Hydrogeologic Setting and Ground-Water Flow Simulations of the San Joaquin Valley Regional Study Area, California

By Steven P. Phillips, Karen R. Burow, Diane L. Rewis, Jennifer Shelton, and Bryant Jurgens

Section 4 of

Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001

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Contents

Figures

Tables

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Abstract

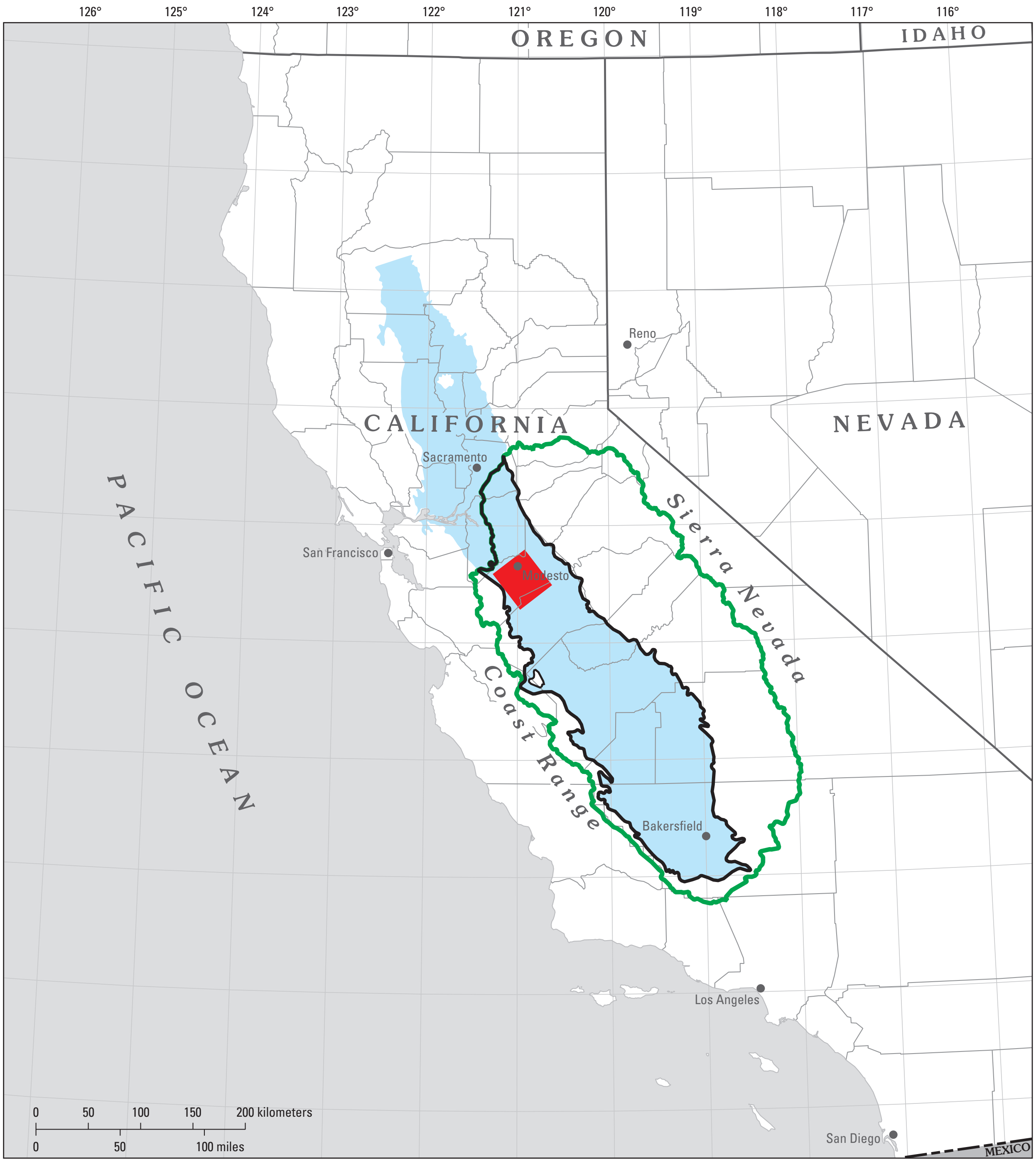
The transport of anthropogenic and natural contaminants to public-supply wells was evaluated in the northeastern part of the San Joaquin Valley near Modesto, California, as part of the U.S. Geological Survey National Water-Quality Assessment Program. The basin-fill aquifer system in the San Joaquin Valley regional study area is representative of the Central Valley aquifer system, is used extensively for agricultural irrigation and public water supply, and is susceptible and vulnerable to contamination. The Central Valley aquifer system in the study area consists of an unconfined to semi-confined aquifer in the upper sediments of the basin above and east of the Corcoran Clay confining unit. A confined aquifer occurs beneath the Corcoran Clay. Irrigation and public-supply wells are completed in both the unconfined and confined aquifers, and pumping in the valley has altered the natural ground-water flow patterns. A 16-layer, steady-state ground-water flow model of the basin-fill aquifer in an area around Modesto, California, was developed and calibrated to water-year 2000 conditions. The calibrated model and advective particle-tracking simulations were used to compute areas contributing recharge and traveltimes from recharge areas for 60 public-supply wells. Model results indicate agricultural irrigation return flow (41.5 percent of inflow) and precipitation (29.3 percent of inflow) provide most of the ground-water inflow, whereas the majority of ground-water discharge is to pumping wells (54.2 percent of outflow) and evapotranspiration (11.9 percent of outflow). Particle-tracking results indicate the areas contributing recharge to wells generally extend upgradient to the northeast of Modesto beyond the extent of the Corcoran Clay. Minimum traveltime from the water table to a well ranges from 3 to 141 years with a median of about 20 years, and maximum traveltime ranges from 18 to more than 1,600 years with a median of 107 years on the basis of particle-tracking results.

Introduction

The San Joaquin Valley regional study area for the transport of anthropogenic and natural contaminants to public-supply wells (TANC) is in the San Joaquin Valley near Modesto, California, and is part of the San Joaquin-Tulare Basins study unit of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program (fig. 4.1).

Purpose and Scope

The purpose of this Professional Paper section is to present the hydrogeologic setting of the San Joaquin Valley regional study area. The section also documents the setup and calibration of a steady-state regional ground-water flow model for the study area. Ground-water flow characteristics, pumping-well information, and water-quality data were compiled from existing data to develop a conceptual understanding of ground-water conditions in the study area. A 16-layer steady-state ground-water flow model of the basin-fill aquifer in an area around Modesto, California, was developed and calibrated to ground-water flow conditions for the water-year 2000. The water-year 2000 was assumed to represent average conditions for the period from 1997 to 2001. The 5-year period 1997–2001 was selected for data compilation and modeling exercises for all TANC regional study areas to facilitate future comparisons between study areas. The calibrated ground-water flow model and associated particle tracking were used to simulate advective ground-water flow paths and to delineate areas contributing recharge to selected public-supply wells. Ground-water traveltimes from recharge to public-supply wells, oxidation-reduction (redox) conditions along flow paths, and presence of potential contaminant sources in areas contributing recharge were tabulated into a relational database as described in Section 1 of this Professional Paper. This section provides the foundation for future ground-water susceptibility and vulnerability analyses of the study area and comparisons among regional aquifer systems.



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972, Albers equal-area projection

EXPLANATION

San Joaquin Valley regional study area

Central Valley aquifer system

USGS NAWQA study unit—San Joaquin-Tulare Basins

San Joaquin Valley

Figure 4.1. Location of the San Joaquin Valley regional study area within the Central Valley aquifer system.

Study Area Description

The San Joaquin Valley regional study area is about 2,700 square kilometers (km^2) centered on the city of Modesto, California, in the San Joaquin Valley. The San Joaquin Valley composes the southern two-thirds of the Central Valley aquifer system of California (fig. 4.1), which is ranked second in total water use of the 62 principal aquifers in the United States (Maupin and Barber, 2005).

Cities in the San Joaquin Valley are among those with the highest growth rates in the Nation, resulting in a gradual urbanization of adjacent farmlands. In Stanislaus County, the estimated population in 2000 was more than 446,000 people, an increase of 20 percent since 1990 (U.S. Census Bureau, 2002). Although more than 90 percent of the 1995 water demands in this region were for irrigation, approximately one-half of the demand for municipal and industrial supply is met by ground water. The increasing population and periods of drought are expected to increase reliance on ground water.

Topography and Climate

The San Joaquin Valley regional study area is bounded on the west by the San Joaquin River, on the north by the Stanislaus River, on the south by the Merced River, and on the east by the Sierra Nevada foothills (fig. 4.2). The Sierra Nevada rise east of the valley to an elevation of more than 4,200 m; the Coast Ranges, of moderate elevations, form the western edge of the valley. Surface topography in the study area slopes downward from the Sierra Nevada foothills to the San Joaquin River with gradients ranging from less than 1 m/km near the river to about 5 m/km near the foothills (fig. 4.2). The climate is semiarid, characterized by hot summers and mild winters, with rainfall (averaging 31.5 cm annually from 1931–1997 [National Oceanic and Atmospheric Administration, 2005]) during late fall through early spring.

Surface-Water Hydrology

The San Joaquin River is the central drainage for the northern San Joaquin Valley; it is the only major surface-water outlet from the valley draining out through San Francisco Bay. The southern San Joaquin Valley is a hydrologically closed basin. The water quality of the San Joaquin River is of critical interest because it flows into the Sacramento-San Joaquin Delta, a key source of drinking water for southern California and irrigation water for the western San Joaquin Valley. The Stanislaus, Tuolumne, and Merced Rivers drain the Sierra Nevada and are tributaries to the San Joaquin River in the study area.

All rivers in the study area have been significantly modified from their natural state. Each has multiple reservoirs for irrigation and power generation, which effectively delays discharge of large amounts of snowmelt runoff. Imprinted over this hydrology is an extensive network of canals used to deliver water for irrigation (fig. 4.2).

Land Use

Agriculture is the primary land use, covering more than 65 percent of the study area, and most of the agricultural land is irrigated. The primary crops are almonds, walnuts, peaches, grapes, grain, corn, pasture, and alfalfa. The towns of Modesto, Turlock, and a number of smaller urban areas composed about 6 percent of the study area in 2000, and the remaining 29 percent of the study area was natural vegetation near the foothills and in riparian areas (Burow and others, 2004).

Water Use

Agricultural irrigation supplied by surface water and ground water accounted for about 95 percent of the total water use in 2000 (Burow and others, 2004). Surface-water supplies originate primarily from a series of reservoirs in the Sierra Nevada foothills, are managed by irrigation districts, and are delivered to agricultural users through hundreds of kilometers of lined canals.

Irrigation districts and private agricultural users pump ground water for irrigation. Some districts also pump ground water to lower the water table in areas where it has risen too close to the land surface to support agriculture without active management. Private agricultural ground-water pumping is not measured in the study area but is estimated as about 32 percent of total agricultural water use in the study area in 2000.

Urban water demand is met by a combination of surface-water and ground-water supplies. Before 1995, the City of Modesto, the largest urban area, used ground water exclusively for public supply. In 1994, a surface-water treatment plant was completed, which, in 2000, provided about one-half of Modesto's municipal and industrial water supplies (Burow and others, 2004). Data from all of the urban areas, as a whole, indicate that about 55 percent of the urban water requirement was met with ground water in 2000 (Burow and others, 2004).

Based on local drillers' logs, about 60 percent of wells in the study area are for domestic use, followed by about 27 percent for irrigation, 4 percent for public supply, and 9 percent for test, stock, industrial, and other uses (Burow and others, 2004). Well depths range from 7 to 368 m below land surface, with a median depth of 59 m. In general, domestic wells tap shallow parts of the aquifer, whereas irrigation and public-supply wells are screened in deeper zones. The wells generally are distributed throughout the region, though fewer wells exist in the older sediments and terraces east of Modesto and Turlock and along the San Joaquin River. The deepest wells generally are in the older sediments in the eastern part of the study area, and the shallowest wells generally are in the western part and along the rivers. Additional clusters of deep wells are in the urban areas (fig. 4.2).

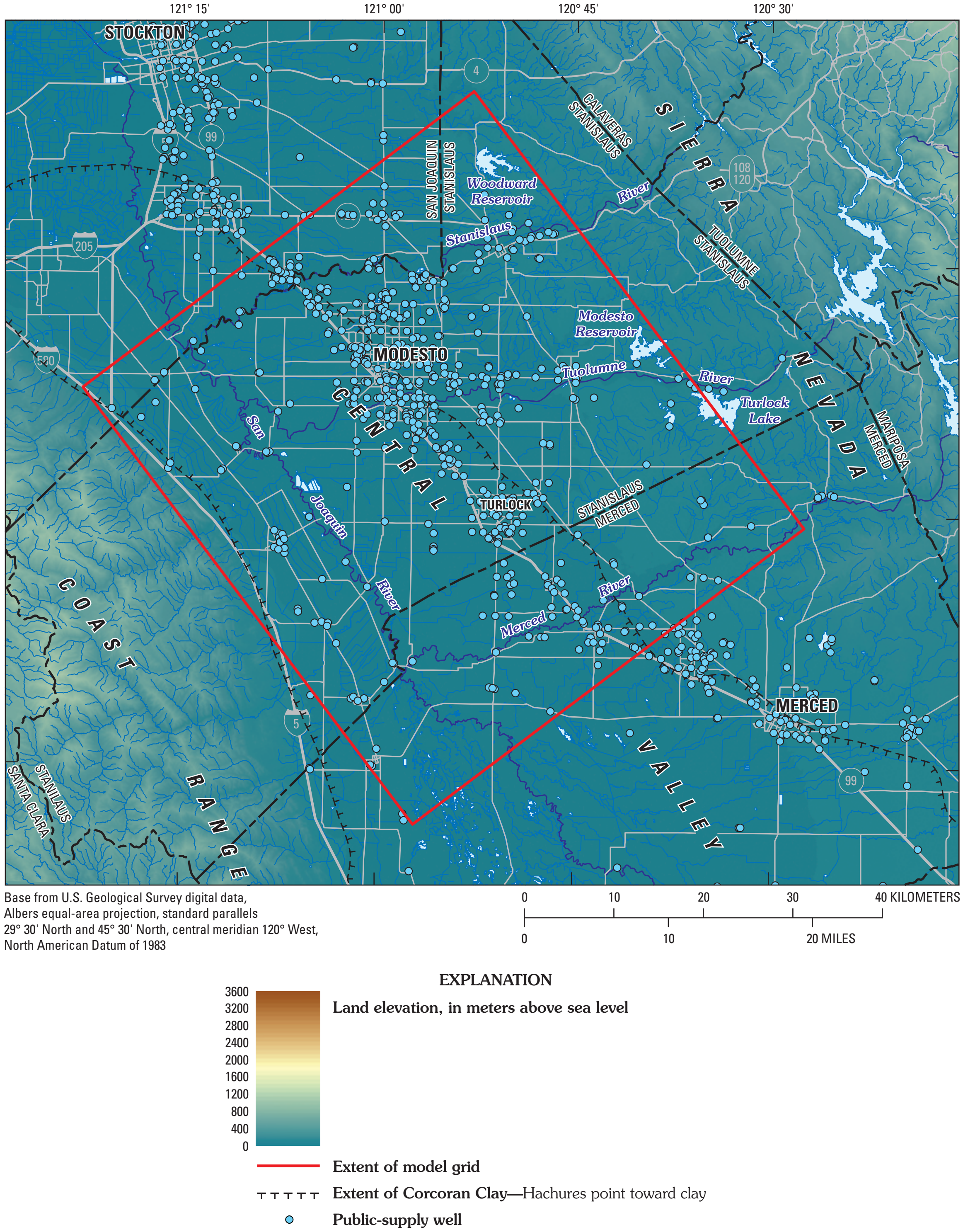


Figure 4.2. Topography, hydrologic features, and location of public-supply wells, San Joaquin Valley regional study area, California.

Conceptual Understanding of the Ground-Water System

The aquifers in the San Joaquin Valley TANC regional study area are composed of Tertiary and Quaternary alluvial deposits shed from the surrounding Sierra Nevada and Coast Ranges. The basin-fill is composed of coalescing alluvial fans, which tend to be coarse grained near the mountains and finer grained toward the center of the basin. The Corcoran Clay, correlated to the Corcoran Clay Member of the Tulare Formation south of the study area, is a lacustrine clay deposit that separates the basin-fill deposits into an upper unconfined aquifer and a lower confined aquifer throughout much of the study area. Under natural conditions, ground-water recharge occurred in the upper parts of the alluvial fans where stream valleys enter the basin, and ground water discharged to the San Joaquin River and surrounding marshlands. However, ground-water pumping in the valley for agricultural irrigation and public water supply has altered ground-water flow patterns. Water flowing laterally toward the center of the basin may be pumped, applied as irrigation, recharge the aquifer, then be pumped and reapplied at the surface several times as it moves toward the San Joaquin River. Ground-water quality is influenced by recharge from the surrounding mountain streams and irrigated agriculture.

Geology

The Central Valley of California is a northwest-trending structural trough filled with Tertiary and Cretaceous continental and marine sediments up to 10 km thick (Gronberg and others, 1998; Bartow, 1991). The Sierra Nevada Range lies on the eastern side of the valley and is composed primarily of pre-Tertiary granitic rocks. In the northern San Joaquin Valley, the Sierra Nevada Range is separated from the Central Valley by a foothill belt of marine and metavolcanic rocks. The Coast Ranges lie on the western side of the valley and are a complex assemblage of rocks, including marine and continental sediments of Cretaceous to Quaternary age (Gronberg and others, 1998).

The San Joaquin Valley can be divided into three physiographic regions (fig. 4.3): the western alluvial fans, the eastern alluvial fans, and the basin (Gronberg and others, 1998) Alluvial fan deposits on both sides of the valley are composed predominantly of coarse-grained sediments near the head of each fan that become finer grained toward the valley trough. The sediments in the eastern alluvial fan region generally are more permeable than sediments in the western alluvial fan region because sediment-source rocks and watershed characteristics are different between the two areas. The basin region is composed of continental (shallow) and marine (deeper) sediments that are overlain by fine-grained, moderately to densely compacted clays. These low-permeability deposits restrict the downward movement of water.

Consolidated rocks and deposits exposed along the margin of the valley floor include Tertiary and Quaternary continental deposits, Cretaceous and Tertiary marine sedimentary rocks, and the pre-Tertiary Sierra Nevada basement complex (Piper and others, 1939; Davis and others, 1959). Most unconsolidated deposits in the study area are contained within the Pliocene-Pleistocene Laguna (not mapped at the surface in study area), Turlock Lake, Riverbank, and Modesto Formations, with minor amounts of Holocene stream-channel and flood-basin deposits (fig. 4.3) (Arkley, 1962, 1964; Davis and Hall, 1959). The Turlock Lake, Riverbank, and Modesto Formations form a sequence of overlapping terrace and alluvial fan systems (Marchand and Allwardt, 1981) indicating cycles of alluviation, soil formation, and channel incision that were influenced by climatic fluctuations and resultant glacial stages in the Sierra Nevada (Bartow, 1991).

The Corcoran Clay Member of the Tulare Formation is a lacustrine deposit that is a key subsurface feature in the San Joaquin Valley. Page (1986) mapped the areal extent of this regional confining unit based on a limited number of well logs and geophysical logs. Additional lithologic data recently were used to modify the extent of this prominent unit in the study area (Burow and others, 2004). The eastern extent of the Corcoran Clay roughly parallels the San Joaquin River valley axis (fig. 4.3). The Corcoran Clay ranges in depth from 28 to 85 m below land surface and in thickness from 0 to 57 m in the study area.

The Mehrten Formation is tapped by wells in the eastern part of the study area. The Mehrten Formation reflects a change in lithology and texture from overlying sediments of primarily unconsolidated coarse-grained sediments of arkosic composition to Mehrten Formation sediments of primarily consolidated sediments of volcanic-derived mafic materials (Burow and others, 2004). The Mehrten Formation outcrops in the eastern part of the study area and lies at depths of at least 120 m below land surface beneath Modesto.

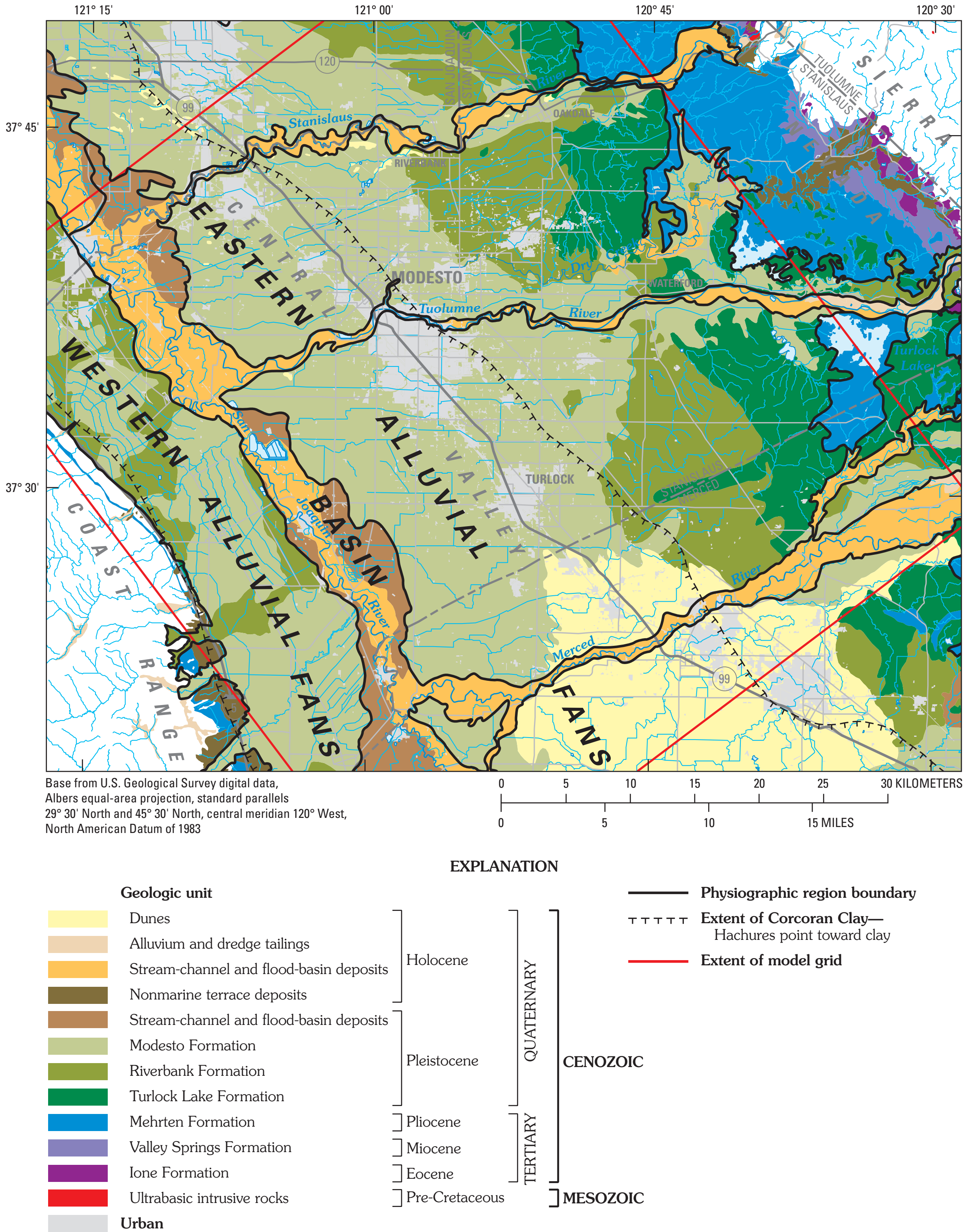


Figure 4. 3. Physiographic provinces and selected geologic units, San Joaquin Valley regional study area, California.

Ground-Water Occurrence and Flow

Ground water in the study area is present in the unconfined to semi-confined aquifer above and east of the Corcoran Clay and in the confined aquifer beneath the Corcoran Clay. The unconfined to semiconfined aquifer above the Corcoran Clay ranges in thickness from about 40 to 70 m. The unconfined to semiconfined aquifer east of the Corcoran Clay is composed primarily of alluvial sediments but includes the upper part of the Mehrten Formation, which is more consolidated than the overlying formations. Coarse-grained gravel and sand layers present in the upper part of the Mehrten are tapped by irrigation and public-supply wells. The confined aquifer is composed of alluvial sediments and upper Mehrten Formation sediments from beneath the Corcoran Clay to the lowermost freshwater. The contribution of ground water from the consolidated rocks beneath the primary aquifers was assumed negligible and was not considered for this study.

Under natural conditions, ground water was primarily recharged at the upper parts of the alluvial fans where the major streams enter the valley (fig. 4.4). Ground-water flow followed the southwest slope of the basement complex and the dip of the overlying sedimentary deposits toward the southwest in the direction of the valley trough. Artesian conditions near the San Joaquin River indicated discharge to the river and surrounding marshlands (Davis and others, 1959).

Ground-water resource development in the basin changed ground-water flow patterns. Pumping for agricultural irrigation and agricultural irrigation return flows are much greater than natural recharge and discharge and caused an increase in vertical flow in the system (fig. 4.4) (Page and Balding, 1973; Londquist, 1981). Ground-water flow direction for 2000 is generally toward the southwest and is somewhat similar to the predevelopment flow regime (fig. 4.5). However, ground water moving along a lateral flow path may be extracted by wells and applied at the surface several times before reaching the valley trough (fig. 4.4), at which point it may cross to the other side of the valley rather than discharge to the river because of pumping on the west side of the valley. South of the Tuolumne River is a centrally located ground-water-flow divide, east of which water flows northeastward toward irrigation wells in an agricultural area with no surface-water supplies. West of the flow divide, water flows southwestward toward the valley trough (fig. 4.5).

The western part of the study area along the San Joaquin River is an area of ground-water discharge where the water table is within 3 m of the land surface. Ground-water pumping is used in this area to keep the water table from affecting crop roots. Depth to the water table increases eastward, particularly south of the Tuolumne River, where depths can exceed 40 m.

Long-term water levels measured in selected wells representing the unconfined to semi-confined aquifer near the city of Modesto indicate water levels generally decreased in the Modesto area until the early 1990s (fig. 4.6). This hydraulic-head decrease likely was caused by increased urban development and associated public-supply pumping punctuated by drought conditions in 1976 and 1987–92. A series of wet years in the early 1990s and completion of a surface-water treatment plant in 1994, which provided an additional source of public-supply and industrial water, resulted in a recovery of ground-water levels near Modesto.

Aquifer Hydraulic Conductivity

The hydraulic properties of the aquifer system were estimated for this study based on the distribution of sediment texture and through calibration of the ground-water flow model. The texture distribution was estimated using the general approach of Laudon and Belitz (1991), which made use of drillers' logs and geophysical logs.

To facilitate this texture-based approach, a database was constructed as part of a cooperative effort between the U.S. Geological Survey and the Modesto Irrigation District to organize information on well construction and subsurface lithology in the study area (Burow and others, 2004). About 10,000 drillers' logs were examined. Because sediment descriptions on drillers' logs can be ambiguous and widely variable, a rating scheme was developed to select a subset of about 3,500 logs for use in this study. In addition to lithologic data, the database contains well-construction information, which was used to vertically distribute ground-water pumping in the flow model.

To visualize subsurface sediment-texture distributions and provide a heterogeneous hydraulic-conductivity field for the flow model, the primary texture of sediments in the study area was characterized using a geostatistical approach (Burow and others, 2004). Lithologic descriptions in the database were expressed as a percentage of coarse-grained sediment. These percentages were then interpolated within each layer of the model grid (using kriging), providing an estimated distribution of sediment texture. The estimated texture distribution for model layer 4 (above the Corcoran Clay) is shown in figure 4.7. The estimated texture distributions are reasonably constrained in the model layers above the Corcoran Clay and in some areas where the deepest wells penetrate the sub-Corcoran part of the system. In deeper parts of the aquifer system, where no data were available, the texture value in the lowest layer estimated was duplicated in all underlying model cells.

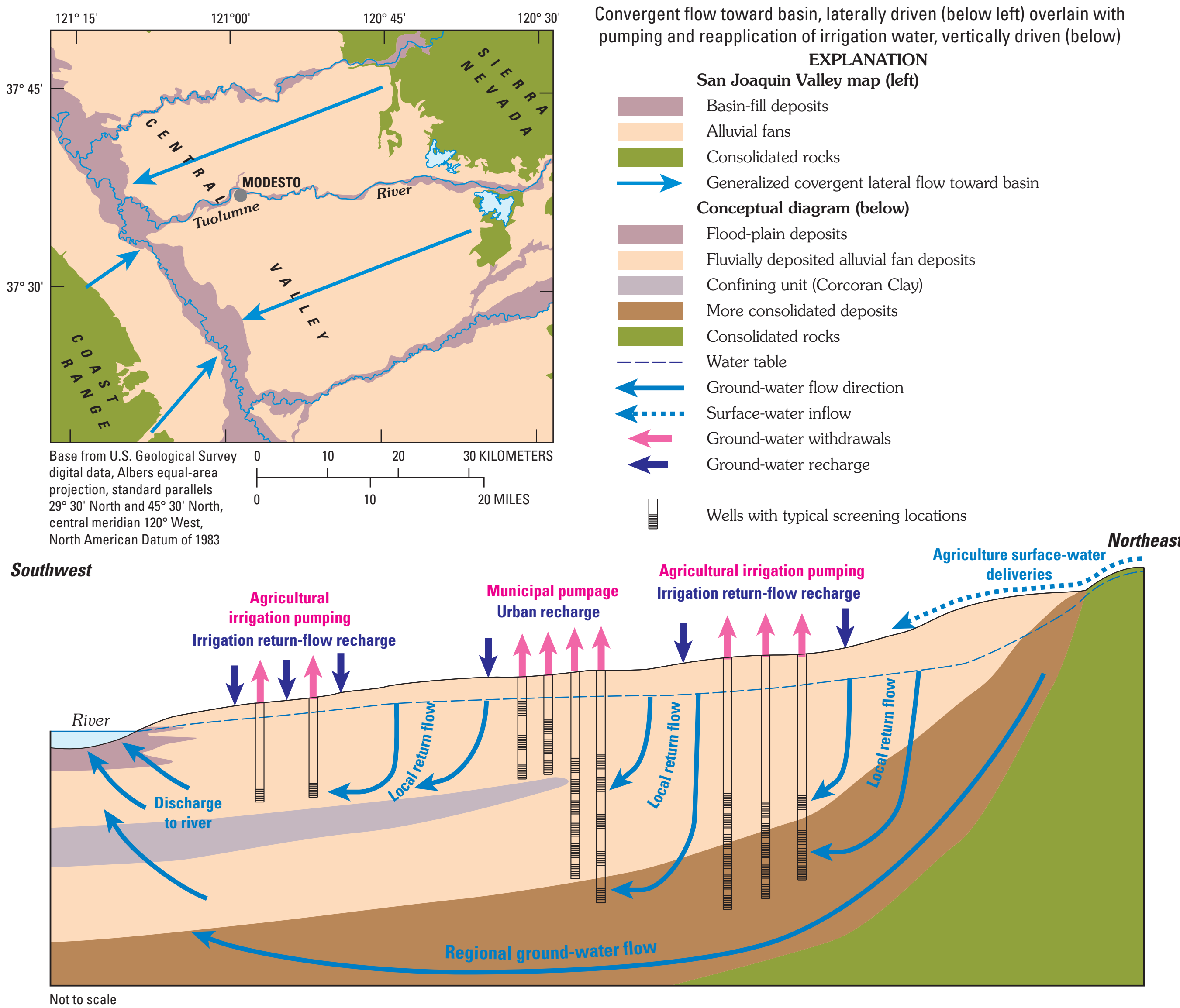
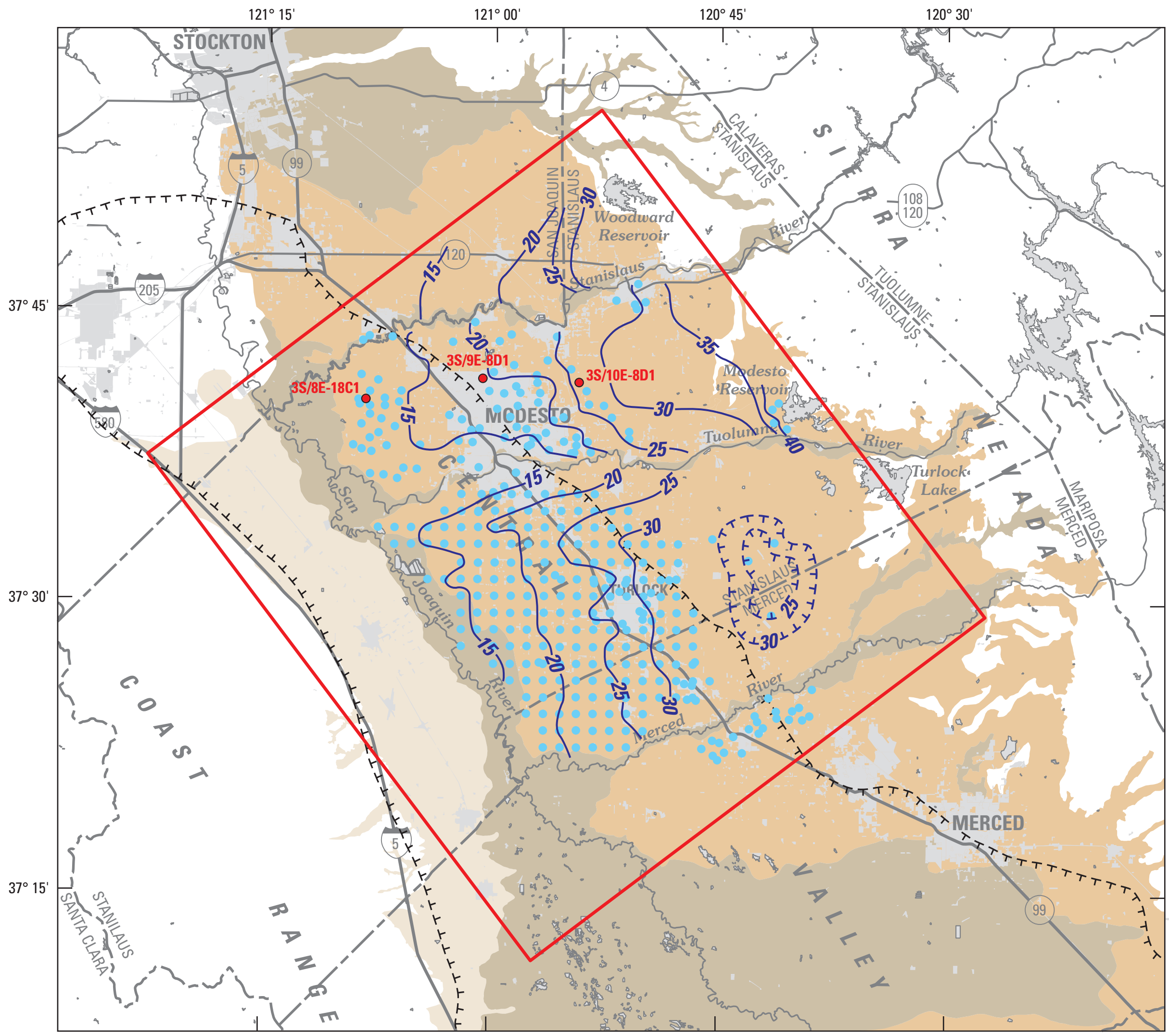


Figure 4. 4. Regional ground-water flow near Modesto, California.



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30' North and 45° 30' North, central meridian 120° West,
North American Datum of 1983

0 10 20 30 40 KILOMETERS
0 10 20 MILES

EXPLANATION

Physiographic region

- Basin
- Eastern alluvial fans
- Western alluvial fans

Urban

Line of equal water-level elevation, in meters—Interval 5 meters. Dashed where approximately located. Hachures indicate depression. Datum is sea level

Extent of model grid

Extent of Corcoran Clay—Hachures point toward clay

Wells used to contour water-level elevation, in meters

3S/10E-8D1 **Wells with long-term measured water levels** (figure 4.6)

Figure 4. 5. Measured hydraulic-head elevations in the unconfined to semi-confined aquifer for spring 2000, San Joaquin Valley regional study area, California.

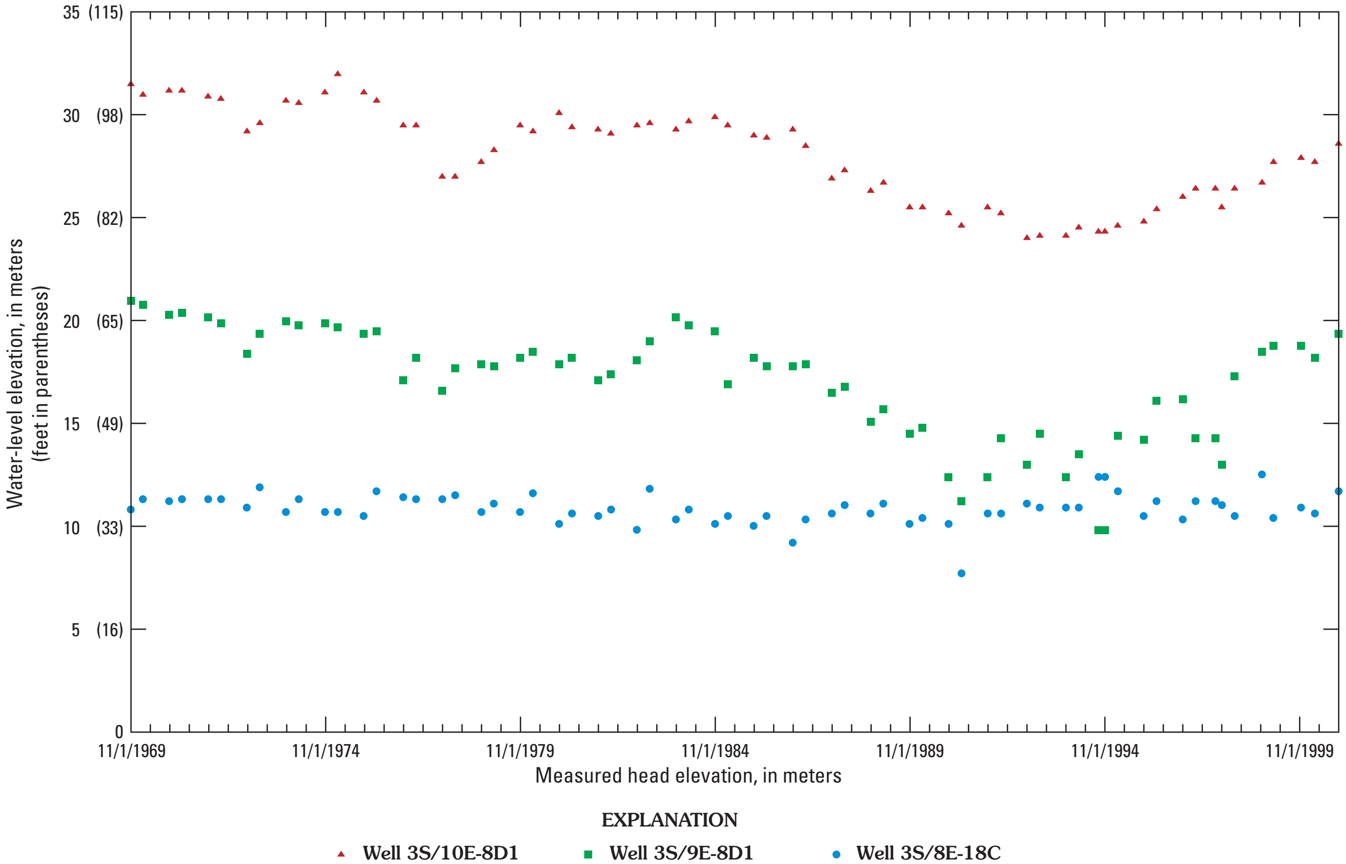


Figure 4. 6. Measured hydraulic-head elevations from November 1969 to November 2000 for selected irrigation wells, San Joaquin Valley regional study area, California. Well locations shown on figure 4.5.

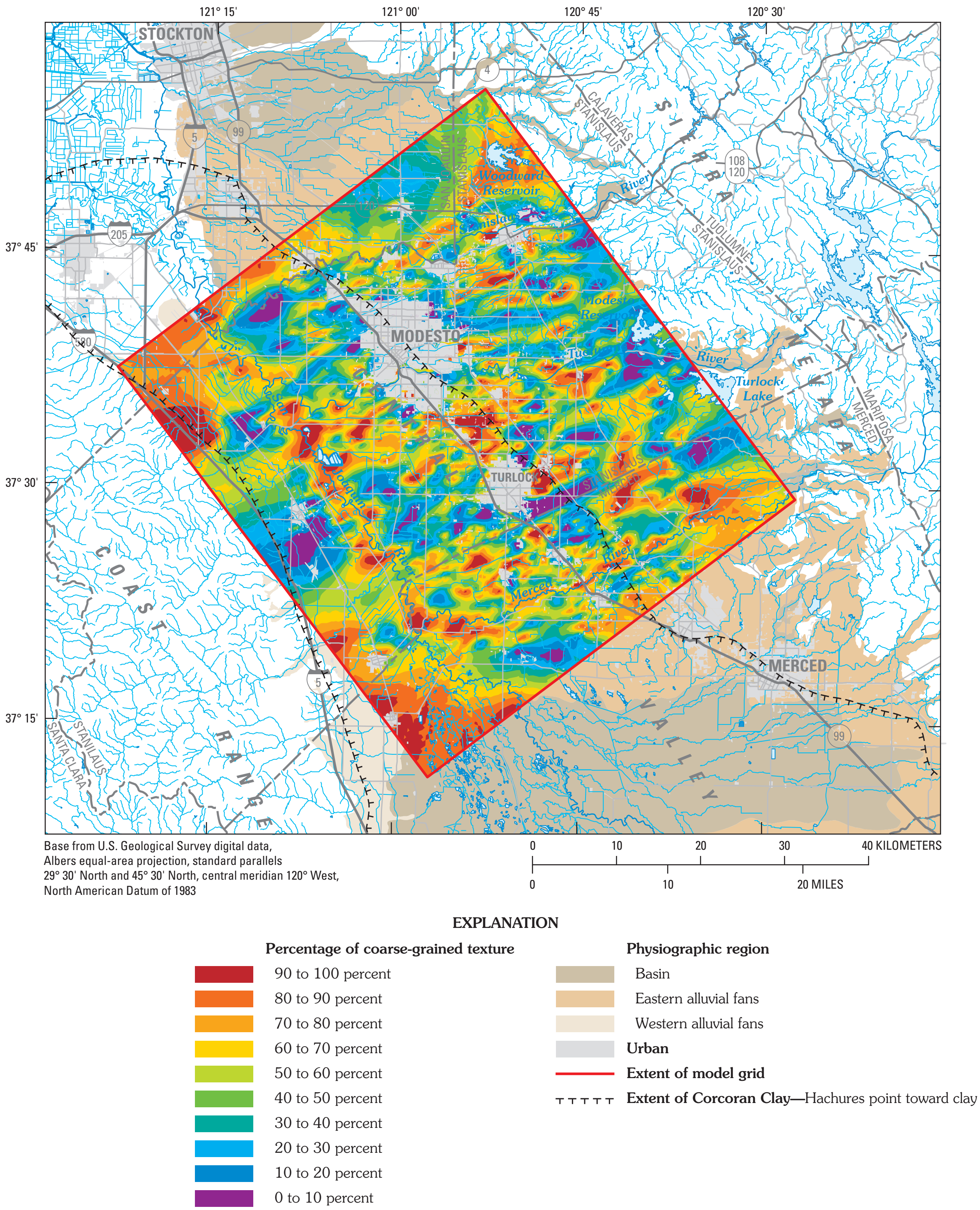


Figure 4. 7. Percentage of coarse-grained texture for model layer 4, San Joaquin Valley regional study area, California

Water Budget

A water-budget approach was used to estimate ground-water pumping and recharge from infiltration of rainfall and irrigation return flow for water-year 2000 (October 1, 1999, through September 30, 2000). Surface water and ground water are used for irrigation in the agricultural areas. Surface-water delivery data were available for most of the water-budget subareas, although private pumping records generally were not. Therefore, the water budget was critical for estimating ground-water use in agricultural areas and was important for estimating areal recharge throughout the model area.

The water budget was derived by dividing the basin into subareas for which surface-water deliveries could be obtained or estimated. A separate water budget was calculated for each of the resulting 47 subareas, which were then grouped into 12 model subareas (table 4.1) (fig. 4.8), which included agricultural and urban settings, foothill areas, riparian areas with natural vegetation and(or) crops, and reservoirs.

A land-use approach (Burow and others, 2004) was used to estimate the water budget for subareas containing primarily nonurban land use. The area of each crop or other vegetation type was determined, a daily crop demand was calculated based on crop or vegetation type and climate, and a daily irrigation demand was estimated for each subarea. The irrigation demand was met by a combination of surface-water deliveries, ground water pumped by irrigation districts, and private ground-water pumping. The total reported or estimated monthly surface-water and ground-water deliveries were subtracted from the estimated monthly irrigation demand to determine the monthly unmet irrigation demand. Private ground-water pumping was then assumed to be the source of unmet irrigation demand.

The consumptive use of applied water, or irrigation efficiency, was estimated at about 63 percent for most of the study area on the basis of irrigation methods used and estimates in subareas with relatively high surface-water deliveries and few known wells. Irrigation efficiency was assumed greater (80 percent) in the older fan deposits in the foothill areas, where the sediments are more indurated and modern and efficient irrigation methods are more commonly used (Burow and others, 2004).

Recharge in the urban areas was estimated using the minimum month method to determine indoor and outdoor

Table 4.1 Summary of water-budget components for water-year 2000 in the Modesto area, San Joaquin Valley regional study area, California.

[m^2, square meters; m^3, cubic meters]

Water-budget subarea	Irrigation demand			Surface-water deliveries	
	Irrigated cropped area, including double and intercropped area (m^2)	Crop demand (m^3)	Irrigation demand (m^3)	Surface-water deliveries (m^3)	Agricultural ground-water pumpage deliveries (m^3)
Eastside Water District (EWD)	214,781,896	192,159,808	240,199,759	—	—
Merced Irrigation District (MER)	134,263,686	118,920,445	188,762,611	85,184,253	2,563,052
Merquin Community Water District (MERQ)	29,744,731	28,761,456	45,653,105	21,909,708	—
Modesto Irrigation District (MID)	252,669,587	236,308,482	375,092,829	172,897,795	25,894,607
Oakdale Irrigation District (OID)	206,238,419	209,521,576	261,901,970	302,202,485	10,274,903
South San Joaquin Irrigation District (SSJID)	127,848,622	119,424,314	189,562,403	157,031,625	—
Stevinson Water District (SWD)	14,464,212	13,809,833	21,920,370	10,654,212	—
Turlock Irrigation District (TID)	603,293,199	529,757,589	840,885,063	554,268,926	94,771,341
Foothills (FOOT)	—	—	—	—	—
Reservoirs (RES)	—	—	—	—	—
Riparian and miscellaneous agricultural areas (RIP)	182,577,869	158,586,562	251,724,701	208,025,236	—
Urban (URB)	—	—	—	38,102,384	—
TOTAL	1,765,882,221	1,607,250,065	2,415,702,811	1,550,276,623	133,503,903

[1] Negative pumpage resulted from excess delivery for calculated crop demand. Pumpage was set to zero in the model.

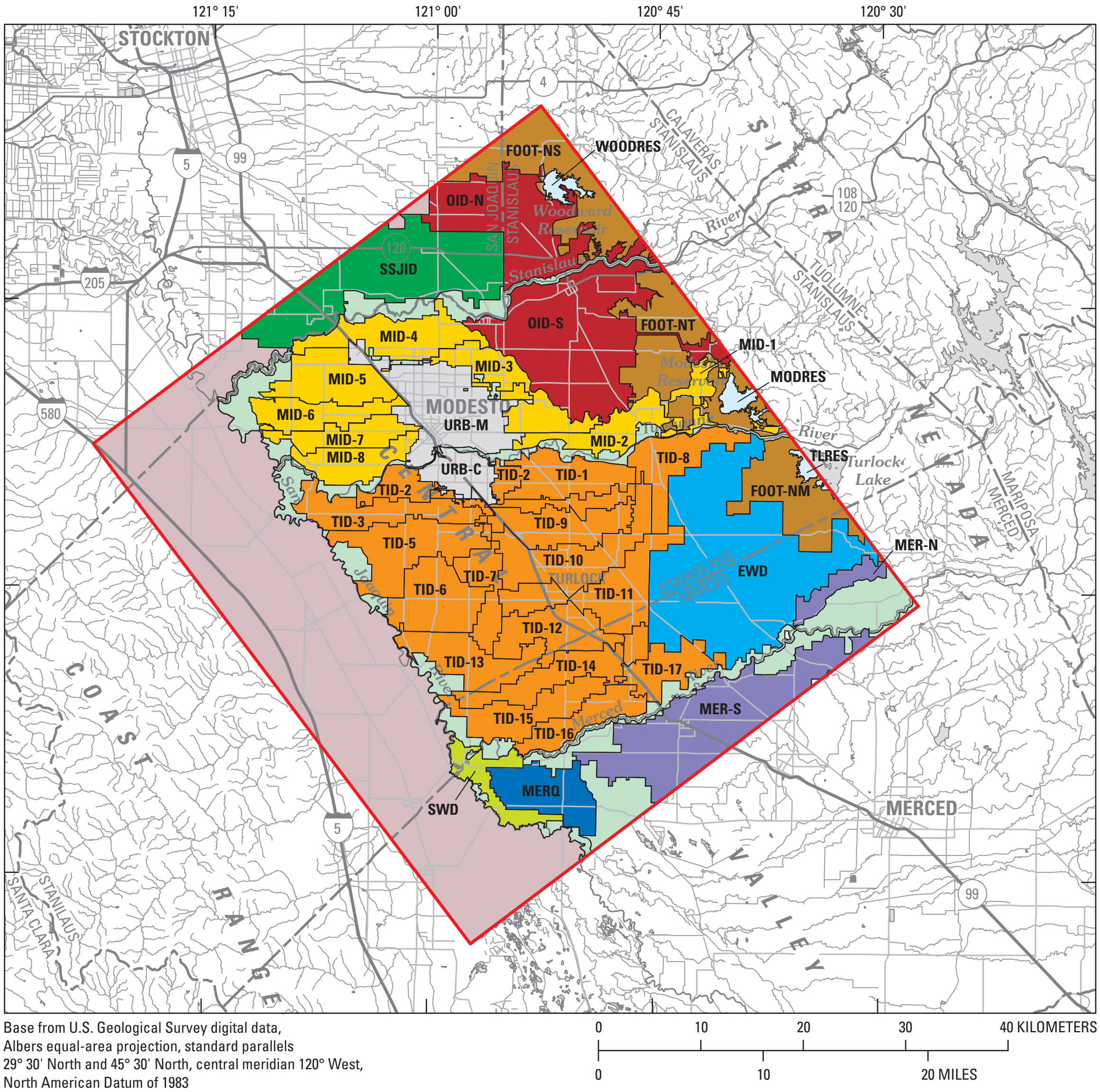
water use (California Department of Water Resources, 1994). Ten percent of the estimated outdoor use was subtracted from the total to account for leakage from water distribution lines (California Department of Water Resources, 1994). Fifty percent of the remaining outdoor water use was assumed to be consumptive use for landscape irrigation or runoff to streams, and the remainder of outdoor use was assumed to be urban recharge (Burow and others, 2004).

The average areal recharge rate for the study area is about 54 cm/yr, which includes recharge from precipitation and irrigation return flow, with the highest recharge rates occurring in the agricultural areas in the western part of the study area and along the rivers in the eastern part (fig. 4.9). The lowest recharge rates were in the foothills and the urban areas. Similarly, the highest pumping rates were in the agricultural areas in the western part of the study area (fig. 4.10). The relatively high rates of pumping and recharge in the western agricultural areas are related to the irrigation efficiency and supplemental pumping required to manage the shallow water table. No information was available regarding pumping rates from domestic wells. Although domestic wells are common in the study area, they were assumed to represent an insignificant percentage of the water budget and were not included.

Ground-Water Quality

Ground-water quality in the study area is influenced by recharge from streams and surface water imported through canals. This recharge can infiltrate from irrigated fields to the water table and by regional ground-water flow from the alluvial fans on the east and west sides of the valley toward the axial trough (Davis and others, 1959; Bertoldi and others, 1991). Ground water on the east side of the San Joaquin River is fairly uniform in composition, consisting of predominantly sodium-calcium-bicarbonate or calcium-sodium-bicarbonate type water (Davis and Hall, 1959), and has generally low dissolved-solids concentrations (less than 500 mg/L). Ground-water quality east of the San Joaquin River reflects recharge of water originating in the granitic Sierra Nevada to the east (Page, 1973; Bertoldi and others, 1991). Ground water on the west side of the San Joaquin River is predominantly of

and ground-water pumpage			Recharge			
Private agricultural ground-water pumpage (m^3)	Urban ground-water pumpage (m^3)	Total ground-water pumpage (m^3)	Recharge from urban water distribution lines (m^3)	Recharge from irrigation (m^3)	Recharge from precipitation (m^3)	Total recharge (m^3)
240,199,759	—	240,199,759	—	48,039,952	62,028,511	110,068,463
101,015,306	1,858,512	105,436,870	—	69,842,166	37,207,316	107,049,482
23,743,397	—	23,743,397	—	16,891,649	10,573,559	27,465,208
176,300,427	11,636,020	213,831,054	—	138,784,347	66,807,374	205,591,721
[1] –50,575,417	3,591,759	[1] –36,708,755	—	52,380,394	58,648,959	111,029,353
32,530,778	2,107,287	34,638,065	—	70,138,089	33,885,822	104,023,911
11,266,159	—	11,266,159	—	8,110,537	6,738,661	14,849,198
206,059,686	33,568,641	334,399,669	—	311,127,473	161,236,620	472,364,093
—	—	—	—	—	61,362,021	61,362,021
—	—	—	—	—	4,995,484	4,995,484
43,699,465	—	43,699,465	—	93,138,139	69,747,688	162,885,828
—	47,182,527	47,182,527	4,101,222	18,455,497	9,858,789	32,415,508
784,239,561	99,944,746	1,017,688,210	4,101,222	826,908,243	583,090,805	1,414,100,270



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30' North and 45° 30' North, central meridian 120° West,
North American Datum of 1983

EXPLANATION

Model subareas

- Eastside Water District (EWD)
- Merced Irrigation District (MER)
- Merquin Community Water District (MERQ)
- Modesto Irrigation District (MID)
- Oakdale Irrigation District (OID)
- South San Joaquin Irrigation District (SSJID)
- Stevinson Water District (SWD)
- Turlock Irrigation District (TID)
- Foothills (FOOT)
- Reservoirs
- Riparian and miscellaneous agricultural areas
- Urban
- **Extent of model grid**
- **Inactive model cells**

Figure 4. 8. Ground-water flow model subareas used for water-budget calculations, San Joaquin Valley regional study area, California.

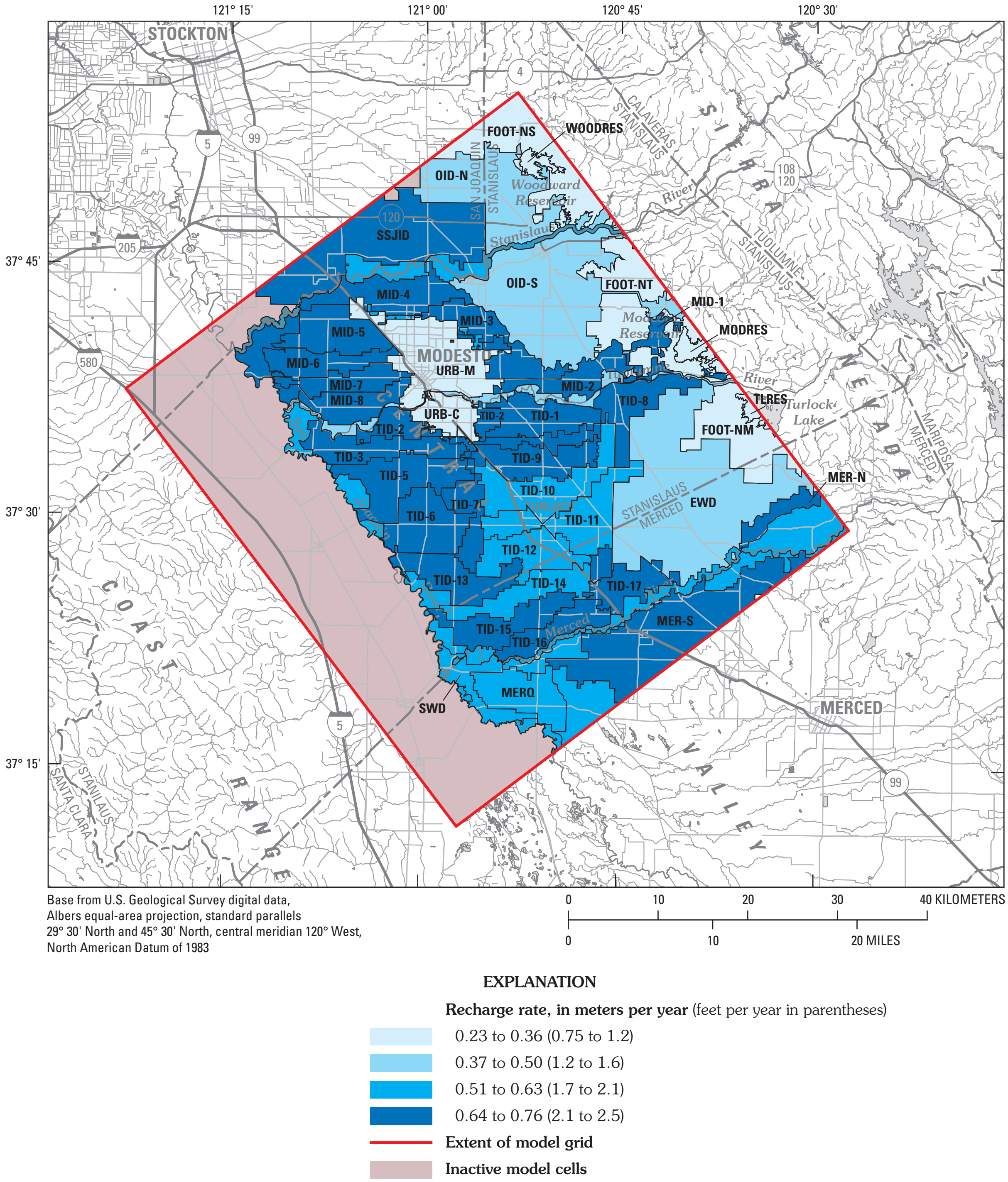


Figure 4. 9. Water-year 2000 estimated recharge rates for model subareas, San Joaquin Valley regional study area, California.

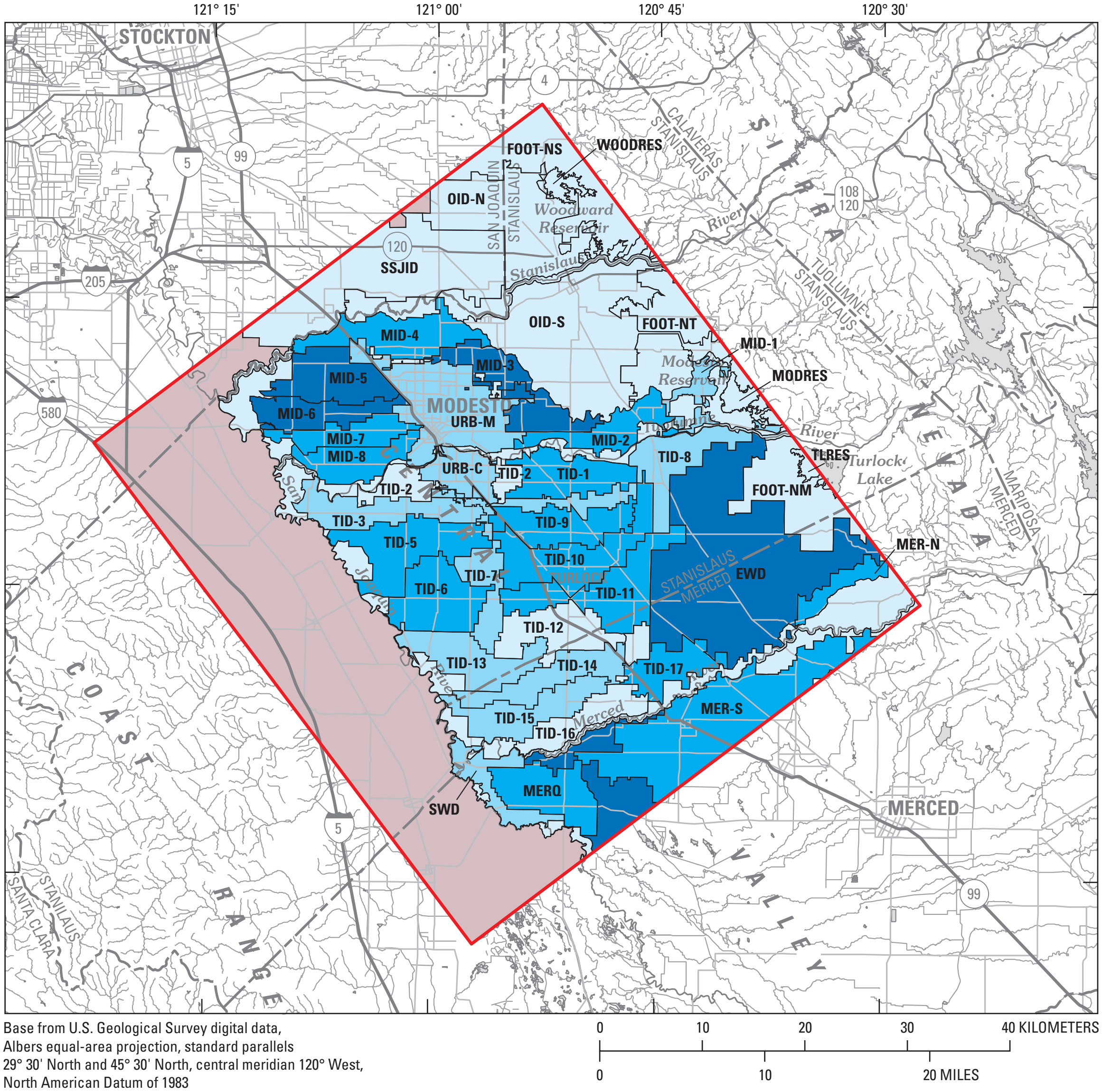


Figure 4. 10. Water-year 2000 estimated ground-water pumping rates for model subareas, San Joaquin Valley regional study area, California.

calcium-sulfate or calcium-bicarbonate type water with dissolved-solids concentrations ranging from 500 to 1,500 mg/L (Davis and others, 1959; Bertoldi and others, 1991), likely reflecting recharge of water originating in the marine and continental sedimentary rocks of the Coast Ranges to the west (Davis and Hall, 1959). Because the axial trough has been the discharge area in the past, ground water in this area is derived from a combination of water from the east and west sides of the valley and varies widely in composition with depth.

The water chemistry is further influenced by an increase in reducing conditions and cation-exchange processes as the water moves through the sediments (Bertoldi and others, 1991). Ground water beneath the alluvial fans in the valley area is largely oxidizing, whereas ground water beneath the axial trough and in discharge areas adjacent to streams typically is geochemically reduced (Gronberg and others, 1998; fig. 4.11). Geochemically reduced water is likely associated with relatively fine-grained sediments of higher organic content, longer residence times of water reaching natural discharge areas, and confined portions of the aquifer. Concentrations of oxidation-reduction- sensitive (redox) species in retrospective ground-water quality data for the study area were used to delineate regional redox patterns. Because of the limited spatial coverage of suitable water-quality samples and the dominantly oxygenated conditions in the aquifer, most of the study area was mapped as conditions consistent with oxygen and nitrate reduction. Areas of manganese reduction and iron reduction with high sulfate were mapped along the axial trough and deep in the more consolidated sediments and confined parts of the aquifer beneath the alluvial fans.

Agricultural water use is the largest nonpoint source of water-quality degradation in the San Joaquin Valley. Irrigation has become the major source of recharge to the ground-water system and can contain elevated concentrations of dissolved solids, nutrients, pesticides, and in some areas, trace elements (Gronberg and others, 1998).

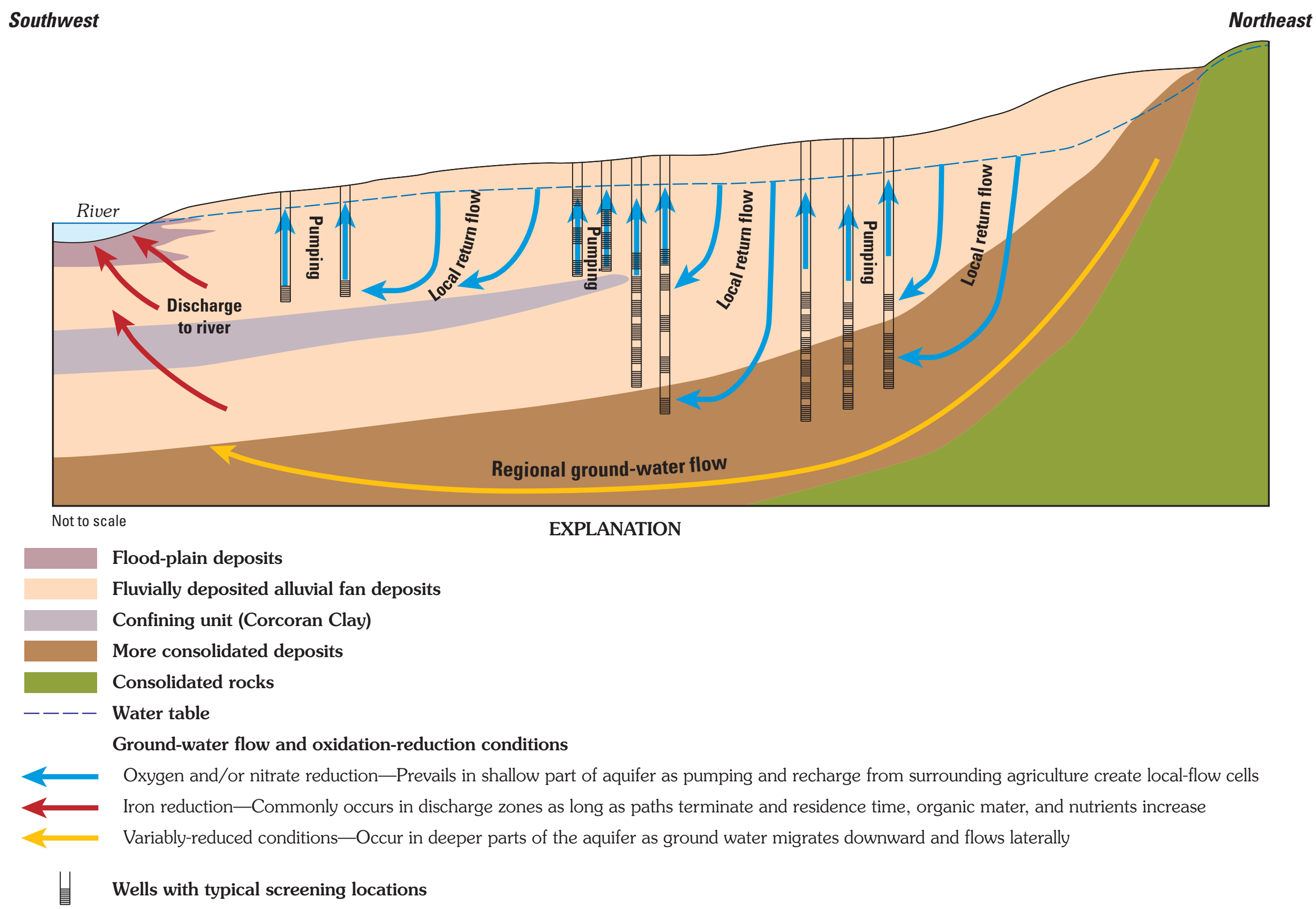


Figure 4. 11. Conceptual diagram of oxidation-reduction conditions near Modesto, California.

Ground-Water Flow Simulations

A steady-state model of ground-water flow in the study area was developed using MODFLOW-2000 (Harbaugh and others, 2000) to estimate aquifer-system properties, delineate areas contributing recharge to public-supply wells in Modesto, and support future local modeling efforts. The model represents the water-year 2000 when the ground-water system was in a quasi-steady-state condition. Measured hydraulic heads in the study area indicate much of the system has been at equilibrium for many years (fig. 4.6), particularly the areas with a shallow water table downgradient from Modesto and Turlock. The two areas where hydraulic heads have recently changed are Modesto and the agricultural area upgradient from Turlock. Water levels recovered rapidly with importation of surface water to the Modesto area in 1995, but the recovery slowed greatly by 2000. Upslope from Turlock, hydraulic heads have declined for about 2 decades due to increased ground-water use associated with new agricultural development. Although water-level data for this area are sparse, they indicate hydraulic heads continue to decline, albeit slowly. Transient conditions cannot be taken into account in a steady-state simulation; therefore, some model error is to be expected in these areas.

Modeled Area and Spatial Discretization

The modeled area for the San Joaquin Valley regional study area extends from the Stanislaus River on the north to the Merced River on the south and bounded on the east by the Sierra Nevada foothills and the west by the San Joaquin River. The model grid is oriented parallel to the valley axis, 37 degrees west of due north (fig. 4.12). The modeled area extends 61.2 km along the valley axis from north of the Stanislaus River to south of the Merced River and 54.8 km from the Coast Ranges to the Sierra Nevada foothills. The model grid is 137 columns and 153 rows and is uniformly spaced; each model cell is 400 m by 400 m in size.

Sixteen model layers were used to represent the geologic materials in the study area with model layers designed as a series of wedges to represent the regional dip of the sediments. The uppermost layer was a constant thickness of 10 m. Layers 2 through 7 represent the unconfined aquifer above and east of the Corcoran Clay. The thicknesses of layers 2 through 7 were assigned as a percentage of the thickness of materials between layer 1 and the top of the Corcoran Clay (10, 10, 15, 20, 20, and 25 percent of that thickness, respectively) and ranged from 1.9 to 18.8 m in thickness. Layer 8 represents the Corcoran Clay, where present, and its specified thickness and presence varies spatially as determined from analysis of drillers' and geophysical logs. A minimum thickness of 10 m was specified for layer 8 where the Corcoran Clay was not present. Layers 9 through 16 represent the confined aquifer beneath the Corcoran Clay, and thickness of layers 9–16 was assigned as a percentage of the thickness of materials between the bottom of the Corcoran Clay and the bottom of the model. Layers 9 through 13 were assigned 10 percent of the total thickness, layers 14 and 15 were assigned 15 percent of the thickness, and layer 16 was assigned 20 percent of the total thickness. Layer thickness below the Corcoran Clay ranged from 17 to 80 m. The bottom of the model was an artificial surface loosely representing topographic variability and the general dip of the Corcoran Clay. The total thickness of the wedge-shaped model ranges from about 230 to 430 m.

Boundary Conditions and Model Stresses

Lateral boundary conditions in the model were no-flow along the Sierra Nevada foothills and general-head elsewhere. The general-head boundaries (fig. 4.12) were specified at a distance of 400 m using a water-level contour map (fig. 4.5) and hydraulic-conductivity estimates for each cell along the boundary. The northwestern and southeastern edges of the model grid were located beyond the Stanislaus and Merced Rivers, respectively, to include these rivers in the modeled area. The southwestern model boundary was coincident with the San Joaquin River, and all cells west of the river were inactive. These general-head boundaries allow for cross-valley flow beneath the San Joaquin River, which is known to occur (Belitz and Phillips, 1995; Phillips and others, 1991), and provide reasonable boundary conditions in the northwest and southeast where no identified hydrologic boundaries exist within a reasonable distance of the study area.

The upper model boundary was simulated as the water table, and the lower model boundary was simulated as no-flow. The lower model boundary was arbitrarily located far below the deepest wells, and significant vertical flow in the lowest model layer is unlikely.

Model stresses included recharge from irrigation return flow; infiltration of precipitation, reservoir leakage, and inflow from rivers; and discharge from ground-water pumping, outflow to rivers, and evaporation from the shallow water table. Irrigation return flow, infiltration of precipitation, and private-agricultural pumping rates were all determined in the water-budget analysis. The two recharge terms were summed for each water-budget subarea and distributed evenly to the uppermost active model layer within each subarea. Private-agricultural pumping was distributed laterally within water-budget subareas assuming an average well spacing of 1,200 m (3 cells). Wells with measured pumping rates (those supplying urban areas or operated by irrigation districts) were placed in the model at their actual locations. The vertical distribution of private-agricultural pumping was estimated using the average screened interval of irrigation wells in each subarea (using the texture data base). Given this average screened interval, the total pumping per well was distributed to the model layers within this interval on the basis of effective transmissivity of these layers. The vertical distribution of measured pumping was distributed using the actual screened intervals (or those of nearby wells of the same type).

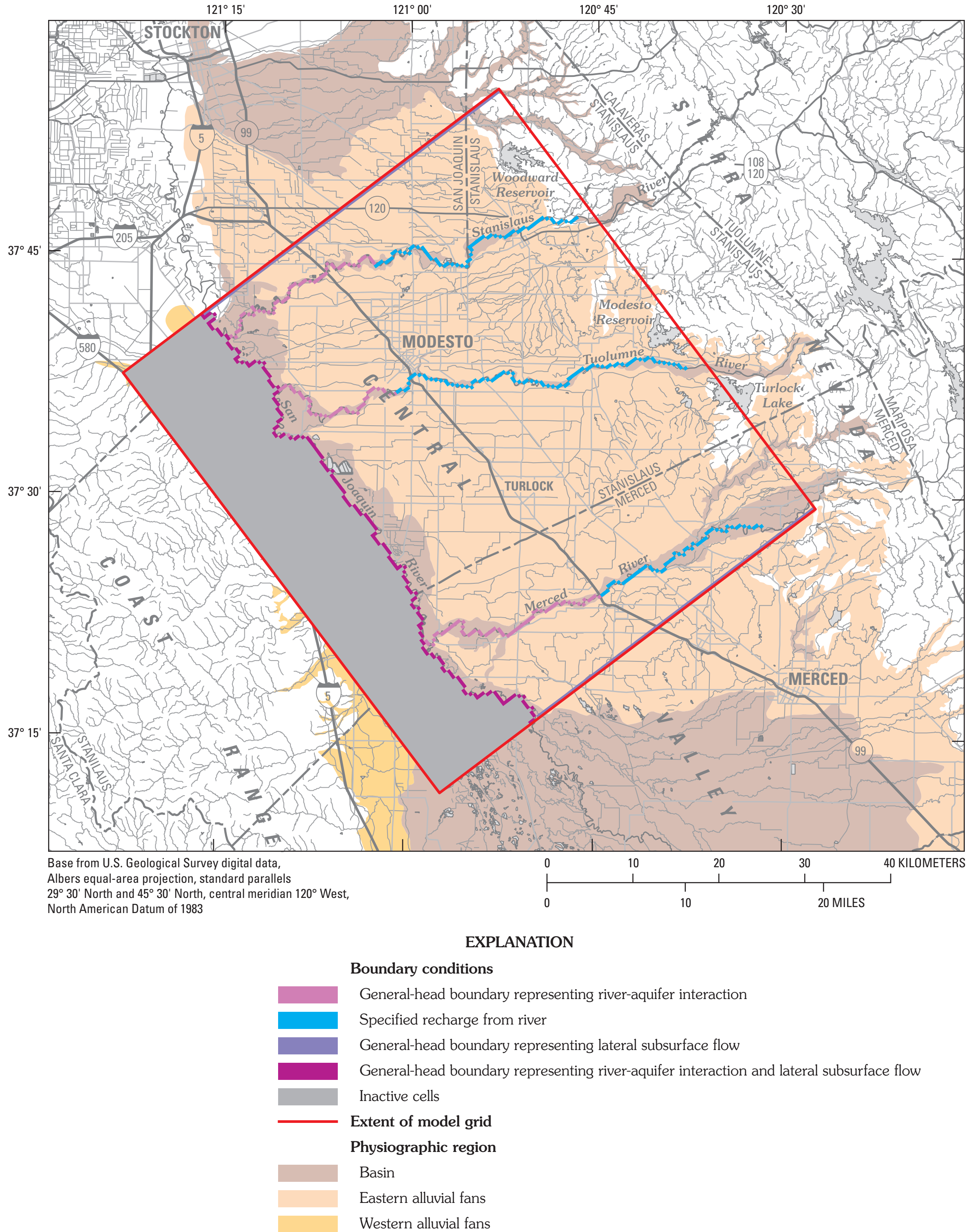


Figure 4.12. Ground-water flow modeled area and boundary conditions, San Joaquin Valley regional study area, California.

The interaction of ground water and surface water is poorly understood in the study area but is incorporated in the model as reservoir leakage and gaining and losing reaches of the four rivers. There are three significant reservoirs along the northeastern model boundary: Woodward and Modesto Reservoirs and Turlock Lake (fig. 4.2). These reservoirs are approximately equal in size, and information on leakage rates was available only for the Modesto Reservoir. Results from a recent short-term study conducted by the Modesto Irrigation District, which manages the reservoir, indicate a leakage rate of about 67,600 to 84,500 m^3/d (Modesto Irrigation District, oral commun., 2001). Leakage rates for the other two reservoirs were assumed to be the same as those for the Modesto Reservoir. The MODFLOW-2000 Reservoir package (Fenske and others, 1996) was used to simulate the reservoirs, which requires specification of reservoir stage and information for calculating the hydraulic conductance of the reservoir bottom. The stage was estimated from U.S. Geological Survey 7.5-minute topographic maps, and the hydraulic conductance terms were adjusted to approximate the assumed leakage rate (the total reservoir leakage in the calibrated model was 207,000 m^3/d).

The four rivers in the study area were represented in the model as a combination of general-head and specified-flux cells. General-head cells were used where the river was directly connected to the water table, which allowed flow into and out of the river. The head term was estimated from streamgage data and topography, and the conductance was calculated using the estimated vertical hydraulic conductivity by cell, the river width, and an assumed riverbed thickness of 1 m. Recharge from the river was specified as a flux where the river was disconnected from the water table. This value (0.005 m/d per river cell) was impossible to estimate with the available data, and its calibration was poorly constrained.

Bare-soil evaporation from the water table was simulated where the water table was within 2.1 m of the land surface. The maximum evaporation rate was 1.6 m/yr at the land surface, and decreased linearly to zero at 2.1 m below land surface.

Aquifer Hydraulic Properties

A method of parameter estimation based on sediment texture, which was used successfully in the development of a transient three-dimensional ground-water flow model of the central western San Joaquin Valley (Belitz and Phillips, 1995; Phillips and Belitz, 1991), was adapted for use in this study. This method uses the estimated sediment texture (as percentage of coarse-grained sediments) for each model cell and several user-specified values of hydraulic conductivity to generate horizontal and vertical hydraulic conductivities throughout the model domain.

The hydraulic-conductivity values specified for the model include that of the Corcoran Clay (K_{corc}) and of the coarse-grained (K_{coarse}) and fine-grained (K_{fine}) lithologic end members of the remaining materials. In the modeled area, the remaining materials were divided into two lithologic subareas during model calibration: the eastern alluvial fans upslope of the Modesto Formation (fig. 4.3) and everywhere else. Horizontal hydraulic conductivity (K_h) was calculated for each cell in these subareas using the arithmetic mean:

$$K_h = K_{coarse} \times F_{coarse} + K_{fine} \times F_{fine} \qquad \text{(eq. 4.1)}$$

where F_{coarse} is the fraction of coarse-grained sediment in a cell, and F_{fine} is the fraction of fine-grained sediment in a cell.

Vertical hydraulic conductivity between model layers (K_v) either was set to K_{corc}, if the Corcoran Clay was present within one of the layers, or was calculated using the geometric mean:

$$K_v = K_{coarse}^{F_{coarsev}} \times K_{fine}^{F_{finev}} \qquad \text{(eq. 4.2)}$$

where $F_{coarsev}$ is the fraction of coarse-grained sediment between layer midpoints, and F_{finev} is the fraction of fine-grained sediment between layer midpoints.

The calibrated value (see next section) of K_{corc} was 4 X 10^{-3} m/d and that for K_{fine} was 4 X 10^{-4} m/d. The calibrated value of K_{coarse} varied by lithologic subarea: 24 m/d for the older fan deposits and 235 m/d for the remaining area. The resulting values of K_h and K_v are summarized in figure 4.13. The distributions of K_h and K_v are the same as those for the sediment texture for the appropriate depth intervals (for example, the distribution of K_h in layer 4 is shown in figure 4.7).

Model Calibration and Sensitivity

Model calibration consisted primarily of a systematic application of the parameter estimation method. K_{coarse} and K_{fine} were varied systematically for a given value of K_{corc}, which was adjusted to roughly match vertical gradients across the Corcoran Clay. Model-computed hydraulic heads were compared to measured water levels in 51 wells representing various parts of the aquifer system. The resulting error distributions constrained the parameter set.

Model-computed and measured hydraulic heads were compared in four areas within the model. The low-lying area where the water table is shallow was represented by 17 wells. The intermediate-depth zone between the water table and the Corcoran clay and the deep zone below the Corcoran were represented by six wells each. The area east of the extent of the Corcoran was represented by 22 wells.

Two statistics were used to quantify model error:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(h_{meas} - h_{sim})_i^2}{n}} \qquad \text{(eq. 4.3)}$$

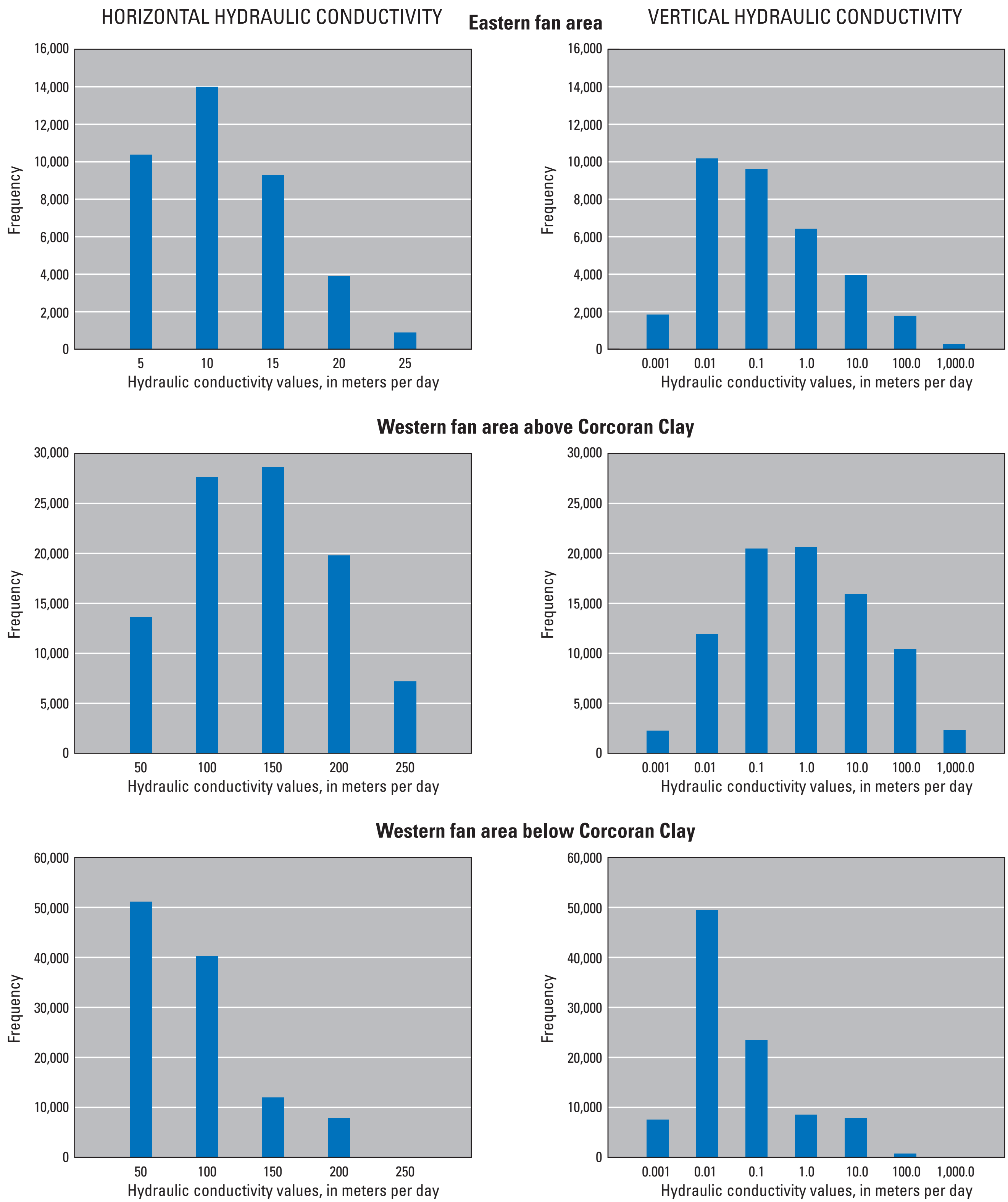


Figure 4. 13. Frequency of estimated horizontal hydraulic conductivity (Kh) and estimated vertical hydraulic conductivity (Kv) for the eastern and western alluvial fans, San Joaquin Valley regional study area, California.

$$BIAS = \sum_{i=1}^{n} (h_{meas} - h_{sim})i \qquad \text{(eq. 4.4)}$$

where *RMSE* is root-mean-square error, h_{meas} is measured hydraulic head, h_{sim} is model-computed hydraulic head, $(h_{meas} - h_{sim})$ is the head residual, i is the summation index, n is the number of measurements, and *BIAS* is the sum of the residuals. The *RMSE* is a measure of error magnitude, and *BIAS* indicates whether model-computed hydraulic heads were higher or lower than measured hydraulic heads.

Model-computed and measured vertical hydraulic gradients also were compared during model calibration. Measured gradients were calculated using water levels from nearby wells screened at different depths in three areas within the model: from the water table to the intermediate-depth zone above the Corcoran (three well pairs), across the Corcoran (three well pairs), and the area east of the Corcoran extent (five well pairs). *RMSE* and *BIAS* were calculated for vertical gradients in the same way as for hydraulic head by replacing the simulated and measured heads in equations 4.3 and 4.4 with the model-computed and measured vertical hydraulic gradients (change in model-computed or measured hydraulic head divided by the vertical distance between the midpoints of model layers or screened intervals, respectively).

The *RMSE* and *BIAS* calculations were used to estimate the values of K_{coarse} and K_{fine} that generated the best-fit parameter distribution for the conceptual model described herein. *RMSE* and *BIAS* values were calculated for 100 simulations representing K_{coarse} values ranging from 60 to 300 m/d and K_{fine} values ranging from 3 X 10^{-4} to 1 m/d. Results from the 100 simulations were plotted as error surfaces describing model fit with respect to hydraulic heads and gradients for various parts of the aquifer system (fig. 4.14). Each plot in figure 4.14 shows contoured *RMSE* and *BIAS* for hydraulic heads and vertical gradients in a specific part of the aquifer system. Lines of minimum *RMSE* and *BIAS* were drawn where possible. Note the model is numerically stable over a wide range of parameter values, but numerical stability decreased with lower values of K_{coarse} and K_{fine}. Pervasive numerical instability was assumed an indication that such parameter combinations are unlikely to be representative of this aquifer system.

The *RMSE* and *BIAS* values shown in figure 4.14, considered as a whole, constrain K_{coarse} and K_{fine} to the lower left-hand region of the plot and indicate relatively high values of K_{coarse} and low values of K_{fine} provide the best model fit for the given conceptual model. The fact that most of the plots do not contain lines of minimum *RMSE* and zero *BIAS*, and that these lines are not coincident where they do coexist, indicates there is some degree of error in the conceptual model and (or) the calibration criteria. Future modeling efforts can focus on reducing these errors, but current results indicate that K_{coarse} and K_{fine} values of about 235 and 4 X 10^{-4} m/d, respectively, generate the best-fit parameter distribution (K_{corc} was 4 X 10^{-3} m/d).

A hydraulic conductivity of 235 m/d is within the typical range for well-sorted gravel, and a hydraulic conductivity of 4 X 10^{-4} m/d is indicative of clay (Fetter, 1994). Both lithologies are common in the study area and represent the lithologic end members. Permeameter tests of cores from the Corcoran Clay indicate vertical hydraulic conductivities ranging from 1 X 10^{-6} to 3 X 10^{-6} m/d (Page, 1977). Previous investigations, however, indicate wells screened across the Corcoran Clay provide direct vertical connection between the unconfined and confined aquifers and have increased the vertical hydraulic conductivity by orders of magnitude (Williamson and others, 1989; Belitz and Phillips, 1995), which is consistent with the calibrated value of K_{corc} from this study.

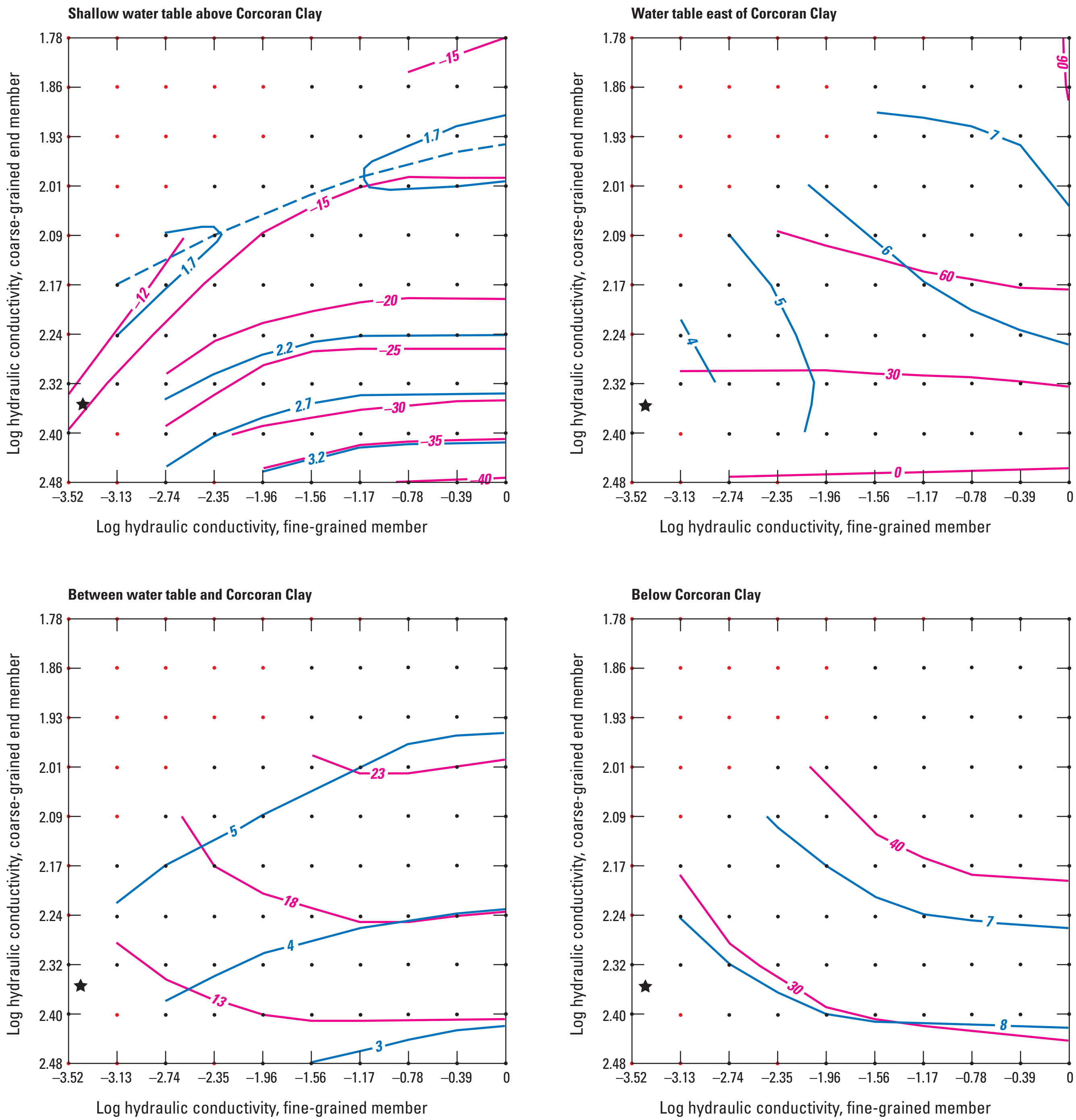
Model-Computed Hydraulic Heads

The simulated water table closely resembles that depicted in figure 4.5. In the area overlying the Corcoran Clay, model-computed hydraulic heads in the area with a shallow water table closely match measured heads with an average residual of 0.92 m and *RMSE* of 1.9 m (fig. 4.15). Water levels in wells east of the Corcoran Clay extent that represent the unconfined aquifer also are simulated reasonably well with an average residual of -1.5 m and *RMSE* of 3.6 m, although there is an apparent increase in residuals with increasing measured hydraulic head for the unconfined aquifer east of the Corcoran Clay extent (fig. 4.16). In general, the residuals are randomly distributed around zero for the entire modeled area (fig. 4.16).

A simple method of assessing overall model fit is to plot the model-computed hydraulic head values against the measured observations. For a perfect fit, all points should fall on the 1:1 diagonal line. Figure 4.17 presents a plot of the model-computed heads as compared to measured hydraulic heads for the San Joaquin Valley regional study area and indicates reasonable model fit. The average residual for the entire model is -0.9 m with a standard deviation of 3.67 m, and residuals range from -10.5 m to 6.0 m (range of 16.5 m). The RMSE for the entire model is 3.75 m, which is about 10 percent of the range of head observations in the model (37.7 m).

Measured hydraulic heads in the Modesto area include those in four clusters of piezometers installed for this study (Phillips and others, 2007). The piezometers that represent the water table range in depth from 11 to 14 m, and the deepest piezometer in each cluster ranges from 102 to 108 m deep. The shallow and deep water levels were closely simulated, with an average error of 0.78 m and 0.35 m, respectively. Consequently, the downward vertical gradient, which features an average head difference of 4.4 m, also was simulated well.

Model-computed hydraulic heads between the water table and the Corcoran Clay were greater than the measured heads by an average of 1.8 m. Coupled with the generally low simulated water table, simulated downward gradients above the Corcoran are, on average, too low. Model-computed heads below the Corcoran were generally greater than measured



EXPLANATION

—1.7— Line of equal root mean square error between model-computed and measured heads

— — Line of minimum root mean square error between model-computed and measured head

—–15— Line of equal bias between model-computed and measured heads

• Parameter combinations simulated and for which error was calculated

• Parameter combinations for which model was numerically unstable

★ Calibrated end-member hydraulic conductivities

Figure 4. 14. Ground-water flow model calibration results, San Joaquin Valley regional study area, California. (Continued on next page.)

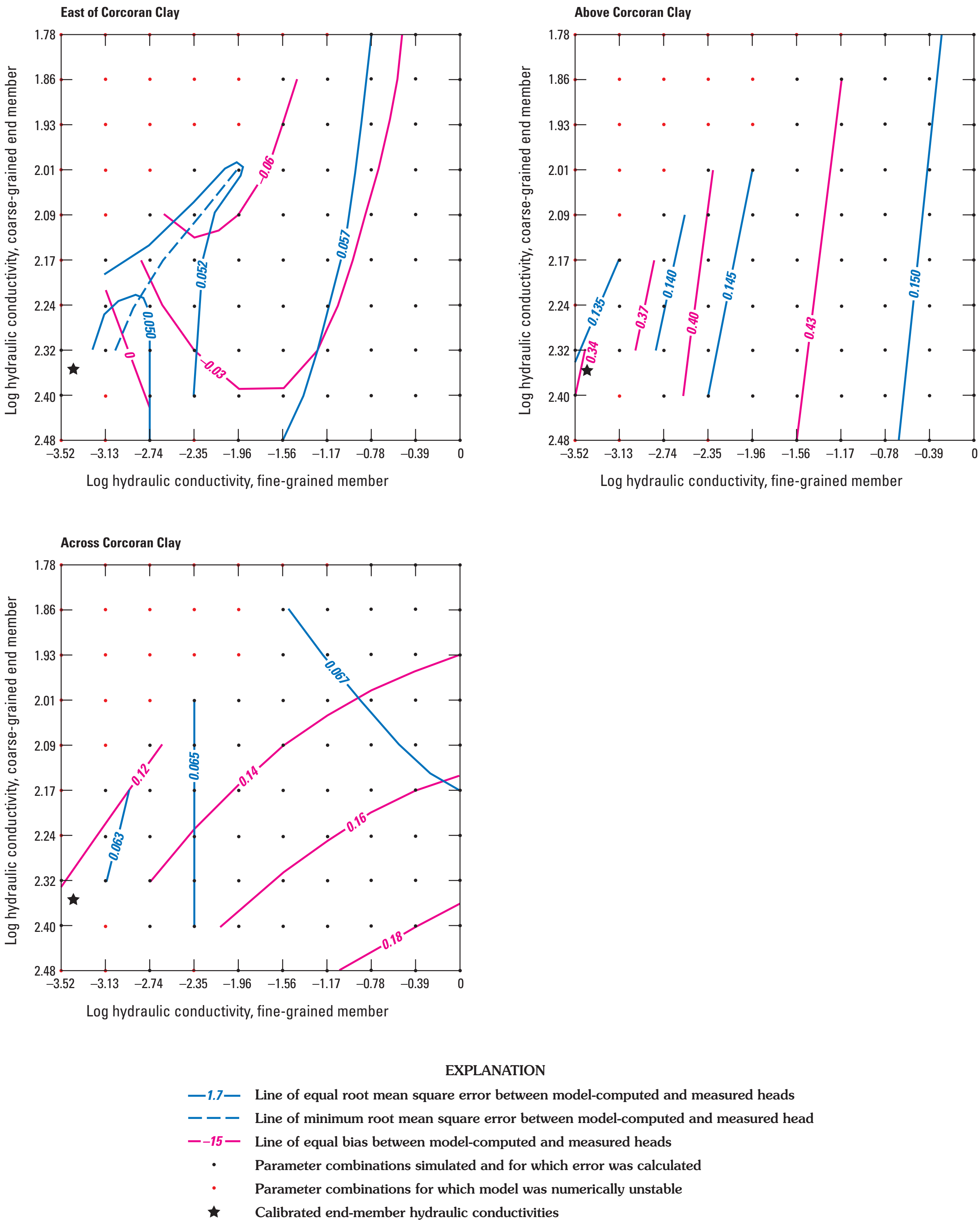
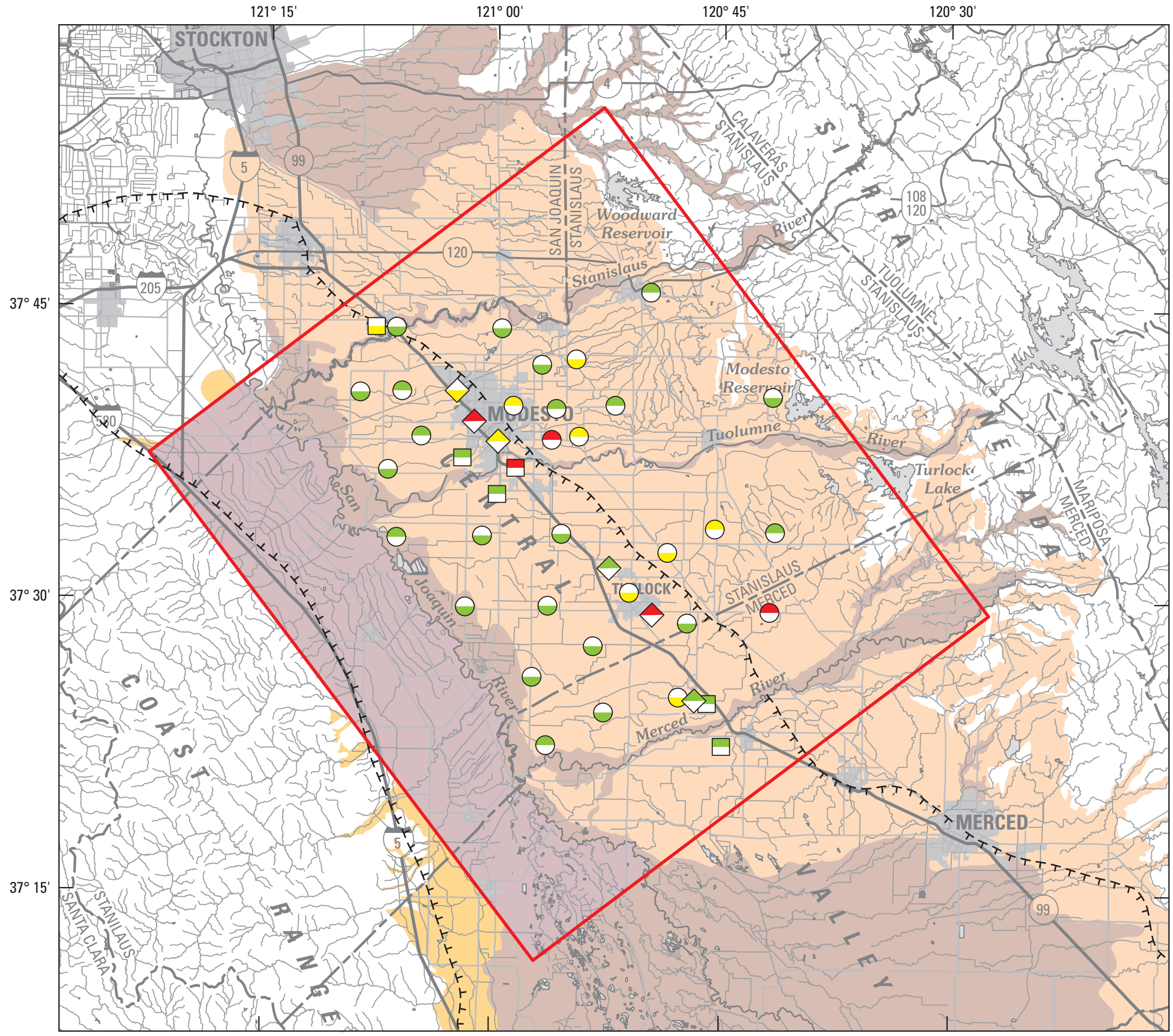


Figure 4. 14. Ground-water flow model calibration results, San Joaquin Valley regional study area, California.—Continued



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30' North and 45° 30' North, central meridian 120° West,
North American Datum of 1983

0 10 20 30 40 KILOMETERS

0 10 20 MILES

EXPLANATION

Physiographic region

- Basin
- Eastern alluvial fans
- Western alluvial fans
- **Urban**
- **Inactive model cells**
- **Extent of model grid**
- **Extent of Corcoran Clay**—Hachures point toward clay

Model-computed as compared to measured hydraulic heads

Location

- Water table
- Between water table and Corcoran Clay
- Below Corcoran Clay

Model-computed residuals—Difference between model-computed and measured head

- Less than 3 meters
- 3 to 6 meters
- 6.1 to 10.5 meters

Relative difference

- Model-computed head greater than measured water level
- Model-computed head lower than measured water level

Figure 4. 15. Spatial distribution of hydraulic-head residuals, San Joaquin Valley regional study area, California.

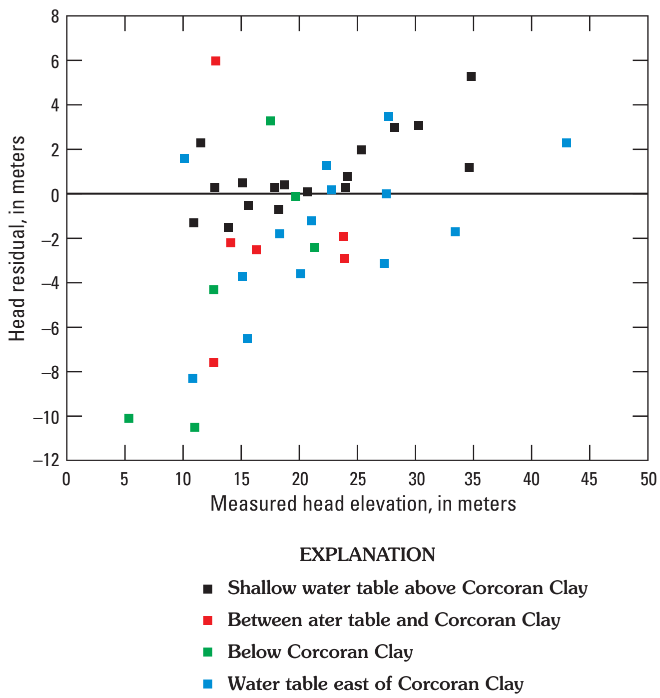


Figure 4. 16. Relation between head residual and measured hydraulic head, San Joaquin Valley regional study area, California.

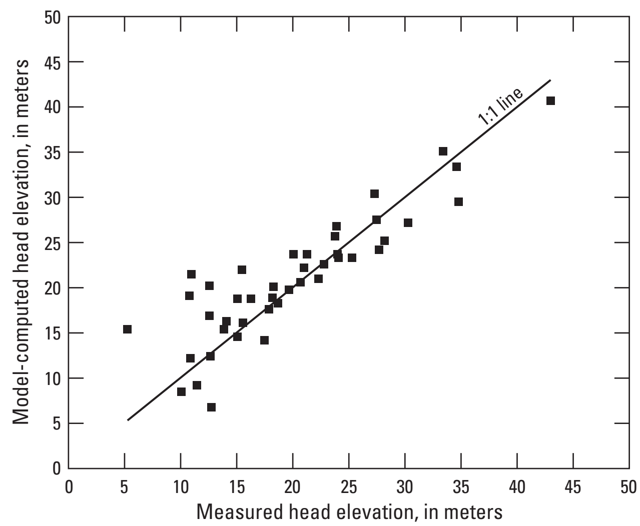


Figure 4. 17. Relation between model-computed and measured hydraulic head, San Joaquin Valley regional study area, California.

heads by an average of 4 m, but the gradient across the Corcoran is simulated reasonably well in the four locations where measurements were available.

Model-Computed Water Budget

Many of the water-budget components simulated by the model were specified values. Areal recharge, which was dominated by agricultural irrigation and precipitation, accounted for about 71 percent of the total recharge (table 4.2). Leakage from reservoirs contributed about 4 percent of the water, and net inflow (inflow minus outflow) from rivers also contributed about 4 percent of the water. Pumping from wells, primarily for agricultural purposes, accounted for about 54 percent of the total discharge. About 12 percent of the discharge was bare-soil evaporation from the shallow water table. The remainder of the model-computed water budget was flow through the lateral head-dependent boundaries, which was a net outflow of about 13 percent. Details of the simulated water budget are listed in table 4.2.

Simulation of Areas Contributing Recharge to Public-Supply Wells

The ground-water flow model was used to simulate capture zones for 60 public-supply wells to aid understanding of the flow system and to elucidate connections between land use and the chemistry of water discharging from public-supply wells. Water extracted from these wells followed various pathways through the aquifer system and is an amalgamation of water that may vary widely in age and origin. Particle tracking was used to approximate the pathway of water particles, associated ages, and points where these particles first entered the aquifer, hereinafter referred to collectively as "the contributing area." The various land uses overlying the contributing area may be associated with different chemical inputs to the aquifer, which may ultimately reach the public-supply well.

Particle-Tracking Simulations

Sixty public-supply wells with a range of pumping rates were selected for particle-tracking analysis. Pumping rates for 109 wells that supplied the city of Modesto during water-year 2000 were available, and 15 wells from each quartile of pumping rate were selected for particle-tracking analysis. The pumping rates ranged from 131 to 13,381 m^3/d, and the total water extracted from the 60 wells represents about 60 percent of the 57 million cubic meters the city pumped during water-year 2000.

Particle-tracking software, MODPATH (Pollock, 1994), was used in conjunction with flux output from the flow model to calculate flow paths and traveltimes for water particles traveling from the contributing area, through the aquifer system, and to the wells. The model-computed areas contrib-

Table 4.2. Model-computed water budget for water-year 2000, San Joaquin Valley regional study area, California.

[m^3/d, cubic meters per day; —, not applicable]

Water-budget component	Specified flow (m^3/d)	Computed flow (m^3/d)	Total flow (m^3/d)	Percentage of inflow or outflow
Model inflow				
Agricultural irrigation return flow	2,267,000	—	2,267,000	41.5
Precipitation	1,598,000	—	1,598,000	29.3
Rivers	500,000	25,000	525,000	9.6
Reservoir leakage	—	207,000	207,000	3.8
Pipe leakage, urban	11,000	—	11,000	0.2
Flow through lateral boundaries				
Northwest	—	102,000	102,000	1.9
Southeast	—	162,000	162,000	3.0
Southwest	—	584,000	584,000	10.7
TOTAL INFLOW			**5,456,000**	**100**
Model outflow				
Wells				
Agricultural	2,732,000	—	2,732,000	
Public supply	274,000	—	274,000	
Total (smaller due to dry cells in upper part of some well screens)	2,955,000	—	2,955,000	54.2
Evaporation from shallow water table	—	651,000	651,000	11.9
Rivers	—	310,000	310,000	5.7
Flow through lateral boundaries				
Northwest	—	952,000	952,000	17.5
Southeast	—	103,000	103,000	1.9
Southwest	—	480,000	480,000	8.8
TOTAL OUTFLOW			**5,452,000**	**100**

uting recharge represent advective ground-water flow and do not account for mechanical dispersion. Advection-dispersion transport simulations would likely yield larger areas contributing recharge than advective particle-tracking simulations because the effects of dispersion caused by aquifer heterogeneity would be included.

Effective porosity was the only hydraulic parameter entered into the MODPATH input files. Effective porosity values were assigned on the basis of percentage of coarse-grained texture in each model cell (table 4.3). The porosity values are based on literature values for different geologic/textural materials (Domenico and Schwartz, 1990) and previous work in similar geologic formations in the eastern San Joaquin Valley (Burow and others, 1999).

Table 4.3. Effective porosity values, by percentage of coarse-grained texture, used for MODPATH simulations, San Joaquin Valley regional study area, California.

[>, greater than; <=, less than or equal to]

Textural material	Percentage coarse material	Effective porosity
Gravel	> 75	0.25
Coarse sand	51–75	0.28
Fine sand	26–50	0.32
Silt and clay	<= 25	0.35

Public-Supply Well Contributing Areas

Fifteen wells in each quartile of pumping in the Modesto area were selected to delineate areas contributing recharge and compute traveltimes. The resulting contributing areas for the 15 wells in the top quartile pumping rate (fig. 4.18) tend to overlap and generally extend to the northeast of Modesto beyond the extent of the Corcoran Clay. The size of the contributing areas generally is a function of the pumping rate, whereas the shape is influenced by geologic setting and well-construction characteristics. The ground-water flow model incorporates the spatial interpolation model of percentage of coarse-grained texture; therefore, the contributing areas reflect, to a degree, the heterogeneous deposits that are characteristic of these dominantly fluvial sediments. This approach results in uniquely shaped contributing areas that generally do not resemble the tear-shaped areas one would expect in a more homogeneous setting.

Differing well characteristics also account for variability in contributing areas. Shallow wells, which tend to have lower production rates, generally have small contributing areas close to the wells. Traveltimes to shallow wells are relatively short. The larger contributing areas and longer flow paths (and traveltimes) are associated with higher producing wells. These high-producing wells tend to have the longest screened intervals and are relatively deep. Consequently, the contributing areas from these wells commonly have two components: a local area, which may be offset from the well, that represents the source of water flowing to the upper portion of the screened interval; and a distant area that represents the source of water flowing to the lower portion of the screened interval. For example, Well 51 in the northwest part of Modesto has a contributing recharge area immediately east of the well that contributes to the upper portion of the screened interval and a small contributing recharge area more than 6 km to the northeast that contributes to the lower portion of the screened interval.

The minimum traveltime from the water table to the well for all 60 wells ranges from 3 to 141 years with a median of about 20 years. The maximum traveltime ranges from 18 years to more than 1,600 years with a median of 107 years. The zones of contribution outlined by pathlines for the 60 public-supply wells occupy more than 143 km^2 within the modeled area. Agricultural and urban land uses dominate in most of the area contributing recharge to public-supply wells.

Limitations and Appropriate Use of the Model

The ground-water flow model for the San Joaquin Valley regional study area was designed to estimate aquifer-system properties, to delineate contributing areas to public-supply wells in Modesto, to help guide data collection, and to support future local modeling efforts. Limitations of the ground-water flow model, assumptions made during model development, and results of model calibration and sensitivity analysis all are factors that constrain the appropriate use of the model and highlight potential future improvements.

A ground-water flow model is a means for portraying and testing a conceptual understanding of a system. Because ground-water flow systems are inherently complex, simplifying assumptions were made in developing this model (Anderson and Woessner, 1992). Models solve for average conditions within each cell, the parameters for which are interpolated or extrapolated from measurements and(or) estimated during calibration. In light of this, the intent in developing the ground-water flow model was not to reproduce every detail of the natural system, but rather to portray its general characteristics.

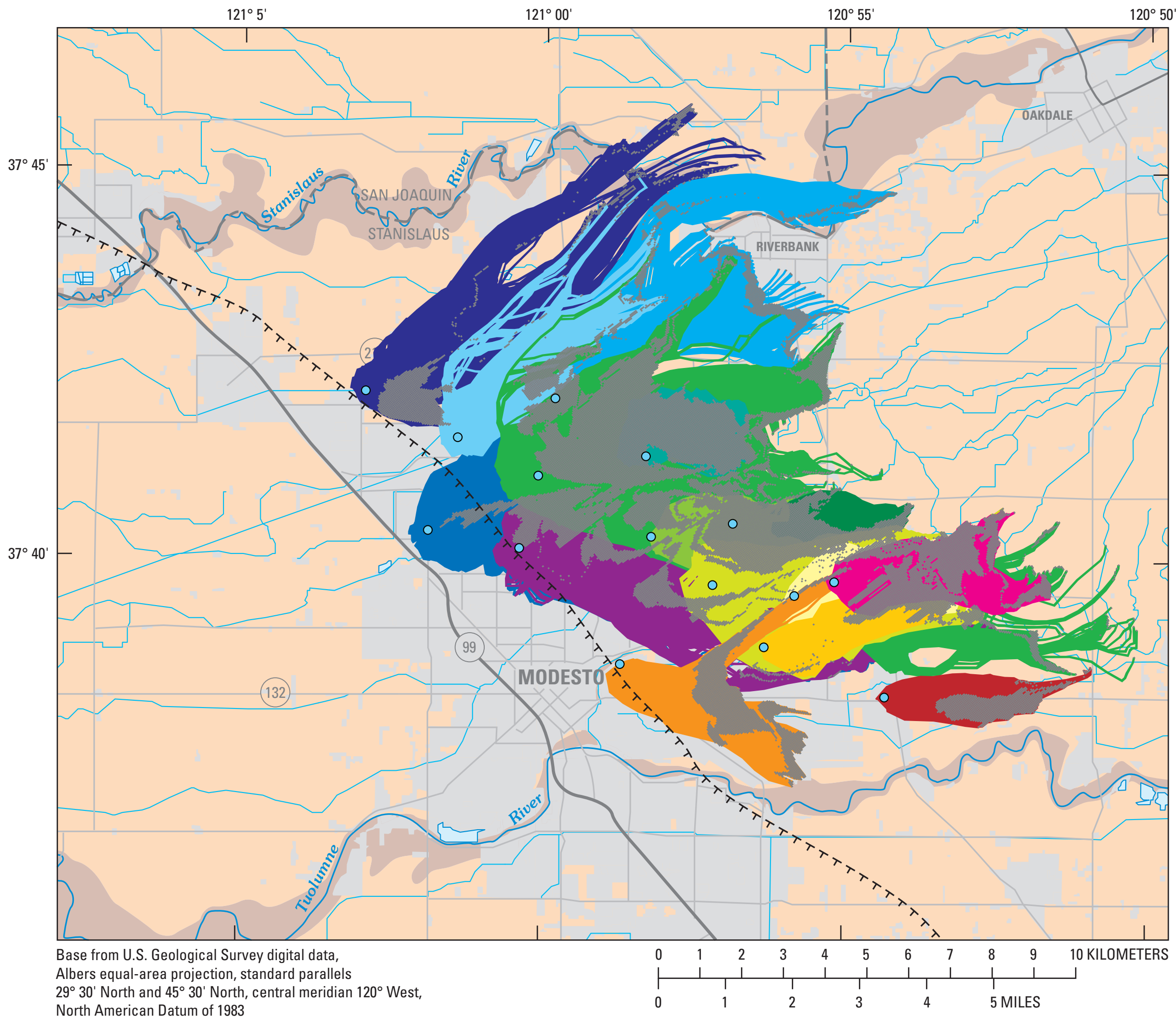
Water-level hydrographs indicate the ground-water system in the study area approximated steady-state equilibrium for water-year 2000 (fig. 4.6); however, the data are not conclusive. Long-term hydrographs are not available for some areas, including the southeastern part of the model area, where hydraulic heads may have been changing with time. Errors related to this assumption can be substantial, and care must be taken in interpreting model results and analyses that depend on model output, including particle tracking.

Some of the boundary conditions of the model are poorly constrained, which may be a source of model error. The lateral boundary along the San Joaquin River is based on sparse data, and the spatial distribution of hydraulic head below the river is poorly understood. Similarly, there is little information on river/aquifer interaction in the study area, and none regarding the hydraulic conductivity of riverbed sediments. Simulation results indicate that fluxes across these poorly constrained boundaries (table 4.2) make up a small part of the water budget; however, these boundaries may be more important in the real system.

The accuracy of model results is related strongly to the quality and spatial distribution of input data, and of measurements of system state (for example, measured hydraulic heads) for comparison with simulation results during model calibration. The Modesto area is the only region of the ground-water flow model that has high-quality input data (particularly pumping by well) coupled with a good distribution of measured hydraulic heads. The stresses in other areas of the model are a combination of measured values and those estimated from the water-budget analysis. Accordingly, the user should have higher confidence in simulation results in the Modesto area than in other areas of the model.

The interpolation of sediment texture data within model layers, or two dimensions, may artificially decrease the vertical connectivity of coarse-grained materials in the aquifer system. This potential shortcoming in the parameter-estimation procedure used for the ground-water flow model may affect simulated particle pathways and associated analyses. Applying a three-dimensional interpolation method may provide a significant improvement over the current parameter distribution.

Computed areas contributing recharge and traveltimes through zones of contribution are based on a calibrated model



EXPLANATION

Physiographic region

- Basin
- Eastern alluvial fans

Urban

Extent of Corcoran Clay—Hachures point to clay

Area contributing recharge to public-supply wells

Pathlines outlining zones of contribution to public-supply wells

Well 285	Well 32	Well 43
Well 45	Well 37	Well 48
Well 211	Well 25	Well 33
Well 47	Well 46	Well 51
Well 41	Well 39	Well 16

Wells selected for contributing-area analysis

Figure 4. 18. Model-computed areas contributing recharge for 15 public-supply wells in top quartile of pumping, San Joaquin Valley regional study area, California.

and estimated effective porosity values. In a steady-state model, changes to input porosity values do not change the area contributing recharge to a given well. Changes to input porosity values will change computed traveltimes from recharge to discharge areas in direct proportion to changes of porosity because there is an inverse linear relation between ground-water flow velocity and effective porosity and a direct linear relation between traveltime and effective porosity. For example, a one-percent decrease in porosity will result in a one-percent increase in velocity and a one-percent decrease in particle traveltime. A detailed sensitivity analysis of porosity distributions was beyond the scope of this study, although future work could compare simulated ground-water traveltimes to ground-water ages to more thoroughly evaluate effective porosity values.

The San Joaquin Valley regional ground-water flow model uses justifiable aquifer properties and boundary conditions and provides a reasonable representation of ground-water flow conditions in the study area for the year 2000. The model is suitable for evaluating regional water budgets and ground-water flow paths in the study area for the time period of interest but may not be suitable for long-term predictive simulations. This regional model provides a useful tool to evaluate aquifer vulnerability at a regional scale, to facilitate comparisons of ground-water traveltime between regional aquifer systems, and to guide future detailed investigations in the study area.

References Cited

Anderson, M.P. and Woessner, W.W., 1992, Applied ground-water modeling—Simulation of flow and advective transport: San Diego, California, Academic Press, Inc., 381 p.

Arkley, R.J., 1962, Soil survey of Merced area, California: U.S. Department of Agriculture, Soil Conservation Service, Soil Survey series 1950, no. 7, 131 p., 101 pls.

Arkley, R.J., 1964, Soil survey, eastern Stanislaus area, California: U.S. Department of Agriculture, Soil Conservation Service, Soil Survey series 1957, no. 20, 160 p.

Bartow, J.A., 1991, The Cenozoic evolution of the San Joaquin Valley, California: U.S. Geological Survey Professional Paper 1501, 40 p.

Belitz, Kenneth, and Phillips, S.P., 1995, Alternative to agricultural drains in California's San Joaquin Valley—Results of a regional-scale hydrogeologic approach: Water Resources Research, v. 31, no. 8, p. 1845–1862.

Bertoldi, G.L., Johnston, R.H., and Evenson, K.D., 1991, Ground water in the Central Valley, California—A summary report: U.S. Geological Survey Professional Paper 1401–A, 44 p.

Burow, K.R., Panshin, S.Y., Dubrovsky, N.M., VanBrocklin, David, and Fogg, G.E., 1999, Evaluation of processes affecting 1,2-dibromo-3-chloropropane (DBCP) concentrations in ground water in the eastern San Joaquin Valley, California, analysis of chemical data and ground-water flow and transport simulations: U.S. Geological Survey Water-Resources Investigations Report 99–4059, 57 p.

Burow, K.R., Shelton, J.L., Hevesi, J.A., and Weissmann, G.S., 2004, Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2004–5232, 54p.

California Department of Water Resources, 1994, Urban water use in California: California Department of Water Resources, Bulletin 166–4, 48 p. plus appendixes.

Davis, G.H., Green, J.H., Olmsted, F.H., and Brown, D.W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1469, 287 p.

Davis, S.N. and Hall, F.R., 1959, Water quality of eastern Stanislaus and northern Merced counties, California: Palo Alto, California, Stanford University Publications, Geological Sciences, v. 6, no. 1, 112 p.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, 824 p.

Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 96–364, 51 p.

Fetter, C.W., 1994, Applied hydrogeology: New York, Macmillan College Publishing Company, 691 p.

Gronberg, J.M., Dubrovsky, N.M., Kratzer, C.K., Domagalski, J.L., Brown, L.R., and Burow, K.R., 1998, Environmental setting of the San Joaquin-Tulare Basins, California: U.S. Geological Survey Water-Resources Investigations Report 97–4205, 45 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Laudon, Julie, and Belitz, Kenneth, 1991, Texture and depositional history of late Pleistocene-Holocene alluvium in the central part of the western San Joaquin Valley, California: Bulletin of the Association of Engineering Geologists, v. 28, no. 1, p. 73–88.

Londquist, C.J., 1981, Digital model of the unconsolidated aquifer system in the Modesto Area, Stanislaus and San Joaquin counties, California: U.S. Geological Survey Water-Resources Investigations Report 81–12, 36 p.

Marchand, D.E., and Allwardt, A., 1981, Late Cenozoic stratigraphic units, San Joaquin-Tulare Basins, California: U.S. Geological Survey Bulletin 1470, 70 p.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 47 p.

National Oceanic and Atmospheric Administration, 2005, Precipitation records for California, Web page accessed Nov. 14, 2005, at *http://lwf.ncdc.noaa.gov/oa/pub/data/coop-precip/california.txt*.

Page, R.W., 1973, Base of fresh ground water (approximately 3,000 micromhos) in the San Joaquin Valley, California: U.S. Geological Survey Hydrologic Investigations Atlas HA–489.

Page, R.W., 1977, Guide for data collection to calibrate a predictive digital ground-water model of the unconfined aquifer in and near the city of Modesto, California: U.S. Geological Survey Water-Resources Investigations Report 76–41, 46 p.

Page, R.W., 1986, Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections: U.S. Geological Survey Professional Paper 1401–C, 54 p.

Page, R.W., and Balding, G.O., 1973, Geology and quality of water in the Modesto-Merced area, San Joaquin Valley, California: U.S. Geological Survey Water-Resources Investigations Report 73–6, 85 p.

Phillips, S.P., Beard, Sherrill, and Gilliom, R.J., 1991, Quantity and quality of ground-water inflow to the San Joaquin River, California: U.S. Geological Survey Water-Resources Investigations Report 91–4019, 64 p.

Phillips, S.P. and Belitz, Kenneth, 1991, Calibration of a texture-based model of a ground-water flow system, western San Joaquin Valley, California: Ground Water, v. 29, no. 5, p. 702-715.

Phillips, S.P., Green, C.T., Burow, K.R., Shelton, J.L., and Rewis, D.L., 2007, Simulation of multiscale ground-water flow in part of the northeastern San Joaquin Valley, California: US Geological Survey Scientific Investigations Report 2007–5009, 43 p.

Piper, A.M., Gale, H.S., Thomas, H.E., and Robinson, T.W., 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geological Survey Water-Supply Paper 780, 230 p.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, accessed Feb. 6, 2007 at *http://water.usgs.gov/nrp/gwsoftware/modpath41/modpath41.html*

U.S. Census Bureau, 2002, State and county quickfacts, for 1990 and 2000: Web page accessed April 26, 2002, at *http://quickfacts.census.gov/qfd/states/06/06099lk.html*.

Williamson, A.K., Prudic, D.E., and Swain, L.A., 1989, Ground-water flow in the Central Valley, California: U.S. Geological Survey Professional Paper 1401–D, 127 p.