Section 8.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the Upper Santa Cruz Basin, Arizona

By David W. Anning and James M. Leenhouts

in

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

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National Water-Quality Assessment Program

Professional Paper 1781

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

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Basin Overview

The Upper Santa Cruz Basin hosts a growing population in the Tucson metropolitan area and several other communities in south central Arizona (fig. 1). Groundwater development to support the population and their economic and cultural activities over the past century has caused substantial changes in the basin-fill aquifer, including water-level declines, a 51 percent increase in groundwater recharge, and a 171 percent increase in groundwater discharge. These and other changes to the aquifer have resulted in an increase in the intrinsic susceptibility of the aquifer to contamination, and the effects of both natural and human-related factors on groundwater quality are discussed in this section of the report.

As a Basin and Range feature, the 2,530-mi^2 Upper Santa Cruz Basin consists of an elongated sediment-filled valley bounded by a several mountain ranges, including the Pajarito, Atascosa, Tumacacori, Cerro Colorado, Sierrita, Tucson, and Tortolita mountains to the west and the Patagonia, San Cayetano, Santa Rita, Rincon, and Santa Catalina mountains to the east (fig. 1). Altitudes of the valley floor range from about 2,100 to 3,900 ft, and the tops of the surrounding mountains reach as high as 9,460 ft. The basin is topographically open and drained by the Santa Cruz River. The basin does not include all tributaries to the Santa Cruz River, but rather it receives surface-water inflow from the Cienega Creek drainage, Sonoita Creek drainage, and also the uppermost part of the Santa Cruz River drainage that is upstream from Nogales, Arizona, and extends into Mexico.

The Upper Santa Cruz Basin has an arid to semiarid climate, but wide variations in altitude cause large differences in precipitation and temperature. Precipitation is greater in the mountains than on the valley floor due to orographic effects, and the higher elevation mountains on the east side of the basin receive more precipitation than the lower elevation mountains on the west side of the basin. Mean annual precipitation from 1971 to 2000 for the entire basin, including the mountains, is about 17 in., whereas the valley floor on average receives about 15 in. (McKinney and Anning, 2009). Rainfall from July through September generally results from the North American Monsoon weather pattern (Adams and Comrie, 1997) and occurs as intense, local convective storms. Precipitation records for Tucson for 1949–06 indicate that about 45 percent of the annual rainfall falls during the months of July through September. Precipitation during the remainder of the year typically results from Pacific frontal storms and dissipating tropical cyclones.

Temperatures are highly variable spatially owing to the variations in elevation. Large diurnal temperature cycles are common and occur due to low atmospheric moisture and frequent cloudless days. For the period 1912–94, mean January temperature in Tucson was about 50°F while mean July temperature was 86°F (Western Regional Climate Center, 2007).

Frequent high temperatures combined with low relative humidity results in potential evaporation that is several times higher than the annual precipitation in many areas of the Upper Santa Cruz Basin. Potential evaporation calculated for a site near Nogales in 1995–96 was about 57 in. (Unland and others, 1998). As a result of the evaporation excess, groundwater recharge is generally thought not to occur by infiltration through the open desert floor, but instead is concentrated at the mountain fronts or at other locations where water collects at least temporarily, such as ephemeral-stream channels (Scanlon and others, 1999).

Land cover for the alluvial basin, excluding the surrounding mountainous areas, is estimated to be about 16 percent urban and about 1 percent agriculture (McKinney and Anning, 2009). Major crops include hay, cotton, grains, nuts, and vegetables. Most of the present-day urban land was previously desert rangeland, although some of the urbanized areas along the Santa Cruz and Rillito Rivers had previously been agricultural lands. The Tucson metropolitan area accounts for much of the urban land, and like many urban areas in the southwestern United States, the population there has undergone steady but rapid growth in the last few decades. The total population of the Upper Santa Cruz Basin in 2005 was estimated to be about 914,000 people (McKinney and Anning, 2009), most of whom are in the Tucson metropolitan area.

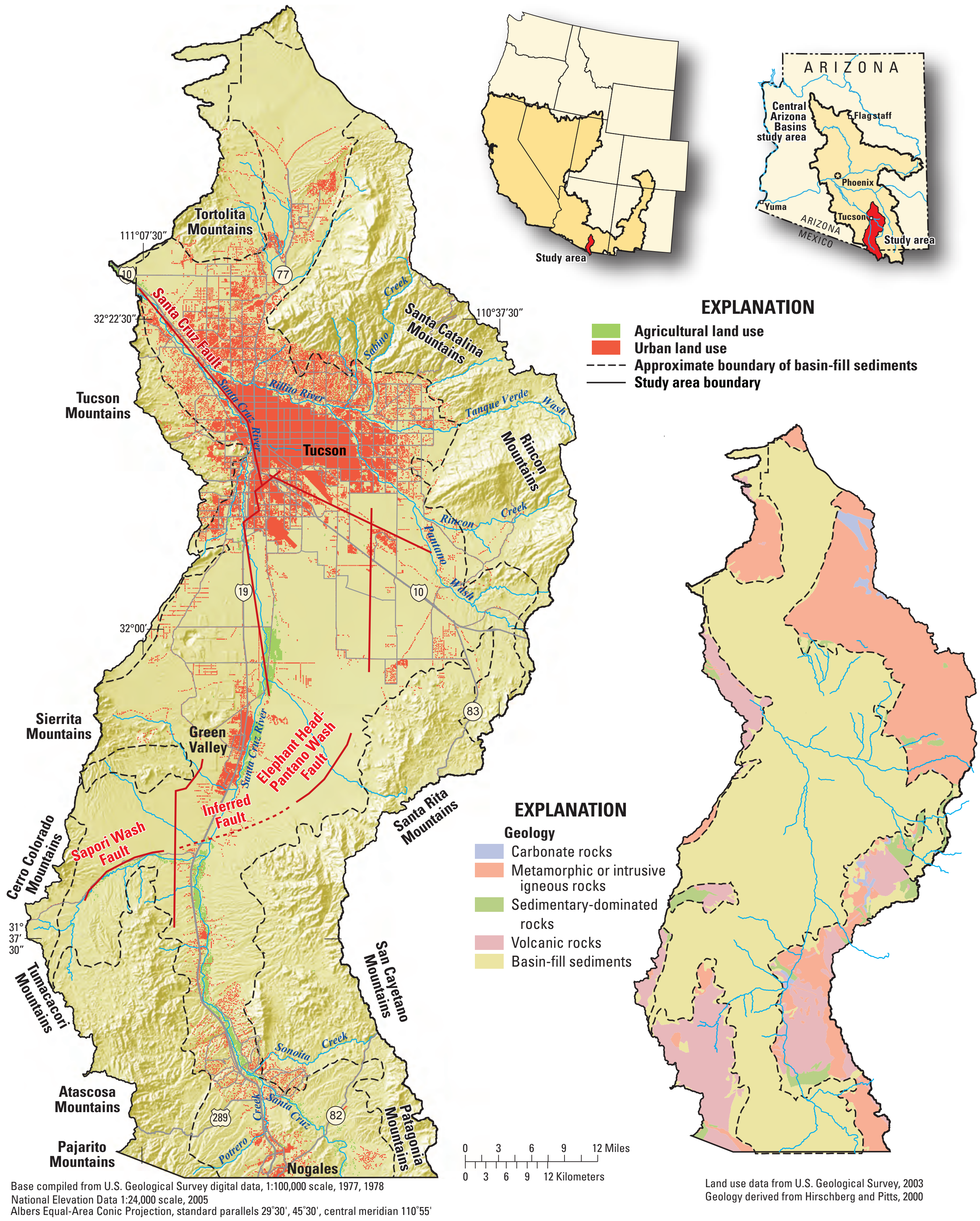

Figure 1. Physiography, land use, and generalized geology of the Upper Santa Cruz Basin, Arizona.

Water Development History

The Upper Santa Cruz Basin has a rich water development history from the Paleoindian period through modern times, and the resulting water supply infrastructure includes several well networks for the City of Tucson and other municipalities in the basin, as well as aqueducts for delivery of Colorado River water through the Central Arizona Project. Archeological evidence indicates that at least transient human occupation of the Upper Santa Cruz Basin began as early as the Paleoindian period between 11,500 and 7,500 BC (Thiel and Diehl, 2006). The groups existing at that time were largely hunter-gathers who did not likely take up permanent residence. The original nomadic residents of the Upper Santa Cruz Basin likely utilized available water supplies only for drinking and cleaning purposes.

Evidence shows that by 400 BC, groups were living in agricultural settlements in the floodplain of the Santa Cruz River (Thiel and Diehl, 2006). The early farming peoples utilized water from then-perennial sections of the Santa Cruz River and from springs to irrigate crops. Native residents continued to exclusively farm and hunt in the area until the arrival of Father Eusebio Franscisco Kino in 1694 (Thiel and Diehl, 2006). The first historical accounts of Tucson, written by Father Kino during the 1690s, suggest that virtually the entire flow of the Santa Cruz River was diverted into irrigation canals (Klimas and others, 2006). In the following 150 years, the Upper Santa Cruz Basin saw a continued increase in numbers of Spanish and Mexican explorers and settlers who brought European agriculture and technology to the area. In 1856, the U.S. Army opened its first outpost in Tucson, thus encouraging further settlement of the area by residents of European descent (Thiel and Diehl, 2006). The residents and temporary occupants of the area relied on surface-water diversions and springs until the development of pump technology allowed significant exploitation of groundwater resources.

Among the communities in the Upper Santa Cruz Basin, Tucson became the population center of the area, and by 1900, Tucson's population had grown to about 7,500. In 1914, a City of Tucson bond issue financed a new storage reservoir and the installation of 6 new wells that utilized new technology that could extract 1 million gallons of water per day per well from the underlying aquifer (Gelt and others, 2006). Groundwater withdrawals in the Upper Santa Cruz Basin were about 7,000 acre-ft in 1915 (Anning and Duet, 1994) and were relatively uniform from 1920 to 1939, at an average of about 34,000 acre-ft/yr (Hanson and Benedict, 1994). As population increased, withdrawals for urban and agricultural uses increased (fig. 2), and groundwater levels declined in response. By the 1940s, groundwater levels had declined sufficiently that surface flow in the perennial reaches of the Santa Cruz River in the Tucson area was captured and the channel became ephemeral (Hanson and Benedict, 1994).

The period after World War II and continuing to the current time was characterized by rapid growth, and the City of Tucson responded by drilling many additional wells. In the 1960s, Tucson determined that the then-established well fields were inadequate to meet growing demands for water and began purchasing land and drilling wells in Avra Valley, which is adjacent and to the west of the Upper Santa Cruz Basin. Groundwater withdrawals increased to a peak of about 281,000 acre-ft in 1976 and generally declined after that to about 210,000 acre-ft in 1990, mostly as a result of decreased agricultural water demand (fig. 2; Anning and Duet, 1994). For the period 1940–86, about 52 percent of withdrawals were for agricultural use, 33 percent for public-supply use, and 15 percent for industrial use (Hanson and Benedict, 1994). In the late 1990s, estimated withdrawals were about 221,000 acre-ft/yr, and by use categories were about 19 percent for agriculture, 55 percent for public supply, and 26 percent for industry (based on data from Arizona Department of Water Resources, 1999b; and Mason and Bota, 2006).

Municipal wastewater effluent has long been treated as a source of water in the Upper Santa Cruz Basin. From about 1900 to 1950, effluent from Tucson was used to irrigate crops (Gelt and others, 2006), and release of treated effluent to the Santa Cruz River and subsequent recharge began in 1951 (Hanson and Benedict, 1994). Starting in 1983, a tertiary treatment plant was constructed to deliver the treated effluent to golf courses and public turf areas for irrigation. Currently, treated effluent is delivered to more than 200 water users including 13 golf courses, 25 parks, and 30 schools. In 1998, about 13,000 acre-ft of treated effluent was delivered for reuse in the Tucson area, and about 54,000 acre-ft was recharged as infiltration through the Santa Cruz River, some of which occurred downstream from the Upper Santa Cruz Basin (Gelt and others, 2006). In the same year, about 14,600 acre-ft of effluent was released to the Santa Cruz River from the Nogales International Wastewater Treatment Plant, which treats sewage from both the United States and Mexico (Nelson and Erwin, 2001).

An additional source of water had been considered for Arizona even before statehood was achieved in 1912: the Colorado River. Arizona's politicians were unified behind the concept by 1960, and in 1968 President Lyndon B. Johnson signed a bill approving the construction of the Central Arizona Project (CAP); construction of the project was started in 1973 (Central Arizona Project, 2007). In the 1970s, however, President Jimmy Carter expressed doubt that project building would solve western water problems and demanded changes in Arizona water laws to promote conservation (Gelt and others, 2006). The response by the Arizona Legislature was the creation of the Groundwater Management Act of 1980. This act established specific Active Management Areas that are subject to a set of specific requirements dealing with water use and development. The Upper Santa Cruz Basin eventually included two Active Management Areas within its bounds.

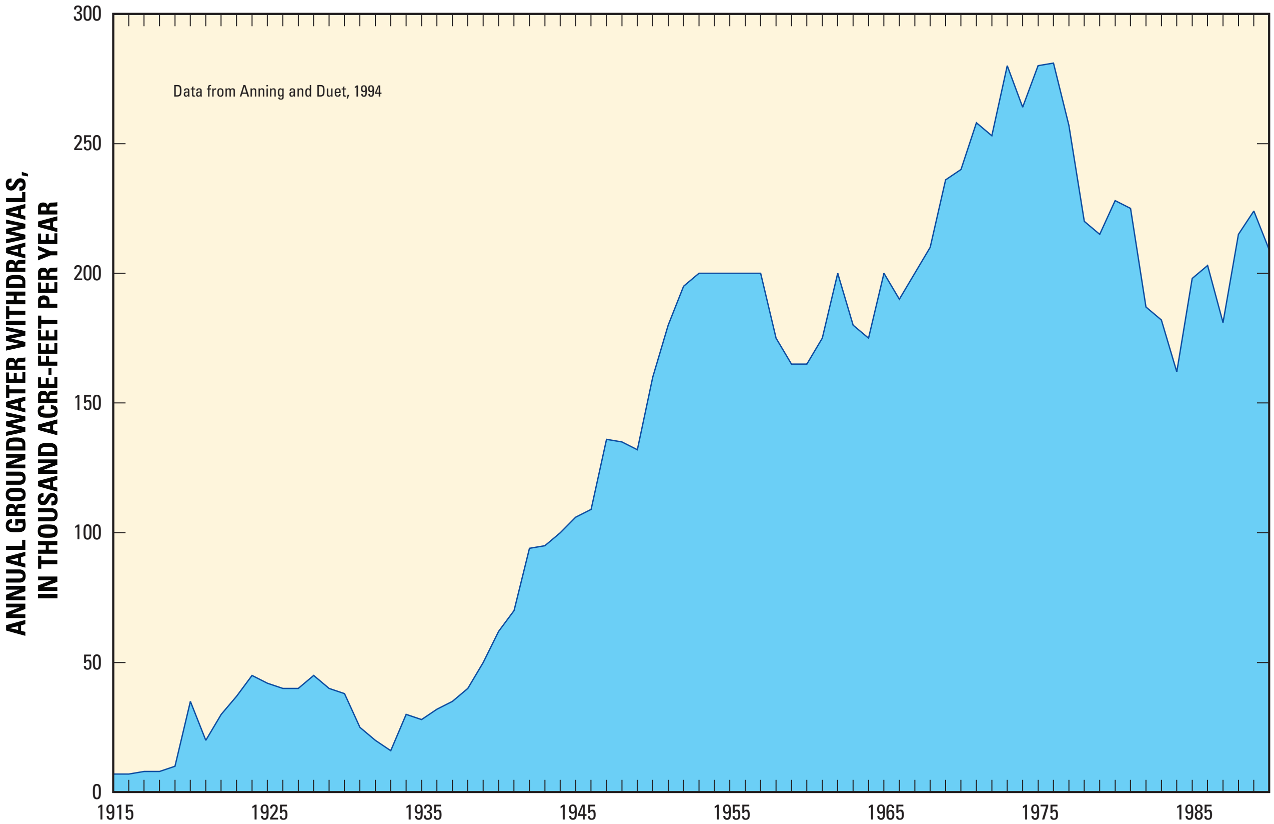

Figure 2. Annual groundwater withdrawals in the Upper Santa Cruz Basin, Arizona, 1915–1990.

The CAP infrastructure to Tucson was completed by 1990. Originally the CAP water was destined for use in agriculture and mining activities, two of the dominant water uses in the state. Eventually, however, few mines or farms utilized the new water owing to concerns about its quality and cost. The City of Tucson began delivering CAP water to customers in 1992, but differences in quality relative to the native groundwater led to problems such as delivery of water with pipe corrosion to consumers' homes (Gelt and others, 2006). As a result, in 1996, the City of Tucson began recharging its CAP allotment in Avra Valley and then pumped the mixture of recharged CAP water and native groundwater for delivery within the Upper Santa Cruz Basin. The delivery of blended CAP water to areas of metropolitan Tucson, which in 2005 was in excess of 150,000 acre-ft, allowed the reduction or cessation of pumping from some wells and resulted in recovery of water levels in certain areas. The chemical characteristics of CAP water differs from that of native groundwater, most notably in dissolved-solids content, so its delivery to customers and eventual appearance as wastewater have implications for groundwater quality in the Upper Santa Cruz Basin.

Hydrogeology

The Upper Santa Cruz Basin is characteristic of the Basin and Range Physiographic Province (Fenneman, 1931) and consists of block-faulted mountains separated by a north-south trending sediment-filled valley. The mountains block virtually all subsurface flow between adjacent valleys and thus serve as hydrologic boundaries both for the groundwater and surface-water systems. The rocks of the surrounding mountains range in age from Precambrian to Tertiary; they consist primarily of granite, andesite, rhyolite, basalt, monzonite, granodiorite, gneiss, and secondarily of limestone, quartzite, conglomerate, sandstone, and shale. The crystalline and metamorphic rocks of the mountains are capable of storing and transmitting small amounts of water through connected fracture systems; the sedimentary rock units of the mountains are generally of low porosity and permeability but locally can have significant capacity to store and transmit water (Davidson, 1973; fig. 1).

Most of the capacity to store and transmit groundwater in the Upper Santa Cruz Basin resides in the sequence of Tertiary to Quaternary alluvial sediments that fill the basin, and where saturated, these sediments form the basin-fill aquifer. The thickness of these sediments varies from a thin veneer along the basin margins where bedrock emerges to more than 11,200 ft in the center of the basin (Hanson and Benedict, 1994). The sediments are of significantly different character and thickness (figs. 3*A*, 3*B*) to either side of a northeast-southwest trending fault that is inferred to connect the Sopori Wash and Elephant Head-Pantano Wash faults (Halpenny and Halpenny, 1988; fig. 1). The sediments north of the inferred fault are thicker than those to the south, and consist of the Pantano Formation, Tinaja beds, and Fort Lowell Formations (Davidson, 1973; fig. 3*A*). A veneer of alluvial fan, sheetflow, and stream alluvial deposits comprise the surface sediments. South of the inferred fault, the sediments that form the basin-fill aquifer consist of the Nogales Formation, thought to be correlative with the lower Tinaja beds (Anderson, 1987), and groupings of older and younger alluvium (fig. 3*B*; Halpenny and Halpenny, 1988).

The Pantano Formation is a consolidated to semiconsolidated sedimentary unit of Tertiary age that overlies bedrock north of the inferred fault. It ranges in thickness from hundreds to thousands of feet and consists of reddish-brown silty sandstone to gravel that is weakly to strongly cemented (Davidson, 1973). Wells in shallow portions of the Pantano Formation tend to yield only small volumes of water, but the unit yields greater volumes at depth. The Pantano Formation crops out along the southern slopes of the Santa Catalina Mountains, the western slopes of the Rincon Mountains, and the northeastern slopes of the Sierrita Mountains. The hydraulic conductivity values of the formation range from about 1 to 10 ft/d (Davidson, 1973).

Unconformably overlying the Pantano Formation are three divisions (lower, middle, and upper) of the Tertiary age Tinaja beds. The Tinaja beds range in thickness from 0 to more than 2,000 ft and crop out only along the margins of the basin where exposed by erosion or where they were never covered by younger sediments. The Tinaja beds consist largely of sandy gravel near the basin periphery, but transitions to gypsiferous clayey silt and mudstone toward the center of the basin. The Tinaja beds constitute a significant portion of the aquifer in the Upper Santa Cruz Basin, with hydraulic conductivity values ranging from about 1 to 50 ft/d (Davidson, 1973).

The Fort Lowell Formation of Quaternary age is a locally derived sedimentary unit that unconformably overlies the Tinaja beds and underlies most of the surface of the Upper Santa Cruz Basin. Its thickness ranges from 0 near the edge of the basin up to about 400 ft in the center of the basin (Davidson, 1973). The Fort Lowell Formation grades from silty gravel near the basin margins to silty sand and clayey silt near the basin center (Coes and others, 2000) and is the most productive part of the aquifer in the Tucson area. The Fort Lowell formation is typically loosely packed to weakly cemented, and hydraulic conductivity values range from about 20 to as much as 100 ft/d (Davidson, 1973).

A veneer of about 5 to 100 ft of alluvium unconformably overlies older sediments in most of the Upper Santa Cruz Basin. These sediments consist of alluvial fan and sheetflow deposits over the basin floor and stream-channel deposits along the Santa Cruz River and many tributary channels (Davidson, 1973). These surficial sediments are unsaturated in most of the Upper Santa Cruz Basin, except along stream channels, where in places they yield useable quantities of groundwater.

South of the inferred fault, the basin fill consists of the Nogales Formation, older alluvium, and younger alluvium. The Nogales Formation is a consolidated conglomerate of Tertiary age that overlies the bedrock in the basin (fig. 3*B*; Halpenny, 1963). The Nogales Formation consists of sandstone, claystone, and conglomerate derived from limestone, granite, and volcanic material and is up to 2,400 ft thick (Halpenny, 1963, Gettings and Houser, 1997). Hydraulic conductivity values range from about 0.3 to 3.0 ft/d (Nelson, 2007).

Older alluvium consists of deposits of weakly cemented gravel, sand, and silt and overlies the Nogales Formation (Halpenny and Halpenny, 1988). The older alluvium is of Tertiary and Quaternary age and forms terraces that mark the old, inner valley of the Santa Cruz River south of the inferred fault. The terraces disappear along the edges of the inner valley north of the inferred fault (Halpenny and Halpenny, 1988). The older alluvium is up to 900 ft thick (Gettings and Houser, 1997), and hydraulic conductivity values range from about 1 to 50 ft/d (Nelson, 2007).

Younger alluvium is of Quaternary age and has been deposited along the Santa Cruz River. Younger alluvium is composed of gravel, sand, and occasional lenses of silt and ranges in thickness from about 30 to 150 ft thick (Halpenny and Halpenny, 1988; Carruth, 1995). The younger alluvium readily transmits water and has hydraulic conductivity values of 100 to 600 ft/d (Nelson, 2007).

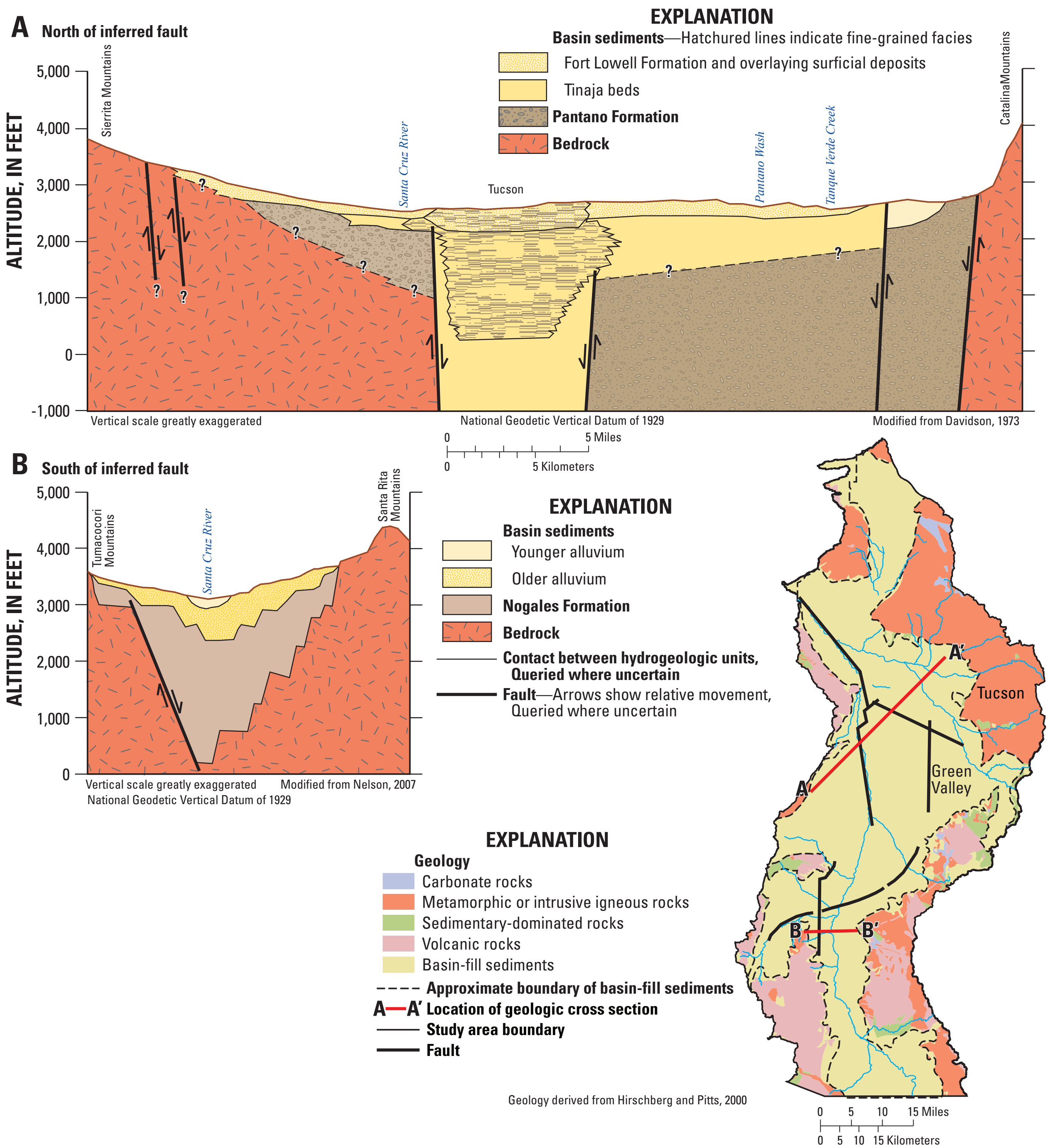

Figure 3. Generalized hydrogeologic sections of the Upper Santa Cruz Basin, Arizona. (*A*) North of the inferred fault, and (*B*) South of the inferred fault.

Conceptual Understanding of the Groundwater Flow System

The predevelopment groundwater flow system of the Upper Santa Cruz Basin resembles that of other Basin and Range systems in southern Arizona. Water levels in the basin-fill aquifer are generally parallel to the land surface of the valley floor and consequently groundwater flows from the basin margins towards the center and then northward along the basin axis. The aquifer is replenished primarily through mountain-front and mountain-block recharge, water losses from the channel of the Santa Cruz River, and as a consequence of water-resources development and use, incidental recharge from human activities. Groundwater leaves the aquifer primarily through evapotranspiration, and with water-resources development, through groundwater pumpage. Details of groundwater recharge, discharge, and flow are described in the following sections, along with the effects that water-resources development has had on the basin-fill aquifer.

Water Budget

A conceptual understanding of the primary and significant fluxes of water through the basin-fill aquifer is summarized in a groundwater budget for predevelopment and modern conditions in the Upper Santa Cruz Basin (fig. 4; table 1). Most water-budget components estimated in this study were derived by combining data reported for the area south of the inferred fault (Nelson, 2007) and the area north of the inferred fault (Mason and Bota, 2006). The water budget and groundwater flow system have changed significantly from the predevelopment period (prior to about 1900) to modern times (circa 2000; fig. 4; table 1).

The relative abundance of precipitation at higher elevations combined with the low permeability of mountain bedrock and the general permeable nature of basin-margin sediments leads to a conceptual model wherein a significant portion of groundwater recharges at the mountain fronts. The estimated mountain-front and mountain-block recharge for the Upper Santa Cruz Basin is 36,000 acre-ft/yr (table 1; Nelson, 2007; Mason and Bota, 2006), most of which originates within the Santa Catalina, Rincon, Santa Rita, and Sierrita Mountains. Streamflow infiltration is also an important recharge mechanism, although it may have varied in magnitude significantly through time. Streamflow was intermittent in the Santa Cruz River over most of its length prior to 1870 (Betancourt and Turner, 1993). In the years from the 1870s through 1890s, the main stem river channel became entrenched. That down cutting led to an increase in groundwater discharge to the streambed while the topmost part of the aquifer near the stream drained and established a new steady-state equilibrium condition (Hanson and Benedict, 1994). The estimated predevelopment streamflow infiltration for the Upper Santa Cruz Basin is 52,000 acre-ft/yr (table 1; Nelson, 2007; Mason and Bota, 2006). The contribution of streamflow infiltration for the area north of the inferred fault of 34,000 acre-ft/yr, however, may be overestimated because the water table was higher along the rivers during predevelopment conditions than during 1940, the year for which Mason and Bota (2006) reported the number. Areally distributed recharge is generally thought to be small or nonexistent in many desert environments (Scanlon and others, 1999) and was not estimated in previous studies of the Upper Santa Cruz Basin. Predevelopment subsurface inflow to the basin from Mexico was estimated to be about 5,000 acre-ft/yr (Nelson, 2007). The total predevelopment recharge for the Upper Santa Cruz Basin is estimated to be 93,000 acre-ft/yr (fig. 4; table 1).

The predominant mode of predevelopment groundwater discharge was evapotranspiration. For the area south of the inferred fault, Nelson (2007) estimated that evapotranspiration of shallow groundwater was about 15,000 acre-ft/yr. Estimates of evapotranspiration for the reach north of the inferred fault under steady state conditions are available for about 1940 (Mason and Bota, 2006). These values, however, are significantly lower than the evapotranspiration amount for predevelopment conditions because pumpage through 1940 had already lowered groundwater levels below the root zone of the predevelopment riparian ecosystem (Hanson and Benedict, 1994). For this study, predevelopment evapotranspiration of 64,000 acre-ft/yr for the area north of the inferred fault was estimated as the sum of evapotranspiration and pumpage under steady-state conditions in 1940 as reported by Mason and Bota (2006). Total predevelopment evapotranspiration is estimated to be 79,000 acre-ft/yr (table 1). The other primary process of groundwater discharge is underflow out of the basin, which is estimated to be about 14,000 acre-ft/yr (Mason and Bota, 2006). Total groundwater discharge under predevelopment conditions is estimated to be 93,000 acre-ft/yr (table 1), which is equal to groundwater recharge under the steady-state assumption.

The development of groundwater resources in the Upper Santa Cruz Basin from predevelopment (circa 1900) to modern (circa 2000) times has significantly changed several components of the water budget. The quantity of water pumped from the aquifer became significant after about 1920. From 1920–40, pumping was relatively steady, averaging about 34,000 acre-ft/yr, and by 1940 the aquifer system was probably in a new state of equilibrium with stable water levels but at lower altitudes relative to predevelopment times (Hanson and Benedict, 1994). Pumping in 1940 was about 50,000 acre-ft. As noted earlier, groundwater pumpage for the late 1990s was about 221,000 acre-ft/yr (table 1).

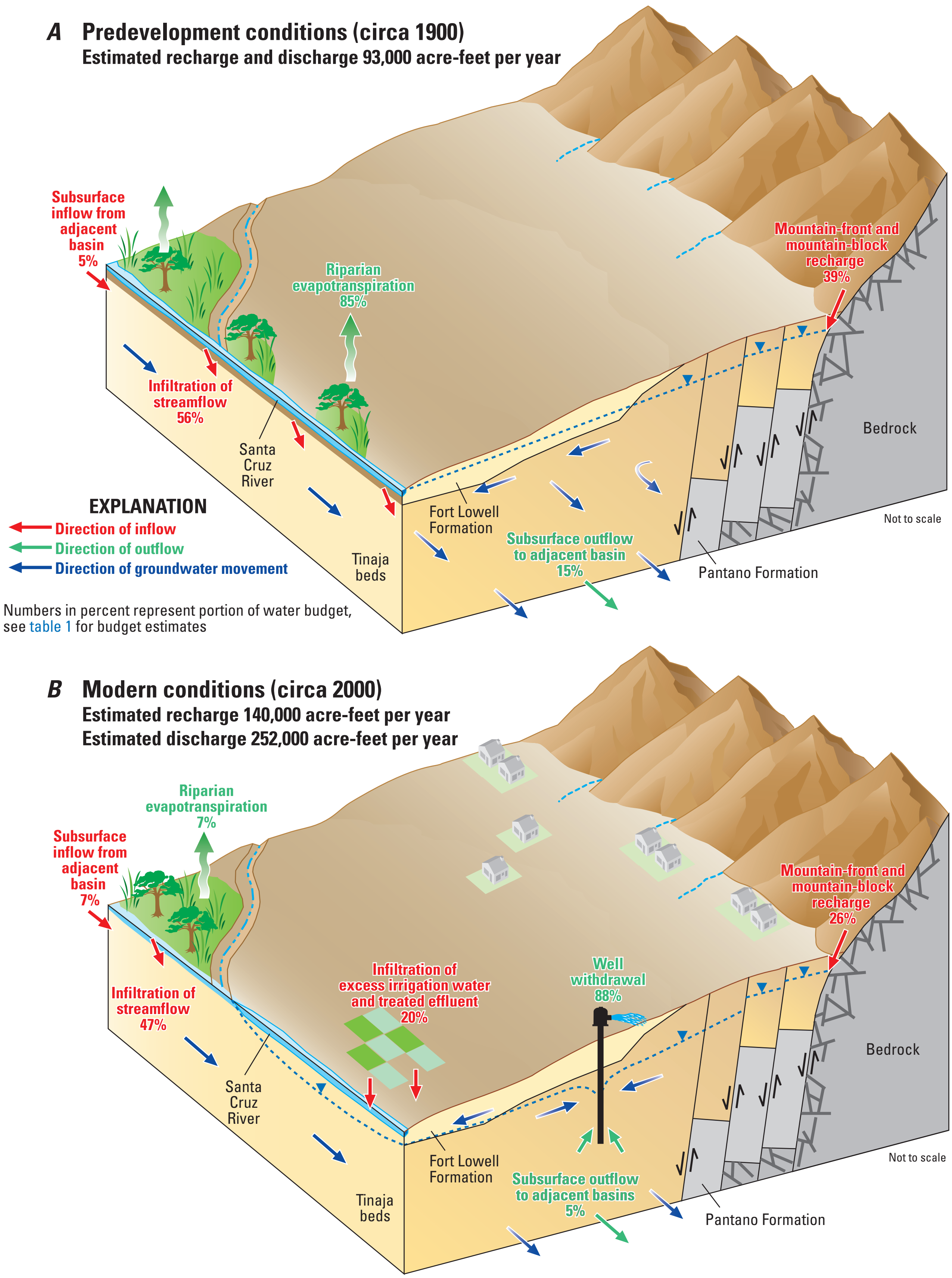

Figure 4. Generalized diagrams for the Upper Santa Cruz Basin, Arizona, showing components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

Table 1. Estimated groundwater budget for the basin fill aquifer in the Upper Santa Cruz Basin, Arizona, under predevelopment and modern conditions.

[All values are in acre-feet per year (acre-ft/yr) and are rounded to the nearest thousand. Estimates of groundwater recharge and discharge for the area south of the inferred fault were derived from Nelson (2007). Estimates for the area north of the inferred fault were derived from Mason and Bota (2006), unless noted here. For the area north of the inferred fault, predevelopment evapotranspiration was computed as reported evapotranspiration plus pumpage for 1940 conditions. Infiltration of streamflow and evapotranspiration in the area north of the inferred fault may have been smaller than values reported here, which represent 1940 conditions, as a result of the groundwater table being lower along the river in 1940 than for predevelopment conditions. Modern infiltration of streamflow in the area north of the inferred fault is computed as predevelopment infiltration of streamflow plus 12,400 acre-ft/yr, a gain reported by Hanson and Benedict (1994) due to lowered groundwater levels near major streams. Estimates of recharge from excess irrigation water, sewage effluent, and industrial wastewater for the area north of the inferred fault are from Hanson and Benedict (1994). 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. Percentages for each water budget component are shown in figure 3. n/a, not applicable]

Budget component	Predevelopment conditions, circa 1900			Modern conditions, circa 2000			Change from predevelopment to modern conditions
	South of inferred fault	North of inferred fault	Total	South of inferred fault	North of inferred fault	Total	
Estimated recharge							
Subsurface inflow from adjacent basin	5,000	N/A	5,000	10,000	N/A	10,000	5,000
Mountain-block and mountain-front recharge	5,000	31,000	36,000	5,000	31,000	36,000	0
Infiltration of precipitation on basin	0	0	0	0	0	0	0
Infiltration of streamflow	18,000	34,000	52,000	20,000	46,000	66,000	14,000
Infiltration of excess irrigation water, sewage effluent, and industrial wastewater	0	0	0	2,000	26,000	28,000	28,000
Artificial recharge	0	0	0	0	0	0	0
Total recharge	28,000	65,000	93,000	37,000	103,000	140,000	47,000
Estimated discharge							
Subsurface outflow to adjacent basin	[1]0	14,000	14,000	[1]0	14,000	14,000	0
Evapotranspiration	15,000	64,000	79,000	15,000	2,000	17,000	-62,000
Discharge to streams	0	0	0	0	0	0	0
Discharge to springs and drains	0	0	0	0	0	0	0
Well withdrawals	0		0	16,000	205,000	221,000	221,000
Total discharge	15,000	78,000	93,000	31,000	221,000	252,000	159,000
Estimated change in storage (recharge-discharge)	N/A	N/A	0	N/A	N/A	-112,000	-112,000

[1]Flow occurs, but goes into area north of inferred fault or comes from area south of inferred fault.

Groundwater pumping has resulted in increases in recharge to and discharge from the aquifer. Pumping causes declines in water levels, which can lead to changes in the direction of flow or to the “capture” of water that under natural, predevelopment conditions was moving toward discharge areas. If the water-level declines are great enough, former discharge areas can become recharge areas. For the Upper Santa Cruz Basin, the lowering groundwater levels north of the inferred fault decreased evapotranspiration by 62,000 acre-ft/yr (table 1) and increased streamflow infiltration by 14,000 acre-ft/yr (table 1; Hanson and Benedict, 1994). At the international border, subsurface inflow into the Upper Santa Cruz Basin increased from predevelopment to modern conditions because pumping increased the hydraulic gradient of the aquifer in that area (Nelson, 2007). For this study, subsurface outflow data were not available for modern conditions, and the value for predevelopment conditions was used (table 1). The true modern subsurface outflow could be smaller than that shown (table 1) due to a decrease in hydraulic gradient or in the saturated cross section through which the water is moving.

As a consequence of the development and use of groundwater, recharge also occurred from incidental sources. North of the inferred fault, incidental recharge from excess irrigation water, effluent infiltration along the channel of the Santa Cruz River, and seepage from mine tailings ponds became major water sources replenishing the aquifer (Mason and Bota, 2006) and have significant implications with respect to water quality. The estimate of 26,000 acre-ft/yr for incidental recharge from these sources by Hanson and Benedict (1994) were used by Mason and Bota (2006) and in this study (table 1).

The cumulative effects of development have caused substantial changes in the groundwater flow system in the Upper Santa Cruz Basin (fig. 4; table 1). Comparison between predevelopment and modern conditions indicates considerable increases in water flowing in and out of the aquifer. Total inflows increased about 51 percent, from 93,000 to 140,000 acre-ft/yr, and outflows increased about 171 percent, from 93,000 to 252,000 acre-ft/yr (table 1). These increases in groundwater flux have implications for groundwater quality. As more water moves into the aquifer, especially if the water has been exposed to contaminant sources, the greater will be the intrinsic susceptibility of the aquifer to contamination. Reversing groundwater gradients so that former discharge areas become recharge areas, which has happened along the channel of the Santa Cruz River, creates new pathways to the aquifer for contaminant sources.

Groundwater Movement

Movement of groundwater in the aquifer of Upper Santa Cruz Basin is controlled by the locations and amounts of recharge and discharge and by the aquifer properties. Under predevelopment conditions, groundwater moved from upgradient mountain-front areas toward the river and then down valley to the north (fig. 5*A*). Changes to the aquifer system due to development can be characterized on a gross scale on the basis of water budget components, and they also can be characterized by changes in groundwater conditions and aquifer characteristics at a more local scale. In the Upper Santa Cruz Basin, such effects of development took the form of steeper vertical hydraulic gradients, thicker unsaturated zones, redirection of groundwater movement toward pumping centers, creation of perched water zones, reductions in aquifer transmissivity, land subsidence, and the capture of perennial streamflow and former riparian evapotranspiration along the channels of the Santa Cruz and Rillito Rivers (Coes and others, 2000).

North of the inferred fault, pumping for municipal, agricultural, industrial, and mining uses has lowered groundwater levels under the central area of Tucson, and also near Green Valley (fig. 5*C*; Arizona Department of Water Resources 1999a) and consequently the direction of groundwater movement has changed from that under predevelopment conditions (figs. 5*A* and 5*B*). By 1995, water-level declines caused by pumping were as great as 200 ft in the Tucson area, and as great as 150 ft in the Green Valley area (fig. 5*C*; Arizona Department of Water Resources 1999a; Anderson and others, 1992). The large water-level declines in the Tucson area have led to measured compaction of the aquifer (Hanson, 1989; Tucson Water, 1993) and predictions of subsidence potentially greater than 10 ft (Anderson, 1988). In less populated areas of the Upper Santa Cruz Basin, the declines have generally been limited to less than about 50 ft (fig. 5*C*; Arizona Department of Water Resources 1999a and 1999b; Anderson and others, 1992).

South of the inferred fault, depth to water has not changed significantly from predevelopment to modern conditions, and is generally less than 100 ft along the Santa Cruz River. North of the inferred fault depths to water are generally between 100 and 500 ft (fig. 5*D*; Arizona Department of Water Resources 1999a). While pumping can create downward hydraulic gradients and promote contaminant transport deep into the aquifer, the resulting water-level declines also dewater the upper part of the aquifer, thereby creating a longer travel path from land-surface sources to the water table and a greater opportunity for contaminant attenuation.

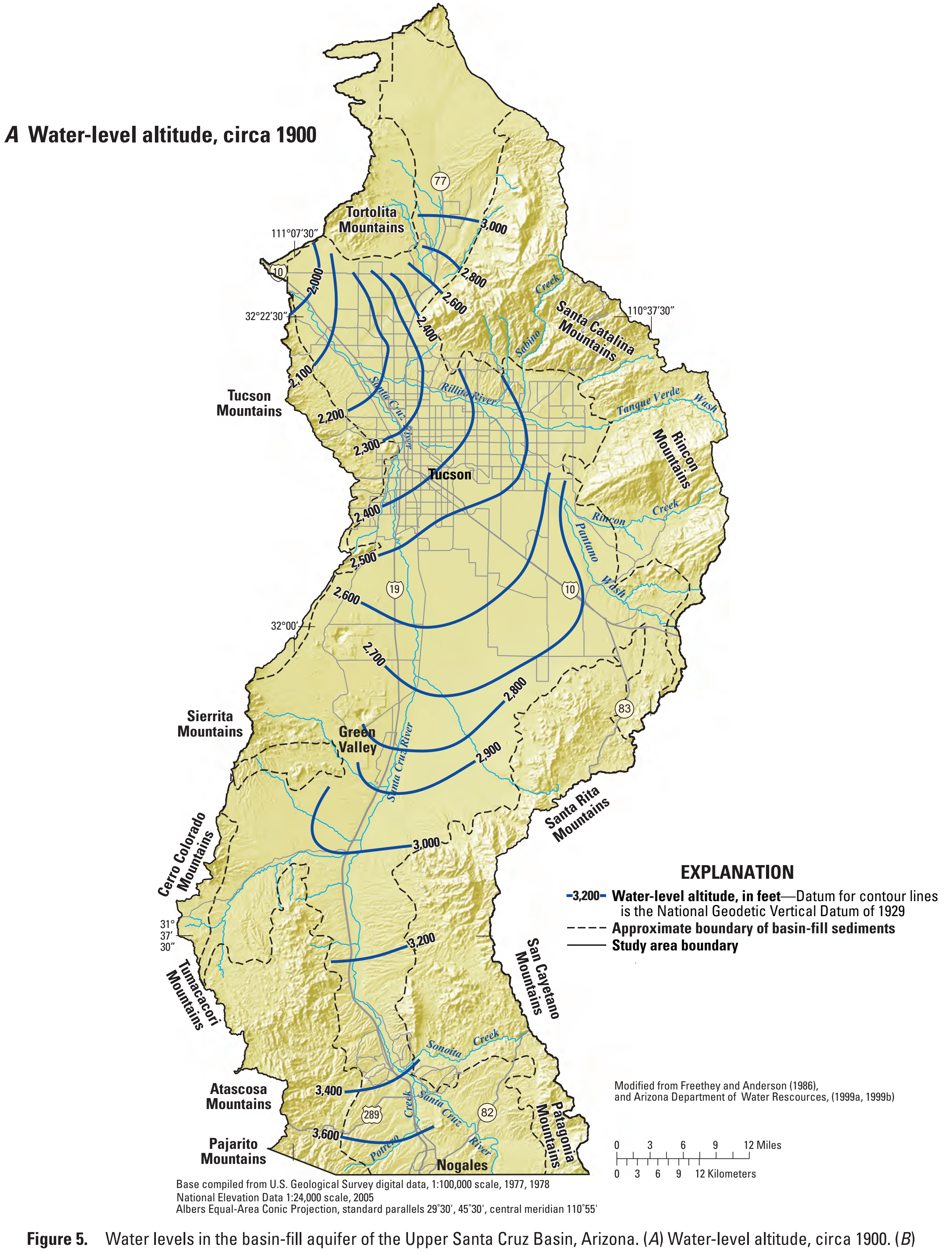

Figure 5. Water levels in the basin-fill aquifer of the Upper Santa Cruz Basin, Arizona. (*A*) Water-level altitude, circa 1900. (*B*) Water-level altitude, 1995. (*C*) Water-level change for 1900–1995. (*D*) Depth to water, 1995.

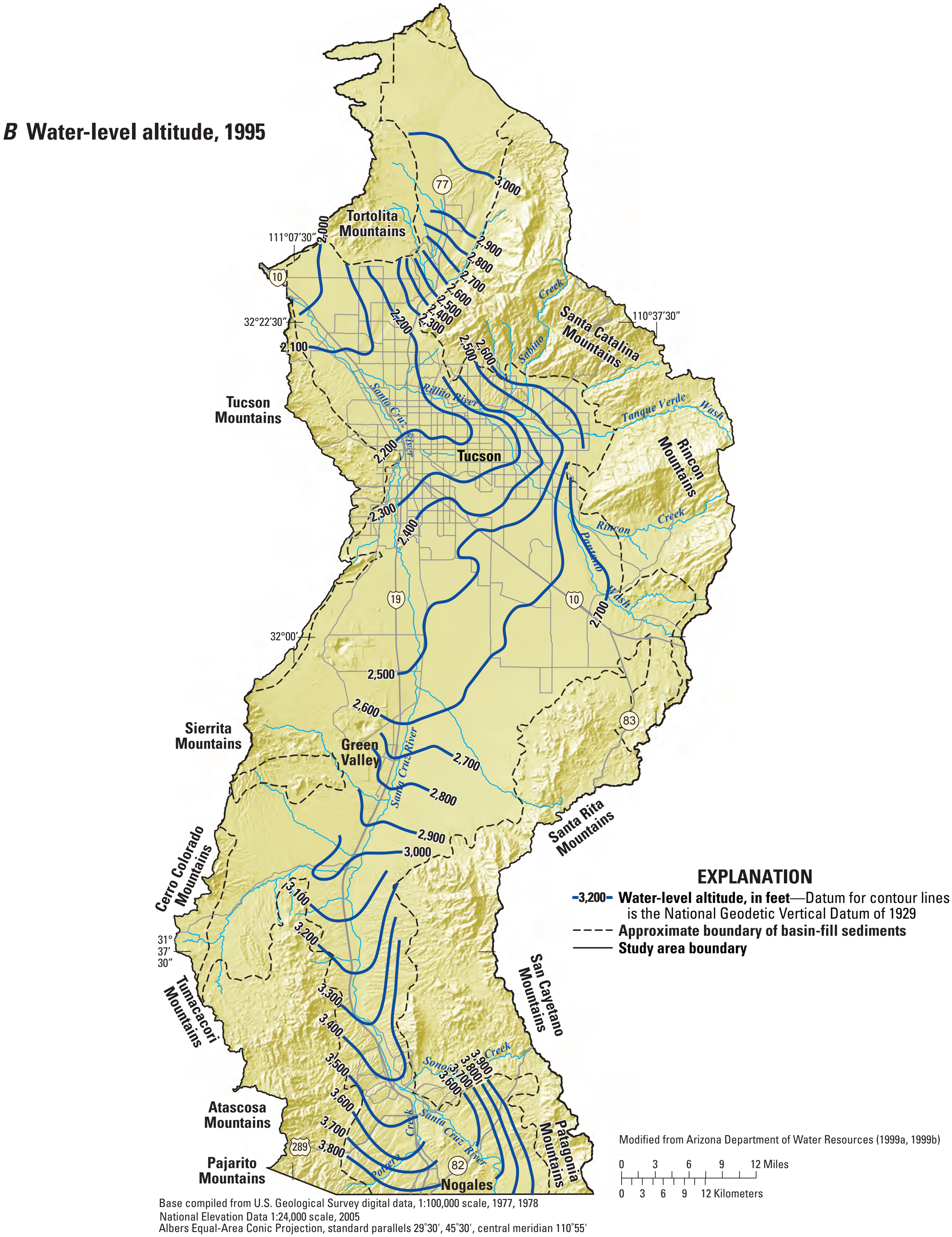

Figure 5. Water levels in the basin-fill aquifer of the Upper Santa Cruz Basin, Arizona. (*A*) Water-level altitude, circa 1900. (*B*) Water-level altitude, 1995. (*C*) Water-level change for 1900–1995. (*D*) Depth to water, 1995—Continued.

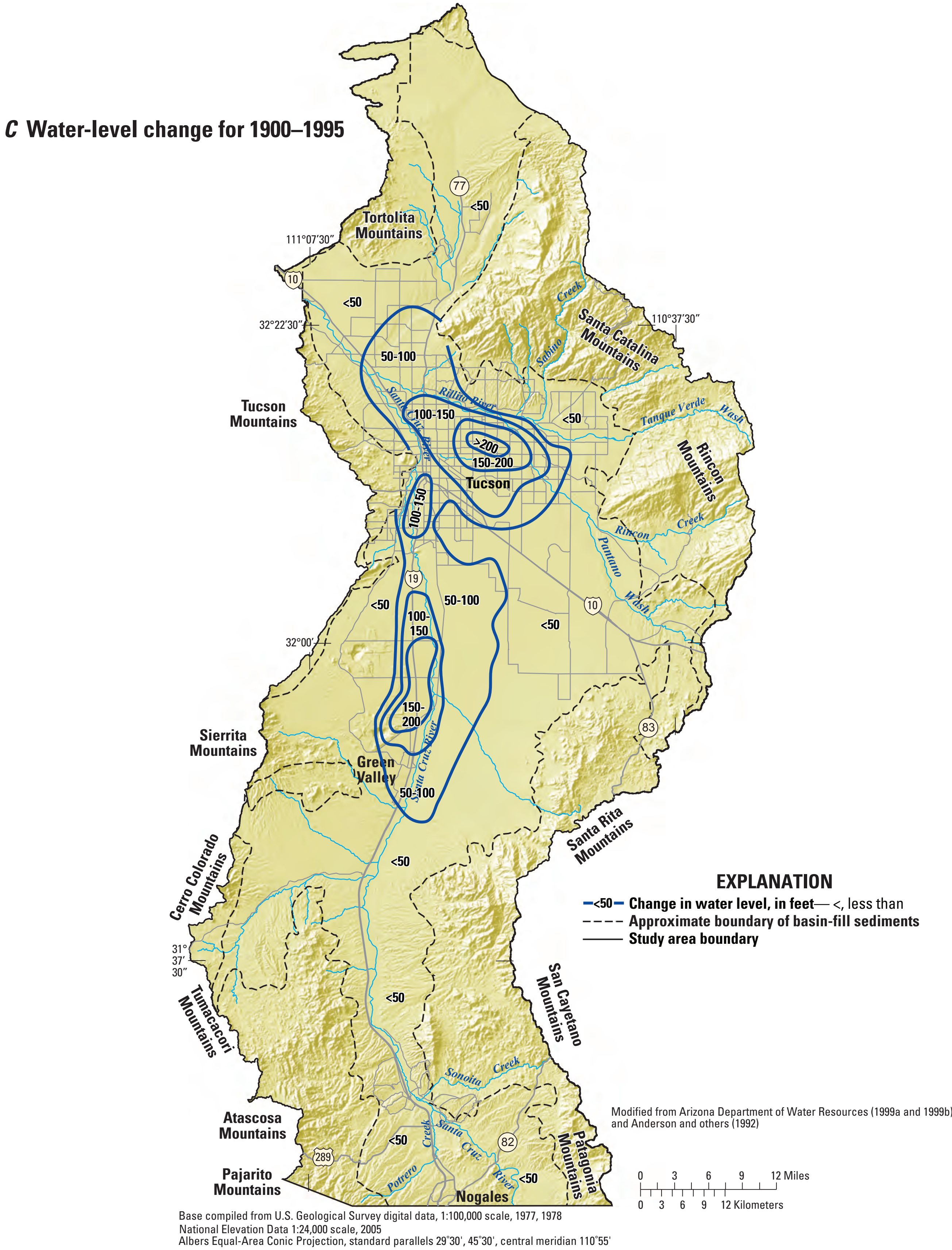

Figure 5. Water levels in the basin-fill aquifer of the Upper Santa Cruz Basin, Arizona. (*A*) Water-level altitude, circa 1900. (*B*) Water-level altitude, 1995. (*C*) Water-level change for 1900–1995. (*D*) Depth to water, 1995—Continued.

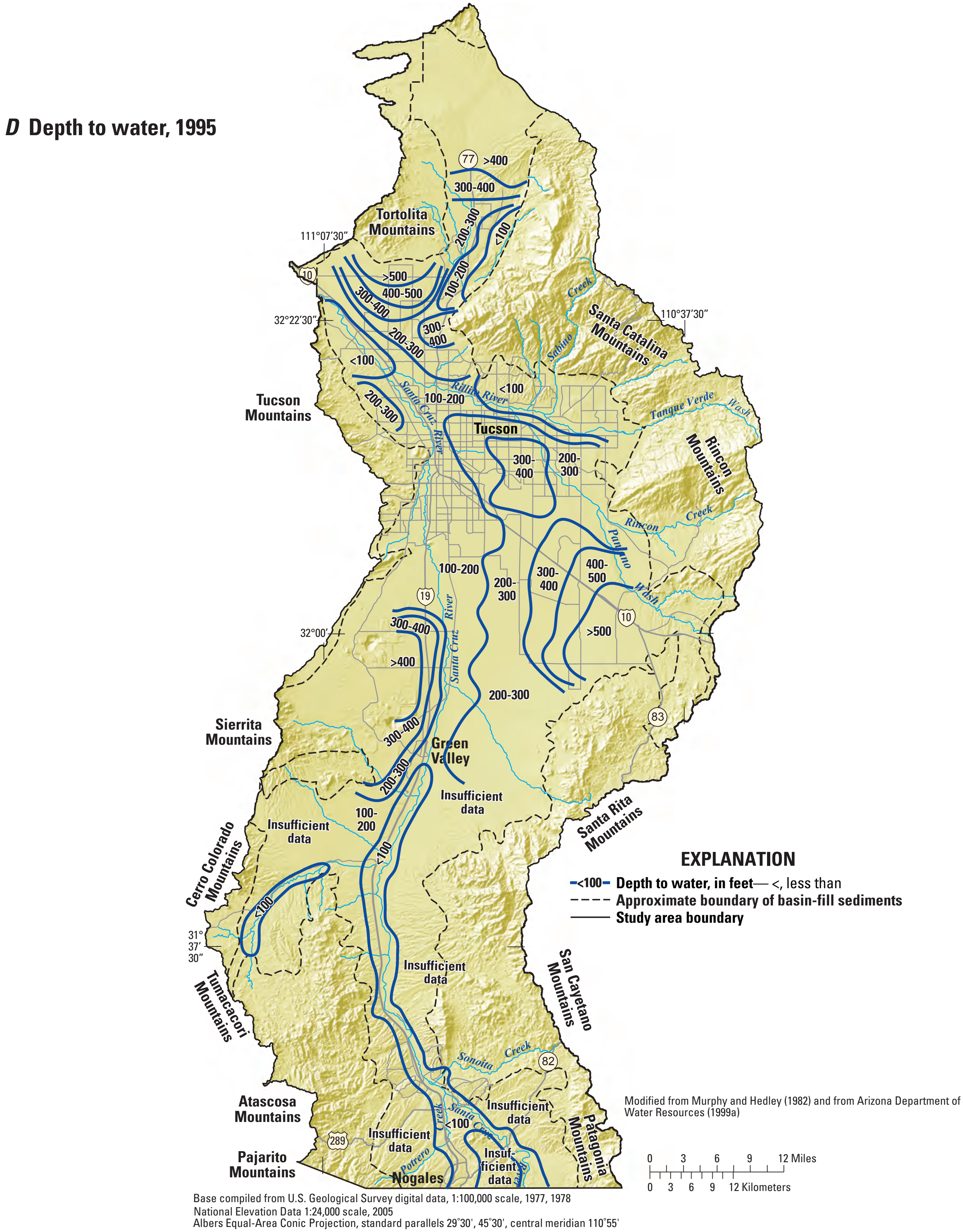

Figure 5. Water levels in the basin-fill aquifer of the Upper Santa Cruz Basin, Arizona. (*A*) Water-level altitude, circa 1900. (*B*) Water-level altitude, 1995. (*C*) Water-level change for 1900–1995. (*D*) Depth to water, 1995—Continued.

Effects of Natural and Human Factors on Groundwater Quality

The quality of water in the basin-fill aquifer system in the Upper Santa Cruz Basin is affected by both natural and human-related factors. That water quality is characterized here on the basis of the analyses of samples collected from 58 wells in 1998 as part of the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) Program (Coes and others, 2000; and Gellenbeck and Anning, 2002). Results of those analyses provided the information that enables an assessment of general chemical parameters, as well as the presence and concentrations of major ions, nutrients, trace constituents, pesticides, and volatile organic compounds relative to location, depth, land use, and geology. Half (29) of the wells were sampled by the ADEQ and the samples were analyzed for major ions, nutrients, trace constituents and tritium. The other 29 wells were sampled by NAWQA scientists and the samples were analyzed for the same constituents, as well as for pesticide and volatile organic compounds (fig. 6). The wells generally were used for domestic or commercial purposes, and all were completed within the developed part of the basin-fill aquifer.

General Groundwater-Quality Characteristics and Effects of Natural Factors

In a broad sense, groundwater in the Upper Santa Cruz Basin is suitable for industrial, agricultural, and municipal consumption, although some areas have water-quality concerns. Seventeen of the 58 wells sampled (29 percent) in 1998 contained one or more constituents at concentrations that exceeded a U.S. Environmental Protection Agency (USEPA) drinking-water standard (fig. 6; U.S. Environmental Protection Agency, 2009). Concentrations exceeded the USEPA primary drinking-water standards for arsenic (10 µg/L) in 7 wells, for fluoride (4 mg/L) in 1 well, and for nitrite plus nitrate (10 mg/L) in 5 wells (fig. 6). The USEPA secondary drinking-water standards were exceeded in 1 well each for iron (300 µg/L), and manganese (50 µg/L), in 2 wells each for pH (6.5 to 8.5 standard units), fluoride (2 mg/L), and sulfate (250 mg/L), and in 14 wells for dissolved solids (500 mg/L; fig. 6). Samples from 8 of 29 wells (28 percent) contained detectable levels of up to 5 pesticides. Volatile organic compounds (VOC) were detected in samples from 15 of 29 wells (52 percent; fig. 6). Analysis of the land use, hydrogeology, and water chemistry indicated that both natural and human-related factors influenced the presence and levels of contaminants in groundwater in the Upper Santa Cruz Basin.

The groundwater of the Upper Santa Cruz Basin is a calcium bicarbonate type, with a median dissolved-solids concentration of 305 mg/L (table 2). The water typically is slightly alkaline, and the median pH was 7.3 standard units. The middle 80 percent of the pH values, excluding the top and bottom 10 percent, were between 6.9 and 7.7 standard units (table 2). The median temperature was 77°F, and the middle 80 percent of the wells had temperatures between 67 and 86°F (table 2).

The most important natural control on groundwater quality in the Upper Santa Cruz Basin is its geology (Coes and others, 2000). Some natural controls, however, do not exhibit statistically significant relations to water quality. Concentrations of major ions, nitrate, and fluoride were not found to be statistically related to the mineralogy of the basin-fill unit or distance from the alluvium of the Santa Cruz River channel (Coes and others, 2000). Additionally, water samples from wells both north and south of the inferred fault exhibited statistically similar chemical characteristics.

Significant differences in the concentrations of dissolved solids, alkalinity, calcium, potassium, chloride, and sulfate were observed between wells less than 1.25 mi (2 km) from major faults in the basin fill and wells greater than 1.25 mi from those faults (faults shown in fig. 1; Coes and others, 2000). These findings corroborate those by Laney (1972), who noted that the concentrations of these constituents were elevated near the Santa Cruz Fault and attributed that fact to upward migration of water from gypsiferous mudstones of the Tinaja beds. Laney also found elevated concentrations of the same constituents downgradient of an area of gypsiferous rocks of the Pantano Formation in an area east of central Tucson.

The median arsenic concentration was 3 µg/L (table 2), and samples from seven wells exceeded the USEPA drinking-water standard for arsenic of 10 µg/L (fig. 6). The occurrence of arsenic in groundwater in Arizona is not considered unusual in that its source is presumed to be minerals in the basin-fill deposits that originated from hydrothermal sulfide and arsenide deposits in the surrounding mountains (Robertson, 1991). Six of the wells with elevated concentrations of arsenic are within about 3 mi of volcanic rocks, which can contain arsenic-bearing minerals (Coes and others, 2000; Welch and others, 1988) and which could be the parent rock for the basin-fill deposits (fig. 6).

The median fluoride concentration was 0.48 mg/L (table 2), and samples from two wells contained fluoride concentrations higher than the USEPA secondary drinking-water standard of 2 mg/L. In both cases, the likely source was attributed to dissolution and/or exchange reactions between groundwater and aquifer materials (Coes and others, 2000; Laney 1972). The Tucson Mountains are primarily volcanic in origin, and fluoride-bearing minerals are abundant in these rocks. Downgradient clays may have exchangeable fluoride adsorbed to ion-exchange sites.

Uranium was detected in samples from all but 4 of the 29 wells sampled for such analysis, and the median concentration was 3.1 µg/L (table 2; data from Tadayon and others, 1999). The largest concentration of uranium detected was 30 µg/L, which is the USEPA primary drinking-water standard. Geologic controls on uranium in basin-fill aquifers of the Upper Santa Cruz Basin, however, were not assessed.

Figure 6. Elevated concentrations and detections of selected compounds in groundwater samples from the Upper Santa Cruz Basin, Arizona, 1998.

Table 2. Summary of groundwater-quality data, Upper Santa Cruz Basin, Arizona, 1998.

[Constituents are dissolved. N/A, not applicable; mg/L, milligrams per liter; µg/L, micrograms per liter; MRL, minimum reporting level. Data from Coes and others (2000) and Gellenbeck and Anning (2002).]

	Number		Minimum reporting level		Percentiles				
	Wells	Detections	Highest	Lowest	10th	25th	50th	75th	90th
pH (standard units)	58	58	N/A	N/A	6.9	7.1	7.3	7.5	7.7
Temperature (degrees Fahrenheit)	58	58	N/A	N/A	67	71	77	82	86
Dissolved oxygen (mg/L)	26	26	N/A	0.1	1.5	3.1	4.3	4.8	6.2
Dissolved solids (mg/L)	58	58	10	1	169	218	305	478	621
Nitrate plus nitrite (mg/L as nitrogen)[1]	58	58	0.05	0.02	0.44	0.68	1.50	3.10	6.90
Phosphorus (mg/L)[1]	58	18	0.020	0.010	[3]0.0003	[3]0.001	[3]0.005	0.030	0.110
Arsenic (µg/L)[4]	55	27	10	1	[3]0.7	[2]2	[2]3	[2]6	12
Barium (µg/L)[4]	55	27	100	1.0	[2]7.1	[2]17	[2]27	[2]48	102
Chromium(µg/L)[1]	55	26	10	1.0	[2]1.6	[2]2.0	[2]2.4	[2]3.0	[2]3.6
Copper (µg/L)[4]	55	11	10	1.0	[2]0.4	[2]0.6	[2]0.9	[2]1.2	[2]1.8
Fluoride (mg/L)[4]	58	54	0.2	0.1	[2]0.17	0.35	0.48	0.65	1.2
Iron (µg/L)[4]	55	19	100	10	[3]1	[3]3	[2]11	[2]23	[2]55
Manganese (µg/L)[1]	55	17	50	1.0	[3]0.2	[3]0.5	[2]1.4	[2]4.5	[2]12
Zinc (µg/L)[4]	55	49	50	1.0	[2]25	[2]38	86	150	320
Uranium (µg/L)	28	24	1	1	[3]0.5	1.3	3.1	7.9	15.9

Notes on other constituents:

Trace constituents—More than 80 percent of the 55 wells with analyses were reported below the highest and lowest MRLs (in parentheses) antimony (5 and 1 µg/L), beryllium (1 and 0.5 µg/L), cadmium (1 and 1 µg/L), lead (5 and 1 µg/L), selenium (5 and 1 µg/L)), and silver (1 and 1 µg/L).

Pesticides—Of the 29 wells analyzed for 86 pesticide compounds, there were 5 compounds detected amongst 8 wells. Compounds included deethylatrazine (6 wells); atrazine (5 wells); and prometon, 2,4-D, and diuron (1 well each).

Volatile organic compounds—Of the 29 wells analyzed for 86 compounds, there were 11 compounds detected amongst 15 wells. Compounds included trichloromethane (7 wells); chloromethane and 1,4-dichlorobenzene (5 wells each); tetrachloroethylene (4 wells); methylbenzene (3 wells); bromodichloromethane and 1,2 dichlorobenzene (2 wells each); trichlorofluoromethane, dichlorodifluoromethane, trichloroethene, and 1,2,4-trimethylbenzene (1 well each).

[1]Summary statistics calculated using maximum likelihood estimation method (Cohen, 1959).

[2]Values are extrapolated between the two minimum reporting levels.

[3]Values are extrapolated below the lowest minimum reporting level.

[4]Summary statistics calculated using probability regression method (Cohen, 1959).

Potential Effects of Human-Related Factors

Human activities can influence groundwater quality, especially when altered land use is coincident with recharge areas. The recharge can carry dissolved contaminants to the aquifer that occur naturally or are introduced by activities at the land surface, such as the application of fertilizers to cropland or lawns. Groundwater quality can also be influenced by human activities in areas where recharge does not normally occur, especially when the contaminants are liquids, such as engine fuels or solvents used for commercial or industrial cleaning purposes.

Water samples were analyzed for tritium to identify wells that received recharge since the 1953 (See Section 1 of this report for a discussion of groundwater age and environmental tracers). Although not statistically tested, tritium detections tended to be in samples from wells near major streams or near the basin margins, where one would anticipate most recharge to the basin-fill aquifer takes place (fig. 6; table 1). Analysis of the locations of wells in which tritium, pesticide, and volatile organic compounds (VOCs) were detected demonstrates the susceptibility of the aquifer to contamination in areas that receive a component of recent recharge. Specifically, of the 12 wells with tritium detections and for which pesticide and VOC analyses are available, one or more pesticides or VOCs were detected in 9 wells (fig. 6). Therefore, 75 percent (9 of 12) wells that received recent recharge, as indicated by tritium detections, were contaminated with pesticides or VOCs.

The land uses that have the greatest potential to affect water quality in the Upper Santa Cruz Basin, on the basis of relative area, are urban and agriculture; mining also may play an important role, though the potential effects of mining on water quality were not evaluated by Coes and others (2000). For wells in urban areas, nitrate plus nitrite (as nitrogen) was elevated in samples of recently recharged water relative to concentrations in samples of “old” (pre-1950) groundwater. The urban areas offer several potential sources of nitrogen compounds, including treated wastewater effluent, lawn and garden fertilizers, and septic-tank systems. In addition, some areas that are currently urban were previously agricultural. Samples from two of five wells with concentrations of nitrate plus nitrite that exceeded the USEPA primary drinking-water standard for nitrate (10 mg/L) were associated with urban land use. One of these exceedences was likely related to wastewater released in Nogales Wash; the same well also contained manganese and dissolved-solids concentrations that exceeded the USEPA secondary drinking-water standards. The second well was in an urban area, but did not contain detectable tritium, and therefore the source of nitrate may be natural.

While the effects of the oxidation-reduction state of the groundwater samples collected in the Upper Santa Cruz River were not determined by Coes and others (2000), most of the nitrogen in the samples is in the form of nitrate, because the groundwater in the Upper Santa Cruz Basin is well oxygenated (data from Coes and others, 2000). The median dissolved-oxygen concentration was 4.3 mg/L (table 2), and concentrations of dissolved oxygen in all but 2 wells were greater than 1.0 mg/L. The oxidation-reduction state may also have affected concentrations of other constituents, such as arsenic, iron, and manganese.

Agriculture has long been practiced in the Upper Santa Cruz Basin, and although its effects on water quality are not widespread, pesticide detections were generally related to agricultural activities (Gellenbeck and Anning, 2002). Pesticides were detected in samples from 8 of 29 (8 percent) wells (fig. 6; table 2). The compounds detected included deethylatrazine, atrazine, prometon, 2,4-D, and diuron, although not all were found in each well. No pesticide concentrations exceeded any USEPA drinking-water standards. In 5 wells, both atrazine and and its degradation product, deethylatrazine, were detected. The herbicide atrazine is used both in agricultural and nonagricultural settings. Owing to their persistence and moderate to high mobility in the subsurface, detections of these two compounds are expected in areas where atrazine is applied. Three of the 5 wells in which atrazine and deethylatrazine were detected are co-located with historical agricultural areas where elevated concentrations of calcium, potassium, alkalinity, and dissolved solids also have been found (Coes and others, 2000). The remaining two wells are not directly adjacent to current or historically agricultural areas; the pesticides in water from those wells may have been transported from agricultural areas by the Santa Cruz River, or they may have come from pesticide use in urban areas.

VOCs are generally indicative of urban activities, and one or more compounds were found in samples from 15 of 29 wells (52 percent) analyzed for VOCs (fig. 6; table 2; Gellenbeck and Anning, 2002). Compounds detected included:

Trichloromethane (chloroform; 7 samples)	1,2 dichlorobenzene (2 samples)
Chloromethane (5 samples)	Trichlorofluoromethane (CFC-11; 1 sample)
1,4,-dichlorobenzene (5 samples)	Dichlorodifluoromethane (CFC-12; 1 sample)
Tetrachloroethylene (PCE; 4 samples)	Trichloroethene (TCE; 1 sample)
Methylbenzene (3 samples)	1,2,4-trimethylbenzene (1 sample)
Bromodichloromethane (2 samples)	

Two wells had samples with 5 VOC detections, while samples from the remaining wells had less detections. The concentration of trichloromethane in one well exceeded the drinking-water standards for that compound established by the USEPA.

Detections of VOCs were qualitatively related to land use in some, but not all, cases (Gellenbeck and Anning, 2002), yet such detections substantiate the potential for activities at the surface to cause the contamination of the underlying groundwater. For one well near the Mexico border, VOC detections were hypothesized to be related to its location near Nogales Wash, where VOCs including trichloroethene and many of its degradation products have been detected previously in surface-water samples. For another well, VOC detections were attributed to its location downgradient both from municipal wastewater releases to the Santa Cruz River and from a landfill near the river. Yet for a third well located in a newly developed residential area that was previously used for rangeland; no definitive sources of VOCs were identified.

Trichloromethane, also known as chloroform, was detected in samples from 7 wells. Chloroform, which is used as a solvent, is also a byproduct of the chlorination of water delivered for public supply. It may enter the ground through lawn irrigation, leaking water mains, and sewers (Squillace and others, 1999).

Analysis of data on major ions, nutrients, and selected trace constituents for six wells sampled annually from the 1980s to 1998 indicated notable trends (Coes and others, 2000). Concentrations of nitrate plus nitrite increased at one well in an area of continued agriculture and decreased in a well where urban development had replaced agriculture. Nitrate plus nitrite concentrations increased, however, at a well where land was converted from rangeland to urban use; lawn fertilizers are thought to contribute to this trend. Concentrations of constituents did not change significantly at three additional wells: one located where land use has been consistently agricultural, one where land use has changed from rangeland to urban, and one where land use has changed from agricultural to urban.

Summary

The Upper Santa Cruz Basin in the Basin and Range Physiographic Province of south central Arizona consists of an elongated sediment-filled valley surrounded by mountain ranges. The basin has a warm arid to semiarid climate, but wide variations in elevation cause large differences in precipitation and temperature. Land use in the basin is predominantly rangeland and urban, with other land uses and land covers including agriculture being minor. In the late 1990s, estimated groundwater withdrawals were about 221,000 acre-ft/yr, of which about 55 percent was for municipal uses, 26 percent for industrial uses, and 19 percent for agricultural uses. Other water sources include treated municipal wastewater and water imported from the Colorado River by the Central Arizona Project.

The basin-fill aquifer north of an inferred fault across the valley consists of unconsolidated to semiconsolidated sediments of the Pantano Formation, Tinaja beds, and Fort Lowell Formations. South of the inferred fault, the basin is filled by unconsolidated to semiconsolidated sediments of the Nogales Formation, older alluvium, and younger alluvium. Water levels in the basin-fill aquifer generally reflect the configuration of the valley floor, and consequently groundwater flows from the basin margins toward the center and then northward along the basin axis. The aquifer is replenished primarily through mountain-front recharge, mountain-block recharge, water losses from the channel of the Santa Cruz River, and with water-resources development, incidental recharge from human activities. Water leaves the aquifer primarily through evapotranspiration, and with water-resources development, through pumping from wells.

The cumulative effects of development have caused substantial changes in the groundwater flow system. Estimated total recharge in the basin-fill aquifer has increased by about 50 percent, from 93,000 to 140,000 acre-ft/yr, and discharge has increased about 170 percent, from 93,000 to 252,000 acre-ft/yr as a result of the development. These increases in flux have implications for groundwater quality. The more water moving into the aquifer, especially if exposed to contaminant sources, the greater intrinsic susceptibility to contamination. Reversing groundwater gradients and thereby changing an area from a discharge area to recharge area which has occurred along the Santa Cruz River, creates new entryways to the aquifer for contaminants. The effects of development took the form of steeper vertical hydraulic gradients, thicker unsaturated zones, redirection of groundwater movement toward pumping centers, creation of perched water zones, reductions in aquifer transmissivity, land subsidence, and the capture of perennial streamflow and former riparian evapotranspiration along the channels of the Santa Cruz and Rillito Rivers.

Analyses of samples collected from 58 wells in 1998 as part of a cooperative investigation by the National Water-Quality Assessment Program and the Arizona Department of Environmental Quality indicates that the water in the basin-fill aquifer of the Upper Santa Cruz Basin generally is suitable for industrial, agricultural, and municipal uses, although some areas have water-quality concerns. About 29 percent of the wells samples contained one or more constituents or properties (such as arsenic, fluoride, nitrate, iron, manganese, pH, or dissolved solids) that exceeded a state or federal water-quality standard. In addition, samples from 28 percent of the wells contained detectable levels of pesticides and samples from 52 percent of the wells contained detectable levels of one or more volatile organic compounds (VOCs).

Analysis of the land use, hydrogeology, and the chemistry of groundwater in the Upper Santa Cruz Basin indicated that both natural and human-related factors influenced the presence and levels of contaminants in the water (table 3). Natural factors, primarily basin geology and the geochemical processes between the groundwater and basin-fill sediments, were attributed as the cause of elevated concentrations of dissolved solids, alkalinity, calcium, potassium, chloride, sulfate, arsenic, and fluoride. The increase in groundwater flux through the aquifer as a consequence of the development, use, and disposal of water has increased the intrinsic susceptibility of the aquifer to contamination from sources present or generated at the land surface. For example, the use of chemical compounds in urban and agricultural areas that receive focused recharge from the infiltration of excess irrigation water has resulted in the presence of pesticides and VOCs in the basin-fill aquifer.

Table 3. Summary of documented effects of natural and human-related factors on groundwater quality in the Upper Santa Cruz Basin, Arizona.

Groundwater-quality effect	Cause	General location(s)	Reference(s)
Primarily natural factors			
Elevated concentrations of dissolved solids, alkalinity, calcium, potassium, chloride, and sulfate	Upward migration of groundwater from gypsiferous mudstones of the Tinaja beds	Within about 1.25 miles of major faults in basin-fill sediments, such as the Santa Cruz Fault	Laney (1972), Coes and others (2000)
Elevated concentrations of dissolved solids, alkalinity, calcium, potassium, chloride, and sulfate	Movement of groundwater through gypsiferous sediments of the Pantano Formation	Vail to central Tucson	Laney (1972)
Elevated concentrations of arsenic	Geochemical reactions between the groundwater and compounds in the basin fill that are presumed to come from hydrothermal sulfide and arsenide deposits in the surrounding mountains	Along the Santa Cruz River and near volcanic rocks in the mountains along the basin margins	Robertson (1991), Coes and others (2000)
Elevated concentrations of fluoride	Geochemical reactions between the groundwater and compounds in the basin fill that are presumed to come from fluoride-bearing minerals in volcanic rocks	Localized parts of basin	Laney (1972), Coes and others (2000)
Primarily human-related factors			
Elevated concentrations of nitrate	Application of nitrogen fertilizers and irrigation of crops and urban landscaped areas; infiltration from septic tanks and treated wastewater released to the Santa Cruz River	Localized parts of basin	Coes and others (2000)
Occurrence of pesticides	Application of pesticide compounds to croplands and urban landscaped areas	Agricultural and urban areas	Gellenbeck and Anning (2002)
Occurrence of volatile organic compounds	Urban and industrial activities on the land surface and subsequent transport of compounds to aquifer	Urban areas	Gellenbeck and Anning (2002)
Occurrence of pesticides and volatile organic compounds	Urban or agricultural use of organic compounds	Areas susceptible to contamination, especially those which receive modern (post-1950) focused recharge, such as along streams and irrigated areas	This study

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