate the upper Newark Aquifer in the shallow aquifer zone from the underlying Centerville, Fremont, and deeper aquifers comprising the deep aquifer zone (California Department of Water Resources, 1968). Thus, the relative minimums and maximums in the Niles Cone subarea reflect local geohydrologic conditions. Similarly, few wells are perforated in the 0- to 50-m depth interval in the San Jose Plain and Merced subareas. This distribution indicates that most production wells in these areas draw water from the deep aquifer zone. Most wells are perforated in the 0- to 50-m depth interval in the Costal subarea. This distribution indicates that production wells in this subarea remove water from a relatively shallow, unconfined aquifer.

Table 5. Reported well pumpage by physiographic subarea during calendar year 1990, south San Francisco Bay and Peninsula area, California

[m^3, cubic meter]

Physiographic subarea	Reported pumpage (1,000,000 m^3)
Exposed Bedrock	0.3
Uplands	.3
East Side Alluvial Apron	.8
West Side Alluvial Apron	71.6
Niles Cone[1]	39.1
Coastal	.7
Merced	7.4
San Jose Plain	59.0
Bay Plain	.3
Total	179.5

[1]Does not include 7.8×10^6 m^3 pumped by Alameda County Water District for aquifer reclamation and discharged to San Francisco Bay.

The magnitude and distribution of reported pumpage in calendar year 1990 is listed in table 5, and almost 95 percent of the total reported pumpage in the study area occurs in northern Santa Clara and southern Alameda Counties (the West Side Alluvial Apron, San Jose Plain, and Niles Cone subareas). Programs for monitoring ground-water pumpage exist in these subareas because fees are imposed on ground-water users to support artificial recharge activities of the Santa Clara Valley and Alameda County Water Districts. Reported pumpage is less in the remaining subareas because of unfavorable geohydrologic conditions, a small number of existing production wells, or lack of monitoring efforts.

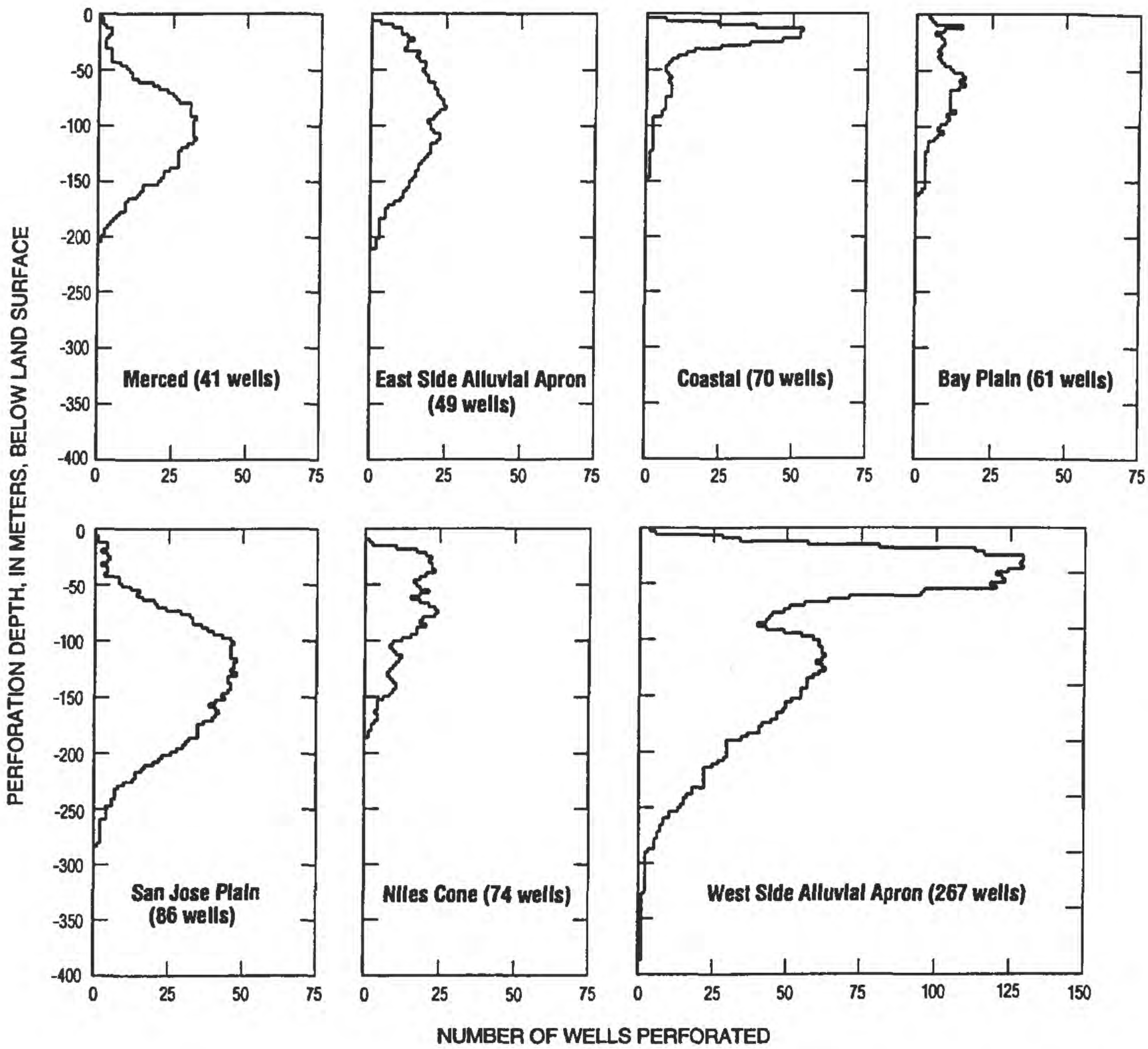


Figure 19. Perforation depths (in 3-meter depth intervals) of production wells in database by regional physiographic subarea in the south San Francisco Bay and Peninsula area, California.

Actual pumpage in these areas can be significantly greater than that given in table 5. For example, reported pumpage for the Merced subarea (7.4×10^6 m^3) is mostly from municipal supply wells, but a local study in 1988 reported annual pumpage to be about 13×10^6 m^3 (Applied Consultants, 1991). The Applied Consultants' study (1991) included pumpage estimates for wells used by golf courses, cemeteries, and nurseries, which were not available for 1990. Improved monitoring of pumpage in this and similar areas is necessary for adequate assessment of development potential and to design improved conjunctive-use practices. Pumpage volumes may be estimated by electrical power-consumption records or water-budget and consumptive-use estimates, if the necessary data are available, but these calculations were beyond the scope of this report.

Pumpage in the Exposed Bedrock subarea (0.3×10^6 m^3) is similar in magnitude to pumpage in the East Side Alluvial Apron (0.8×10^6 m^3), Coastal (0.7×10^6 m^3), Bay Plain (0.3×10^6 m^3), and Uplands (0.3×10^6 m^3) subareas. This similarity is surprising, given the limited permeability of bedrock relative to the alluvial deposits in the other subareas. Close inspection of the database reveals that about 60 percent of the reported pumpage in the Exposed Bedrock subarea was for wells in small coastal alluvial valleys, and 31 percent of the reported pumpage was for wells near the boundary between the Exposed Bedrock and West and East Side Alluvial Apron subareas. Therefore, reported pumpage for wells in bedrock is substantially less than pumpage records compiled with the regional boundaries of the physiographic subareas. Similarly, reported pumpage for subareas can be in error if wells are erroneously grouped in adjacent subareas by the regional boundaries.

Hydraulic Heads

The hydraulic-head surface was estimated from average 1990 water-level measurements in wells perforated in the shallow and deep aquifer zones (fig. 20). Hydraulic heads and ground-water storage have increased since 1965 (fig. 14*A*) as a result of increases in recharge and decreases in pumpage. Horizontal gradients in the shallow zone of the inland valley and in aquifers of the Coastal subarea are toward south San Francisco Bay and the Pacific Ocean, respectively. A substantial cone of depression in the deep zone of the Merced subarea indicates that horizontal flow is in a landward direction from the bay in the southeast and the Pacific Ocean in the northwest. Similarly, horizontal flow in the deep zone is landward from beneath south San Francisco Bay toward the Niles Cone subarea and the northern part of the East Side Alluvial Apron subarea.

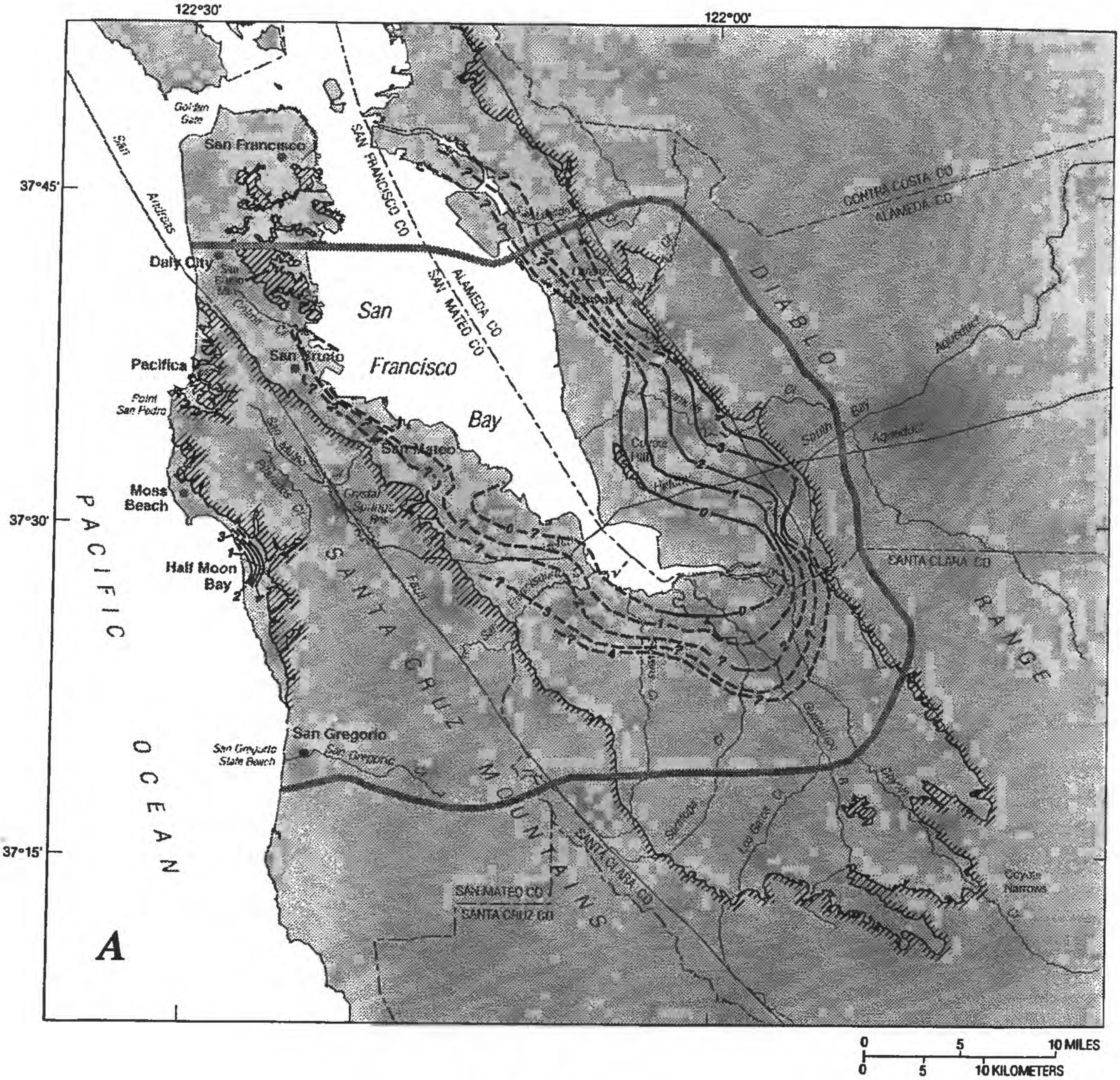
The vertical component of flow was inferred from hydraulic-head gradients between wells perforated in the shallow and deep aquifer zones. Calculated vertical hydraulic-head gradients using water-level measurements in the database range from a maximum upward gradient of 0.010 to a maximum downward gradient of -0.406. Vertical gradients generally are downward in the upslope areas that surround south San Francisco Bay indicating downward flow, but hydraulic heads can increase with depth in the downslope areas adjacent to the bay, indicating upward flow. Heads that decrease with depth and downward flow generally are associated with recharge areas or drawdowns of the hydraulic-head surface in the deep zone, or both, whereas heads that increase with depth and upward flow are associated with pressure-head increases as a result of confined conditions, drawdowns of the hydraulic-head surface in the shallow zone, or both. The vertical movement of water is dependent upon the gradient and permeability. Thus, vertical flow is probably substantial in upslope areas where sediments are predominantly coarse grained (fig. 10) and greatly reduced in areas where fine-grained clays and silts impede the vertical movement of water.

Water Quality

The criteria used to judge the quality of water are determined by its intended use; ground water in the study area is used for various domestic, agricultural, and industrial purposes. Water-quality criteria are based on the quantity and character of dissolved constituents, which are determined by the net result of physiochemical and biological reactions between water, air, and rock. The ultimate concentration of constituents can be modified further by reactions and mixing between surface and ground waters of different types. This mixing can occur along natural ground-water-flow paths between recharge and discharge areas or from alterations to hydrologic conditions because of human activities. For example, as stated previously, historical gradients from excessive pumping which induced the inland movement of saltwater resulted in a reduction in quality of ground-water supplies in some areas. Finally, natural and synthetic constituents and compounds released into the environment by human activities can reach unacceptable levels and further degrade the quality of ground water.

Dissolved constituents in ground water, as indicated by the concentration of dissolved solids and chloride ion, reflect the regional geohydrology and historical overdraft conditions. The concentration of dissolved solids is relatively low in the upslope areas (less than 500 mg/L), where most of the recharge to the ground-water system occurs (fig. 21). Dissolved solids in recharge, as indicated by surface-water runoff in northern Santa Clara County, typically range from about 170 to 250 mg/L (Iwamura, 1980); in contrast, ground water in areas adjacent to the Pacific Ocean, south San Francisco Bay, and in areas affected by historical saltwater contamination has concentrations of dissolved solids greater than 1,000 mg/L. The 500-mg/L boundary generally extends inland beneath stream channels and follows the general shape of the bay in areas between stream channels. This distribution indicates that relatively high concentrations of dissolved solids may be associated with sediments deposited in estuarine conditions during historical high stands of south San Francisco Bay. Ground-water samples from areas near San Francisquito and Stevens Creeks have lower concentrations of dissolved solids than ground-water samples from areas between these two creeks. This may indicate a displacement of salts in ground water beneath these creeks by percolating runoff, or that the wells near these creeks capture a substantial amount of recharge from percolating runoff.

Information on the character of dissolved constituents in ground water is useful for classifying water types, as well as identifying waters with unacceptable levels of various constituents of concern. The quality of recharge, as indicated by chemical



EXPLANATION

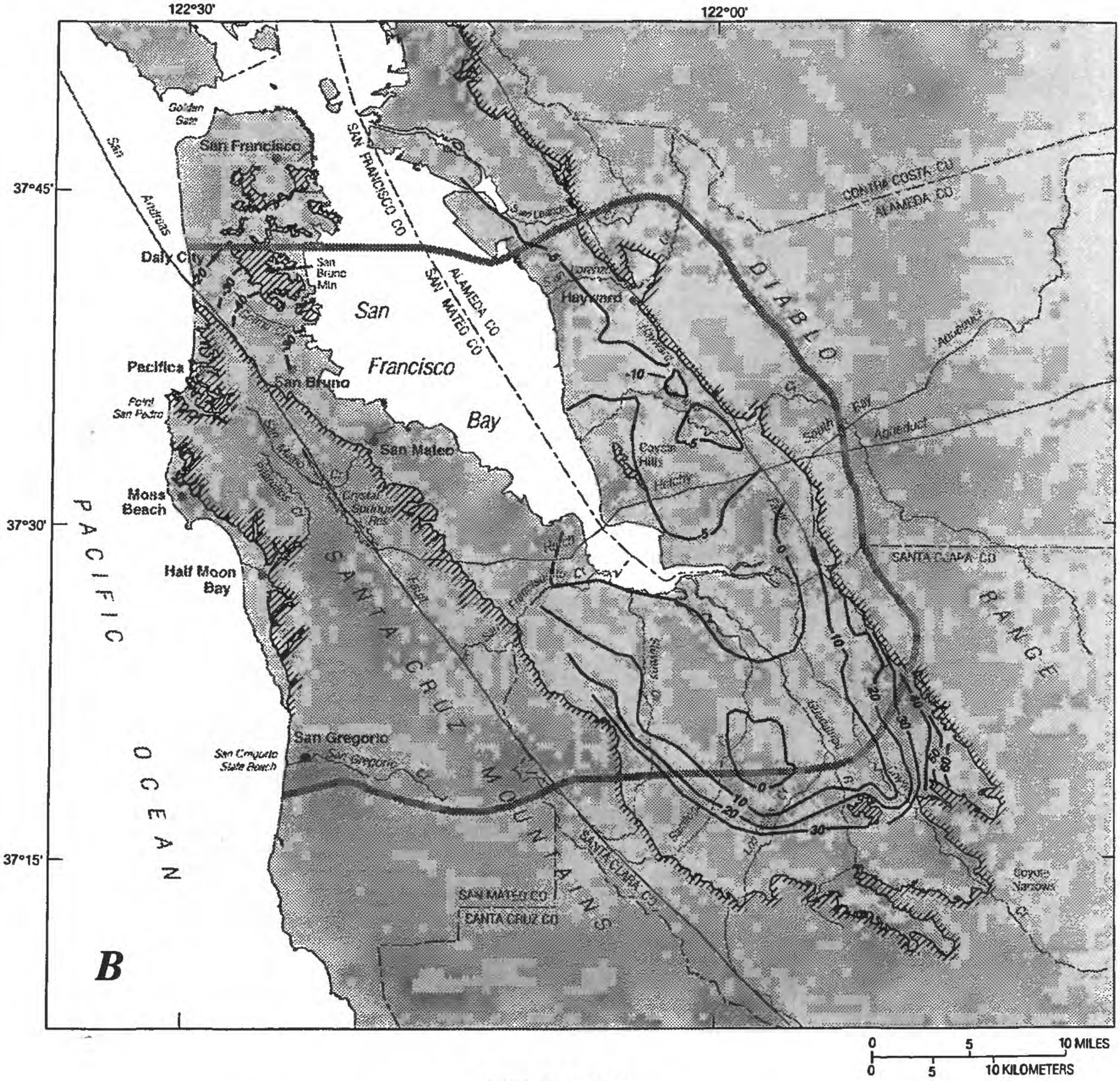
—4 - - - - **Hydraulic-head contour**--Shows altitude of water-level surface. Dashed lines are approximate locations of contours using the few data points available and a modified regional map of the water table from Webster (1973). Queried in areas of greatest uncertainty. Contour interval, in meters, is variable. Datum is sea level

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 20. Hydraulic-head surface in 1990, south San Francisco Bay and Peninsula area, California. *A*, shallow zone. *B*, deep zone.

analyses on streamflow samples in Santa Clara County, indicates that bicarbonate is the principal anion in recharge for this part of the study area and magnesium and calcium are the principal cations (Sylvester, 1986). Results from the SNORM (Bodine and Jones, 1986) simulations done for this



EXPLANATION

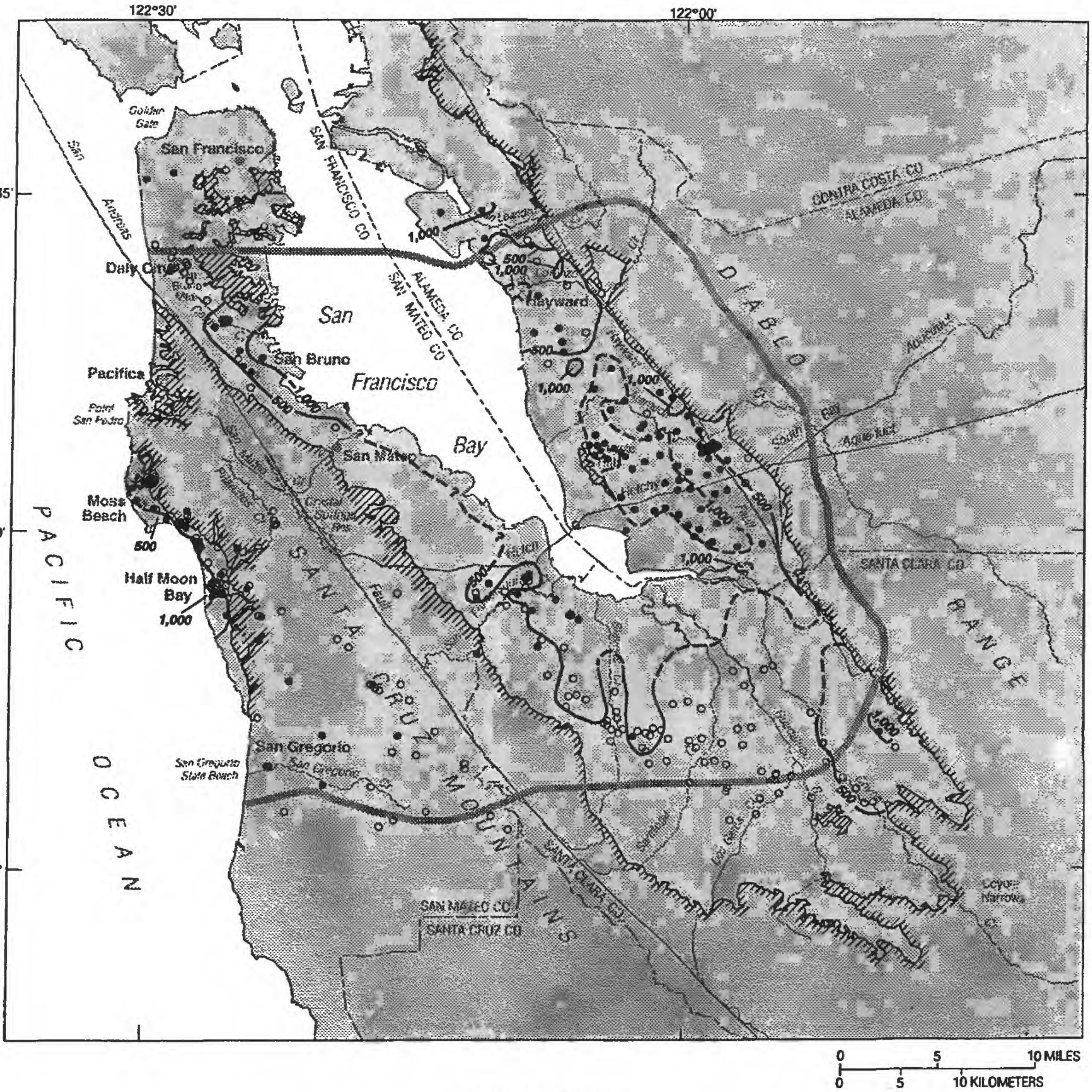
—5— **Hydraulic-head contour--Shows altitude of water-level surface. Contour interval, in meters, is variable. Datum is sea level**

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

Figure 20. *Continued.*

study confirm these results and indicate that reported ground-water analyses on samples collected in the upslope areas have a normative salt assemblage dominated by dolomite (calcium-magnesium-carbonate waters). The relative importance of sodium and chloride increases as ground water moves downslope, and reported analyses for samples dominated by halite (greater than 50 percent by weight) consist of an intermediate group (50- to 70-percent halite by weight) and a marine group (greater than

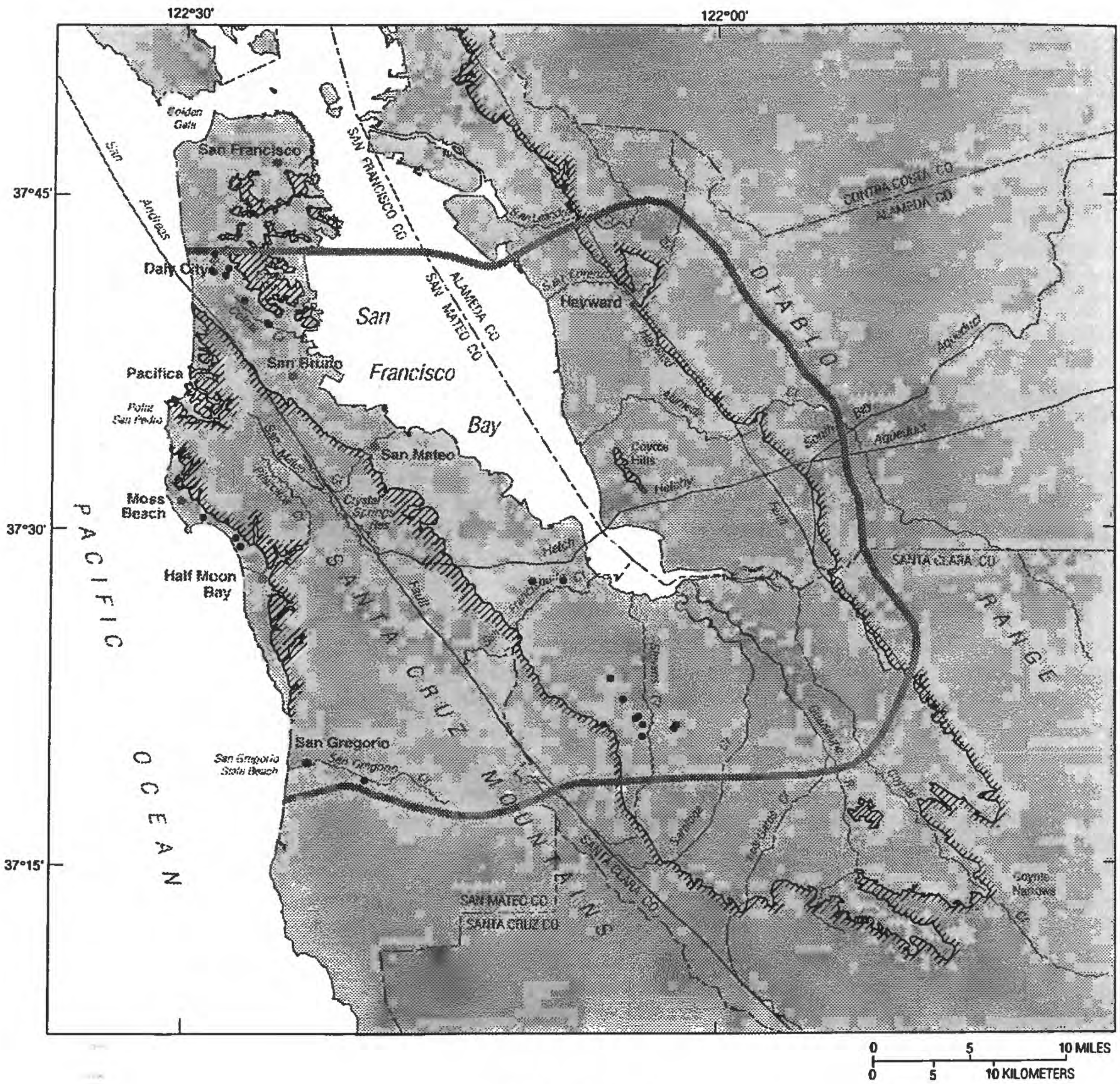


EXPLANATION

—— 500 - - -	Line of equal dissolved-solids concentrations where consistently greater than 500 milligrams per liter (or 1,000 milligrams per liter). Dashed where approximately located. Queried in areas of greatest uncertainty
(hachured line)	Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium
(heavy line)	Study-area boundary
	Chloride ion concentration in well water--in milligrams per liter
o	Less than 100
•	Greater than or equal to 100

Figure 21. Average concentration of dissolved solids and chloride ion in ground-water samples, south San Francisco Bay and Peninsula area, California, 1980-90.

70-percent halite by weight). Samples in the marine group were reportedly collected from wells near south San Francisco Bay, and samples in the intermediate group were collected from wells farther



EXPLANATION

Contact between semiconsolidated and consolidated bedrock assemblages (hachured side) and unconsolidated alluvium

Study-area boundary

• Well from which water sample contained nitrate concentration equal to or greater than 45 milligrams per liter

Figure 22. Location of wells having nitrate concentrations greater than or equal to 45 milligrams per liter, south San Francisco Bay and Peninsula area, California, 1980-90.

inland and in areas along the coast of the Pacific Ocean (not shown). A number of ground-water samples collected from the Coastal and Merced subareas reportedly did not have a dominant ionic composition, which made it difficult to distinguish different water types.

Calcium and magnesium ions in recharge and downslope-moving ground water probably exchange with adsorbed sodium ions in the lowlands. This ionic exchange could contribute to the increasing importance of sodium ions in ground-water samples near the bay and ocean. The increasing importance of chloride ions in the lowlands (fig. 21) may be the result of connate water associated with historical marine environments and more recent problems with saltwater contamination, or both. Most of the areas within the 500-mg/L dissolved-solids boundaries of figure 21 have chloride-ion concentrations greater than 100 mg/L, and areas within the 1,000-mg/L boundaries have chloride-ion concentrations greater than 250 mg/L; a chloride-ion concentration equal to and greater than 100 mg/L has been used as an indication of saltwater contamination in northern Santa Clara County (Iwamura, 1980). In general, the chloride-ion concentration in well-water samples decreases with increasing well depth; water samples from all wells deeper than 250 m below land surface have chloride-ion concentrations less than 250 mg/L, and the samples with the greatest concentrations of chloride ion (greater than 1,000-mg/L chloride) were collected from wells less than 82 m deep.

The concentration of sodium, magnesium, and calcium ions in ground water can affect its potential for various uses. For example, the soap-consuming capacity of water is typically referred to as its hardness (Hem, 1985) and is a measure of the quantity of dissolved calcium and magnesium ions. Most of the wells in the study area (199 of the 207 wells having adequate chemical data during 1980-90) produce water classified as hard to very hard (121 to greater than 180 mg/L of calcium-carbonate equivalent hardness). Hard to very hard waters can be objectionable for ordinary domestic purposes and have problems with encrustations and scaling when heated. Substantial concentrations of sodium ions can cause deflocculation of clays and damage to the soil structure and infiltration rate of water. The sodium-adsorption ratio is used to predict the hazard of sodium in irrigation water (Hem, 1985); during 1980-90, 31 of the 205 wells reported produced water that can cause increasing to severe problems when used for irrigation. These water samples generally were collected from wells north of Alameda Creek, near San Francisquito Creek, and in the coastal areas and lowlands near the bay.

Additional constituents of concern reported in the database of Leighton and others (1994) include boron and nitrate. Boron can be unsuitable in irrigation water for sensitive crops at concentrations of about 1 mg/L (for example, citrus trees, some nut trees, and other fruit trees such as apricot, peach, pear, and plum) and unsuitable for the most tolerant crops at concentrations greater than about 4 mg/L (Hem, 1985). Boron concentrations greater than 1.0 mg/L were reported in water samples from only a few wells in the database, and these wells were adjacent to south San Francisco Bay.

Excessive concentration of nitrate in drinking water is a concern because it may cause methemoglobinemia in small children (blue-baby disease); nitrate concentrations greater than or equal to 45 mg/L can cause this problem (Hem, 1985). A total of 22 wells in the study area reportedly had nitrate concentrations greater than 45 mg/L during the period 1980-90 (fig. 22). The depth of these wells ranges from 19 to 213 m below land surface (median depth of 133 m below land surface), and the wells are on the western side of the bay and in the coastal areas. Webster (1972) reported a substantial part of the east bay area as having nitrate problems in ground water also, and this constituent may present greater concern than implied by the reported data available for compilation into the database. Sources of nitrate in ground water include leaching of fertilizers, seepage of sewage flows, degradation of plant materials, and microbial activity. Identification of nitrate sources is beyond the scope of this report, but recent studies indicate that fertilizers and leaking sewers contribute the greatest quantities of nitrate in ground water in the city of San Francisco (Phillips and others, 1993).

SUMMARY AND CONCLUSIONS

Existing data in the form of published maps, reports, and paper and digital datafiles provided by local, State, and Federal agencies were used to conduct a regional assessment of geohydrologic and water-quality conditions in the south San Francisco Bay and Peninsula area. Well construction, subsurface lithology, ground-water levels, and ground-water-quality data were entered into a Geographic Information System database and used to develop various maps and conduct spatial analyses of the data. Because resources were limited, this subset of wells does not represent all of the sites in the study area for which there are useful geohydrologic and water-quality data. Additional compilation efforts are necessary for greater data density and smaller subregional analyses or to improve data coverage in areas currently lacking information.

Semiconsolidated and unconsolidated sand and gravel deposited during the Pliocene, Pleistocene, and Holocene age form productive aquifers in the study area. The principal aquifers are in the large interior valley and alluvial aprons that surround south San Francisco Bay. These aquifers are composed of a heterogeneous mixture of fine- and coarse-grained alluvium, and it is difficult to delineate distinct aquifers and aquifer boundaries. Conceptually, the ground-water system consists of a shallow zone (depths less than 45 m below land surface) underlain by an areally extensive sequence of fine-grained sediment separating it from a deeper zone (depths greater than 60 m below land surface). The underlying bedrock surface consists of local highs and lows, which produce deep valleys of sediment that can be more than 400 m thick in some areas. Most wells in the shallow and deep zones withdraw ground water under confined conditions, but ground water in the region is found under both unconfined and confined conditions.

Regional variability in physiographic features was used to delineate the following generalized ground-water subareas: Exposed Bedrock, Uplands, East and West Side Alluvial Aprons, Niles Cone, Coastal, Merced, San Jose Plain, and Bay Plain. These subareas do not necessarily conform to discrete hydrologic units or ground-water basins. Hence, the exchange of ground water between subareas can be significant and must be quantified in order to fully assess the implications of water-use practices within a subarea for hydrologic conditions in adjacent subareas. This information will be useful for the modification of the boundaries of the ground water subareas to more adequately reflect geohydrologic conditions and formulation of plans for regional conjunctive-use practices.

The principal aquifers in the study area are formed by coarse-grained deposits of sand and gravel associated with stream channels that drained into the Pacific Ocean and south San Francisco Bay. Twenty-four percent of the variability in transmissivity values reported from pumping tests is explained by the depth-averaged fraction of coarse-grained sediment. This variability indicates that the distribution of coarse-grained sediment can be used to infer general trends in aquifer permeability. Additional factors can affect the permeability of the aquifer matrix and test conditions at the well site, and thus, expected values of transmissivity at a specific location can deviate considerably from values estimated from the fraction of coarse-grained sediment.

Maximum ground-water overdrafts occurred in the study area around 1965, at which time increasing supplies of imported surface water were beginning to reduce demands for ground water. Less pumping and greater recharge due to deliveries of imported surface water increased ground-water levels and storage, which brought a temporary halt to subsidence in northern Santa Clara County and saltwater contamination in southern Alameda County. Most ground-water subareas have already undergone significant development of the resource, and a minimum estimate of 1990 pumpage, as indicated by reported well pumpage, was 179.5×10^6 m^3. Most wells in the study area withdraw water from depths greater than 70 m below land surface.

Hydraulic heads generally have increased in the study area since maximum overdraft conditions in 1965, and in the deep zone, hydraulic heads have increased as much as 30 to 40 m during the past 25 years. Horizontal gradients in the shallow zone in 1990 are toward south San Francisco Bay and the Pacific Ocean, respectively. A substantial cone of depression in the deep zone of the Merced subarea indicates that horizontal flow is in a landward direction from the bay in the southeast and the Pacific Ocean in the northwest. Similarly, horizontal flow in the deep zone is landward from beneath south San Francisco Bay toward the Niles Cone subarea and northern part of the East Side Alluvial Apron subarea. Vertical gradients generally are downward in the upslope recharge areas that surround south San Francisco Bay, but can be upward in the downslope areas adjacent to the bay.

The quantity and quality of dissolved constituents in ground water reflect regional geohydrology and historical overdraft conditions. The concentration of dissolved solids increases from less than 500 mg/L in the upslope areas to an excess of 1,000 mg/L in the lowlands adjacent to south San Francisco Bay and the Pacific Ocean. Ground-water samples from wells in the upslope areas principally are calcium magnesium carbonate waters, whereas in the downslope areas, sodium and chloride become increasingly important. The increasing importance of sodium and chloride can be attributed to sediments deposited in marine environments during historically high stands of San Francisco Bay and to saltwater contamination problems during the past 70 years. Most ground water can be classified as hard to very hard, and some wells produce water that can cause soil problems due to high concentrations of sodium when used for irrigation. The database indicates that water samples from 22 wells in the study area reported nitrate concentrations greater than 45 mg/L and may cause harm to young children. Previous studies indicate that the area affected by unacceptable nitrate concentrations may be greater than is reflected by the data in the database.

The results presented in this report are regional in scope, and their extrapolation into local areas of study and smaller scales of observation may not be warranted. Uncertainty exists in areas where data are sparse, and additional study is necessary to assess the sensitivity of the geohydrologic and water-quality conditions described in this report to the uncertainty levels present in the data set. Optimal allocation of water resources and conjunctive use of surface- and ground-water supplies require tools that can forecast the response of the ground-water system to alterations in recharge and pumping conditions. From a regional perspective, this will require greater understanding of the hydrologic interaction between subareas within both the shallow and the deeper aquifer systems; the quantity of recharge moving between subareas and the general nature of the deep aquifer system are not well understood. The conceptual description of geohydrologic conditions in this report will provide the background for such studies, but are of limited usefulness for making quantitative projections. Additional work would be necessary to develop models capable of assessing the cause and effect relation between water-resource management decisions and the regional response of the ground-water system.

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