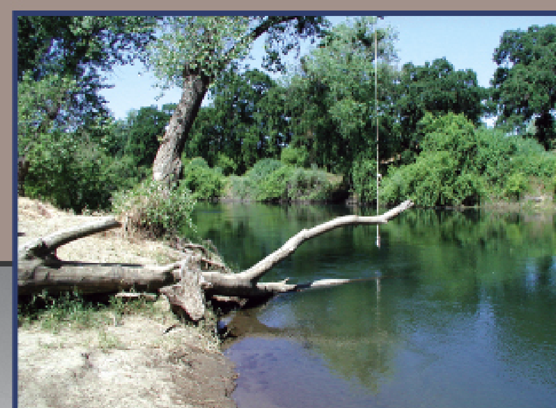
In cooperation with the Modesto Irrigation District

Hydrogeologic Characterization of the Modesto Area, San Joaquin Valley, California



Scientific Investigations Report 2004-5232

U.S. Department of the Interior
U.S. Geological Survey

Hydrogeologic Characterization of the Modesto Area, San Joaquin Valley, California

By Karen R. Burow, Jennifer L. Shelton, Joseph A. Hevesi, and
Gary S. Weissmann

Prepared in cooperation with the Modesto Irrigation District

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U.S. Department of the Interior
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Conversion Factors, Vertical Datum, Abbreviations and Acronyms, and Well-Numbering System

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)
gallon per minute (gal/min)	0.00379	cubic meter per minute (m^3/min)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
square foot per minute (ft^2/min)	0.0934	square meter per minute (m^2/min)
	Hydraulic conductivity	
foot per day (ft/day)	0.3048	meter per day (m/day)
	Transmissivity*	
foot squared per day (ft^2/day)	0.09290	meter squared per day (m^2/day)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^2)	0.0008107	acre-foot (acre-ft)
	Flow rate	
meter per year (m/yr)	3.281	foot per year ft/yr)
liter per second (L/s)	15.85	gallon per minute (gal/min)
	Specific capacity	
liter per second per meter [(L/s)/m]	4.831	gallon per minute per foot [(gal/min)/ft]
square meter per minute (m^2/min)	10.71	gallon per minute (gal/min)
	Hydraulic conductivity	
meter per day (m/day)	3.281	foot per day (ft/day)
	Transmissivity*	
meter squared per day (m^2/day)	10.76	foot squared per day (ft^2/day)

Spatial Datums

Vertical coordinate information is referenced to National Geodetic Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/day)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/day), is used for convenience.

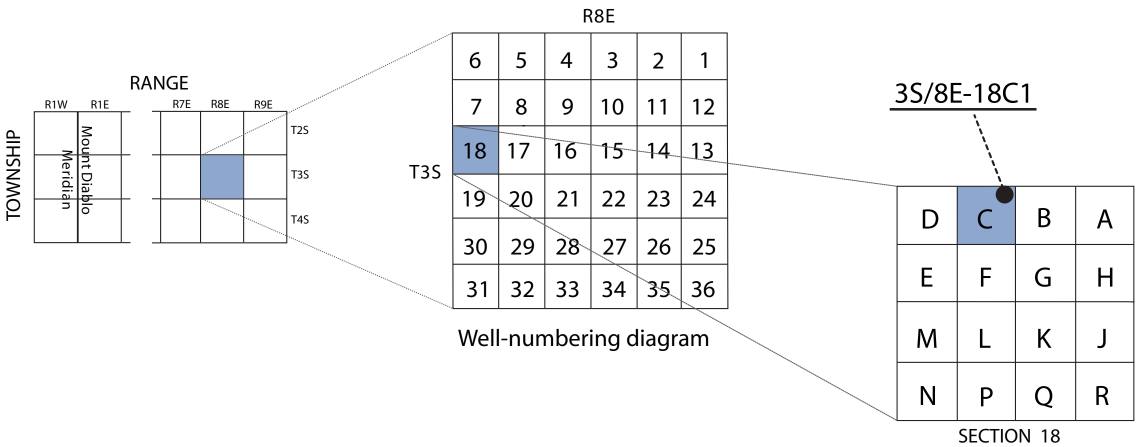
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Abbreviations and Acronyms

DWR	California Department of Water Resources
EWD	Eastside Water District
ETc	daily crop demand
ETo	daily normal evapotranspiration
FOOT	foothills
Kc	daily crop coefficients
MER	Merced Irrigation District (commonly referred to as MID)
MID	Modesto Irrigation District
NAWQA	National Water-Quality Assessment program
OID	Oakdale Irrigation District
RES	reservoir
RIP	riparian
SSJID	South San Joaquin Irrigation District
SWD	Stevinson Water District
TID	Turlock Irrigation District
URB	urban
USGS	U.S. Geological Survey
WY	water year

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is 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. Well numbers consist of 15 characters and follow the format 003S008E18C001. In this report, well numbers are abbreviated and written 3S/8E-18C1. The following diagram shows how the number for well 3S/8E-18C1 is derived.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as **“18C1”**)

Hydrogeologic Characterization of the Modesto Area, San Joaquin Valley, California

By Karen R. Burow, Jennifer L. Shelton, Joseph A. Hevesi, and Gary S. Weissmann

Abstract

Hydrogeologic characterization was done to develop an understanding of the hydrogeologic setting near Modesto by maximizing the use of existing data and building on previous work in the region. A substantial amount of new lithologic and hydrologic data are available that allow a more complete and updated characterization of the aquifer system. In this report, geologic units are described, a database of well characteristics and lithology is developed and used to update the regional stratigraphy, a water budget is estimated for water year 2000, a three-dimensional spatial correlation map of aquifer texture is created, and recommendations for future data collection are summarized.

The general physiography of the study area is reflected in the soils. The oldest soils, which have low permeability, exist in terrace deposits, in the interfan areas between the Stanislaus, Tuolumne, and Merced Rivers, at the distal end of the fans, and along the San Joaquin River floodplain. The youngest soils have high permeability and generally have been forming on the recently deposited alluvium along the major stream channels. Geologic materials exposed or penetrated by wells in the Modesto area range from pre-Cretaceous rocks to recent alluvium; however, water-bearing materials are mostly Late Tertiary and Quaternary in age.

A database containing information from more than 3,500 drillers' logs was constructed to organize information on well characteristics and subsurface lithology in the study area. The database was used in conjunction with a limited number of geophysical logs and county soil maps to define the stratigraphic framework of the study area. Sequences of red paleosols were identified in the database and used as stratigraphic boundaries. Associated with these paleosols are very coarse grained incised valley-fill deposits. Some geophysical well logs and other sparse well information suggest the presence of one of these incised valley-fill deposits along and adjacent to the Tuolumne River east of Modesto, a feature that may have important implications for ground-water flow and transport in the region.

Although extensive work has been done by earlier investigators to define the structure of the Modesto area aquifer system, this report has resulted in some modification to the lateral extent of the Corcoran Clay and the regional dip of the Mehrten Formation. Well logs in the database indicating the presence of the Corcoran Clay were used to revise the eastern extent of the Corcoran Clay, which lies approximately parallel to the axis of valley. The Mehrten Formation is distinguished in the well-log database by its characteristic black sands consisting of predominantly andesitic fragments. Black sands in wells listed in the database indicate that the formation may lie as shallow as 120 meters (400 feet) below land surface under Modesto, approximately 90 meters (300 feet) shallower than previously thought.

The alluvial aquifer system in the Modesto area comprises an unconfined to semiconfined aquifer above and east of the Corcoran Clay confining unit and a confined aquifer beneath the Corcoran Clay. The unconfined aquifer is composed of alluvial sediments of the Modesto, Riverbank, and upper Turlock Lake formations. The unconfined aquifer east of the Corcoran Clay becomes semiconfined with depth due to the numerous discontinuous clay lenses and extensive paleosols throughout the aquifer thickness. The confined aquifer is composed primarily of alluvial sediments of the Turlock Lake and upper Mehrten Formations, extending from beneath the Corcoran Clay to the base of fresh water.

Ground water in the unconfined to semiconfined aquifer flows to the west and southwest. The primary source of present-day recharge is percolating excess irrigation water. The primary ground-water discharge is extensive ground-water pumping in the unconfined to semiconfined aquifer, imposing a significant component of vertical flow in the system.

A water budget was calculated for water year 2000 using a land-use approach. During water year 2000, the total water supply in the Modesto area was more than 2.5 billion m^3 (cubic meter) (2 million acre-ft [acre-foot]). Surface-water deliveries accounted for 60 percent of the total water supply, whereas ground-water pumpage accounted for 40 percent. Ninety-four percent of the water supply was used to meet irrigation demand and approximately 6 percent was used to meet urban demand. The total recharge in the model area was estimated at 1.4 billion m^3 (1,100,000 acre-ft). The largest component of recharge is from excess irrigation water (58 percent); precipitation in excess of crop requirements accounted for 41 percent of the recharge.

Geostatistical methods were used to develop a spatial correlation model of the percentage of coarse-grained texture in the Modesto area. The mean percentage coarse-grained texture calculated for each depth increment indicates a regional trend of decreasing coarse-grained texture with increasing depth, which is consistent with increasingly consolidated sediments with depth in the study area. The three-dimensional kriged estimates of percentage coarse-grained texture show significant heterogeneity in the texture of the sedimentary deposits. Assuming the hydraulic conductivity is correlated to the texture, the kriged result implies significant heterogeneity in the hydrogeologic framework.

Introduction

Background

The population of California is expected to increase by another 17.7 million people, to a total of nearly 50 million people by 2025 (U.S. Census Bureau, 2002a, accessed April 26, 2002). Cities in the Central Valley, including the Modesto area (*fig. 1*), 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, 2002b, accessed April 26, 2002). Although more than 90 percent of the 1995 water demands in this region were for irrigation, the increasing population and periods of drought are expected to increase the reliance on ground water. Changes in land-use practices affect the dynamics of the ground-water and surface-water systems, often requiring the development of better tools to evaluate water-resources management strategies and ensure adequate water supplies.

Purpose and Scope

Many previous investigations have been done in the Modesto area; however, a significant amount of new data is available that allows for a more complete hydrogeologic characterization of the aquifer system. The objective of this study is to improve the understanding of the hydrogeologic framework of the aquifer system by using a combination of tools to evaluate existing data. The objective of this report is to present the results of the analysis of existing data within the context of previous investigations.

In this report, existing data are used to characterize the hydrogeology of the Modesto area. Previous investigations are summarized, a database of well characteristics and lithology is developed and used to update the regional stratigraphy, a water budget is estimated for water year 2000, and a three-dimensional spatial correlation map of sediment texture is developed. The water budget and the spatial distribution of aquifer texture are used in a regional ground-water flow model developed for ongoing investigations of the USGS (U.S. Geological Survey) National Water-Quality Assessment program (NAWQA) in the region. This study is a cooperative effort between the Modesto Irrigation District (MID) and the USGS.

The primary units used in this report are metric; however, both metric and English equivalents are given throughout this report because of the inconsistent units of the source data and on request of the cooperator.

Description of Study Area

The San Joaquin Valley occupies the southern two-thirds of the Central Valley of California (*fig. 1*), a large, northwest-trending, asymmetric structural trough filled with marine and continental sediments up to 10 km (6 mi) thick (Page, 1986; Gronberg and others, 1998). The San Joaquin Valley is a level depression more than 400 km (250 mi) long and 32 to 89 km (20 to 55 mi) wide. The area of the valley is about 26,000 km^2 (10,000 mi^2), excluding the rolling foothills that skirt the mountains (Davis and others, 1959). East of the valley, the Sierra Nevada rise to an elevation of more than 4,200 m (14,000 ft); west of the valley are the Coast Ranges, a series of parallel ridges of moderate elevations (Mendenhall and others, 1916). Streams in the northern part of the San Joaquin Valley drain through the San Joaquin River northward to the San Francisco Bay; the southern part of the valley is hydrologically closed. During predevelopment, ground water generally moved toward the center of the valley and northward to the San Francisco Bay; however, diversion of surface waters from streams and development of ground-water supplies significantly altered the natural flow system. Following development of the ground-water basin, percolating irrigation water became the primary form of ground-water recharge and irrigation pumpage became the primary form of ground-water discharge in the San Joaquin Valley (Davis and others, 1959).

The study area, which is about 2,300 km^2 (900 mi^2) in the northeastern San Joaquin Valley, is in an area commonly referred to as the Modesto and Turlock ground-water basins (California Department of Water Resources, 1980). The 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 consolidated rocks and deposits of the Sierra Nevada (*fig. 1*). The study area was defined to provide data at a scale that supports interpretation of the regional stratigraphic framework and to supplement the USGS NAWQA investigations of the sources, transport, and fate of agricultural chemicals, and the transport of contaminants to water-supply wells (Wilbur and Couch, 2002).

The hydrologic system in the Modesto area is complex, in part because of the heterogeneous nature of the hydrogeologic setting. The primary aquifers in the study area are a complex sequence of overlapping structures comprising sediments derived from the San Joaquin River and three major tributaries that drain the Sierra Nevada.

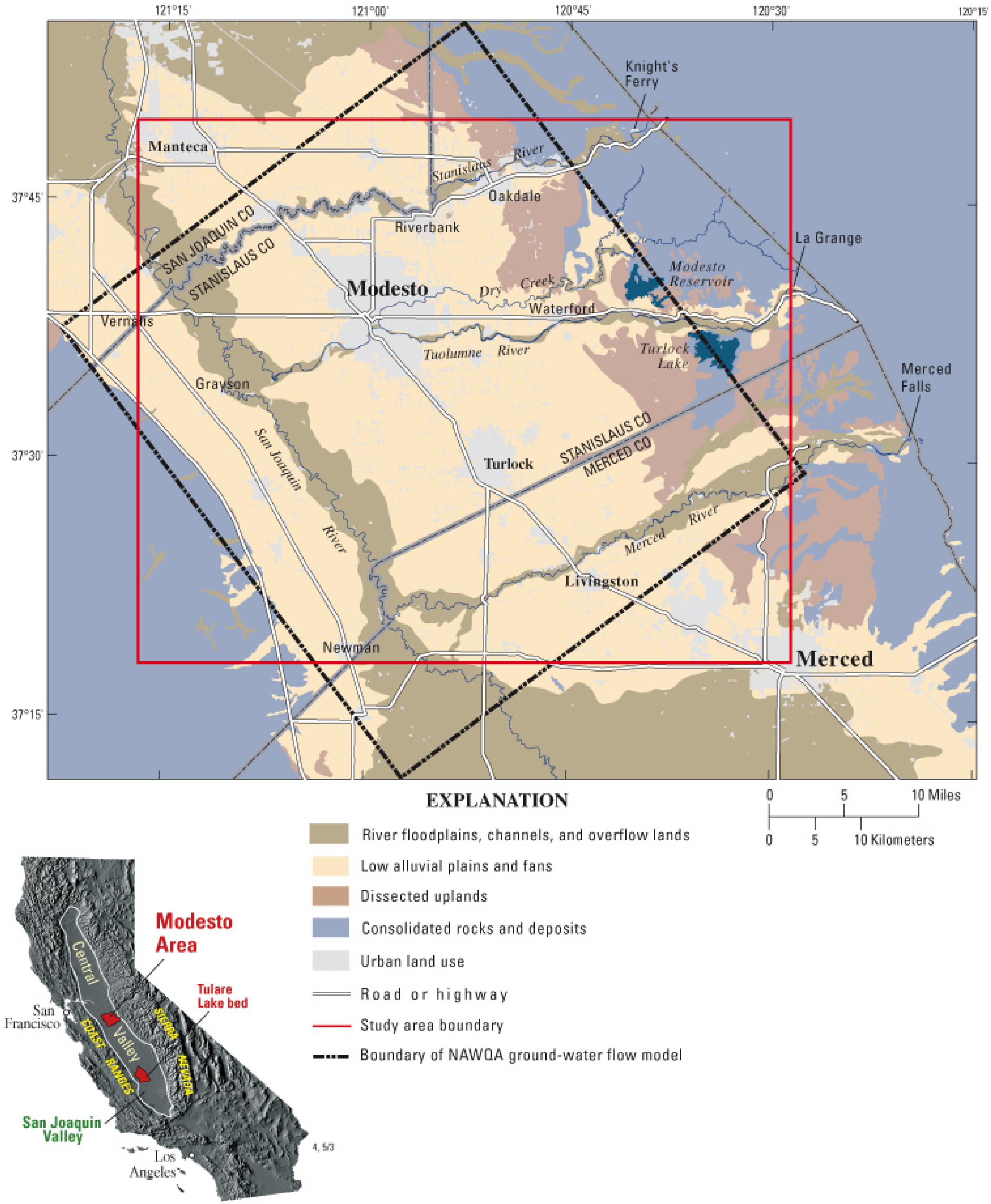


Figure 1. Study area near Modesto, San Joaquin Valley, California. Physiography approximated using defined geologic units from California Division of Mines and Geology, 1966. NAWQA, National Water-Quality Assessment Program.

Irrigation began in the study area in the early 1900s and is the primary use of water. Agricultural patterns are strongly influenced by available water, local drainage, and geologic factors that control soil fertility (Davis and Hall, 1959; Arkley, 1964, 1962b; McElhiney, 1992). About 70 percent of the study area is planted in irrigated crops. Dominant crops include almonds, walnuts, peaches, grapes, grain, corn, pasture, and alfalfa. The intensive pumping and recharge resulting from irrigated agriculture and continued growth of the urban areas have induced changes in the natural flow system.

Ground-water and surface-water supplies north of the Tuolumne River are managed primarily by the Modesto Irrigation District (MID), the City of Modesto, the southern portion of the Oakdale Irrigation District (OID), and private landowners. South of the Tuolumne River supplies are managed primarily by Turlock Irrigation District (TID), the city of Turlock, Eastside Water District (EWD), and Merced Irrigation District (commonly referred to as MID, but referred to as MER in this report). Within the regional study area, surface-water supplies from the Stanislaus, Tuolumne, and Merced Rivers are delivered by a series of canals. In the western part of the study area, numerous shallow drainage wells are pumped to maintain water levels below the root zone, although west of Modesto the amount of drainage pumping has decreased in recent years as ground-water use has increased. Prior to 1995, the city of Modesto used ground water for municipal supply. In 1994, MID completed a surface-water treatment plant at Modesto Reservoir that supplies about half of Modesto's municipal and industrial water to reduce ground-water pumping and mitigate accompanying ground-water level declines in the area.

Previous Studies

A large number of regional and local studies of the geology and ground-water hydrology of the San Joaquin Valley have been published. Some of the earliest work that includes the Modesto study area is reported by Mendenhall and others (1916), who summarize early investigations of water supply and ground-water quality in the San Joaquin Valley. In 1931, the California Department of Water Resources (DWR) published a State water plan, which included the San Joaquin Valley. Davis and others (1959) completed an appraisal of ground-water conditions, water quality, and storage capacity of the San Joaquin Valley, following extensive ground-water development in the decades since the report by Mendenhall (1916). Subsidence in the Central Valley was reported by Poland and Evenson (1966), Poland and others (1975), and Ireland and others (1984). Page (1972) provided a preliminary appraisal of ground-water conditions near Modesto, including the movement of ground water and general water quality.

Arkley (1962a,b; 1964) completed detailed soil maps of the sequence of major Pleistocene alluvial deposits in portions of Stanislaus and Merced Counties, and McElhiney (1992) completed the soil maps for San Joaquin County. Davis and Hall (1959) interpreted Arkley's soils classification in the context of geologic formation names and extrapolated the surface expression of the formation boundaries into the subsurface, providing a detailed characterization of the geologic setting and ground-water quality in the study area. Marchand and Allwardt (1981) also built on the work of Arkley (1962ab; 1964), presenting a revised detailed description of stratigraphic units for Tertiary and Quaternary formations in the northeastern San Joaquin Valley.

Although the Mokelumne River study area described by Piper and others (1939) is about 60 km (40 mi) north of Modesto, the detailed formation descriptions apply directly to the geology of the Modesto area. Similarly, Croft's (1972) study of the subsurface geology of water-bearing deposits in the southern San Joaquin Valley aids in understanding the geology of the Modesto study area.

Page (1972) revised the data on the extent and thickness of the Corcoran Clay member of the Tulare formation (hereinafter referred to as the Corcoran Clay). Hotchkiss (1972a,b) published a separate report defining the thickness and extent of the Corcoran Clay in the northern San Joaquin Valley, and Page and Balding (1973) supplemented earlier studies by reporting on the chemical quality of water and detailed subsurface geology of the ground-water system in the Modesto–Merced area. Page (1986) described post-Eocene continental rocks and deposits and used descriptions of the different proportions of coarse-grained to fine-grained sediments to map the subsurface geology of the Central Valley and revise descriptions of the thickness and extent of the Corcoran Clay.

Lettis (1988) summarized late Cenozoic stratigraphy and depositional history of the northern San Joaquin Valley and proposed stratigraphic correlations between sediments on the eastern and western side of the valley. Additionally, Lettis (1982; 1988) identified extensive paleosols that delineate Quaternary units in the subsurface. Weissmann and others (2002) used these paleosols to identify depositional sequences in the Kings River alluvial fan south of Fresno. Bartow (1991) reviewed the Cenozoic geologic history of the San Joaquin Valley in the context of tectonic events.

Page (1977b) reviewed available ground-water data and characterized the hydrologic system in support of the development of a ground-water flow model of the Modesto area. Londquist (1981) published the Modesto ground-water flow model. The model was designed to assist the city in evaluating effects of increased pumping and water use on future water levels. Williamson and others (1989) completed a flow model of the entire Central Valley, simulating the thickness of the continental deposits as one aquifer system with varying vertical leakance.

Methods

Compilation of the Existing Well Data

A database was constructed to organize information on well construction and subsurface lithology in the study area. Approximately 10,000 drillers' logs for the regional study area were obtained from DWR. Because sediment descriptions in the drillers' logs are often ambiguous and widely variable, a rating scheme used by Laudon and Belitz (1991) was modified to select a subset of logs for use in this study. Logs were selected for potential entry into the database if at least one depth interval contained a textural modifier (such as silty-sand or gravelly sand), at least one depth interval contained a color descriptor (such as blue clay), and location information on the log was adequate to place the well on a topographic map. Following this initial screening, additional logs were selected to help identify the extent of the Corcoran Clay, even if they only included a single blue clay interval.

Latitude-longitude locations were derived from topographic maps and entered into the database for the selected well logs. Elevation, topographic map name, township, range, and section number, water use, seal depth, well depth, hole depth, casing material, casing diameter, screened interval, construction date, drilling method, and driller's name were also included. In addition, sediment descriptions and depth intervals were entered into the database exactly as they appeared on the log.

Water Budget Calculations

The water budget was calculated by dividing the NAWQA ground-water flow model area into the smallest subareas for which surface-water deliveries could be obtained or estimated for water year 2000 (*fig. 2*). A separate water budget was calculated for each of the resulting 47 subareas, which included agricultural and urban settings, foothill areas, riparian areas with natural vegetation and (or) crops, and reservoirs.

A land-use approach was used to estimate recharge and pumpage for subareas containing primarily nonurban land. The areas of each crop or vegetation type were determined using local irrigation district data and field-verified land-use surveys of Stanislaus County and San Joaquin County for 1996 and of Merced County for 1995 (California Department of Water Resources, 1971; 2001a,b). Then, a daily crop evapotranspiration, or daily crop demand (ETc), was calculated based on the crop or vegetation type and climate. Daily crop coefficients (Kc) specific to each crop type and growing cycle (Snyder and others, 1987a,b) were multiplied by daily normal evapotranspiration (ETo) values specific to the Modesto climate (California Irrigation Management Information System, accessed April 26, 2002) to determine the daily crop demand:

$$\text{ETc} = \text{Kc} \times \text{ETo}$$

Daily precipitation values (California Irrigation Management Information System, accessed April 26, 2002) were subtracted from the ETc when the amount of precipitation was less than or equal to the ETc to give an estimate of daily unmet crop demand. The daily unmet crop demand was summed for each month for each crop type and multiplied by the total area of the crop in each subarea to obtain the monthly unmet crop demand.

Precipitation in excess of the daily ETc was summed for the year for each crop and allocated to recharge. Precipitation occurred for three or more consecutive days only six times during water year 2000. Runoff was considered to be minimal and was not factored into the water-budget estimates. It was assumed that runoff from the fields is accounted for in surface-water records because the regional slope of the land surface is generally flat.

The consumptive use of applied water, or irrigation efficiency, was estimated to be about 63 percent for most of the study area on the basis of the irrigation methods used and estimates for subareas with relatively high surface-water deliveries and few known wells. Crops are irrigated using flood, sprinkler, drip, or furrow irrigation methods. The estimate of 63 percent is similar to values for other areas that use sprinkler and flood irrigation methods (Solomon, K.H., accessed September 17, 2002). Irrigation efficiency was assumed to be greater (80 percent) in the older fan deposits in the foothill areas, where the sediments are more indurated and modern, efficient irrigation methods are more commonly used.

Monthly irrigation demand was determined by dividing the monthly unmet crop demand by the irrigation efficiency:

$$\text{Irrigation demand} = \text{unmet crop demand} / 0.63$$

The amount of water delivered to the subareas within the model area was estimated from current and historical delivery records obtained from local irrigation districts. In Oakdale Irrigation District (OID) and South San Joaquin Irrigation District (SSJID), owing to a lack of data, flow data from a USGS gage was used to estimate deliveries (Anderson and others, 2001). The monthly reported or estimated surface-water and ground-water deliveries were subtracted from monthly irrigation demand estimates to determine the monthly unmet irrigation demand. The unmet irrigation demand was assumed to be supplied by private pumpage, except in OID, where irrigation district pumpage was estimated by averaging historical pumpage from 1981 to 1998. In the riparian areas along the rivers, private surface-water deliveries were assumed to be equivalent to the estimated crop demand. In the foothills, precipitation was assumed to meet the estimated crop demand by native vegetation.

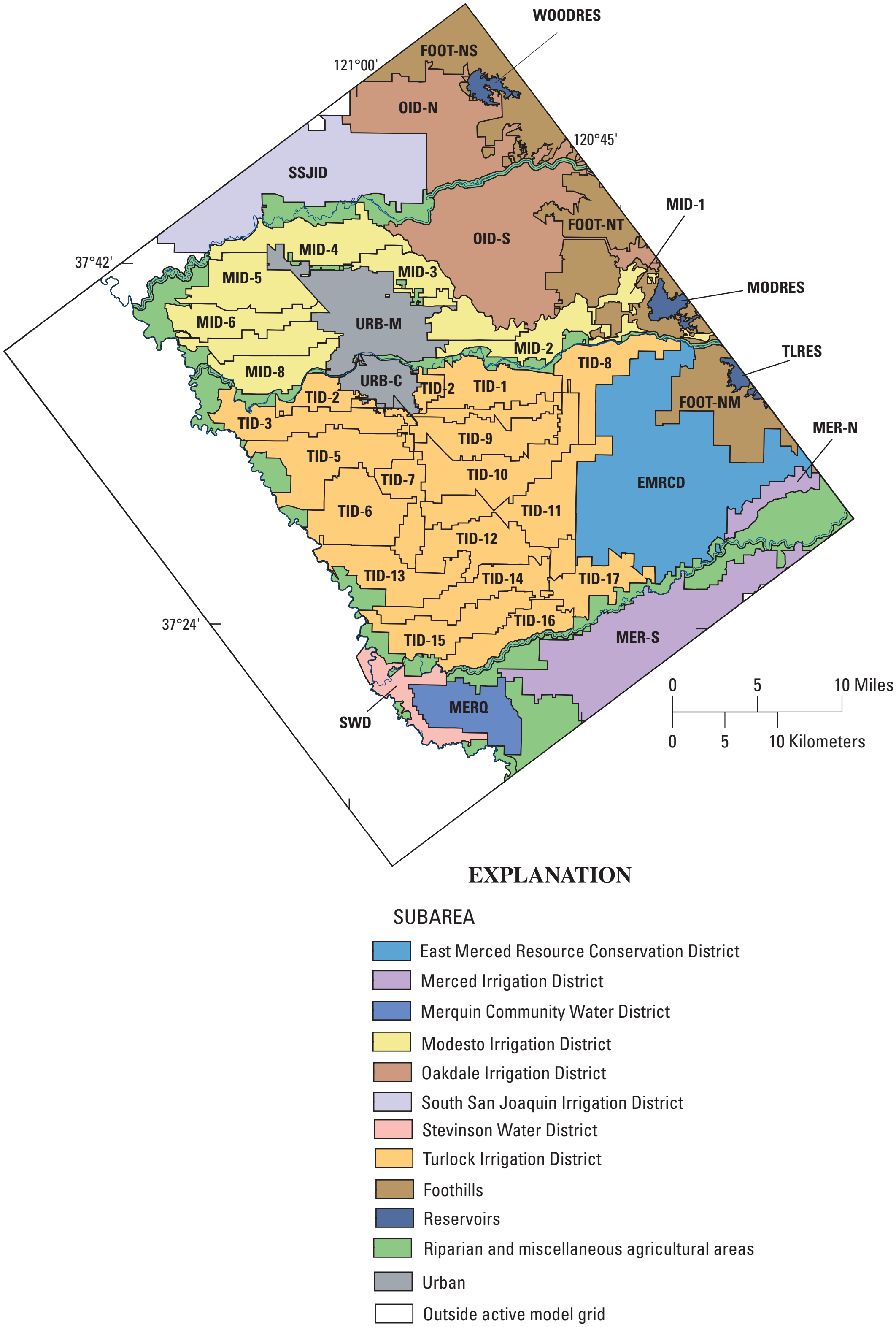


Figure 2. Model subareas used for water budget for water year 2000 for the Modesto area, San Joaquin Valley, California. Water budget and abbreviations for each subarea given in *table 3*.

Total recharge in the urban subarea was determined by summing the estimates of recharge of applied water, leakage from water distribution lines, and precipitation recharge. The minimum month method was used to determine indoor and outdoor water use (California Department of Water Resources, 1994). The indoor water use is assumed to be equal to the amount of water used during the month of lowest use, and is assumed to be constant throughout the year. The seasonal outdoor water use is assumed to be zero in the minimum month and varies according to outdoor irrigation demands, peaking in the summer months. The indoor water use is subtracted from the total water supply for the city (ground-water pumpage plus surface water purchased) to estimate seasonal outdoor water use for irrigation:

$$\text{Seasonal outdoor water use} = \text{total water supply} - \text{indoor water use}$$

Ten percent of the seasonal outdoor water use was subtracted from the total seasonal outdoor water use to account for leakage from water distribution lines (California Department of Water Resources, 1994); recharge from leakage from water distribution lines was accounted for separately. Fifty percent of the remaining outdoor water use was assumed to be consumptively used by landscape irrigation or runoff to streams; the remaining was assumed to be recharge:

$$\text{Recharge of applied water} = 0.5 \times [\text{seasonal outdoor water use} - (0.10 \times \text{seasonal outdoor water use})]$$

Forty percent of the precipitation in the urban area was assumed to drain to streams; the remaining was assumed to be recharge (Kratzer, 1998).

Stratigraphic and Geostatistical Analysis

Subsurface stratigraphy for the study area was estimated from the well log (drillers' log) data in conjunction with a limited number of geophysical well logs and soil surveys. Though the quality of drillers' well-log reports is highly variable, approximate depths to various stratigraphic horizons could be determined in some locations.

Quantitative methods of data analysis also were used to extend the applicability of the large amount of data contained in the well-log database by developing a spatial interpolation model of the percentage of coarse-grained texture for input to the NAWQA regional ground-water flow model. Ground-water flow models require some spatial interpolation and averaging to estimate parameter values representative of the volume and location of model elements. In this study, a three-dimensional geostatistical model of the percentage of coarse-grained texture was developed to represent the heterogeneity of the hydrogeologic system (J.A. Hevesi, U.S. Geological Survey, unpub. data, 2004).

Development of Primary and Derivative Datasets

Referring to a methodology based on earlier work by Page (1983, 1986) and Laudon and Belitz (1991), the primary variable selected for the geostatistical analysis was the percentage of coarse-grained texture. In this approach, the amount of coarse- and fine-grained sediment was derived from geophysical logs and drillers' logs and used to compute the percentage of coarse-grained texture. The term texture is used to indicate the dominant grain size in the lithologic description of sediments, as provided by the well logs. Grain shape and sorting also are often included as texture characteristics, but were not included as part of the texture classification used in this study.

A binary texture classification of either "coarse grained" or "fine grained" was used to assign a texture parameter to each interval noted in the logs (*fig. 3*). A texture value of 100 percent was assigned to all intervals categorized as coarse grained. Coarse-grained texture is defined as consisting principally of sand or gravel including sand; clayey and silty sand; gravel; and clayey, silty, and sandy gravel. A texture value of 0 percent was assigned to all intervals defined as fine grained. Fine-grained texture was defined as consisting principally of silt or clay, including silt, clayey silt, clay, and silty or sandy clay. A texture value of 0 percent was also assigned to sediment types indicating increasingly consolidated sediments, such as sandstone and shale, in order to reflect the lower permeability of the consolidated sediments in the study area.

For use in the geostatistical analysis, the percentage of coarse-grained texture was calculated over 1-m depth increments using the 3,504 logs from the database of existing wells. For 1-m depth intervals containing both 100 percent and 0 percent coarse-grained intervals, the total vertical distance of each texture class within the 1-m depth increment was used to calculate a weighted average value of percentage coarse-grained texture (*fig. 3*). The 1-m incremented texture data, referred to in this study as the primary texture data, was the source data used to develop all secondary derivative data sets included in the geostatistical analysis.

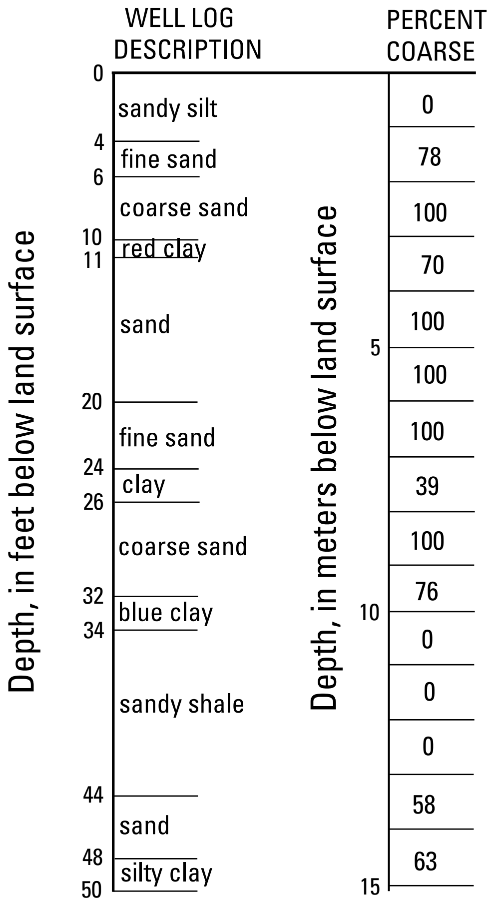


Figure 3. Examples of binary texture classification for texture analysis in Modesto, San Joaquin Valley, California.

Derivative texture data sets were developed from the primary texture dataset using data smoothing and resampling methods. For data smoothing, the 1-m primary data was averaged within a sliding neighborhood (moving window) having specified dimensions in the vertical and horizontal directions. Selected values in the vertical direction located at specified depth increments were used to resample the primary data. For example, for a 5-m depth increment, every fifth data value along the vertical direction was retained for the resampled data set (4 of the 5 samples in each 5-m depth increment were omitted). The derivative dataset was developed for several reasons: (1) to resample the 1-m vertically incremented data as 5- or 10-m vertically incremented data in order to mitigate the vertical clustering effect of the data aligned along boreholes, (2) to extract subsets of two-dimensional data for 10-m depth layers that were used in a two-dimensional analysis, (3) to smooth or filter-out local-scale heterogeneity in order to emphasize regional-scale patterns in the three-dimensional texture field, (4) to facilitate transformations of the data to better approximate a normally distributed regionalized variable (this is an important consideration for the parametric geostatistical methods used in this study), and (5) to reduce the overall number of samples, allowing for a larger area or volume to be included in the search neighborhood used for estimation.

Geostatistical Methods

Geostatistics is a set of applications and statistical techniques used to analyze spatial and (or) temporal correlations of variables distributed in space and (or) time (Isaaks and Srivastava, 1989). The spatial correlation structure can be modeled using a positive definite, continuous function, which is then used to provide a best linear unbiased estimate of the local mean value of the regionalized variable at unsampled locations. In addition to estimating local mean values, the spatial correlation model can be used to simulate multiple realizations or to provide quantitative measures of uncertainty associated with the estimated mean values (Deutsch and Journel, 1998). These aspects of a spatial correlation model can be applied to help analyze uncertainty in the input used for ground-water flow models and to help select the best locations for additional sampling sites (boreholes). The simulation of multiple realizations of the texture field allows for a Monte Carlo analysis using the output distributions in the ground-water models.

An advantage of using geostatistical models instead of simple spatial interpolation methods, such as the inverse-distance-squared linear interpolator, is that the spatial correlation structure of the available sample can be analyzed. The geostatistical model is fitted to the observed spatial correlation structure, whereas simple interpolation methods are based on an assumed spatial correlation structure. Additionally, anisotropy in the spatial correlation structure can be modeled by combining several different models aligned along the principal axis of anisotropy to form a nested set of models. Significant differences in the spatial correlation structure of geologically-based datasets are often observed between the horizontal and vertical directions, and known or assumed characteristics of the underlying geology can be incorporated into the development of the spatial correlation model.

Exploratory data analysis was done during the first phase of the geostatistical analysis by evaluating sample distributions, trends, data clustering, biases, and outliers (J.A. Hevesi, U.S. Geological Survey, unpub. data, 2004). The data analysis was needed for decisions concerning data transformations, data smoothing, de-clustering methods, and interpreting the sample variograms. Following the exploratory data analysis, variography was used. Variography consists of evaluating the spatial correlation structure of the available sample using statistical measures (commonly the variogram) and then representing the spatial structure using variogram models. A set of sample variograms representing different scales and directions was calculated using both the primary texture data and the derivative texture data (J.A. Hevesi, U.S. Geological Survey, unpub. data, 2004). Model variograms were visually fitted to the sample variograms by combining standard, positive definite model variogram functions (for example, the spherical, exponential, Gaussian, and power models) into nested variogram structures, including a nugget component.

Kriging is a best linear unbiased estimator used to calculate a local mean based on the variogram model and on the values and location of the sample included in the estimation neighborhood. The method provides a best estimate by solving a system of equations to obtain a set of weights providing the minimum estimation variance (similar to the least-squares fitting used in regression methods). For the ordinary kriging method used in this study, the interpolation is theoretically unbiased because the system of kriging equations requires the sum of the weights to be unity. The kriging estimate is a simple linear combination of the calculated kriging weights and the sample values included in the estimation neighborhood. The kriging weights can also be used to calculate an estimation variance, which provides the measure of uncertainty associated with the estimated value. The kriging estimator is usually applied to spatial interpolation, for which an estimated value is required for locations between sample values. Although not recommended, the estimator can be applied to extrapolation, for which an estimated value is required for locations outside of the region defined by the sample configuration. In this study, some degree of extrapolation was required because the ground-water flow model extended below the depth of the deepest well. Although extrapolated estimates can be calculated, a much higher degree of uncertainty should be associated with these estimates relative to the interpolated estimates. For this study, the vertical extent of the spatial correlation model was approximately defined by the depth of the deepest well recorded in the well-log database and the horizontal extent was defined by the areal coverage of wells recorded in the well-log database. Although adequate data existed at the depth of the Corcoran Clay, this confining unit was represented explicitly in the NAWQA ground-water flow model.

Hydrogeologic Characterization

Physiography and Soils

Consolidated rocks and deposits exposed along the margin of the valley floor in the Modesto ground-water basin include Tertiary and Quaternary continental deposits, Cretaceous and Tertiary marine sedimentary rocks, and the pre-Tertiary Sierra Nevada basement complex. Surficial features on the valley floor in the Modesto ground-water basin can be divided into physiographic units as described by Davis and others (1959): river flood plains, channels, and overflow lands, low alluvial plains and fluvial fans, and dissected uplands (*fig. 1*). The dissected uplands lie along the flanks of the valley between the Sierra Nevada to the east and the alluvial plains and fluvial fans to the west. The local relief ranges up to 30 m (100 ft) in the form of dissected hills and gently rolling lands. A belt of coalescing fluvial fans of low relief (less than 3 m) forms the low alluvial plains and fans that range in width from about 22 to 32 km (14 to 20 mi). These fans lie between the dissected uplands and the nearly flat surface of the valley trough. River floodplains and channels occur as narrow, disconnected strips along the channels of the major rivers. Overflow lands of the valley trough tributary to the San Joaquin River define the area inundated by rivers when floods are highest under natural conditions.

In the northern San Joaquin Valley, which includes the study area, the major rivers on the east side have headwaters high in the Sierra Nevada and flow southwest toward the axis of the valley. Little deposition is taking place currently and the rivers are cutting downward on the upper reaches of the fans where the river floodplains are commonly entrenched to depths of 15 to 24 m (50 to 80 ft). However, toward the lower ends of the fans, where the river gradients are low, many small streams and tributaries of the major rivers are actively aggrading their beds (Davis and others, 1959). The San Joaquin River is the principal drainage outlet of the northern San Joaquin Valley, flowing northward through the study area to its confluence with the Sacramento River in the Sacramento–San Joaquin Delta.

Three major southwest-flowing tributaries to the San Joaquin River are in the study area: (1) the Stanislaus River, (2) the Tuolumne River, and (3) the Merced River (*fig. 1*). The Stanislaus River drains a watershed of about 2,700 km^2 (1,051 mi^2) (Grunsky, 1899) and flows through the dissected uplands between Knights Ferry and Oakdale, along the low alluvial plains and fans near the city of Riverbank to the confluence with the San Joaquin River near Vernalis (Davis and others, 1959). The Tuolumne River drains a watershed of about 4,200 km^2 (1,635 mi^2)(Grunsky, 1899) and flows through the dissected uplands from La Grange to Waterford, along the low alluvial plains and fans near the city of Modesto to the confluence with the San Joaquin River near Grayson (Davis and others, 1959). The Merced River drains a watershed of about 2,800 km^2 (1,076 mi^2) (Grunsky, 1899) and flows through the dissected uplands downstream of Merced Falls, along the low alluvial plains and fans near the city of Livingston to the confluence with the San Joaquin River near Newman (Davis and others, 1959). Streams entering the San Joaquin River from the Coast Ranges are intermittent and flow only during the short rainy season.

The general physiography of the study area also is reflected in the soils, characterized by Arkley (1964) for eastern Stanislaus County, Arkley (1962a) for eastern Merced County, and McElhiney (1992) for San Joaquin County. The oldest soils are on the nearly level high terraces and old fluvial fans in the eastern part of the area. The oldest soils usually have claypan or hardpan layers at depths of 0.6 m (2 ft) or less. The youngest soils are forming on the recently deposited alluvium along stream bottoms and on recently exposed surfaces. These soils are generally deep and rich in nutrients. The soils at intermediate stages of development are on the low terraces (Arkley, 1964).

Mapped soil units, grouped by permeability classes defined by Arkley (1964) and McElhiney (1992), provide information on the hydrogeologic properties of near surface deposits. Highly permeable soils (indicated by rapid percolation rates) are generally young and are located along major stream channels and on the most recent Tuolumne and Stanislaus River fans (*fig. 4*). Low permeability soils (indicated by low percolation rates) exist in the interfan areas between the major streams, at the distal end of several fans, and along the San Joaquin River floodplain. Low permeability soils having claypan or hardpan layers exist in older terrace deposits. It is important to note that the soil classification provides a good description of general soil development and character, but locally, features such as hardpan layers may have since been altered by farming or other land uses.

Soil permeability in the study area is strongly correlated with the depth to a shallow hardpan of the Riverbank Formation (*fig. 5*). Areas where the Riverbank hardpan is missing (light colored areas) likely correspond to the most recent deposits of the rivers, which are highly permeable. Apparently recent deposits of the Tuolumne River fluvial fan cover a larger area to the south of the current channel than to the north. In southern San Joaquin County, apparently recent deposits of the Stanislaus River cover the area north of the current channel, although a narrow trace of an apparently recent channel skirts along the northwest part of Modesto (*fig. 5*).

Description of Geologic Units

The basin that contains the San Joaquin Valley (*fig. 1*) evolved during the Cenozoic era through the actions of plate tectonics, sea level change, and climate (Bartow, 1991). During this time, the region changed from a marine shelf on the west edge of North America to a northwest-trending structural trough between the Sierra Nevada and the Coast Ranges (Bartow, 1991). Tectonic processes during this time include basin subsidence, uplift of the Sierra Nevada and Coast Ranges, and deformation. The Sierra Nevada lies on the eastern side of the valley, comprises primarily Mesozoic granitic rocks, and is separated from the Central Valley by a foothill belt of Mesozoic and Paleozoic marine rocks and Mesozoic metavolcanic rocks. The Coast Ranges lie on the western side of the valley and comprise the Franciscan subduction-zone complex of primarily Mesozoic age and Mesozoic ultramafic rocks. These rocks are overlain by marine and continental sediments of Cretaceous to Quaternary age and some Tertiary volcanic rocks (Page, 1977a; Page, 1986; Gronberg and others, 1998).

Rocks exposed or penetrated by wells in the Modesto area range from pre-Cretaceous (144 million years old) to recent in age (*fig. 6*). Water-bearing rocks are mostly Late Tertiary and Quaternary in age. Previous to this study, investigators identified local scale formations that were later traced for greater distances; they grouped different geologic units together because of minimal textural or lithologic basis for subdivision. Some units also have been described without using a formal geologic formation name. This report will follow the example of previous authors (for example, Croft, 1972; Hotchkiss, 1972b; Page and Balding, 1973; and Page, 1986) and group stratigraphic units into two primary categories: consolidated rocks and unconsolidated deposits (*table 1*). Further delineation of the Tertiary and Quaternary formations generally corresponds to the designation by Marchand and Allwardt (1981).

Consolidated Rocks

Exposed metamorphic and igneous rocks that occur as foothill ridges and the metamorphic rocks and intrusive igneous rocks that underlie the Modesto area (*fig. 6*) are defined as the basement complex (Croft, 1972; Page and Balding, 1973). Marine sandstones and shale overlie the basement complex, which consists of micaceous sandy shale, sandstone, and siltstone with some fine sand with shells (Davis and Hall, 1959). These rocks are not exposed but were encountered during exploratory drilling for gas and oil.

The Ione Formation is the oldest sedimentary unit exposed along the eastern boundary of the San Joaquin Valley. The Ione Formation predominantly comprises fluvial deposits with some lacustrine, lagoonal, and marine deposits (Davis and Hall, 1959; Marchand and Allwardt, 1981). Cemented beds form resistant westward-sloping cuestas over basement outcrops that can be seen along the eastern San Joaquin Valley (Marchand and Allwardt, 1981).

The Valley Springs Formation rests unconformably on the Ione Formation and consists of a nonmarine sequence of rhyolitic tuff, sandstone, siltstone, and claystone with rhyolitic ash, sandy clay, and siliceous sand and gravel generally in a clay matrix (Piper and others, 1939; Davis and Hall, 1959; Marchand and Allwardt, 1981; Page, 1986). The Valley Springs Formation erodes easily, forming a series of valleys between the Ione and the overlying Mehrten Formations (Page and Balding, 1973); however, ledges also are formed from altered zones within the Valley Springs Formation that are kaolinitic and often pisolitic and may be diagenetically altered paleosols formed under much wetter climatic conditions (Marchand and Allwardt, 1981).

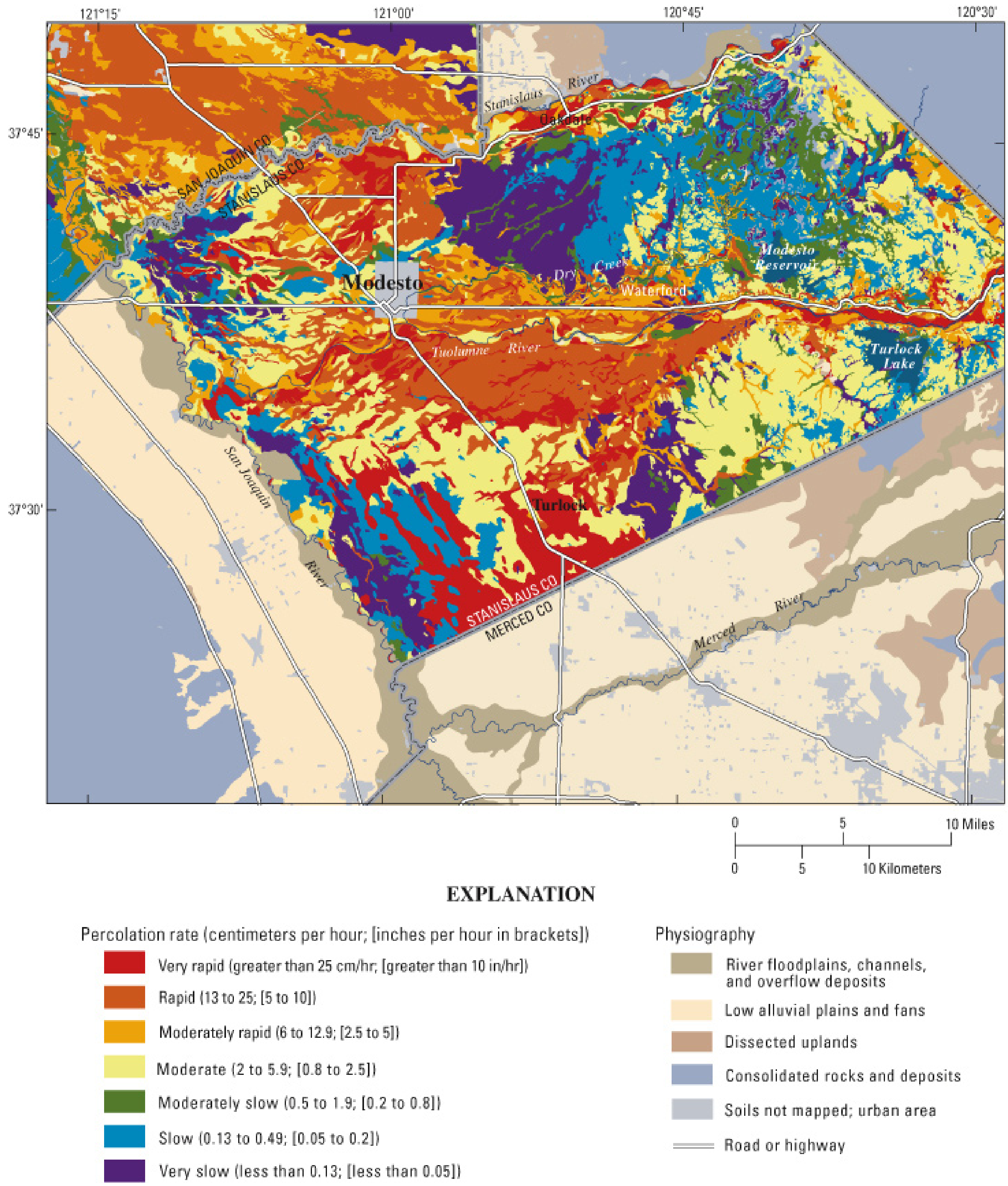


Figure 4. Soil percolation rate near Modesto, San Joaquin Valley, California. Soils data for Stanislaus County derived from Arkley (1964) and for San Joaquin County derived from McElhiney (1992).

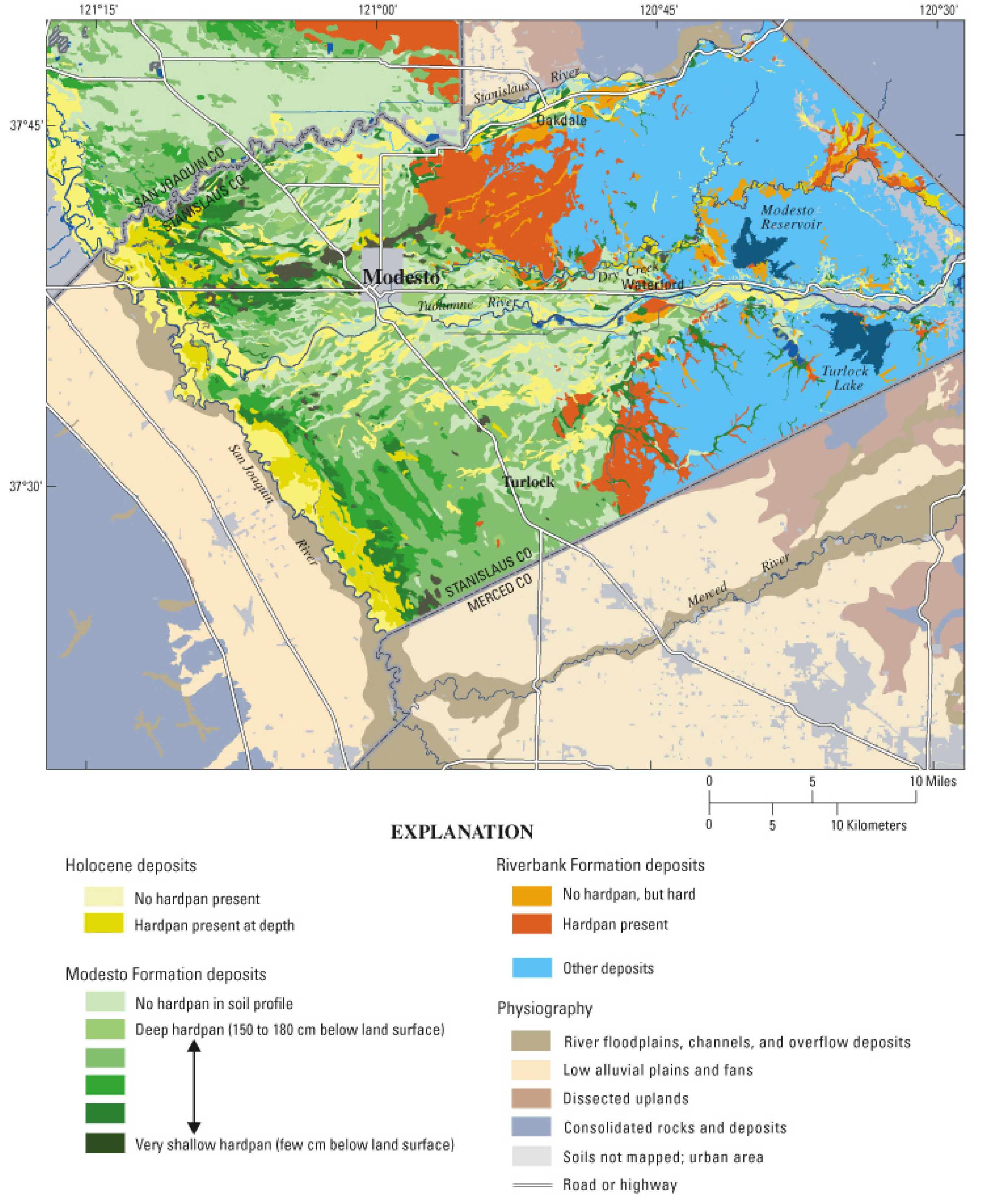


Figure 5. Relative depth to Riverbank Formation hardpan horizon in surficial deposits near Modesto, San Joaquin Valley, California. Soils data for Stanislaus County derived from Arkley (1964) and for San Joaquin County derived from McElhiney (1992). cm, centimeter.

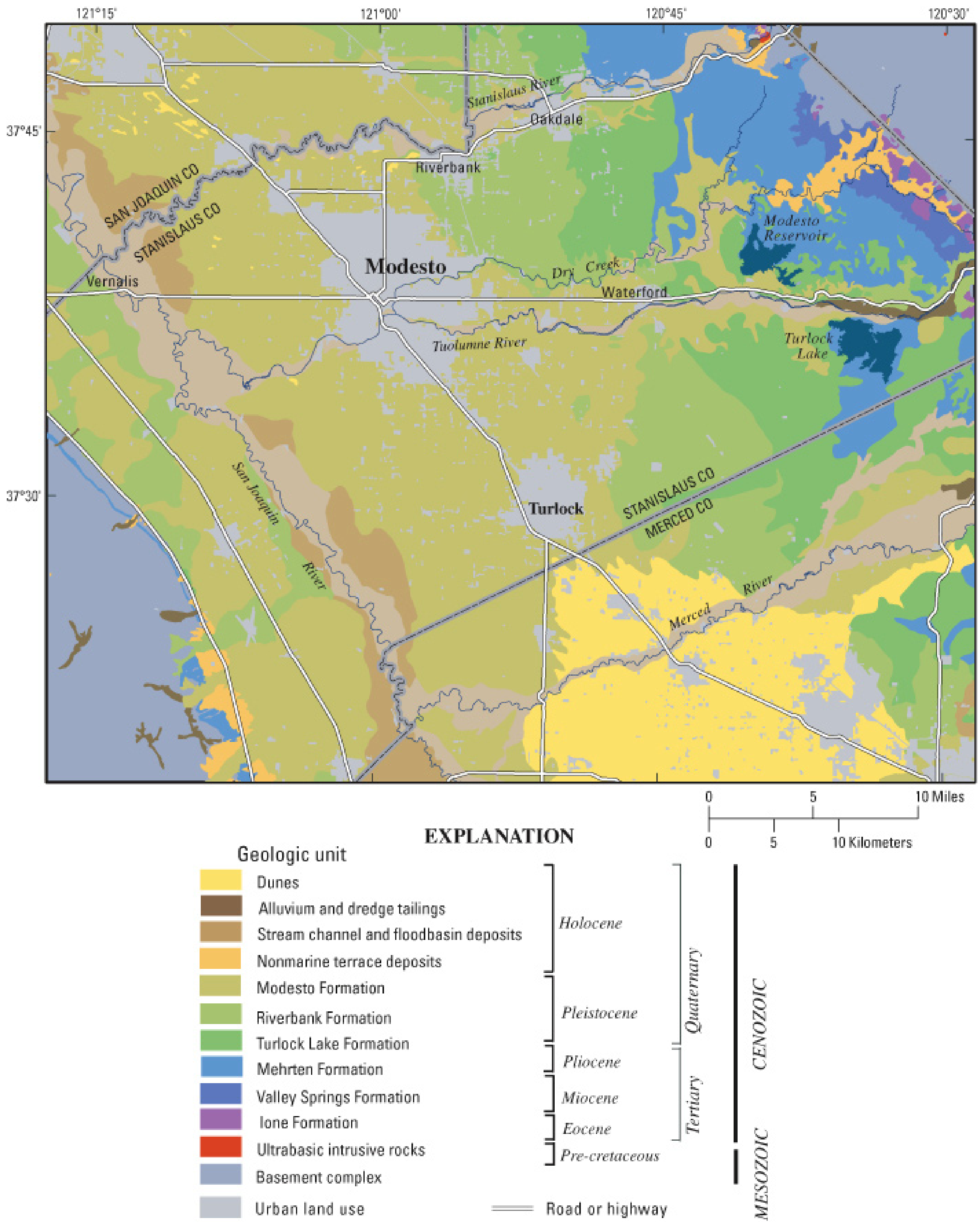


Figure 6. Map of selected geologic units near Modesto, San Joaquin Valley, California. Modified from California Division of Mines and Geology, 1966.

Table 1. Summary of stratigraphic units and corresponding soil series mappping units for the Modesto area, San Joaquin Valley, California.

[m, meter; ft, foot; m/km, meter per kilometer; gal/min, gallon per minute; >, greater than; %, percent]

Era	Period	Epoch	Stratigraphic unit	Description	Distinguishing characteristics	Maximum thickness; slope	Water- bearing characteristics	Soil series mapping unit	Source
					Unconsolidated deposits				
Cenozoic	Quarternary	Holocene	Holocene deposits	Alluvium along modern rivers with point bar, levee, crevasse splay, interdistributary, and floodplain deposits. Some lacustrine, swamp and marsh deposits in the basin; some areas of dunes. Generally thin and unweathered.	Unconsolidated sand, silt, and some clay along modern rivers. Lower contact with Modesto Formation is difficult to distinguish, although Modesto Formation deposits are more deeply oxidized and weathered than the Holocene deposits.	Thickness less than 15 m (50 ft).	Generally not saturated except by the San Joaquin River.	Columbia, Grangeville, Honcut, Riverwash,. Tujunga.	Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Lettis, 1982 1988.
Cenozoic	Quarternary	Pleistocene	Modesto Formation	Arkosic sand, gravel, and silt consisting of mainly quartz and feldspar with lesser amounts of biotite and minor amounts of heavy minerals, including magnetite and hornblende. Upper surface modified by wind action in some places.	Topography is flat and slopes westward with few shallow drainage courses on surface; weakly developed B-horizon that is compact with minor clay and abundant sand-sized grains of quartz and feldspar; coarse-grained material not significantly weathered; granitic material usually fresh. Lithology similar to that of Laguna, Turlock Lake, and Riverbank Formations, although more fine-grained.	Thickness 20 to 40 m (65 to 130 ft); slope about 1.5 m/km.	Moderate yields where saturated.	Chualar, Delhi, Dello, Dinuba, Fresno, Greenfield, Hanford, Hilmar, Modesto, Oakdale.	Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Lettis, 1982, 1988.
Cenozoic	Quarternary	Pleistocene	Riverbank Formation	Arkosic sand, gravel, and silt of mainly quartz and feldspar with lesser amounts of biotite and minor amounts of magnetite and hornblende.	Slightly steeper slope than Modesto Formation; B-horizon soils fairly compact with considerable clay, coarse-grained material weathered and stained, but granite pebbles and cobbles commonly intact. Reddish, clay-rich duripan caps this unit. Lithology similar to that of Laguna, Turlock Lake, and Modesto Formations, although more fine-grained material and less gravel than in Turlock Lake formation, and magnetite more common.	Variable thickness, 45 to 80 m (150 to 250 ft); slope about 2 m/km.	Moderate yields.	Madera, Ramona, Ryer, San Joaquin, Snelling, Yokohl.	Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Lettis, 1982, 1988.

Table 1. Summary of stratigraphic units and corresponding soil series mappping units for the Modesto area, San Joaquin Valley, California—*Continued.*

[m, meter; ft, foot; m/km, meter per kilometer; gal/min, gallon per minute; >, greater than; %, percent]

Era	Period	Epoch	Stratigraphic unit	Description	Distinguishing characteristics	Maximum thickness; slope	Water- bearing characteristics	Soil series mapping unit	Source
Cenozoic	Quarternary	Pleistocene	Turlock Lake Formation	Arkosic sand, gravel, and silt, that coarsen upward; sand- and silt-sized sediments are mostly quartz, feldspars, biotite, and minor amounts of heavy minerals; coarser-grained materials consist of andesite, rhyolite, quartz, greenstone, schist, and granidiorite rock types; gray to grayish pink silts and clays and gray, brown, and reddish sands; reddish paleosol divides upper and lower unit; upper unit capped by paleosol.	Succession of gravel and coarse sand that overlies well sorted, fine-grained sand, silt, and clay of possible lacustrine origin. Sands distinguishable from the Mehrten sands by dominant quartz and feldspar lithology (>70%). Reddish, clay-rich paleosol at the top of the upper unit; blue lacustrine Corcoran Clay at base of upper unit covers much of the study area; Corcoran Clay is overlain by Friant pumice in places.	Thickness 90 to 260 m (300 to 850 ft) in eastern Stanislaus County; 50 to 220 m (160 to 720 ft) south of study area. The Corcoran Clay ranges in thickness from 0 to 30 m (0 to 100 ft) at depths of 24 to 64 m (80 to 210 ft); slope is about 3 m/km.	Large yields from gravel and sand units (up to 2,000 gal/min), most developed aquifer in the Modesto area; not extensivly developed around Corcoran Clay; Corcoran Clay impedes vertical movement of ground water;ground water confined below Corcoran Clay.	Montpelier, Rocklin, Whitney.	Davis and Hall, 1959; Arkley, 1962a; Helley, 1967; Croft, 1969; Hotchkiss, 1972; Page and Balding, 1973; Marchandt and Allwardt, 1981; Lettis, 1982, 1988.
	Quarternary/Tertiary	Pliocene-Pleistocene	North Merced Gravel	Gravel veneer predominantly quartz or mixed metamorphic source, no granitic pebbles or cobbles; matrix is locally-derived materials, weathered to clay.	Erosional pediment surface that may or may not have an equivalent unit in subsurface; darker colored, locally derived matrix of gravel as compared to arkosic matrix of Laguna Fm gravels; Lettis (1982, 1988) identified relatively thick unit in subsurface near Madera, California.	Thickness in outcrop 2 to 4 m (4 to 13 ft); variable slope that conforms to local topography.	Unknown .	Redding, Corning.	Arkley, 1962a; Marchand and Allwardt, 1981.

Table 1. Summary of stratigraphic units and corresponding soil series mappping units for the Modesto area, San Joaquin Valley, California`—*Continued*.

[m, meter; ft, foot; m/km, meter per kilometer; gal/min, gallon per minute; >, greater than; %, percent]

Era	Period	Epoch	Stratigraphic unit	Description	Distinguishing characteristics	Maximum thickness; slope	Water- bearing characteristics	Soil series mapping unit	Source
Cenozoic	Tertiary	Pliocene	Laguna Formation	Alluvial, coarsening-upward sequence of gravel, sand, and silt; coarse material composed of quartz and metamorphic fragments; fine-grained matrix materials are arkosic. Lower and upper unit divided by strongly developed reddish brown to yellowish brown clay-rich buried soil with no duripan.	Discontinuous distribution in outcrop, but may exist in subsurface; lithologic character may not serve to distinguish it from overlying Pleistocene sediments, although feldspars more weathered and biotite altered or bleached; may contain reworked andesitic detritus from Mehrten. Moderate to strong degree of compaction.	Regional angular unconformity between Mehrten and Laguna Formations, thickness uncertain but estimated at 15 to 70 m (50 to 230 ft).	Variable yields	Redding, Corning	Piper and others, 1939; Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Lettis, 1982, 1988; Page, 1986
					Consolidated rocks				
		Miocene and Pliocene	Mehrten Formation	Dark sandstone, siltstone, claystone, conglomerate, and andesitic breccia and tuff. Rhyolitic tuff and pumice at base of formation from reworked Valley Springs formation; alternating andesitic gravels, sands, and silts 1 to 6 m (3 to 20 ft) thick in middle subunit; soft pink clay, silt, and sands in upper unit; weakly to moderately developed paleosols, light-colored to reddish gravels and sand beds.	Distinguishable from overlying formations by predominance of andesitic materal (>50%) and generally well sorted beds of more uniform texture; general decrease in mean grain size southward from Stanislaus River.	Thickness 60 to 350 m (190 to 1,200 ft); variable thickness in valley-fill areas; slope of about 20 m/km; rests conformably on Valley Springs Formation.	Moderate to large yields to wells, penetrated by many irrigation and public-supply wells; saline water reported in western part of study area and locally in eastern study area.	Pentz, Peters, Raynor.	Piper and others, 1939; Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Page, 1977a; Marchand and Allwardt, 1981; Page, 1986.

Table 1. Summary of stratigraphic units and corresponding soil series mappping units for the Modesto area, San Joaquin Valley, California—*Continued.*

[m, meter; ft, foot; m/km, meter per kilometer; gal/min, gallon per minute; >, greater than; %, percent]

Era	Period	Epoch	Stratigraphic unit	Description	Distinguishing characteristics	Maximum thickness; slope	Water- bearing characteristics	Soil series mapping unit	Source
Cenozoic	Tertiary	Oligocene and Miocene	Valley Springs Formation	Rhyolitic tuff, pumice-bearing sandstone and siltstone, claystone, and conglomerate; ash, sandy clay, and siliceous sand and gravel generally in clay matrix; varies in color, including yellow, yellowish-brown, brown, reddish-brown, gray, greenish-gray, white, pink, green, and blue.	Presence of rhyolitic materials distinguishes theValley Springs from the Ione Formation. Absence of andesitic fragments delineates it from the Mehrten Formation; erodes to form valleys; altered zones that are kaolinitic and pisolitic form ledges	Thickness 20 to 140 m (75 to 450 ft); variable thickness in valley-fill areas; rests unconformably on Ione Formation.	Generally small yields to wells of fair to poor water quality, although some wells reportedly sustained moderate yields and good quality water.	Amador.	Piper and others, 1939; Taliaferro and Solari, 1946; Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Page, 1986.
Cenozoic	Tertiary	Eocene[1]	Ione Formation and other undifferentiated Eocene sediments	Light brown, gray to pinkish or yellowish quartz sandstone with interbedded white kaolinitic clay near the base, becoming conglomeratic and very strongly cemented in the upper part; gray or blue micaceous shale and clay containing coal and other carbonaceous beds; in some places undifferentiated gray or blue micaceous shale and sand lies below the base of the Ione formation.	Lateritic soils containing crystalline iron oxides and kaolinitic clay; locally contains marine fossils.	Thickness 60 to 140 m (200 to 450 ft); slope of about 30 m/km; rests unconformably on Cretaceous rocks.	Expected small yields to wells; some successful irrigation wells east of Modesto, although saline water reported near LaGrange.	Hornitas.	Allen, 1929; Piper and others, 1939; Davis and Hall, 1959; Arkley, 1962a; Page and Balding, 1973; Marchand and Allwardt, 1981; Page, 1986.
Mesozoic	Cretaceous		Marine sandstone and shale	Dark gray micaceous sandy shale, sandstone, siltstone, some fine sand filled with shells.	Approximately 60% shale, 40% sandstone, and less than 1% limestone; marine fossils, including ammonites.	Thickness 0 to 2,900 m (9,500 ft); thickens westward; wedges out east of Oakdale, Waterford, and Montpelier.	Unknown yields; one well reportedly yielded saline water.	Not exposed.	Piper and others, 1939; Davis and Hall, 1959; Jennings and Hart, 1956; Page and Balding, 1973.
Mesozoic	Pre-Cretaceous		Basement complex	Metavolcanic schist, gray slate, narrow dikes of light-colored intrusive rocks, intrusive bodies of quartz porphyry, chert, slate, and conglomerate.	Outcrops chiefly as eastern foothill ridges and underlie San Joaquin Valley sediments.	Unknown thickness but depths to 11,000 ft; slope south-westward 4 to 8 degrees.	Small yields to wells through fractures and joints where complex is exposed or near land surface.	Daulton, White rock, Auburn.	Taliaferro, 1943; Taliaferro and Solari, 1946; Davis and Hall, 1959; Arkley, 1962a; Page, 1972; Page and Balding, 1973, Page, 1986.

[1]Paleocene deposits not present in study area.

The Mehrten Formation consists of sandstone, conglomerate, siltstone, and claystone derived from fluvial deposits of predominantly andesitic volcanic detritus of the central and northern Sierra (Piper and others, 1939; Davis and Hall, 1959). Most of the Mehrten Formation lies conformably on the Valley Springs Formation but, in places, lies unconformably on pre-Tertiary rocks (Page, 1986). In the northeastern part of the San Joaquin Valley, the Mehrten can be divided into three units characterized by texture; however, the contacts between the units are gradational and the units have not been mapped (Page, 1986).

Unconsolidated Deposits

The majority of the unconsolidated deposits in the study area are contained within the Pliocene-Pleistocene Laguna, Turlock Lake, Riverbank, and Modesto Formations, but also consist of minor amounts of locally-derived materials and Holocene stream channel and floodbasin deposits (*fig. 6*). 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).

At the base of the unconsolidated deposits is the Pliocene Laguna Formation, which lies unconformably on the consolidated Mehrten Formation. The Laguna Formation is characterized by alluvial deposits of gravel, sand, and silt in at least two upward coarsening units, separated by a well-developed paleosol, which Marchand and Allwardt (1981) used to informally separate the formation into lower and upper units. Previous to this report, investigators had not identified the Laguna Formation in outcrop in the Modesto area; however, the exposure of the Laguna Formation north of the Stanislaus River and in Merced County (Arkley, 1962a) indicates it may be beneath the surface. Investigators in the Modesto area have mapped the Laguna Formation as part of the Turlock Lake Formation (Davis and Hall, 1959) or as continental deposits containing the Laguna, China Hat Gravel, North Merced Gravel, and the lower Turlock Lake Formations (Page and Balding, 1973).

The North Merced Gravel, representing the boundary between the Tertiary Laguna Formation and overlying Pleistocene formations, comprises locally-derived, predominantly mafic materials. The North Merced Gravel has not been identified in outcrop in the northern part of the study area, although in the Merced area, the North Merced Gravel has been mapped as part of the Laguna Formation (Lettis, 1988).

The Pleistocene Turlock Lake Formation primarily consists of fluvially deposited arkosic silt, sand, and gravel (Davis and Hall, 1959; Marchand and Allwardt, 1981). A well-developed paleosol separates the Turlock Lake Formation into two units (Marchand and Allwardt, 1981). Both units exhibit an upward-coarsening sequence, similar to alluvium derived from all major glaciated river basins draining to the northeastern San Joaquin Valley (Marchand and Allwardt, 1981). The lower unit contains gravel and coarse sand underlain by sand, silt, and clay of possible lacustrine origin. The lower unit may represent more than one period of aggradation (Marchand and Allwardt, 1981), and deposits that appear to be correlative with this unit predate the Matayama-Brunhes magnetic reversal (Davis and others, 1977). The upper unit contains sand, silt, and gravel underlain by well-stratified silt and fine sand in the middle to lower part of the unit of possible lacustrine origin, likely representing a single period of aggradation. Strongly developed paleosols at the top of the upper unit define a boundary between the Turlock Lake Formation and the overlying Riverbank Formation (Marchand and Allwardt, 1981).

The Corcoran Clay, an areally extensive diatomaceous lake clay, first described by Frink and Kues (1954), is a formally designated member of the Tulare Formation (Croft, 1972). The Corcoran Clay is considered equivalent to the E-clay in the southern San Joaquin Valley (Page, 1986) and correlates to the diatomaceous clay described by Davis and others (1959). The Corcoran Clay is correlated to the extensive lacustrine clay underlying the Modesto area at the base of the upper unit of the Turlock Lake Formation (Marchand and Allwardt, 1981).

The Corcoran Clays is dark greenish gray, but is commonly referred to as the blue clay. The clay is a generally well sorted clay to silty clay with no sand. Other blue silt and clay beds are above and below the Corcoran Clay but could not be correlated over large distances (Page and Balding, 1973). The Corcoran Clay and other lacustrine blue clays described in drillers logs and in electric logs resulted from the expansion of lakes and the resulting deposition of extensive clays in the San Joaquin Valley. Davis and Green (1962) showed that the Tulare Lake bed in the southern San Joaquin Valley (*fig. 1*) is an area of structural downwarping; active tectonic subsidence controls the aggradation rates in the basin. Page (1986) postulated that the Corcoran Clay (or E-clay) is thinner in the northern San Joaquin Valley than the southern San Joaquin Valley because a similar downwarping of the basin did not develop in the Sacramento Valley. The Corcoran Clay may have been deposited in a large lake that existed at the same time as glaciation in the Sierra Nevada (Janda and Croft, 1967), but Davis and others (1977) suggested that the Corcoran Clay was formed during an interglacial stage. The Friant Pumice Member occurs within and near the base of the upper unit of the Turlock Lake Formation and is believed to rest conformably on the Corcoran Clay in the subsurface (Marchand and Allwardt, 1981).

The Riverbank Formation consists of fluvially deposited arkosic sediment with some locally derived sediment from small drainage basins along the foothills. The alluvium comprises mostly sand with some pebbles, gravel lenses, and interbedded fine sand and silt (Davis and Hall, 1959; Marchand and Allwardt, 1981). At least three distinct upward-coarsening sequences have been identified within the Riverbank Formation; a paleosol exists at the top of the upper unit, below the Modesto Formation deposits (Davis and Hall, 1959; Marchand and Allwardt, 1981).

The Modesto Formation similarly comprises fluvially deposited arkosic sediment and locally derived deposits, gravel, sand, and silt, formed during the last major aggradational period in the eastern San Joaquin Valley (Marchand and Allwardt, 1981). Outcrops of the Modesto Formation appear throughout most of the study area and are visible between the Riverbank Formation and the San Joaquin River, except south of Turlock near the Merced River, where they are covered by stabilized and modern reactivated sand dunes.

Thin deposits of relatively unweathered sediments are contained within the Holocene alluvium along modern river channels. Texture ranges from coarse cobbles and boulders in the Sierra foothills to fine silt in the floodplain of the San Joaquin River (Davis and Hall, 1959). The Holocene alluvium primarily formed in point bar, levee, crevasse splay, interdistributary, and floodplain deposits. Some lacustrine, swamp and marsh deposits have accumulated near the center of the basin and some areas have dunes.

Characteristics of Existing Wells

The database of existing wells constructed for this study contains information from more than 3,500 drillers' logs, representing approximately one-third to one-half of the total number of wells drilled in this region. Although the existing well database does not include all well records, the data likely provides a representative sampling of existing wells. The majority (61 percent) of wells are for domestic use (2,170 wells), followed by irrigation (951 wells), municipal (147 wells), test (45 wells), stock (42 wells), industrial (39 wells), other (78 wells), or uses not identified (33 wells). Well depths ranged from 7.3 to 368 m (24 to 1,208 ft) below land surface, with a median depth of 59 m (195 ft). In general, domestic wells are screened in shallow parts of the aquifer system, whereas irrigation and municipal wells tend to be screened in deeper zones (*table 2*). The wells are widely distributed throughout the region (*fig. 7*), although some wells are clustered along highways and roads, and noticeably fewer wells exist in the older sediments and terraces east of Modesto and Turlock and along the San Joaquin River. As may be expected, the municipal wells are located primarily in the urban areas, and domestic and irrigation wells are widely distributed throughout the nonurban areas. Irrigation wells dominate the older deposits east of Turlock (*fig. 7*).

Although the areal distribution of well depths varies, the deepest wells generally are in the older sediments in the eastern part of the area and the shallowest wells generally are in the western part of the area and along the upper reaches of the rivers (*fig. 8*). Additional clusters of deep wells are in the area adjacent to the north and east side of the Modesto urban area, the area southwest of Turlock, and west of the San Joaquin River. Well depths provide some indication of water depth: areas with the deepest wells likely coincide with the greatest water-table depths and areas with the shallowest wells likely coincide with shallow water-table depths. The latter includes areas near the lower Tuolumne River west of Modesto and the area southwest of Turlock near the lower Merced River.

Changes in the number of newly drilled wells reflect changes in land use and water supplies. Since 1977, more than 5,000 wells were completed in the study area (California Department of Water Resources, 1993). Based on data from the existing well database, the number of domestic and municipal wells constructed during the 1970s through the 1990s increased (*fig. 9*), whereas the number of irrigation wells constructed in the 1980s and 1990s decreased compared with the 1970s. These trends may reflect the increase in population and decrease in irrigated farm acreage in the region. Land-use changes likely have an effect on the ground-water flow system, but long-term effects of these changes are unknown.

Table 2. Construction characteristics noted in database of wells in the Modesto area, San Joaquin Valley, California.

[Depths are in meters below land surface (feet in parentheses)]

Water use	Number of wells in database	Well depth			Screened interval depth		Median of depths to midpoint of screen
		Minimum	Median	Maximum	Median of top	Median of bottom	
Domestic	2,170	9.8 (32)	52 (170)	368 (1,208)	44 (143)	51 (168)	47 (155)
Irrigation	951	12 (40)	84 (277)	238 (780)	51 (166)	74 (242)	63 (206)
Municipal	147	20 (65)	85 (280)	171 (560)	59 (195)	75 (245)	68 (224)
All	3,505	7.3 (24)	59 (195)	368 (1,208)	46 (150)	60 (197)	53 (172.5)

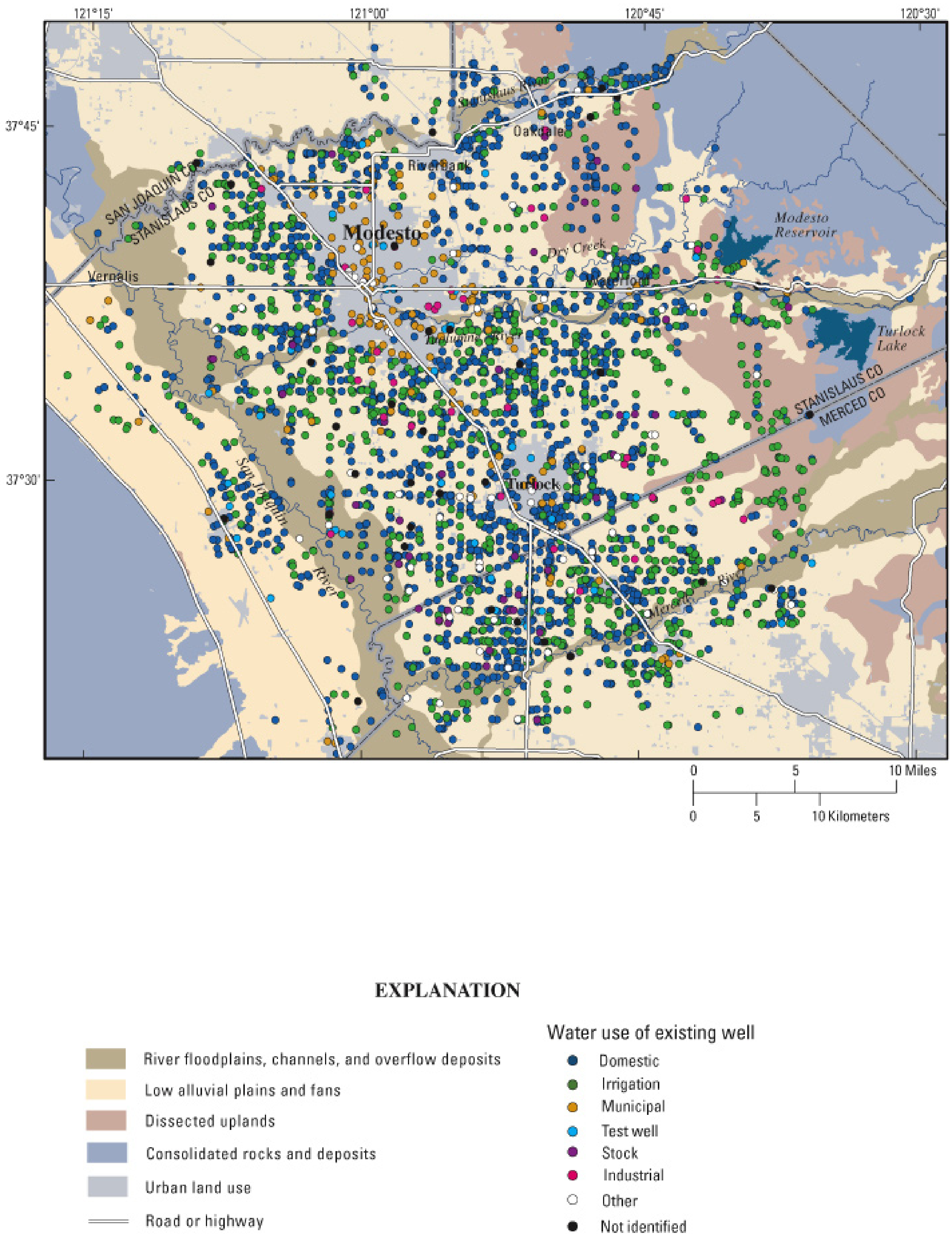


Figure 7. Water use of wells listed in database, near Modesto, San Joaquin Valley, California.

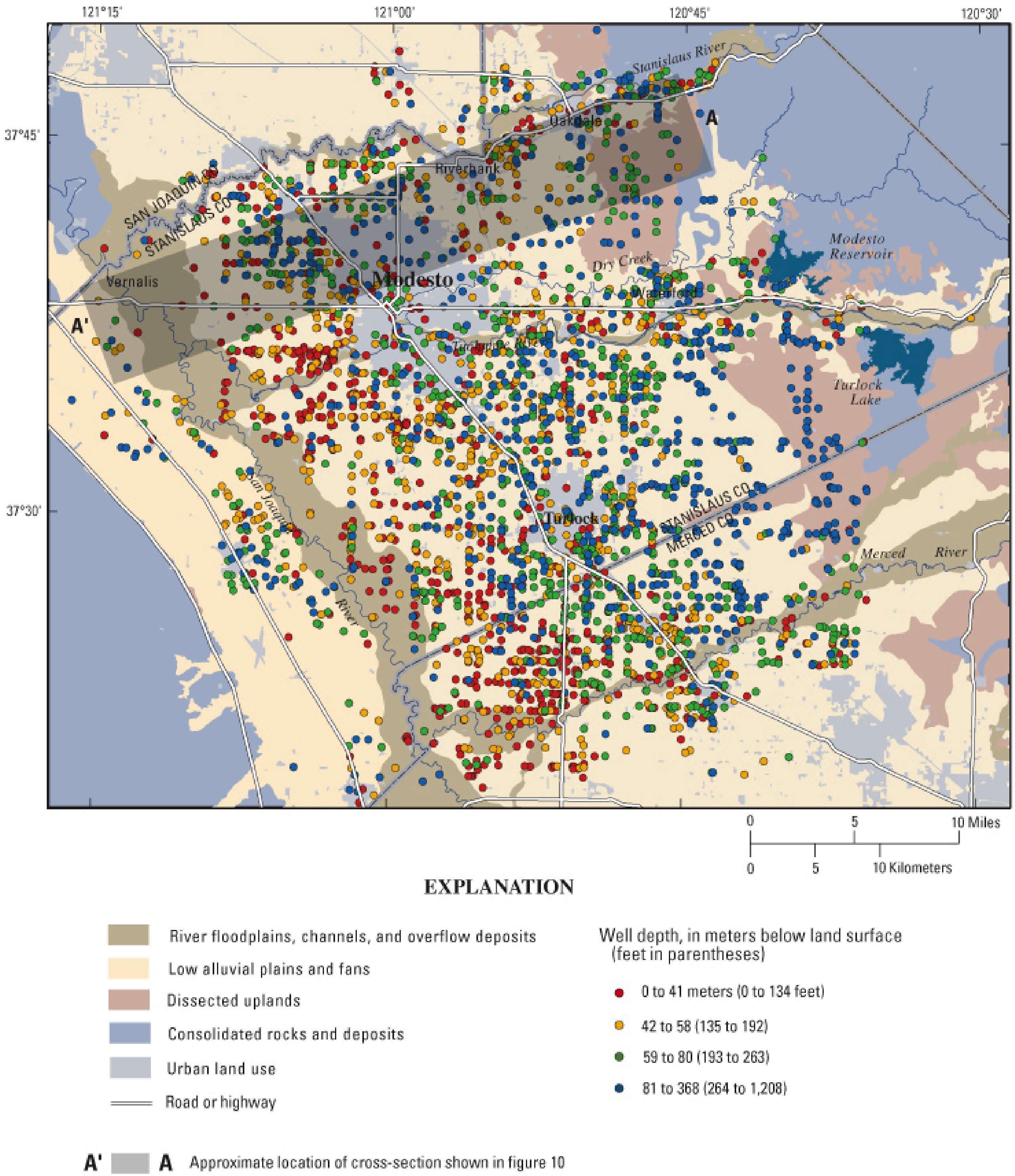


Figure 8. Depth of wells listed in database, near Modesto, San Joaquin Valley, California.

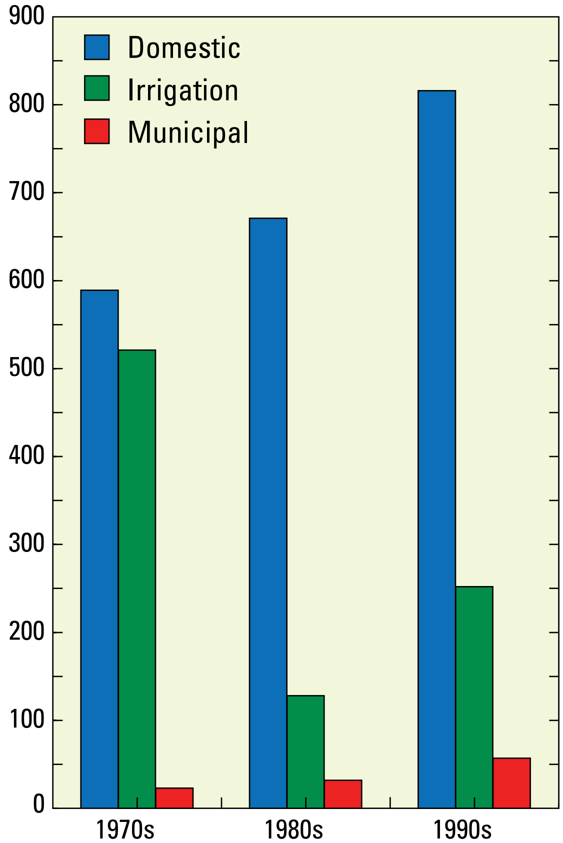


Figure 9. Number of domestic, irrigation, and municipal wells constructed during the 1970s, 1980s, and 1990s near Modesto, San Joaquin Valley, California. Data is from the well database used for this study and therefore does not include data on all wells in the study area.

Lithology and Stratigraphy

The database of existing wells was used in conjunction with a limited number of geophysical logs and the county soil maps (Arkley, 1962a, 1964; McElhiney, 1992) to define the lithologic and stratigraphic framework of the study area. The stratigraphic framework has been described in detail in earlier published reports; however, a significant number of new wells have been drilled since the earlier studies. The availability of the lithologic data in digital form and advances in computer software with three-dimensional analysis capabilities allow for easier visualization of correlations. However, the large number of moderate- to poor-quality lithology data made the analysis somewhat problematic because of the large amount of "noise" in the data. The interpretation of lithology and the stratigraphic framework in this report was intended to provide a generalized regional representation of the late Tertiary and Quaternary sediments in the subsurface using the new data and analysis tools. Additional analysis and collection of continuous cores from several wells would be required to provide detailed lithologic information at the local or site-specific scale.

Soils Data

Since the soils that develop on each of the stratigraphic units are distinctive, the county soil maps (Arkley, 1962a, 1964; McElhiney, 1992) can be used to determine the surface exposures of each unit (Davis and Hall, 1959; Arkley, 1962b; Marchand and Allwardt, 1981) and enable the stratigraphic units at shallow depths to be identified. The stratigraphic units and corresponding soil series mapping units in the Modesto region are listed in *table 1*.

Modesto Formation soils cover most of the western part of the study area (*fig. 6*). The Modesto Formation is characterized by generally well drained and poorly developed soils that are forming on either fluvial channel (*fig. 4*) and overbank deposits or aeolian dunes. Riverbank Formation deposits are exposed adjacent to and east of the Modesto Formation deposits. A relatively shallow hardpan or hard B-horizon typifies soils that are forming on the Riverbank Formation. Several Modesto Formation soil descriptions show that this Riverbank hardpan exists at shallow depths of 1 to 2 m (3 to 6 ft) under much of the Modesto Formation, indicating that the Modesto Formation is a thin veneer over the Riverbank exposure surface. Therefore, most of the wells in the study area are drilled through both the Modesto and Riverbank deposits near the surface. The thickest (greater than 2 m) Modesto Formation deposits exist near the foothills on the Tuolumne and Stanislaus River alluvial fans. The relative thickness of the Modesto Formation indicates that most of the formation was deposited south of the current Tuolumne River channel and north of the current Stanislaus River channel.

Well Data

Much of the deeper subsurface stratigraphic analysis is based on the well data. The large number of well logs and identification of color of the lithologic units provides a conceptual view of the regional stratigraphic patterns and character of the sediments, although the generalized lithologic descriptions prohibit characterization of specific sequences within the formations. Notable features with distinct colors include the paleosols, possible ash layers, the Corcoran Clay, and the Mehrten Formation. The paleosols are typically characterized as red hardpan or clay layers and are useful for stratigraphic characterization because they can be mapped over long distances (Davis and Hall, 1959; Lettis, 1982, 1988; Weissmann and others, 2002). White ash layers corresponding to the Bishop ash or Friant ash may be present in the logs as white clay, but few recordings of white clay in the logs make these layers difficult to characterize. The Corcoran Clay is usually noted in the logs as blue clay. The Corcoran Clay is an extensive, mappable unit, and is a notable confining unit in the western part of the study area. The

Mehrten Formation contains andesitic sands, often noted in the logs as black sands. The Mehrten Formation is an extensive, mappable unit composed of consolidated Tertiary sediments. Yields to wells are expected to be lower in the Mehrten Formation than in the overlying Pleistocene formations.

An east-west cross-sectional view of well-log data for the area between the Stanislaus and Tuolumne Rivers demonstrates the typical variability or noise in the data (*figs. 8*, *10*). However, it is difficult to distinguish between the variability caused by the uncertainty in the well-log descriptions and the variability caused by the heterogeneity in the deposits.

Turlock Lake Formation

Paleosols and Gravels

Lettis (1982, 1988) and Weissmann and others (2002) used reddish paleosols (described in well logs and core) to delineate stratigraphic boundaries between the Riverbank and the upper and lower Turlock Lake Formations. Red layers in the well-log database suggest that the top of the Turlock Lake Formation generally ranges from 15 to 30 m (50 to 100 ft) deep, although data are sparse north of the Tuolumne River. The presence of red layers is more consistent in the southern part of the study area between Turlock and the Merced River. The sparseness of data for wells north of the Tuolumne River may be due to the poor quality of the logs, although the paleosols in this area likely have been eroded.

Gravel exists at different depths in the study area, although it is primarily in the center of the cross section (*fig. 10*). Some gravel layers appear to have continuity, although tracing the gravel along local stream channels is difficult. The gravels likely represent channel deposits of the major rivers. The areal extent of the gravel noted in the well logs suggests that much channel activity took place along and adjacent to the Tuolumne River during the time when the upper Turlock Lake Formation was deposited (*fig. 11*). The apparent paleosols at the base of the upper Turlock Lake Formation (or above) typically fall outside of the areas with significant gravels.

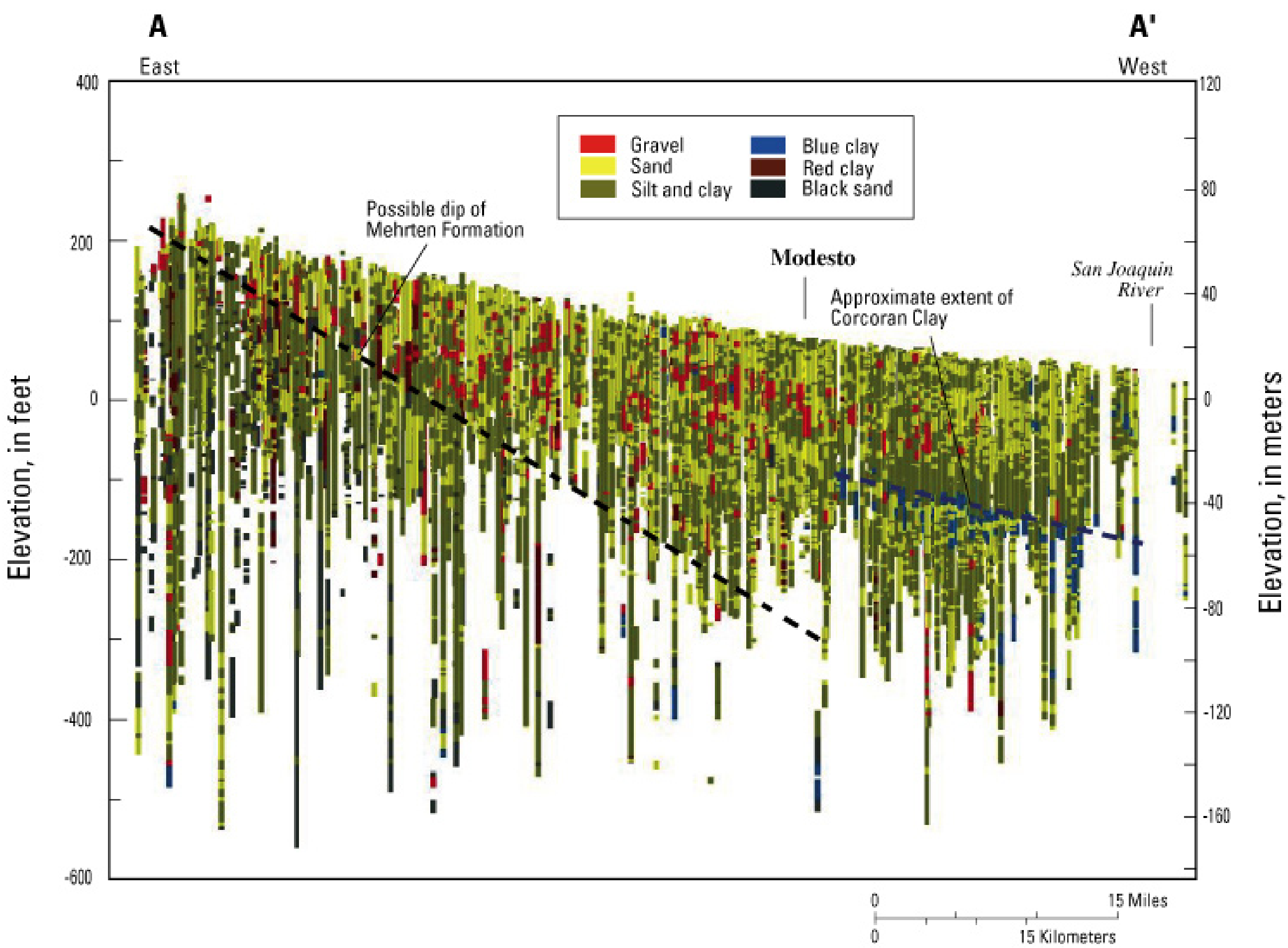


Figure 10. Cross-sectional view of lithologic well-log data along azimuth of 50 degrees between the Stanislaus and Tuolumne

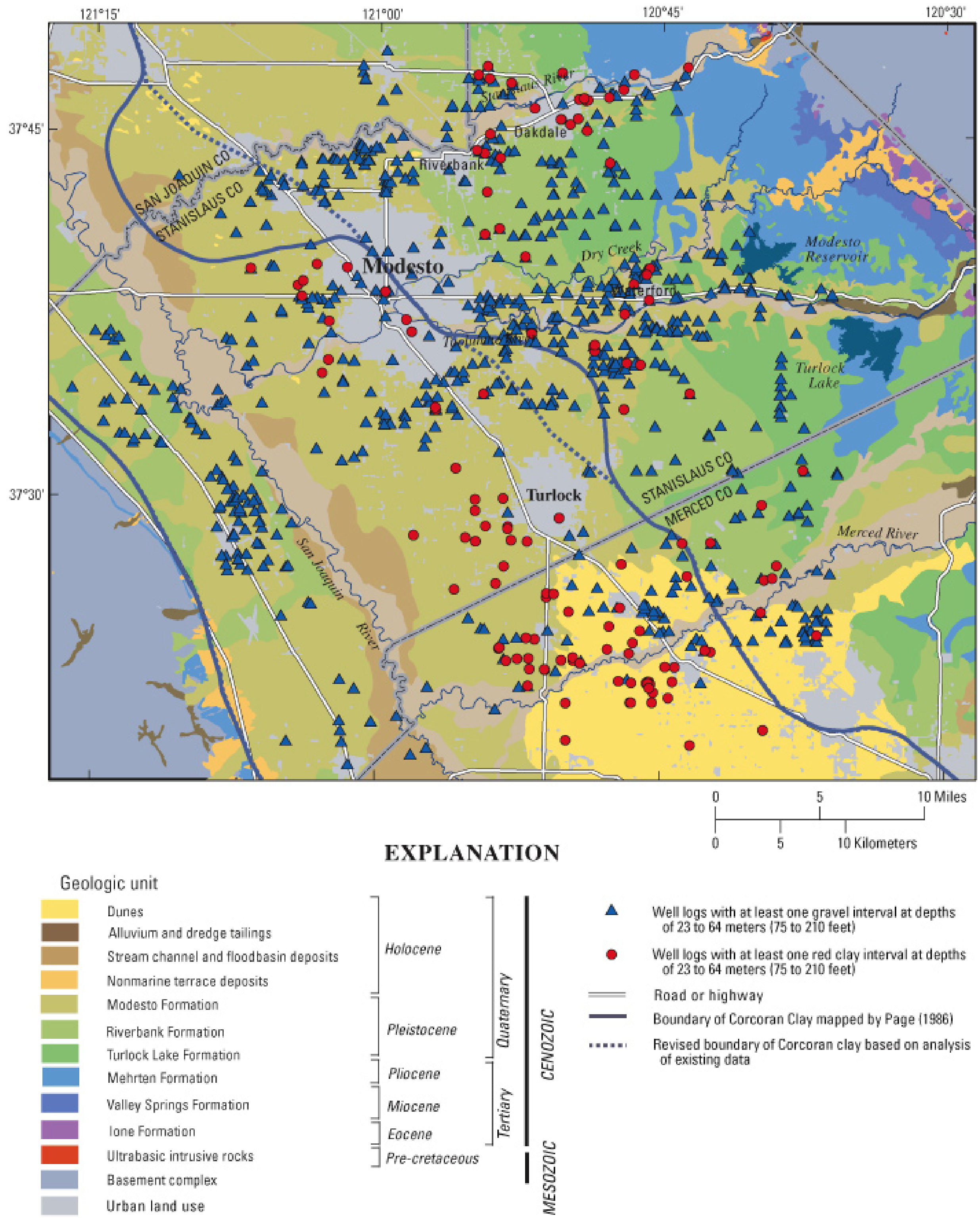


Figure 11. Gravel and red clay contained primarily within the Turlock Lake Formation near Modesto, San Joaquin Valley, California.

Alternatively, Weissmann and others (2002) showed that very coarse grained, incised valley-fill deposits (upward-fining cobble to sand sequence) are typically associated with each sequence-bounding paleosol. These incised valley-fill features are characteristically about 30 m (100 ft) thick and about 1.6 km (1 mi) wide and likely have a significant influence on ground-water flow and contaminant transport (Weissmann and others, in press). Incised valley-fill deposits in the Modesto, Riverbank, or Turlock Lake Formations have not been positively identified in the study area. Data from some geophysical logs from wells near and in Modesto, however, may indicate the presence of one of these incised valley-fill deposits adjacent to the Tuolumne River (*fig. 12*), as suggested by the upward-fining channel-fill deposits. Future drilling could aid in delineating these important hydrostratigraphic features.

Corcoran Clay

The most notable feature that can be determined in the cross section of the well-log data is the dip and extent of the Corcoran Clay in the western part of the cross section (*fig. 10*). The Corcoran Clay, located at the base of the upper Turlock Lake Formation (Marchand and Allwardt, 1981), is typically identified in well logs as blue clay, although in places, the color more closely resembles a dark greenish gray, and in a few locations, the clay has been described as brown or reddish brown (Davis and others, 1959), and not all blue clay is part of the Corcoran Clay. The Corcoran Clay generally is well sorted with a notable absence of sand; however, the clay becomes more silty and more difficult to recognize along the edges where the unit either grades into coarser materials of the same age or wedges out (Davis and others, 1959). Page (1986) most recently mapped the extent of the Corcoran Clay throughout the San Joaquin Valley; however, well logs in the database used in the current study indicate that blue clay extends to the east of the boundary mapped by Page (1986), northwest of Modesto and to the west of the boundary along the present-day Tuolumne River east of Modesto (*fig. 13*). Based on the well database, the eastern extent of the Corcoran Clay appears to lie approximately parallel to the axis of the Valley.

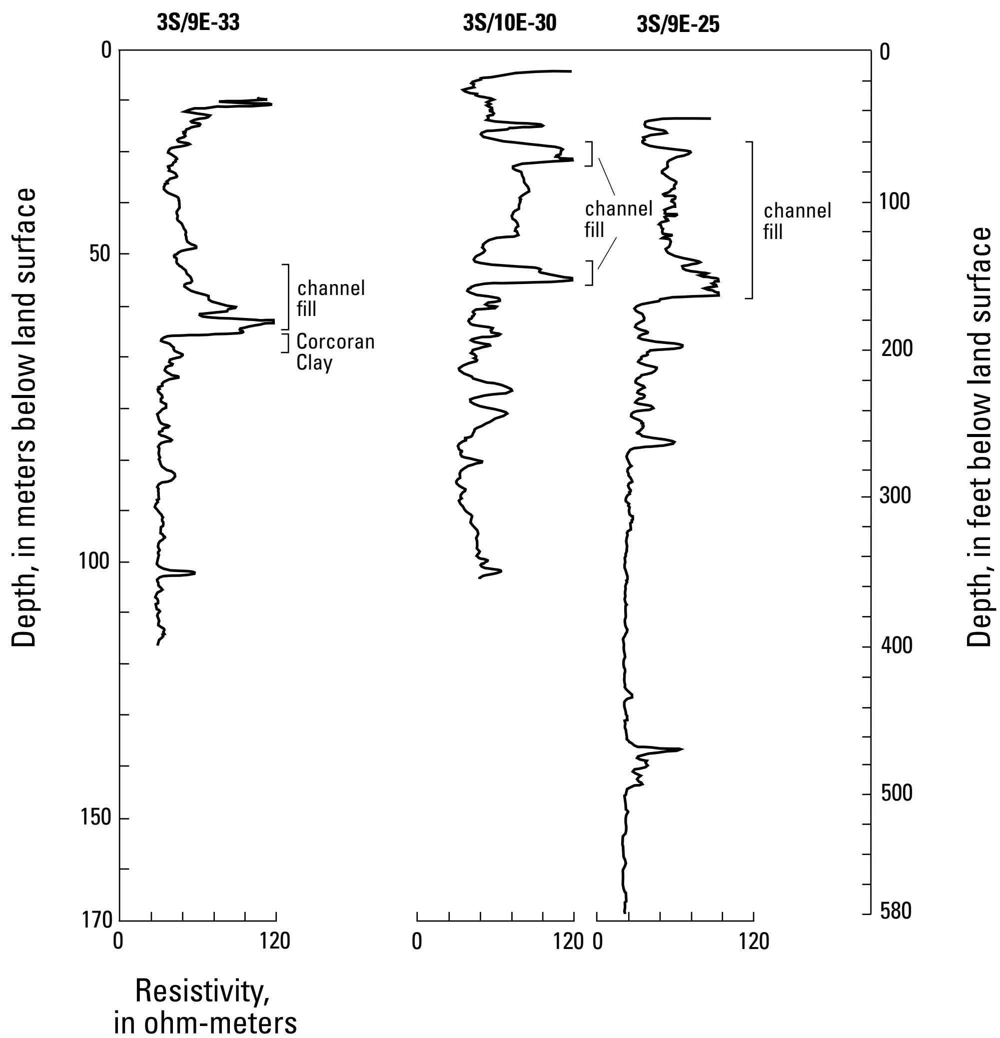


Figure 12. Resistivity log of selected test holes near Modesto, San Joaquin Valley, California. See *figure 13* for locations of test holes.

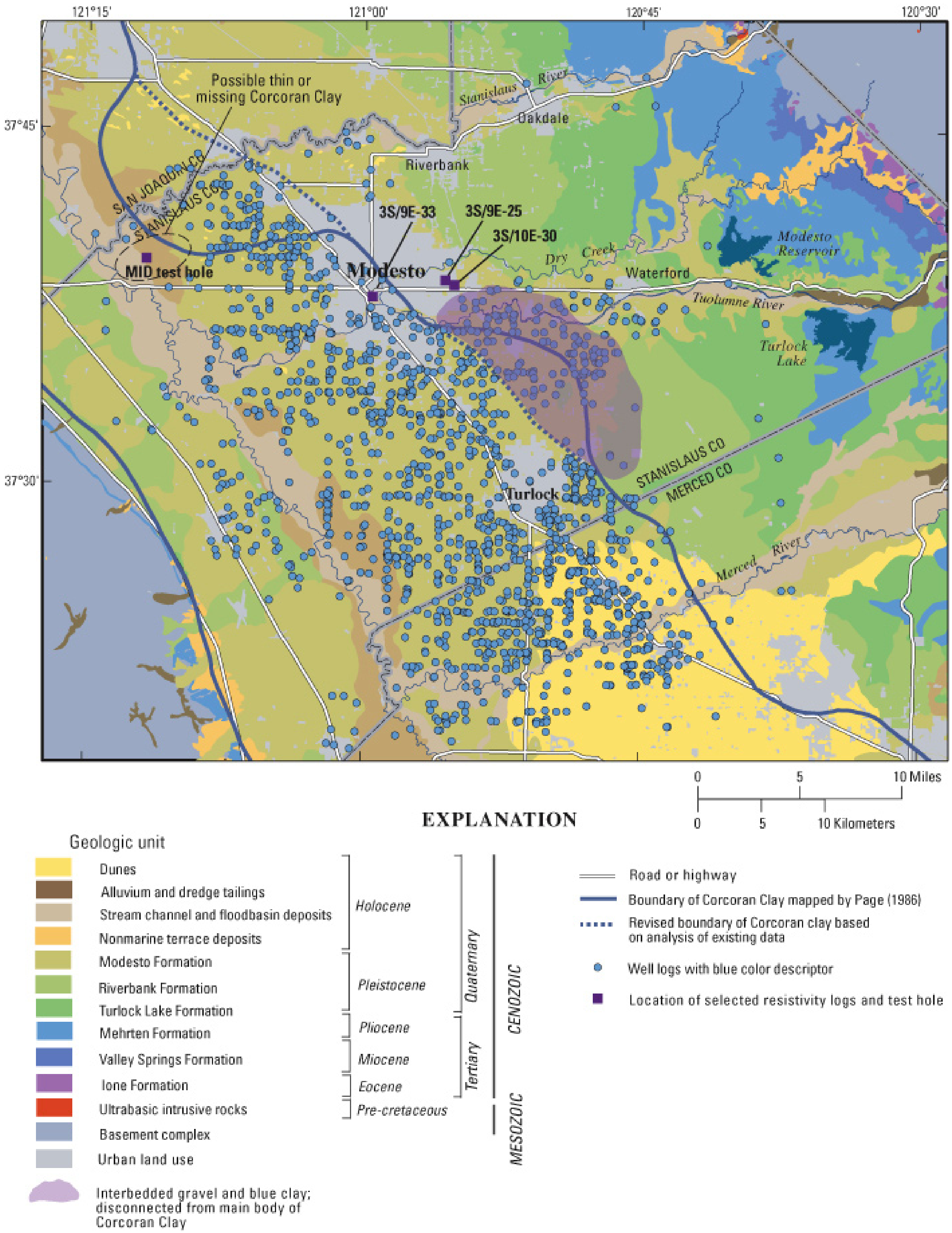


Figure 13. Occurrence of blue color noted in well logs and revised extent of Corcoran Clay boundary near Modesto, San Joaquin Valley, California.

In the area northwest of Modesto, between the eastern extent of the Corcoran Clay as mapped by Page (1986) and the eastern extent determined for this study, numerous drillers' logs indicate blue clay at depths of about 60 m (200 ft), which is consistent with depths mapped by Page (1986), although blue clay was also noted in these logs at depths above and below the Corcoran Clay. Kvenvolden (1957) discussed the difficulty of identifying the Corcoran Clay in a test hole drilled for MID (*fig. 13*) near the confluence of the Stanislaus and San Joaquin Rivers. Kvenvolden (1957) noted that a significant blue clay was seen at 80 m (262 ft) below land surface; however, the depth was too deep to correlate with the Corcoran Clay encountered in other wells. New data obtained from the current study was consistent with that given by Kvenvolden (1957) in that no new wells exposed the Corcoran Clay at the expected depths near the MID test hole. Although relatively few well logs were available in this area, the apparent lack of continuity of the Corcoran Clay suggests that it may have been thin or eroded in this area, or was subject to deformation or oxidation, making it difficult to characterize.

Additional data from resistivity logs in the same area and a few kilometers east of the MID test hole indicate that a clay of unidentified color and a thickness of 12 to 18 m (40 to 60 ft) lies above the apparent depth of the Corcoran Clay. A thick silt and clay layer above the Corcoran Clay is noted in many of the drillers' logs and is evident in the lithologic cross section generated from the logs (*fig. 10*). This fine-grained unit could be related to the Corcoran Clay; however, additional data and analysis would be needed to determine the relation between this unit and the Corcoran Clay.

The blue clay in the Tuolumne River channel area (*fig. 13*) is a mixture of blue clays at different depths. A laterally continuous blue clay is present at about the same depth as the Corcoran Clay at the eastern end of the mapped blue clay (between Waterford and the easternmost extent mapped by Page [1986]). Between this contiguous clay and the main body of the Corcoran Clay are disconnected segments of a shallow blue clay, less than 30 m deep (100 ft), a deep blue clay, greater than 67 m (220 ft) deep, and what may be the remnant Corcoran Clay (*fig. 13*). Extensive gravel deposits in this intermediate area between the boundary described by Page and the current boundary suggest that the Corcoran Clay was eroded by one or more stream channels or that the Corcoran Clay deposits interfinger with the Tuolumne River deposits, perhaps having formed a small delta that eventually diverted the river to the north or south. Because of the hydrologic significance of the continuity of the Corcoran Clay, for this study, the blue clays in the upper Tuolumne River area were not included as part of the Corcoran Clay. As a result, the eastern boundary was moved to the west where the blue clay is contiguous with the main body of the Corcoran Clay. The Corcoran Clay boundary near the Merced River does not extend eastward as it does near the Tuolumne River, although the well-log data is not adequate to speculate on the differences between the Merced and Tuolumne River fans during the time of deposition of the Corcoran Clay.

Mehrten Formation

The Mehrten Formation is distinguished in the well-log database by its characteristic "black sands" consisting of predominantly andesitic fragments (*fig. 14*). The Mehrten Formation is tapped by wells primarily in the eastern part of the study area, from the outcrop of the Mehrten Formation to the Modesto and Turlock areas. The top of the Mehrten Formation has been identified in geophysical well logs by a significant change from coarse-grained dominated units of the overlying Quaternary sediments to the relatively fine grained and compacted Mehrten Formation. Silt and clay mixed with black sand and red clay dipping from their exposure at the land surface at the eastern end of the lithologic cross section (*fig. 10*) may indicate this boundary at the top of the Tertiary sediments.

Although the black sands noted in the well logs likely are not the top contact of the Mehrten Formation, the first occurrence of black sands in wells in the database indicate that the formation dips to the southwest at a slope of about 0.006. Previous investigators characterized the Mehrten with a much steeper slope of about 0.04 (Davis and Hall, 1959), indicating that the Mehrten would exist at depths as much as 210 m (700 ft) below the city of Modesto. Results of the analysis for this report, however, suggest the Mehrten Formation may lie as shallow as 120 m (400 ft) below Modesto, approximately 90 m (300 ft) shallower than previously thought. Because the Mehrten Formation sediments have been characterized as being less permeable than the overlying Quaternary sediments, the existence of the Mehrten Formation at shallow depths in the study area may have implications for future development of the ground-water resource. The previous work was based primarily on surface exposures of the Mehrten. Deformation along the mountain front could have added significant uncertainty to the apparent slope.

In some locations, the black sands appear to be at much shallower depths than expected (*fig. 14*), even accounting for the shallower slope. The apparent black sands in the overlying formations are likely reworked Mehrten materials. The Laguna and lower Turlock Lake Formations contain andesitic fragments in coarse-grained units, although the percentage of andesitic fragments is smaller than in the Mehrten Formation. The unusually shallow black sands noted in well logs appear to lie along possible buried stream channels (*fig. 14*), although the data are insufficient to determine whether paleochannels exist in these areas.

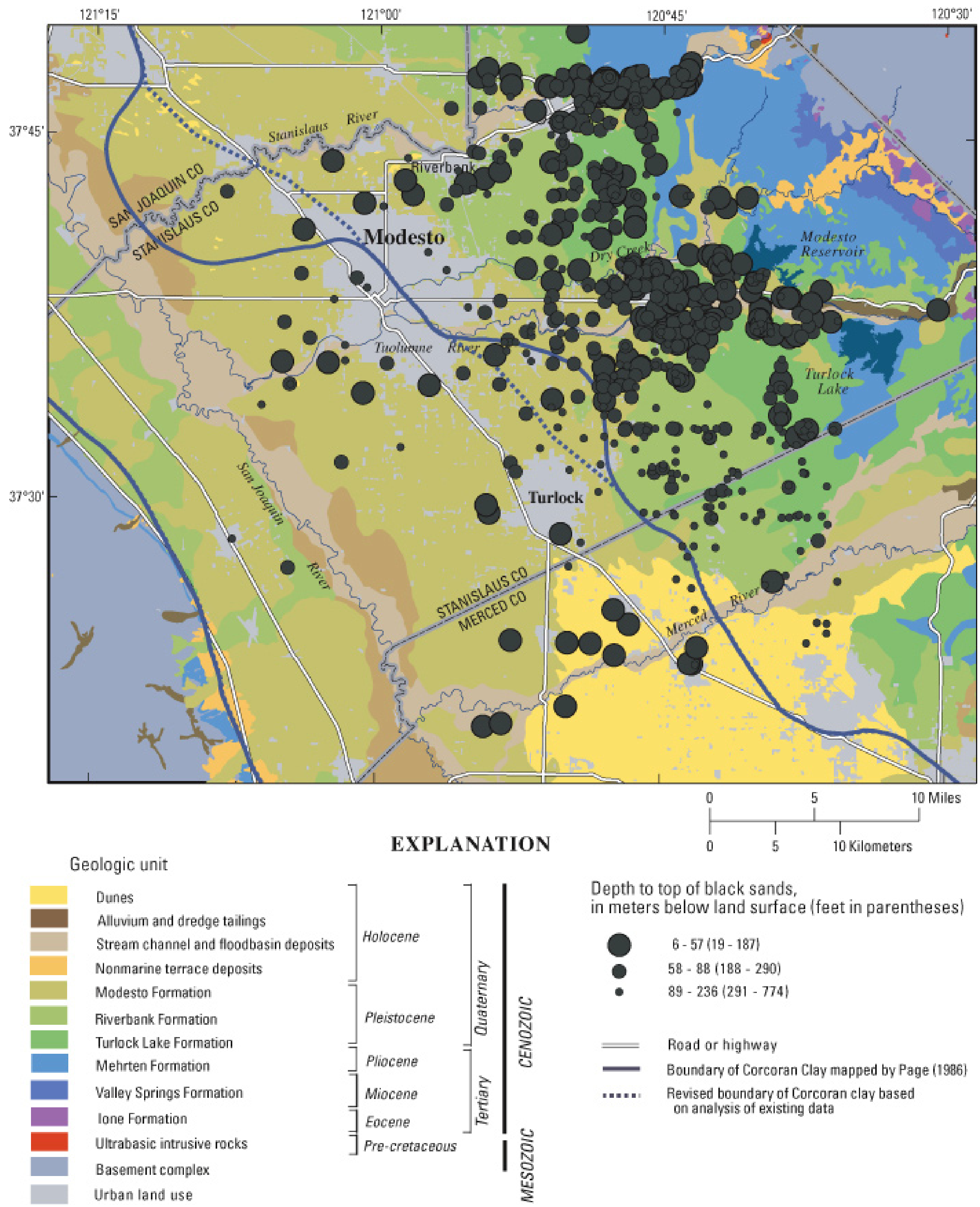


Figure 14. Extent of Mehrten Formation as indicated by the depth of black sands near Modesto, San Joaquin Valley, California.

Hydrology and Water Use

Description of Aquifer System

The alluvial aquifer system in the Modesto area comprises an unconfined to semiconfined aquifer in the unconsolidated to partly-consolidated deposits above and east of the Corcoran Clay confining unit and a confined aquifer in the unconsolidated to partly-consolidated deposits beneath the Corcoran Clay. Ground water is also in the consolidated rocks below the principal aquifers.

The unconfined aquifer above the Corcoran Clay ranges from about 40 to 70 m (130 to 220 ft) thick (Page, 1977b) and comprises alluvial sediments of the Modesto, Riverbank, and upper Turlock Lake Formations. Where the Corcoran Clay does not exist, the unconfined aquifer becomes semiconfined with depth owing to the numerous discontinuous clay lenses and extensive paleosols (hardpan layers) throughout the aquifer thickness. This unconfined to semiconfined aquifer is composed primarily of alluvial sediments of the Riverbank and Turlock Lake Formations; however, the lower portion of this aquifer comprises sediments from the upper Mehrten Formation. Coarse-grained gravel and sand layers present in the upper part of the Mehrten Formation may have adequate permeability (Page, 1986) for water supply; however, the Mehrten sediments are more consolidated than the overlying formations and the sand beds are generally thin and their degree of interconnection is unknown. Some earlier researchers thought that the unconfined to semiconfined aquifer was restricted to the Quaternary sediments. As mentioned previously, results from this study indicate that the Mehrten Formation dips much less steeply than originally thought. As a result, current production wells in the central and eastern parts of the study area likely derive a significant amount of water from the Mehrten Formation sediments.

The confined aquifer comprises primarily alluvial sediments of the Turlock Lake and upper Mehrten formations, extending from beneath the Corcoran Clay to the base of fresh water. Page (1973) mapped the base of fresh water as the boundary where the specific conductance of water changed from greater than 3,000 microsiemens per centimeter to less than 3,000 microsiemens per centimeter. In the Modesto area, the mapped base of fresh water ranges from about 60 m (200 ft) below land surface in the eastern part of the study area where the Mehrten formation is shallow, to a depth of 210 m (700 ft) beneath the western part of the city of Modesto, and to a depth of 120 m (400 ft) below land surface in the northwestern part of the study area near the confluence of the Stanislaus and San Joaquin Rivers (Page, 1973). Saline water also exists as shallow as about 90 m (300 ft) below land surface in the area west and southwest of Turlock according to measurements in two irrigation wells (5S/9E-17Q2 and 6S/10E-20R2) (U.S. Geological Survey, 2002, accessed August 7, 2002) during the 1980s. High salinity water in the eastern San Joaquin Valley is statistically correlated with geochemically reduced ground water, attributed to the longer residence times of ground water moving toward natural discharge areas along streams and in the center of the basin (Burow and others, 1998), although local high salinity areas could result from anthropogenic activities.

The aquifer in the consolidated rocks below the principal aquifers and above the base of fresh water is not well defined because of the lack of data, although Page and Balding (1973) reported that the consolidated rock aquifer is likely both perched and confined within the Ione, the Valley Springs, and the Mehrten Formations.

Movement of Ground Water

During predevelopment, ground water was primarily recharged at the upper parts of the alluvial fans in the eastern part of the study area where the major streams enter the valley. In the lower parts of the alluvial fans, ground water moved generally westward and toward the Merced and Tuolumne Rivers from both sides, and artesian conditions in the western part of the study area reflected the upward movement from the confined aquifer in the center of the basin (Davis and others, 1959). Since development of the basin, ground water in the unconfined to semiconfined aquifer has flowed to the west and southwest along the dip of the water bearing units (*fig. 15A*). The primary source of recharge has been percolating excess irrigation water, and the primary means of ground-water discharge has been extensive pumping of ground water in the unconfined to semiconfined aquifer (Page and Balding, 1973; Londquist, 1981). These forms of recharge and discharge provide a significant component of vertical flow in the system. In the western part of the study area, ground-water movement is downward to the confined aquifer from the overlying unconfined aquifer through the Corcoran Clay. Although water-level data are insufficient to map the piezometric surface of the confined aquifer, the downward flow direction is likely induced by pumping beneath the Corcoran Clay on the west side of the San Joaquin River (Hotchkiss and Balding, 1971; Page and Balding, 1973). In the southeastern part of the study area where ground water is the sole source of irrigation supply, a pumping depression exists, but it is only approximated on the spring 2000 water-level map owing to insufficient data (*fig 15A).*

Ground-Water Development

Water-level and pumping records indicate that as pumping in the basin has increased, flow to and from streams and rivers in the area have been affected. Water has been diverted from the rivers to recharge the semiconfined aquifer, and ground-water discharge to streams has been diverted by pumping wells. Thus, the ground-water and surface-water systems are interconnected.

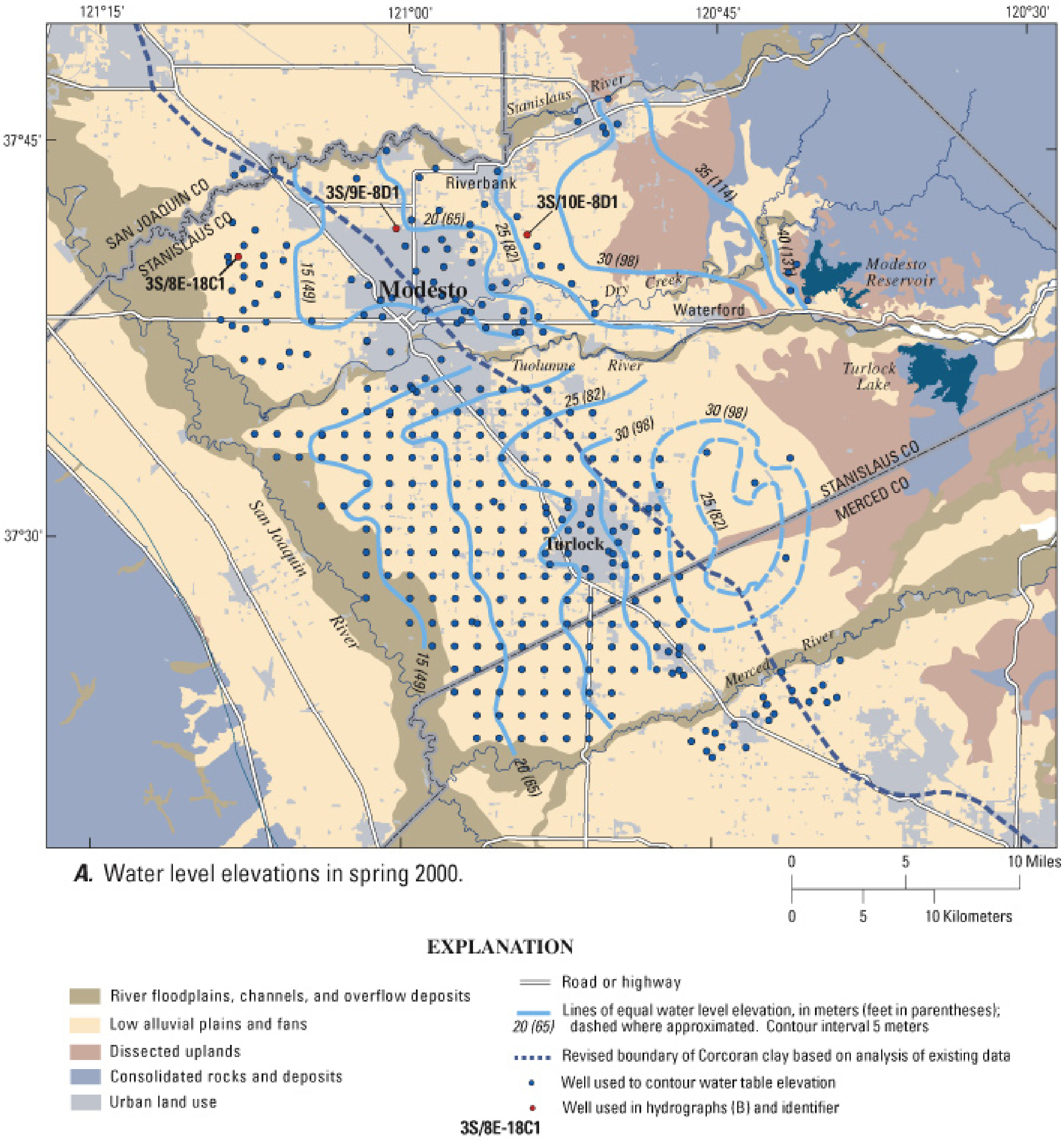


Figure 15. Water-level elevations in unconfined to semiconfined aquifer near Modesto, San Joaquin Valley, California. *A*. Water level elevations in spring 2000. *B*. Water level elevations from November 1969 to November 2000 in selected irrigation wells. Well locations shown in *A*.

Surface water is used extensively for irrigation. In the unconfined aquifer above the Corcoran Clay, drainage pumping is used to maintain water levels in the shallow aquifer below the root zone. The amount of drainage pumping has decreased over time as municipal pumping has increased (Modesto Irrigation District, 1996).

Since the 1960s, water levels have responded to increases in pumpage and drought. Increases in pumpage and the associated depletions in streamflow are due to increasing urbanization. Drought years in the late 1970s and during the late 1980s through the early 1990s also have affected water levels. Using a ground-water model constructed for the Modesto area, Londquist (1981) determined that 54 percent of the total pumpage increase from 1952 to 1978 was derived from storage, 38 percent from streams, and the remainder from flow across constant-head boundaries. Stream depletion was less than 1 percent of the total surface-water flow out of the model area. Long term water-level data in selected wells representing the unconfined to semiconfined aquifer east of Modesto, adjacent to Modesto, and west of Modesto suggest that water levels generally decreased in the eastern and central Modesto area until the early 1990s (*fig. 15B*). A series of wet years, as well as the completion of a surface-water treatment plant in 1994 that provided an additional source of municipal and industrial water supply, resulted in recent recovery of water levels. The well closest to the city (well 3S/9E-8D1) shows the greatest change in water levels. Alternatively, water levels in the unconfined aquifer in the northwestern part of the study area (well 3S/8E-18C1) have remained relatively constant during this same period.

Hydraulic Properties

The unconfined to semiconfined aquifer yields large amounts of water to wells, with an average yield of 7.2 m^3/min (1,900 gal/min) reported for 96 large capacity wells (Page and Balding, 1973). Average specific capacity for 26 wells perforated in the unconfined aquifer above and east of the Corcoran Clay was 0.7 m^2/min (7.5 ft^2/min or 56 gal/min/ft), whereas 6 wells perforated in the confined aquifer below the Corcoran Clay had an average value of 0.3 m^2/min (3.2 ft^2/min or 24 gal/min/ft). Reported values of transmissivity in the upper unconsolidated part of the aquifer were about 1,090 m^2/day (11,700 ft^2/day) (Page and Balding, 1973); reported hydraulic conductivities in the unconfined aquifer above the Corcoran Clay ranged from 8 to 16 m/day (27 to 54 ft/day) (Page, 1977b). Transmissivities in the shallow aquifer are generally lower in the eastern part of the study area where the aquifer sediments are more consolidated, resulting in yields of about 3.8 m^3/min (1,000 gal/min) and a transmissivity of 850 m^2/day (9,100 ft^2/day) (California Department of Water Resources, 1967; Page and Balding, 1973). Transmissivity in the deeper, partly-consolidated sediments was about 740 m^2/day (8,000 ft^2/day), and reported hydraulic conductivities in the Mehrten Formation ranged from about 0.003 to 20 m/day (0.01 to 67 ft/day) (Page and Balding, 1973). The Corcoran Clay ranges in thickness from 6 to 30 m (20 to 100 ft), with vertical hydraulic conductivities that ranged from 1×10^{-6} to 3×10^{-6} m/day (3×10^{-6} to 9×10^{-6} ft/day) and specific storage estimates that ranged from 4×10^{-6} for elastic conditions to 2×10^{-4} for inelastic conditions (Page, 1977b).

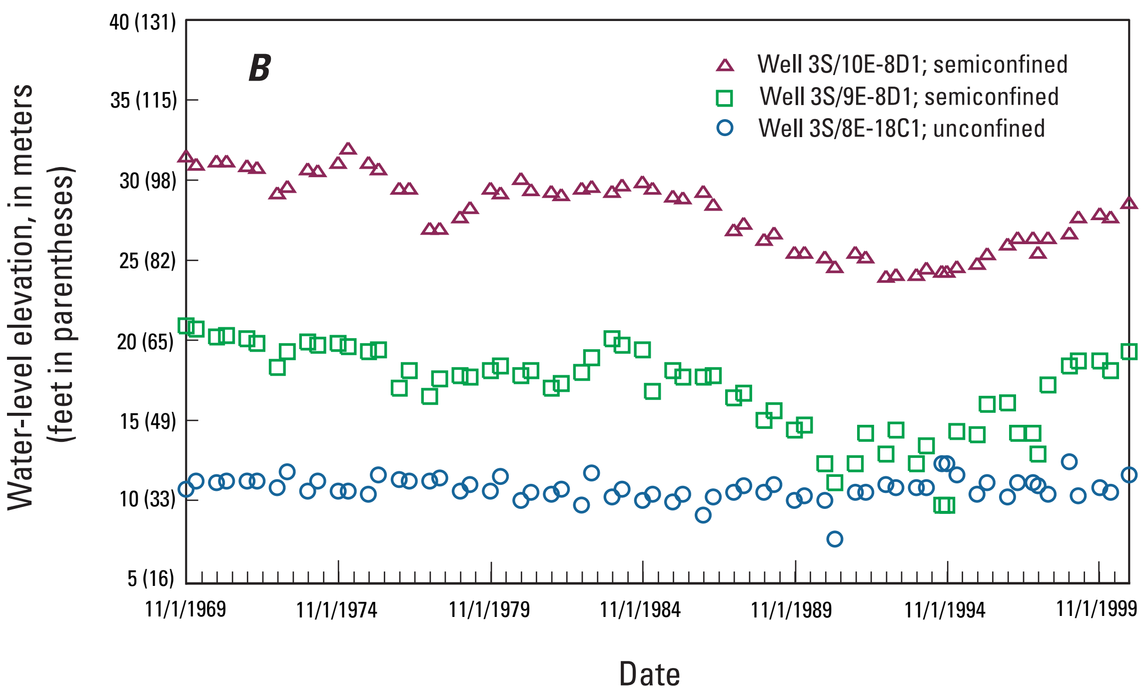


Figure 15. *Continued.*

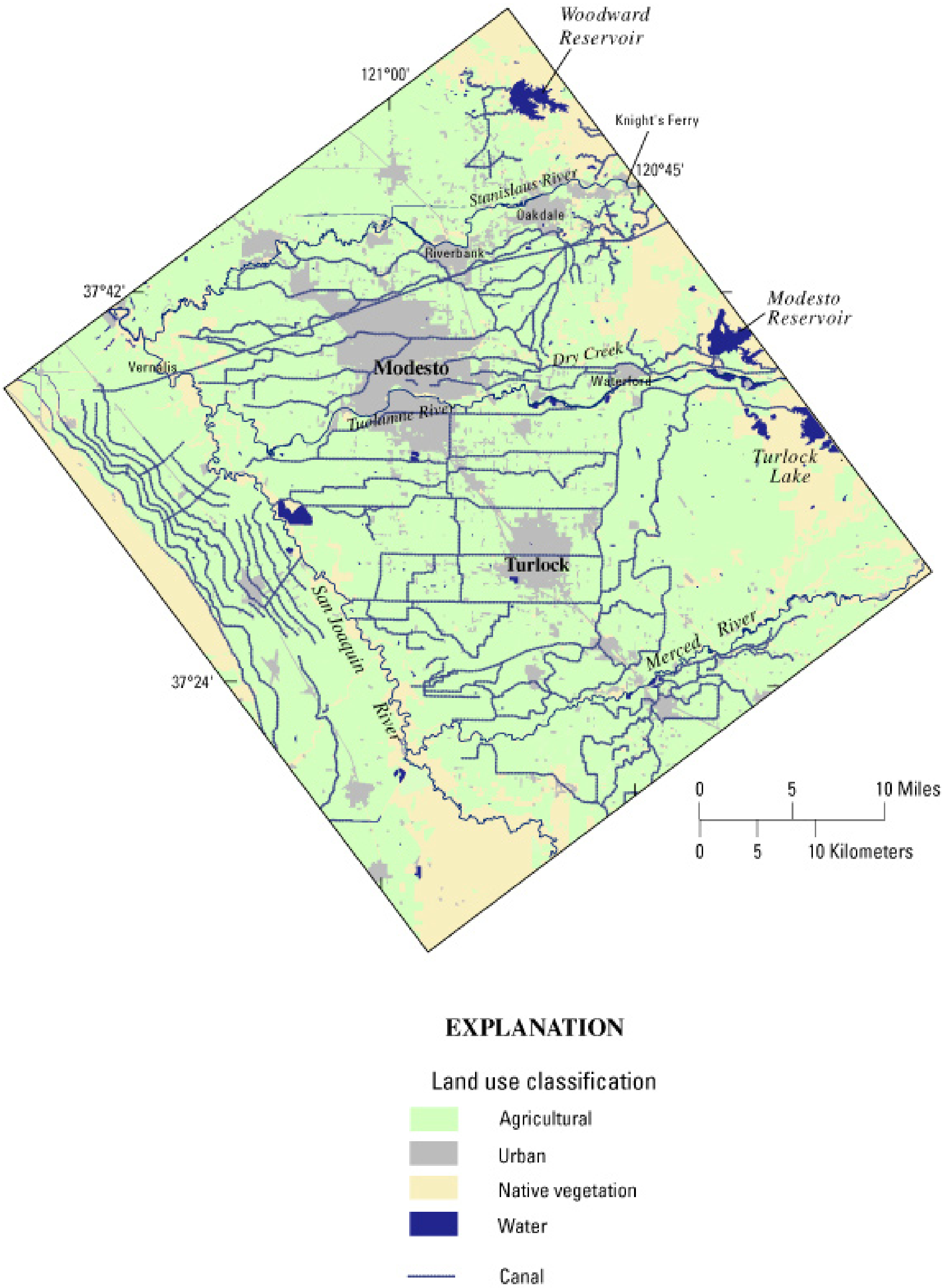


Figure 16. Land-use classification in 1996 in model area near Modesto, San Joaquin Valley, California. Land use data from California Department of Water Resources (2001b).

Hydraulic conductivities assigned in the NAWQA regional ground-water flow model (S.P. Phillips, U.S. Geological Survey, unpub. data, 2004) varied depending on the amount of coarse-grained material (sand or gravel) in each model cell; calibrated hydraulic conductivity for the coarse-grained end-member (100 percent sand or gravel) was 235 m/day (770 ft/day) and the calibrated hydraulic conductivity for the fine-grained end-member (0 percent sand or gravel) was 0.0004 m/day (0.0013 ft/day). The model-calibrated vertical hydraulic conductivity of the Corcoran Clay in the NAWQA regional ground-water flow model was 0.004 m/day (0.013 ft/day) (S.P. Phillips, U.S. Geological Survey, unpub. data, 2004).

Water Budget

A water budget was computed and used to estimate recharge and ground-water pumpage for the NAWQA regional steady-state ground-water flow model for the Modesto area (*fig. 1*). Water-budget data is derived from local agency records for water year 2000 (WY2000), from October 1, 1999, through September 30, 2000. WY2000 data were used in the model because this dataset was the most complete available between WY1997 and WY2002 and water levels had generally recovered since the early 1990s (*fig. 15B*). The NAWQA ground-water flow model area is more than 2,600 km^2 (643,000 acres), of which about 68 percent is irrigated agricultural land (*fig. 16*). Thousands of kilometers of canals deliver surface water for irrigating crops and for municipal drinking-water supply.

The water budget was calculated by dividing the area into the smallest subareas for which data for surface- and ground-water deliveries could be obtained or estimated for WY2000. A separate water budget was calculated for each of the resulting 47 subareas (*fig. 2*), including 8 MID subareas, 16 TID subareas, and 7 subareas comprising riparian areas along river corridors and recently converted agricultural land around the northern Modesto city limits (*table 3*). Surface-water delivery data and some limited ground-water delivery data were available; however, private pumpage records were not available. Therefore, estimated pumpage and recharge were determined using a land-use approach (described in more detail in the methods section of this report). The largest proportion of wells in the study area is domestic wells; however, domestic well pumpage was not included in the water budget for the model. Because of their small pumping rates, they are not expected to significantly influence the ground-water flow system.

In OID and 3 TID subareas, the estimated surface-water deliveries exceeded the crop demand, resulting in an estimated private pumpage that was negative (*table 3*). Most irrigation canals are concrete lined, which significantly reduces ground-water recharge from the canals; estimates of canal leakage were not included in the water-budget calculations. The urban water budget was estimated using the minimum month method (as described in methods section) to separate indoor and outdoor water use (California Department of Water Resources, 1994) and thus estimate the amount of water recharged through outdoor landscape irrigation. Monthly totals for pumpage and surface-water deliveries for Modesto (California Department of Water Resources, 2002) indicated that the baseline indoor water use was about 3.8 million m^3 (3,100 acre-ft or 1,000 million gallons) in WY2000 (*fig. 17*).

Water Supply

The total water supply (surface water deliveries and total ground-water pumpage) was estimated at more than 2.5 billion m^3 (2 million acre-ft) for WY2000 (*table 3*). Surface-water deliveries accounted for the largest part (60 percent) at more than 1.5 billion m^3 (1.2 million acre-ft). Ground-water pumpage accounted for 40 percent, at slightly more than 1 billion m^3 (830,000 acre-ft). Approximately 2.4 billion m^3 (2 million acre-ft) (94 percent) of water was used to meet irrigation demand; 62 percent was supplied by surface water and 38 percent was supplied by ground water. In contrast to irrigation demand, of the approximately 140 million m^3 (110,000 acre-ft) (6 percent) of water used to meet urban demand, 28 percent was supplied by surface water and 72 percent was supplied by ground water.

Recharge

The total recharge was estimated at 1.4 billion m^3 (1,100,000 acre-ft) during WY2000 (*table 3*). The largest component of recharge is irrigation recharge (58 percent), totaling 830 million m^3 (670,000 acre-ft). Precipitation in excess of crop requirements accounted for 41 percent of the recharge, totaling 580 million m^3 (470,000 acre-ft). Because the urban area is smaller than the agricultural area and because of the differences between urban and agricultural water use, the urban recharge (including landscape irrigation and excess precipitation) was a minor part (2 percent) of the total recharge, totaling only 32 million m^3 (26,000 acre-ft).

The average areal recharge rate was about 0.54 m/yr (1.8 ft/yr). The highest recharge rates generally are in the agricultural areas in the western part of the study area, along the canals north and south of the Tuolumne River east of Modesto and along the canals south of the Merced River (*fig. 18*). The recharge rates generally are lowest in the eastern part of the study area, in the foothills and adjacent uplands, and in the Modesto urban area (*fig. 18*). The average areal pumpage rates generally are highest in the agricultural areas in the western part of the study area (*fig. 19*). Pumpage rates often correspond to recharge rates (for example, high pumpage in high recharge areas), although in the OID and SSJID subareas, the riparian areas along the Merced River, and several subareas in the southern TID area, pumpage is lower than recharge. Some subareas have pumpage rates that are higher than recharge rates, including the EWD and Modesto urban subareas.

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California.

[Areal distribution of subareas shown in figure 2. m^2, square meter; m^3, cubic meter; —, not included in water budget]

	Irrigation demand				Surface-water deliveries and ground-water pumpage				
Water budget subarea (acronym)	**Total area (m^2)**	**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)**	**Private agricultural ground-water pumpage (m^3)**	**Urban ground-water pumpage (m^3)**	**Total ground-water pumpage (m^3)**
Eastside Water District (EWD)									
EWD	250,401,821	214,781,896	192,159,808	240,199,759	—	—	240,199,759	—	240,199,759
Merced Irrigation District (MER)									
North of Merced River (MER-N)	17,160,043	15,958,943	14,831,227	23,541,630	11,536,755	—	12,004,875	—	12,004,875
South of Merced River (MER-S)	142,981,961	118,304,742	104,089,218	165,220,981	73,647,498	2,563,052	89,010,431	1,858,512	93,431,995
Total MER	160,142,004	134,263,686	118,920,445	188,762,611	85,184,253	2,563,052	101,015,306	1,858,512	105,436,870
Merquin Community Water District (MERQ)									
MERQ	45,880,569	29,744,731	28,761,456	45,653,105	21,909,708	—	23,743,397	—	23,743,397
Modesto Irrigation District (MID)									
MID-1	16,984,889	15,264,431	14,701,371	23,335,510	19,003,714	—	4,331,796	—	4,331,796
MID-2	33,587,124	28,370,601	27,934,122	44,339,876	22,322,225	295,172	21,722,478	2,009,194	24,026,844
MID-3	46,078,833	36,436,879	34,396,306	54,597,310	24,230,446	1,400,495	28,966,369	6,784,279	37,151,143
MID-4	51,457,144	41,480,204	38,857,079	61,677,903	28,263,589	1,041,059	32,373,255	2,558,238	35,972,552
MID-5	46,487,815	43,823,163	40,034,319	63,546,538	21,706,800	8,073,878	33,765,860	—	41,839,738
MID-6	37,664,875	33,992,564	32,831,035	52,112,755	19,263,534	9,259,254	23,589,966	—	32,849,220
MID-7	28,542,825	25,526,003	22,924,511	36,388,113	18,335,346	5,192,095	12,860,673	—	18,052,768
MID-8	32,182,435	27,775,742	24,629,739	39,094,823	19,772,141	632,653	18,690,030	284,310	19,606,992
Total MID	292,985,940	252,669,587	236,308,482	375,092,829	172,897,795	25,894,607	176,300,427	11,636,020	213,831,054
Oakdale Irrigation District (OID)									
North of Stanislaus River (OID-N)	106,127,584	86,610,116	88,632,467	110,790,584	120,906,045	—	[1]–10,115,461	—	[1]–10,115,461
South of Stanislaus River (OID-S)	170,505,494	119,628,303	120,889,109	151,111,386	181,296,440	10,274,903	[1]–40,459,956	3,591,759	[1]–26,593,294
Total OID	276,633,078	206,238,419	209,521,576	261,901,970	302,202,485	10,274,903	[1]–50,575,417	3,591,759	[1]–36,708,755
South San Joaquin Irrigation District (SSJID)									
SSJID	146,113,624	127,848,622	119,424,314	189,562,403	157,031,625	—	32,530,778	2,107,287	34,638,065
Stevinson Water District (SWD)									
SWD	27,374,305	14,464,212	13,809,833	21,920,370	10,654,212	—	11,266,159	—	11,266,159

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

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California—*Continued*.

[Areal distribution of subareas shown in figure 2. m², square meter; m³, cubic meter; —, not included in water budget]

Water budget subarea (acronym)	Recharge			
	Recharge from urban water distribution lines (m^3)	Recharge from irrigation (m^3)	Recharge from precipitation (m^3)	Total recharge (m^3)
Eastside Water District (EWD)				
EWD	—	48,039,952	62,028,511	110,068,463
Merced Irrigation District (MER)				
North of Merced River (MER-N)	—	8,710,403	4,290,244	13,000,647
South of Merced River (MER-S)	—	61,131,763	32,917,072	94,048,835
Total MER	—	69,842,166	37,207,316	107,049,482
Merquin Community Water District (MERQ)				
MERQ	—	16,891,649	10,573,559	27,465,208
Modesto Irrigation District (MID)				
MID-1	—	8,634,139	3,995,087	12,629,226
MID-2	—	16,405,754	7,557,964	23,963,718
MID-3	—	20,201,005	9,810,400	30,011,405
MID-4	—	22,820,824	11,514,163	34,334,987
MID-5	—	23,512,219	11,380,003	34,892,222
MID-6	—	19,281,719	8,681,617	27,963,336
MID-7	—	13,463,602	6,589,604	20,053,206
MID-8	—	14,465,085	7,278,536	21,743,621
Total MID	—	138,784,347	66,807,374	205,591,721
Oakdale Irrigation District (OID)				
North of Stanislaus River (OID-N)	—	22,158,117	24,600,848	46,758,964
South of Stanislaus River (OID-S)	—	30,222,277	34,048,112	64,270,389
Total OID	—	52,380,394	58,648,959	111,029,353
South San Joaquin Irrigation District (SSJID)				
SSJID	—	70,138,089	33,885,822	104,023,911
Stevinson Water District (SWD)				
SWD	—	8,110,537	6,738,661	14,849,198

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California—*Continued*.

[Areal distribution of subareas shown in figure 2. m², square meter; m³, cubic meter; —, not included in water budget]

Water budget subarea (acronym)	Irrigation demand				Surface-water deliveries and ground-water pumpage				
	Total area (m²)	Irrigated cropped area, including double and intercropped area (m²)	Crop demand (m³)	Irrigation demand (m³)	Surface-water deliveries (m³)	Agricultural ground-water pumpage deliveries (m³)	Private agricultural ground-water pumpage (m³)	Urban ground-water pumpage (m³)	Total ground-water pumpage (m³)
Turlock Irrigation District (TID)									
TID-1	42,527,533	37,439,810	35,071,568	55,669,156	29,862,884	—	25,806,272	1,487,394	27,293,666
TID-2	25,443,097	21,938,675	19,425,098	30,833,488	37,579,379	—	[1]-6,745,890	—	[1]-6,745,890
TID-3	44,775,636	39,086,536	34,484,031	54,736,558	37,302,916	2,922,782	14,510,859	—	17,433,642
TID-5	60,507,196	54,553,562	49,067,811	77,885,415	39,715,238	14,110,372	24,059,805	—	38,170,177
TID-6	51,125,539	43,649,545	37,347,468	59,281,696	27,915,411	10,542,570	20,823,715	—	31,366,285
TID-7	33,540,427	30,470,796	26,020,482	41,302,353	30,606,643	10,423,003	272,707	—	10,695,710
TID-8	59,051,492	49,805,811	46,780,620	74,254,952	55,625,310	13,586	18,616,057	206,193	18,835,836
TID-9	42,962,055	37,504,848	34,057,179	54,059,014	32,050,121	912,347	21,096,546	1,523,329	23,532,222
TID-10	61,715,027	41,565,382	36,167,157	57,408,186	28,527,055	1,626,791	27,254,341	17,619,670	46,500,802
TID-11	62,480,163	47,105,351	43,187,613	68,551,766	40,187,427	5,282,497	23,081,842	7,343,666	35,708,005
TID-12	43,797,573	31,740,230	26,719,888	42,412,521	40,331,775	7,364,804	[1]-5,284,057	3,148,832	5,229,579
TID-13	46,021,039	40,899,840	34,687,225	55,059,087	32,050,121	12,399,109	10,609,857	—	23,008,966
TID-14	39,499,289	31,594,418	25,426,015	40,358,754	27,903,178	11,633,464	822,112	659,443	13,115,019
TID-15	44,055,342	36,895,874	29,722,160	47,178,032	35,343,210	14,019,765	[1]-2,184,942	199,108	12,033,930
TID-16	40,671,112	34,413,513	29,398,578	46,664,409	39,744,597	3,520,252	3,399,559	920,671	7,840,483
TID-17	31,526,930	24,629,008	22,194,696	35,229,676	19,523,662	—	15,706,014	460,335	16,166,349
Total TID	729,699,450	603,293,199	529,757,589	840,885,063	554,268,926	94,771,341	206,059,686	33,568,641	334,399,669
Foothills (FOOT)									
Foothills north of Merced River (FOOT-NM)	63,256,904	—	—	—	—	—	—	—	—
Foothills north of Stanislaus River (FOOT-NS)	84,447,139	—	—	—	—	—	—	—	—
Foothills North of Tuolumne River (FOOT-NT)	95,865,982	—	—	—	—	—	—	—	—
Reservoirs (RES)									
Modesto Reservoir (MODRES)	9,169,398	—	—	—	—	—	—	—	—
Turlock Lake (TLRES)	4,698,462	—	—	—	—	—	—	—	—
Woodward Reservoir (WOODRES)	7,426,271	—	—	—	—	—	—	—	—

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California—*Continued*.

[Areal distribution of subareas shown in figure 2. m^2, square meter; m^3, cubic meter; —, not included in water budget]

Water budget subarea (acronym)	Recharge			
	Recharge from urban water distribution lines (m^3)	Recharge from irrigation (m^3)	Recharge from precipitation (m^3)	Total recharge (m^3)
Turlock Irrigation District (TID)				
TID-1	—	20,597,588	9,659,382	30,256,969
TID-2	—	11,408,391	5,944,023	17,352,414
TID-3	—	20,252,526	10,511,995	30,764,521
TID-5	—	28,817,603	14,678,722	43,496,325
TID-6	—	21,934,227	11,989,969	33,924,197
TID-7	—	15,281,870	7,930,304	23,212,175
TID-8	—	27,474,332	13,362,682	40,837,015
TID-9	—	20,001,835	9,625,019	29,626,854
TID-10	—	21,241,029	10,988,044	32,229,073
TID-11	—	25,364,153	12,163,525	37,527,678
TID-12	—	15,692,633	8,425,685	24,118,318
TID-13	—	20,371,862	10,751,908	31,123,770
TID-14	—	14,932,739	8,896,753	23,829,492
TID-15	—	17,455,872	9,990,634	27,446,506
TID-16	—	17,265,831	9,654,338	26,920,170
TID-17	—	13,034,980	6,663,636	19,698,616
Total TID	—	311,127,473	161,236,620	472,364,093
Foothills (FOOT)				
Foothills north of Merced River (FOOT-NM)	—	—	15,936,162	15,936,162
Foothills north of Stanislaus River (FOOT-NS)	—	—	21,274,568	21,274,568
Foothills north of Tuolumne River (FOOT-NT)	—	—	24,151,291	24,151,291
Reservoirs (RES)				
Modesto Reservoir (MODRES)	—	—	2,151,089	2,151,089
Turlock Lake (TLRES)	—	—	1,102,233	1,102,233
Woodward Reservoir (WOODRES)	—	—	1,742,161	1,742,161

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California—*Continued*.

[Areal distribution of subareas shown in figure 2. m², square meter; m³, cubic meter; —, not included in water budget]

Water budget subarea (acronym)	Irrigation demand				Surface-water deliveries and ground-water pumpage				
	Total area (m^2)	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)	Private agricultural ground-water pumpage (m^3)	Urban ground-water pumpage (m^3)	Total ground-water pumpage (m^3)
Riparian and miscellaneous agricultural areas (RIP)									
Miscellaneous Modesto agricultural (MODAG)	4,068,622	3,354,302	2,597,014	4,122,245	4,122,245	—	—	—	—
Merced River riparian (RIP-M)	87,345,163	57,248,387	50,964,722	80,896,385	80,896,385	—	—	—	—
Stanislaus River riparian (RIP-S)	46,860,025	26,636,003	25,357,337	40,249,742	40,249,742	—	—	—	—
San Joaquin River riparian south of Merced River (RIPSJ-MS)	47,659,587	35,816,712	27,530,663	43,699,465	—	—	43,699,465	—	43,699,465
San Joaquin River riparian north of Tuolumne River (RIPSJ-TN)	24,458,396	17,768,039	16,552,441	26,273,716	26,273,716	—	—	—	—
San Joaquin River riparian south of Tuolumne River (RIPSJ-TS)	49,159,900	26,347,259	22,066,645	35,026,420	35,026,420	—	—	—	—
Tuolomne River riparian (RIP-T)	32,143,608	15,407,167	13,517,739	21,456,728	21,456,728	—	—	—	—
Urban (URB)									
Modesto urban (URB-M)	89,831,504	—	—	—	29,100,798	—	—	38,802,207	38,802,207
Ceres urban (URB-C)	27,787,062	—	—	—	9,001,585	—	—	8,380,320	8,380,320
Total of all subareas	2,603,408,815	1,765,882,221	1,607,250,065	2,415,702,811	1,550,276,623	133,503,903	784,239,561	99,944,746	1,017,688,210

Table 3. Summary of water budget components for water year 2000 in the Modesto area, San Joaquin Valley, California—*Continued.*

[Areal distribution of subareas shown in figure 2. m², square meter; m³, cubic meter; —, not included in water budget]

Water budget subarea (acronym)	Recharge			
	Recharge from urban water distribution lines (m³)	Recharge from irrigation (m³)	Recharge from precipitation (m³)	Total recharge (m³)
Riparian and miscellaneous agricultural areas (RIP)				
Miscellaneous Modesto agricultural (MODAG)	—	1,525,231	931,568	2,456,799
Merced River riparian (RIP-M)	—	29,931,662	21,202,731	51,134,393
Stanislaus River riparian (RIP-S)	—	14,892,404	10,332,846	25,225,251
San Joaquin River riparian south of Merced River (RIPSJ-MS)	—	16,168,802	11,989,754	28,158,556
San Joaquin River riparian north of Tuolumne River (RIPSJ-TN)	—	9,721,275	6,111,430	15,832,705
San Joaquin River riparian south of Tuolumne River (RIPSJ-TS)	—	12,959,776	12,276,919	25,236,694
Tuolomne River riparian (RIP-T)	—	7,938,989	6,902,440	14,841,430
Urban (URB)				
Modesto urban URB-M)	3,132,319	14,095,436	7,529,677	24,757,432
Ceres urban (URB-C)	968,903	4,360,061	2,329,112	7,658,076
Total of all subareas	4,101,222	826,908,243	583,090,805	1,414,100,270

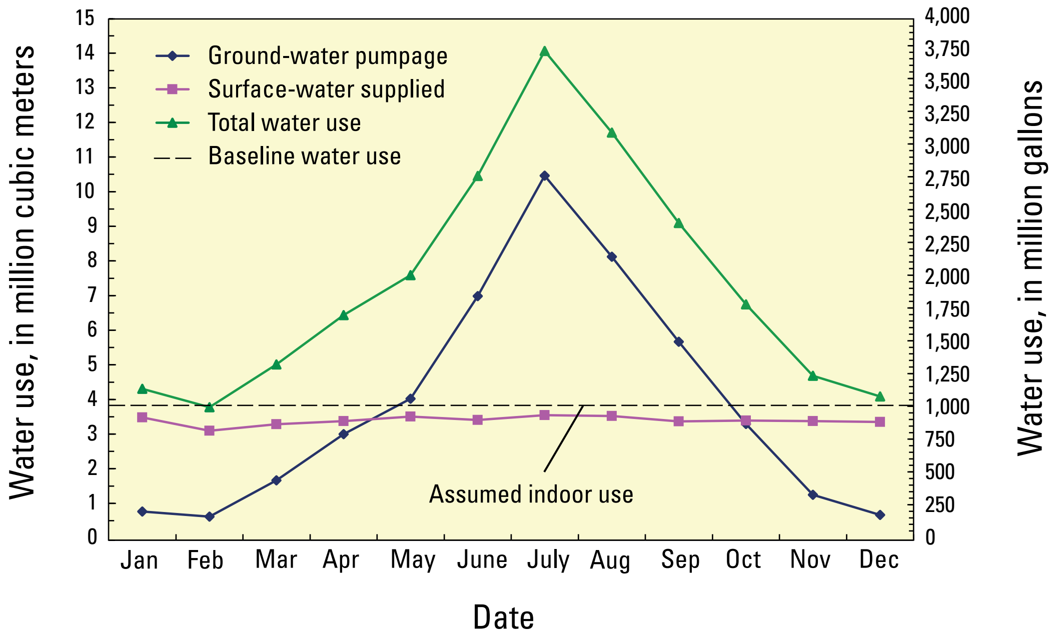


Figure 17. Modesto urban area water-use data used to compute urban water budget for Modesto area, San Joaquin Valley, California.

Regional Analysis Using Percentage of Coarse-Grained Texture

Geostatistics was used to develop a spatial correlation model of the percentage of coarse-grained texture in the Modesto area (J.A. Hevesi, U.S. Geological Survey, unpub. data, 2004). The geostatistical model was developed primarily to provide a basis for estimates of hydraulic conductivity in the NAWQA regional ground-water flow model (Page, 1983; Laudon and Belitz, 1991; Phillips and Belitz, 1991). The geostatistical model is also expected to provide information on (1) the characterization of the regional hydrogeologic stratigraphy, structure, and depositional history, (2) local-scale heterogeneity of the hydrogeologic framework, (3) development of stochastic distributions of texture for use in ground-water models which can then be used to evaluate model uncertainty, and (4) identifying locations where additional data are needed by using an analysis of estimation uncertainty.

Description of Datasets

The primary texture dataset, sampled from 3,504 well logs using a 1-m depth interval, consists of 228,576 data values of percentage coarse-grained texture. The global mean percentage coarse-grained texture is 39.6 percent, with a sample variance of 2,144 percent coarse-grained texture squared. Assuming that the spatial configuration of the well logs is not biased towards the fine-grained sediments, the global mean indicates a prevalence of fine-grained texture (greater than 60 percent) throughout the region. The majority of the data values were for depths less than 100 m (330 ft), with a maximum number of 2,793 data values for a depth of 22 m (72 ft) (*fig. 20A*). Many of the well-log values entered into the database are not continuous from the ground surface to the bottom of the borehole. Thus, no single depth interval includes data values for all 3,504 boreholes. For depths less than 165 m (540 ft), there are at least 100 data values for any given depth interval. For depths more than 226 m (740 ft), there were fewer than 10 data values for any given depth interval. Only 2 well logs had data values for depth intervals below 250 m (820 ft), and only 1 well log had data for intervals at depths between 302 m (990 ft) and 320 m (1,050 ft). The spatial correlation model was developed using depth below land surface so that the model will better correspond to dip of the stratigraphic layers. Using a datum of land surface, however, does not account for local variability in elevation between boreholes. Because of the substantial amount of data at the land surface and the accuracy of the depth of intervals recorded in the drillers' logs, the effect of local variability in borehole elevation is assumed to be minor.

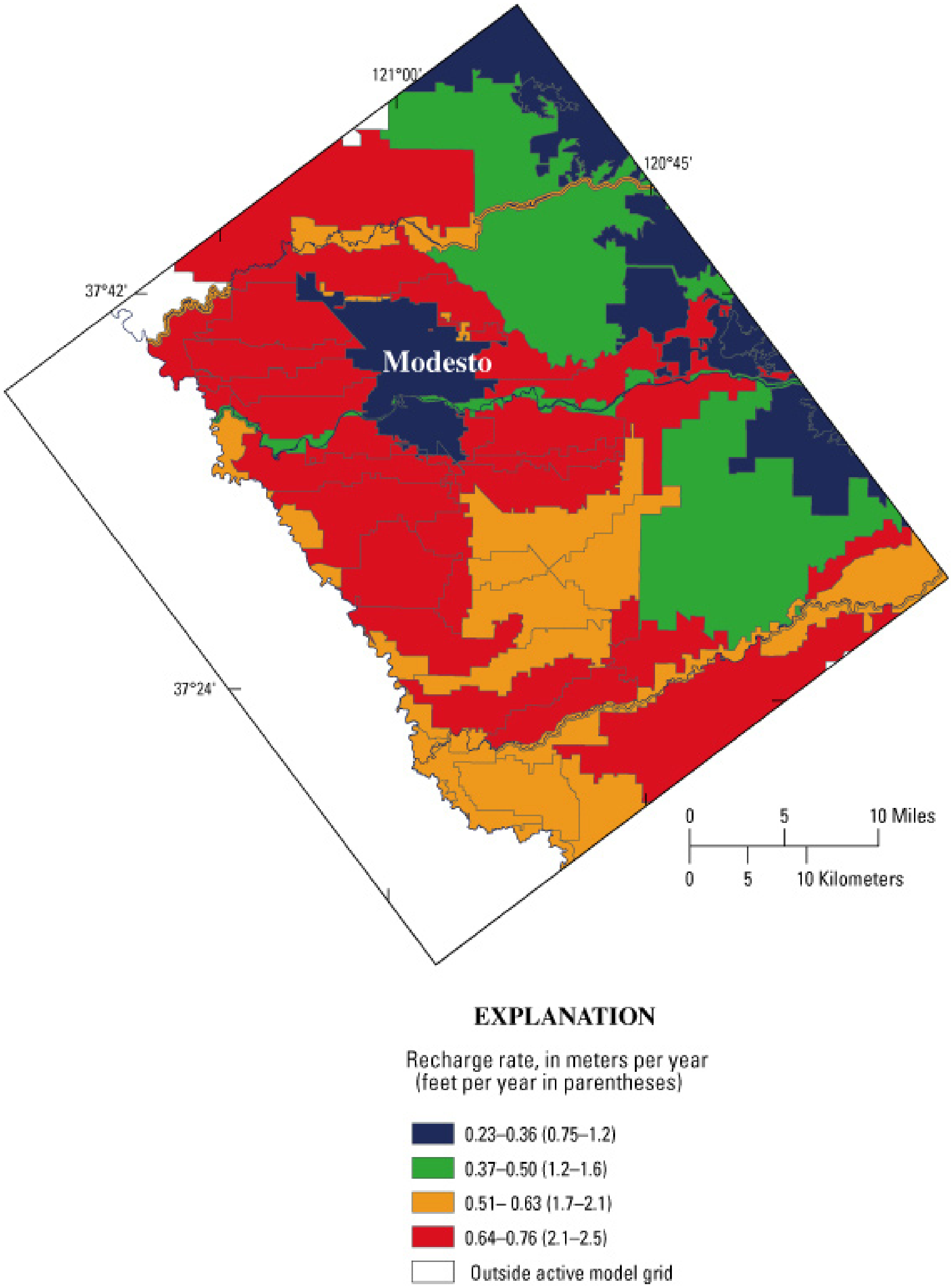


Figure 18. Estimated recharge rates for model subareas, water year 2000 in the Modesto area, San Joaquin Valley, California. Rates are amount of recharge (*table 3*) divided by area.

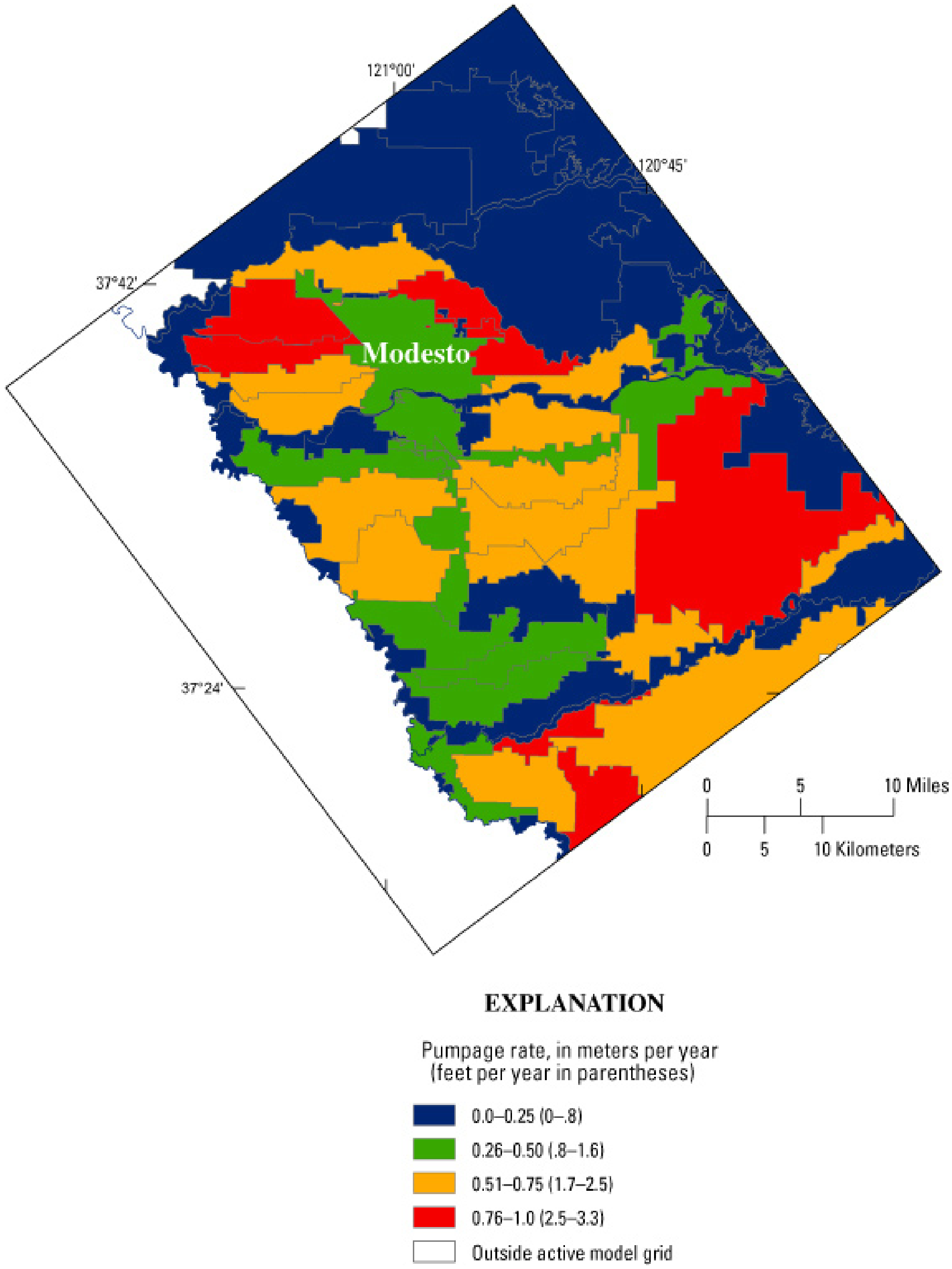


Figure 19. Estimated pumpage rates for model subareas, water year 2000 in the Modesto area, San Joaquin Valley, California. Rates are amount of pumpage (*table 3*) divided by area.

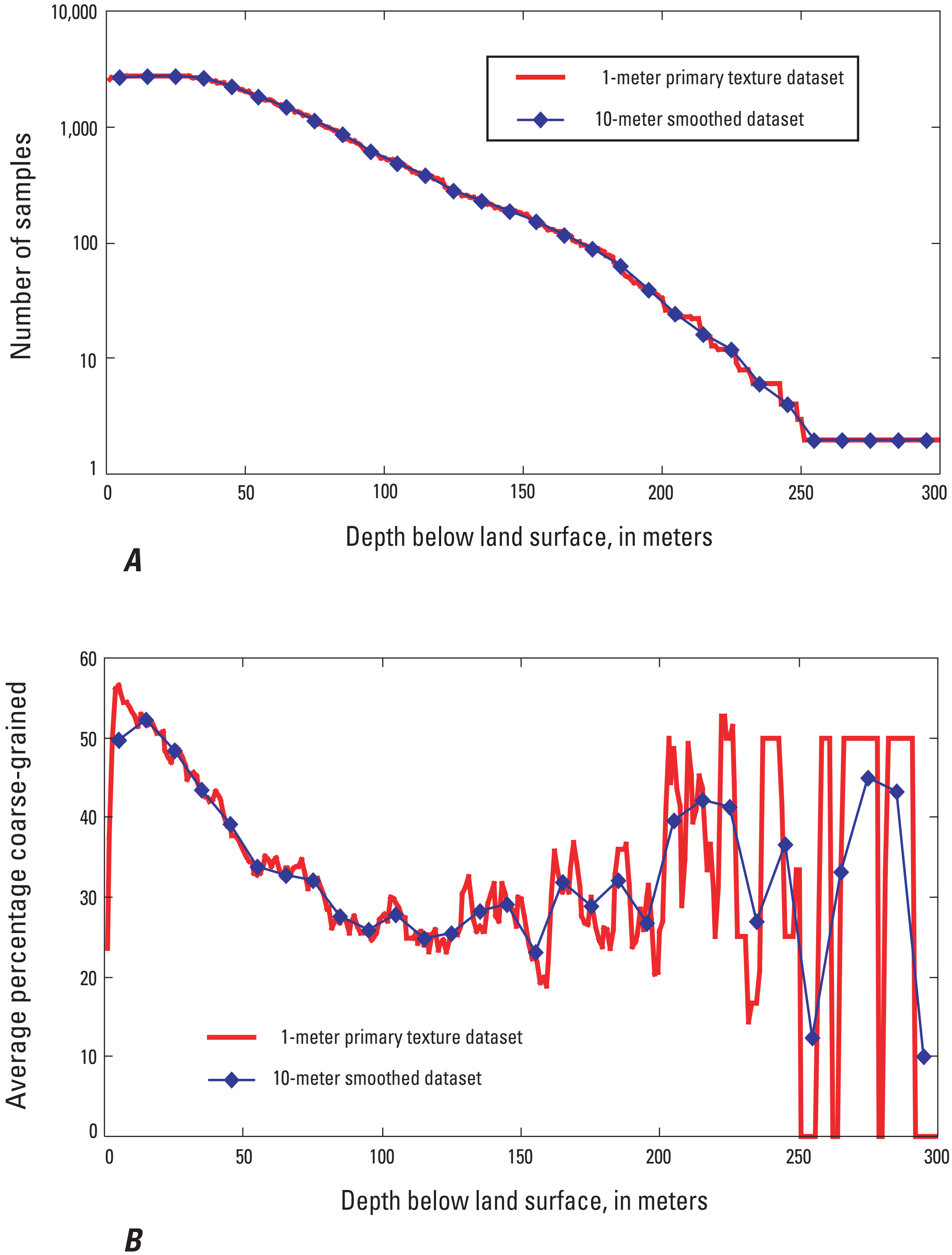


Figure 20. Descriptive statistics for the primary and smoothed percentage coarse-grained texture dataset as a function of depth below land surface. *A*. The total number of samples for each depth interval. *B*. The average percentage coarse-grained texture for each depth interval.

A smoothed derivative dataset was developed using the average percentage coarse-grained texture value of all primary 1-m texture data within a 10-m vertical window (5 m above and 5 m below the point being sampled) and a 1,000-m horizontal search radius around the point being sampled. The smoothed dataset comprised 209,312 data values. The smoothed dataset was resampled at every 5-m depth increment from depths of 5 to 295 m, providing a total of 45,577 data values. The resampling in the vertical direction was used to help de-cluster the primary texture data, in which data are clustered vertically along boreholes. The global mean percentage coarse-grained texture for the derivative dataset is 40.5 percent, with a variance of 557 percentage coarse-grained squared. The average percentage coarse-grained texture calculated for each 1-m depth increment of the primary texture data and for each 10-m depth increment of the smoothed and resampled derivative data set indicates a pronounced trend of decreasing percentage coarse-grained texture with increasing depth for the 1- to 100-m depth range (*fig. 20B*). Assuming that no biases exist in the spatial configuration of the well logs, the observed trend is an important characteristic of the hydrogeologic framework. The trend of decreasing coarse-grained texture with increasing depth is consistent with increasingly fine-grained and more consolidated sediments with depth in the study area, as noted in the description of the Mehrten Formation (fewer sands and more shale) and other partly-consolidated to consolidated sediments.

Analysis of the sample variance for each depth increment indicated an increase in the variability of average percentage coarse-grained texture with increasing depth for depths greater than approximately 120 m (390 ft) (*fig. 20B*). The primary reason for the increased variability is the decrease in the number of well logs available for wells of increasing depth. For depths greater than approximately 200 m (660 ft), the number of well logs is likely no longer sufficient to provide a representative average percentage coarse-grained texture at a given depth. Results obtained using the smoothed instead of the primary data may provide a better representation of average percentage coarse-grained texture for depths greater than 200 m (660 ft). For depths greater than 250 m (820 ft), the average percentage coarse-grained texture for a given depth layer is either 0 or 50 percent using the primary 1-m texture data, whereas the smoothed data provides more reasonable values (an average value of 0 percentage coarse-grained texture is considered unrealistic for an entire depth interval).

Three-Dimensional Model of Percentage of Coarse-Grained Texture

The three-dimensional spatial correlation model presented in this report is derived from the 10-m smoothed derivative dataset and a variogram model that was defined using two nested structures, a nugget component of 2 percent coarse-grained squared. The first nested structure was defined using a Gaussian variogram model with a sill of 180 percent coarse-grained squared, an effective range of 28 m in the vertical direction, and an effective range of 5,000 meters in the horizontal direction. The second nested structure was defined using an exponential model, using a sill of 375 percent coarse-grained texture squared, an effective range of 80 meters in the vertical direction, and an effective range of 28,000 meters in the horizontal direction. The horizontal discretization of the estimation grid was defined by the grid used for the NAWQA ground-water flow model (*fig. 1*), consisting of 137 cells in the x-direction and 153 in the y-direction, with a uniform cell dimension of 400 m (1,312 ft). The origin of the grid is the lower left corner of the grid. The vertical discretization was defined by 10-m (33-ft) increments, starting at 5 m (16 ft) below land surface and ending at 295 m (970 ft) below land surface, for a total of 30 grid layers in the vertical direction. This discretization defined a total of 628,830 grid cells for the 3-dimensional estimation grid.

The estimation grid was limited to the upper 295 m (970 ft) of the ground-water model domain because the geostatistical methods used in this study were not considered appropriate for extrapolation of data for depths below the deepest interval. The estimation neighborhood was defined using an upper limit of 400 data samples per kriged estimate. The spatial dimensions of the search neighborhood were not constrained for either the primary texture data or the derivative data. Thus, for locations of the estimation grid having densely spaced and relatively deep boreholes with continuous well logs, the effective search neighborhood was relatively small. For locations of the estimation grid having sparsely spaced well logs, the effective search neighborhood expanded vertically and horizontally until the limit of 400 data samples was reached.

The three-dimensional kriged estimates of percentage coarse-grained texture show significant heterogeneity in the texture of the sedimentary deposits (*fig. 21*). Assuming the hydraulic conductivity is correlated to the texture, the kriged result implies significant heterogeneity in the hydrogeologic framework. For the shallower depths (0–100 m), the large number of well logs reduces the variance of the estimate of the percentage coarse-grained texture, and zones of very coarse-grained texture (greater than 90 percent coarse-grained texture) are common. An apparent horizontal layer of fine-grained textures starting at depths of about 60 m near the San Joaquin River suggests the influence of the Corcoran Clay on the distribution of percentage coarse-grained texture (*fig. 21*). The three-dimensional geostatistical method used here cannot precisely represent sharp boundaries, however. The Corcoran Clay was modeled as an explicit layer in the NAWQA regional ground-water flow model.

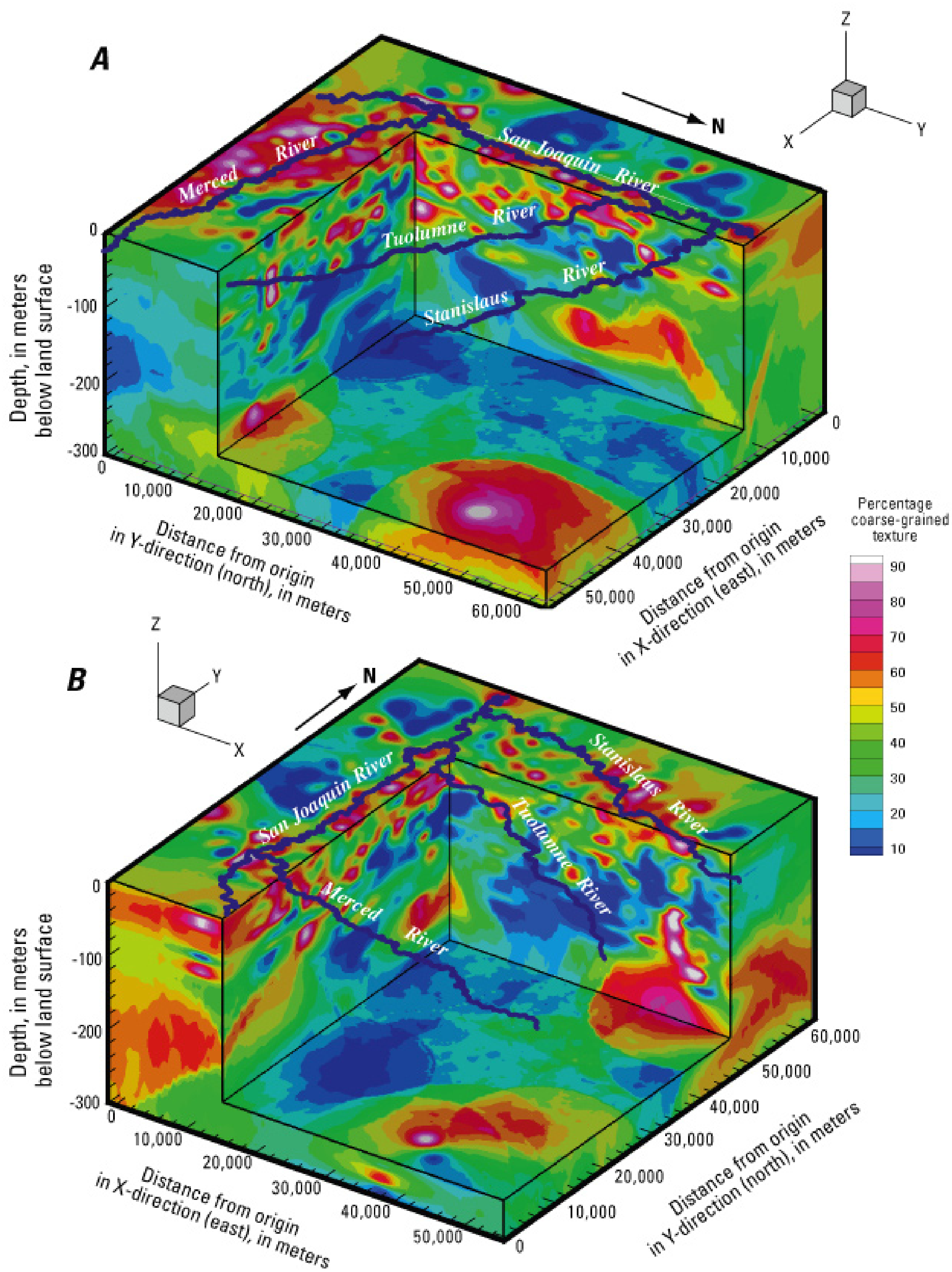


Figure 21. Three-dimensional model of percentage coarse-grained texture near Modesto, San Joaquin Valley, California.

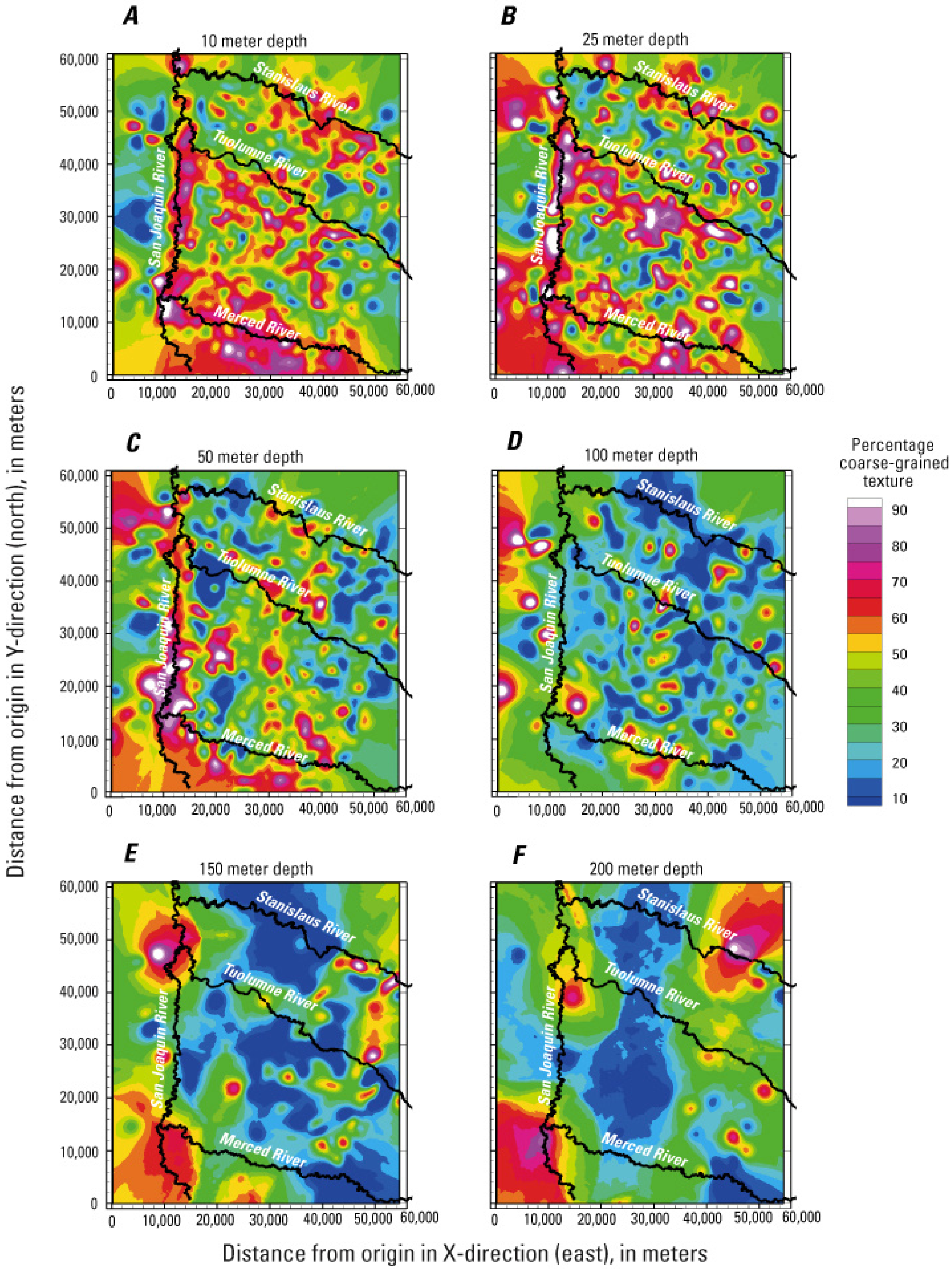


Figure 22. Two-dimensional slices through three-dimensional model of percentage coarse-grained texture near Modesto, San Joaquin Valley, California.

For intermediate depths of 100 to 200 m (330 to 660 ft), the number of well logs is still adequate to control the estimated percentage coarse-grained texture. Very fine grained texture zones (less than 10 percent coarse-grained texture) are common in the intermediate depths, whereas the very coarse-grained texture zones are less common than in the shallow depths (*fig. 21*).

For the lower depths of 200 to 300 m (660 to 980 ft) and along the boundary of the model grid, horizontal and vertical lineation patterns are common, particularly in the northeastern, southeastern, and southwestern corners of the grid, where there is a lack of well logs (*fig. 21*). These lineation patterns are artifacts (artificially generated features) caused by the combination of sparse data coverage and edge effects. Although the estimation neighborhood used 400 data values for each kriged estimate, most estimates in the corners and along the boundaries of the grid are extrapolated rather than interpolated values.

Further analysis of the spatial patterns of percentage coarse-grained texture can be illustrated in two-dimensional horizontal slices of the three-dimensional spatial interpolation model (*fig. 22*). Kriged results for the 10-m depth layer (33 ft) indicate a predominance of intermediate values of 30 to 70 percent coarse-grained texture (*fig. 22A*). A few isolated areas of fine-grained texture (less then 20 percent coarse-grained) exist west of the San Joaquin River and north of the Tuolumne River. Areas of coarse-grained texture (greater then 70 percent coarse-grained texture) are more widespread than the areas of fine-grained texture, and occur along the San Joaquin River, the Merced River, along the southern boundary of the model grid, and along the upper Stanislaus River.

Kriged results for the 25-m depth layer (82 ft) are characterized by an increase in spatial variability, evidenced by an increase in the number of very coarse grained texture zones (greater than 90 percent coarse-grained texture) and by an increase in the number of very fine grained texture zones (less then 10 percent coarse-grained texture) (*fig. 22B*). Zones with greater than 90 percent coarse-grained texture partially underlie the San Joaquin River and are approximately aligned with the channels of the Merced and Tuolumne Rivers, and to a lesser extent, the Stanislaus River. In the central part of the model grid, zones with 10 percent or less coarse-grained texture generally occur in the inter-channel areas, possibly indicating floodplain or lacustrine deposits. Results for the 50-m depth layer (160 ft) indicates a reduction in the existence of the very coarse grained zones (*fig. 22C*), although very coarse grained textures are estimated in the southern part of the grid, underlying the San Joaquin River. The spatial distribution of the coarse-grained texture for the 25- and 50-m depths are similar to that of gravel mapped from the well-log database (*fig. 11*), suggesting that very coarse grained texture in the spatial correlation model may correspond to buried channel deposits.

Kriged results for the 100-m depth layer (330 ft) indicate a pronounced reduction in percentage coarse-grained texture (*fig. 22D*). In contrast to the overlying layers, zones of very fine grained texture (less than 10 percent coarse-grained texture) exist throughout most of the grid. Zones of 70 percent and greater coarse-grained texture are in the southern and eastern part of the grid, but the pattern of coarse-grained texture is not as clearly aligned with the Merced, Tuolumne, and Stanislaus Rivers. The fine-grained zones in the eastern and northeastern parts of the grid likely reflect the more consolidated Tertiary deposits near the surface on the eastern side of the study area that dip westward.

Kriged results for the 150- and 200-m depth layers (490 and 660 ft) show little relation between the spatial pattern of percentage coarse-grained texture and the geography of the river channels (*figs. 22E, F*). The spatial pattern for these lower depth layers also is not well correlated to the spatial pattern characterizing the upper layers (10 to 100 m). Artificial edge effects caused by the search neighborhood have some impact on the spatial pattern, associated with a moderate degree of downward extrapolation using data at the bottom of boreholes in the overlying layers.

Results for the 200- and 290-m depth layers (*figs. 22F*, *21B*, respectively) indicate a continuous zone of fine-grained texture in the northern and central part of the model area, aligned in a northwest to southeast trending belt roughly parallel to the San Joaquin river channel. Based on the depths, this fine-grained zone in the center of the study area may represent the middle part of the westward-dipping Mehrten Formation, with older deposits to the east and younger deposits to the west.

Geostatistical analysis using the derivative texture data indicated a strong spatial correlation structure for distances less than 40 to 50 m (130 to 160 ft). The regional horizontal spatial structure was affected by repeated zones of coarse-grained texture correlated to the position of the main river channels for the shallow depths and a regional trend of increasingly fine-grained sediments from west to east and north to south for the deeper layers. The repeating structures are likely caused by differences in fluvial depositional environments in channel and interchannel areas combined with the fairly equal spacing and alignment of the main tributaries to the San Joaquin River. All estimation models indicate some correlation of the very coarse grained texture zones in the shallower depths to the location of the main river channels, and all models indicate an increase in fine-grained texture zones with increasing depth, with the finer-grained zones existing mostly in the northern and eastern parts of the model grid. The trend of increasingly fine-grained sediments from west to east and with depth is consistent with increasingly consolidated sediments with depth to the east, noted in the well-log database as sandstone and shale. The Tertiary sediments, which outcrop in the east, are more compacted and less permeable than overlying unconsolidated sediments and were assigned a textural parameter of fine grained in the analysis.

In general, the geostatistical analysis suggests a complex spatial structure on the scale of the model grid. The complex spatial structure is attributed to the combined effects of the repeated east-west alignment of the tributary rivers (Stanislaus, Merced, and Tuolumne) combined with the asymmetry of the north-south aligned San Joaquin River dominating the western part of the model grid and the alluvial fans of the higher Sierra Nevada foothills bounding the eastern part of the grid. The alignment of the river channels and the physiography of the valley likely played an important role in the depositional history to depths of 300 m (980 ft) and possibly greater.

Data Requirements for Improvement of Ground-Water Management

This study has focused on maximizing the use of existing data by organizing the data into databases and geostatistical and hydrologic models, and further developing our understanding of the system. The results of this study indicate that additional data are needed to improve the geostatistical and hydrologic models and improve understanding of the system. Additional data collection and analysis will reduce uncertainty in the models, resulting in more reliable tools to evaluate management strategies.

In the Modesto area, the primary factors likely to influence the uncertainty in evaluating future management and development strategies include, (1) the quality of the water budget data, including delivery, pumpage, evapotranspiration estimates, and irrigation efficiency, (2) the quality of seasonal and long-term water-level data in discrete aquifer zones, (3) quantification of the interaction of ground water and surface water along the major rivers, (4) information on aquifer hydraulic properties and ground-water velocities, (5) detailed characterization of dominant flow pathways such as incised valley-fill deposits, and (6) updated water-quality data.

Water Budget

Following an extensive effort to compute a steady-state water budget, many components were estimated with a high level of uncertainty. Data for quantities of irrigation spills water deliveries, seasonal cropping patterns and resulting evapotranspiration estimates, public and private pumpage, and irrigation efficiency were not available for all subareas. Because the region is dominated by irrigation and pumping, collection and aggregation of complete records within all subareas would improve the estimates of the distribution of recharge and pumpage in the model.

Water-Level Data

Characterization of the hydrologic system, especially vertical gradients, was limited by the lack of discrete water-level data. Most water-level data are from long-screened production wells containing water having a mixture of hydraulic heads from different parts of the aquifer. Discrete water-level data are needed for the confined aquifer below the Corcoran Clay, the shallow aquifer above and west of the Corcoran Clay, and the semiconfined aquifer east of the Corcoran Clay. Seasonal and long-term annual water-level measurements in discrete parts of the system would provide needed information on water levels and hydraulic gradients for model calibration and would give insight on how the hydrologic system responds to changing hydraulic stresses.

Ground-Water and Surface-Water Interaction

Because rivers predominate the study area and are used as model boundaries, interaction between the rivers and the ground-water system needs to be quantified. River-stage data are available and should continue to be collected; however, establishing vertical hydraulic conductivity of the riverbeds and characterizing seasonal changes in flux in selected locations would greatly reduce the uncertainty in representing the interaction of the rivers and ground water in the model.

Hydraulic Properties

Limited data were available on aquifer hydraulic properties such as hydraulic conductivity and the storage coefficient. The use of the spatial distribution of sediment texture as a proxy for the hydraulic conductivity distribution is a robust approach to characterizing aquifer properties in the model (Williamson and others, 1989; Phillips and Belitz, 1991). Additional data characterizing hydraulic properties for the range of coarse- and fine-grained sediment texture would improve the ground-water flow model. Characterization of aquifer storage will be needed for development of a transient model. Data on ground-water velocity distributions with depth would also provide important flux data to calibrate the model accurately.

Flow Path Characterization

Further characterization of the incised valleys would allow assessment of the degree of connection between the channels and provide further understanding of the role of dominant flow paths in managing the ground-water supply and ground-water quality. The presence of the incised valley-fill deposits provides a potential opportunity for successful aquifer recharge. Because of the available quantities of surface water in the basin, investigation of in-lieu or artificial recharge as a part of conjunctive basin management is a viable option. Various methods should be investigated, such as surface spreading or injection.

Water Quality

Additional ground-water quality data, such as age-dates and other ground-water tracers, would further refine understanding of dominant ground-water flow directions and velocities in this region. In concert with an accurate characterization of the flow system, characterization of areas of poor water quality will likely have a direct impact on the feasibility of further development of the ground-water supplies. More water-quality data are needed to ensure supplies are suitable for the increasing population in the area.

Summary and Conclusions

A summary of previous work and an analysis of existing data was done to develop an understanding of the hydrogeologic setting near Modesto in the northeastern San Joaquin Valley. The objective of the study was to maximize the use of existing data and to support the development of a numerical ground-water flow model that can be used to optimize management strategies for conjunctive use of water in the basin.

The hydrologic system in the Modesto area is complex, in part because of the heterogeneous nature of the hydrogeologic setting. The primary aquifers in the study area comprise sediments derived from the San Joaquin River and three major tributaries that drain the Sierra Nevada, resulting in a complex sequence of overlapping structures built by sediment erosion and deposition.

The general physiography of the study area is reflected in the soils. The oldest soils have low permeability and exist in terrace deposits, in the interfan areas between major streams, at the distal end of the fans, and along the San Joaquin River floodplain. The youngest soils are characterized by high permeability and are generally forming on the recently deposited alluvium along the major stream channels. Soil permeability in this area is strongly correlated to the depth of a shallow hardpan of the Pleistocene Riverbank Formation: soils are more permeable in areas where the Riverbank Formation hardpan is deep or missing.

Geologic materials exposed or penetrated by wells in the Modesto area range from pre-Cretaceous rocks to recent alluvium; however, water-bearing materials are mostly Late Tertiary and Quaternary in age. The consolidated rocks include a metamorphic and intrusive igneous basement complex overlain by marine sandstones and shales and fluvial deposits, nonmarine sequences of rhyolitic tuff, sandstone, siltstone, and claystone with rhyolitic ash, sandy clay, and siliceous sand and gravel in a clay matrix. The upper consolidated rocks are characterized by sandstone, conglomerate, siltstone, and claystone of the Mehrten Formation. These sediments are derived from fluvial deposits of predominantly andesitic volcanic detritus of the central and northern Sierra.

At the base of the unconsolidated deposits is the Pliocene Laguna Formation, characterized by alluvial deposits of gravel, sand, and silt that lie unconformably on the Mehrten Formation. The Turlock Lake, Riverbank, and Modesto Formations, separated by the North Merced Gravel in some locations, overlie the Laguna Formation and form a sequence of overlapping terrace and alluvial fan systems representing cycles of alluviation, soil formation, and channel incision that were influenced by climatic fluctuations and resultant glacial stages in the Sierra Nevada. The Pleistocene Turlock Lake Formation consists primarily of fluvially deposited arkosic silt, sand, and gravel. An areally extensive clay, referred to in this report as the Corcoran Clay, occurs at the base of the upper unit of the Turlock Lake Formation. The Riverbank Formation consists of fluvially deposited arkosic sand with some pebbles, gravel lenses, and interbedded fine sand and silt. The Modesto Formation similarly comprises fluvially deposited arkosic sediment and locally derived deposits, gravel, sand, and silt, from the last major aggradational period in the eastern San Joaquin Valley. Thin deposits of relatively unweathered sediments are contained within the Holocene alluvium along modern river channels.

A database of more than 3,500 drillers' logs was constructed to organize information on well construction and subsurface lithology in the study area. The majority (61 percent) of wells represented in the well database are for domestic (2,170 wells), irrigation (951 wells), and municipal use (147 wells). Well depths ranged from 7.3 to 368 m (24 to 780 ft) below land surface, with a median depth of 59 m (195 ft).

The database of existing wells was used in conjunction with a limited number of geophysical logs and the county soil maps to define the stratigraphic framework of the study area. Although extensive work has been done by earlier investigators to define the structure of the Modesto area aquifers, this analysis has resulted in some modification to the mapping of lateral extent and regional dip of the Corcoran Clay and the regional dip of (and thus depth to) the Mehrten Formation.

Data in the well-log database indicating red layers was used to define the paleosol at the top of the Turlock Lake Formation and other bounding paleosols. The sparse data on apparent paleosols north of the Tuolumne River may be due to active channels along and adjacent to the Tuolumne River during the time when the upper Turlock Lake Formation was deposited. A feature that may have important implications to ground-water flow and transport is the very coarse grained incised valley fill typically associated with each sequence bounding paleosol. Some geophysical well logs and sparse well database information suggest the presence of one of these incised valley-fill deposits adjacent to the Tuolumne River east of Modesto.

Well logs in the database indicate that "blue clay," often indicating the Corcoran Clay, extends northwest of Modesto and along the present-day Tuolumne River channel east of Modesto. Based on analysis of the data from the well database, the eastern extent of the Corcoran Clay has been revised and appears to lie approximately parallel to the axis of the valley.

The Mehrten Formation is distinguished in the well-log database by its characteristic black sands consisting of predominantly andesitic fragments. Data in the well database concerning black sands indicates that the formation dips to the southwest at a slope of about 0.006, indicating that the Mehrten Formation may lie as shallow as 120 m (400 ft) below land surface under Modesto. The top of the Mehrten Formation has been identified as a significant change in geophysical well log character from coarse-grained dominated units of the overlying Quaternary sediments to the relatively fine-grained and compacted Mehrten Formation. Because the Mehrten Formation sediments have been characterized as being less permeable than the overlying Quaternary sediments, the existence of the Mehrten Formation at shallow depths in the study area may have implications for future development of the ground-water resource.

The alluvial aquifer system in the Modesto area comprises an unconfined to semiconfined aquifer above and east of the Corcoran Clay confining unit and a confined aquifer in the unconsolidated to partly-consolidated deposits beneath the Corcoran Clay. The unconfined aquifer above the Corcoran Clay ranges from about 40 to 70 m (130 to 220 ft) thick and comprises alluvial sediments of the Modesto, Riverbank, and upper Turlock Lake Formations. The unconfined aquifer east of the Corcoran Clay becomes semiconfined with depth due to the numerous discontinuous clay lenses and extensive paleosols throughout the aquifer thickness. The confined aquifer comprises primarily alluvial sediments of the Turlock Lake and upper Mehrten Formations, extending from beneath the Corcoran Clay to the base of fresh water.

Ground-water flow under natural conditions flows from recharge areas in the upper alluvial fans toward the west and southwest in the direction of the valley trough. Following development of the basin, ground water in the unconfined to semiconfined aquifer still flows to the west and southwest; however, the primary source of recharge is through percolating excess irrigation water. The primary ground-water discharge is through extensive ground-water pumping in the unconfined to semiconfined aquifer. This pumping and recharge pattern provides a significant component of vertical flow in the system. In the western part of the study area, ground-water movement is downward to the confined aquifer from the overlying unconfined aquifer through the Corcoran Clay, likely due to pumping beneath the Corcoran Clay on the west side of the San Joaquin River.

A water budget was computed and used to estimate recharge and ground-water pumpage for the NAWQA regional ground-water flow model in the Modesto area. Water budget estimates are for water year 2000, from October 1, 1999 through September 30, 2000. The water budget was calculated by dividing the area into 47 separate subareas for which surface- and ground-water deliveries could be obtained or estimated for water year 2000. Surface-water delivery data and some limited ground-water delivery data were available; however, private pumpage records were not available. Therefore, estimated pumpage and recharge were determined using a land-use approach.

The total water supply in the model area was estimated at more than 2.5 billion m^3 (2 million acre-ft) for WY2000. Surface-water deliveries accounted for 60 percent of the total water supply at more than 1.5 billion m^3 (1.2 million acre-ft). Ground-water deliveries accounted for 40 percent of the total supply at about 1 billion m^3 (830,000 acre-ft). Approximately 2.4 billion m^3 (2 million acre-ft) (94 percent) was used to meet irrigation demand; 62 percent was supplied by surface water and 38 percent was supplied by ground water. Approximately 140 million m^3 (110,000 acre-ft) (6 percent) was used to meet urban demand; 28 percent was supplied by surface water and 72 percent was supplied by ground water. The total recharge in the model area was estimated at 1.4 billion m^3 (1,100,000 acre-ft) during WY2000. The largest component of recharge is irrigation recharge (58 percent), whereas precipitation in excess of crop requirements accounted for 41 percent of the recharge.

In a spatial context, the average areal recharge rate in the model area was about 0.54 m/yr (1.8 ft/yr). The recharge rates are generally highest in the agricultural areas in the western part of the study area, along the canals north and south of the Tuolumne River east of Modesto, and along the canals south of the Merced River. The recharge rates are generally lowest in the eastern part of the study area, in the foothills and adjacent uplands, and in the Modesto urban area. The pumpage rates are generally highest in the agricultural areas in the western part of the study area.

Geostatistics was used to develop a spatial correlation model of the percentage coarse-grained texture in the Modesto area. The primary dataset used in the analysis was sampled from the well-log database using a 1-m (3.3-ft) depth interval. The mean percentage coarse-grained texture calculated for each depth increment indicates a pronounced trend of decreasing coarse-grained texture with increasing depth for the 1- to 100-m (3.3- to 330-ft) depth range. Assuming hydraulic conductivity is correlated to texture, the kriged result implies significant heterogeneity in the hydrogeologic framework.

Geostatistical analysis indicates that the regional horizontal spatial structure is affected by repeated zones of coarse-grained texture correlated to the position of the main river channels for the shallow depths and a regional trend of increasingly fine-grained sediments from west to east and north to south for the deeper layers. The repeating structures are likely caused by differences in fluvial depositional environments between channel and interfan areas combined with the relatively equal spacing and alignment of the main tributaries to the San Joaquin River. The trend of increasingly fine-grained sediments from west to east and with depth is consistent with increasingly consolidated sediments to the east and at depth, noted in the well-log database as sandstone and shale. The Tertiary sediments, which outcrop in the east, are more compacted and lower in permeability than overlying unconsolidated sediments and were assigned a textural parameter of fine-grained in the analysis.

Future work in the Modesto area may be focused on the primary factors that are likely to influence the uncertainty in evaluating future management and development strategies. The primary factors identified that influence the uncertainty include (1) the quality of the water-budget data, including delivery, pumpage, evapotranspiration estimates, and irrigation efficiency, (2) the quality of seasonal and long term water-level data in discrete aquifer zones, (3) quantification of the interaction of ground water and surface water along the major rivers, (4) information on aquifer hydraulic properties and ground-water velocities, (5) detailed characterization of dominant flow pathways such as incised valley-fill deposits, and (6) updated water-quality data.

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