Section 12.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifers in the Santa Ana Basin, 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

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Basin Overview

The hydrologic cycles of the groundwater basins in the Santa Ana Basin are greatly affected by human activities as a result of the semiarid climate and the water demands of the large urban population (Belitz and others, 2004). Pumping from the basin-fill aquifers and changes in the sources and distribution of recharge that have accompanied development have accelerated the rate of groundwater flow and the transport of dissolved constituents through the aquifers. The quality of groundwater in parts of these aquifers reflects the quality of the surface water used for recharge during the past 50 years. Groundwater recharged before any substantial human effects on water quality or the flow system occurred has been partly replaced by human-affected water that has entered the aquifers since the early 1950s. Similarly, the future quality of groundwater will be affected by the quality of surface water currently being used for recharge in the basins.

The 2,700-mi^2 Santa Ana Basin watershed is within the Coastal Range Physiographic Province in southern California, which is characterized by prominent mountains that rise steeply from the relatively flat-lying coastal plain and inland valleys (fig. 1). The tallest peaks in the San Gabriel, San Bernardino, and San Jacinto Mountains rise to altitudes greater than 10,000 ft. The Santa Ana Basin comprises three distinct groundwater basins that were studied by the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program—the San Jacinto Basin, the Inland Basin, and the Coastal Basin. These sediment-filled basins are hydraulically separated from each other by relatively impervious rocks of intervening hills and mountains. The groundwater basins of the Santa Ana Basin are three of many such basins along the length of the State of California (Planert and Williams, 1995) and are part of the California Coastal Basin aquifers, a principal aquifer of the United States (U.S. Geological Survey, 2003a).

The climate of the Santa Ana Basin is Mediterranean, with hot, dry sum¬mers and cool, wet winters. Average annual precipitation ranges from 10 to 24 in. in the coastal plain and inland valleys and from 24 to 48 in. in the San Gabriel and San Bernardino Mountains (Belitz and others, 2004, p. 3). Most of the precipitation occurs between November and March in the form of rain, but with variable amounts of snow in the higher elevations. This seasonal precipitation pattern can result in high streamflow in the spring, followed by low flow during the dry season.

The Santa Ana Basin is drained by the Santa Ana River, which has the largest drainage area of any stream in southern California. The Santa Ana River begins in the San Bernardino Mountains and flows westward more than 100 mi to the Pacific Ocean near Huntington Beach. Streamflow during the summer months is maintained by discharge from wastewater treatment plants, urban runoff, mountain runoff, and groundwater forced to the surface by shallow bedrock (Belitz and others, 2004, p. 1). Currently, the lower part of the Santa Ana River is a concrete channel from the city of Santa Ana to the City of Huntington Beach that usually does not contain water during dry periods (Santa Ana Watershed Project Authority, 2005, p. 28).

The Santa Ana Basin has one of the fastest growing populations in California and includes parts of Orange, San Bernardino, Riverside, and Los Angeles Counties. The watershed was home to about 5.1 million people in 2000 (Santa Ana Watershed Project Authority, 2002, table 11.1). Land use in the Santa Ana Basin is about 35 percent urban, 10 percent agricultural, and 55 percent open spaces that are primarily on steep mountain slopes. Population density for the entire study area is 1,500 people/mi^2; excluding the land area that is steep, the population density is about 3,000 people/mi^2 (Belitz and others, 2004, p. 3). The most densely populated part of the basin is in the city of Santa Ana, where there are as many as 20,000 people/mi^2.

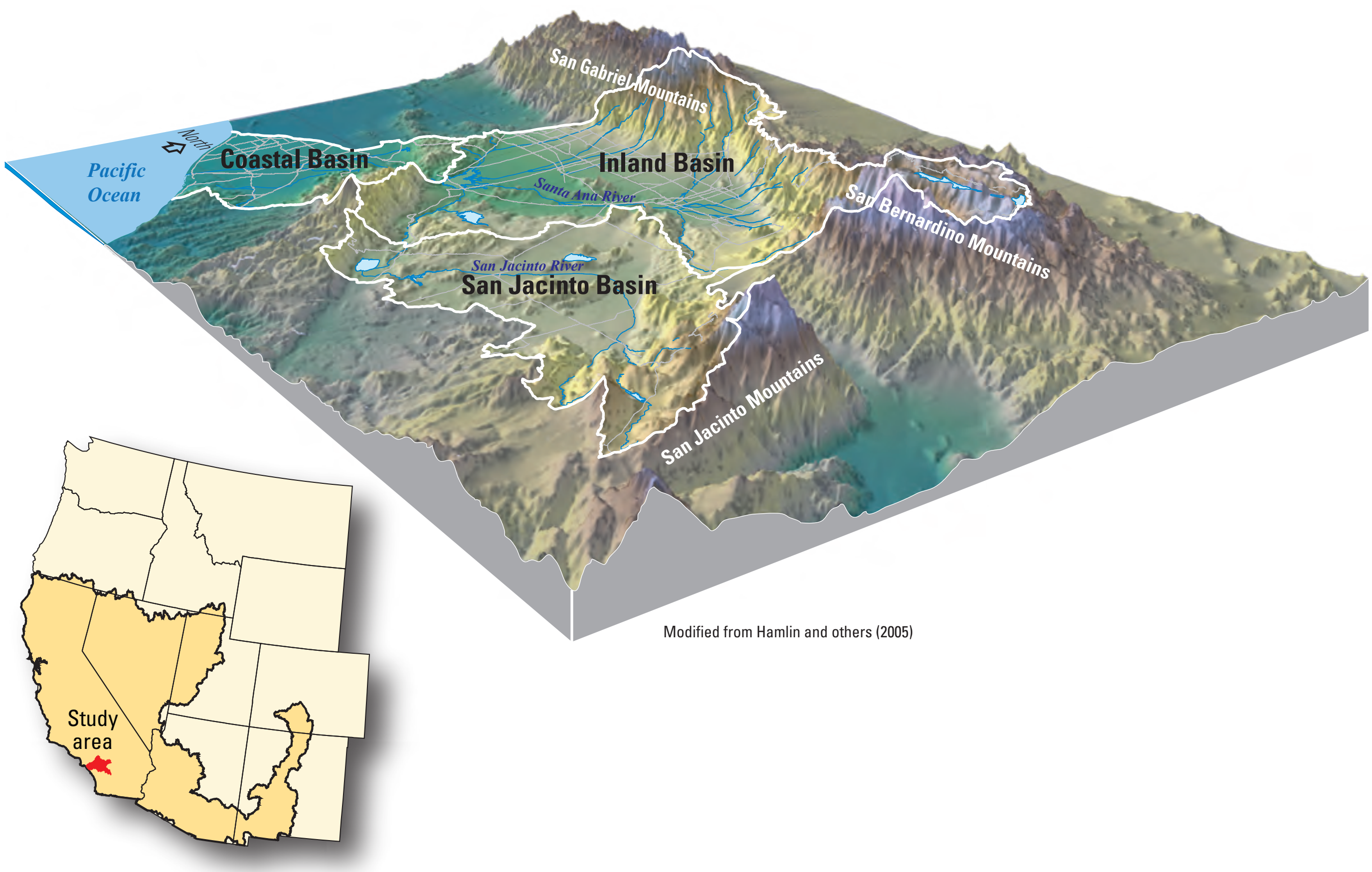


Figure 1. View to the northwest of the San Jacinto, Inland, and Coastal Basins in the Santa Ana drainage basin, California.

About 1.4 million acre-ft of water (467 billion gallons) was required to meet demand in the Santa Ana River watershed in 2000 (Santa Ana Watershed Project Authority, 2002, table 2.1). Estimated urban water use (70 percent of the estimated total use) exceeded estimated agricultural water use in the groundwater basins in 2000 based on county water-use data disaggregated to irrigated agricultural land and urban areas in the basins (McKinney and Anning, 2009, table 1). Groundwater pumped from the basins is the major water supply in the watershed, providing about two-thirds of the total water used (Belitz and others, 2004, p. 3). Water imported from northern California and the Colorado River also are important sources of water supply, accounting for 27 percent of the consumptive demand. Imported water is treated and delivered to consumers and is or has been used to recharge the aquifers. Projections are that the demand for water will increase by about 48 percent from 2000 to 2050, so that in 2050 the total water demand within the watershed will be about 2.1 million acre-ft (Santa Ana Watershed Project Authority, 2002, table 2.1).

Water Development History

Modifications to the natural surface-water system began in the early 1800s to supply water for irrigation in the San Bernardino area (Scott, 1977). San Bernardino is in the upper part of the Santa Ana River drainage basin, within the Inland Basin. Widespread irrigation began in 1848 (Scott, 1977) and by the 1880s, large tracts of land were dedicated to citrus and other crops, and diversions from the Santa Ana River and other streams were common. Groundwater in the Coastal Basin was used for irrigation beginning in the late 1800s. Around 1940, the urban population began to steadily increase along with water use for municipal purposes, while water use for irrigation began to decrease due to the urbanization of agricultural land (Scott, 1977).

Much of the runoff from the San Bernardino Mountains is diverted into storm-detention basins in or adjacent to stream channels along the mountain front. These facilities have been in operation since the early 1900s, and others have been constructed in other parts of the Inland, Coastal, and San Jacinto Basins to recharge the heavily used basin-fill aquifers. The groundwater recharge facilities near the San Bernardino Mountains began receiving imported water from the Colorado River via the Colorado Aqueduct in 1948 and from northern California through the State Water Project in the 1970s (Hardt and Freckleton, 1987; Reichard and others, 2003, p. 24). Imported Colorado River water is not currently used for artificial recharge and its use as a public supply in many areas of the Santa Ana Basin is limited because of its high concentration of dissolved solids—an average of 700 mg/L—and the effect of this level of salinity on treated wastewater discharge (Santa Ana Watershed Project Authority, 2002, p. 3-11). Pumping from the aquifer and additional sources of recharge have accelerated groundwater flow and the transport of dissolved constituents through the basin-fill aquifers in the San Jacinto, Inland, and Coastal Basins.

Hydrogeology

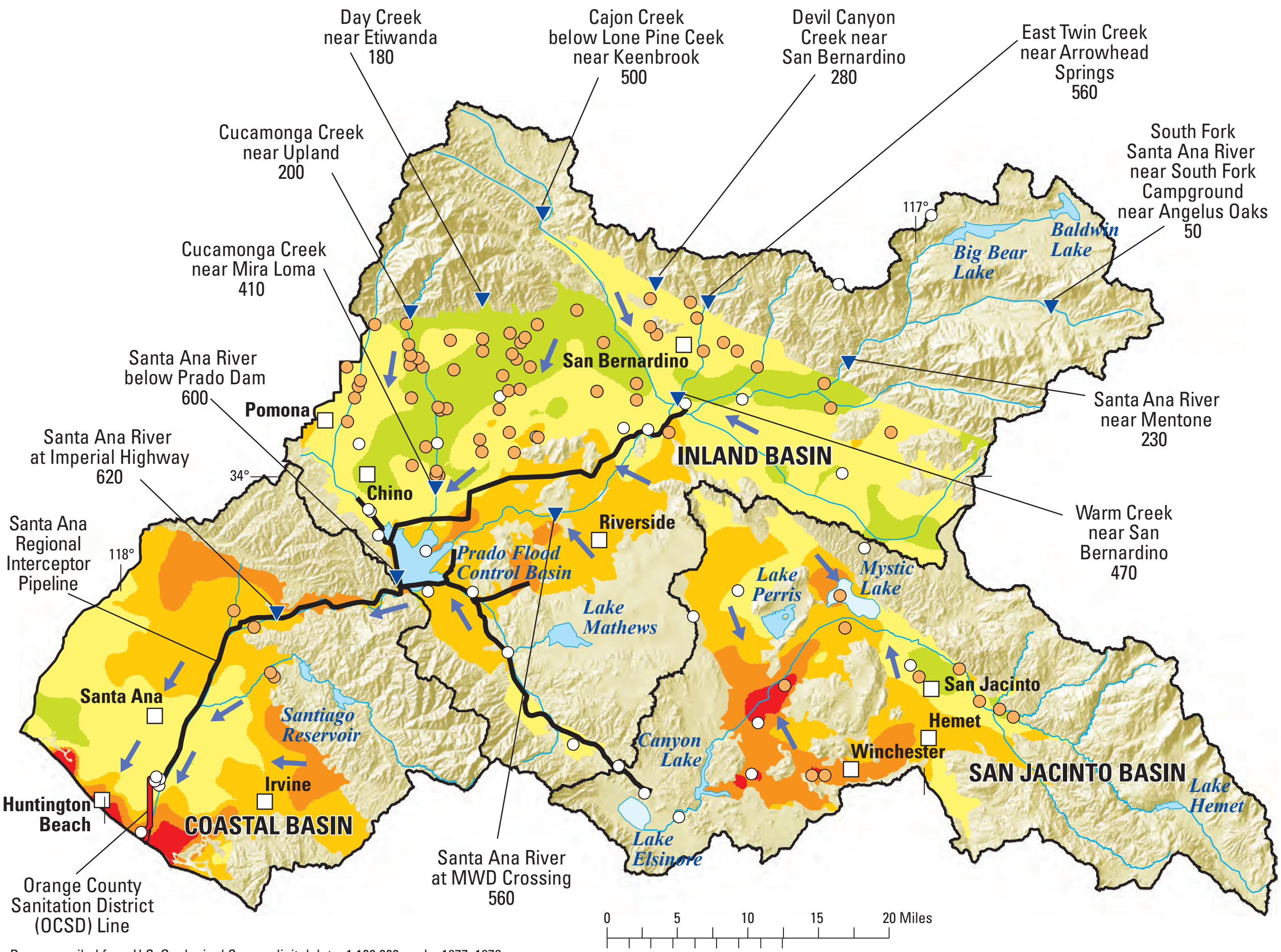
The dominant structural features in the Santa Ana Basin are its major fault zones. Motion along the San Andreas Fault Zone, which trends southeast-northwest along the western base of the San Bernardino Mountains and the eastern base of the San Gabriel Mountains, has caused the uplift of these generally east-west trending (transverse) mountain ranges. The San Jacinto Mountains are the result of uplift along both the San Andreas (eastern base) and San Jacinto (western base) Fault Zones. The Elsinore, Chino, and Whittier Fault Zones merge south of the Santa Ana River and bound the Santa Ana Mountains and Chino Hills (Morton and Miller, 2006, fig. 3). The Perris Block is an area between the Santa Ana Mountains and the San Jacinto Fault Zone of lower relief than the surrounding mountains where mainly Quaternary sediments discontinuously overlie bedrock. The adjacent basins have been filled with sediments eroded from these uplifted areas. The northwest-trending Newport-Inglewood Fault Zone extends into the Coastal Basin from offshore near Newport Beach. Faulting along the zone has formed the Newport-Inglewood Uplift, a series of folds visible as hills or mesas along the coast (Reichard and others, 2003, p. 5).

Groundwater flow in the basins is highly controlled by the geology, including the configuration of the surrounding and underlying bedrock and the extensive faulting that can create barriers to flow within the aquifer system. The basin-fill aquifers in the Santa Ana Basin consist primarily of Quaternary-age unconsolidated alluvium with interbedded marine sediments in the Coastal Basin (Dawson and others, 2003, p. 4). Unconfined conditions exist in most of the aquifer area; however, layers of fine-grained material, variable depth to bedrock, and the presence of faults can cause pressure zones where water flows toward (or to) the ground surface. Groundwater flow generally follows the topography and surface flow. Exceptions include areas where groundwater pumping has produced depressions in the water table and areas where faults act as barriers to flow.

Conceptual Understanding of the Groundwater Flow System

The three groundwater basins described in this section illustrate a wide range in groundwater and land-use conditions within the Santa Ana Basin. The groundwater system in the San Jacinto Basin is largely unconfined and land use is still primarily agricultural. The groundwater system in the Inland Basin also is predominantly unconfined and the major land use is now urban. Groundwater flow in the San Bernardino area of the Inland Basin, known as the Bunker Hill groundwater subbasin, is characterized by flow paths that originate along the mountain front and converge to a focused discharge area (Dawson and others, 2003, p. 58; Wildermuth Environmental, Inc., 2000, p. 3-4). The groundwater system in the mostly urban Coastal Basin consists of a relatively small unconfined recharge area and a relatively large confined area in which pumping is now the predominant form of groundwater discharge. Groundwater flow is generally characterized by areas of focused recharge and distributed discharge.

Some of the recharge to the groundwater basins occurs at facilities that receive and temporarily hold local stormwater and urban runoff, tertiary-treated municipal wastewater, or imported surface water. Such recharge facilities are more numerous in the Inland and San Jacinto Basins than in the Coastal Basin (fig. 2). Currently, flow in the Santa Ana River to the Coastal Basin consists predominantly of perennial base flow that is mostly treated wastewater discharged from municipal treatment plants in the Inland Basin (Mendez and Belitz, 2002) and intermittent stormflow that includes runoff from urban and agricultural land. Almost all of the flow in the Santa Ana River is diverted after it enters the Coastal Basin for recharge at engineered recharge facilities designed to replenish the basin-fill aquifer used for public supply. Treated wastewater from Coastal Basin communities is injected into the aquifer along the coast as a barrier to seawater intrusion, and starting recently (2008), is recharged at spreading basins near the Santa Ana River after advanced treatment. The remainder is discharged to the ocean. Groundwater discharge in the Santa Ana Basin is primarily by pumping, but also occurs as base flow to the Santa Ana River and its tributaries in some areas of the Inland Basin.



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 117°55'

EXPLANATION

Dissolved-solids concentration in groundwater, in milligrams per liter

- Less than 250
- 251 to 500
- 501 to 1,000
- 1,001 to 3,000
- 3,001 to 25,000

Approximate direction of groundwater flow

Basin boundary

Stream-water-quality monitoring site—Annotation is station name, number is median dissolved-solids concentration for samples collected from 1998–2001, in milligrams per liter

Recharge facility

Wastewater-treatment plant

Stream concentration data from Kent and Belitz (2004);
Groundwater concentration data from Wildermuth Environmental, Inc. (2008, appendix 8)

Figure 2. Dissolved-solids concentrations in groundwater in the San Jacinto, Inland, and Coastal Basins and in surface water in the Santa Ana Basin, California.

Groundwater Quality

In general, the quality of surface and groundwater in the Santa Ana Basin becomes progressively poorer— its content of dissolved mineral, chemical, and organic constituents increase as the water moves along flow paths. On the basis of this definition, the best quality water in the watershed is the flow in streams that drain the surrounding mountains and the parts of the groundwater system recharged by these flows. As the water flows away from the mountains, either on the surface or in the subsurface, its chemical composition is affected or changed by mineral dissolution, urban runoff, discharge of treated wastewater, agricultural operations, landscape irrigation, the use of surface water imported from the Colorado River and from northern California, and by enhanced recharge at engineered facilities. Groundwater quality can also be affected by accidents or activities at the land surface, such as spills and leaks of industrial solvents and by agricultural practices. Major water-quality issues in the Santa Ana Basin are elevated (above background) concentrations of dissolved solids, nitrate, perchlorate, and volatile organic compounds (VOCs) in groundwater.

The distribution of concentrations of dissolved solids and nitrate in groundwater within the Santa Ana Basin is monitored by local water suppliers (Wildermuth Environmental, Inc., 2008, p. 1-1). Concentrations of dissolved solids and nitrate in well water sampled from 1987 to 2006 were used to compute point statistics (Wildermuth Environmental, Inc., 2008, appendix B) that were then contoured to provide maps of the distribution of these constituents within the basin (figure 2 shows dissolved-solids concentrations). The distribution of dissolved solids in the Coastal Basin and parts of the Inland Basin (the confined parts of the Bunker Hill and Chino subbasins) was estimated from the results of analyses of water samples collected from intermediate depths, the zone from which water is generally withdrawn for public supply, as well as analyses of water from shallower depths.

Concentrations of dissolved solids in water in the basin-fill aquifers within the Santa Ana Basin are generally lowest (less than 250 mg/L) in areas recharged by surface runoff originating in the surrounding higher altitude mountain drainages (fig. 2). Concentrations can increase as groundwater moves away from the mountains because of urban and agricultural activities, alteration of the hydrologic cycle—including the importation of surface water to the basin—and from contact with natural sources of dissolved solids, such as salts released from geologic materials (Anning and others, 2007, p. 102). Desalting plants are used to reduce concentration of dissolved solids in groundwater in parts of the San Jacinto, Inland, and Coastal Basins. Brine generated at these facilities is typically transported through the Santa Ana Regional Interceptor pipeline to the Pacific Ocean for disposal.

Water samples were collected from 207 wells in the Santa Ana Basin from 1999 to 2001 as part of eight studies by the NAWQA Program to assess the occurrence and distribution of dissolved constituents in groundwater (Hamlin and others, 2002). These studies were designed to gain a better understanding of the used groundwater resource at different scales: (1) three studies were done to characterize water quality at a basin scale; (2) two studies focused on spatial and temporal variations in the chemical characteristics of water along selected flow paths; (3) two studies assessed aquifer susceptibility to VOC contamination; and (4) one study focused on an evaluation of the quality of shallow groundwater in an urban area. The aquifer susceptibility studies were done in collaboration with the California State Water Resources Control Board as part of the California Aquifer Susceptibility Program (Hamlin and others, 2002, p. 13).

Most of the samples collected for the NAWQA studies were analyzed for the field parameters temperature, specific conductance, dissolved oxygen content, and pH as well as for a wide suite of constituents, including the major ions, trace elements, radon, nutrients, dissolved organic carbon, pesticides, VOCs, and isotopes (oxygen-18, deuterium, and tritium) (Hamlin and others, 2002, appendixes). The samples collected for the aquifer susceptibility studies were analyzed for selected VOCs and isotopes (Shelton and others, 2001; Dawson and others, 2003; Hamlin and others, 2005). A summary of the physical properties and chemical characteristics of the water in wells sampled by NAWQA in the Santa Ana Basin is presented in table 1. The wells are divided into classes based on groundwater basin, aquifer confinement, and (or) depth. Information from local entities and studies and the findings of the several NAWQA studies are used to describe in this section of the report the general groundwater flow system, water-quality characteristics, and the potential effects of natural and human factors on groundwater quality in the San Jacinto, Inland, and Coastal groundwater basins within the larger Santa Ana Basin.

Table 1. Summary of physical and water-quality characteristics of wells in the Santa Ana Basin, California, sampled by the NAWQA Program, 1999–2001.

[ps, public-supply well; irr, irrigation well; mon, monitoring well; per mil, parts per thousand; pCi/L, picocuries per liter; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; pesticide and volatile organic compound (VOC) detections include estimated values below the laboratory reporting level]

Well class	A	B	C	D	E	F	G	H	I
Number of wells	[1] 10 / [2] 13 depth to top of well screen less than 270 feet	[1] 10 / [2] 18 depth to top of well screen greater than 270 feet	9	17	[3] 15 depth to top of well screen less than 240 feet	[3] 14 depth to top of well screen greater than 240 feet	[4] 16 / [5] 35	[4] 26 / [5] 58	26
Predominant well type sampled	ps, irr	ps, irr	ps, mon	ps, mon	ps, irr	ps, irr	ps	ps	mon (shallow)
Ground-water basin	San Jacinto Basin	San Jacinto Basin	Bunker Hill subbasin	Bunker Hill subbasin	Inland Basin	Inland Basin	Coastal Basin	Coastal Basin	Coastal Basin
General aquifer confinement	Unconfined	Unconfined	Unconfined	Confined	Unconfined	Unconfined	Unconfined	Confined	Unconfined
General location	Basin wide	Basin wide	Closer to recharge facilities	Near San Jacinto Fault	Basin wide	Basin wide	Forebay area	Pressure area	Mostly pressure area
Land use	Agricultural and urban	Agricultural and urban	Mostly urban areas	Mostly urban areas	Mostly urban areas	Mostly urban areas	Urban	Urban	Urban
Physical characteristics									
Median well depth, feet	[1] 569 / [2] 625	[1] 960 / [2] 1,238	575	400	415	843	[4] 554 / [5] 714	[4] 876 / [5] 966	24
Median depth to top of well screen, feet	[1] 173 / [2] 170	[1] 420 / [2] 402	500	300	126	385	[4] 272 / [5] 342	[4] 338 / [5] 372	14
Median deuterium concentration, per mil	[2] -56.8	[2] -58.2	-68.9	-55.4	-56.5	-57.6	[5] -54.6	[5] -56.5	-48.3
Median tritium concentration, pCi/L	4.3	1.0	12.2	6.0	9.0	2.6	19.2	4.5	21.6
Water-quality characteristics									
Median dissolved-solids concentration, mg/L	504	460	226	354	338	276	583	436	2,390
Median nitrate concentration, mg/L	5.6	1.7	3.4	0.99	6.0	6.1	4.3	1.4	<0.05
Median dissolved-oxygen concentration, mg/L	5.8	0.4	7.2	0.7	7.6	8.0	1.9	1.6	0.9
Median arsenic concentration, µg/L	1.2	1.6	<0.9	1.8	1.1	0.85	1.2	1.4	3.0
Number of different pesticides detected	14	7	10	7	17	13	17	6	18
Number of pesticide detections	38	10	18	26	64	57	64	13	45
Percentage of wells where pesticides were detected	100%	30%	67%	47%	87%	79%	56%	23%	69%
Number of different VOCs detected	[2] 10	[2] 8	11	36	22	18	[5] 19	[5] 31	22
Number of VOC detections	[2] 31	[2] 21	16	94	82	49	[5] 109	[5] 114	68
Percentage of wells where VOCs were detected	[2] 84%	[2] 67%	56%	94%	87%	79%	[5] 80%	[5] 64%	88%

[1] The median depth to the top of the well screen in 20 wells sampled as part of study to characterize water quality in the San Jacinto Basin is 270 feet (Hamlin and others, 2005, p. 6).

[2] Includes wells sampled as part of the San Jacinto Aquifer Susceptibility Study (Hamlin and others, 2002, p. 13).

[3] The median depth to the top of the well screen in 29 wells sampled as part of study to characterize water quality in the Inland Basin is 240 feet (Hamlin and others, 2005, p. 6).

[4] Wells sampled as part of studies to characterize water quality in the Coastal Basin on basin and flow path scales (Hamlin and others, 2002, p. 12).

[5] Includes wells sampled as part of the Orange County Aquifer Susceptibility Study (Hamlin and others, 2002, p. 13).

San Jacinto Basin of the Santa Ana Basin

The San Jacinto Basin covers about 350 mi^2 in the Santa Ana drainage basin and contains Perris, Moreno, San Jacinto, and Menifee Valleys (fig. 3). Granitic and metamorphic rock "islands," the largest of which are the Lakeview Mountains, protrude through and underlie the unconsolidated sediment in the valleys (Wildermuth Environmental, Inc., 2000, p. 3-10). Excluding the consolidated rock protrusions, altitudes within the sediment-filled part of the basin range from about 1,400 to 2,000 ft, and reach 10,751 ft at the crest of the San Jacinto Mountains in the drainage area to the east. The San Jacinto Basin is bounded by fault zones on the east and west and by consolidated rock on the north and south. The San Jacinto Fault Zone separates the basin-fill deposits of the San Jacinto Valley from the San Jacinto Mountains (fig. 3), which are composed mostly of igneous and metamorphic rocks, and the San Timoteo Badlands, composed chiefly of Tertiary-age sedimentary rocks to the east (Schlehuber and others, 1989, p. 81).

The San Jacinto Basin has a semiarid climate, with hot dry summers and cooler, wetter winters. Analysis of modeled precipitation data for 1971–2000 (PRISM Group, Oregon State University, 2004) resulted in an average annual precipitation value of about 13.7 in. over the groundwater basin as a whole (McKinney and Anning, 2009, table 1). The San Jacinto Mountains receive up to 47 in. of precipitation annually. Most precipitation falls from October to March and most runoff in the basin results from winter storms. Drainage from the 800-mi^2 watershed is mostly to the San Jacinto River and its tributaries, which become ephemeral streams after entering the groundwater basin. Runoff from the watershed flows out of the San Jacinto Basin to Lake Elsinore and the Santa Ana River via Temescal Wash only during extremely wet periods. Water imported from northern California for public supply in the San Jacinto Basin and other parts of southern California is stored in Lake Perris.

Analysis of LandScan population data for 2005 (Oak Ridge National Laboratory, 2005) indicated a population of about 385,000 in the San Jacinto Basin (McKinney and Anning, 2009, table 1) and a population density of about 1,600 people/mi^2. About 34 percent of the basin was classified as urban and 42 percent as irrigated agricultural land in 2001 (U.S. Geological Survey, 2003b) (fig. 3). County-level water-use data for 2000 (U.S. Geological Survey, 2004) was disaggregated to a finer scale based on spatially distributed agricultural land use and population data in order to distribute water use on a basin scale (McKinney and Anning, 2009, p. 9). This method of determining water use in a basin may have a large uncertainty in the San Jacinto Basin because it is a relatively small part of Riverside County, which extends to the California/Arizona stateline and includes other large areas of agricultural land use. On the basis of this method of determining water use, the largest use of water in the San Jacinto Basin is the irrigation of crops. Groundwater pumped from wells is estimated to provide about 74 percent of public supply, the other major used of water in the basin.

Conceptual Understanding of the Groundwater System in the San Jacinto Basin

Geologically, the San Jacinto Basin can be characterized as a series of interconnected alluvium-filled valleys that are bounded by bedrock mountains and hills and cut by faults and bedrock highs (figs. 3 and 4). As part of a study to estimate the concentrations of dissolved solids and nitrate in groundwater in the Santa Ana watershed, the basin was subdivided into groundwater management zones that correspond to groundwater subbasins (fig. 3) on the basis of relatively impermeable boundaries such as bedrock and faults, bedrock constrictions, groundwater divides, and internal flow systems (Wildermuth Environmental, Inc., 2000, p. 3-12). The Canyon, San Jacinto-Upper Pressure, Hemet North, and Hemet South groundwater management zones were grouped together as the eastern subbasins, and the San Jacinto-Lower Pressure, Lakeview, Perris North, Perris South, and Menifee groundwater management zones were grouped together as the western subbasins. These groupings follow those of the groundwater management plans for the San Jacinto Basin (Eastern Municipal Water District, 2007a and 2007b) and are not based solely on similarities in the groundwater flow systems.

The Canyon, San Jacinto-Upper Pressure, and San Jacinto-Lower Pressure subbasins are west of the San Jacinto Mountains and between faults in the San Jacinto Fault Zone. Coincident with the San Jacinto Valley, a graben, this area consists of a forebay area in the southeast, where surface water recharges the groundwater basin, and a pressure area in the northwest, where groundwater occurs under confined conditions. The thickness of unconsolidated deposits in the graben is not known, but may exceed 5,000 ft (California Department of Water Resources, 2003a). A branch of the fault zone separates the Canyon and San Jacinto-Upper Pressure subbasins where it cuts through the basin fill and crosses the San Jacinto River. The low permeability of this fault zone causes groundwater to back up behind it, with water levels about 200 ft higher on the up gradient side than on the down gradient side. Water levels on the Canyon subbasin side of the fault zone in the early 1900s were high enough that groundwater discharged to the river channel (MacRostie and Dolcini, 1959).

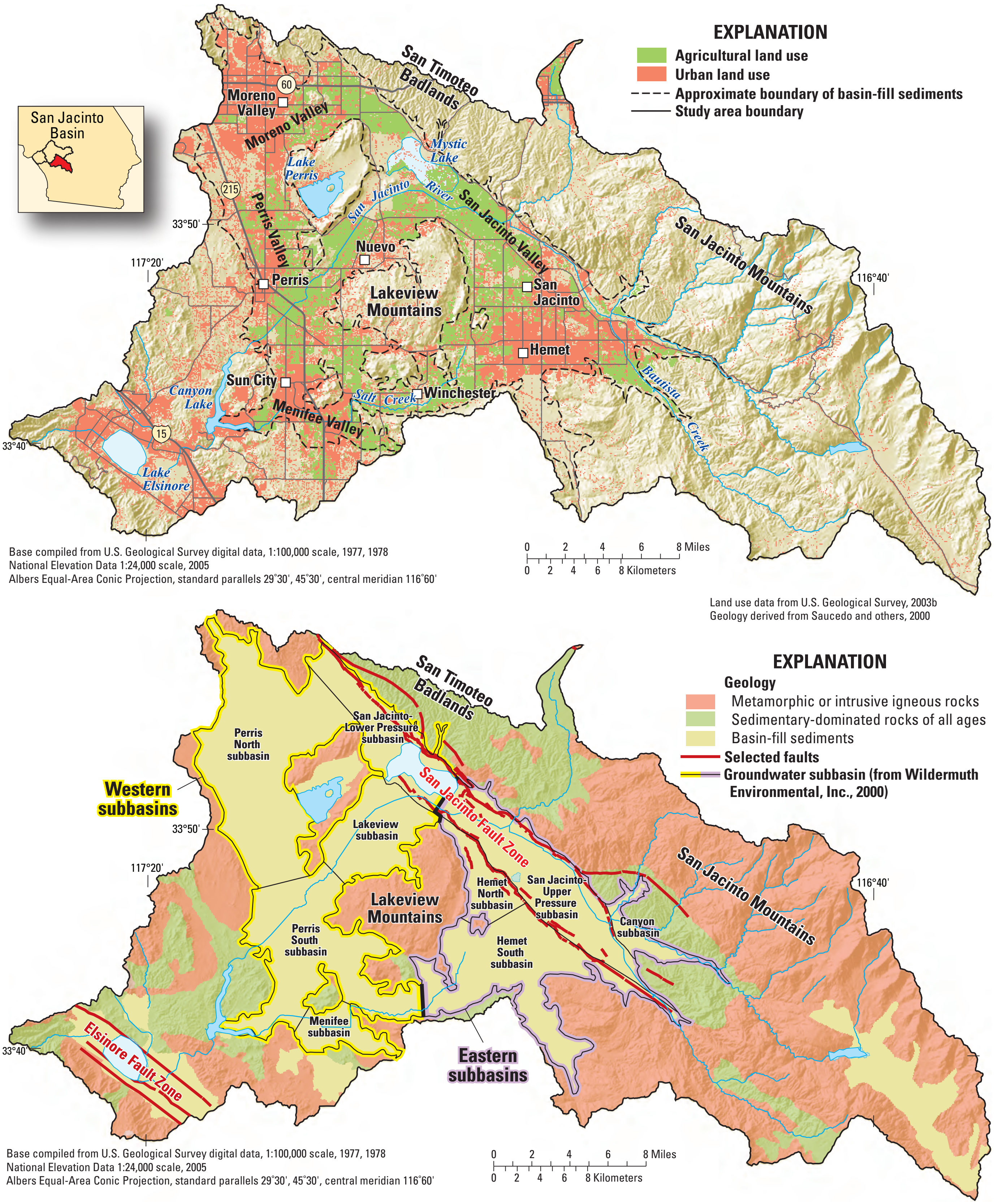


Figure 3. Physiography, land use, and generalized geology of the San Jacinto Basin, California.

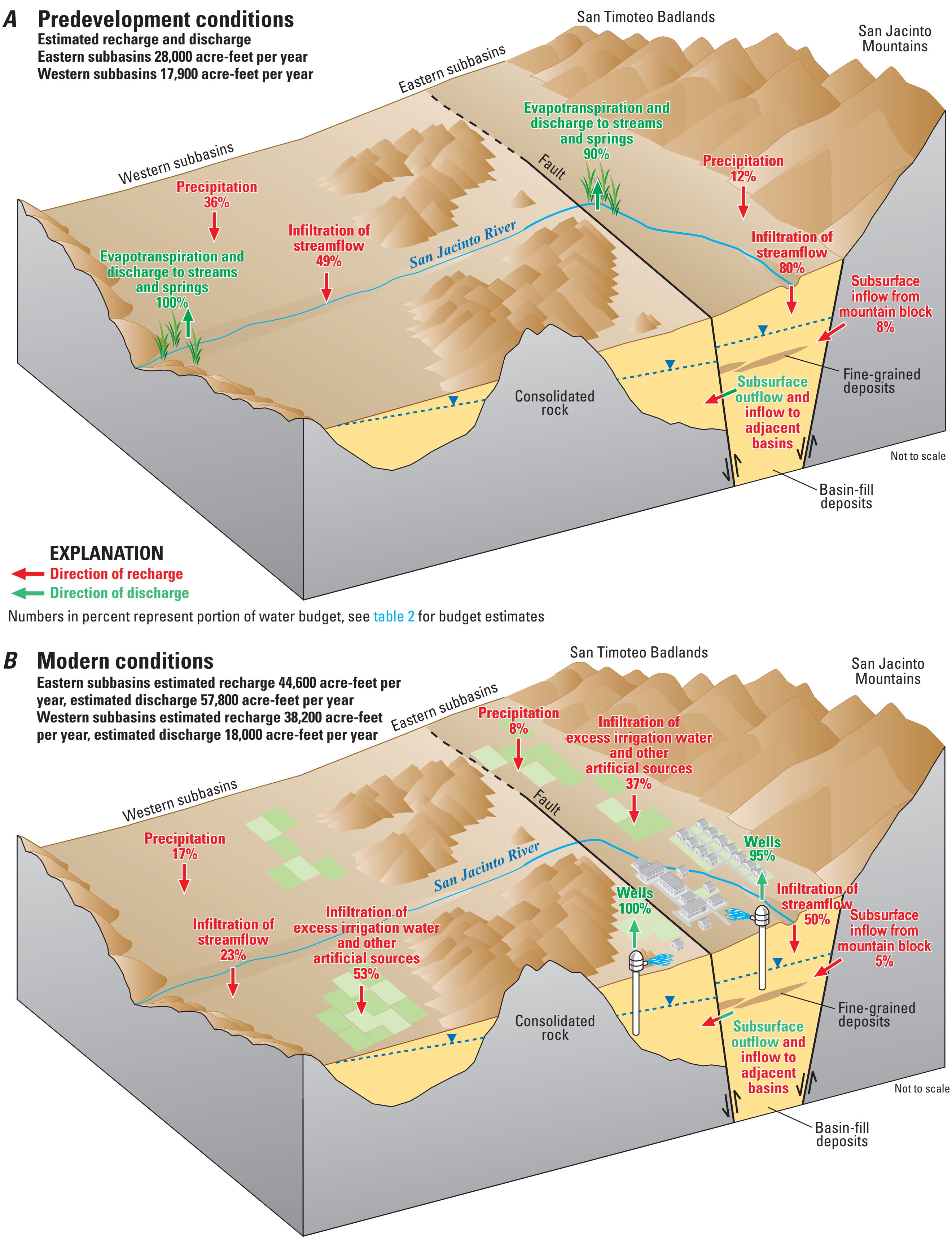


Figure 4. Generalized diagrams for the San Jacinto Basin, California, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

Confined conditions caused by layers of fine-grained material and faults occur in much of the San Jacinto-Upper and Lower Pressure subbasins. A large area around the town of San Jacinto within which groundwater was under artesian pressure was noted between 1904 and 1915 where flowing wells were generally open to sand and gravel layers 100–200 ft below land surface (Waring, 1919, plate 3 and p. 27). Discharge from flowing wells and presumably by evapotranspiration occurred in this area before water levels were lowered by pumping. Silt and clay deposition in the tectonically subsiding basin contributes to the formation of the ephemeral Mystic Lake. This topographically low area with low permeability soils receives overflow from the San Jacinto River and from shallow perched groundwater, and probably some discharge from the confined groundwater system. Subsurface flow from the San Jacinto-Upper and Lower Pressure subbasins to the west is impeded by the western branch of the fault zone, so that under natural conditions, artesian pressure exists along the east side of the fault. Some groundwater was thought to move west to the Hemet North, Hemet South, and Lakeview subbasins under natural conditions (Wildermuth Environmental, Inc., 2000, p. 3-11).

The San Jacinto River enters the Canyon and San Jacinto-Upper Pressure subbasins from the mountains at the south end of the San Jacinto Valley and flows northwesterly. In most years, the river becomes ephemeral within these subbasins, mainly as a result of infiltration of the river's flow into the coarse-grained basin-fill deposits. The loss of water from the river channel is the source of most of the groundwater recharge to the Canyon and San Jacinto-Upper Pressure subbasins.

The thickness of unconsolidated deposits in the subbasins west of the San Jacinto Fault Zone (Hemet North, Hemet South, Lakeview, Perris North, Perris South, and Menifee subbasins) typically ranges from 200 to 1,000 ft. These basins are basically erosional depressions back-filled with alluvial sediments. The basin fill is thinnest adjacent to bedrock outcrops and is thickest along probable paleochannels incised in the underlying bedrock (Wildermuth Environmental, Inc., 2000, fig. 3-5). Groundwater in these subbasins generally occurs under unconfined conditions in the more permeable deposits. Depths to water, flow directions, recharge sources, and forms of discharge have changed in these subbasins due to water development in the area (Wildermuth Environmental, Inc., 2000, p. 3-11).

Water Budget and Groundwater Flow

Prior to development, most recharge to basin-fill aquifers in the San Jacinto Basin took place by infiltration of mountain streamflow, primarily the San Jacinto River near where it enters the basin, and runoff from precipitation on consolidated rocks within the basin and on the basin fill. Some groundwater moved through the subsurface across faults to recharge adjacent subbasins. Little information is available about groundwater conditions prior to development in the basin and estimates of recharge to and discharge from the aquifers presented in this report are intended only to provide a basis for comparison of change with development. Recharge to the eastern subbasins under predevelopment conditions is estimated to be about 28,000 acre-ft/yr: 3,400 acre-ft/yr from infiltration of precipitation on the basin; 22,500 acre-ft/yr from infiltration of streamflow in the San Jacinto River and its tributaries near the mountain front; and 2,100 acre-ft/yr from subsurface inflow from the mountain block (table 2). These estimates of natural recharge are based on average values determined for the area for the period 1958–2001 (Water Resources and Information Management Engineering Inc., 2003). In reality, recharge from these sources likely varies with extremes in annual precipitation. Groundwater recharge to the western subbasins under predevelopment conditions was estimated from long-term averages to be about 17,900 acre-ft/yr: 6,400 acre-ft/yr from infiltration of precipitation on the basin, 8,700 acre-ft/yr from infiltration of streamflow, and 2,800 acre-ft/yr from subsurface inflow from adjacent subbasins (Eastern Municipal Water District, 2005, appendix B, table 4-2).

The San Jacinto Basin is virtually closed to subsurface outflow because of low permeability consolidated rock surrounding the basin-fill deposits. Discharge of groundwater from the basin prior to development was primarily by evapotranspiration and by seepage to streams along the lower reaches of the San Jacinto River and Salt Creek in the western part of the basin (Wildermuth Environmental, Inc., 2000, p. 3-11). Subsurface flow between subbasins under predevelopment conditions occurred as a result of the larger volumes of natural recharge to the eastern subbasins spilling across faults or through bedrock constrictions into the western subbasins.

Water development in the San Jacinto Basin has significantly altered the groundwater systems and has caused changes in the groundwater budgets and flow directions. Under modern conditions in the basin, infiltration of excess irrigation water has become a large component of recharge to the basin-fill aquifers, and groundwater discharge is primarily withdrawals from wells (Wildermuth Environmental, Inc., 2000). Stable oxygen and hydrogen isotope ratios indicate that now groundwater in the basin is recharged from runoff derived from high-altitude precipitation in the San Jacinto Mountains, from low-altitude precipitation on the basin and hills, and from imported surface water (Williams and Rodoni, 1997, p. 1728). Aqueducts carrying State Project water from northern California and water from the Colorado River pass through the San Jacinto Basin. Lake Perris is adjacent to the Perris North subbasin and has served as a storage reservoir for northern California water since its construction in the 1970s. Both of these imported water sources have been utilized for irrigation and municipal supply. Recharge also occurs through seepage at retention basins, spreading basins, and percolation ponds filled with stormwater, imported surface water, and treated wastewater.

Table 2. Estimated groundwater budget for the basin-fill aquifer system in the San Jacinto Basin, California, under predevelopment and modern conditions.

[All values are in acre-feet per year. Estimates of natural recharge that are assumed to represent predevelopment conditions in the eastern subbasins are based on 1958–2001 averages determined for the area (Water Resources and Information Management Engineering Inc., 2003) and those in the western subbasins are from long term averages listed in a groundwater management plan for the west San Jacinto groundwater basin adopted in 1995 (Eastern Municipal Water District, 2005, appendix B, table 4-2), unless footnoted. 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
Eastern subbasins			
Budget component	**Estimated recharge**		
Infiltration of precipitation on basin	3,400	3,400	0
Infiltration of streamflow	22,500	22,500	0
Subsurface inflow from mountain block	2,100	2,100	0
Infiltration of excess irrigation water and other artificial sources	0	16,600	16,600
Total recharge	**28,000**	**44,600**	**16,600**
Budget component	**Estimated discharge**		
Evapotranspiration and discharge to streams and springs	[1] 25,200	0	-25,200
Subsurface outflow to adjacent subbasins	[2] 2,800	[2] 2,800	0
Well withdrawals	0	55,000	55,000
Total discharge	**28,000**	**57,800**	**29,800**
Change in storage (total recharge minus total discharge)	0	-13,200	-13,200
Western subbasins			
Budget component	**Estimated recharge**		
Infiltration of precipitation on basin	6,400	6,400	0
Infiltration of streamflow	8,700	8,700	0
Subsurface inflow from adjacent subbasins	[2] 2,800	[2] 2,800	0
Infiltration of excess irrigation water and other artificial sources	0	[3] 20,300	20,300
Total recharge	**17,900**	**38,200**	**20,300**
Budget component	**Estimated discharge**		
Evapotranspiration and discharge to streams and springs	[1] 17,900	0	-17,900
Subsurface outflow to adjacent subbasins	0	0	0
Well withdrawals	0	[4] 18,000	18,000
Total discharge	**17,900**	**18,000**	**100**
Change in storage (total recharge minus total discharge)	0	20,200	20,200

[1] Assumed to be the difference between estimated predevelopment recharge and estimated discharge from subsurface outflow to adjacent subbasins.

[2] Listed as subsurface inflow from mountain boundaries in 1995 groundwater management plan (Eastern Municipal Water District, 2005, appendix B, table 4-2) and assumed to be mainly subsurface outflow from the eastern subbasins to the western subbasins.

[3] Includes only irrigation component of estimated recharge from deep percolation of applied water listed in the 1995 groundwater management plan (Eastern Municipal Water District, 2005, appendix B, table 4-2).

[4] Average well withdrawals from 1985–2004 (Metropolitan Water District of Southern California, 2007, table 17-3).

Prior to the importation of surface water to the San Jacinto Basin, water pumped from the basin-fill aquifer was a major source of public use and irrigation supply. The 1958–2001 average withdrawal rate from wells in the eastern subbasins was about 55,000 acre-ft/yr and estimated average recharge from excess irrigation water and artificial recharge sources was about 16,600 acre-ft/yr (Water Resources and Information Management Engineering Inc., 2003). Coupled with estimates of natural recharge that are assumed to be the same as under predevelopment conditions (28,000 acre-ft/yr) and subsurface outflow to the western subbasins (an estimated 2,800 acre-ft/yr), the difference in estimated recharge and discharge in the eastern subbasins is a deficit of about 13,000 acre-ft/yr. Although this is a rough estimate of overdraft that should not be used to calculate an accumulated volume of water removed from storage, it corresponds to lowered water levels and changes in flow directions in the eastern subbasins. The general directions of groundwater flow in 1973 and in 2006 in the San Jacinto Basin are shown on fig. 5.

Groundwater production in the western subbasins is monitored as part of the groundwater management plan and totaled about 18,700 acre-ft in 2004 (Eastern Municipal Water District, 2005, table 3.3), 16,800 acre-ft in 2005, and 23,100 acre-ft in 2006 (Eastern Municipal Water District, 2007a, table 3-5). Average production from wells in the western subbasins for 1985–2004 is listed at about 18,000 acre-ft/yr by the Metropolitan Water District of Southern California (2007, table 17-3) and is limited mainly by groundwater quality (elevated concentrations of dissolved solids) in parts of the area. Groundwater recharge to the western subbasins under modern conditions has increased due mostly to the infiltration of excess irrigation water and is estimated to be about 20,000 acre-ft/yr more than discharge based on estimates listed in table 2. These estimates were mostly from the groundwater management plan for the western part of the San Jacinto Basin adopted in 1995 (Eastern Municipal Water District, 2005, appendix B, table 4-2). Recharge from the infiltration of imported surface water and treated wastewater through storage ponds and reservoirs in the western subbasins is localized and variable (Kaehler and Belitz, 2003, p. 3). In this budget analysis, it is assumed that infiltration of excess irrigation water decreases as infiltration from these other sources increases due to land-use changes. Much uncertainty exists in the groundwater budgets for the San Jacinto Basin, and more information and analysis are needed to arrive at a better estimate for recharge and discharge components.

Water levels generally declined in the western subbasins from 1945 to the mid 1970s due to withdrawals from wells and periods of below-normal precipitation (Eastern Municipal Water District, 2005, appendix B, p. 4-6). Between 1973 and 2006, however, water levels typically rose in the Perris North, Perris South, and Menifee subbasins (fig. 5). The rise in water levels in these areas is attributed to decreased withdrawals and additional recharge of excess irrigation water, imported surface water, and treated wastewater to the basin-fill aquifer.

Effects of Natural and Human Factors on Groundwater Quality

The amount and source of recharge to the basin-fill deposits in the San Jacinto Basin affects the quality of the groundwater. Subbasins that receive a large percentage of recharge from mountain-front runoff carried by the San Jacinto River have groundwater quality that is typically similar to that of the recharged water. Some areas in the basin receive little recharge and others receive a large percentage from excess irrigation water. The concentration of dissolved minerals in this groundwater is generally elevated above background levels as a result of evapotranspiration. Other factors that affect groundwater quality in the basin are infiltration of water from overlying agricultural and urban areas, water/aquifer matrix reactions, movement of poorer quality water induced by withdrawals from wells, and the extensive use of imported water.

Water samples are collected annually from selected private, public-supply, and irrigation wells as part of water-quality monitoring programs in the San Jacinto Basin. In 2006, 102 wells were sampled in the western subbasins and 125 wells were sampled in the eastern subbasins (Eastern Municipal Water District, 2007a, p. 3-6 and 2007b, p. 27). NAWQA studies were done in 2001 in the San Jacinto Basin to help assess general water-quality conditions (samples were collected from 18 wells used for public supply and 5 wells used for irrigation) and to evaluate the susceptibility of public-supply wells to contamination by VOCs (samples were collected from 11 wells) (Hamlin and others, 2002) (fig. 6). Wells sampled by the NAWQA Program in the basin ranged in depth from 328 to 1,720 ft.

General Water-Quality Characteristics and Natural Factors

Groundwater quality in the San Jacinto Basin, in terms of the concentration of dissolved minerals, varies with the recharge source and location within the basin. The source of most recharge is runoff from the San Jacinto Mountains, a calcium-bicarbonate type water with low concentrations of dissolved solids (about 100 mg/L) (Anning and others, 2007, p. 103). Dissolved-solids concentrations in water from wells near the San Jacinto River and associated engineered recharge facilities near the mountain front in the Canyon and San Jacinto Upper Pressure subbasins were mostly less than about 500 mg/L (fig. 2). Dissolved-solids concentrations in water from wells in the Hemet North, Hemet South, San Jacinto Lower Pressure, Lakeview, and Perris North subbasins were generally higher, but usually less than 1,000 mg/L.

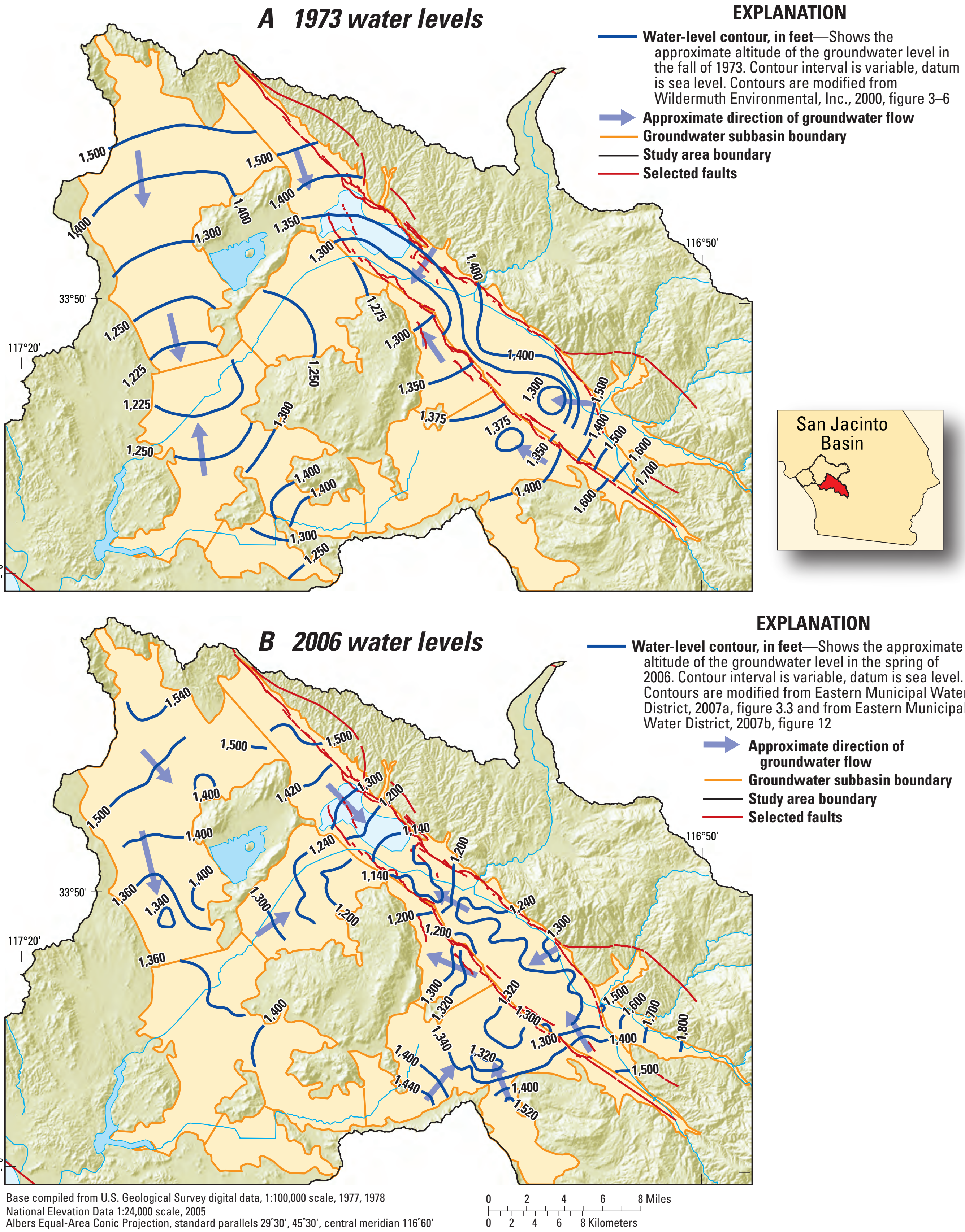
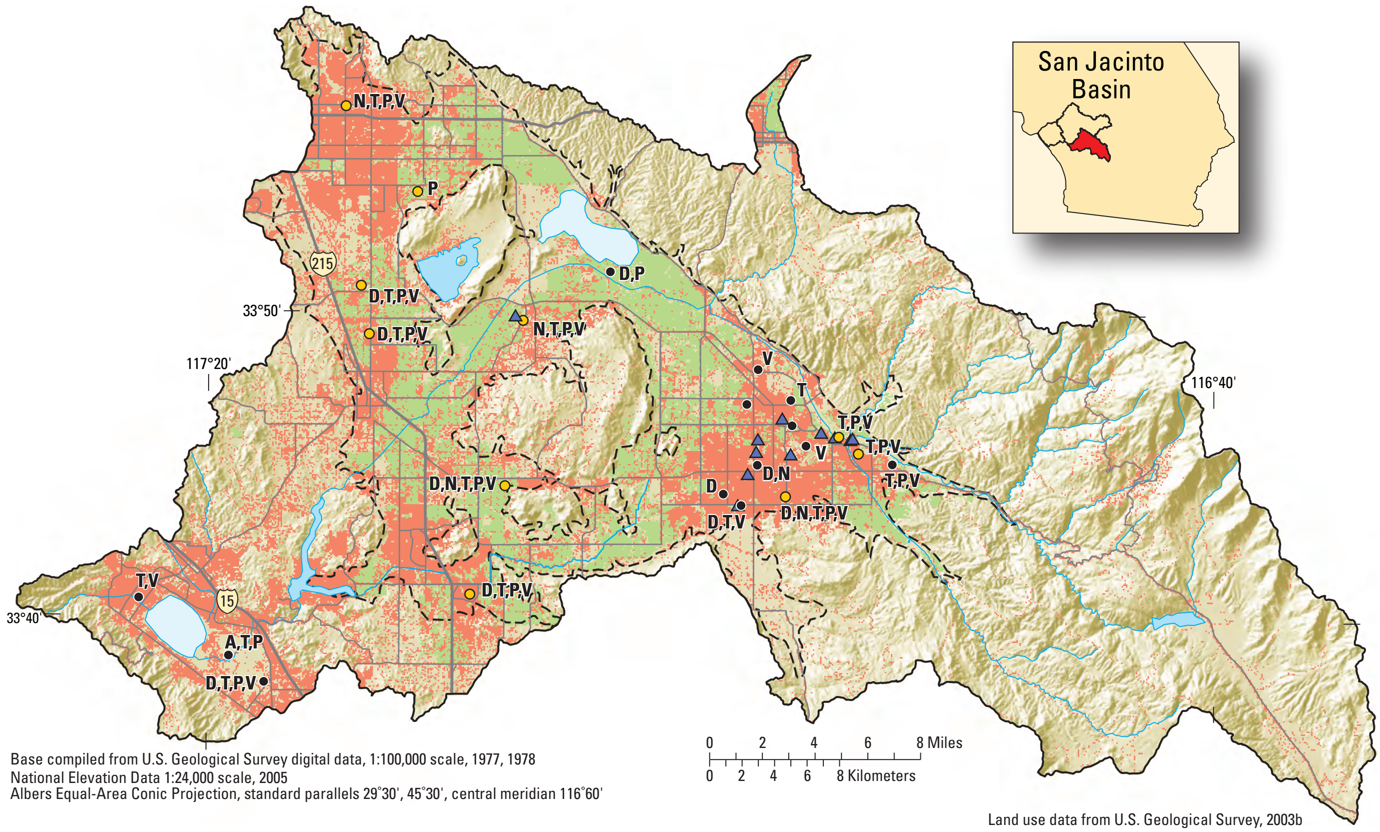


Figure 5. Groundwater levels and generalized flow directions in (*A*) 1973 and in (*B*) 2006 in the San Jacinto Basin, California.



EXPLANATION

- **Agricultural land use**
- **Urban land use**
- **Approximate boundary of basin-fill sediments**
- **Study area boundary**
- **Water-supply well sampled to assess water-quality conditions**—Wells sampled by NAWQA Program in the San Jacinto Basin. Well label represents water-quality constituent detected, see list at right
  - ● Depth to top of well screen is more than 270 feet
  - ○ Depth to top of well screen is less than 270 feet
- ▲ **Public-supply well sampled for volatile organic compounds as part of a susceptibility study**

D	Dissolved-solids concentration greater than 500 milligrams per liter
A	Arsenic concentration greater than 10 micrograms per liter
N	Nitrate concentration greater than 10 milligrams per liter as nitrogen
T	Tritium activity greater than 1 picocurie per liter
P	One or more pesticide compound detected
V	One or more volatile organic compound detected

Figure 6. Locations of and chemical characteristics of water in wells sampled in the San Jacinto Basin, California, by the NAWQA Program, 2001.

These subbasins contain groundwater primarily recharged from mountain runoff and from excess irrigation. Concentrations in water from wells in the Perris South and Menifee subbasins, which are furthest from major sources of mountain-front recharge, were mostly greater than 1,000 mg/L (Kaehler and Belitz, 2003).

Before appreciable use of groundwater began, water levels in the lower parts of the San Jacinto Basin were near or at the ground surface, resulting in evapotranspiration and naturally high concentrations of dissolved solids in groundwater. Because of issues related to the use of high-salinity water, relatively few water-supply wells have been drilled in areas where the groundwater has concentrations of dissolved solids greater than 1,000 mg/L (Burton and others, 1996; Kaehler and others, 1998; Kaehler and Belitz, 2003). The highest concentration of dissolved solids measured in groundwater sampled in 2006, about 15,000 mg/L, was from a well in the Perris South subbasin (Eastern Municipal Water District, 2007a, table 3-3). Saline groundwater is pumped from wells and then treated by reverse osmosis at two desalination facilities in the Menifee Valley (Anning and others, 2007, p. 103; Eastern Municipal Water District, 2005, p. 88). The dissolved-solids concentration of treated wastewater recharged to the western subbasins is actually less than that of the local groundwater (Burton and others, 1996, p. 2).

Vertical differences in dissolved-solids and major ion concentrations were observed in water from a nested well site near the boundary between the Hemet South and Perris South subbasins (Kaehler and others, 1998, p. 32). Dissolved-solids concentrations in water sampled from 3 wells completed in shallower parts of the basin-fill aquifer (screened intervals from 72 to 236 ft below land surface) ranged from 1,620 to 3,380 mg/L. Water sampled from 2 wells screened at depths from 450 to 460 ft and from 630 to 640 ft below land surface had dissolved-solids concentrations of 595 and 483 mg/L, respectively. Evaporation and reactions with the aquifer matrix are likely causes of relatively high concentrations of dissolved solids in water in the shallower parts of the aquifer (Kaehler and others, 1998, p. 32).

The trace elements arsenic and uranium are present in the sampled groundwater, but are not contaminants of concern in the San Jacinto Basin. Concentrations of dissolved arsenic ranged from 0.3 to 19.4 µg/L, with a median of 1.2 µg/L, in samples collected by NAWQA from 23 water-supply wells in the San Jacinto Basin (Hamlin and others, 2002, appendix 6). Only one sample had an arsenic concentration greater than the drinking-water standard of 10 µg/L (U.S. Environmental Protection Agency, 2008). Concentrations of dissolved uranium in samples from the 23 water-supply wells ranged from less than 0.02 to 15.7 µg/L with a median value of 2.1 µg/L (Hamlin and others, 2002, appendix 8), all less than the drinking-water standard of 30 µg/L (U.S. Environmental Protection Agency, 2008).

The dissolved oxygen content of groundwater provides an indication of the oxidation-reduction (redox) environment within the aquifer, which affects the mobility of many constituents (McMahon and Chapelle, 2008). Suboxic and anoxic redox conditions are associated with concentrations of dissolved oxygen less than 0.5 mg/L and with nitrate reduction and(or) other reduction processes in the case of anoxic conditions (McMahon and Chapelle, 2008, table 1). Samples collected by NAWQA from wells in which the top of the screen was deeper than a median value of 270 ft below land surface had a median concentration of dissolved oxygen and nitrate (as nitrogen) of 0.4 mg/L and 1.7 mg/L, respectively, compared to wells with shallower open intervals in which the median concentration of dissolved oxygen and nitrate (as nitrogen) was 5.8 mg/L and 5.6 mg/L, respectively (table 1). These results suggest that the geochemical environment becomes more reducing with depth, which would cause consumption of dissolved oxygen and nitrate by biochemical processes.

Tritium, an isotope of hydrogen that is incorporated into the water molecule, is an indicator of young groundwater (see Section 1 of this report for a discussion of groundwater age and environmental tracers). Tritium was detected in 15 of 23 (65 percent) of the NAWQA sampled wells in the basin at activities greater than 1 pCi/L, indicating that a component of the groundwater in most of the samples was recharged since the early 1950s (young water) (Hamlin and others, 2005, p. 5). Shallow groundwater has higher tritium activities than deeper water (table 1) and therefore is assumed to be younger than the deeper water. This finding indicates that a major component of recharge is from the overlying land surface rather than by lateral flow from more distant areas.

Potential Effects of Human Factors

In addition to the natural factors described above, agricultural and urban land uses and activities and the extensive use of imported water also affect groundwater quality in the San Jacinto Basin. Withdrawals from wells have altered groundwater-flow directions in some areas, allowing new sources of recharge and the movement of poor quality groundwater to have a greater effect on water quality.

Groundwater monitoring programs in 2006 measured concentrations of nitrate (as nitrogen) ranging from not detected to 30 mg/L in the San Jacinto Basin (Eastern Municipal Water District, 2007a, table 3-3 and 2007b, table 9). The drinking-water standard for nitrate (as nitrogen) is 10 mg/L (U.S. Environmental Protection Agency, 2008). Water sampled from 12 of 58 public-supply wells (21 percent) in the basin had concentrations of nitrate (as nitrogen) greater than 10 mg/L (California Department of Water Resources, 2003a). Nitrate (as nitrogen) concentrations exceeded 10 mg/L in 5 of 23 of the NAWQA samples (22 percent) from wells used for municipal supply and irrigation (Hamlin and others, 2002). Contours of computed statistics representing concentrations of nitrate (as nitrogen) in groundwater in the San Jacinto Basin show areas with concentrations greater than 10 mg/L in the San Jacinto Upper Pressure, Hemet South, Lakeside, Perris North, and Perris South subbasins (Wildermuth Environmental, Inc., 2008, appendix B). Potential sources of nitrate in the basin are the infiltration of water affected by agricultural practices and wastewater from animal feeding facilities, septic tanks, and from municipal wastewater treatment plants (Rees and others, 1995).

Pesticides were detected in 14 of 23 of the NAWQA sampled wells (61 percent) at concentrations that were much lower than applicable drinking-water standards (Hamlin and others, 2002, appendix 9F). The most commonly detected pesticides in groundwater from the San Jacinto Basin were atrazine (9 samples), simazine (8 samples), and atrazine degradates (8 samples). VOCs were detected in 24 of 34 of the NAWQA sampled wells (71 percent) at low concentrations (Hamlin and others, 2002, appendixes 11G and 11H) well below applicable drinking-water standards. The most commonly detected VOCs were chloroform (21 samples) and perchloroethene (PCE, 7 samples).

Pesticides and VOCs were detected more frequently in water from 10 shallower wells (where the top of the well screen is within 270 ft of land surface) than in water from 10 deeper wells sampled by NAWQA (Hamlin and others, 2005, fig. 14) (fig. 7, table 1). One or more pesticides were detected in all of the wells and one or more VOCs were detected in 84 percent of the wells in which the top of the well screen was shallower than the median value of 270 ft below land surface (table 1). This finding compares to the detection of one or more pesticides in 30 percent and one or more VOCs in 67 percent of the wells with deeper open intervals. Pesticides were detected in more than 72 percent of the samples containing young (post-1950 recharge) water, but were detected in only 20 percent of the samples made up of older water (Hamlin and others, 2005, p. 17). Similarly, VOCs were detected in 83 percent of the samples containing young water and in 20 percent of the samples made up of older water. The differences in detection frequency based on depth are comparable to the differences based on age. The higher detection frequencies in shallower and younger groundwater suggest that these compounds have been introduced to the aquifer system since the early 1950s. Because the aquifers are generally unconfined, they are susceptible to contamination from sources at the land surface. The potential for contamination of groundwater by VOCs can be expected to increase as urban development in the basin continues.

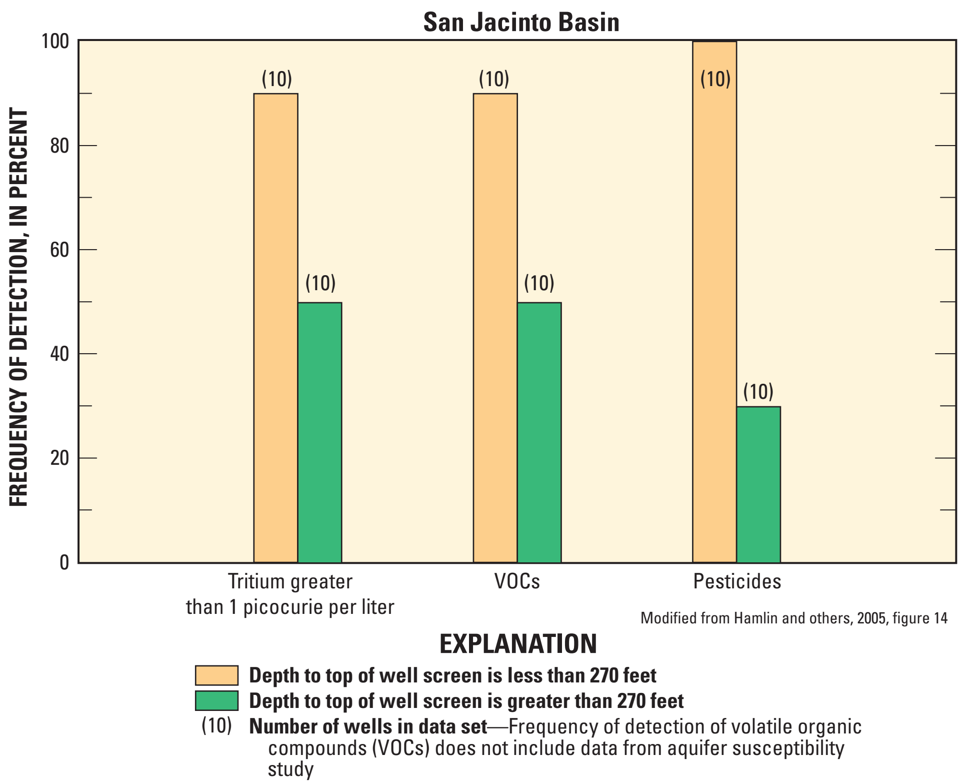


Figure 7. Detection frequencies of tritium, volatile organic compounds, and pesticides in water samples from wells in the San Jacinto Basin, California.

Inland Basin of the Santa Ana Basin

The Inland Basin covers about 655 mi^2 in the central part of the Santa Ana drainage basin (fig. 8) and is also called the Upper Santa Ana Valley Groundwater Basin (California Department of Water Resources, 2003b, p. 148). It is bounded by the San Bernardino Mountains on the northeast; the San Gabriel Mountains on the northwest; the Chino Hills and Santa Ana Mountains to the west; and various hills and relatively low altitude mountains to the south. Altitudes in the 1,484-mi^2 drainage basin range from 486 ft at the Prado Flood Control Basin dam to 11,499 ft in the San Bernardino Mountains. Alluvial fans extend from the mountain fronts into the basin and the watershed eventually drains to the Santa Ana River.

The Inland Basin has a semiarid climate, with hot dry summers and cooler, wetter winters. Analysis of modeled precipitation data for 1971–2000 (PRISM Group, Oregon State University, 2004) resulted in an average annual precipitation value of about 16.4 in. over the groundwater basin as a whole (McKinney and Anning, 2009, table 1). Parts of the San Bernardino Mountains receive more than 50 in. of precipitation during the year. Most precipitation falls from October to March and most runoff results from winter storms. Natural recharge to the Inland Basin groundwater system is primarily from the infiltration of runoff originating in the mountains.

Analysis of LandScan population data for 2005 (Oak Ridge National Laboratory, 2005) indicated a population of 2.1 million in the groundwater basin (McKinney and Anning, 2009, table 1) and a population density of about 3,200 people/mi^2. About 68 percent of the basin was classified as urban and about 6 percent as irrigated agriculture in 2001 (U.S. Geological Survey, 2003b) (fig. 8). The largest use of water in the basin is for public supply, which was estimated using county-level water-use data disaggregated to a finer scale (McKinney and Anning, 2009, p. 9) at about 504,000 acre-ft in 2000 with about 74 percent supplied by groundwater. Water use for irrigation was estimated to be about 148,000 acre-ft in 2000, about 23 percent of which was pumped from wells. This method of determining water use in the basin may have a larger uncertainty because the Inland Basin is a relatively small part of San Bernardino County.

Conceptual Understanding of the Groundwater System in the Inland Basin

The Inland Basin is bounded on the east by the San Andreas Fault, which lies along the base of the San Bernardino Mountains; on the north by the Cucamonga Fault Zone, which follows the base of the San Gabriel Mountains; and on the west by the Chino Fault, which separates the basin from the Chino Hills (fig. 8). Other faults and consolidated rock constrictions divide the Inland Basin into groundwater subbasins. These interior faults locally restrict groundwater flow and control the location of natural groundwater discharge. The Chino, Cucamonga, Rialto-Colton, Bunker Hill, Yucaipa, San Timoteo, Riverside-Arlington, and Temescal groundwater subbasins within the Inland Basin are shown on figure 8 and are condensed from groundwater management zones used for water-quality monitoring within the basin (Wildermuth Environmental, Inc., 2008, fig. 1-1).

The groundwater basins are generally unconfined near the mountain fronts where precipitation and mountain runoff is distributed and recharged through natural streambeds and engineered recharge facilities. Confined conditions typically occur down gradient from the mountain fronts and at greater depths due to finer grained deposits interlayered with sand and gravel. The entire surface-water outflow from the Inland Basin is stored in the Prado Flood Control Basin before flowing in the Santa Ana River into the Coastal Basin. The Bunker Hill and Chino subbasins are the two largest subbasins and account for more than 50 percent of the basin-fill area in the Inland Basin (17 and 34 percent, respectively). The groundwater systems and water quality of the Bunker Hill and Chino subbasins are described in this section of the report because of their relatively large areas and relatively well understood flow systems. Thus, conceptual models of groundwater systems in the Inland Basin are based primarily on those of the Bunker Hill and Chino subbasins, which are discussed separately because of substantial differences in their hydrogeologic settings. Other subbasins, such as the Rialto-Colton subbasin, also have been extensively investigated (Woolfenden and Kadhim, 1997; Woolfenden and Koczot, 2001), but have characteristics that are represented by either the Bunker Hill or Chino subbasins.

The Bunker Hill subbasin, which covers 112 mi^2 in the San Bernardino area, is bounded by the San Bernardino Mountains and the San Jacinto Fault Zone in the northeastern part of the Inland Basin. It has a large mountain drainage area (466 mi^2) that contributes water to the subbasin. The sediments in the Bunker Hill subbasin generally consist of coarse-grained unconsolidated alluvial fan and stream deposits near the mountain fronts that become layered with finer grained material further away from the mountains. Although layers could be correlated only over short distances, Dutcher and Garrett (1963, plate 7) divided the basin-fill deposits into three water-bearing zones separated by intervals of primarily clay and silt (fig. 9). The thin Quaternary-age stream-channel deposits are among the most permeable sediments in the subbasin and allow large seepage losses from streams. Hydraulic conductivity values for these deposits range from about 40 to 100 ft/d (Dutcher and Garrett, 1963, p. 51-56). Basin-fill deposits near the land surface, but away from the streams, are generally less permeable and act to confine deeper groundwater.

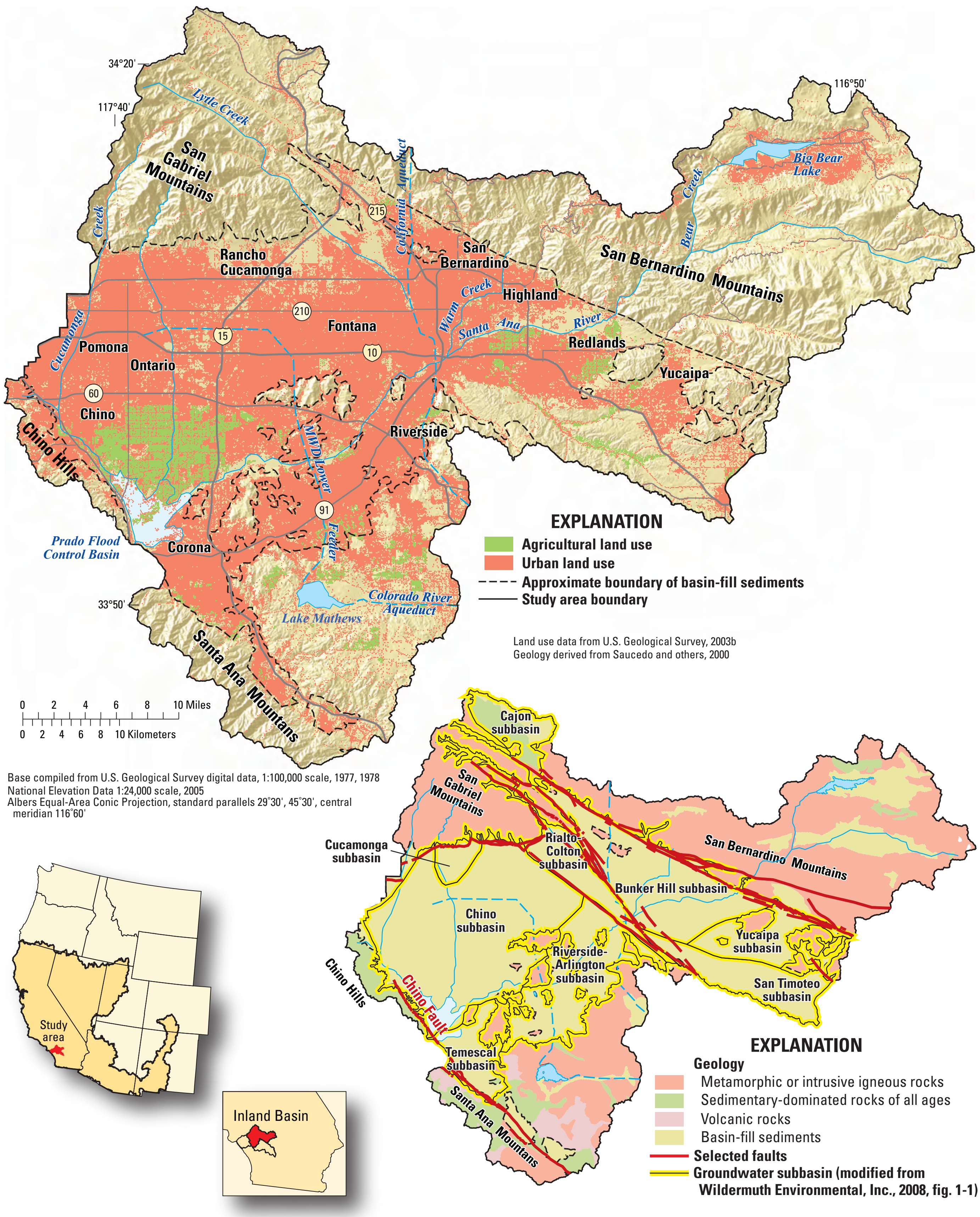


Figure 8. Physiography, land use, and generalized geology of the Santa Ana Inland Basin, California.

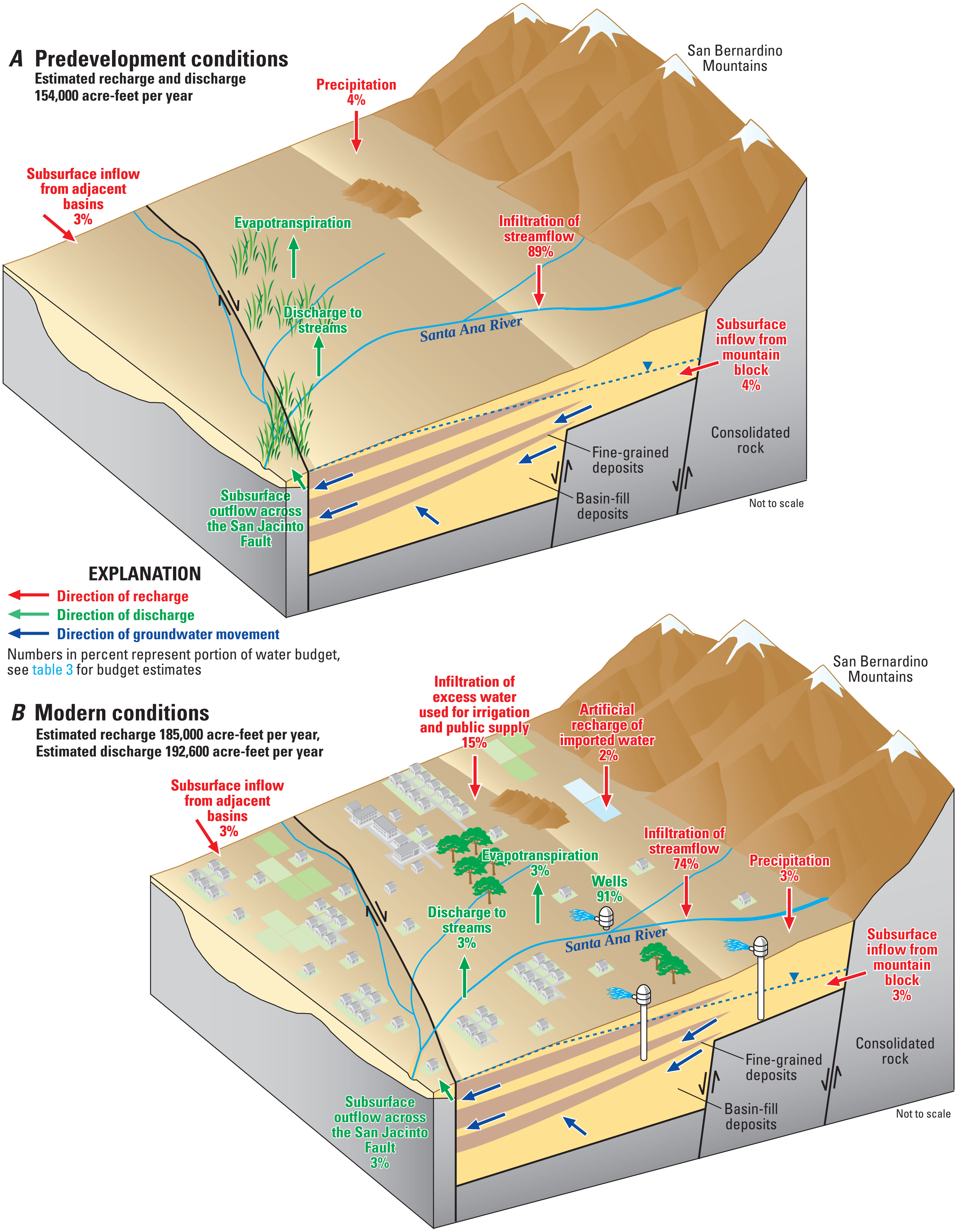


Figure 9. Generalized diagrams for the Bunker Hill subbasin, California, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

The upper and middle water-bearing zones contain layers of well-sorted sand and gravel that provide most of the water to public-supply and agricultural wells in the Bunker Hill subbasin. The hydraulic conductivity of the upper water-bearing zone is estimated to be about 60 ft/d on the basis of transmissivity values used in a numerical groundwater flow model of the subbasin (Danskin and others, 2006, fig. 40A). The upper and middle water-bearing zones are separated by as much as 300 ft of interbedded silt, clay, and sand in the central part of the subbasin. Although not as permeable as the adjacent water-bearing zones, the confining material does yield significant quantities of water to wells. As a result, most production wells are open to one or both of the water-bearing zones and to the intervening confining zone. The lower water-bearing zone is composed of poorly consolidated to partly cemented older Quaternary-age basin fill or older semiconsolidated to consolidated Tertiary-age deposits.

The Chino subbasin covers about 222 mi^2, but unlike the Bunker Hill subbasin, has a mountain drainage area of only 62 mi^2. It slopes from north to south towards the Santa Ana River. The upgradient Cucamonga subbasin receives much of the runoff from the San Gabriel Mountains as recharge, but faults cutting through the basin-fill deposits restrict groundwater flow to the Chino subbasin. Other faults bounding and within the subbasin impede the movement of groundwater to varying degrees. A detailed description of the geology and hydrostratigraphy of the basin is provided by the Chino Basin Watermaster (Wildermuth Environmental, Inc., 2007a).

The Chino subbasin is filled with an average of about 500 ft of unconsolidated sediment eroded from the surrounding mountains during the Pleistocene Epoch that is overlain by thinner, more recent flood plain and alluvial fan deposits associated with the mountain-draining streams and the Santa Ana River (California Department of Water Resources, 2003c). In the deepest parts of the subbasin, these sediments are greater than 1,000 ft thick. Laterally extensive and continuous layers of permeable sediment or of confining material are not present as a result of the alluvial fan depositional environment. The unconsolidated basin-fill deposits overlie semiconsolidated to consolidated Tertiary-age sediment, which overlie an irregular surface of igneous, metamorphic, and sedimentary rocks that are considered to be relatively impermeable.

The upper part of the unconsolidated basin-fill deposits is generally coarse grained and permeable. It ranges from having a thick unsaturated zone in the northern and eastern unconfined parts of the subbasin to being almost fully saturated in the southern and western semiconfined to confined parts, where the shallow deposits contain a larger fraction of silt and clay layers (fig. 10). Groundwater moving from higher altitude recharge areas in the northern and eastern parts of the subbasin becomes confined beneath fine-grained sediments in the western and southwestern parts of the subbasin. These fine-grained sediments are generally characterized by lower permeabilities and better water quality than that in the shallower deposits. The minimum extent of the confining layers in the southwestern part of the Chino subbasin is indicated by the area mapped by Mendenhall (1905a, plate 1) as having artesian conditions in the early 1900s (fig. 11).

Groundwater Budget

Sources of recharge to the basin-fill aquifer in the Bunker Hill subbasin under modern conditions are primarily infiltration of streamflow along the mountain front and infiltration of excess water used for irrigation and public supply. Infiltration of precipitation on the basin floor, artificial recharge of imported water, and subsurface inflow from the mountain block and adjacent groundwater subbasins are relatively minor sources of recharge to the basin-fill aquifer. The largest component of groundwater discharge in the subbasin is now withdrawals from wells (91 percent), mainly for public supply. Danskin and others (2006, p. 55) compiled a groundwater budget for the Bunker Hill subbasin for 1945–98, which is listed in table 3. The estimated amounts of recharge from natural sources such as precipitation on the basin, infiltration of streamflow along the mountain front, and subsurface inflow from the mountain block and from adjacent subbasins, are assumed to be unchanged from predevelopment to modern conditions.

Under modern conditions, about 74 percent (136,500 acre-ft) of the estimated average annual recharge to the basin-fill aquifer in the Bunker Hill subbasin is from the infiltration of mountain runoff (Danskin and others, 2006, table 11). Wetter-than-normal periods contribute large quantities of recharge to the groundwater system and result in higher water levels (Hardt and Freckleton, 1987, p. 14) and increased amounts of groundwater in storage. Much of the runoff is diverted into stormwater-detention basins in or adjacent to stream channels along the mountain front that also operate as groundwater recharge facilities. Some of these basins have been in operation since the early 1900s. The Seven Oaks Dam on the Santa Ana River, completed in 1999, allows for additional recharge of streamflow in the Bunker Hill subbasin through the storage of excess runoff and subsequent release to allow infiltration in the stream channel and artificial recharge basins (Danskin and others, 2006, p. 19).

Artificial recharge of imported surface water from northern California began in 1972 with generally decreasing amounts imported through 1986 (Danskin and others, 2006, figure 19). Recharge of imported water at engineered facilities is estimated to average about 3,000 acre-ft/yr from 1945–98 and about 6,000 acre-ft/yr from 1972–98. Higher rates in 1973–82 of artificial recharge of imported water may have contributed to rising water levels and flooding in formerly artesian areas in San Bernardino (Danskin and others, 2006, p. 29).

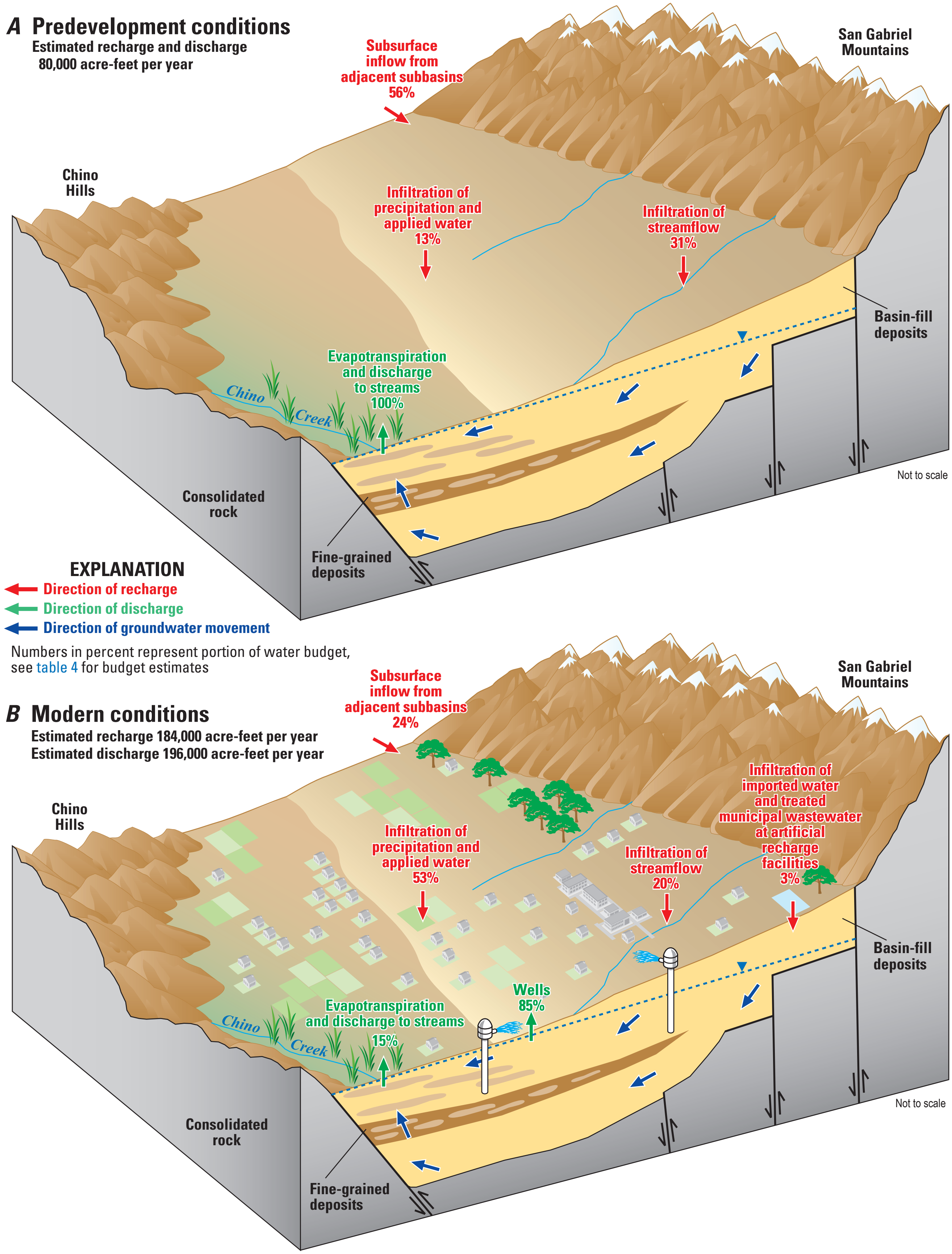


Figure 10. Generalized diagrams for the Chino subbasin, California, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

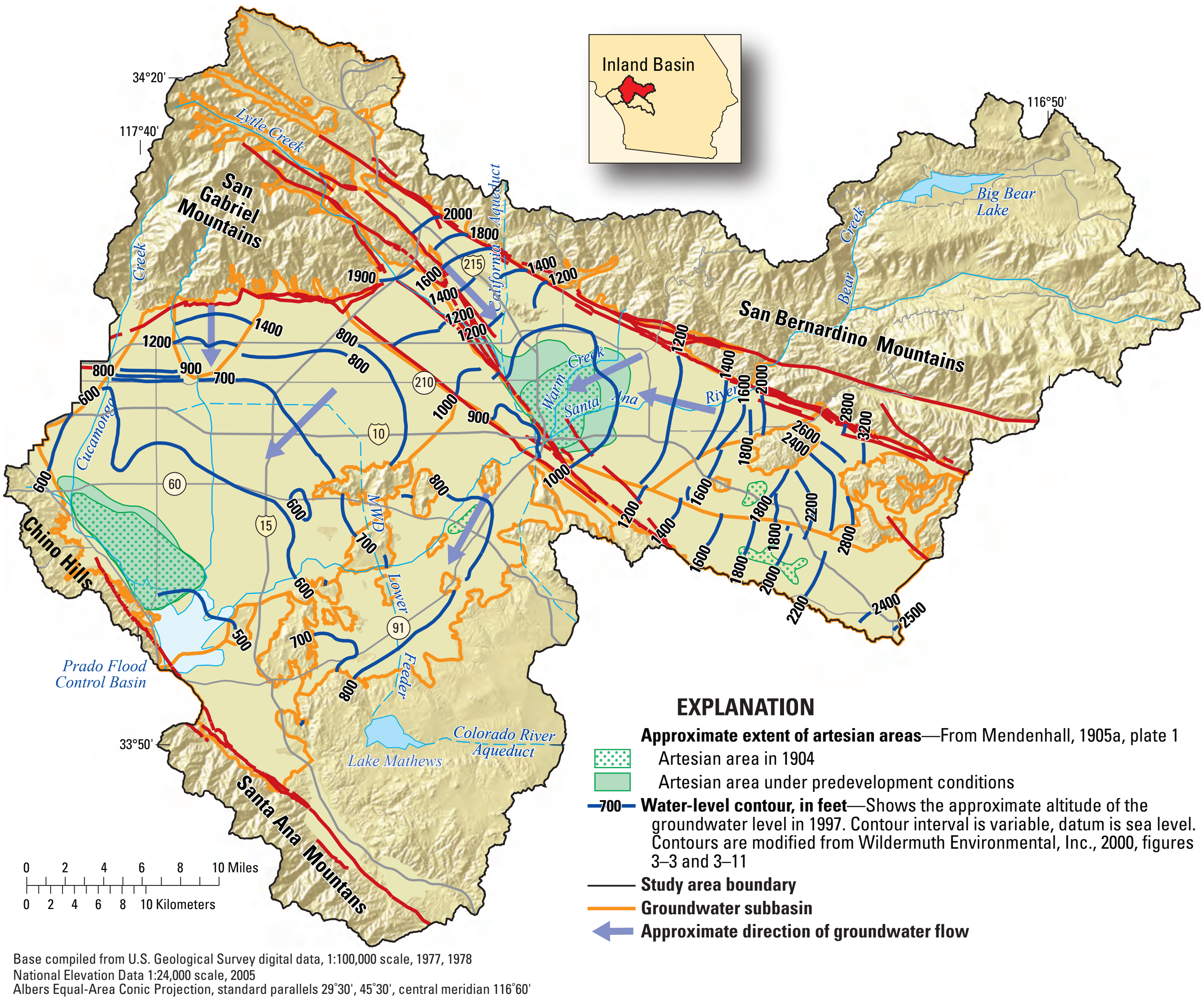


Figure 11. Groundwater levels and generalized flow directions in 1997 in the Inland Basin, California.

Infiltration of excess water used for irrigation and public supply that recharges the aquifer system is mainly derived from pumped groundwater and is called return flow. Although water is extracted from different zones within the Bunker Hill basin-fill aquifer depending on well construction, return flow recharges only the shallow part of the aquifer through infiltration at the land surface. The downward movement of return flow is restricted by the presence of shallow confining layers in much of the area. For 1945–98, estimated recharge from infiltration of excess water used for irrigation and public supply averaged about 28,000 acre-ft/yr (Danskin and others, 2006, p. 42).

Seepage from consolidated rocks surrounding and underlying the basin-fill groundwater system commonly is assumed to be zero, but a heat-transport model suggested that as much as 15,000 acre-ft/yr of water could be contributed to the Bunker Hill subbasin from the consolidated-rock mountain block (Hughes, 1992). Danskin and others (2006, p. 53) noted that the inflow is greater than zero, though how much greater is unknown, and estimated about 6,000 acre-ft/yr of recharge by subsurface inflow from the mountain block.

Groundwater is discharged naturally by subsurface underflow out of the Bunker Hill subbasin, by upward flow into the lower reaches of Warm Creek, and by evapotranspiration. Underflow out of the subbasin near the Santa Ana River occurs only in the younger stream-channel deposits, which are about 100 ft thick (Danskin and others, 2006, p. 44). The river has eroded and redeposited these materials, removing most of the restriction to groundwater flow caused by the San Jacinto Fault (Dutcher and Garrett, 1963, p. 101). In the older, deeper deposits, fault gouge and the offset of permeable zones restrict groundwater flow.

Table 3. Estimated groundwater budget for the basin-fill aquifer system in the Bunker Hill subbasin, California, under predevelopment and modern conditions.

[All values are in acre-feet per year. Estimates of groundwater recharge and discharge are 1945–98 averages determined for the area and adjusted to compensate for the residual between recharge, discharge, and change in storage (Danskin and others, 2006, table 11) or are derived from these estimates. The budgets are intended only to provide a basis of comparison for 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] 6,500	6,500	0
Infiltration of streamflow near mountain front (includes engineered recharge under modern conditions)	[1] 136,500	136,500	0
Subsurface inflow from mountain block	[1] 6,000	6,000	0
Subsurface inflow from adjacent subbasins	[1] 5,000	5,000	0
Infiltration of excess irrigation water used for irrigation and public supply	0	28,000	28,000
Artificial recharge of imported water	0	3,000	3,000
Total recharge	**154,000**	**185,000**	**31,000**
Budget component		**Estimated discharge**	
Subsurface outflow across the San Jacinto Fault	[2] 51,400	6,600	-44,800
Evapotranspiration	[2] 51,300	6,000	-45,300
Discharge to streams	[2] 51,300	5,000	-46,300
Well withdrawals	0	175,000	175,000
Total discharge	**154,000**	**192,600**	**38,600**
Change in storage (total recharge minus total discharge)	0	-7,600	-7,600

[1] Assumed to be the same as estimated recharge under modern conditions.

[2] Assumed to be about one third of the estimated total recharge under predevelopment conditions.

Underflow near the Santa Ana River is mostly dependent on groundwater levels in the Bunker Hill subbasin. As groundwater levels in the subbasin rise, more water is forced out as underflow. As groundwater levels fall, less water leaves the subbasin as underflow. The water level in the lower (down gradient) part of the flow system controls the amount of storage in the subbasin, even though there is storage available in the upgradient part. Underflow out of the Bunker Hill subbasin was simulated at about 6,600 acre-ft/yr for 1945–98 (Danskin and others, 2006, table 11). Similarly, groundwater discharge to Warm Creek was shown to correspond to water levels in the aquifer with an average annual discharge from 1945–98 of about 5,000 acre-ft (Danskin and others, 2006, table 32).

Pumped groundwater in the Bunker Hill subbasin is used for agricultural, municipal, and industrial purposes. As the area has become urbanized, the quantity of water pumped for agricultural use has declined considerably. Withdrawals from wells for 1945–98 averaged about 175,000 acre-ft/yr, and ranged from about 123,000 acre-ft in 1945 to about 215,000 acre-ft in 1996 (Danskin and others, 2006, p. 47). As the San Bernardino area has become urbanized, wells have been installed higher on the alluvial fans, closer to the mountains and closer to the new urban demand.

Recharge to the groundwater system in the Chino subbasin is by infiltration of precipitation and water applied at the land surface, infiltration of streamflow (including stormwater runoff), subsurface inflow from adjacent subbasins, and infiltration of imported water and treated municipal wastewater at artificial recharge facilities such as spreading basins and storage ponds (table 4). Virtually all groundwater discharge under predevelopment conditions was by evapotranspiration and discharge to streams in areas where groundwater levels were at or near the land surface (fig. 10). Shallow bedrock in the gap between the Chino Hills and the Santa Ana Mountains forces groundwater to discharge to the river before it exits the subbasin. Groundwater discharge is now mostly from wells in the subbasin. Little information is available about groundwater conditions prior to development in the Chino subbasin, and estimates of recharge to and discharge from the aquifer presented in this section are intended only to provide a basis for comparison of change with development.

Table 4. Estimated groundwater budget for the basin-fill aquifer system in the Chino subbasin, California, under predevelopment and modern conditions.

[All values are in acre-feet per year. Estimates of groundwater recharge and discharge are from measurements and estimates for the July 1960 through June 2006 calibration period used by a groundwater flow model of the Chino subbasin (Wildermuth Environmental, Inc., 2007b, table 3-1) unless footnoted. Estimates for predevelopment conditions were not available. This budget is intended only to provide a basis of comparison for overall magnitudes of recharge and discharge between predevelopment and modern conditions, and does 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 streamflow	[1] 25,000	[2] 36,000	11,000
Subsurface inflow from adjacent subbasins	[3] 45,000	45,000	0
Infiltration of precipitation and applied water	[4] 10,000	[5] 98,000	88,000
Infiltration of imported water and treated municipal wastewater at artificial recharge facilities	0	5,000	5,000
Total recharge	**80,000**	**184,000**	**104,000**
Budget component		**Estimated discharge**	
Evapotranspiration	[6] 45,000	15,000	-30,000
Discharge to streams	[7] 35,000	14,000	-21,000
Well withdrawals	0	167,000	167,000
Total discharge	**80,000**	**196,000**	**116,000**
Change in storage (total recharge minus total discharge)	0	-12,000	-12,000

[1] Calculated as the residual of other components of recharge and discharge estimated for predevelopment conditions.

[2] Infiltration of streamflow includes the Santa Ana River and tributary streams. Recharge from the Santa Ana River has increased over time due to increased upstream streamflow while recharge from the tributaries has decreased due to channel lining (Wildermuth Environmental, Inc., 2007b, fig. 3-4).

[3]Assumed to be the same as the amount estimated for modern conditions.

[4] Estimated to be about 5 percent of average annual precipitation (16.4 inches per year) on the Chino subbasin (222 square miles).

[5] Could not separate out Temescal subbasin part of budget component.

[6] Estimated predevelopment evapotranspiration is based on an assumed evapotranspiration rate of 2 feet per year occurring over approximately 35 square miles, which includes the artesian area mapped by Mendenhall (1905a) and the area covered by the Prado Flood Control Basin within the Chino subbasin.

[7] Estimated to be the average groundwater outflow for 1930–40 calculated by French (1972, table 1). This period is affected by withdrawals from wells resulting in reduced groundwater discharge to streams.The estimate includes discharge by evapotranspiration to the lowland area along the Santa Ana River.

Recharge to the Chino subbasin from subsurface inflow from adjacent subbasins was simulated using a groundwater flow model of the subbasin calibrated to conditions from 1960 to 2006 and averaged about 45,000 acre-ft/yr (Wildermuth Environmental, Inc., 2007b, table 3-1). Much of the subsurface inflow moves across faults from the Cucamonga and Rialto-Colton subbasins. Infiltration of precipitation was estimated to be about 10,000 acre-ft/yr, or 5 percent of the average annual precipitation (16.4 in.) on the basin-fill area (222 mi^2). Recharge from excess irrigation water began in the 1800s and an average of about 98,000 acre-ft/yr of areal recharge, which includes infiltration of precipitation and excess water applied to the land surface, was specified in the groundwater model of the subbasin from 1960–2006 (Wildermuth Environmental, Inc., 2007b, table 3-1). This estimate includes a relatively small amount of recharge from the Temescal subbasin, which was not removed for this analysis.

Spreading and impounding local stormwater runoff in the northern part of the Chino subbasin began in the early 1900s. Flood control projects, mainly the lining of stream channels, have been constructed to capture and convey runoff in tributary streams to the Santa Ana River and out of the Chino subbasin. Urbanization has resulted in the creation of more impermeable surfaces in the basin that divert runoff to these lined channels. After 1987, minimal recharge to the groundwater system was modeled from tributary stream channels in the subbasin (Wildermuth

Environmental, Inc., 2007b, fig. 3-4). Infiltration from the Santa Ana River to the basin-fill aquifer has increased with time as a result of increased flow in the river associated with upstream urbanization. The infiltration of water from the channels of the Santa Ana River and its tributaries (including stormflow) specified in the groundwater flow model averaged about 36,000 acre-ft/yr from 1960–2006 (Wildermuth Environmental, Inc., 2007b, tables 3-1 and 3-2). Infiltration of streamflow under predevelopment conditions was estimated to be about 25,000 acre-ft/yr, the residual of estimated discharge and other estimated recharge components (table 4).

Urbanization has increased the volume of stormwater runoff that can be diverted to artificial recharge basins and has resulted in the artificial recharge of imported water and treated wastewater effluent in the subbasin. The infiltration of imported water and treated municipal wastewater at artifical recharge facilities began in 1978, and an average of about 5,000 acre-ft/yr for 1960–2006 was specified in the groundwater flow model (Wildermuth Environmental, Inc., 2007b, tables 3-1 and 3-3).

Evapotranspiration under predevelopment conditions was estimated to be about 45,000 acre-ft/yr (table 4) based on an approximate area of shallow groundwater within the Chino subbasin and an estimated evapotranspiration rate of 2 ft/yr. An area of about 23 mi^2 in which artesian conditions prevailed in the early 1900s was mapped in the western part of the subbasin (Mendenhall, 1905a, plate 1) indicating that the groundwater level was at or above the ground surface (fig. 11). Combined with other areas of shallow groundwater, including the area of the Prado Flood Control Basin, evapotranspiration is estimated to have occurred across approximately 35 mi^2 of the subbasin under predevelopment conditions. Evapotranspiration has decreased as groundwater levels have declined and was estimated to average about 15,000 acre-ft/yr from 1960–2006 (Wildermuth Environmental, Inc., 2007b, p. 3-1 and table 3-1).

Groundwater discharge to the Santa Ana River in the Chino subbasin was estimated by French (1972, table 3) to average about 35,000 acre-ft/yr from 1933 to 1939. French developed his water budget values from data for measured streamflow at the upstream and downstream ends of the subbasin, direct runoff to the river, inflows and outflows, evapotranspiration along the river, and inflow from the Temescal subbasin. Groundwater discharge to streams in the subbasin under predevelopment conditions was estimated at about 35,000 acre-ft/yr (table 4). This estimate is at best a very "rough" one, but is assumed to be reasonable if evapotranspiration near the river and inflow from the Temescal subbasin are accounted for. More discharge to the river resulting from higher groundwater levels and groundwater discharge to Chino Creek and other creeks draining the artesian area prior to development also must be accounted for. The difference in discharge in the Santa Ana River at upstream and downstream ends of the subbasin during the relatively dry summer months of July, August, and September were compiled by Post (1928, p. 357) for 6 years during 1891–1905. The average summer base flow determined from this data extended through a year equals about 16,000 acre-ft of streamflow that is assumed to be primarily groundwater discharge to the river under early development conditions. Groundwater discharge to streams averaged about 14,000 acre-ft/yr from 1960–2006 in the groundwater flow model of the Chino subbasin (Wildermuth Environmental, Inc., 2007b, p. 3-3).

Withdrawals from wells in the Chino subbasin averaged about 167,000 acre-ft/yr from 1960–2006 (Wildermuth Environmental, Inc., 2007b, table 3-4) (table 4). Land and water use in the Chino subbasin has progressively shifted from agricultural to urban. The area of urban land increased from 7 percent in 1933 (Wildermuth Environmental, Inc., 1999, table 2-1) to 75 percent of the subbasin area in 2001 (McKinney and Anning, 2009), mainly at the expense of irrigated and non-irrigated agricultural land. Groundwater withdrawals for agriculture, primarily in the southern part of the subbasin, decreased from about 54 percent of the total production in 1977–78 to about 18 percent in 2005–06 (Wildermuth Environmental, Inc., 2007a, p. 3-4). During the same period, withdrawals for municipal and industrial uses, mainly in the northern half of the basin, increased from about 40 percent of total production in 1977–78 to 80 percent in 2005–06. In 2005–06, about 119,000 acre-ft/yr was pumped for municipal and industrial use and about 29,000 acre-ft/yr was pumped for agricultural use (Wildermuth Environmental, Inc., 2007b, table 3-4).

The groundwater budget for modern conditions (1960–2006) in the Chino subbasin has more than doubled from the estimated budget for predevelopment conditions (table 4), mainly as a result of the infiltration of excess applied water. Under modern conditions, more water is discharged than is recharged to the aquifer, resulting in the removal of water from storage. This rough estimate of overdraft, however, should not be used to calculate an accumulated volume of water removed from storage.

Groundwater Flow

Groundwater in the Bunker Hill subbasin generally moves from dispersed areas of recharge along the base of the San Bernardino Mountains towards a more focused area of discharge where the Santa Ana River crosses the San Jacinto Fault Zone as it did under predevelopment conditions (Danskin and others, 2006, p. 56) (fig. 11). The convergence of flow paths is caused by the San Jacinto Fault acting as a partial barrier to groundwater flow. The mountain-front streams generally lose most or all of their water to the groundwater system as they enter the basin and flow across the alluvial deposits. Under predevelopment conditions, flow resumed further downstream as a result of groundwater, restricted from flowing across the less permeable San Jacinto Fault at depth, rising to the land surface and discharging to Warm Creek or as subsurface outflow near the Santa Ana River (Danskin and others, 2006, p. 15).

Historically, a downward vertical gradient was present in the recharge areas of the Bunker Hill subbasin, and an upward vertical gradient was present in the discharge area. Under predevelopment conditions, a large artesian area covered nearly one-third of the subbasin and extended east towards the San Bernardino Mountains (Mendenhall, 1905b) (fig. 11). Natural groundwater discharge occurred at extensive, but somewhat discontinuous bogs, swamps, and marshlands generally near the lower stream reaches.

The vertical pattern of groundwater flow in the Bunker Hill subbasin has changed significantly from predevelopment to modern conditions because of withdrawals from wells. As groundwater production increased, water was withdrawn from increasingly deeper parts of the basin-fill aquifer. Natural discharge to the land surface was replaced by discharge to pumping wells. Hydraulic head within the aquifer changed to reflect the change in groundwater flow patterns, and the upward vertical gradient was reduced or reversed. The size of the artesian area has fluctuated historically depending on the amount of water recharged and discharged from the groundwater system (Hardt and Freckleton, 1987, fig. 3). By 1992, the area of historically flowing wells east of the San Jacinto Fault had a downward vertical gradient.

Near the base of the San Bernardino Mountains, large rises or declines in water levels occur in response to changes in recharge from streams. During times of drought and increased pumping, water levels decline as much as 200 ft, which limits the ability of water purveyors to supply sufficient groundwater to meet demand (Danskin and others, 2006, p. 8). Water levels also fluctuate in the area where the Santa Ana River crosses the San Jacinto Fault. During a period of extensive groundwater extractions from 1950 to 1970, water levels fell by as much as 100 ft and induced land subsidence of as much as 1 ft (Miller and Singer, 1971). After 1970, both natural and artificial recharge increased, so that by 1980, water levels had risen to within a few feet of the land surface (Hardt and Freckleton, 1987).

Groundwater flow in the Chino subbasin generally follows surface drainage patterns and moves from the higher altitude alluvial fans flanking the San Gabriel Mountains towards lower altitude discharge areas near the Santa Ana River and Prado Flood Control Basin (fig. 11). Depth to water ranges from more than 500 ft below land surface in the northern part of the subbasin to near land surface in the southern part, with steeper gradients in the northern part. Water levels in the subbasin have declined since development began, with larger declines in the northern unconfined part. Withdrawals from wells has reversed or changed groundwater flow directions in some areas of the Chino subbasin. Water levels measured in 1997 are as much as 200 ft below land surface in the formerly artesian area (Wildermuth Environmental, Inc., 1999, fig. 2-23). Land subsidence in this area is attributed to compaction of the fine-grained material caused by local groundwater withdrawals. Changes in groundwater levels in the Chino subbasin in response to periods of above-normal-precipitation are small, on the order of a few feet, because of the relatively small mountain drainage area that is tributary to the subbasin. In addition, the relatively large size of the subbasin coupled with thick unsaturated zones in the unconfined recharge areas delay the effects of recharge on groundwater levels.

Effects of Natural and Human Factors on Groundwater Quality

Agricultural and urban development have caused groundwater quality changes in the Inland Basin, primarily increased concentrations of dissolved solids and nitrate and the presence of VOCs and perchlorate. The basin-fill aquifers are susceptible to water-quality changes because of the unconfined conditions in much of the area, and are vulnerable to contamination because of the overlying land uses that utilize chemicals and water.

General Water-Quality Characteristics and Natural Factors

Extensive analyses of water sampled from active production and monitoring wells have been made to determine groundwater quality in the Inland Basin, especially in the Chino subbasin (Wildermuth Environmental, Inc., 2005, fig. 4-1). Concentrations of dissolved solids in groundwater from much of the Inland Basin generally are less than about 500 mg/L, except in downgradient discharge areas near the Santa Ana River and south of the river in much of the Temescal and Riverside-Arlington subbasins (fig. 2 and Wildermuth Environmental, Inc., 2008, appendix B). Shallow groundwater (between land surface and the first major confining layer) in the area of the Chino subbasin near the Prado Flood Control Basin had higher concentrations of dissolved solids that were statistically computed from multiple values per well (about 1,000–1,800 mg/L) than deeper confined groundwater (about 300–500 mg/L) (Wildermuth Environmental, Inc., 2008, appendix B). Wildermuth Environmental, Inc. (2005, p. 4-8) states that most areas in the Chino subbasin with either significant irrigated land use or dairy waste disposal histories overlie groundwater with elevated concentrations of dissolved solids (see 'Potential Effects of Human Factors' section). Concentrations of dissolved solids in water sampled from 204 public-supply wells in the Bunker Hill subbasin range from 155 to 1,140 mg/L, with a mean value of 324 mg/L (California Department of Water Resources, 2003d). Shallow groundwater in the confined part of the subbasin near the San Jacinto Fault had higher statistically derived concentrations (about 350-600 mg/L) than deeper confined groundwater (about 250-400 mg/L) (Wildermuth Environmental, Inc., 2008, appendix B).

Most of the 50 water-supply wells in the Inland Basin sampled as part of NAWQA studies (fig. 12) produced calcium-bicarbonate type water (Hamlin and others, 2002), which primarily reflects the quality of recharge water originating in high-altitude areas of the adjacent San Gabriel and San Bernardino Mountains. Dissolved-solids concentrations in water sampled from these wells in areas of natural recharge or near recharge facilities primarily ranged from about 180 to 250 mg/L.

The trace elements arsenic and uranium are present in the groundwater sampled, but typically are not contaminants of concern in the Inland Basin. Concentrations of dissolved arsenic ranged from less than 1.0 to 10 µg/L with a median of 1.1 µg/L in samples collected by NAWQA from 29 production wells, used for both public supply and irrigation, in the Inland Basin (Hamlin and others, 2002, appendix 6). Along the flow paths sampled by NAWQA in the Bunker Hill subbasin, arsenic concentrations were less than 0.9 µg/L in the unconfined proximal parts compared to generally greater concentrations (up to 12.1 µg/L) in the confined distal part (Hamlin and others, 2002, appendix 6). The longer contact time between groundwater and aquifer material at the end of the flow path is a likely cause of the greater concentrations of arsenic. Only one of the samples collected by NAWQA in the Inland Basin had a concentration of uranium greater than the drinking-water standard of 30 µg/L (40.5 µg/L in water from an irrigation well) (Hamlin and others, 2002, p. 34 and appendix 8).

Water sampled from 26 wells along flow paths in the Bunker Hill subbasin by the NAWQA Program was classified as being withdrawn from unconfined or confined parts of the aquifer (table 1). The unconfined part of the aquifer corresponds to the area in which recharge occurs in the subbasin, whereas the confined part is at the confluence of many groundwater flow paths in the discharge area. The median concentration of dissolved solids was lower and the median concentration of nitrate was higher for water sampled from wells in the upgradient unconfined part of the aquifer than for water from the downgradient confined part. Lower concentrations of dissolved oxygen indicate likely nitrate-reducing conditions in the confined part of the aquifer, whereas higher concentrations of dissolved oxygen would limit denitrification in the unconfined part of the aquifer. The median concentration of the stable isotope deuterium also was lighter in water sampled from the unconfined part of the aquifer compared to the confined part (table 1) indicating that there is some recharge at lower altitudes in the subbasin.

Potential Effects of Human Factors

Elevated concentrations of dissolved solids and nitrate in groundwater have resulted from past and present agricultural practices and urban development in parts of the Inland Basin. Dissolved solids in Chino subbasin groundwater has increased primarily due to evaporative concentration after irrigation, from the leaching of fertilizer and manure in agricultural areas, and from the recharge of treated wastewater and imported water (Wildermuth Environmental, Inc., 2005, p. 4-8). In general, sources of nitrate to groundwater include leaching of fertilizers and animal wastes applied to the land, leakage from sewer pipes, and reuse of treated wastewater. Another source of nitrate in groundwater in the Chino subbasin is infiltration of wastewater from animal feeding facilities. Runoff from these facilities can have high concentrations of ammonia, which can in turn result in high concentrations of nitrate. Computed statistics representing nitrate (as nitrogen) concentrations in shallow groundwater in the area of the Chino subbasin between the Prado Flood Control Basin and Highway 60 ranged from about 20 mg/L to greater than 100 mg/L (Wildermuth Environmental, Inc., 2008, appendix B). Computed statistics representing nitrate (as nitrogen) concentrations for the deeper confined groundwater in this area are much lower than in the overlying shallow groundwater and range from 5 to 18 mg/L.

Water-quality monitoring during 1999–2004 for the Chino subbasin groundwater management plan showed concentrations of dissolved solids and nitrate (as nitrogen) mostly greater than the secondary drinking-water standard of 500 mg/L and the primary drinking-water standard of 10 mg/L, respectively, in water sampled from the upper part of the aquifer system in the southern part of the subbasin (Wildermuth Environmental, Inc., 2005, figs. 4-4 and 4-7). Concentrations measured from wells in the northern part of the Chino subbasin (north of Highway 60) during this period were typically less than 300 mg/L for dissolved solids and generally varied from less than 2 to greater than 10 mg/L for nitrate (as nitrogen).

Concentrations of nitrate (as nitrogen) were greater than 10 mg/L in water from 14 percent of the 29 production wells sampled by NAWQA in the Inland Basin. In samples from all 4 wells with nitrate concentrations greater than 10 mg/L, tritium was greater than 1 pCi/L, and VOCs and (or) pesticides were detected; dissolved-solids concentrations greater than 500 mg/L occurred in samples from 3 of these 4 wells.

Most of the agricultural land use in the southern part of the Chino subbasin (fig. 12) is projected to be converted to urban uses over the next 20 to 30 years. Groundwater pumped from this area will have to be treated before it can be used for public supply because of elevated concentrations of dissolved solids and nitrate. More of this poorer quality groundwater is projected to move toward and discharge to the Santa Ana River if withdrawals from wells in the area decrease. About 500 acres of constructed wetlands in the Prado Flood Control Basin were designed primarily to lower nitrate concentrations in the Santa Ana River below the Prado Dam.

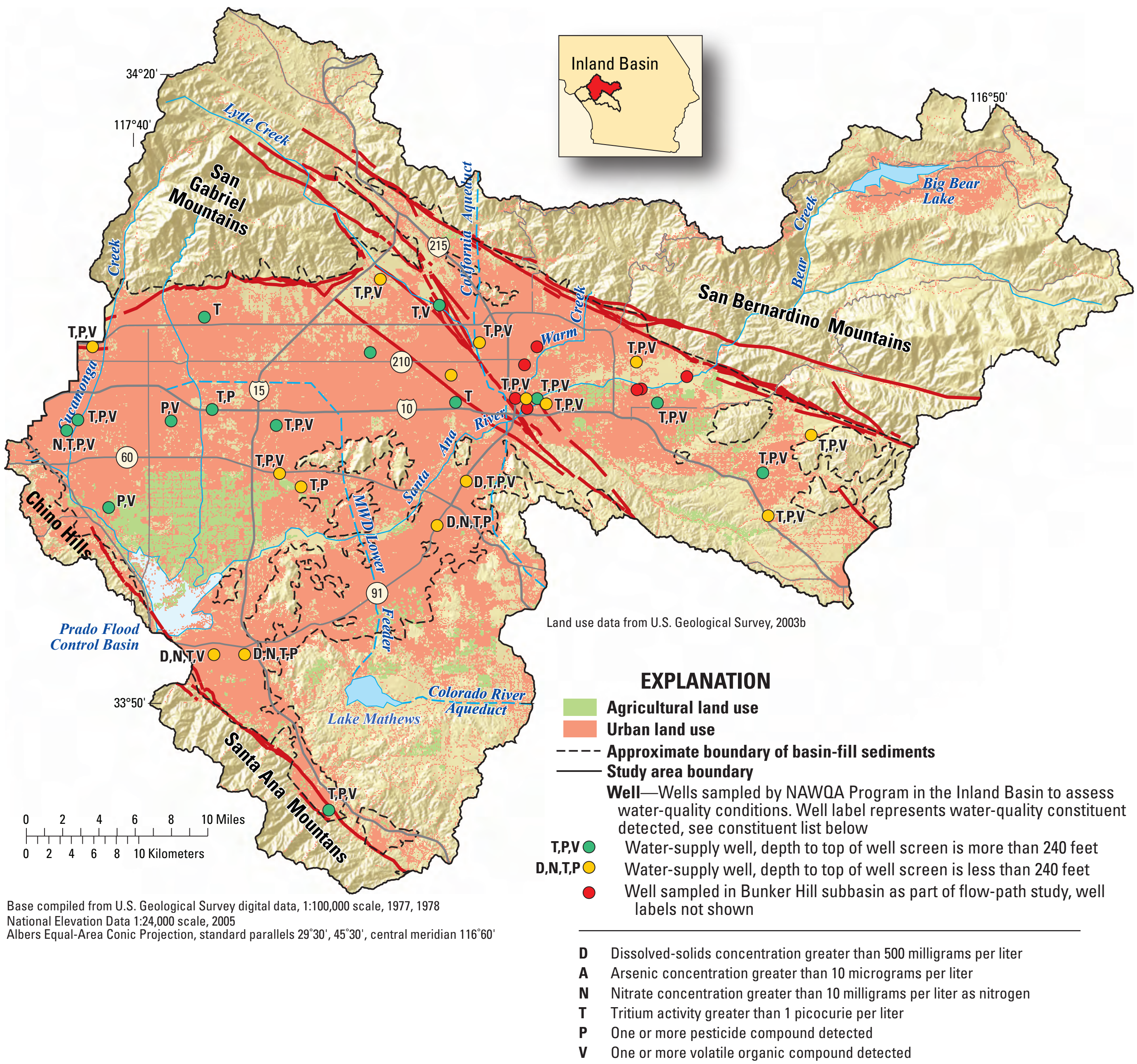


Figure 12. Locations of and chemical characteristics of water in wells sampled in the Inland Basin, California, by the NAWQA Program, 2000.

This surface water is used to recharge the basin-fill aquifer in the Coastal Basin. A plan to manage groundwater quality in the Chino subbasin has been developed that attempts to balance recharge to the subbasin with discharge from wells (Wildermuth Environmental, Inc., 2007b, p. 7-2). Wells and treatment plants (desalters) are being used to reduce the amount of groundwater discharge that contains elevated concentrations of dissolved solids and nitrate from the Chino subbasin to the Santa Ana River through the manipulation of hydraulic gradients. Desalters also are in operation in the Riverside-Arlington and Temescal subbasins (Santa Ana Watershed Authority, no date). As the demand for water increases with time, the artificial recharge of treated municipal wastewater (recycled water) in the subbasin is projected to increase from about 12,500 acre-ft in 2005 to about 58,000 acre-ft in 2010, corresponding to an equal reduction in the demand for imported water from northern California (Wildermuth Environmental, Inc., 2007b, p. 7-2). The change in concentrations of dissolved solids and nitrate in the recharge water must be accounted for as part of managing the groundwater system.

Numerous contaminant plumes (mainly VOCs and perchlorate) in the Inland Basin that are related to industrial activities extend miles from the source of contamination (Hamlin and others, 2005, fig. 3; Wildermuth Environmental, Inc., 2005, figs. 4-18 and 4-26; and California Department of Water Resources, 2003d). Since about 1980, these contaminants have become widespread in the groundwater, and have affected the operation of many public-supply wells in the basin (Danskin and others, 2006, p. 59; Santa Ana Watershed Project Authority, 2002, p. 3-10). Perchlorate contamination in Chino subbasin groundwater has been attributed to known point source releases and possibly from fertilizers historically used on citrus orchards in the northern part of the subbasin (Wildermuth Environmental, Inc., 2007a, p. 4-10).

Pesticides and VOCs were frequently detected, although mostly at very low concentrations (Hamlin and others, 2002, appendixes 9D, 9E, 10D, 10E, 11E, 11F, 12D, and 12E), in water sampled by NAWQA from 50 wells in the Inland Basin (table 1 and fig. 12). The large number of detections of these compounds in this small subset of existing wells probably reflects generally unconfined conditions in the groundwater system, present and past land uses, and the relatively low organic content of aquifer materials (Hamlin and others, 2005). The most frequently detected pesticides were atrazine; one of its degradation products, deethylatrazine; and simazine.

The most frequently detected VOCs in the samples collected by NAWQA were chloroform, trichloroethene (TCE), and perchloroethene (PCE). Some wells with VOC detections were near known VOC plumes emanating from industrial sites (Hamlin and others, 2005) and concentrations above drinking-water standards were detected in water sampled from 4 irrigation wells and 2 flow-path study monitoring wells (Hamlin and others, 2002, appendixes 9D, 9E, 11E, and 11F). Wells without VOC detections were generally deep or near recharge areas upgradient from urban areas along the mountain front. About 94 percent of the wells sampled by NAWQA at the lower end of the flow paths in the confined part of the Bunker Hill subbasin had a VOC detected compared to about 56 percent of the wells nearer to the mountain front (table 1). This suggests that either (1) high concentrations of these VOCs reached the groundwater at some time in the past in the unconfined, upgradient area of the flow paths and have moved downgradient or (2) VOCs are introduced all along the flow paths, even in the confined part of the aquifer. Methyl *tert*-butyl ether (MTBE) is an oxygenate added to gasoline to improve combustion and motor vehicle emissions. Its use in California was banned in 1999 because of groundwater contamination. The absence of MTBE in the unconfined part of the flow paths and its presence in the confined part suggest downward groundwater flow and that the confining units present in the distal part of the Bunker Hill subbasin do not prevent VOCs from reaching the aquifer (Dawson and others, 2003, p. 71).

The median depth to the top of the well-screen interval for the 29 production wells sampled by NAWQA in the Inland Basin was 240 ft below land surface. Samples from wells in which the top of the well-screen interval ranged in depth from 26 to 240 ft below land surface had a higher median concentration for dissolved solids and tritium and had more pesticide and VOC detections than did samples from wells in which the top of the well-screen interval ranged in depth from 250 to 650 ft below land surface (table 1 and fig. 13). Most of the wells in this sample set tap unconfined aquifers and therefore may be susceptible to receiving compounds generated by overlying land-use activities (Hamlin and others, 2002, p. 25). Wells with deeper screened intervals likely encounter more layers of fine-grained material that can impede the downward movement of water recharged at the land surface.

Since 1980, when extensive groundwater contamination by VOCs was discovered in the Bunker Hill subbasin, many new wells have been installed with perforations only below a depth of 200 to 300 ft below land surface. This change in construction, largely to avoid water-quality problems near the land surface, has further altered the vertical movement of groundwater in the subbasin. About the same amount of water is now pumped from the shallower and deeper parts of the aquifer in the Bunker Hill subbasin (Danskin and others, 2006, p. 49). The hydraulic head in the deeper part of the aquifer will decline with additional withdrawals. This may induce some groundwater flow to the deeper pumped zones from underlying older, more consolidated basin-fill deposits, through faults and fractures, and possibly from the surrounding and underlying bedrock.

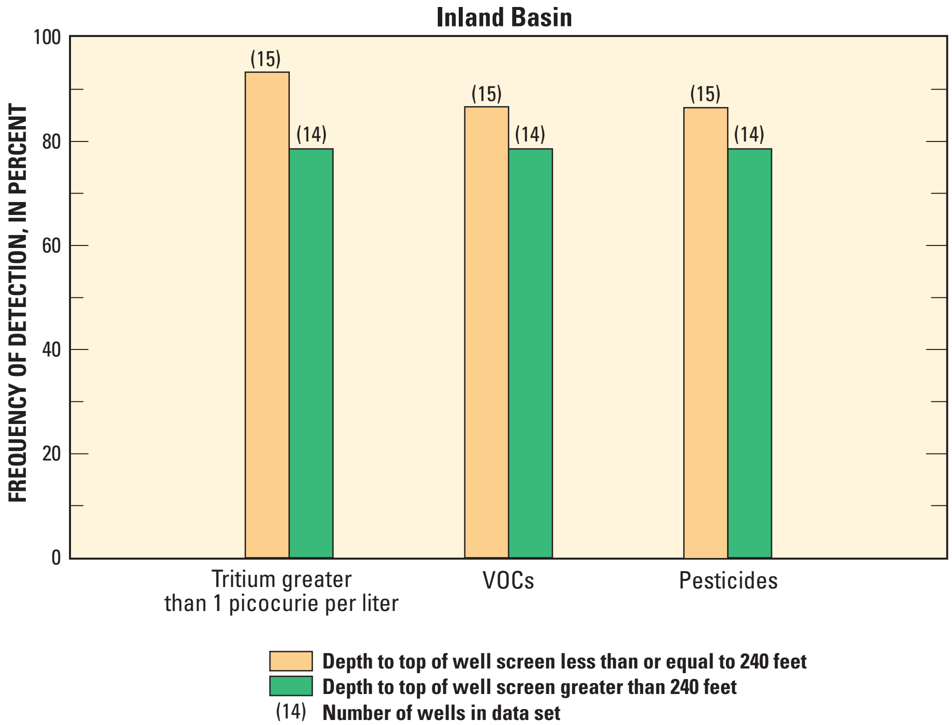


Figure 13. Detection frequencies of tritium, volatile organic compounds, and pesticides in water samples from wells in the Inland Basin, California.

Coastal Basin of the Santa Ana Basin

Artificial recharge to the groundwater system and pumping from wells has accelerated the movement of water through the Coastal Basin basin-fill aquifer. To a large extent, native water in the aquifer has been replaced by water recharged since the early 1950s (Belitz and others, 2004, p. 8). Groundwater quality in the basin is affected by the enhanced recharge of water from the Santa Ana River, including the infiltration of treated wastewater that now is a large component of base flow in the river, and the infiltration of imported water.

The approximately 800-mi^2 Los Angeles physiographic basin is subdivided into two groundwater basins on the basis of sources of recharge water—the Coastal Los Angeles Basin in the north and the Coastal Santa Ana Basin in the south. The hydrogeologic settings of the two groundwater basin are similar, in that each contains flow paths originating at focused engineered recharge facilities where major streams enter the basin and the water then moves radially outward toward dispersed areas of pumping in the confined part of the basin. The Coastal Santa Ana Basin is described in this section and is referred to as the Coastal Basin (fig. 14).

Analysis of modeled precipitation data for 1971–2000 (PRISM Group, Oregon State University, 2004) resulted in an average annual precipitation value of about 13.2 in. over the 340 mi^2 Coastal Basin (McKinney and Anning, 2009, table 1). Analysis of LandScan population data for 2005 (Oak Ridge National Laboratory, 2005) indicated a population of almost 2.6 million in the Coastal Basin and a population density of about 7,000 people/mi^2 (McKinney and Anning, 2009, table 1). Groundwater from the Coastal Basin supplies about 70 percent of the total water demand. The remaining 30 percent is obtained from water imported through the Colorado River Aqueduct and from northern California (Orange County Water District, 2008). Overall, the Coastal Basin has the highest percentage of urbanized land (94 percent) in 2001 (U.S. Geological Survey, 2003b) of the three NAWQA studied groundwater basins in the Santa Ana Basin. Groundwater use also is highest in the Coastal Basin, and in contrast to the Inland and San Jacinto Basins, most of the aquifer is confined and insulated from the effects of overlying land uses.

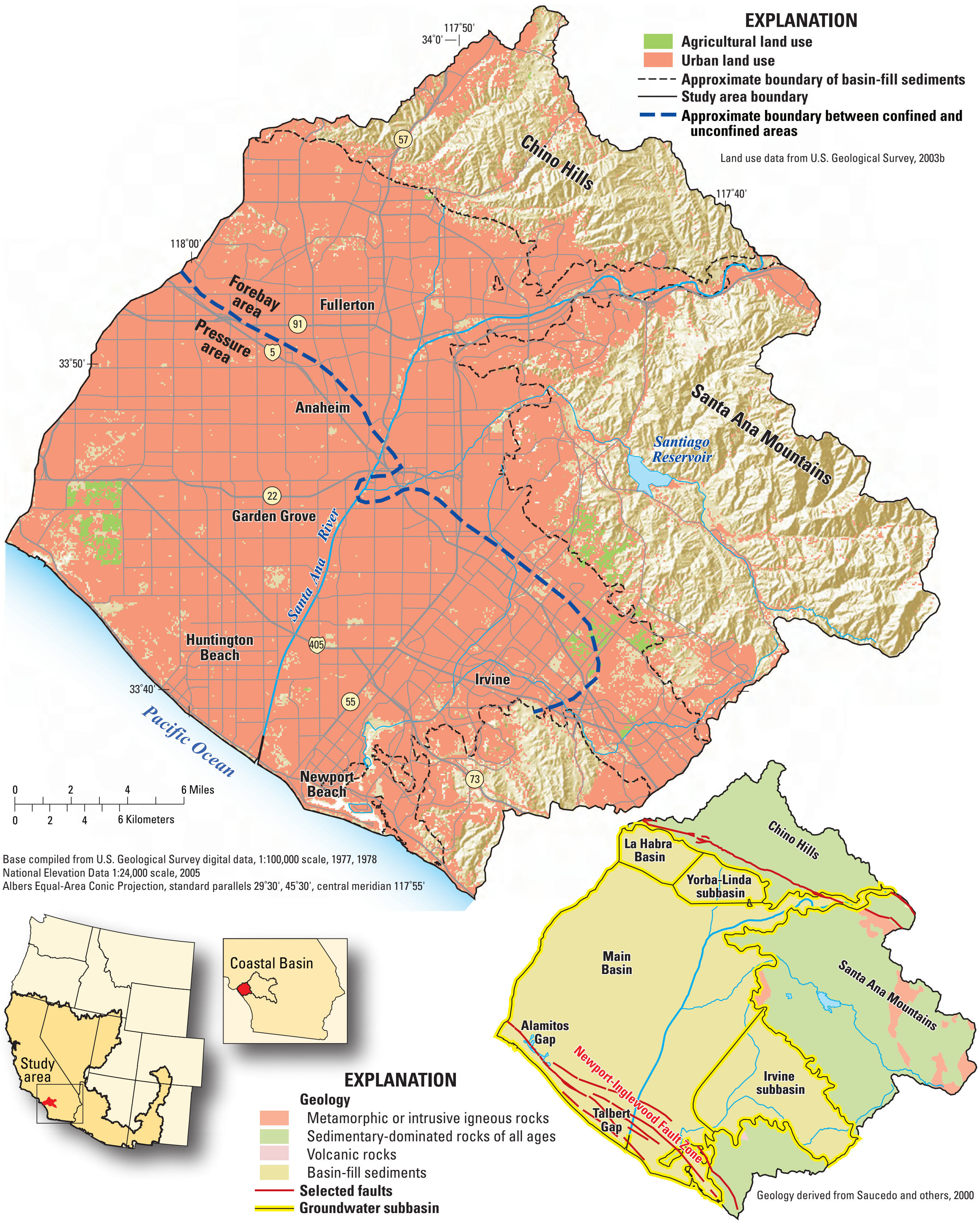


Figure 14. Physiography, land use, and generalized geology of the Coastal Santa Ana Basin, California.

Conceptual Understanding of the Groundwater System in the Coastal Basin

The Coastal Basin groundwater system is analogous to a bowl filled with sediment and water, the central part of which contains freshwater-bearing deposits up to 4,000 ft thick (California Department of Water Resources, 1967). Deposits along the margins of the basin, in the Irvine and Yorba Linda subbasins and the La Habra Basin, are less thick and less permeable than in the main part (Main Basin). The Coastal Basin has been divided into a forebay area and a pressure area on the basis of the relative abundance of shallow clay layers in the subsurface. The forebay area is small (38 percent of the basin) compared to the pressure area (62 percent) and occupies about 130 mi^2 along the west side of the Santa Ana Mountains, generally north and east of the Interstate-5 freeway (fig. 14). The unconsolidated sediments in the forebay area deepen to about 1,000 ft thick away from the basin margins and consist mainly of interbedded sands and gravels with occasional lenses of silt and clay derived from the mountains to the east and southeast and from marine deposits. Hydraulic conductivity values used in a groundwater flow model of part of the forebay area ranged from 150–300 ft/d (Tompson and others, 1999, p. 2985) and a value of about 600 ft/d was estimated for coarse-grained deposits from tracer studies (Davisson and others, 2004, p. 93). The fine-grained sediments in the forebay area are laterally discontinuous and generally do not restrict the vertical movement of groundwater, resulting in unconfined to semiconfined conditions and a downward hydraulic gradient. A hydraulic conductivity value of 1 ft/d was used to simulate fine-grained material in the forebay area (Tompson and others, 1999, table 4). Groundwater recharge in the Coastal Basin primarily occurs in the forebay area.

The pressure area extends from the western edge of the forebay area to the Pacific Ocean. The pressure area contains relatively continuous, thick layers of silt and clay that confine underlying sands and gravels and typically impede the vertical movement of groundwater. The Newport-Inglewood Fault Zone parallels the coastline and generally forms a barrier to groundwater flow. This impedance to flow causes hydrostatic pressure within the aquifer and upward vertical gradients in the western part of the basin. Seawater intrusion can occur where the less permeable uplifted rocks are breached by gaps that are filled with alluvium coupled with lower water levels upgradient of the barrier, such as at the Alamitos and Talbert Gaps (California Department of Water Resources, 2003e).

A simplified conceptual model for the groundwater system in the Coastal Basin consists of an upper (shallow) aquifer system, a middle (principal) aquifer system, and a lower (deep) aquifer system (California Department of Water Resources, 2003e; Orange County Water District, 2004, fig. 2-2) (fig. 15). Water recharged in the generally unconfined forebay area moves to each of these aquifer systems, although vertical flow is impeded by discontinuous layers of silt and clay and horizontal flow is affected by faults and bedrock structure in the subsurface. The shallow aquifer system, generally the uppermost 200 ft of basin-fill deposits, provides about 5 percent of the total groundwater production in the basin, mainly for irrigation use (Orange County Water District, 2004, p. 2-2).

Most of the groundwater withdrawals in the Coastal Basin are from wells completed in the principal aquifer system, with the main production zones generally between 300 and 1,500 ft below land surface. The main production zones in the confined part of the principal aquifer system can be overlain by 300 to 500 ft of sediment containing large amounts of silt and clay, which typically impede vertical groundwater flow (Herndon and others, 1997). As of 2004, few wells have been drilled and completed in the deep aquifer system (Orange County Water District, 2004, p. 2-2) due to depth and aesthetic issues with the water, such as color and odor. The deep aquifer system is tapped by wells in the southwest part of the basin at depths of about 600–1,200 ft below land surface. These wells reduce the upward pressure and migration of colored water into the principal aquifer system in the area (Mesa Consolidated Water District, 2005).

Water Budget

Recharge to the Coastal Basin groundwater system under predevelopment conditions was primarily from the infiltration of water through the channels of the Santa Ana River and smaller streams flowing into the forebay area. Groundwater recharge under predevelopment conditions is estimated to be about 163,000 acre-ft/yr (table 5). Gross estimates of recharge prior to water development in the Coastal Basin from the infiltration of Santa Ana River water, precipitation on the basin, and inflow along the mountain fronts are derived from estimates for modern conditions. Little information is available on groundwater conditions prior to development in the basin and these estimates of recharge to and discharge from the aquifer are intended only to provide a basis for comparison of change with development.

Under modern-day conditions, flow in the Santa Ana River to the Coastal Basin consists predominantly of perennial base flow that is mostly treated wastewater (Mendez and Belitz, 2002) and intermittent stormflow that includes runoff from urban and agricultural land. According to the Orange County Water District (2004, p. 5-5), the Santa Ana River loses about 100 ft^3/sec of flow (72,400 acre-ft/yr) to the groundwater system along a 6-mile segment near where it enters the groundwater basin. Downstream from this reach, a low permeability clay layer in the subsurface impedes infiltration of water from the river to the aquifer (Orange County Water District, 2004, p. 5-3).

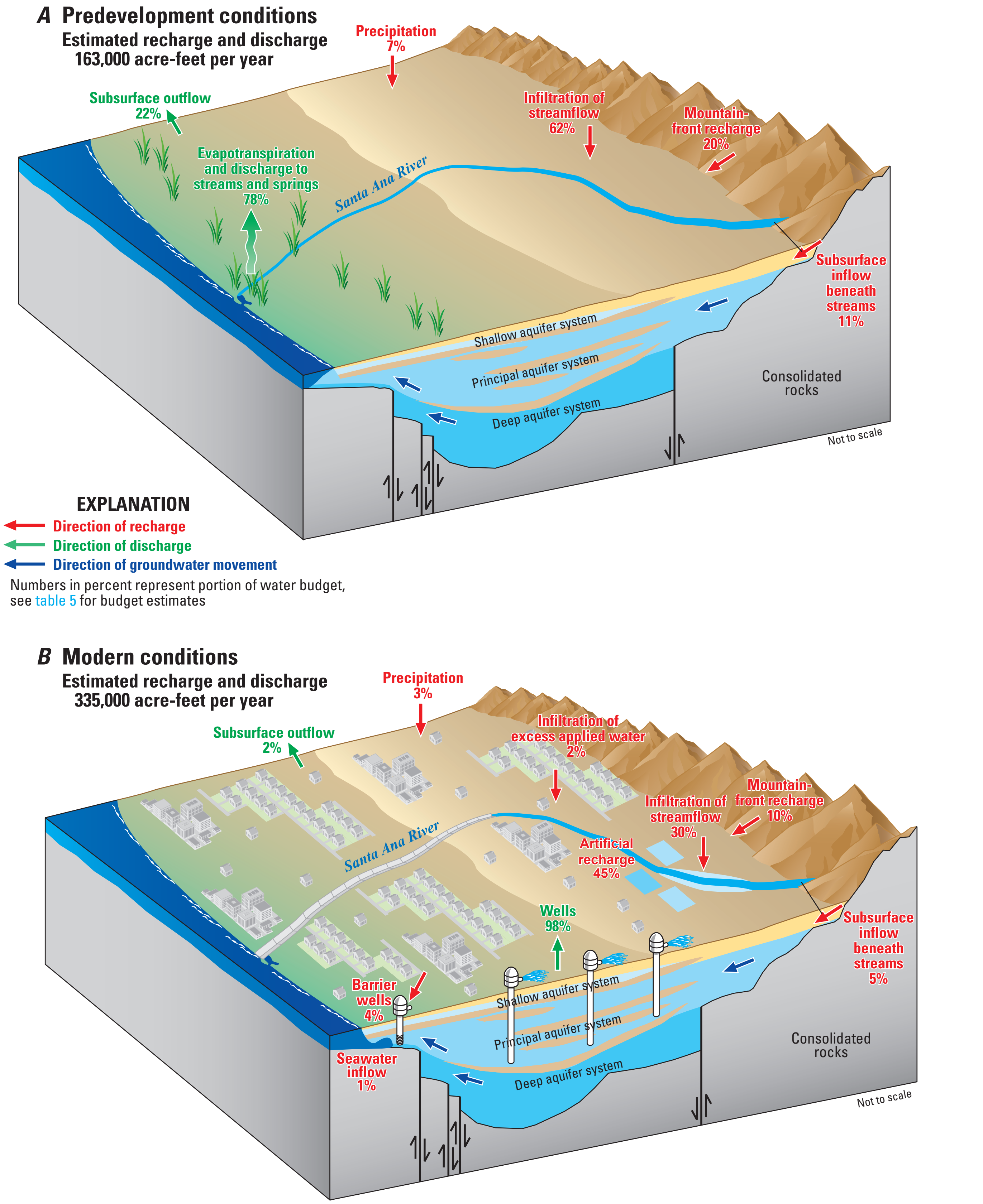


Figure 15. Generalized diagrams for the Coastal Basin, California, showing the basin-fill deposits and components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

Table 5. Estimated groundwater budget for the basin-fill aquifer system in the Coastal Basin, California, under predevelopment and modern conditions.

[All values are in acre-feet per year. Estimates of groundwater recharge and discharge under modern conditions are from the Orange County Water District (2004, table 2-1). Estimates for predevelopment conditions are derived from those for modern conditions or were estimated as described in the footnotes and text. The budgets are intended only to provide a basis of comparison for 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**	
Mountain-front recharge	33,000	33,000	0
Infiltration of precipitation on basin	12,000	12,000	0
Infiltration of streamflow	[1] 100,000	100,000	0
Subsurface inflow beneath major streams	18,000	18,000	0
Infiltration of excess applied water	0	5,500	5,500
Artificial recharge in forebay area	0	150,000	150,000
Seawater inflow through coastal gaps	0	2,000	2,000
Seawater intrusion barrier wells	0	14,500	14,500
Total recharge	**163,000**	**335,000**	**172,000**
Budget component		**Estimated discharge**	
Evapotranspiration and discharge to streams and springs	[2] 127,000	0	-127,000
Subsurface outflow across county line	36,000	8,000	-28,000
Well withdrawals	0	327,000	327,000
Total discharge	**163,000**	**335,000**	**172,000**
Change in storage (total recharge minus total discharge)	0	0	0

[1] Estimated natural base flow and stormflow in the Santa Ana River.

[2] Calculated to be the difference between predevelopment recharge and discharge from subsurface outflow out of the Coastal Basin at the Los Angeles/Orange County line.

Estimated base flow in the Santa Ana River below Prado Dam has increased from about 40,000 acre-ft in 1970 to about 155,000 acre-ft in 2001, owing primarily to increases in treated wastewater discharge in upstream basins (Orange County Water District, 2004, fig. 5-3). Summer base flow (monthly flow in July, August, and September) from 1878 to 1928 in the Santa Ana River below the location of Prado Dam averaged about 10,000 acre-ft (Post, 1928, p. 356). Assuming that this summer flow is not affected by storm runoff and is consistent throughout the year, base flow prior to major urban development in the upper part of the watershed is estimated at about 40,000 acre-ft/yr. This amount of base flow in the Santa Ana River is assumed to approximate predevelopment conditions and to have recharged the aquifer in the Coastal Basin.

Annual recharge to the aquifer from captured Santa Ana River stormflow is estimated to average about 60,000 acre-ft (Orange County Water District, 2004, p. 2-7). Although the amount of stormflow in the river entering the Coastal Basin prior to the construction of Prado Dam may have been greater, average recharge from the Santa Ana River under predevelopment conditions is assumed to be the sum of the estimates for base flow (40,000 acre-ft/yr) and stormflow (60,000 acre-ft/yr), about 100,000 acre-ft/yr (table 5). Climatic conditions greatly influence annual recharge to the Coastal Basin, and wet periods result in more recharge to the groundwater system due to expansion of the river in its floodplain and more runoff from precipitation on and flowing to the forebay area.

Stable-isotope data for older groundwater sampled from the pressure area of the Coastal Basin indicate that in the predevelopment state, recharge from near-coastal precipitation was minor compared to recharge from the Santa Ana River (Williams, 1997, p. 241). Areal recharge from precipitation on the basin floor is estimated to average about 12,000 acre-ft/yr. Infiltration of direct precipitation to the aquifer system was estimated to be about 10 percent of annual average precipitation (0.11 ft/yr) on the forebay area (about 9,000 acre-ft/yr) and 2 percent on the pressure area (about 3,000 acre-ft/yr), based on the occurrence of fine-grained sediment layers near land surface. Tompson and others (1999, p. 2985) estimated areal recharge from precipitation in the forebay area at 0.1 ft/yr. Recharge from infiltration of excess applied irrigation water in the basin is estimated at about 5,500 acre-ft/yr, the difference between recharge from rainfall and irrigation estimated by the Orange County Water District (2004, table 2-1) and the estimate for recharge from precipitation on the basin.

The Santa Ana River and Santiago Creek are estimated to lose about 8,000 and 10,000 acre-ft/yr, respectively, as subsurface inflow to the basin and as infiltration through their channels near the mountain front (Orange County Water District, 2004, table 2-1). Recharge from ephemeral streams and runoff from consolidated rocks in the hills and mountains bounding the Coastal Basin (mountain-front recharge) is estimated to be about 33,000 acre-ft/yr (Orange County Water District, 2004, table 2-1). These estimates of natural recharge are assumed to represent both predevelopment and modern conditions (table 5).

In a water budget constructed by the Orange County Water District (2004, table 2-1), estimated recharge and discharge to the modern Coastal Basin aquifer system is about 335,000 acre-ft/yr. The groundwater basin is managed to maintain an overall balance over many years that incorporates periods of above- and below-average precipitation. The balanced budget is based on the following assumptions: (1) average precipitation, (2) recharge at the Santa Ana River and at recharge facilities in the forebay area (both natural and engineered) is held to the current maximum capacity of 250,000 acre-ft/yr, and (3) withdrawals from wells are adjusted so that total groundwater inflows and outflows are equal (Orange County Water District, 2004, p. 2-6).

Currently, water managers utilize almost all of the base flow and much of the stormflow in the Santa Ana River that enters the Coastal Basin to recharge the aquifer system. About 100,000 acre-ft/yr of water is estimated to infiltrate from the Santa Ana River to the aquifer naturally (the same amount of recharge from the river as estimated for predevelopment conditions). Additional streamflow, mostly from increased base flow and stormflow, is introduced artificially at engineered recharge facilities in and along the Santa Ana River channel and at a smaller facility on Santiago Creek. Imported Colorado River and northern California water also have been artificially recharged in the forebay (Herndon and others, 1997). Artificial recharge in the forebay area is estimated at about 150,000 acre-ft/yr (table 5), or about 45 percent of the total recharge to the basin.

Under modern-day water-level conditions, seawater has intruded into the aquifer. The Orange County Water District (2004, table 2-1) estimates about 2,000 acre-ft/yr of seawater flows into the basin-fill aquifer through coastal gaps. To limit this seawater intrusion, about 14,500 acre-ft/yr of freshwater is injected into the aquifer in the Talbert and Alamitos Gaps (Orange County Water District, 2004, table 2-1).

The Orange County Water District and the Orange County Sanitation District have developed an additional source of water that began recharging the aquifer in the Coastal Basin in 2008. About 42,000 acre-ft/yr of treated wastewater is processed using microfiltration, reverse osmosis, and advanced oxidation processes for infiltration at a recharge facility near the Santa Ana River (Orange County Water District, 2004, 5-14). Another 30,000 acre-ft/yr of treated wastewater is injected into seawater intrusion barrier wells at the Talbert Gap to prevent further movement of seawater into the aquifer. These sources of recharge are not included in the groundwater budget listed in table 5.

Under natural, predevelopment conditions, the Coastal Basin was full to overflowing, with discharge occurring primarily by evapotranspiration and springs, including submarine springs (Poland and Piper, 1956, p. 50). Natural discharge varied in response to changes in precipitation on the Santa Ana River watershed and the resulting recharge to the groundwater basin. Subsurface flow out of the basin across the Orange/Los Angeles County line as a result of higher water levels under predevelopment conditions was simulated at about 36,000 acre-ft/yr (Orange County Water District, 2004, fig. 2-4).

Increased withdrawals from large-capacity wells pumped for irrigation, coupled with generally below-normal precipitation from 1917–36, cumulatively caused water levels in wells to drop to near or below sea level in much of the Coastal Basin by 1936 (Poland, 1959, p. 11). Seawater intruded into the aquifer along the western margin of the basin due to the decline in groundwater levels, and injection wells were installed in the bedrock gaps to create a hydraulic barrier between the seawater and the basin-fill aquifer containing freshwater. Generally above-normal precipitation from 1937–44 resulted in water level rises and the return of flowing-well conditions to some areas near the coast.

Beginning in about 1940, the urban population began to steadily increase along with water use for municipal and industrial purposes. Agricultural water uses in Orange County decreased from 100,000 acre-ft in 1954 to 10,000 acre-ft in 2004, while the population increased from 300,000 to 2,300,000 (Orange County Water District, 2004, p. 4-1). Withdrawals from wells increased steadily from about 150,000 acre-ft in 1954 to about 350,000 acre-ft in 2002 (Orange County Water District, 2004, fig. 1-3). There are about 500 active production wells in the Coastal Basin with approximately 200 large-capacity public-supply wells accounting for 97 percent of the total production in 2001–02 (Orange County Water District, 2004, p. 2-8). Discharge from the groundwater system under modern conditions is almost completely through pumping from wells (327,000 acre-ft/yr) in the balanced water budget (Orange County Water District, 2004, table 2-1) (table 5). The remaining 8,000 acre-ft/yr flows out of the basin in the subsurface across the Orange/Los Angeles County line (Orange County Water District, 2004, table 2-1).

Groundwater Flow

On a regional scale, groundwater in the Coastal Basin moves from areas of unconfined conditions in the forebay area westward to areas of confined conditions in the pressure area. This pattern of groundwater flow in the Coastal Basin can be conceptualized as a slice of pie, starting from a small area at the Santa Ana River and its recharge facilities and expanding outward toward the coast (Shelton and others, 2001, p. 13). Under predevelopment conditions, recharge entered the relatively thin, coarse-grained basin-fill deposits along the mountain-front stream channels, moved laterally and vertically into thicker deposits in the middle of the basin, and eventually was forced towards the land surface by the sedimentary rock offset along the Newport-Inglewood Fault Zone near the ocean (fig. 15). Layers of fine-grained sediment serve to confine the aquifer system in the pressure area resulting in artesian conditions where groundwater levels once were at or above the land surface in wells, springs, and seepage areas.

The artesian area for the Coastal Basin groundwater system under predevelopment conditions (prior to about 1870) was estimated by Mendenhall (1905a, plate 1) to cover about 154 mi^2, almost 75 percent of the pressure area, and extended more than 10 mi inland from the coastline in the central part of the basin (fig. 16). By August 1904, the artesian area in the Coastal Basin had decreased to about 111 mi^2, corresponding to a reduction in artesian pressure in the aquifer caused by the installation of many flowing wells.

The groundwater surface for the principal aquifer in the Coastal Basin for 2005 constructed by the Orange County Water District (2006, plate 1) indicates that recharge occurring near and along the Santa Ana River and Santiago Creek moves southwestward towards the coast (fig. 16). Water levels were below land surface throughout the basin and below sea level in approximately the western third of the basin. This is in contrast to the extent of the artesian area described in 1904 by Mendenhall (1905a, plate 1). Water-surface gradients are relatively steep along the northeast and southeast margins of the basin where little recharge occurs.

Artificial recharge and withdrawals from wells have resulted in very large vertical and lateral rates of groundwater flow through the basin-fill deposits in parts of the forebay and pressure areas. Water-quality data show that water that entered the ground at the recharge facilities extends over 11 mi into the aquifer along a studied flow path (Dawson and others, 2003, p. 37). Apparent ages of water sampled from 300–500 ft below land surface along a flow path originating at recharge basins near the Santa Ana River were determined using the tritium-helium-3 (^3H-^3He) dating method. The age distribution indicates that groundwater less than 5 years old had traveled more than one mile from the recharge basins, implying a mean linear groundwater velocity of around 2,000 ft/yr (Davisson and others, 2004, p. 89). Groundwater ages progressively increased to more than 20 years at a distance of approximately 5-6 mi west of the recharge basins (Davisson and others, 2004, fig. 28b). The decrease in linear velocity of groundwater flow with distance from the recharge basins is due to the increasing aquifer width and thickness away from the recharge basins (Clark and others, 2004, p. 170). Vertically, groundwater is less than one year old more than 500 ft below the recharge basins on the basis of ^3H-^3He age determinations (Davisson and others, 2004, p. 89). The water can move quickly into and laterally through the aquifer because a thin unsaturated zone underlies the recharge basins. Layers of lower permeability sediment, however, slow the vertical movement of water at depths of about 1,000 ft near the recharge basins.

Shallow groundwater ages beneath the Santa Ana River channel near the artificial recharge facilities varied from 1 to 10 years old (Davisson and others, 2004, fig. 29b). The large volume of annual recharge infiltrating through the channel is likely “held up” at shallow depths (less than 100 ft below land surface) by discontinuous layers of less transmissive sediments. A subsurface fault may impede the westward movement of groundwater at depth and force older groundwater upward, which also would restrict the downward movement of recharged river water. Extensive lateral flow parallel to the river, dominated by flow paths near the water table, likely moves most of the recharged river water away from the channel and into the aquifer system (Davisson and others, 2004, p. 91).

Effects of Natural and Human Factors on Groundwater Quality

Groundwater in the Coastal Basin’s forebay area has primarily been recharged since the early 1950s, and its chemical characteristics are influenced by the recharge sources. In the pressure area nearer to the forebay area, those characteristics reflect historical variations in recharge water quality and mixing with older groundwater. The quality of groundwater at the lower end of the flow system near the coast typically represents predevelopment conditions (native groundwater) but, in some areas, may be affected by seawater intrusion.

Extensive analyses of water sampled from active production and monitoring wells have been made to determine groundwater quality in the Coastal Basin. The Orange County Water District (2004, p. 3-10) collects water samples from about 200 potable-supply wells and about 225 non-potable production wells annually to meet regulatory requirements, to gain a better understanding of the aquifer system, and for special studies. Several NAWQA studies were done from 1999–2001 to assess general water-quality conditions in the Coastal Basin aquifer system and to characterize variation in groundwater quality as it moves from recharge facilities in the forebay area toward natural discharge areas near the coast (Hamlin and others, 2002, p. 14) (fig. 17, table 1).

Figure 16. Groundwater levels and generalized flow directions in the Coastal Basin, California, in 2005, and artesian areas in 1904 and under predevelopment conditions.

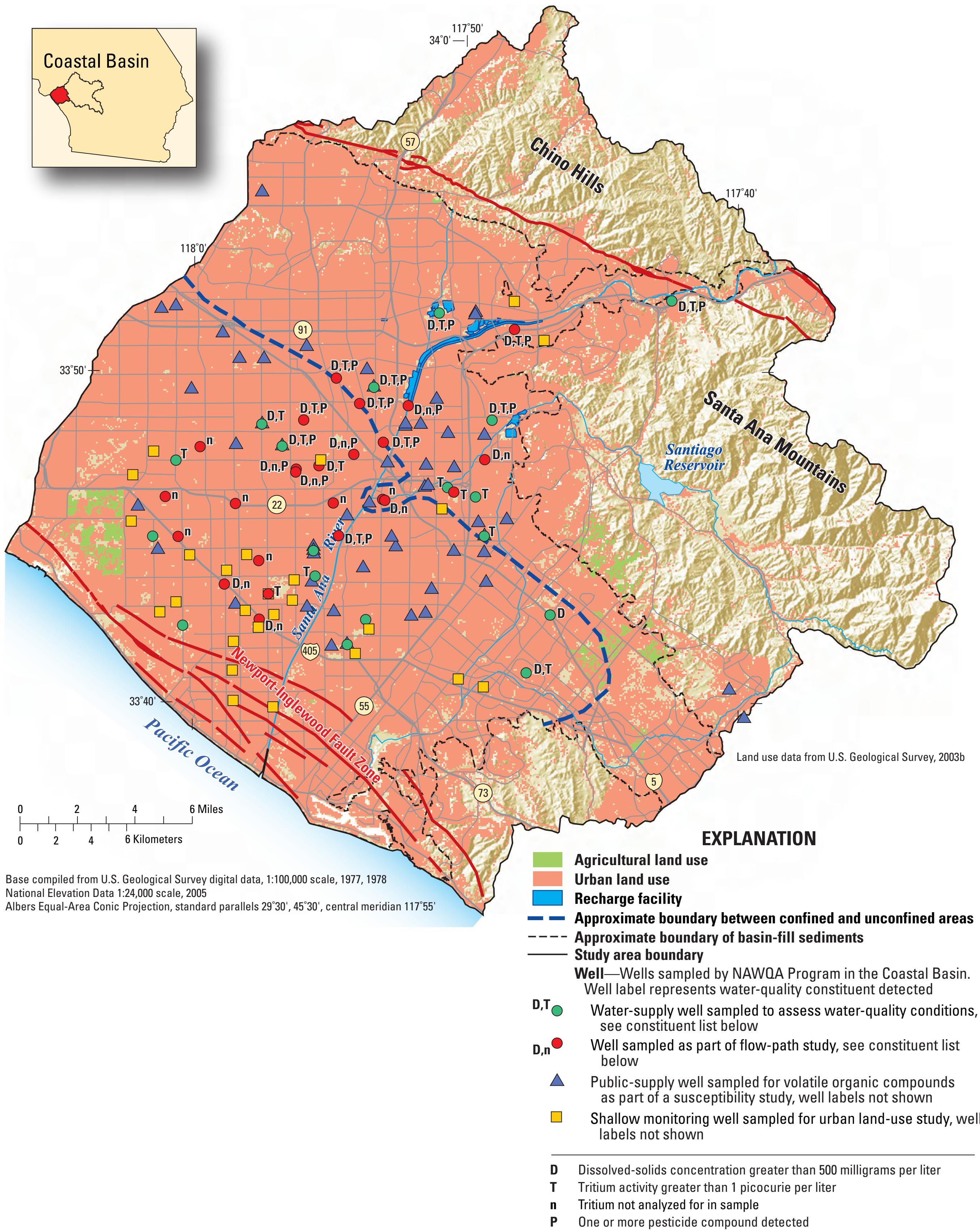


Figure 17. Locations of and chemical characteristics of water in wells in the Coastal Basin, California, sampled by the NAWQA Program, 1999–2001.

A set of 56 public-supply wells was sampled for analysis of VOCs in the water in collaboration with the California State Water Resources Control Board as part of its California Aquifer Susceptibility Program (Shelton and others, 2001; Hamlin and others, 2002). Groundwater samples collected from production wells in the Coastal Basin as part of NAWQA studies were grouped on the basis of well location in the unconfined forebay area or in the confined pressure area (table 1).

General Water-Quality Characteristics and Natural Factors

Groundwater used for public supply within the Coastal Basin is primarily a sodium-calcium bicarbonate type (California Department of Water Resources, 1967). The concentration of dissolved solids in groundwater varies with depth and location and its general spatial distribution in the used part of the aquifer is shown in figure 2. Although the basin is highly urbanized, wells in the pressure area are screened in confined aquifers that are protected to a degree from the effects of overlying land uses by layers of clay and silt. Deeper groundwater in much of the western part of the pressure area has concentrations of dissolved solids less than 400 mg/L that are associated with recharge that occurred prior to development in the basin (Orange County Water District, 2004, fig. 6-4) and are indicative of recharge from mountain-front and storm runoff in the forebay area. The highest concentrations of dissolved solids in groundwater are found in the Irvine area and along the coast in association with seawater intrusion. The concentration of dissolved solids in groundwater recharged along the mountain front in the Irvine area exceeds 1,000 mg/L, due to leaching of salts from marine sediments in the Santa Ana Mountains (Singer, 1973). High concentrations of dissolved solids in the Irvine area also reflect the effects of past and current agricultural practices.

The deep aquifer system in the western part of the basin sometimes produces water colored with an amber tint imparted by natural organic material buried with the coastal plain deposits, an unpleasant odor due to the presence of hydrogen sulfide, and a slightly warmer than average temperature. On the basis of its position along regional flow paths, this water was recharged prior to development in the basin and contains relatively low concentrations of dissolved solids (a median value of 240 mg/L is listed for water from 7 wells by the Orange County Water District (2004, table 6-5)). Some water from the deep aquifer system is now treated to remove color and odor and is distributed for public supply (Mesa Consolidated Water District, 2005).

Water from 41 deeper wells in the Coastal Basin sampled by NAWQA (well classes G and H in table 1) had dissolved-solids concentrations that ranged from 215 to 868 mg/L (water from one of the wells in class H was not analyzed for dissolved solids). The range in dissolved-solids concentrations in water from 26 shallow monitoring wells sampled by NAWQA is large (432- 25,500 mg/L with a median value of 2,390 mg/L) and is affected by activities at the land surface, by seawater intrusion, and by the upward movement of water from deeper aquifers in the pressure area (Hamlin and others, 2002, p. 21). The monitoring wells, which were constructed to sample the upper 10 to 15 ft of the aquifer system, ranged in depth from 18.5 to 143.5 ft with a median depth of 24 ft (well class I in table 1).

Two naturally occurring elements, arsenic and uranium, can affect the suitability of water for drinking. Concentrations of dissolved arsenic in water sampled by NAWQA from 20 water-supply wells to assess water-quality conditions in the basin ranged from less than 1.0 to 5.7 µg/L with a median value of 1.4 µg/L. However, 5 of the 25 shallow monitoring wells (well class I) sampled for arsenic had concentrations greater than 10 µg/L (11.2 to 37.4 µg/L) (Hamlin and others, 2002, appendix 6). Concentrations of dissolved uranium in the 20 water-supply wells ranged from less than 1.0 to 16.1 µg/L with a median value of 4.4 µg/L (Hamlin and others, 2002, appendix 8). Water from 48 percent of the shallow monitoring wells sampled for uranium had concentrations greater than 30 µg/L (43.2 to 312 µg/L). These wells are in a historically marshy area in which geochemical conditions and evaporation may tend to concentrate some trace elements (Hamlin and others, 2002, p. 34).

Potential Effects of Human Factors

Groundwater near the recharge basins and the Santa Ana River reflects the quality of recently recharged water. Concentrations of dissolved solids have increased in water from public-supply wells in much of the basin as a result of recharge water with relatively high concentrations of dissolved solids from the Santa Ana River and imported from the Colorado River. Streamflow in the Santa Ana River is affected by increased urban development in its watershed and by greater discharges of treated wastewater resulting from increases in population. The Orange County Water District began large-scale recharge to the Coastal Basin using water imported from the Colorado River in the early 1950s, and that water was the dominant source of recharge from about 1957 to 1971 (Wildermuth Environmental, Inc., 2000, p. 6-4). The imported water historically had higher concentrations of dissolved solids (about 700 mg/L) than the native groundwater, and as a consequence, concentrations of dissolved solids in groundwater began to increase (Herndon and others, 1997). Subsequently, alternative water supplies with lower concentrations of dissolved solids were developed to minimize the use of Colorado River water for aquifer recharge. During 1995–96, the Orange County Water District recharged water imported from northern California with an average dissolved-solids concentration of 321 mg/L (Herndon and others, 1997). Although imported water from northern

California has a lower concentration of dissolved solids than Colorado River water, it contains higher concentrations of organic carbon that may produce trihalomethanes (includes the compound chloroform) when the water is disinfected by chlorination. Local increases in concentrations of dissolved solids may also be related to the downward migration of shallow groundwater that has been affected by past agricultural and industrial activity (Orange County Water District, 2004, p. 6-6).

Sources of nitrate in water from public-supply wells in the Coastal Basin include recharge from the Santa Ana River (nitrate (as nitrogen) concentrations range from about 2 to 8 mg/L) and infiltration of water affected by past and present-day human activities (Herndon and others, 1997). Past agricultural land uses, such as pastures, livestock holding, cropland, vineyards, and orchards, are a major cause of elevated concentrations of nitrate detected in Coastal Basin groundwater (Orange County Water District, 2004, p. 6-1). Concentrations of nitrate (as nitrogen) typically range from 1 to 4 mg/L in the confined pressure area and from 4 to 7 mg/L in the unconfined forebay area (Orange County Water District, 2004, p. 6-4). The deeper production wells sampled by NAWQA in the confined part of the aquifer had a median concentration of nitrate (as nitrogen) of 1.4 mg/L compared to 4.3 mg/L for water sampled from production wells in the unconfined part (table 1), but none of the concentrations exceeded the drinking-water standard of 10 mg/L. Only one third of the shallow monitoring wells sampled by NAWQA had concentrations of nitrate (as nitrogen) greater than 1.0 mg/L, likely due to reducing conditions in parts of the shallow aquifer system.

Pesticides were detected in 56 percent of the NAWQA-sampled production wells in the Coastal Basin forebay area and in 23 percent of the production wells in the pressure area (table 1 and fig. 18). While all of the pesticide concentrations were very small (Hamlin and others, 2002, appendixes 9A, 9C, 10A, and 10C) and well below applicable drinking-water standards, concentrations and detection frequencies generally were highest in groundwater in the forebay area near the recharge facilities and decreased downgradient along the flow paths. In addition, the number of pesticides detected per well was significantly higher in the forebay area than in the pressure area. The occurrence of trace concentrations of pesticides in water from wells completed in the unconfined forebay area may be related to recharge at the spreading basins that utilize water from the Santa Ana River and to applications of pesticides in the forebay area. The lower detection frequency for wells in the confined pressure area probably results from mixing of younger water with pesticides with older water without pesticides and possibly degradation and adsorption of pesticides along the longer flow paths.

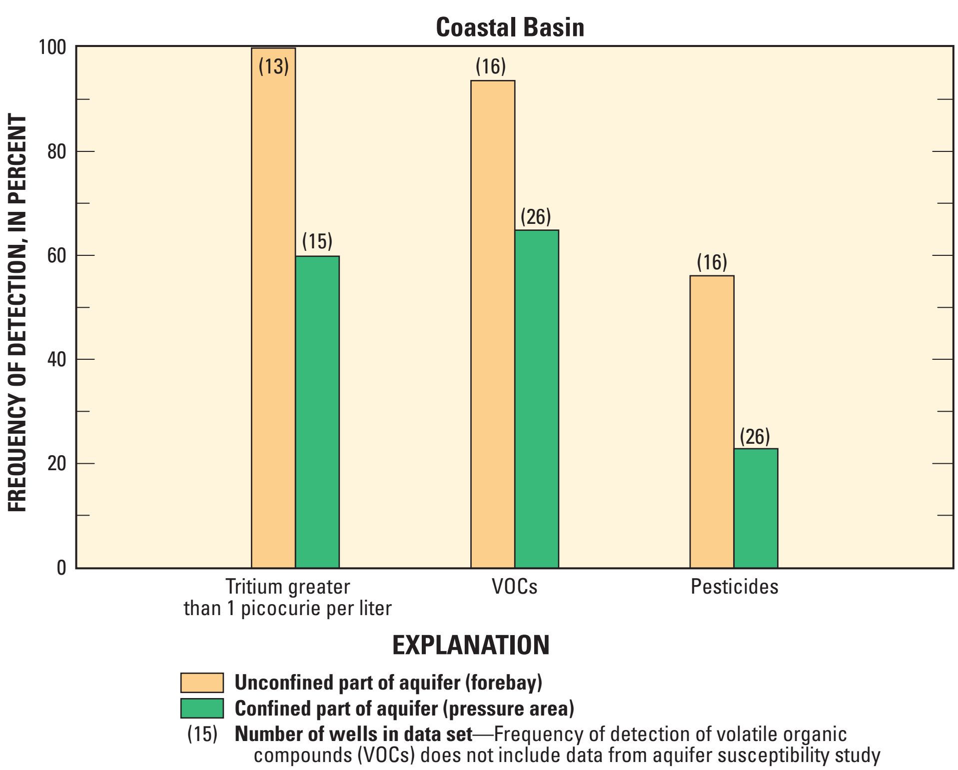


Figure 18. Detection frequencies of tritium, volatile organic compounds, and pesticides in water samples from wells in the Coastal Basin, California.

The most commonly detected pesticides in Coastal Basin groundwater (atrazine, simazine, tebuthiuron, and the degradation product deethylatrazine) were among the most frequently detected pesticides in the Santa Ana River below Prado Dam (Izbicki and others, 2000). Pesticides were detected in 69 percent of the shallow monitoring wells sampled by NAWQA in the basin (table 1) at very small concentrations (Hamlin and others, 2002, appendix 9B). The detection of prometon and tebuthiuron in water from the shallow wells, pesticides commonly used in urban areas, reflects the urban land use in the vicinity of these wells.

Many of the water-supply wells in the Coastal Basin have been sampled by the Orange County Water District for analyses of VOCs (Orange County Water District, 2004, p. 3-13). Areas with concentrations of VOCs near or above the drinking-water standards, mainly the chlorinated solvents trichloroethene (TCE) and perchloroethene (PCE), have been delineated in the shallow part of the aquifer system in the forebay area of the basin (Orange County Water District, 2004, p. 6-15). Work is underway to prevent the further movement of VOC-contaminated groundwater in the area.

Water samples collected by the NAWQA Program from production wells in the unconfined forebay areas had a higher detection frequency of VOCs (80 percent) than wells in the adjacent confined pressure area of the aquifer system (64 percent) (table 1). All of the detections were below drinking-water standards, most at very small concentrations (Hamlin and others, 2002, appendixes 11A, 11C, 11D, 12A, 12C, and 12D). Many of the production wells are downgradient from engineered recharge facilities along the Santa Ana River. VOCs may be introduced in the coarse-grained forebay areas either at the recharge facilities or in other sources of recharge that have encountered point or nonpoint contaminant sources (Shelton and others, 2001; Dawson and others, 2003). However, because of changes in the source and quality of recharge water over time, the chemical characteristics of the groundwater in the flow system is not the same as that of water currently entering the aquifer at the recharge facilities.

The most commonly detected VOCs in samples collected by NAWQA from production wells in the forebay area were chloroform, 1,1,1-trichloroethane (TCA), and the gasoline additive methyl *tert*-butyl ether (MTBE). The most commonly detected VOCs in samples from productions wells in the pressure area were chloroform and the refrigerants CFC-113 and CFC-11. Chloroform and MTBE were the most frequently detected VOCs in shallow monitoring wells in the basin sampled by NAWQA. The source of chloroform is likely chlorinated water and the source of MTBE is probably atmospheric deposition and proximity to leaky underground storage tanks.

The spatial distribution of VOCs detected above the laboratory reporting level (LRL) in groundwater sampled by NAWQA (fig. 19) was quantified in terms of the distance between recharge facilities and the location of the well. This distance is assumed to be the distance traveled along a flow path and is used as a surrogate for the time of travel (Shelton and others, 2001, p. 14). Samples with 2 or more VOC detections in the Coastal Basin are from wells within about 11 mi of the recharge facilities, with one exception, and only one or no VOCs were detected in wells sampled beyond this distance (Shelton and others, 2001, fig. 4).

Statistical analysis indicates a significant difference in the number of VOC detections in groundwater with depth in the forebay area of the Coastal Basin, but not in the pressure area (Shelton and others, 2001, p. 18). This indicates that there could be a vertical component of transport in the forebay area, but that the greater thickness of fine-grained layers likely impedes the downward movement of VOCS in the pressure area.

Stable isotope data presented by Shelton and others (2001, fig. 7) support the interpretation that VOCs detected in groundwater in the forebay area are associated with water introduced at the recharge facilities. Stable isotope composition indicates that groundwater containing VOCs is a mixture of local precipitation, runoff, and water that is isotopically lighter than the local sources. The isotopically lighter water could either be Colorado River water or northern California water, both of which have been imported to the basin and used as a source of groundwater recharge.

Tritium activity in water greater than 1 pCi/L is widespread in the Coastal Basin aquifer system, but is more prevalent in the unconfined part (fig. 18) indicating that groundwater in the forebay area is younger than groundwater in the downgradient pressure area. Data from the NAWQA studies indicate that pesticides were detected in almost 40 percent of the younger water samples, but in none of the older samples. VOCs were detected in more than 90 percent of the samples containing tritium, but in only 50 percent of the samples with tritium activities less than 1 pCi/L (Hamlin and others, 2005, p. 27). Pumping and engineered recharge in the Coastal Basin have caused the lateral rate of flow in the aquifer system to increase and are likely the dominant factors in controlling the distribution of VOCs in active public-supply wells.

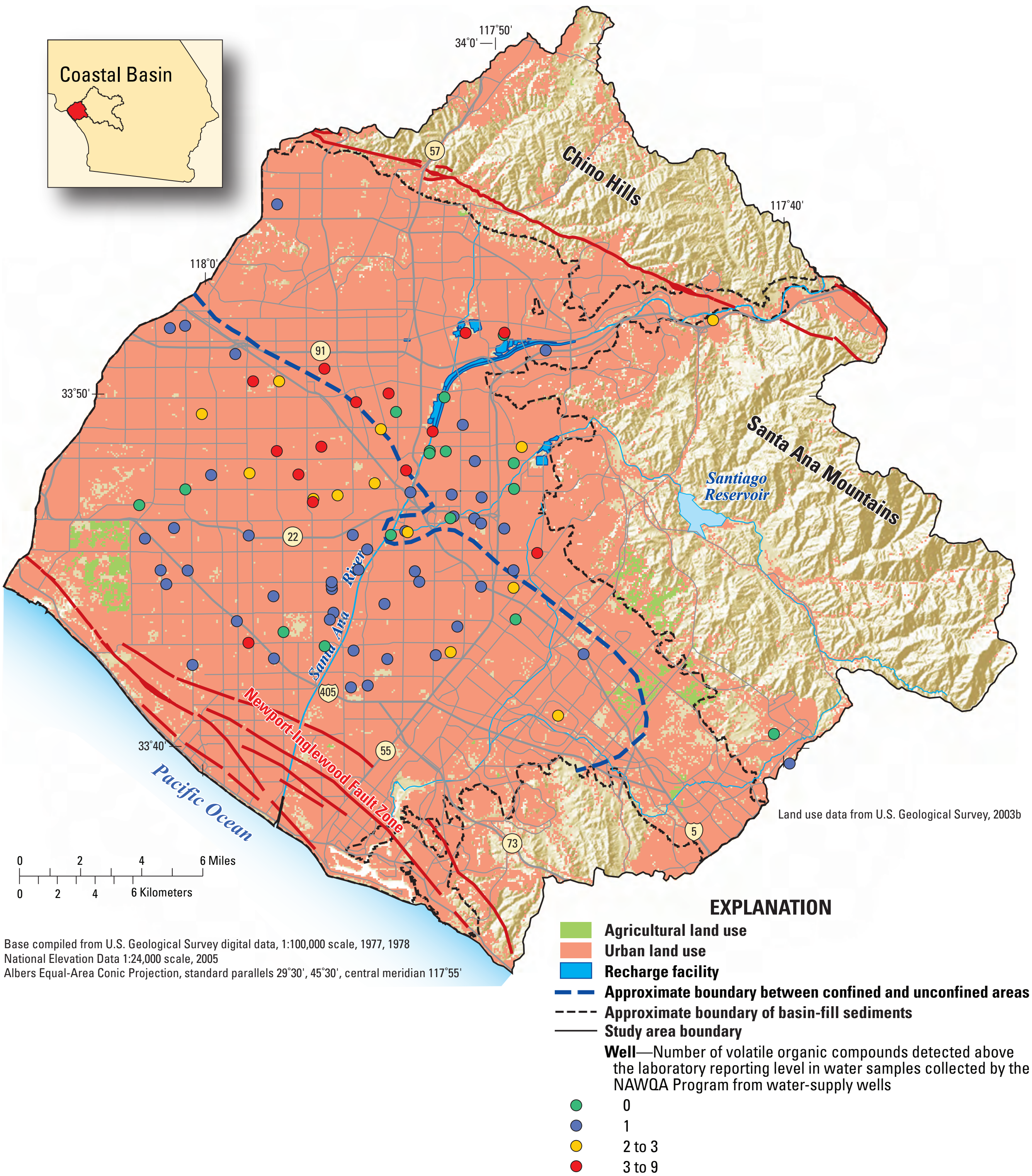


Figure 19. Public-supply wells sampled in the Coastal Basin, California, and the number of volatile organic compounds detected at concentrations above the laboratory reporting level in each well.

Summary

The hydrologic cycles of the groundwater basins in the Santa Ana Basin are greatly affected by human activities as a result of the semiarid climate and the water demands of the large urban population. The drainage basin has one of the fastest growing populations in California and was home to about 5.1 million people in 2000. Groundwater pumped from the basin is the major water supply, providing about two-thirds of the total water used. Imported water from northern California and the Colorado River also are important sources of the water supply. Pumping and additional sources of recharge have accelerated groundwater flow and the transport of dissolved constituents through the aquifers in the three distinct groundwater basins within the larger Santa Ana Basin—the San Jacinto, Inland, and Coastal Basins. Major water-quality issues in the Santa Ana Basin are elevated concentrations of dissolved solids, nitrate, perchlorate, and VOCs in groundwater.

The groundwater system in the San Jacinto Basin is largely unconfined and the overlying land use is a mixture of undeveloped rangeland, urban, and agricultural land. The amount and source of recharge to the basin-fill aquifer affects the quality of the groundwater. Subbasins that receive a large percentage of recharge from mountain-front runoff carried by the San Jacinto River have groundwater quality that is typically similar to that of the recharged water. Some areas in the basin receive little recharge and others receive a large percentage from excess irrigation water. Groundwater in these areas is affected by mineral concentration resulting from evapotranspiration. Agricultural and urban land uses and the extensive use of imported water also affect groundwater quality in the San Jacinto Basin. Withdrawals from wells have altered groundwater-flow directions in areas, allowing new sources of recharge and the movement of poorer quality groundwater to have an effect on water quality.

Faults bound and divide the mostly urban Inland Basin into several groundwater subbasins. These interior faults locally restrict groundwater flow and control the location of natural groundwater discharge. The groundwater basins are generally unconfined near the mountain fronts, where mountain runoff is distributed and recharged through natural streambeds and engineered recharge facilities. Confined conditions typically occur downgradient from the mountain fronts and at greater depths due to finer grained deposits interlayered with more permeable sand and gravel. The Bunker Hill subbasin covers 112 mi^2 in the northeastern part of the Inland Basin, but has a mountain drainage area of 466 mi^2. Three-fourths of the estimated average annual recharge to the basin-fill aquifer is from the infiltration of mountain runoff. The Chino subbasin covers about 222 mi^2, but unlike the Bunker Hill subbasin, has a mountain drainage area of only 62 mi^2. Recharge to the groundwater system in the Chino subbasin is by infiltration of precipitation and water applied at the land surface, infiltration of streamflow (including stormwater runoff), subsurface inflow from adjacent subbasins, and infiltration of imported water and treated municipal wastewater at artificial recharge facilities.

Agricultural and urban development have caused changes in groundwater quality in the Inland Basin, primarily increased concentrations of dissolved solids and nitrate and the presence of VOCs and perchlorate. The basin-fill aquifers are susceptible to water-quality changes because of the unconfined conditions in much of the area and are vulnerable to contamination because of the overlying land uses and activities that utilize chemicals and water. Dissolved solids in Chino subbasin groundwater has increased primarily due to evaporative concentration after irrigation, from the leaching of fertilizer and manure in agricultural areas, and from the recharge of treated wastewater and imported water. In general, sources of nitrate to groundwater include leaching of fertilizers and animal wastes applied to the land, leakage from sewer pipes, and reuse of treated wastewater. Another source of nitrate in groundwater in the Chino subbasin is infiltration of wastewater from animal feeding facilities.

Numerous contaminant plumes (mainly VOCs and perchlorate) in the Inland Basin that are related to industrial activities extend several miles from the source of contamination and have affected the operation of many public-supply wells in the basin. Pesticides and VOCs were frequently detected in water sampled by NAWQA from wells in the Inland Basin. The large number of detections of these compounds probably reflects generally unconfined conditions in the groundwater system, present and past land uses, and the relatively low organic content of aquifer materials.

The mostly urban Coastal Basin includes a relatively small unconfined recharge area and a relatively large confined area where pumping is now the predominant form of discharge from the groundwater system. The groundwater quality is affected by enhanced recharge of water from the Santa Ana River, including the infiltration of treated wastewater that now is a large component of base flow in the river, and the infiltration of imported water. On a regional scale, groundwater in the Coastal Basin moves from unconfined conditions in the forebay area westward to confined conditions in the pressure area. Wells in the pressure area are screened in confined aquifers that are protected to a degree from the effects of overlying land uses by layers of clay and silt.

Artificial recharge and pumping have resulted in very large vertical and lateral rates of groundwater flow through the basin-fill deposits in parts of the forebay and pressure areas. Water-quality data show that water that entered the ground at the recharge facilities extends over 11 miles into the aquifer system along a studied flow path. The quality of groundwater at the lower end of the flow system near the coast typically represents predevelopment conditions but, in some areas, may be affected by seawater intrusion. Groundwater quality in the pressure area nearer to the forebay area reflects historical variation in recharge water quality and mixing with naturally recharged groundwater. Concentrations of dissolved solids have increased in water from public-supply wells in much of the basin as a result of recharge water with relatively high concentrations of dissolved solids from the Santa Ana River and imported from the Colorado River. Sources of nitrate in water from public-supply wells in the Coastal Basin include recharge from the Santa Ana River and infiltration of water affected by past and present human activities.

Production wells sampled by NAWQA in the unconfined forebay areas of the Coastal Basin had a higher detection frequency of VOCs (82 percent) than wells in the adjacent confined pressure area of the aquifer system (65 percent). Groundwater samples with 2 or more VOC detections are from wells within about 11 miles of the recharge facilities, with one exception, and only one or no VOCs were detected in wells sampled beyond this distance in the basin.

References Cited

Anning, D.W., Bauch, N.J., Gerner, S.J., Flynn, M.E., Hamlin, S.N., Moore, S.J., Schaefer, D.H., Anderholm, S.K., and Spangler, L.E., 2007, Dissolved solids in basin-fill aquifers and streams in the southwestern United States: U.S. Geological Survey Scientific Investigations Report 2006–5315, 168 p. Available at http://pubs.usgs.gov/sir/2006/5315/.

Belitz, K., Hamlin, S.N., Burton, C.A., Kent, R.H., Fay, R.G., and Johnson, T.J., 2004, Water quality in the Santa Ana Basin California, 1999–2001: U.S. Geological Survey Circular 1238, 37 p. Available at http://pubs.usgs.gov/circ/2004/1238/.

Burton, C.A., Kaehler, C.A., and Christensen, A.H., 1996, Well-construction, water-quality, and water-level data, and pond-infiltration estimates, for three ground-water subbasins, Riverside County, California: U.S. Geological Survey Water-Resources Investigations Report 96–4294, 114 p.

California Department of Water Resources, 1967, Progress report on ground water geology of the Coastal Plain of Orange County, 138 p.

California Department of Water Resources, 2003a, California’s groundwater—San Jacinto groundwater basin: Bulletin 118, updated 1/20/06, accessed December 1, 2010 at http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/8-5.pdf.

California Department of Water Resources, 2003b, California’s groundwater—South Coast hydrologic region: Bulletin 118, updated 2003, accessed December 1, 2010 at http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_groundwater__bulletin_118_-_update_2003_/bulletin118_4-sc.pdf.

California Department of Water Resources, 2003c, California’s groundwater—Upper Santa Ana Valley groundwater basin, Chino Subbasin: Bulletin 118, updated 1/20/06, accessed December 1, 2010 at http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/8-2.01.pdf.

California Department of Water Resources, 2003d, California’s groundwater—Upper Santa Ana Valley groundwater basin, Bunker Hill Subbasin: Bulletin 118, updated 2/27/04, accessed July 7, 2009 at http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/8-2.06.pdf.

California Department of Water Resources, 2003e, California’s groundwater—Coastal Plain of Orange County groundwater basin: Bulletin 118, updated 2/27/2004, accessed December 1, 2010 at http://www.water.ca.gov/pubs/groundwater/bulletin_118/basindescriptions/8-1.pdf.

Clark, J.F., Hudson, G.B., Davisson, M.L., Woodside, Greg, and Herndon, Roy, 2004, Geochemical imaging of flow near an artificial recharge facility, Orange County, California: Ground Water, vol. 42, no. 2, p. 167–174.

Danskin, W.R., McPherson, K.R., and Woolfenden, L.R., 2006, Hydrology, description of computer models, and evaluation of selected water-management alternatives in the San Bernadino area, California: U.S. Geological Survey Open-File Report 2005–1278, 178 p. and 2 plates. Available at http://pubs.usgs.gov/of/2005/1278/.

Davisson, M.L., Hudson, G.B., Clark, J.F., Woodside, Greg, and Herndon, Roy, 2004, Final report on isotope tracer investigations in the forebay of the Orange County groundwater basin: Lawrence Livermore National Laboratory UCRL–TR–201735, 115 p.

Dawson, B.J.M., Belitz, K., Land, M.T., and Danskin, W.R., 2003, Stable isotopes and volatile organic compounds along seven ground-water flow paths in divergent and convergent flow systems, southern California, 2000: U.S. Geological Survey Water-Resources Investigations Report 03–4059, 79 p. Available at http://water.usgs.gov/pubs/wri/wrir034059/.

Dutcher, L.C., and Garrett, A.A., 1963, Geologic and hydrologic features of the San Bernardino area, California —With special reference to underflow across the San Jacinto Fault: U.S. Geological Survey Water-Supply Paper 1419, 114 p.

Eastern Municipal Water District, 2005, Eastern Municipal Water District urban water management plan 2005, accessed April 29, 2008 at http://www.emwd.org/news/pubs_uwmp.html.

Eastern Municipal Water District, 2007a, West San Jacinto groundwater basin management plan—2006 annual report, accessed April 29, 2008 at http://www.emwd.org/news/pubs_sj-subbasin.html.

Eastern Municipal Water District, 2007b, Hemet/San Jacinto Water Management Area—2006 annual report, accessed April 29, 2008 at http://www.emwd.org/news/pubs_hemet-subbasin.html.

French, J.J., 1972, Ground-water outflow from the Chino Basin, Upper Santa Ana Valley, southern California: U.S. Geological Survey Water-Supply Paper 1999–G, 28 p.

Hamlin, S.N., Belitz, K., Kraja, S., and Dawson, B.J., 2002, Ground-water quality in the Santa Ana Watershed, California: Overview and data summary: U.S. Geological Survey Water-Resources Investigations Report 02–4243, 137 p. Available at http://pubs.usgs.gov/wri/wri02-4243/.

Hamlin, S.N., Belitz, K., and Johnson, T., 2005, Occurrence and distribution of volatile organic compounds and pesticides in ground water in relation to hydrogeologic characteristics and land use in the Santa Ana Basin, southern California: U.S. Geological Survey Scientific Investigations Report 2005–5032, 40 p. Available at http://water.usgs.gov/pubs/sir/2005/5032/.

Hardt, W.F., and Freckleton, J.R., 1987, Aquifer response to recharge and pumping, San Bernardino ground-water basin, California: U.S. Geological Survey Water-Resources Investigations Report 86–4140, 69 p.

Herndon, R.L., Brukner, D.B., and Sharp, G., 1997, Groundwater systems in the Orange County groundwater basin, Phase 1A Task 2.2 Report, prepared for the Santa Ana Watershed Project Authority, TIN/TOS Task Force: Orange County Water District, 12 p.

Hughes, C.L., 1992, 2–D modeling of heat flow in the San Bernardino Valley, southern California: Riverside, University of California, M.S. thesis, 169 p.

Izbicki, J.A., Mendez, G.O., Burton, C.A., 2000, Stormflow chemistry in the Santa Ana River below Prado Dam and at the diversion downstream from Imperial Highway, southern California, 1995–98: U.S. Geological Survey Water-Resources Investigations Report 2000–4127, 92 p.

Kaehler, C.A., and Belitz, K., 2003, Tracing reclaimed water in the Menifee, Winchester and Perris-South ground-water subbasins, Riverside County, California: U.S. Geological Survey Water-Resources Investigations Report 03–4039, 49 p. Available at http://water.usgs.gov/pubs/wri/wri034039/.

Kaehler, C.A., Burton, C.A., Rees, T.F., and Christensen, A.H., 1998, Geohydrology of the Winchester Subbasin, Riverside County, California: U.S. Geological Survey Water-Resources Investigations Report 98–4102, 90 p.

Kent, Robert, and Belitz, Kenneth, 2004, Concentrations of dissolved solids and nutrients in water sources and selected streams of the Santa Ana Basin, California, October 1998 to September 2001: U.S. Geological Survey Water-Resources Investigations Report 03–4326, 61 p. Available at http://pubs.usgs.gov/wri/wrir034326/.

MacRostie, W. and Dolcini, A.J., 1959, Santa Ana River investigation: California Department of Water Resources Bulletin No. 15, 194 p.

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, 16 p. 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.

Mendez, G.O., and Belitz, Kenneth, 2002, Identifying sources of base flow in the Santa Ana River, CA: American Water Resources Association 2002 summer specialty conference proceedings—Ground water/surface water interactions, p. 567–572.

Mendenhall, W.C., 1905a, Development of underground waters in the central coastal plain region of southern California: U.S. Geological Survey Water-Supply and Irrigation Paper 138, 162 p.

Mendenhall, W.C., 1905b, Hydrology of San Bernardino Valley, California: U.S. Geological Survey Water-Supply Paper 142, 124 p.

Mesa Consolidated Water District, 2005, Colored water treatment facility and wells 6 and 11 (revised May 2005): Mesa Consolidated Water District Well Fact Sheet, accessed on February 29, 2008 at http://www.mesawater.org/pdf/fact_sheets/factsheet6_11.pdf.

Metropolitan Water District of Southern California, 2007, Groundwater assessment study: Metropolitan Water District of Southern California Report Number 1308, accessed October 2, 2008 at http://www.mwdh2o.com/mwdh2o/pages/yourwater/supply/groundwater/gwas.html.

Miller, R.E., and Singer, J.A., 1971, Subsidence in the Bunker Hill-San Timoteo area, southern California: U.S. Geological Survey Open-File Report 71–209, 28 p.

Morton, D.M., and Miller F.K., 2006, Geologic map of the San Bernardino and Santa Ana 30' x 60' quadrangles, California, U.S. Geological Survey Open File Report 2006–1217. Available at http://pubs.usgs.gov/of/2006/1217.

Oak Ridge National Laboratory, 2005, LandScan Global Population Database, accessed May 17, 2010 at http://www.ornl.gov/landscan/.

Orange County Water District, 2004, Ground-water management plan, accessed May 17, 2010 at http://www.ocwd.com/Publications—-Newsletters/ca-43.aspx.

Orange County Water District, 2006, 2004–2005 Engineer's report on groundwater conditions, water supply and basin utilization in the Orange County Water District.

Orange County Water District, 2008, Orange County Water District: OCWD Fact Sheet—May 2008, accessed on May 6, 2009 at http://www.ocwd.com/Publications—-Newsletters/ca-43.aspx.

Planert, M., and Williams, J.S., 1995, Ground water atlas of the United States—California, Nevada: U.S. Geological Survey Hydrologic Atlas HA 730–B.

Poland, J.F., 1959, Hydrology of the Long Beach-Santa Ana area, California: U.S. Geological Survey Water-Supply Paper 1471, 257 p.

Poland, J.F. and Piper, A.M., 1956, Ground-water geology of the coastal zone, Long Beach-Santa Ana area, California: U.S. Geological Survey Water-Supply Paper 1109, 162 p.

Post, W.S., 1928, Santa Ana investigation—Flood control and conservation: California Department of Public Works Bulletin No. 19, 357 p. accessed June 23, 2009 at http://www.archive.org/details/santaanainvestig00postrich.

PRISM Group, Oregon State University, 2004, Precipitation-elevation regression on independent slopes model (PRISM), Oregon State University, accessed May 17, 2010 at http://www.ocs.oregonstate.edu/prism/.

Rees, T.F., Bright, D.J., Fay, R.G., Christensen, A.H., Anders, Robert, Baharie, B.S., and Land, M.T., 1995, Geochemistry in the saturated and unsaturated zones beneath various land uses, Riverside and San Bernardino Counties, California, 1991–93: U.S. Geological Survey Water-Resources Investigations Report 94–4127, 267 p.

Reichard, E.G., Land, M., Crawford, S.M., Johnson, T., Everett, R.R., Kulshan, T.V., Halford, K.J., Johnson, T.A., Paybins, K.S., and Nishikawa, T., 2003, Geohydrology, geochemistry, and ground-water simulation-optimization of the Central and West Coast Basins, Los Angeles County, California: U.S. Geological Survey Water-Resources Investigations Report 03–4065, 184 p. Available at http://pubs.usgs.gov/wri/wrir034065/wrir034065.html.

Santa Ana Watershed Project Authority, 2002, Santa Ana integrated watershed plan—Volume 1 water resources component, accessed on April 7, 2009, at http://www.sawpa.org/pdf/IWRP_Complete.pdf.

Santa Ana Watershed Project Authority, 2005, Santa Ana integrated watershed plan—2005 update, 183 p.

Santa Ana Watershed Authority, no date, Major water infrastructure—Treatment and delivery: Santa Ana Watershed Authority, accessed on July 9, 2009 at http://sawpa.org/documents/MapGallery/1421_WaterRelatedInfrastructure.pdf.

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.

Scott, M.B., 1977. Development of water facilities in the Santa Ana River Basin, California, 1810–1968, a compilation of historical notes derived from many sources describing ditch and canal companies, diversions, and water rights: U.S. Geological Survey Open-file Report 77–398, 231 p.

Schlehuber, M.J., Lee, T.C., and Hall, B.S., 1989, Groundwater level and hydrochemistry in the San Jacinto Basin, Riverside County, California: Journal of Hydrology, vol. 106, p. 79–98.

Shelton, J.L., Burow, K.R., Belitz, K., Dubrovsky, N.M., Land, M., and Gronberg, J., 2001, Low-level volatile organic compounds in active public supply wells as ground-water tracers in the Los Angeles physiographic basin, California, 2000: U.S. Geological Survey Water-Resources Investigations Report 01–4188, 29 p., accessed September 23, 2008 at http://ca.water.usgs.gov/archive/reports/wrir014188/.

Singer, J.A., 1973, Geohydrology and artificial-recharge potential of the Irvine area, Orange County, California: U.S. Geological Survey Open-File Report 73–264, 41 p.

Tompson, A.F.B., Carle, S.F., Rosenberg, N.D., and Maxwell, R.M., 1999, Analysis of ground water migration from artificial recharge in a large urban aquifer: A simulation perspective: Water Resources Research, vol. 35, no. 1, p. 2981–2998.

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, 2003a, Principal aquifers in National Atlas of the United States of America, accessed on August 26, 2009 at http://water.usgs.gov/ogw/aquiferbasics/alphabetical.html.

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

U.S. Geological Survey, 2004, Estimated use of water in the United States; county-level data for 2000: U.S. Geological Survey web site, accessed on May 5, 2010 at http://water.usgs.gov/watuse/data/2000/index.html.

Waring, G.A., 1919, Ground water in the San Jacinto and Temecula basins, California: U.S. Geological Survey Water-Supply Paper 429, 113 p.

Water Resources and Information Management Engineering Inc., 2003, Operational yield study, Hemet/San Jacinto Groundwater Management Area: prepared in coordination with the California Department of Water Resources, 36 p.

Wildermuth Environmental, Inc., 1999, Optimum Basin Management Program, Phase I Report: prepared for the Chino Basin Watermaster, August 19, 1999, accessed May 9, 2008 at http://www.cbwm.org/docs/engdocs/obmpphas1rep/Text/OBMP_Ph1_Report.pdf.

Wildermuth Environmental, Inc., 2000, TIN/TDS Phase 2A: Tasks 1 through 5, TIN/TDS study of the Santa Ana Watershed, Technical Memorandum, July 2000.

Wildermuth Environmental, Inc., 2005, Chino Basin Optimum Basin Management Program, State of the Basin Report—2004: prepared for the Chino Basin Watermaster, July 2005, accessed May 9, 2008 at http://www.cbwm.org/rep_engineering.htm.

Wildermuth Environmental, Inc., 2007a, Chino Basin Optimum Basin Management Program, State of the Basin Report—2006: prepared for the Chino Basin Watermaster, July 2007, accessed May 9, 2008 at http://www.cbwm.org/rep_engineering.htm.

Wildermuth Environmental, Inc., 2007b, 2007 CBWM groundwater model documentation and evaluation of the Peace II project description: prepared for the Chino Basin Watermaster, November 2007.

Wildermuth Environmental, Inc., 2008, Recomputation of ambient water quality in the Santa Ana Watershed for the period 1987 to 2006: Final Technical Memorandum prepared for the Basin Monitoring Program Task Force, August 2008.

Williams, A.E., 1997, Stable isotope tracers: natural and anthropogenic recharge, Orange County, California: Journal of Hydrology, vol. 201, p. 230–248.

Williams, A.E., and Rodoni, D.P., 1997, Regional isotope effects and application to hydrologic investigations in southwestern California, Water Resources Research, vol. 33, no. 7, p. 1721–1729.

Woolfenden, L.R., and Kadhim, D., 1997, Geohydrology and water chemistry in the Rialto-Colton Basin, San Bernadino County, California: U.S. Geological Survey Water-Resources Investigations Report 97–4012, 101 p.

Woolfenden, L.R., and Koczot, K.M., 2001, Numerical simulation of ground-water flow and assessment of the effects of artificial recharge in the Rialto-Colton Basin, San Bernadino County, California: U.S. Geological Survey Water-Resources Investigations Report 00–4243, 148 p. Available at http://pubs.usgs.gov/wri/wri004243/.

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