Section 13.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the Central Valley, California

By Susan A. Thiros

in

Conceptual Understanding and Groundwater Quality of Selected Basin-Fill Aquifers in the Southwestern United States

Edited by Susan A. Thiros, Laura M. Bexfield, David W. Anning, and Jena M. Huntington

National Water-Quality Assessment Program

Professional Paper 1781

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

Contents

Figures

Tables

Section 13.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the Central Valley, California

By Susan A. Thiros

Basin Overview

The Central Valley aquifer system is contained within the basin-fill deposits in the Central Valley of California. The distribution of water in the valley has been modified to even out differences between where it naturally occurs and where the agricultural and urban demand exist. Surface water that under natural conditions mostly flowed out of the valley is now used for irrigation within the valley resulting in additional recharge to the aquifer system. Groundwater also is used extensively for irrigation and public supply. This water development has resulted in major changes to the groundwater flow system in the Central Valley, such as reversals in vertical and lateral directions of flow, which in turn, affect the groundwater quality.

The Central Valley is roughly 400 mi long, averages about 50 mi in width, and comprises about 20,000 mi^2. The Sacramento Valley occupies the northern third of the Central Valley and the San Joaquin Valley the southern two-thirds (fig. 1). The San Joaquin Valley is made up of the San Joaquin Basin in the northern part, which is drained by the San Joaquin River, and the internally drained Tulare Basin in the southern part. The Sacramento and San Joaquin Valleys are separated by a low-lying area called the Delta, where the Sacramento and San Joaquin Rivers converge and discharge through a natural outlet into San Francisco Bay on the Pacific Ocean. This is the only natural outlet for surface water from the Central Valley.

Topographically, the Central Valley is relatively flat and at low altitude compared to the surrounding mountains. The only feature of prominent relief within the valley is Sutter Buttes, a volcanic plug that rises about 2,000 ft above the valley floor near the center of the Sacramento Valley. The altitude of the boundary between unconsolidated basin-fill deposits in the valley and consolidated rock of the mountains is about 500 ft along much of the east side of the valley and ranges from 50 to 350 ft on the west side. The drainage area for the Central Valley is almost 49,000 mi^2 and includes the crest of the Sierra Nevada to the east and the Coast Ranges to the west.

The Central Valley has a Mediterranean climate, with hot, dry summers and cool, wet winters. Average annual precipitation, a value developed from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) temperature data for September 1961 through September 2003, mostly ranges from 13 in. to 26 in. in the Sacramento Valley and from 6 to 18 in. in the San Joaquin Valley, and decreases from the northeast to the southwest (Faunt, Hanson, and Belitz, 2009, fig. A5). About 85 percent of the precipitation falls during November through April, and rainfall varies greatly from year to year. Average annual precipitation in the Sierra Nevada ranges from about 40 in. to more than 90 in., and increases with altitude. The Coast Ranges are not as high and have much less precipitation and smaller drainage areas available to sustain streamflow. The western part of the Central Valley is in the rain shadow of the Coast Ranges and is therefore drier than the eastern part.

The Sacramento River drains the Sacramento Valley and has more flow than the San Joaquin River. Major tributaries include the Feather, American, and Yuba Rivers. The major tributaries of the San Joaquin River include the Mokelumne, Stanislaus, Tuolumne, and Merced Rivers. The Tulare Basin in the southern part of the Central Valley receives streamflow from the Kings, Kaweah, and Kern Rivers. The natural flow of these rivers over thousands of years has deposited sediment on the slopes of alluvial fans and terminated in the topographically closed sinks Tulare Lake, Kern Lake, and Buena Vista Lake. The estimated amount of streamflow entering the Central Valley around its perimeter ranged from 10 million acre-ft in 1977 to more than 78 million acre-ft in 1983, with a median inflow of about 29 million acre-ft/yr for the period 1961–2003 (Faunt, Hanson, and Belitz, 2009, p. 46). Streamflow in the Central Valley is highly variable from year to year and is influenced by variability in climate. Most of the flow originates as snowmelt runoff from the Sierra Nevada during January through June and most of the surface-water flow is controlled by dams, which capture and store the water for use during the dry season. Below the dams, a complex network of streams and canals distribute the water throughout the valley.

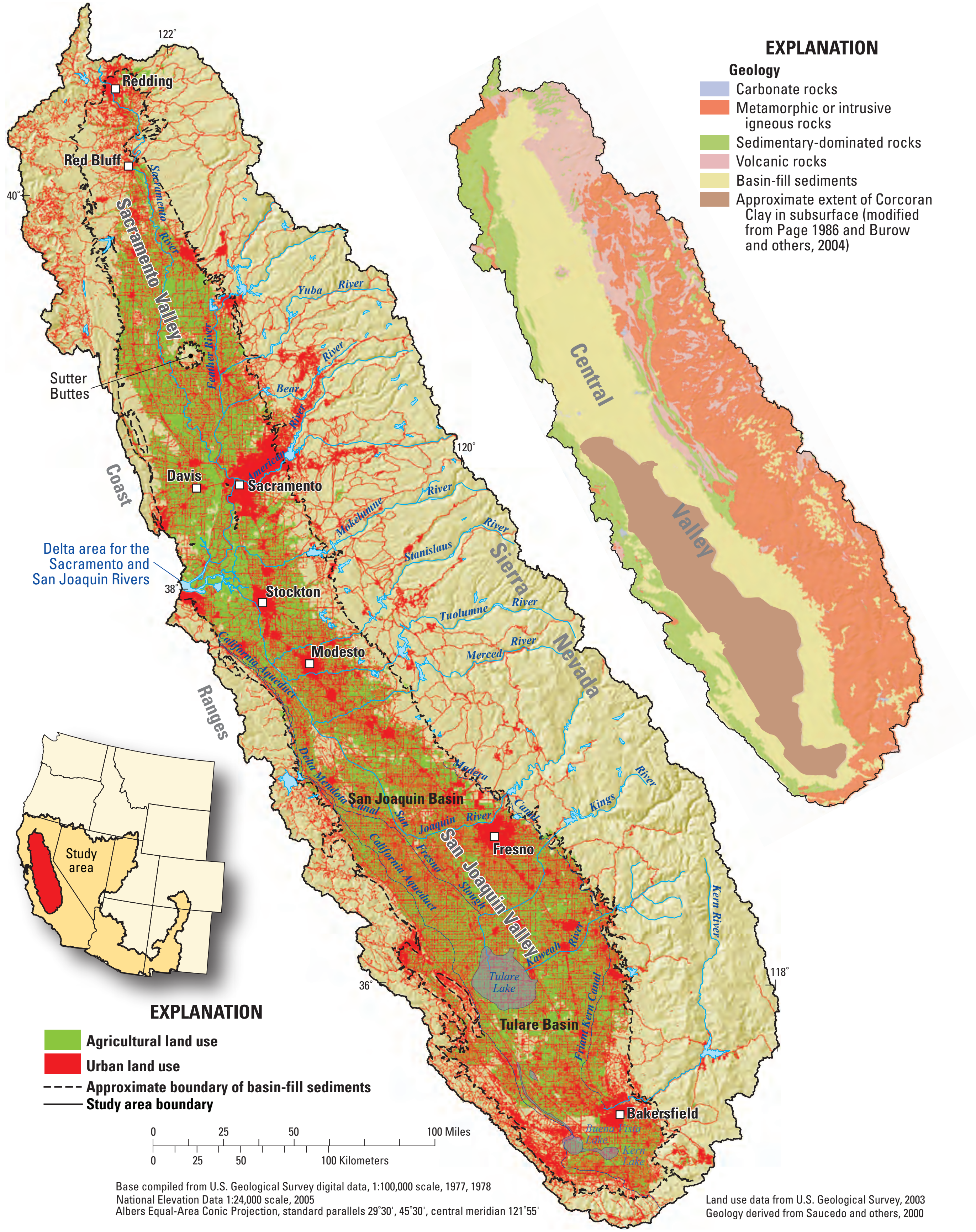


Figure 1. Physiography, land use, and generalized geology of the Central Valley, California.

Agriculture is the predominant land use in the Central Valley (fig. 1). About 57 percent of the total land area in the valley was agricultural in 2000, with about 1.76 million acres of irrigated crops in the Sacramento Valley and about 5.46 million irrigated acres in the San Joaquin Valley (McKinney and Anning, 2009). Major crop types include grains, hay, cotton, tomatoes, vegetables, citrus and other fruits, nuts, grapes, corn, and rice. Groundwater withdrawals from the Central Valley aquifer system were the second largest for a principal aquifer in the United States (after the High Plains aquifer), accounting for 13 percent of total withdrawals in 2000 (Maupin and Barber, 2005, p. 24). The withdrawals supplied about 10.7 million acre-ft (43 percent) of the water used for agriculture and public supply in the Central Valley in 2000 (McKinney and Anning, 2009, table 1) and are especially important in dry years because they supplement the variable surface-water supplies in the valley.

The population in the Central Valley more than doubled from about 2.7 million in 1970 (U.S. Census Bureau, 1995) to about 6.0 million people in 2005 (McKinney and Anning, 2009). Large urban areas include Sacramento, Fresno, Bakersfield, Stockton, and Modesto. Urban land use in the Central Valley has increased from 3 percent in 1961 to 7 percent in 2000 (Faunt and others, 2009, table C3) at the expense of both undeveloped and agricultural lands. Nearly every city in the San Joaquin Valley uses groundwater as its main source for municipal and industrial supplies (Faunt, Belitz, and Hanson, 2009, p. 62).

The U.S. Geological Survey (USGS) has recently reported on the availability and use of groundwater in the Central Valley as part of its Ground-Water Resources Program (Faunt, Hanson, and Belitz, 2009). Information on the regional groundwater flow system compiled and developed as part of that study is described in this section of the report.

Water Development History

Water development in the Central Valley began in about 1790 with the diversion of surface water for irrigation (Williamson and others, 1989, p. D44). Early farming was concentrated close to the delta formed by the San Joaquin and Sacramento Rivers and in other areas where the water table was near the land surface throughout the year. Agriculture in the San Joaquin Valley increased in the late 1850s with the drainage and reclamation of river bottom lands and by 1900, an extensive system of canals and ditches had been built and much of the flow of the Kern River and the entire flow of the Kings River had been diverted to irrigate lands in the southern San Joaquin Valley (Nady and Larragueta, 1983). Because no large storage facilities were built along with these early diversions, the agricultural water supply, and therefore crop demand, was largely limited by the amount of summer base flow in streams. By 1910 nearly all of the available surface-water supply in the San Joaquin Valley had been diverted, leading to more extensive development of groundwater resources.

Groundwater was first used in the Central Valley in about 1880 in areas where artesian conditions were present and flowing wells could be drilled, particularly near the central part of the San Joaquin Valley and around the terminal lake basins. After 1900, the yields of flowing wells were reduced due to declining water levels, and it became necessary to install pumps in the wells to sustain flow rates. Around 1930, the development of an improved deep-well turbine pump and rural electrification enabled additional groundwater development for irrigation (Galloway and Riley, 1999). Years of pumping in the valley for irrigation has caused large declines in the water table, resulting in many wells going dry and thousands of acres of farmland taken out of production (Faunt, Belitz, and Hanson, 2009, ch. B, p. 60).

In 1935, as part of the Federal Central Valley Project, planning began to use water from the San Joaquin and Sacramento Rivers to irrigate about 12 million acres in the San Joaquin Valley (Faunt, Belitz, and Hanson, 2009, p. 60). The need to prevent groundwater overdraft in the Central Valley and for additional water to support population growth in southern California prompted construction of the State Water Project. These two projects resulted in the storage of most of the tributary streamflow behind dams for use throughout the year. Surface water was diverted for the Central Valley Project for irrigation and transported to the southern San Joaquin Valley through the Madera and Friant-Kern Canals beginning in the mid-1940s and the State Water Project delivered water to the west side of the valley through the Delta-Mendota Canal in 1951. The Central Valley relies on a combination of local and imported surface water and local groundwater. Generally, most farms near surface water distribution canals use surface water. When surface water is not available later in the growing season or during drought, groundwater is used.

Hydrogeology

The Central Valley is a large structural trough filled with sediment that is bounded by primarily granitic and metamorphic rocks in the Sierra Nevada that were probably uplifted between Late Jurassic and Late Cretaceous time on the east (Planert and Williams, 1995) and a complex assemblage of late Jurassic- to Quaternary-age marine and continental rocks in the Coast Ranges on the west (Gronberg and others, 1998, p. 5). The northeastern corner of the valley is at the southern end of the Cascade Range and contains material derived from volcanic rocks (Planert and Williams, 1995, p. B16). The east side of the Central Valley is underlain by a westward sloping surface of consolidated rocks that are the subsurface continuation of the Sierra Nevada to the east. The trough tilts to the south and has been filled with marine and continental deposits of Tertiary age and continental deposits of Quaternary age. The continental sediments consist mostly of sand and gravel interbedded and mixed with clay and silt deposited by streams and lakes. Depending on location, deposits of fine-grained materials—mostly clay and silt—make up as much as 50 percent of the thickness of the basin-fill sediments (Planert and Williams, 1995, p. B17).

Alluvial fans have formed on all sides of the Central Valley with coarse-grained material deposited close to the valley margins and finer grained detritus transported farther toward the valley axis. On the east side of the valley, shifting stream channels have created coalescing fans consisting of broad sheets of inter-fingering, wedge-shaped lenses of gravel, sand and finer sediment (Faunt, Hanson, and Belitz, 2009, p. 18).

The basin-fill deposits in the Sacramento and San Joaquin Valleys have somewhat different depositional environments and textural compositions. A three-dimensional model of the percentage of sediments with coarse-grained texture in the Central Valley was developed by Faunt, Hanson, and Belitz, (2009, p. 2) from information on drillers' logs. The model shows significant heterogeneity in the texture of the sediments, although sediments in the Sacramento Valley are generally finer grained than in the San Joaquin Valley (Faunt, Hanson, and Belitz, 2009, figs. A12 and A14). Fine-grained sediments likely associated with nearby volcanic activity, relatively low energy drainage basins, and the lack of glacially derived deposits are interbedded with coarse-grained alluvial sediments in and near river channels, flood plains, and alluvial fans in the Sacramento Valley. No extensive layers of fine-grained sediments have been found in the Sacramento Valley (Faunt, Hanson, and Belitz, 2009, p. 20).

Areas of coarse-grained sediments are more widespread in the San Joaquin Valley, especially on the east side, and occur along the major rivers. Alluvial fans in the southern San Joaquin Valley are derived from glaciated parts of the Sierra Nevada and are much coarser grained than the alluvial fans to the north (Faunt, Hanson, and Belitz, 2009, p. 2). Generally thin, discontinuous lenses of fine-grained sediments (clay, sandy clay, sandy silt, and silt) are distributed throughout the San Joaquin Valley. The shales and marine deposits of the Coast Ranges generally yield finer grained sediments than the crystalline rocks of the Sierra Nevada and contribute to the sediments of the western San Joaquin Valley being finer grained overall than the eastern part. Alluvium derived from the Coast Range and the Sierra Nevada interfinger near the surface at the valley bottom. The large percentage of fine-grained sediments in the western San Joaquin Valley impedes the downward movement of groundwater and may contribute to agricultural drainage problems and to land subsidence in the area (Faunt, Hanson, and Belitz, 2009, p. 40).

The areally extensive lake-deposited Corcoran Clay of Pleistocene age underlies as much as 6,600 mi^2 of the San Joaquin Valley, extending to near the valley's western margin (Page, 1986; Faunt, Hanson, and Belitz, 2009, p. 21) (fig. 1). An analysis of well logs by Burow and others (2004, p. 29) indicates that the eastern extent of the Corcoran Clay lies approximately parallel to the axis of the valley and thins eastward or was eroded by the rivers draining the Sierra Nevada in the Modesto area. The top of the Corcoran Clay is up to 900 ft deep and the clay is as much as 200 ft thick beneath the Tulare Lake bed (Davis and others, 1959; Page, 1986).

Conceptual Understanding of the Groundwater Flow System

The main source of groundwater in the valley is the upper 1,000 ft of basin-fill deposits (Page, 1986). Granitic, volcanic, and metamorphic rocks that crop out and underlie the eastern part of the valley form an almost impermeable boundary for the basin-fill groundwater system. Little water flows through the extensive deposits of consolidated marine and mixed marine and continental rocks that overlie the crystalline rocks and bound the western part of the valley because of low permeability. Most of the freshwater (water with less than 1,000 mg/L of dissolved solids) is contained in continental deposits in the Sacramento Valley, where the depth to the base of freshwater is as much as 2,500 ft (Planert and Williams, 1995 p. B20). In the San Joaquin Valley, most of the freshwater is within continental deposits, but also is in marine rocks on the southeast side of the valley. The sediments in the San Joaquin Valley saturated with freshwater range in thickness from 100 to more than 4,000 ft. Saline water (water with a minimum dissolved-solids concentration of 2,000 mg/L) occurs at depth throughout the Central Valley, usually as connate water in marine sediments and rocks.

The general conceptual model for groundwater flow in the Central Valley is that of a heterogeneous aquifer system comprising confining units and unconfined, semiconfined, and confined aquifers (Williamson and others, 1989, p. D14; Faunt, Hanson, and Belitz, 2009, p. 20). Alluvial sediments transported from the surrounding Sierra Nevada and Coast Ranges make up the aquifer system. Unconfined (water table) or semiconfined conditions occur in shallower deposits and along the margins of the valley. The aquifer system becomes confined in most areas within a few hundred feet of land surface because of numerous overlapping lenses of fine-grained sediments (fig. 2). Generally, these lenses are discontinuous and are not vertically extensive or laterally continuous. An exception is the Corcoran Clay that separates the basin-fill deposits over a large area in the central, western, and southern parts of the San Joaquin Valley into an upper unconfined to semiconfined zone and a lower confined zone (Williamson and others, 1989, p. D16; Burow and others, 2004) (fig. 2). The drilling of thousands of large-diameter irrigation wells through and perforated above and below the Corcoran Clay has connected the upper and lower zones, resulting in a substantial increase in downward leakage (Bertoldi and others, 1991).

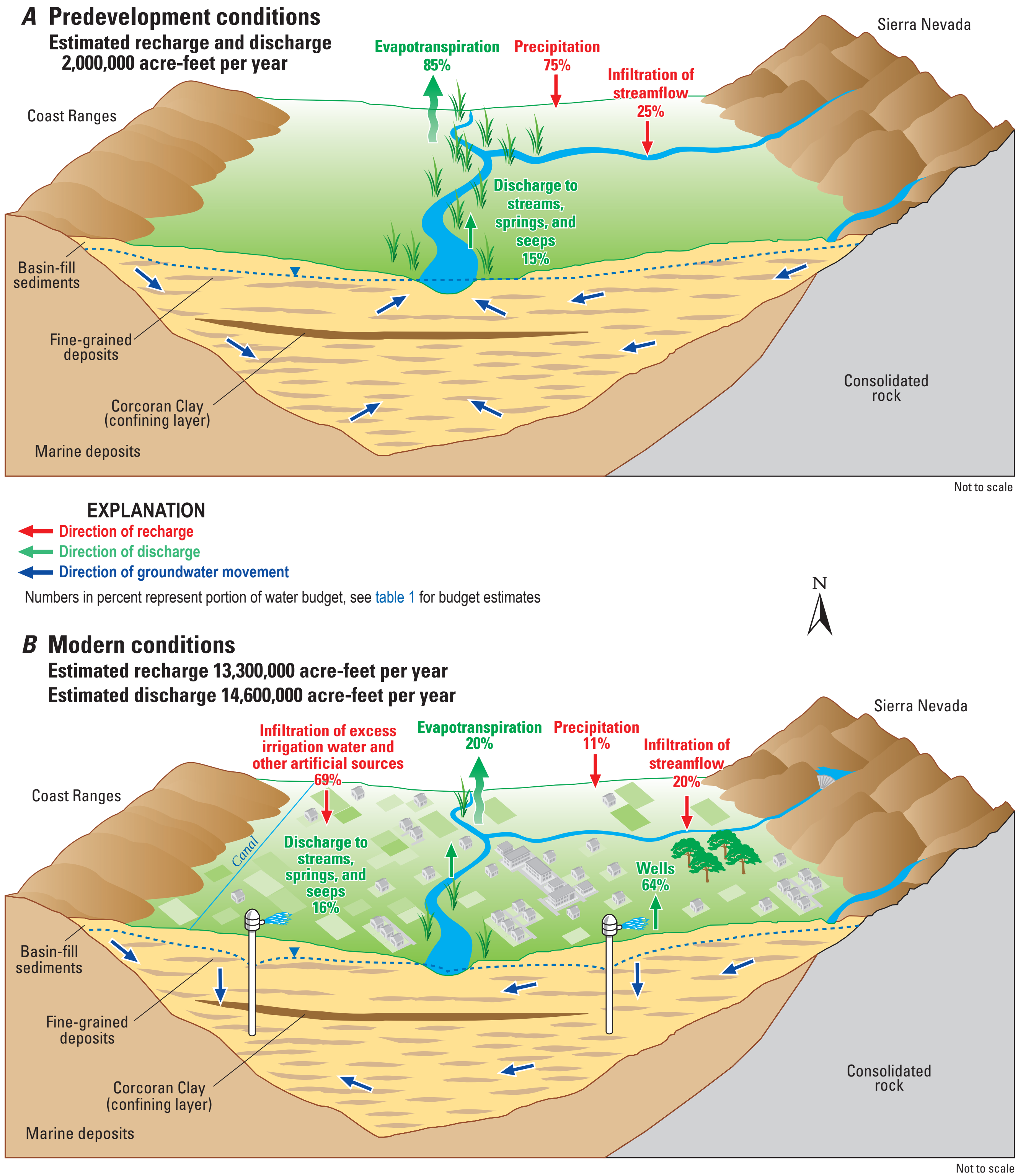


Figure 2. Generalized diagrams for the Central Valley, California, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

The considerable variability in hydraulic properties, both laterally and vertically, within the Central Valley aquifer system reflects the various depositional environments of the sediments. The water-transmitting properties of aquifer sediments are functions of lithology and differ according to grain size and the degree of sorting of the sediments. Hydraulic conductivity values used in a recent numerical groundwater flow model of the Central Valley aquifer system were assumed to be correlated to sediment texture, which was determined from the fraction of coarse-grained material recorded on multiple drillers' logs. Calibrated hydraulic conductivities ranged from 0.075 ft/d for fine-grained material to 670 ft/d for coarse-grained material in the Sacramento Valley and from 0.024 ft/d for fine-grained material to 330 ft/d for coarse-grained material in the San Joaquin Valley (Faunt and others, 2009, p. 156). For both valleys, the distributions of horizontal and vertical conductivities are the same as those for the sediment texture (Faunt, Hanson, and Belitz, 2009, fig. A12).

Groundwater Budget and Flow

Under predevelopment conditions, before surface-water diversions and irrigation began to affect the groundwater system in the Central Valley in about 1850 (Williamson and others, 1989, p. D32), recharge occurred naturally from the infiltration of precipitation on the valley floor and from stream losses in the upper parts of the alluvial fans, where the major streams enter the valley (fig. 2). Streams carrying runoff from the Sierra Nevada provided most of the water lost to the groundwater system. The volume of precipitation on the valley floor that infiltrates to the groundwater system is presumed to be significantly larger during wetter years (Faunt, Belitz, and Hanson, 2009, table B1). Estimates of selected components of the groundwater budget for subbasins within the Central Valley are presented where available by the California Department of Water Resources (2003).

Estimates of recharge and discharge to the Central Valley groundwater system under predevelopment conditions are presented in table 1. Because of a paucity of data before water development began, these values are considered to be rough estimates and represent recharge and discharge to both shallow, local aquifers and the deeper, more regionally extensive part of the groundwater system (Williamson and others, 1989, p. D38 and D57). Under predevelopment conditions, groundwater recharge was balanced by groundwater discharge, which occurred primarily through evapotranspiration and by leakage to streams in the bottom of the valley (fig. 2). Before water development substantially affected the aquifer, groundwater generally moved from recharge areas along the valley margins toward topographically low areas in the center of the valley and to the Sacramento or San Joaquin Rivers (fig. 3*A*). The vertical gradient was downward around the margins of the valley and upward in the center of the valley. The areas of natural discharge in the central part of the valley generally coincided with a large artesian area that was documented prior to 1900 (Hall, 1889; Mendenhall and others, 1916). The direction of groundwater flow in the southern San Joaquin Valley was toward Tulare Lake, an area of natural groundwater discharge that existed prior to water development in the area.

The natural patterns of groundwater movement and the rates of recharge and discharge throughout the Central Valley have been substantially altered by groundwater development and the diversion and redistribution of surface water for irrigation. These modifications have changed the amount and distribution of recharge to the aquifer system, which has affected the configuration of the water table in parts of the valley (fig.3*B*). Streams that naturally would have recharged the aquifer are now diverted to irrigate crops in other areas or the water is stored for seasonal release. Recharge from excess irrigation water and discharge from wells for irrigation and public supply, simulated to average about 9,200,000 and 9,300,000 acre-ft/yr from 1962 to 2003, respectively (Faunt, Belitz, and Hanson, 2009, table B2), are much larger than natural sources of recharge and discharge (table 1 and fig. 2). Groundwater withdrawals have lowered water levels, altered the direction and rates of groundwater flow, and have caused the land to subside in some areas (Williamson and others, 1989, p. D52).

Withdrawals from wells in the Central Valley averaged 11.5 million acre-ft/yr during the 1960s and 1970s, and during the drought of 1976–77, withdrawals increased to a high of about 15 million acre-ft (Bertoldi and others, 1991, p. A22). More surface water is available for irrigation during years with average or above average precipitation, resulting in a decrease in withdrawals from wells and a rise in groundwater levels. During drought years, less surface water is available for irrigation and wells are more heavily pumped, leading to water-level declines. Most of the approximately 100,000 high-capacity wells in the Central Valley are used for either irrigation or public supply (Bertoldi and others, 1991, p. A22). Well depths in the San Joaquin Valley range from about 100 to 3,500 ft, and the deepest wells are in the

Table 1. Estimated groundwater budget for the Central Valley basin-fill aquifer system, California, under predevelopment and modern conditions.

[All values are in acre-feet per year (acre-ft/yr). Estimates of groundwater recharge and discharge under predevelopment conditions are from Williamson and others (1989, fig. 19). Estimates for modern conditions are derived from averages listed for 1962–2003 by Faunt, Belitz, and Hanson (2009, table B2 and figure B1). The budgets are intended only to provide a basis for comparison of the overall magnitudes of recharge and discharge between predevelopment and modern conditions, and do not represent a rigorous analysis of individual recharge and discharge components]

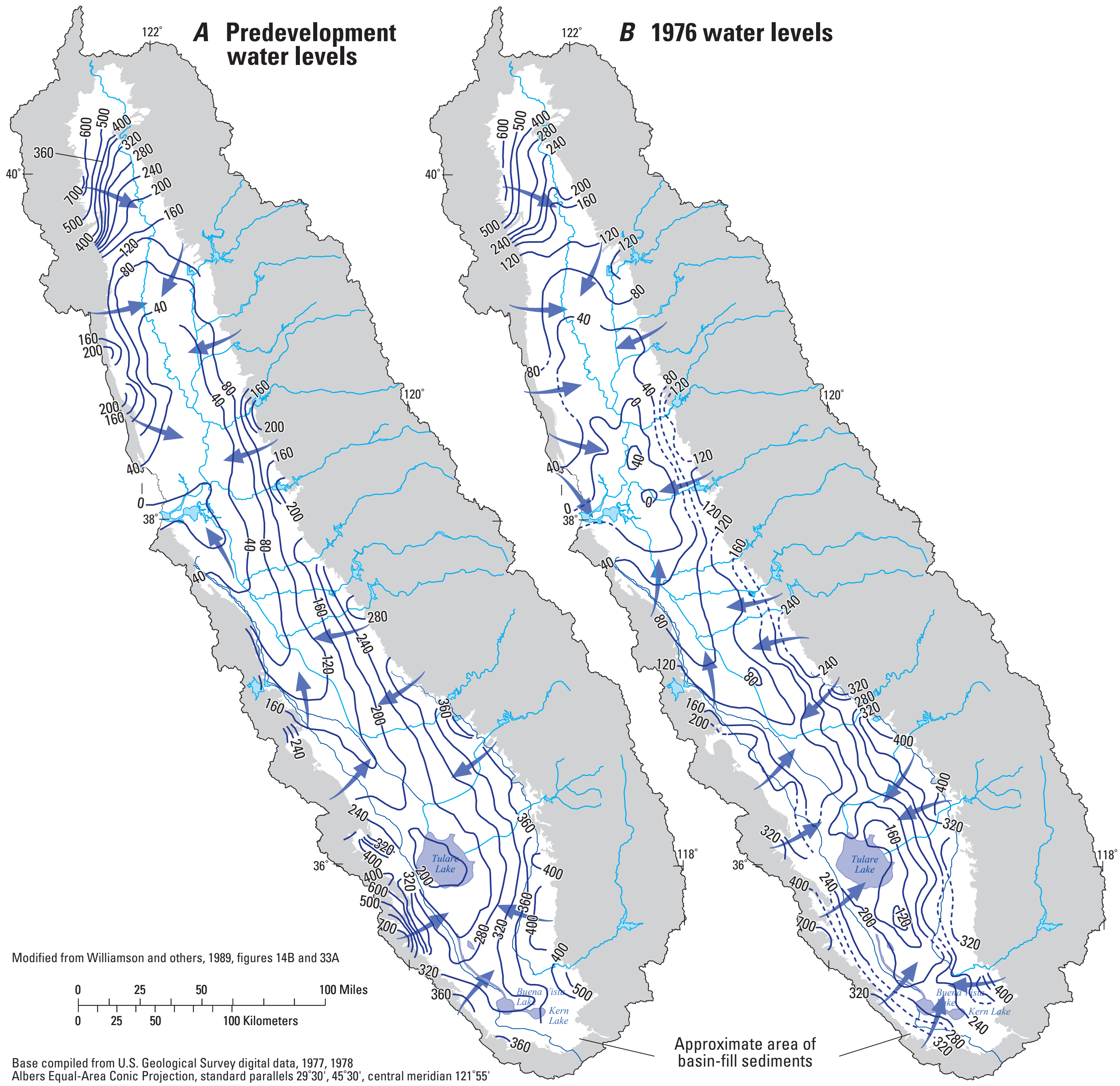
	Predevelopment conditions	Modern conditions	Change from predevelopment to modern conditions
Budget component		**Estimated recharge**	
Infiltration of precipitation on basin	1,500,000	[1]1,500,000	0
Infiltration of streamflow	500,000	2,600,000	2,100,000
Infiltration of excess irrigation water and other artificial sources	0	[1]9,200,000	9,200,000
Total recharge	**2,000,000**	**13,300,000**	**11,300,000**
Budget component		**Estimated discharge**	
Evapotranspiration	1,700,000	3,000,000	1,300,000
Discharge to streams, springs, and seeps	300,000	[2]2,300,000	2,000,000
Well withdrawals	0	9,300,000	9,300,000
Total discharge	**2,000,000**	**14,600,000**	**12,600,000**
Change in storage (total recharge minus total discharge)	0	-1,300,000	-1,300,000

[1] The simulated average recharge for 1962–2003 from landscape processes (includes infiltration of precipitation and excess irrigation water) was 10,700,000 acre-ft/yr (Faunt, Belitz, and Hanson, 2009, table B2). To fit the components in this table, recharge from the infiltration of precipitation on the basin was assumed to be the same as under predevelopment conditions (Williamson and others, 1989) and the remainder was assumed to be from excess irrigation water and from other artificial sources.

[2] Includes a simulated average discharge of 100,000 acre-ft/yr to the San Joaquin River Delta (Faunt, Belitz, and Hanson, 2009, fig. B1 and table B2).

west-central and south-central parts of the valley. Many of the wells are constructed with long perforated or screened intervals that connect several water-bearing layers and thus increase the vertical hydraulic connection through the aquifer system (Bertoldi and others, 1991, p. A23). Public-supply wells typically have long intervals open to the deeper part of the aquifer system. Vertical flow between permeable layers, either upward or downward, can be substantial in many unpumped and unsealed abandoned wells.

Recharge from excess irrigation water and discharge from wells for irrigation and public supply have increased the amount of water flowing vertically in the aquifer system from that under predevelopment conditions. Under modern conditions with water development, the combination of increased recharge to the water table and increased pumping from the lower confined zone has reversed the direction of the hydraulic gradient from upward to downward in the center of the valley (Williamson and others, 1989). In addition, groundwater moving along a lateral flow path may be extracted by wells and reapplied at the surface multiple times before reaching the natural discharge area in the valley bottom (Phillips and others, 2007, p. 4-7) (fig. 4). Under modern conditions in some areas, groundwater flows beneath the river toward pumping centers on the west side of the valley rather than discharging to the river (Bertoldi and others, 1991, p. A21).



EXPLANATION

Predevelopment water levels—Water-level altitude, in feet. Contour interval is variable. Datum is National Geodetic Vertical Datum of 1929

Study area boundary

Direction of water flow

EXPLANATION

Spring 1976 water levels—Water-level altitude, in feet. Contour interval is variable, dashed where approximately located. Datum is National Geodetic Vertical Datum of 1929

Study area boundary

Direction of water flow

Figure 3. Groundwater levels in the unconfined part of the aquifer system in the Central Valley, California (*A*) estimated for predevelopment conditions, and (*B*) in 1976.

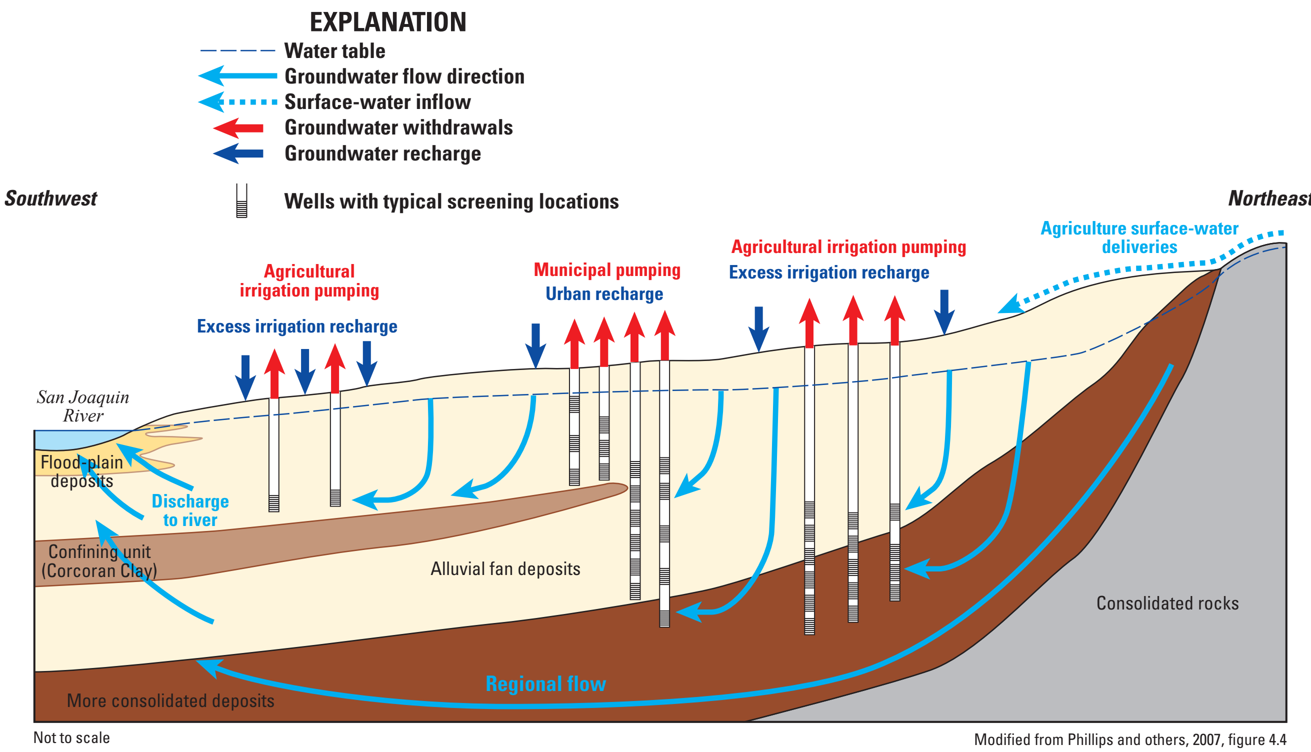


Figure 4. Conceptual diagram showing effects of pumping and irrigation on vertical groundwater flow, and natural discharge areas near Modesto, California.

From predevelopment conditions to 1961, water levels generally declined less than 100 ft in unconfined parts of the aquifer system and more than 100 ft in the deeper confined parts of the system in the western and southern San Joaquin Valley (Williamson and others, 1989, figs. 32A and 32B) (figs. 5A and 5B). Water levels have dropped more than 300 ft in some westside areas. Pumping in the western and southern San Joaquin Valley was reduced in 1967 when delivery of surface water through the California Aqueduct to farms in the area began. Increased surface-water delivery and decreased groundwater withdrawals caused water levels to rise in both the upper and lower zones in much of the area (Faunt, Belitz, and Hanson, 2009, p. 97). The water table also rose in much of the Sacramento Valley due to the recharge of excess irrigation water.

The decrease in groundwater stored in the Central Valley from predevelopment conditions to 1977 was calculated with a numerical model to be about 60 million acre-ft (Williamson and others, 1989, p. D95). About 1,400,000 acre-ft/yr less groundwater was simulated in storage using average annual conditions from 1962 to 2003 (Faunt, Belitz, and Hanson, 2009, p. 70), about the difference between estimated recharge and discharge for modern conditions listed in table 1. This depletion of water in storage is made up of three components: long-term decline of the water table; inelastic compaction of the aquifer (permanent reduction of pore space resulting in land subsidence); and elastic storage (compression of sediments and expansion of water). Although a large amount, this long-term decrease in aquifer storage is only a small part of the more than 800 million acre-ft of freshwater estimated to be stored in the upper 1,000 ft of sediments in the Central Valley (Williamson and others, 1989, p. D96).

The area affected by land subsidence includes much of the southern San Joaquin Valley, smaller areas in the Sacramento Valley, and in the delta area for the Sacramento and San Joaquin Rivers. Large groundwater withdrawals and associated water-level declines, mainly in deeper parts of the aquifer system during the 1950s and 1960s, caused about 75 percent of the total volume of land subsidence in the San Joaquin Valley. In 1970, subsidence in excess of 1 ft had affected more than 5,200 mi^2 of irrigable land in the San Joaquin Valley (Poland and others, 1975). The maximum subsidence was more than 28 ft near Mendota, about 30 mi west of Fresno in the bottom of the valley. Water levels in deeper parts of the aquifer system recovered as much as 200 ft in the 6 years from 1967 to 1974 (Ireland and others, 1984) and subsidence slowed or stopped over much of the affected area. Subsidence is likely to resume in the future if groundwater withdrawals cause water levels to drop below the previous low levels.

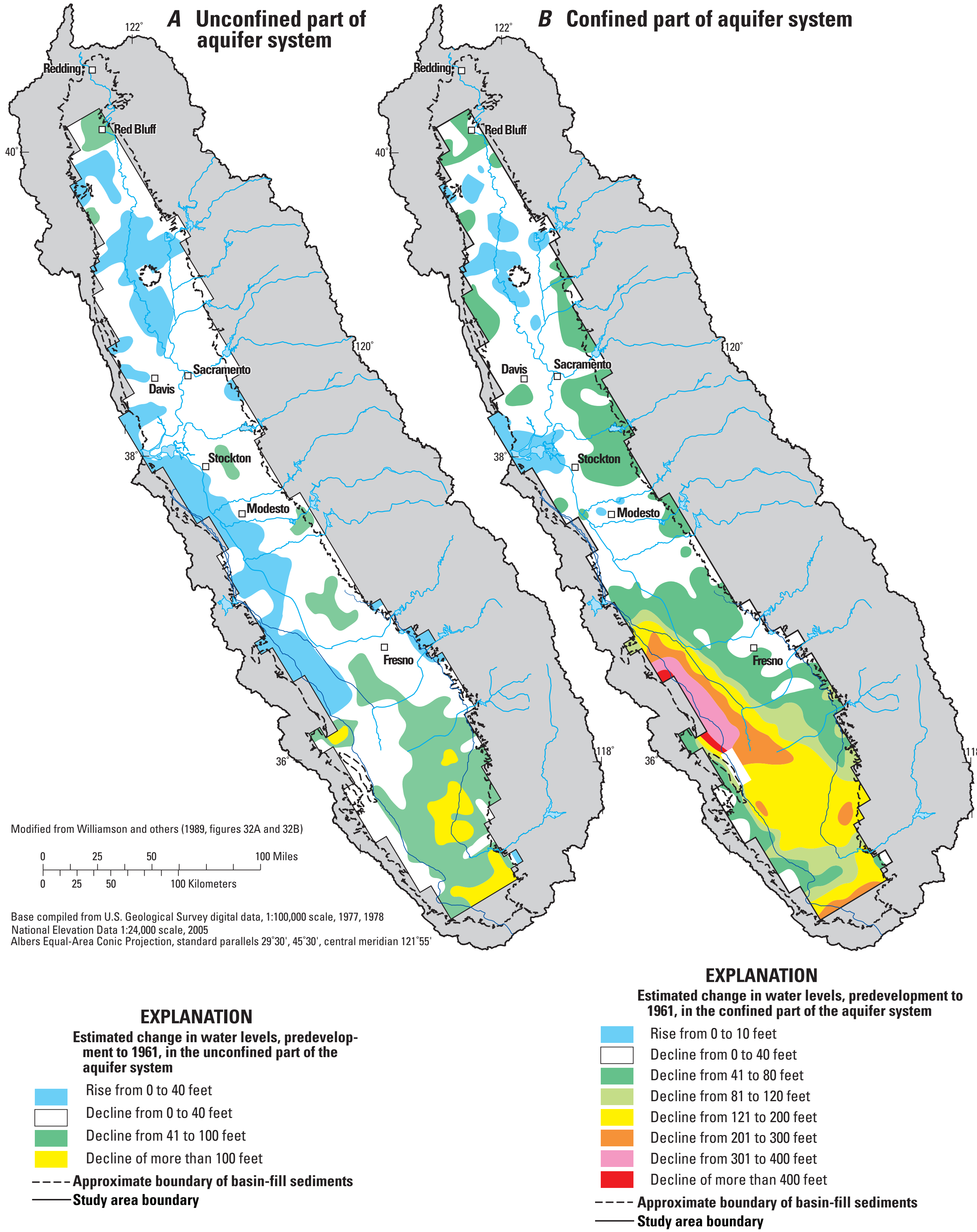


Figure 5. Changes in groundwater levels in the Central Valley, California, from predevelopment conditions to spring 1961 in the (*A*) unconfined part of the aquifer system and (*B*) confined part of the aquifer system.

Effects of Natural and Human Factors on Groundwater Quality

Many factors influence the quality of groundwater in the Central Valley aquifer system, but the predominant factors are the bedrock geology and chemistry of soils derived from bedrock, land use, and water use. Activities associated with agricultural land and water use have affected groundwater quality across the Central Valley. The infiltration of water pumped from deeper parts of the aquifer system and surface water applied to fields for irrigation has resulted in recharge to the shallow unconfined part of the aquifer system with water that has been exposed to agricultural chemicals and natural salts concentrated by evapotranspiration. Excess irrigation water has become a major source of recharge to the Central Valley aquifer system and may contribute to elevated concentrations of nutrients, pesticides, volatile organic compounds (VOCs), major ions, and trace elements in groundwater.

Groundwater-quality data has been collected in the Central Valley as part of several local- and regional-scale studies by the USGS, including the San Joaquin Valley Drainage Program (Gilliom and others, 1989), the Regional Aquifer Systems Program (Bertoldi and others, 1991), and the National Water-Quality Assessment (NAWQA) Program. The California Ground-Water Ambient Monitoring and Assessment (GAMA) Program also is collecting data from parts of the Central Valley aquifer system that will be used to identify the natural and human factors affecting groundwater quality (Belitz and others, 2003; Kulongoski and Belitz, 2006). Groundwater used for public drinking-water supplies was sampled in the southern Sacramento Valley (Milby Dawson and others, 2008) and the northern San Joaquin Valley (Bennett and others, 2006) in 2005; the southeastern San Joaquin Valley (Burton and Belitz, 2008) in 2005–06; and the middle Sacramento Valley (Schmitt and others, 2008), the Kern County part of the southern San Joaquin Valley (Shelton and others, 2008), and the central part of the eastern San Joaquin Valley (Landon and Belitz, 2008) in 2006. Water-quality data collected by the USGS are stored in the National Water Information System (NWIS) database.

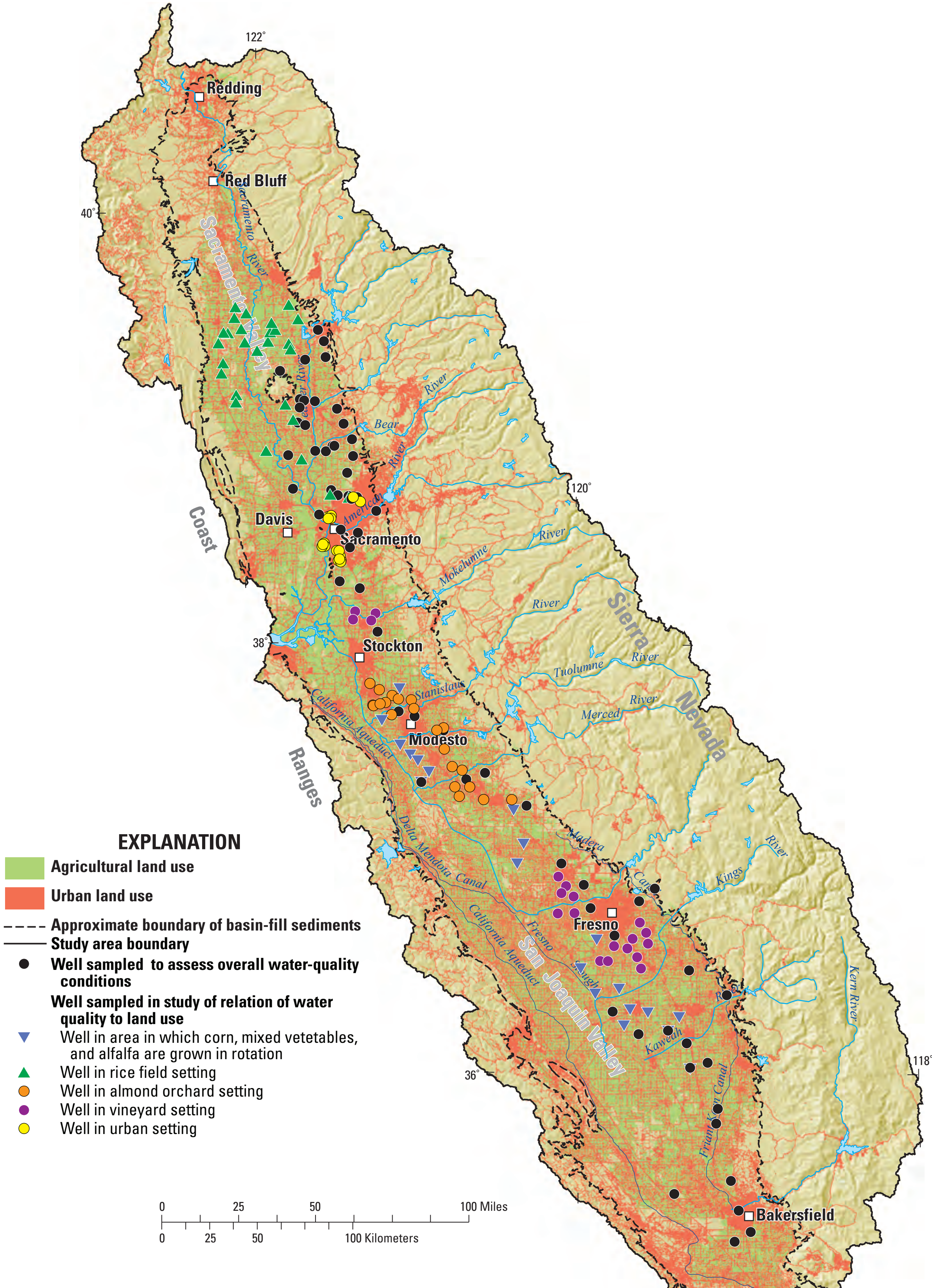
Studies made as part of the NAWQA Program on groundwater quality in parts of the Sacramento Valley (Domalgalski and others, 2000) and in the eastern San Joaquin Valley (Dubrovsky and others, 1998) have provided information on the factors affecting water quality in a portion of the Central Valley. The location of the NAWQA sampled wells are shown on figure 6. Water was sampled from 61 wells (59 domestic wells and 2 monitoring wells) completed in alluvial fan deposits along the east side of the valleys as part of regional aquifer studies to assess the concentration and distribution of major chemical constituents, nutrients, pesticides, VOCs, trace elements, and radon. The study in the southeastern Sacramento Valley is described by Dawson (2001a) and the study in the eastern San Joaquin Valley is described by Burow and others (1998a). Because domestic wells are typically screened in the upper part of the aquifer system, this dataset generally represents the water quality of the unconfined part of the aquifer system in the eastern San Joaquin Valley and southeastern Sacramento Valley.

Shallow groundwater was sampled from 28 monitoring wells completed near the water table beneath or near rice fields in the central Sacramento Valley (Dawson, 2001b) and from 19 monitoring wells beneath recently urbanized areas of Sacramento (Shelton, 2005) to determine the water chemistry of recently recharged groundwater and the effects of these land uses on water quality. Three land-use studies were done in the eastern San Joaquin Valley: in agricultural areas dominated by vineyards, in almond orchards, and in areas in which corn, alfalfa, and vegetables were grown in rotation (Burow and others, 1998b). Combined, these three crop groups account for 47 percent of the agricultural land in the eastern San Joaquin Valley.

A local-scale network of 20 monitoring wells near Fresno along an approximately horizontal groundwater flow path was designed and sampled by NAWQA investigators to characterize the spatial and temporal distribution of water quality in relation to groundwater flow in a vineyard land-use setting (Burow and others, 1999). A network of 23 monitoring wells in the zone of contribution to a public-supply well in Modesto was designed and sampled as part of the NAWQA Transport of Anthropogenic and Natural Contaminants (TANC) to public-supply wells topical study (Jurgens and others, 2008).

General Water-Quality Characteristics and Natural Factors

The quality of groundwater in the Central Valley is influenced by the surface water that enters the valley from the surrounding mountains. Runoff and snowmelt from the Sierra Nevada have low concentrations (less than 200 mg/L) of dissolved solids (fig. 7) because of the low solubility of the quartz and feldspar minerals that comprise the granitic bedrock and sediment derived from this rock. In contrast, the rocks and sediments of the Coast Ranges in the western part of the valley contain highly soluble minerals. Of particular importance are marine sedimentary formations with soluble calcium, sodium, and magnesium sulfates, and elevated concentrations of various nitrogen-containing minerals and trace elements (Gronberg and others, 1998, p. 27). Precipitation on the Coast Ranges dissolves these constituents and the resulting runoff has elevated concentrations of dissolved solids and other minerals. Chemical constituents also may be concentrated in the soil and in shallow groundwater by evapotranspiration.



Base compiled from U.S. Geological Survey digital data, 1:100,000 scale, 1977, 1978
National Elevation Data 1:24,000 scale, 2005
Albers Equal-Area Conic Projection, standard parallels 29°30', 45°30', central meridian 121°55'

Land use data from U.S. Geological Survey, 2003

Figure 6. Location of wells sampled in the Central Valley, California, by the NAWQA Program, 1993–98.

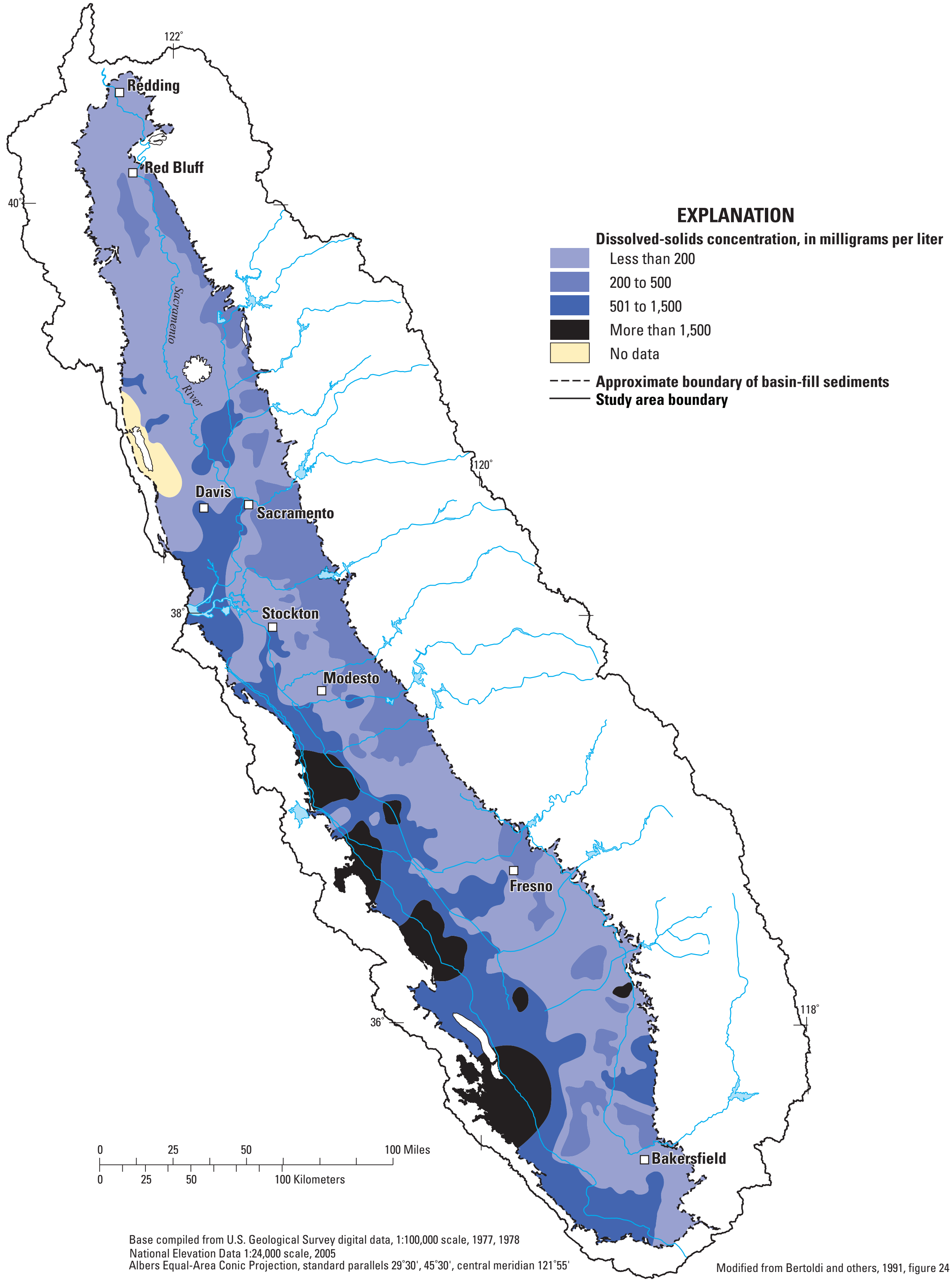


Figure 7. Distribution of dissolved-solids concentrations in groundwater of the Central Valley, California.

Groundwater chemistry varies spatially in the Central Valley. Calcium is a predominant cation and bicarbonate the predominant anion in groundwater in the northern Sacramento Valley and the eastern Sacramento and San Joaquin Valleys. Groundwater on the west side generally has higher concentrations of sulfate, chloride, and dissolved solids than groundwater on the east side (Bertoldi and others, 1991, fig. 25). Groundwater in the center of the valley is a combination of water from the east and west sides, is generally more geochemically reduced, and contains higher concentrations of dissolved solids than groundwater on the east side (Davis and others, 1959). The higher concentrations of dissolved solids result from cation exchange processes as the water moves through the sediments and from evaporative concentration in the discharge area of the aquifer system. Concentrations tend to increase from the north to south along the axis of the Sacramento Valley, but generally do not exceed 500 mg/L. On the east side of the San Joaquin Valley, concentrations of dissolved solids generally do not exceed 500 mg/L and tend to increase to the west. In general, dissolved-solids concentrations increase with depth in the Central Valley aquifer system. Therefore, typically deeper wells in the western and southern parts of the San Joaquin Valley are likely to produce water with higher concentrations of dissolved solids than the typically shallower wells in the Sacramento Valley and the eastern San Joaquin Valley (Planert and Williams, 1995, p. B20).

Groundwater in the coarse-grained alluvial-fan deposits on the east side of the valley is generally oxic (contains dissolved oxygen), while in the finer grained basin and lake deposits near the axis of the valley it is usually anoxic (contains less than 0.5 mg/L of dissolved oxygen according to a framework described by McMahon and Chapelle (2008)). Geochemically reducing conditions commonly occur in discharge areas where long flow paths terminate and residence time and content of organic matter increase (Gronberg and others, 1998, p. 29). In the northwestern San Joaquin Valley, sediments derived from the Sierra Nevada are more reduced than interbedded sediments from the Coast Range (Dubrovsky, and others, 1991, p. 24). In the NAWQA land-use study, median concentrations of dissolved oxygen in samples from shallow wells in rice field areas in the Sacramento Valley and in the corn-alfalfa-vegetable rotation fields in the San Joaquin Valley were 0.36 and 1.5 mg/L, respectively. Wells sampled as part of these studies are in the center of the valleys or near where the alluvial fans and basin bottom deposits meet, where sediments are generally fine-grained and have a relatively high organic content. Wells sampled for the other NAWQA studies are generally completed in the upper parts of the alluvial fan deposits and had median concentrations of dissolved oxygen greater than 3 mg/L. The redox environment in the aquifer strongly influences the potential for degradation or accumulation of redox sensitive constituents, such as selenium, uranium, arsenic, nitrate, and some pesticides and VOCs. The median pH for groundwater sampled as part of the Central Valley NAWQA studies ranged from 7.1 to 7.4 standard units.

Soils in the western San Joaquin Valley are derived primarily from the marine rocks that form the western boundary of the aquifer system and contain relatively large amounts of selenium. When these soils are irrigated, naturally occurring minerals containing selenium are dissolved and mobilized into the shallow groundwater (Gilliom and others, 1989, p. 1). Excess irrigation water applied to remove salts from the soil, thus preventing salt buildup, leaches selenium from the soil and the marine rocks and transports it to shallow groundwater or to surface drains. Generally, concentrations of selenium in groundwater are highest in areas of the western San Joaquin Valley where soil selenium and groundwater salinity are high, where the water table has been near the land surface and evaporative concentration has occurred, and where groundwater is oxic (Dubrovsky and others, 1993, p 543). Water that contains dissolved selenium concentrations of 1,400 ug/L is present in some of the regional surface drains and concentrations as high as 3,100 ug/L have been detected in shallow groundwater in the western San Joaquin Valley, west of the San Joaquin River flood plain (Planert and Williams, 1995, p. B20). The elevated concentrations of selenium in the western part of the valley are known only to be in the shallow groundwater and not in the deeper parts of the aquifer system from which most wells that supply municipalities obtain water (Planert and Williams, 1995, p. B20).

Arsenic is a minor constituent of minerals within the granitic rocks of the Sierra Nevada and the marine rocks of the Coast Ranges. Although arsenic concentrations in soil are consistently higher in the western and southernmost parts of the San Joaquin Valley than in the eastern part (Belitz and others, 2003, p. 58), analysis of water-quality data from public-supply wells retrieved from the California Department of Health Sevices database and from a variety of well types retrieved from the NWIS database indicate that high concentrations of arsenic in soil are not sufficient to cause high concentrations of arsenic in groundwater. The presence and concentration of arsenic in groundwater also is influenced by reducing conditions and high pH (greater than 8) (Belitz and others, 2003 p. 60). Groundwater sampled from the central San Joaquin Valley that historically was the discharge zone for regional groundwater flow generally is reduced and has higher concentrations of arsenic than groundwater sampled from the eastern and western alluvial fan areas. Arsenic concentrations in the upper semiconfined zone in the northwestern San Joaquin Valley were significantly higher in reduced groundwater from the Sierra Nevada sediments than in oxic groundwater from the Coast Range sediments (Dubrovsky, and others, 1991, p. 25). Some of the high concentrations of arsenic in shallow wells in the Tulare Lake Bed in the southern San Joaquin Valley have been attributed to evaporative concentration (Fujii and Swain, 1995), a process that also affects dissolved solids, selenium, and other trace elements in the hydrologically closed basin.

Hull (1984) proposed that reducing conditions in the fine-grained sediments in basin areas with flood-plain deposits are a major influence on groundwater chemistry of the Sacramento Valley. Concentrations of arsenic exceeded the drinking-water standard of 10 µg/L (U.S. Environmental Protection Agency, 2008) in 7 (23 percent) of the 31 domestic and monitoring wells in the southeastern Sacramento Valley and in 10 (11 percent) of the 88 domestic wells in the eastern San Joaquin Valley sampled as part of the NAWQA Program. A significant inverse correlation was found between arsenic and dissolved oxygen concentrations in water sampled from the Sacramento Valley, suggesting that the presence and concentration of arsenic is related to the redox condition of the groundwater (Dawson, 2001a, p. 17). At a local scale, concentrations of arsenic in water sampled from the TANC network of wells in the Modesto area ranged from 2.3 to 15.9 µg/L (Jurgens and others, 2008, p. 38). Water sampled from the public-supply well had a concentration of 6.2 µg/L. Some reductive dissolution of iron oxyhydroxides and the subsequent release of adsorbed arsenic is thought to be responsible for the elevated arsenic concentrations in these water samples.

Naturally-occurring uranium is commonly adsorbed to aquifer sediments derived from the Sierra Nevada. The median concentration of uranium in water from wells sampled as part of the local-scale TANC study in Modesto was 10 µg/L (Jurgens and others, 2008, p. 39), and water from two monitoring wells had concentrations of uranium above the drinking-water standard of 30 µg/L (U.S. Environmental Protection Agency, 2008). Large rates of recharge in the agricultural area surrounding the city of Modesto and large withdrawals from wells within the city have caused oxygenated, high-alkalinity groundwater near the water table to move downward and laterally toward the wells. The continued downward migration of oxygenated, high-alkalinity groundwater is likely to mobilize uranium adsorbed to deeper sediments and to increase concentrations of uranium in that part of the aquifer (Jurgens and others, 2008, p. 51). Groundwater in other areas on the east side of the Central Valley also is susceptible to increasing concentrations of uranium where concentrations of bicarbonate are elevated and water is being pumped from deeper parts of the aquifer.

Potential Effects of Human Factors

The agricultural development in the Central Valley discussed in previous parts of this section has affected groundwater quality by adding millions of pounds of nitrate and pesticides to the land surface and modifying groundwater recharge so that these compounds can be more easily transported to the subsurface. Excess irrigation water can move chemicals applied at the land surface to the upper part of the aquifer system and eventually to the deeper part that is used for public supply. Groundwater in agricultural areas also can become excessively saline and damaging to crops because evaporation of sprayed irrigation water and evapotranspiration of soil moisture and shallow groundwater leaves behind dissolved salts. Shallow irrigation wells can accelerate the process by recirculating the saline shallow groundwater. Irrigation return-water drainage systems have been used to remove some of the saline shallow groundwater (Planert and Williams, 1995, p. B20).

Elevated concentrations of nitrate have been measured in shallow groundwater in areas of the Sacramento Valley (Planert and Williams, 1995, fig. 101) and sporadically in the San Joaquin Valley. Fogelman (1983) suggested that contamination from the land surface by leaching of applied nitrate fertilizers, urban waste-treatment facilities, and septic systems are the probable sources of nitrate in the groundwater in the Sacramento Valley. The median concentration of nitrate in water sampled in 1996 as part of the NAWQA regional aquifer study in the southeastern Sacramento Valley was 1.3 mg/L. The depth to the top of the openings in the well casings ranged from 29 to 215 ft below land surface and the mostly domestic wells were completed in basin-fill deposits with no continuous confining layers or other distinct internal boundaries that might impede the movement of groundwater. Water sampled from 8 (26 percent) of the 31 wells had nitrate concentrations greater than 3 mg/L, a level that may indicate an impact from human activities. Water sampled from 10 of the wells (32 percent) had dissolved oxygen concentrations less than or equal to 1 mg/L indicating anoxic conditions (Dawson, 2001a, p. 17). The median concentration of nitrate in water from these wells was 0.09 mg/L, and all of the wells were near the center of the Sacramento Valley in areas with finer grained deposits. The median concentration of nitrate in shallow groundwater sampled from monitoring wells in rice farming areas was 0.59 mg/L and in urban areas was 2.4 mg/L. The drinking-water standard for nitrate of 10 mg/L (U.S. Environmental Protection Agency, 2008) was exceeded in only one of the NAWQA samples from the Sacramento Valley.

Concentrations of nitrate were greater than 10 mg/L in 24 percent (21 of 88) of the domestic wells sampled in 1993–95 and in 29 percent (30 of 102) of the domestic wells sampled in 2001–02 as part of the NAWQA regional aquifer and land-use studies in the eastern San Joaquin Valley. The median concentration of nitrate of 5.6 mg/L in samples collected from these wells in 1993–95 and 6.4 mg/L in samples collected in 2001–02 (Burow and others, 2008, table 2) indicates that groundwater is affected over a large part of the area because of the input of nitrate from human activities, most likely agricultural practices.

The amount of coarse-grained sediments (sand- or gravel-sized) in the subsurface is a major factor in the susceptibility of groundwater to nitrate contamination. Sediment texture influences the rates of infiltration and groundwater flow, which in turn controls how rapidly water at the surface, with high nitrate concentrations, can infiltrate the soil and move downward into the aquifer. The sediment texture in the almond orchard and vineyard settings sampled by NAWQA in the eastern San Joaquin Valley is generally coarse-grained, and in the corn, alfalfa, and vegetable setting it is generally fine-grained with abundant clay. These contrasts in sediment texture, along with the amount of nitrogen applied, help explain the range in nitrate concentrations in groundwater underlying the different land-use settings. Nitrate concentrations in groundwater were highest in the almond orchard setting where high susceptibility and large amounts of nitrogen fertilizer applied occurred together (median concentration was 10 mg/L); nitrate concentrations in groundwater were lowest in the vineyard setting, where the amount of nitrogen applied was relatively small, even though the aquifer's susceptibility to contamination was high (median concentration was 4.6 mg/L); and nitrate concentrations in groundwater were intermediate in the corn, alfalfa, and vegetable setting where the amount of nitrogen applied was large, but the susceptibility was low (median concentration was 6.2 mg/L) (Burow and others, 1998b, p. 20).

Nitrate concentrations exceeded the drinking-water standard in 1.8 percent (19 of 1,045) of public-supply wells sampled in the Sacramento Valley and in 4.3 percent (27 of 629) of public-supply wells sampled in the San Joaquin Valley from 1994–2000 as part of the California Department of Health Services Title 22 water-quality monitoring program (California Department of Water Resources, 2003, subbasin descriptions). Wells in the Central Valley used for public supply and irrigation are generally deeper than wells used for domestic supply, based on average well depths listed by subbasins (California Department of Water Resources, 2003, subbasin descriptions).

Mean groundwater ages estimated for water sampled from the NAWQA local-scale networks of monitoring wells near Fresno and Modesto indicate that groundwater age increases with depth below land surface (Burow and others, 2008, p. S253). Shallow groundwater (less than 30 ft below the water table) was generally less than 15 years old, and deeper groundwater (more than than 180 ft below the water table) was greater than 45 years old. The water table in these areas is typically about 30–50 ft below land surface. Nitrate concentrations in water sampled from these monitoring wells were generally highest near the water table, decreased with depth, and were higher in the agricultural setting than in the urban setting (Burow and others, 2008, fig. 3). The groundwater system in these areas is largely oxic; therefore denitrification is not expected to significantly reduce nitrate concentrations.

Concentrations of nitrate in both shallow and deep parts of the aquifer system in the eastern San Joaquin Valley have gradually increased during the last 50 years (Burow and others, 2008, p. S261). The amount of nitrogen fertilizer applied in the eastern San Joaquin Valley increased from 114 milliion pounds in 1950 to 745 million pounds in 1980, an increase of 554 percent (Dubrovsky and others, 1998, p. 17). Anthropogenic nitrogen inputs, and hence, elevated nitrate concentrations in groundwater are likely to continue into the future. Nitrate concentrations in deeper groundwater will likely continue to increase over time as the water moves downward from the water table, although concentrations will be influenced by increased mixing of water and dispersion of nitrate with depth.

Pesticides have been used intensively in the Central Valley for many years and are expected to be detected widely throughout the area. A study of pesticides in San Joaquin Valley groundwater found that most detections occurred on the east side of the valley (Domagalski and Dubrovsky, 1991). Factors found to affect pesticide detections include the generally more permeable coarse-grained sediments, a relatively shallow water table in many areas, and the use of water-soluble pesticides with long environmental half-lives. The fewer detections on the west side of the San Joaquin Valley are attributed to a much longer residence time in finer grained sediments of the unsaturated zone, which allows for degradation to occur (Domagalski, 1997). The most frequently detected pesticide was 1,2-dibromo-3-chloropropane (DBCP), a soil fumigant commonly used in orchards and vineyards in the San Joaquin Valley beginning in the 1950s. DBCP was detected in about 31 percent of 4,507 wells in the San Joaquin Valley sampled from 1971through 1988 (Domagalski, 1997). Agricultural use of DBCP was banned in California in 1977 in response to concern about its potential hazardous effects on human health.

Pesticides were detected in 61 of the 88 domestic wells (69 percent) sampled in the eastern San Joaquin Valley as part of the NAWQA Program during 1993–95, but concentrations of most pesticides were low, less than 0.1 µg/L. Only five pesticides were detected in more than 10 percent of the samples: simazine, DBCP, atrazine, deethylatrazine (a degradation product of atrazine), and diuron. The number of pesticide detections in groundwater in the eastern San Joaquin Valley was related to sediment texture, concentrations of dissolved oxygen, pesticide application rates, groundwater recharge rates, and groundwater residence times (Burow and others, 1998a). Concentrations of DBCP in water sampled from 18 of the 88 domestic wells (20 percent) in the eastern part of the valley during 1993–95 exceeded the U.S. Environmental Protection Agency's drinking-water standard of 0.2 µg/L (Burow and others, 1998a, p. 24 and 1998b, p. 25). The occurrence of this pesticide in groundwater near Bakersfield, Fresno, Modesto, and north of Merced and Stockton coincides with land-use patterns. DBCP was detected in 25 of the 50 domestic wells in the almond orchard and vineyard settings that were sampled in 2001–02, and concentrations in 32 percent of the samples exceeded the drinking-water standard (Burow and others, 2008, table 3). Local-scale studies indicate that DBCP detections and concentrations may increase in the deeper part of the aquifer system in the future because of the dominantly downward movement of groundwater and the lack of significant attenuation processes in the subsurface (Burow and others, 2007, p. 1004).

In the southeastern part of the Sacramento Valley, only simazine, deethylatrazine, and bentazon were detected in 10 percent or more of the NAWQA regional aquifer study samples, all at concentrations much less than drinking-water standards. The herbicide bentazon was applied on rice fields in the Sacramento Valley from 1978 until 1989, when its use was banned in California. It was detected in 20 of the 28 monitoring wells (71 percent) in the rice field setting sampled in 1997, all at concentrations much lower than the drinking-water standard (Dawson, 2001b, table 9). Rice cultivation requires that fields be flooded during the growing season, from May through September. The high detection frequency of bentazon almost 10 years since its last known use in the area suggests that it is easily transported to the water table and does not readily degrade (Domagalski and others, 2000, p. 23). Bentazon also was detected in 4 of the 24 (17 percent) domestic well samples collected in the southeastern Sacramento Valley, but was detected in only 1 of the 19 monitoring wells in the urban setting and was not detected in any of the groundwater samples collected for the NAWQA studies in the San Joaquin Valley. This confirms the association between this herbicide and the rice field setting.

Water from less than 1 percent of public-supply wells sampled from 1994–2000 in the Sacramento Valley (3 of 820 wells) had a pesticide concentration that exceeded its drinking-water standard compared to more than 8 percent (18 of 608 wells) in the San Joaquin Valley (California Department of Water Resources, 2003, subbasin descriptions). This distribution agrees with the general occurrence of pesticides detected by the NAWQA studies of shallower parts of the groundwater systems in the Sacramento and and San Joaquin Valleys.

Volatile organic compounds were infrequently detected in groundwater samples collected for the NAWQA studies in the Sacramento and San Joaquin Valleys, except for in the setting in Sacramento, where 16 of the 19 monitoring wells (84 percent) contained one or more VOCs (Shelton, 2005, table 4). Chloroform, a byproduct formed during chlorination of water for drinking purposes, was the most frequently detected VOC (16 samples) in the urban area. A likely source of chloroform in the shallow groundwater is the use of disinfected public-supply water to irrigate lawns and gardens. The presence of chloroform and tritium in water from the monitoring wells indicates a component of young water that was recharged after 1953 (Shelton, 2005, p. 28). See Section 1 of this report for a discussion of groundwater age and environmental tracers. The occurrence of VOCs in groundwater sampled from the urban Sacramento area, like those of pesticides and elevated concentrations of nitrate in other parts of the Central Valley, is generally related to the amount of coarse-grained sediments in the subsurface. Monitoring wells that penetrated finer grained sediments generally had no or only one detection of a VOC in the water sample, and pesticides and nitrate were typically not detected. This likely is a result of reducing conditions in the aquifer in discharge areas. Results of multivariate analysis of the data indicate that most of the detections of VOCs and pesticides, and elevated concentrations of nitrate in the urban area occurred in oxic groundwater that is found in coarser grained alluvial fan deposits (Shelton, 2005, p. 42).

Water from three percent of public-supply wells sampled from 1994–2000 in the Sacramento Valley (24 of 810 wells) and in the San Joaquin Valley (18 of 608 wells) had a VOC concentration that exceeded its drinking-water standard (California Department of Water Resources, 2003, subbasin descriptions). Generally, subbasins on the east side of the Central Valley had a higher percentage of concentrations that exceeded drinking-water standards than did subbasins on the west side.

Summary

The Central Valley aquifer system is contained within basin-fill deposits in the Central Valley of California. Agriculture is the predominant land use in the Central Valley, and groundwater withdrawals supplied about 10.7 million acre-ft (43 percent) of the water used for agriculture and public supply in 2000. Groundwater is especially important in dry years because it supplements the variable surface-water supplies in the valley.

Alluvial fans have formed on all sides of the Central Valley with coarse-grained material deposited closer to the valley margins and finer grained detritus transported farther toward the valley axis. Sediment in the Sacramento Valley is generally finer grained than in the San Joaquin Valley, but with no extensive layers of fine-grained sediments. The Corcoran Clay separates the basin-fill deposits into an upper unconfined to semiconfined zone and a lower confined zone in the central, western, and southern parts of the San Joaquin Valley. The conceptual model for groundwater flow in the Central Valley is that of a heterogeneous aquifer system comprised of confining units and unconfined, semiconfined, and confined aquifers. Unconfined (water table) or semiconfined conditions occur in shallower deposits and along the margins of the valley. The aquifer system becomes confined in most areas within a few hundred feet of land surface because of numerous overlapping lenses of fine-grained sediments.

Under predevelopment conditions, before surface-water diversions and irrigation began, recharge occurred naturally from the infiltration of precipitation on the valley floor and from stream losses in the upper parts of the alluvial fans where the major streams enter the valley. The natural patterns of groundwater movement and the rates of recharge and discharge have been substantially altered by groundwater development and the diversion and redistribution of surface water throughout the Central Valley for irrigation. Recharge from excess irrigation water and discharge from wells for irrigation and public supply are much larger than natural sources of recharge and discharge and have increased the amount of water flowing vertically in the aquifer system from that under predevelopment conditions. Groundwater withdrawals have lowered water levels and have caused the land to subside in some areas.

The predominant factors that influence the quality of groundwater in the Central Valley aquifer system are the bedrock geology and chemistry of soils derived from bedrock, land use, and water use. The infiltration of water pumped from deeper parts of the aquifer system and surface water applied to fields for irrigation has resulted in recharge to the shallow unconfined part of the aquifer system with water that has been exposed to agricultural chemicals and natural salts concentrated by evapotranspiration. Groundwater in the coarse-grained alluvial-fan deposits on the east side of the valley is generally oxic, while in the finer grained basin and lake deposits near the axis of the valley the water is usually anoxic. The redox environment in the aquifer strongly influences the potential for degradation or accumulation of redox sensitive constituents, such as selenium, arsenic, uranium, nitrate, and some pesticides and volatile organic compounds.

Generally, concentrations of selenium in groundwater are highest in areas of the western San Joaquin Valley where soil selenium and groundwater salinity are high, where the water table has been near the land surface and evaporative concentration has occurred, and where groundwater is oxic. Groundwater in the central San Joaquin Valley that historically was the discharge zone for regional groundwater flow generally is chemically reduced and has higher concentration of arsenic than groundwater in the eastern and western alluvial fan areas. Naturally-occurring uranium is commonly adsorbed to aquifer sediments derived from the Sierra Nevada. Groundwater recharge and discharge has caused oxygen-rich, high-alkalinity water to move downward and to likely mobilize uranium adsorbed to sediments. Groundwater in the eastern Central Valley is susceptible to increasing concentrations of uranium where concentrations of bicarbonate are elevated and water is being pumped from deeper parts of the aquifer.

Agricultural development in the Central Valley has affected groundwater quality by adding millions of pounds of nitrate and pesticides to the land surface and modifying groundwater recharge so that these compounds can be more easily transported to the subsurface. The amount of coarse-grained sediments in the subsurface is a major factor in the susceptibility of groundwater to nitrate contamination. Sediment texture influences the rates of infiltration and groundwater flow, which control how rapidly water at the surface, with high concentrations of nitrate, can infiltrate the soil and move downward into the aquifer. Concentrations of nitrate in both the shallow and deep parts of the aquifer system in the eastern San Joaquin Valley have gradually increased during the last 50 years. Pesticides have been used intensively in the Central Valley for many years and are expected to be detected widely throughout the area. Local-scale studies indicate that DBCP detections and concentrations may increase in the deeper part of the aquifer system in the future because of the dominantly downward movement of groundwater and the lack of significant attenuation processes of the compound in the subsurface. The high detection frequency of bentazon in shallow groundwater in a Sacramento Valley rice field setting almost 10 years since its last known use in the area suggests that it is easily transported to the water table and does not readily degrade.

References Cited

Belitz, Kenneth, Dubrovsky, Neil M., Burow, Karen, Jurgens, Bryant, and Johnson, Tyler, 2003, Framework for a ground-water quality monitoring and assessment program for California: U.S. Geological Survey Water-Resources Investigations Report 03–4166, 78 p. Available at http://pubs.usgs.gov/wri/wri034166/.

Bennett, G.L., V, Belitz, Kenneth, Milby Dawson, B.J., 2006, California GAMA Program: ground-water quality data in the northern San Joaquin basin study unit, 2005: U.S. Geological Survey Data Series 196, 122 p. Available at http://pubs.usgs.gov/ds/2006/196/.

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

Burow, K.R., Stork, S.V., and Dubrovsky, N.M., 1998a, Nitrate and pesticides in ground water in the eastern San Joaquin Valley, California: Occurrence and trends: U.S. Geological Survey Water-Resources Investigations Report 98–4040, 33 p. Available at http://ca.water.usgs.gov/sanj/pub/usgs/wrir98-4040a/wrir98-4040a.html.

Burow, K.R., Shelton, J.L., and Dubrovsky, N.M., 1998b, Occurrence of nitrate and pesticides in ground water beneath three agricultural land-use settings in the eastern San Joaquin Valley, California, 1993–1995: U.S. Geological Survey Water-Resources Investigations Reports 97–4284, 51 p. Available at http://ca.water.usgs.gov/sanj/pub/usgs/wrir97-4284/wrir97-4284.html.

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

Burow, K.R., Shelton, J.L., Hevesi, J.A., and Weissmann, G.S., 2004, Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2004–5232, 62 p. Available at http://pubs.usgs.gov/sir/2004/5232/sir_2004-5232.pdf.

Burow, K.R., Dubrovsky, N.M., and Shelton, J.L., 2007, Temporal trends in concentrations of DBCP and nitrate in ground water in the eastern San Joaquin Valley, California, USA: Hydrogeology Journal, v. 15, no. 5, p. 991–1007.

Burow, K.R., Shelton, J.L., and Dubrovsky, N.M., 2008, Regional nitrate and pesticide trends in ground water in the eastern San Joaquin Valley, California: Journal of Environmental Quality, v. 37, September-October supplement, p. S249–S263.

Burton, C.A. and Belitz, Kenneth, 2008, Ground-water quality data in the southeast San Joaquin Valley, 2005–2006—Results from the California GAMA Program: U.S. Geological Survey Data Series 351, 103 p. Available at http://pubs.usgs.gov/ds/351/.

California Department of Water Resources, 2003, California's groundwater, Update 2003, groundwater maps and descriptions: California Department of Water Resources Bulletin 118, groundwater maps and descriptions, accessed August 7, 2009 at http://www.water.ca.gov/groundwater/bulletin118/gwbasin_maps_descriptions.cfm.

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

Dawson, B.J., 2001a, Ground-water quality in the southeastern Sacramento Valley aquifer, California, 1996: U.S. Geological Survey Water-Resources Investigations Report 2001–4125, 24 p. Available at http://pubs.usgs.gov/wri/wri014125/.

Dawson, B.J., 2001b, Shallow ground-water quality beneath rice areas in the Sacramento Valley, California, 1997: U.S. Geological Survey Water-Resources Investigations Report 2001–4000, 33 p. Available at http://ca.water.usgs.gov/archive/reports/wrir014000/.

Domagalski, J.L., 1997, Pesticides in surface and ground water of the San Joaquin-Tulare Basin, California; analysis of available data, 1966 through 1992: U.S. Geological Survey Water-Supply Paper 2468, 74 p.

Domagalski, J.L. and Dubrovsky, N.M., 1991, Regional assessment of nonpoint-source pesticide residues in ground water, San Joaquin Valley, California: U.S. Geological Survey Water-Resources Investigations Report 91–4027, 64 p.

Domagalski, J.L., Knifong, D.L., Dileanis, P.D., Brown, L.R., May, J.T., Connor, V., Alpers, C.N., 2000, Water quality in the Sacramento River Basin, California, 1994–98: U.S. Geological Survey Circular 1215, 36 p. Available at http://pubs.usgs.gov/circ/circ1215/.

Dubrovsky, N.M., Neil, J.M., Welker, M.C., and Evenson, K.D., 1991, Geochemical relations and distribution of selected trace elements in ground water of the northern part of the western San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 2380, 51 p.

Dubrovsky, N.M., Deverel, S.J., and Gilliom, R.J., 1993, Multiscale approach to regional ground-water quality assessment—Selenium in the San Joaquin Valley, California in Regional ground-water quality, W.M. Alley, ed.: Van Nostrand Reinhold, New York, p. 537–562.

Dubrovsky, N.M., Kratzer, C.R., Brown, L.R., Gronberg, J.M., and Burow, K.R., 1998, Water quality in the San Joaquin-Tulare Basins, California, 1992–95: U.S. Geological Survey Circular 1159, 38 p. Available at http://pubs.usgs.gov/circ/circ1159/.

Faunt, C.C., Belitz, Kenneth, and Hanson, R.T., 2009, Chapter B. Groundwater availability in California's Central Valley, *in* C.C. Faunt, ed., Groundwater availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766. Available at http://pubs.usgs.gov/pp/1766/.

Faunt, C.C., Hanson, R.T., and Belitz, Kenneth, 2009, Chapter A. Introduction, overview of hydrology, and textural model of California's Central Valley, *in* C.C. Faunt, ed., Groundwater availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766. Available at http://pubs.usgs.gov/pp/1766/.

Faunt, C.C., Hanson, R.T., Belitz, Kenneth, Schmid, Wolfgang, Predmore, S.P., Rewis, D.L., and McPherson, Kelly, 2009, Chapter C. Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley, *in* C.C. Faunt, ed., Groundwater availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766. Available at http://pubs.usgs.gov/pp/1766/.

Fogelman, R.P., 1983, Ground-water quality in the Sacramento Valley, California—Water types and potential nitrate and boron problem areas: U.S. Geological Survey Hydrologic Atlas 651, 1 map.

Fujii, R. and Swain, W.C., 1995, Areal distribution of selected trace elements, Salinity, and major ions in shallow ground water, Tulare Basin, Southern San Joaquin Valley, California: U.S. Geological Survey Water-Resources Investigations Report, 95–4048, 67 p.

Galloway, Devin and Riley, F.S., 1999, San Joaquin Valley, California, *in* Galloway, Devin, Jones, D.R., and Ingebritsen, S.E., eds., Land subsidence in the United States: U.S. Geological Survey Circular 1182, 177 p. Available at http://pubs.usgs.gov/circ/circ1182/.

Gilliom, R.J., Belitz, Kenneth, Deverel, S.J., Dubrovsky, N.M., and Fujii, Roger, 1989, Preliminary assessment of sources, distribution, and mobility of selenium in the San Joaquin Valley, California: U.S. Geological Survey Water-Resources Investigations Report 88–4186, 129 p.

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

Hall, W. H., 1889, Irrigation in California: National Geographic, v. 2, no. 4, p. 281.

Hull, L.C., 1984, Geochemistry of ground water in the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1401–B, 36 p.

Ireland, R.L., Poland, F.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, as of 1980: U.S. Geological Survey Professional Paper 437–I, 93 p.

Jurgens, B.C., Burow, K.R., Dalgish, B.A., and Shelton, J.L., 2008, Hydrogeology, water chemistry, and factors affecting the transport of contaminants in the zone of contribution of a public-supply well in Modesto, eastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2008–5156, 78 p. Available at http://pubs.usgs.gov/sir/2008/5156.

Kulongoski, Justin and Belitz, Kenneth, 2006, Ground-water ambient monitoring and assessment program: U.S. Geological Survey Fact Sheet 2004–3088 version 1.1, 2 p. Available at http://pubs.usgs.gov/fs/2004/3088/.

Landon, M.K. and Belitz, Kenneth, 2008, Ground-water quality data in the Central Eastside San Joaquin Basin 2006: results from the California GAMA Program: U.S. Geological Survey Data Series 325, 88 p. Available at http://pubs.usgs.gov/ds/325/.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p. Available at http://pubs.usgs.gov/circ/2005/1279/.

McKinney, T.S., and Anning, D.W., 2009, Geospatial data to support analysis of water-quality conditions in basin-fill aquifers in the southwestern United States: U.S. Geological Survey Scientific Investigations Report 2008–5239. Available at http://pubs.usgs.gov/sir/2008/5239/.

McMahon, P.B. and Chapelle, F.H., 2008, Redox processes and water quality of selected principal aquifer systems: Ground Water, vol. 46, p. 259–271.

Mendenhall, W.C., Dole, R.B., and Stabler, Herman, 1916, Ground water in San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 398, 310 p.

Milby Dawson, B.J., Bennett, G.L. V, and Belitz, Kenneth, 2008, Ground-water quality data in the southern Sacramento Valley, California, 2005—Results from the California GAMA Program: U.S. Geological Survey Data Series 285, 99 p. Available at http://pubs.usgs.gov/ds/285.

Nady, Paul, and Larragueta, L.L., 1983, Development of irrigation in the Central Valley of California: U.S. Geological Survey Hydrologic Investigations Atlas HA–649, scale 1:500,000, 2 sheets.

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

Phillips, S.P., Burow, K.R., Rewis, D.L., Shelton, Jennifer, and Jurgens, Bryant, 2007, Section 4. Hydrogeologic setting and ground-water flow simulations of the San Joaquin Valley regional study area, California, *in* Paschke, S.S., ed., Hydrogeologic settings and ground-water flow simulations for regional studies of the transport of anthropogenic and natural contaminants to public-supply wells—Studies begun in 2001: U.S. Geological Survey Professional Paper 1737–A, p. 4-1 to 4-31. Available at http://pubs.usgs.gov/pp/2007/1737a/.

Planert, Michael and Williams, J.S., 1995, Ground water atlas of the United States, segment 1, California, Nevada: U.S. Geological Survey Hydrologic Investigations Atlas 730–B, 28 p. Available at http://pubs.usgs.gov/ha/ha730/ch_b/index.html.

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, R.G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437–H, 78 p.

Saucedo, G. L., Bedford, B. R., Raines, G. L., Miller, R. J., and Wentworth, C. M., 2000, Modified from California Division of Mines and Geology, CD-ROM 2000–007, GIS data for the geologic map of California.

Shelton, J.L., 2005, Assessment of shallow ground-water quality in recently urbanized areas of Sacramento, California, 1997: U.S. Geological Survey Scientific Investigations Report 2005–5148, 51 p. Available at http://pubs.usgs.gov/sir/2005/5148/.

Shelton, J.L., Pimentel, Isabel, Fram, M.S., and Belitz, Kenneth, 2008, Ground-water quality data in the Kern County subbasin study unit, 2006—Results from the California GAMA Program: U.S. Geological Survey Data Series 337, 75 p. Available at http://pubs.usgs.gov/ds/337.

Schmitt, S.J., Fram, M.S., Milby Dawson, B.J., and Belitz, Kenneth, 2008, Ground-water quality data in the middle Sacramento Valley study unit, 2006—Results from the California GAMA Program: U.S. Geological Survey Data Series 385, 100 p. Available at http://pubs.usgs.gov/ds/385/.

U.S. Census Bureau,1995, California population of counties by decennial census 1900 to 1990, compiled and edited by R.L. Forstall: accessed August 26, 2008 at http://www.census.gov/population/cencounts/ca190090.txt.

U.S. Environmental Protection Agency, 2008, List of drinking water contaminants & their MCLs: accessed September 23, 2008 at http://www.epa.gov/safewater/contaminants/index.html.

U.S. Geological Survey, 2003, Multi-Resolution Land Characteristics (MRLC) Consortium, National Land Cover Database (NLCD 2001), accessed May 17, 2010 at http://www.mrlc.gov/.

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

This page intentionally left blank.