Section 9.—Conceptual Understanding and Groundwater Quality of the Basin-Fill Aquifer in the Sierra Vista Subbasin of the Upper San Pedro 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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Basin Overview

The Sierra Vista subbasin (fig. 1) hosts a growing human population as well as a remarkable riparian ecosystem along the San Pedro River in southeastern Arizona. Groundwater in this subbasin is important because it is the primary source of water for the residents and also because it sustains the base flow of and the riparian ecosystem along the San Pedro River. Groundwater development to support the population and the economic and cultural activities over the past century has caused substantial changes in the basin-fill aquifer. These changes include a 38 percent increase in recharge and a 103 percent increase in discharge. These and other changes to the aquifer have resulted in an increase in its intrinsic susceptibility to contamination, and the effects of both natural and human-related factors on groundwater quality are discussed in this section of the report.

The Sierra Vista subbasin is a 1,826-mi^2 hydrogeologic area defined in McKinney and Anning (2009) and is roughly coincident with the Sierra Vista groundwater subbasin defined by the state of Arizona in the southern part of the upper San Pedro Basin. The United States-Mexico border forms the southern study area boundary and excludes about 700 mi^2 of the subbasin in Mexico that drains northward (fig. 1). The state of Arizona further divides the Sierra Vista groundwater subbasin into two surface-water drainages: the Sierra Vista subwatershed to the south and the Benson subwatershed to the north (fig. 1). The results of several hydrologic studies of these two subwatersheds are integrated in this discussion.

The San Pedro River drains both the surface and groundwater systems of the Sierra Vista subbasin and is perennial for about 11 mi (Leenhouts and others, 2006). One tributary to the San Pedro River, the Babocomari River, also includes perennial reaches. Nearly all other reaches of, and tributaries to, the San Pedro, with the exception of short reaches in the mountains, are ephemeral. An act of Congress in 1988 formally protected much of the riparian ecosystem as the San Pedro Riparian National Conservation Area (fig. 1), which is now managed by the U.S. Bureau of Land Management. The biological importance of the river stems from the ecosystem contrast between the riparian corridor and the surrounding area. The riparian corridor supports a diverse biota and is a primary corridor for migrating birds. The riparian corridor provides habitat for more than 400 bird species, and the Sierra Vista subbasin supports the second highest known number of mammal species in the world (Goodrich and others, 2000).

The climate in the Sierra Vista subbasin is semiarid, but a wide range in altitude causes significant variations in precipitation and temperature. Altitude along the river ranges from 4,300 ft at the United States-Mexico border in the south to 3,300 ft at the downstream end of the basin in the north, and the highest altitudes extend to 9,500 ft in the Huachuca Mountains. Annual rainfall averages about 30 in. in the mountains and about 12 in. on the low basin floor (Leenhouts and others, 2006).

Temperatures in the Sierra Vista subbasin range from a mean maximum temperature of 80°F to a mean minimum temperature of 45°F (1971–2000 averages recorded in Benson). Annual precipitation amounts for 1971–2000 are 12.3 in. in Benson, 14 in. in Tombstone, and 15.2 in. in Sierra Vista, though rainfall in this area is highly variable, both spatially and temporally. About 25 percent of the average annual precipitation is attributed to winter frontal storms during November through February that typically are longer in duration and less intense than storms during the remainder of the year. During winter, most of the vegetation is inactive and nighttime frosts are common. During April through June, days are typically dry and hot. During July through September, the Sierra Vista subbasin is under the influence of the North American Monsoon (Adams and Comrie, 1997), which brings in moist subtropical air that combines with intense surface heating to generate high intensity, typically short duration convective storms. About 60 percent of the annual precipitation in the valley occurs during the monsoon (Goodrich and others, 2000).

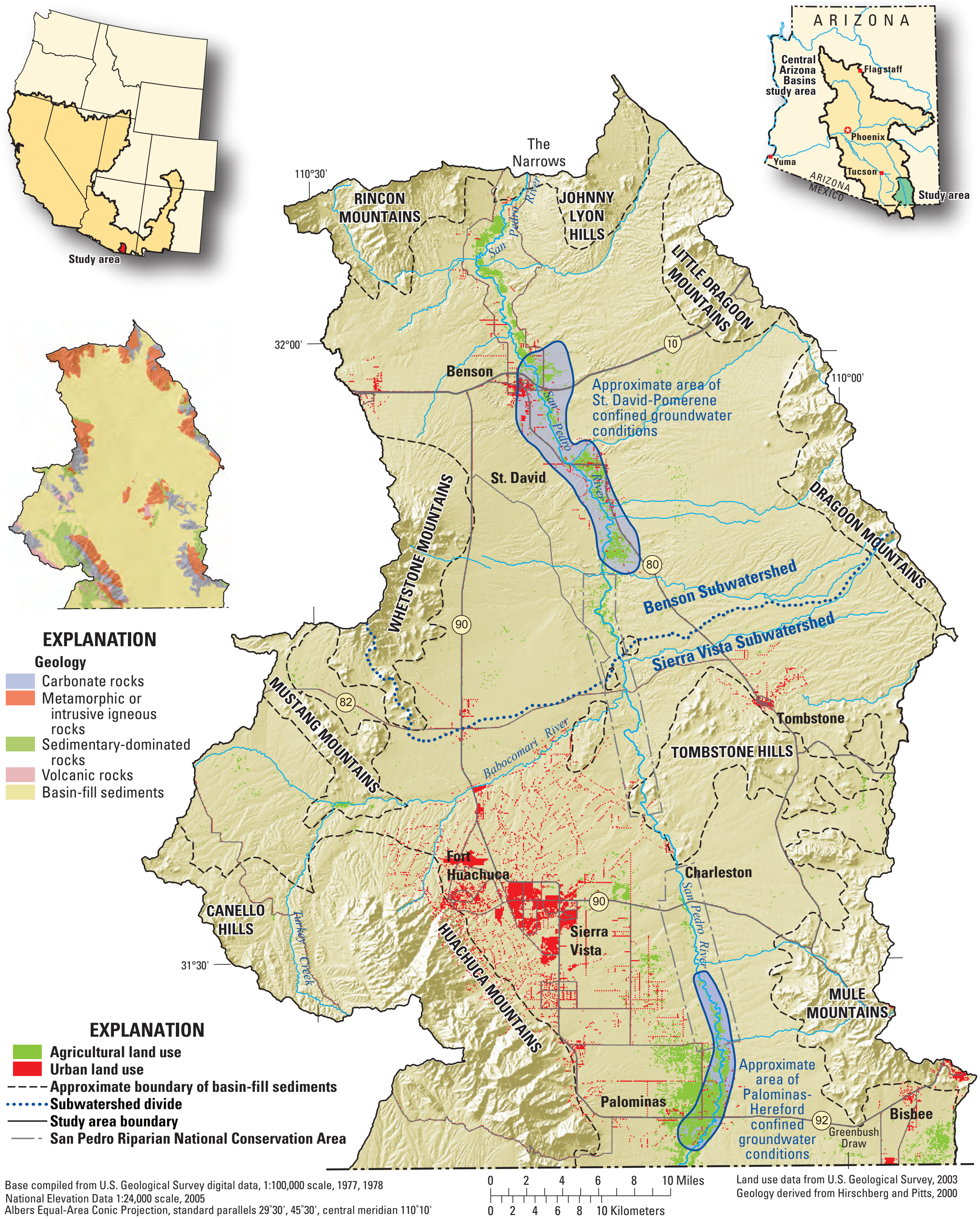


Figure 1. Physiography, land use, and generalized geology of the Sierra Vista subbasin, Arizona.

As is typical for semiarid to arid regions, potential evaporation in the Sierra Vista subbasin exceeds normal annual precipitation. A pan evaporation study at a site along the San Pedro River measured a total open-water evaporation rate of 46 in. for 2003, whereas the potential evapotranspiration was 70 in. (Scott and others, 2006). As a result of the evaporation excess, recharge is generally thought not to occur through the open desert floor, but instead is concentrated at the mountain fronts or at other locations where water collects, even if only temporarily (Scanlon and others, 1999).

Land use in the alluvial basin, excluding the surrounding mountainous areas, includes about 3 percent urban and 3 percent agricultural lands (McKinney and Anning, 2009). Land use patterns on the valley floor of the Sierra Vista subbasin have become increasing urban over the last several decades, particularly in the area of Sierra Vista and Fort Huachuca (fig. 1). Some of this urbanization has occurred to provide housing and support services for Fort Huachuca. In addition, the pleasant climate and environs have made the area a retirement destination. Sierra Vista was incorporated in 1956 with 1,671 people, and in 2000 hosted a population of 37,775 (includes Fort Huachuca; City of Sierra Vista, 2006). On the basis of 2000 data, the total population of the Sierra Vista subbasin is estimated to be about 80,000 people (McKinney and Anning, 2009).

Water Development History

The Sierra Vista subbasin has a long history of human habitation and water development. Although the earliest Paleo-Indian sites date from the late Pleistocene (Haynes, 1987), the human activities that have affected the water resources of the region likely occurred within the past 400 to 500 years. During this period, the valley was explored, settled, and exploited primarily by three cultures—the Spanish, Mexican, and Anglo (Trischka, 1971; Hereford, 1993). The area has also hosted Native American populations such as the Sobaipuri Indians, who grew crops in irrigated fields.

The Spanish exploratory expeditions of the 1600s and 1700s kept the first records of water use in the Sierra Vista subbasin. Around this time, a population of about 2,000 Sobaipuri Indians was observed to be farming using diversions from the San Pedro River for irrigation (Arizona Department of Water Resources, 2005a).

Padre Eusebio Francisco Kino led the first Christian missions into the area in the late 1600s and early 1700s, and is credited with establishing cattle ranching in the San Pedro Valley (Hereford, 1993). Attempts to attract settlers to the area in significant numbers were unsuccessful until the late 19th century owing to Apache depredations (Hereford, 1993), although some ranching and farming were practiced through the 1800s. Although these agricultural industries undoubtedly used water, information about the amounts, locations, and character of such use is scarce. Fort Huachuca was established in 1877 to provide a base for protection of settlers and has remained an important part of the area's population to the current day.

Utilization of water began to increase significantly in the late 1800s and was dominated until about the mid 1980s by two industries: mining and agriculture. The discovery of lead, copper, and silver deposits near Tombstone and Bisbee in the late 1870s initiated significant settlement and development of the Sierra Vista subbasin (Rodgers, 1965). Although Tombstone's boom was short-lived, around 1880 it was briefly the largest town in Arizona with a population of about 15,000 (Arizona Department of Water Resources, 1991). During development of Tombstone's mine in 1881, workers struck water at 520 ft below land surface. Water was removed from the mine at an estimated 1,000 gallons per minute; Tombstone Mayor John Clum urged residents to water their lawns with the excess water (Arizona Department of Water Resources, 1991). Removal of water from the mine ended temporarily in 1886 when a fire destroyed the pump works. Pumping was reinitiated from about 1902 to 1911, with maximum withdrawals of about 6,000 acre-ft in 1910. A brief period of minor pumping from the mine occurred around 1955. The other significant mining operation was the Copper Queen mine in Bisbee. Rich ore deposits were first discovered in the Mule Mountains near Bisbee in the late 1870s. Withdrawals of water from the mine began in 1905 and quickly increased to about 6,000 acre-ft/yr. Maximum annual withdrawals exceeded 10,000 acre-ft/yr in the 1940s, and pumping ceased in about 1987 (Pool and Dickinson, 2007). The area of the Copper Queen mine straddles the Upper San Pedro and Douglas Basin divide, and it is likely that some portion of water drawn from the mine was Douglas-Basin water. Mining was a major industry in the United States portion of the basin through about 1985 and played a role in the establishment of several communities. Another large copper mine has pumped groundwater upgradient of the Sierra Vista subbasin near Canenea, Mexico (Pool and Dickinson, 2007).

Agricultural water use increased in the Sierra Vista subbasin from the late 1800s to about 1985, but generally decreased through 2006. The bulk of irrigated acreage, mostly alfalfa, has historically been in the northern half of the basin in the Benson subwatershed. The Arizona Department of Water Resources (1991) estimated that about 3,500 acres of land were under cultivation in 1899. By 1934, total cultivated acreage had increased to 4,200, of which about 3,300 acres were irrigated by diversions from the San Pedro River near St. David and Benson (Bryan and others, 1934). At this time, about 650 acres of alfalfa were irrigated near Bisbee using groundwater pumped from the copper mines. Areas of land irrigated using diversions from the San Pedro River were also noted in the Palominas-Hereford area, but were not quantified (Bryan and others, 1934).

In 1952, the area of cultivated land in the Sierra Vista subbasin was estimated at about 5,600 acres, with a net demand for groundwater of 14,500 acre-ft/yr (Heindl, 1952). All other uses were estimated at about 3,800 acre-ft/yr, for a total estimated basin use of 18,300 acre-ft/yr. By 1968, estimated total annual basin groundwater use was 35,300 acre-ft, including 22,100 acre-ft (62.6 percent) for agriculture, 6,600 acre-ft (18.7 percent) for mining and industrial uses, and 6,600 acre-ft (18.7 percent) for municipal and all other purposes (Roeske and Werrell, 1973). About 28,300 acre-ft of groundwater were pumped in the Sierra Vista subbasin in 1985, with about 13,300 acre-ft (47.0 percent) supporting agriculture, 13,000 acre-ft (45.9 percent) used for municipal purposes, and 2,000 acre-ft (7.1 percent) for industrial and other purposes (Arizona Department of Water Resources, 2005a).

After 1985, groundwater use for irrigation in the Sierra Vista subbasin declined owing to retirement of agricultural lands. Increases in population, however, caused increased groundwater pumping for municipal purposes. In 2002, total water use was 31,100 acre-ft, of which 27,800 acre-ft (89.4 percent) was supplied by groundwater (Arizona Department of Water Resources, 2005b). Total agricultural use was estimated at about 9,800 acre-ft (31.5 percent of total), with about 7,500 acre-ft (76.5 percent) being supplied by groundwater and 2,300 acre-ft (23.5 percent) from San Pedro River diversions. Total municipal water use was about 18,900 acre-ft (60.7 percent of total), of which 17,900 acre-ft (94.7 percent) was supplied by groundwater and the remaining 1,000 acre-ft (5.3 percent) supplied by surface water and treated municipal effluent. Other water use, including that by industry, was about 2,400 acre-ft (7.7 percent of total) and was supplied by groundwater.

Future water development in the Sierra Vista subbasin will likely be highly influenced by Section 321 of Public Law 108-136, a congressional directive to the residents of the Sierra Vista subwatershed that they determine and attain a sustainable yield of groundwater withdrawals by 2011.

Hydrogeology

The San Pedro River flows through typical basin and range physiography. Basins have formed in the grabens between block-faulted mountain ranges and have filled with Miocene through early Pleistocene sediments eroded from the uplifted blocks. The result is a series of roughly linear and parallel northwest-trending complexes of mountains and basins (Brown and others, 1966; fig. 1).

The Sierra Vista subbasin is bounded on the east by the Mule and Dragoon Mountains and on the west by the Huachuca and Whetstone Mountains (fig. 1). The Huachuca, Whetstone, and Dragoon Mountains, as well as the Rincon Mountains at the northwestern edge of the subbasin, are composed largely of granite, limestone, dolomite, conglomerate, and claystone ranging in age from Precambrian to Cretaceous (fig. 1; Drewes, 1996). The Mule Mountains consist of early Precambrian schist unconformably overlain by Mesozoic conglomerate, red mudstone, siltstone, and limestone (fig. 1; Hayes, 1970).

The earliest sedimentary unit in the basin is the Oligocene to lower Miocene Pantano Formation (fig. 2; Gettings and Houser, 2000). It is described by Brown and others (1966) as semiconsolidated brownish-red to brownish-grey conglomerate, and according to Gettings and Houser (2000), it is as much as 2,300-ft thick at the southern end of the study area. The Pantano Formation yields water through fractures to many wells in the Sierra Vista area and is an important water-bearing unit in some locations (Pool and Coes, 1999).

Alluvial sediments that are as much as about 750-ft thick overlie the Pantano Formation (Pool and Coes, 1999) and, for the purposes of this study, are subdivided into three groups: basin-fill sediments, terrace deposits, and stream alluvium (fig. 2). The basin-fill sediments are further divided into upper and lower units. The lower basin fill is Miocene to Pliocene in age and consists largely of interbedded gravel and sandstone, but can include clay, siltstone, and silt (Pool and Coes, 1999). Sorting in gravel beds and sandstones is generally poor, and the degree of cementation is variable (Brown and others, 1966). In most of the basin, the lower basin-fill sediments serve as an important water-bearing unit; its thickness ranges from about 150 to 350 ft. In the southern part of the subbasin, hydraulic conductivity values of the lower basin fill average about 3.2 ft/d for sand and gravel, about 2.6 ft/d for interbedded sand and gravel, and about 0.016 ft/d for silt and clay (Pool and Dickinson, 2007).

The upper basin-fill sediments consist of Pliocene- to Pleistocene-age reddish-brown clay, silt, sand, and gravel that are generally weakly cemented (Pool and Coes, 1999). The lithology grades from gravels with high permeability in the fan deposits along the flank of the Huachuca Mountains to relatively impermeable silts and clays near Charleston. Aquifer thickness is 400 ft or less. In the southern part of the subbasin, hydraulic conductivity values of the upper basin fill average about 11 ft/d for sand and gravel, about 2.9 ft/d for interbedded sand and gravel, and about 0.75 ft/d for silt and clay (Pool and Dickinson, 2007).

The terrace deposits began forming in the middle Pleistocene when changes in the climatic regime caused a transition from deposition to erosion (Brown and others, 1966). These deposits mark the location of the San Pedro River through the process of several episodes of downcutting, and extend from the base of the mountains to the San Pedro's current flood plain. The terrace deposits form a veneer near the mountains, but can be as much as 50 to 100 ft thick in erosional channels near the current San Pedro River (Pool and Coes, 1999). The sediments are a poorly sorted mixture of gravel, sand, and clay from local sources (Brown and others, 1966).

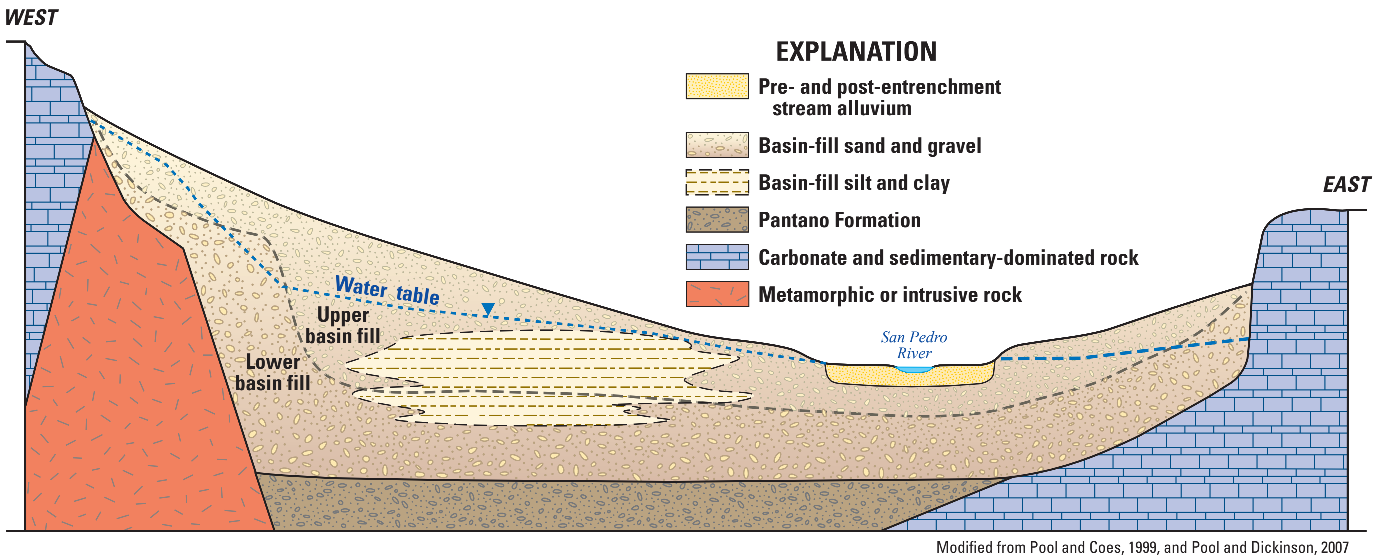


Figure 2. Generalized hydrogeologic cross section, Sierra Vista subbasin, Arizona.

The youngest terrace deposit comprises the modern stream alluvial sediments. The modern stream alluvium is subdivided into the pre-entrenchment and post-entrenchment units (fig. 2). They are Holocene in age, generally 20 ft or less in thickness, as much as 1 mi wide, and have average hydraulic conductivity values of about 25 ft/d (Pool and Dickinson, 2007). The post-entrenchment alluvium is equivalent to the present-day flood plain. The pre-entrenchment alluvium is at a higher altitude, is only rarely flooded, and is basically flat lying. The pre-entrenchment alluvium is also called the terrace. Portions of the pre-entrenchment terrace in the San Pedro Riparian National Conservation Area were cleared for agricultural use in the mid-20th century.

Conceptual Understanding of the Groundwater Flow System

The predevelopment groundwater flow system of the Sierra Vista subbasin resembles 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 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 San Pedro River, and with water-resources development, incidental recharge from human activities. Water leaves the aquifer primarily through evapotranspiration, and with water-resources development, through groundwater pumping. 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 through the basin-fill aquifer is summarized in the groundwater budget for predevelopment and modern conditions in the Sierra Vista subbasin (fig. 3; table 1). Natural predevelopment flow in the aquifer is characterized by a predominance of recharge from stream-channel infiltration near the contact between the low-permeability rocks of the mountains and basin fill, and discharge along the San Pedro River either as contributions to stream baseflow or as evapotranspiration. This pattern is consistent with many arid to semiarid environs where orographically induced precipitation leads to excess available water in and near the mountains. Recent evidence, however, has suggested that about 12 to 19 percent of total recharge in the Sierra Vista subwatershed of the Sierra Vista subbasin occurs at some distance from the mountain front in ephemeral stream channels where runoff water is concentrated (Coes and Pool, 2005). Relatively deep groundwater levels across most of the basin prevent direct access by plant roots except near the river. In addition, a small fraction of total groundwater discharge occurs through springs.

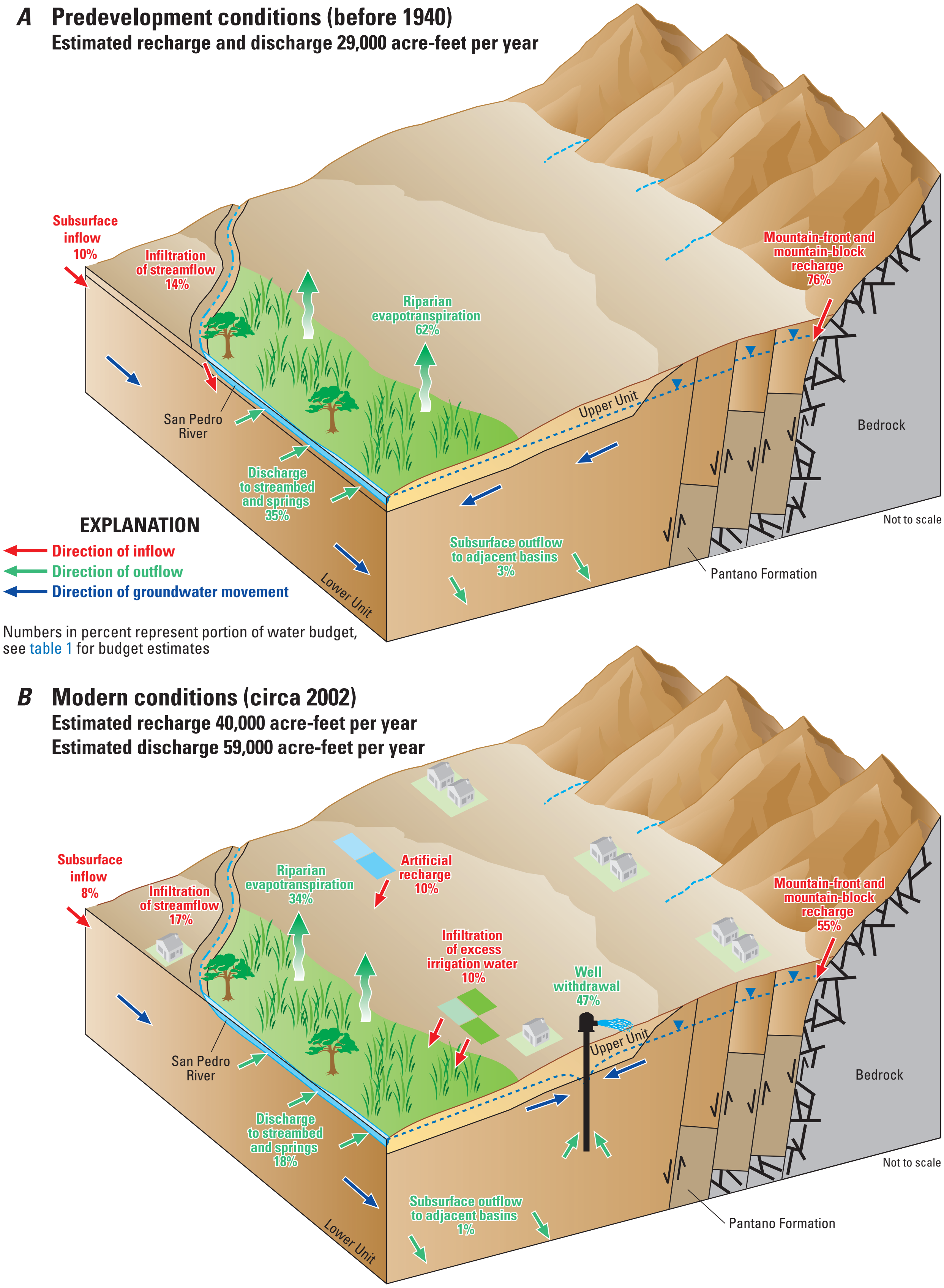


Figure 3. Generalized diagrams for the Sierra Vista subbasin, Arizona, showing components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

Table 1. Estimated groundwater budget for the basin-fill aquifer in the Sierra Vista subbasin, 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 under predevelopment and modern conditions were derived from the footnoted sources. 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. <, less than]

Budget component	Predevelopment conditions (before 1940)	Modern conditions (2002)	Change from predevelopment to modern conditions
Estimated recharge			
Subsurface inflow	[1]3,000	[1]3,000	0
Mountain-front and mountain-block recharge	[1]22,000	[1]22,000	0
Infiltration of precipitation on basin	0	0	0
Infiltration of streamflow	[2]4,000	[2]7,000	3,000
Infiltration of excess irrigation water	0	[3]4,000	4,000
Artificial recharge	0	[1,4]4,000	4,000
Total recharge	29,000	40,000	11,000
Estimated discharge			
Subsurface outflow to adjacent basins	[1]<1,000	[1]<1,000	0
Evapotranspiration	[1,5]18,000	[1,6]20,000	2,000
Discharge to streams	[7]10,000	[7]10,000	0
Discharge to springs	[8]<1,000	[8]<1,000	0
Well withdrawals	0	[1]28,000	28,000
Total discharge	29,000	59,000	30,000
Estimated change in storage	0	-19,000	-19,000

[1]From Arizona Department of Water Resources (2005a).

[2]Includes flood recharge in San Pedro River from Coes and Pool (2005). Modern conditions includes additional 3,000 acre-ft/yr because of increased runoff from urban areas.

[3]Based on net pumpage from Arizona Department of Water Resources (2005a) and an assumption of a 34 percent loss to groundwater system.

[4]Artifical recharge from municipal effluent recharge facilities, turf facility, and septic tank return flows.

[5]Combined value of Sierra Vista subwatershed evapotranspiration from Pool and Dickinson (2007) and Benson subwatershed evapotranspiration from Arizona Department of Water Resources (2005b).

[6]From Leenhouts and others (2006).

[7]Computed as residual of total discharge reported by Anderson and Freethey (1995) minus other discharge terms listed here.

[8]From Pool and Dickinson (2007); value for Sierra Vista subwatershed only.

The flux of water through the basin-fill aquifer of the Sierra Vista subbasin under predevelopment conditions has been estimated on the basis of available streamflow records and groundwater flow model calibration, and most of these efforts have focused on the Sierra Vista subwatershed (Freethey, 1982; Vionnet and Maddock, 1992; Anderson and Freethey, 1995; Corell and others, 1996; Thomas and Pool, 2006; Pool and Dickinson, 2007). One effort has been completed that utilized geochemical tracers to quantify recharge from the Huachuca Mountains (Wahi, 2005). Dickinson and others (2004) used inverse analysis of time-varying groundwater levels to infer recharge from the Huachuca Mountains. Generally, it is assumed that the natural portion of recharge is unchanged since predevelopment times, although work by Pool (2005) has related temporal variations in climate to changes in recharge.

Groundwater fluxes for the basin-fill aquifer of the Sierra Vista subbasin is estimated at 29,000 acre-ft annually for predevelopment conditions (fig. 3; table 1). Mountain-front and mountain-block recharge are the largest inflows to the aquifer, about 22,000 acre-ft/yr (Arizona Department of Water Resources, 2005a). Other sources of recharge include about 3,000 acre-ft/yr subsurface inflow to the aquifer along the United States-Mexico international boundary (Arizona Department of Water Resources, 2005a) and about 4,000 acre-ft/yr stream loss (Coes and Pool, 2005).

Evapotranspiration is the major pathway of groundwater discharge from the basin-fill aquifer and has been studied in detail for modern conditions in the Sierra Vista subwatershed (Leenhouts and others, 2006) and in much less detail for modern and predevelopment conditions in the Benson subwatershed. Pool and Dickinson (2007) calculated evapotranspiration from groundwater for the Sierra Vista subwatershed and the portion of the Upper San Pedro River Basin in Mexico as about 8,000 acre-ft/yr for predevelopment conditions. Arizona Department of Water Resources (2005b) estimated evapotranspiration from groundwater in the Benson subwatershed for modern times as about 10,000 acre-ft/yr, but did not make a predevelopment estimate. Assuming predevelopment and modern values are the same for the Benson subwatershed, total predevelopment evapotranspiration from the basin-fill aquifer was about 18,000 acre-ft/yr. Pool and Dickinson (2007) estimated less than 1,000 acre-ft/yr of discharge from the basin-fill aquifer as springflow, and Arizona Department of Water Resources (2005a) also estimated subsurface underflow out of the basin to be less than 1,000 acre-ft/yr. Given that the total groundwater recharge is estimated as 29,000 acre-ft/yr, stream gain in the Sierra Vista subbasin computed as a residual of the groundwater budget is about 10,000 acre-ft/yr. This estimate is confirmed by steady-state modeling performed separately for the Sierra Vista and Benson subwatersheds (Anderson and Freethey, 1995) from which an estimate of about 12,000 acre-ft/yr of net stream gain was simulated.

The act of developing a groundwater system changes an assumed initial steady-state condition into a transient condition. As a result, the development conditions are a function of the time period of interest. For this discussion, 2002 is taken to represent the modern condition.

Total groundwater recharge increased about 38 percent, from about 29,000 to 40,000 acre-ft/yr, as a result of water-resources development (table 1). Subsurface inflow, natural recharge through the mountain fronts, mountain blocks, and ephemeral stream channels is assumed to be invariant through time. An estimated 3,000 acre-ft/yr of recharge, however, was added to stream losses for modern conditions as a result of increases in the number and extent of impermeable surfaces in urban areas that generate more runoff that subsequently infiltrates the channel beds of ephemeral washes. Recharge under modern conditions was increased by about 8,000 acre-ft/yr as a result of artificial recharge facilities and incidental recharge from irrigated agricultural and urban lands and from septic tanks.

Total discharge nearly doubled, from about 29,000 to 59,000 acre-ft/yr, as a result of water-resources development (table 1). This increase was caused largely by groundwater pumping, which as discussed previously was nearly 28,000 acre-ft in 2002 (Arizona Department of Water Resources, 2005b). Estimated evapotranspiration increased by about 2,000 acre-ft/yr from predevelopment to modern conditions, but this increase may be an artifact of the different techniques used for the estimates provided by the different data sources. A quantitative evaluation of evapotranspiration changes through time has not been completed.

Groundwater Movement

The general pattern of groundwater movement under predevelopment conditions is of flow from the bounding mountains toward the San Pedro River and downgradient with the river (fig. 4*A*; Freethey and Anderson, 1986). This pattern of movement is about the same under modern conditions (fig. 4*B*; Arizona Department of Water Resources, 2005b). Differences between the location of the 100-ft water-level altitude contours from 1900 and 2001, shown in figures 4*A* and 4*B*, are more likely a result of differences in the interpretation of data by different studies rather than actual changes in water levels. Anderson and others (1992) indicate that water levels have not declined more than 50 ft from predevelopment conditions through 1980.

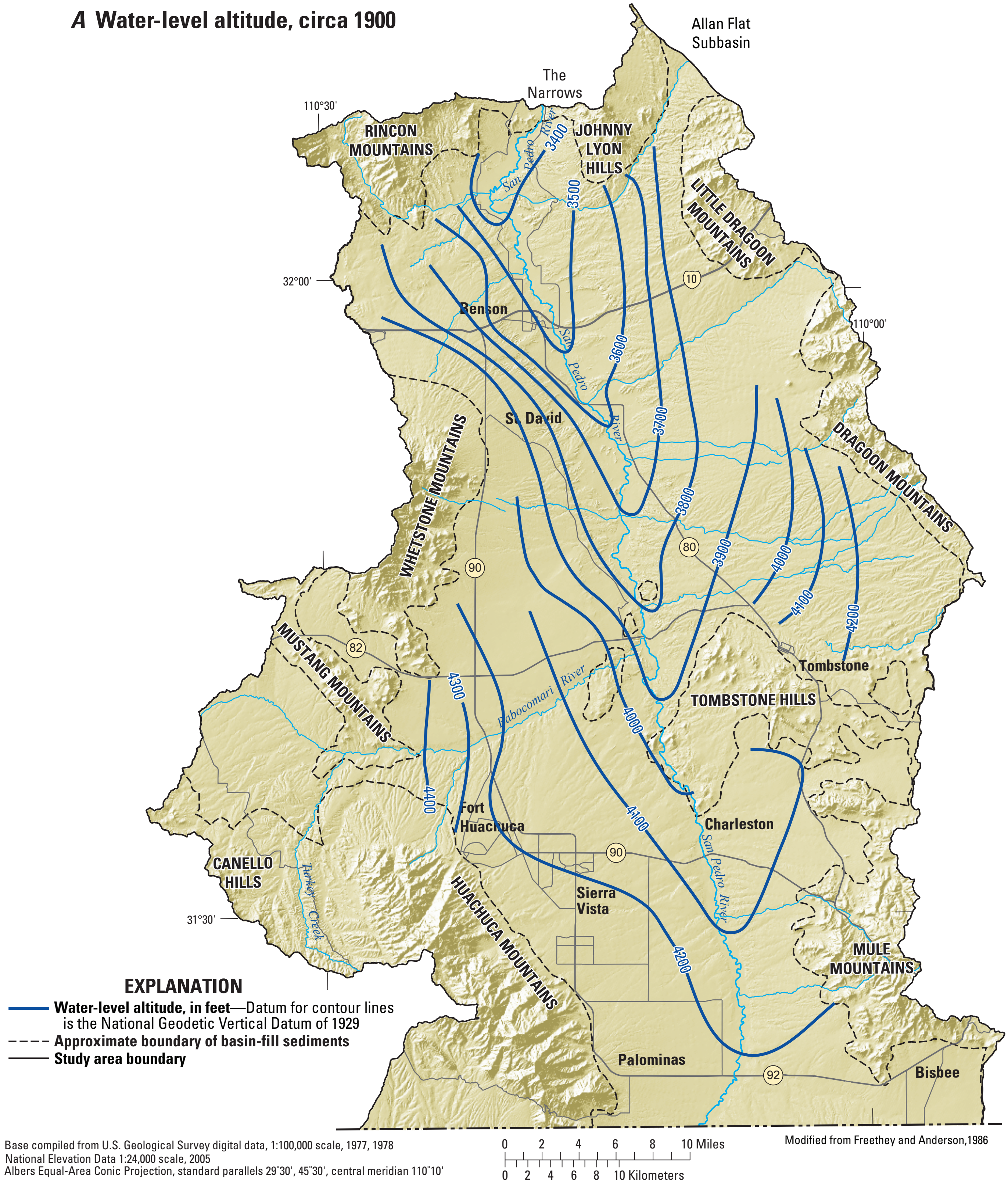
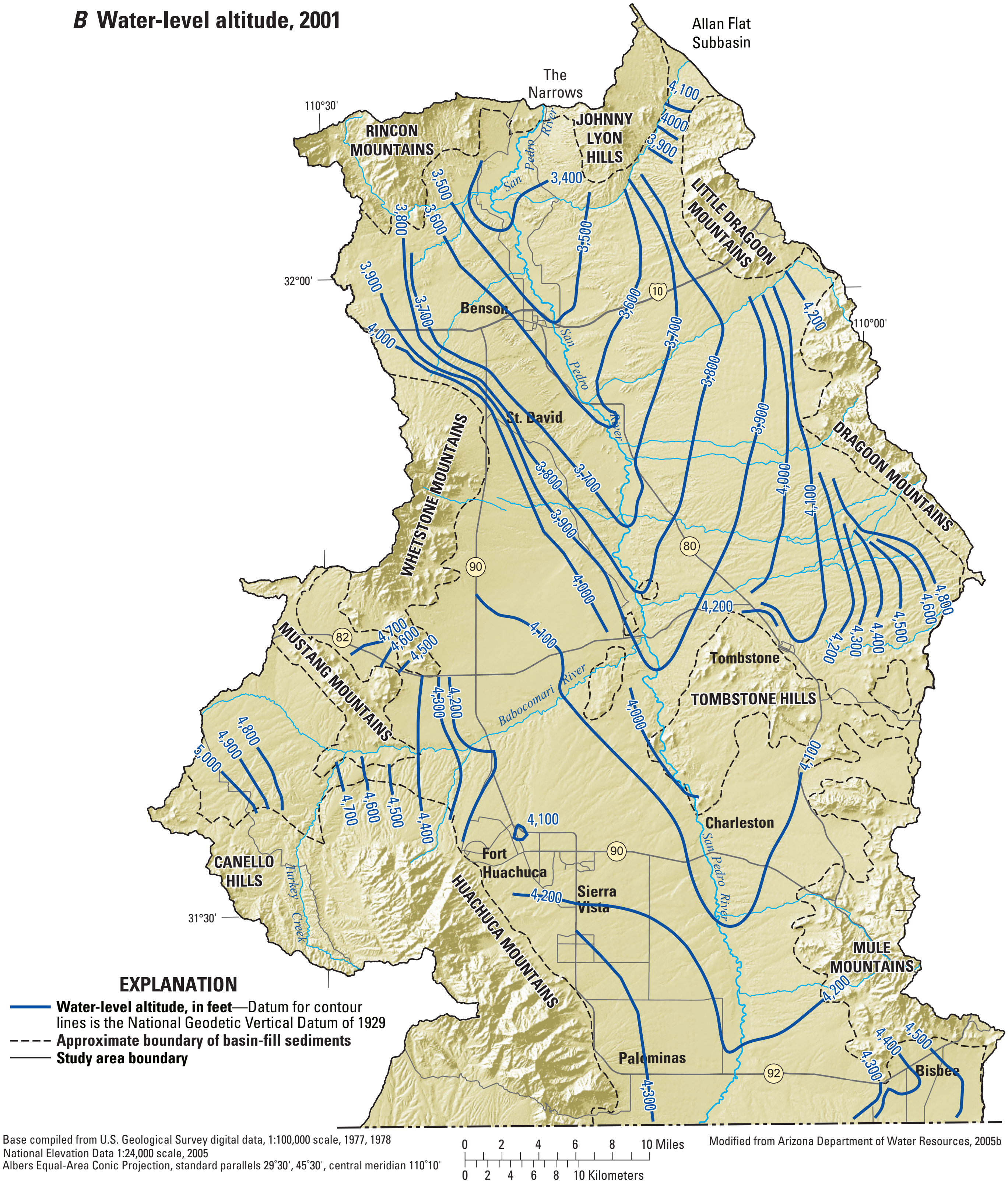


Figure 4. Water levels in the basin-fill aquifer of the Sierra Vista subbasin, Arizona. (*A*) Water-level altitude, circa 1900. (*B*) Water-level altitude, 2001. (*C*) Water-level change for 1990–2001. (*D*) Depth to water, 2001.



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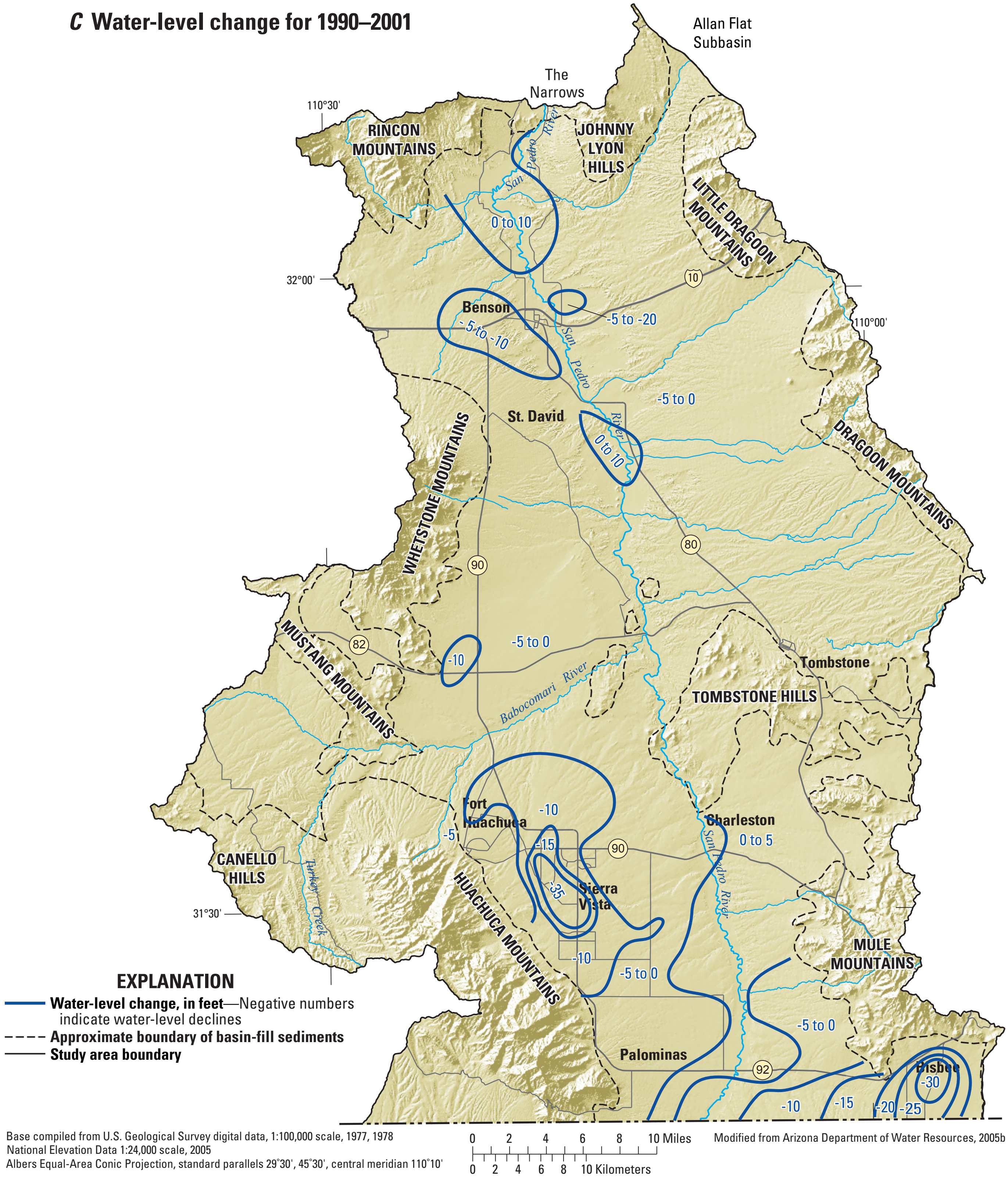

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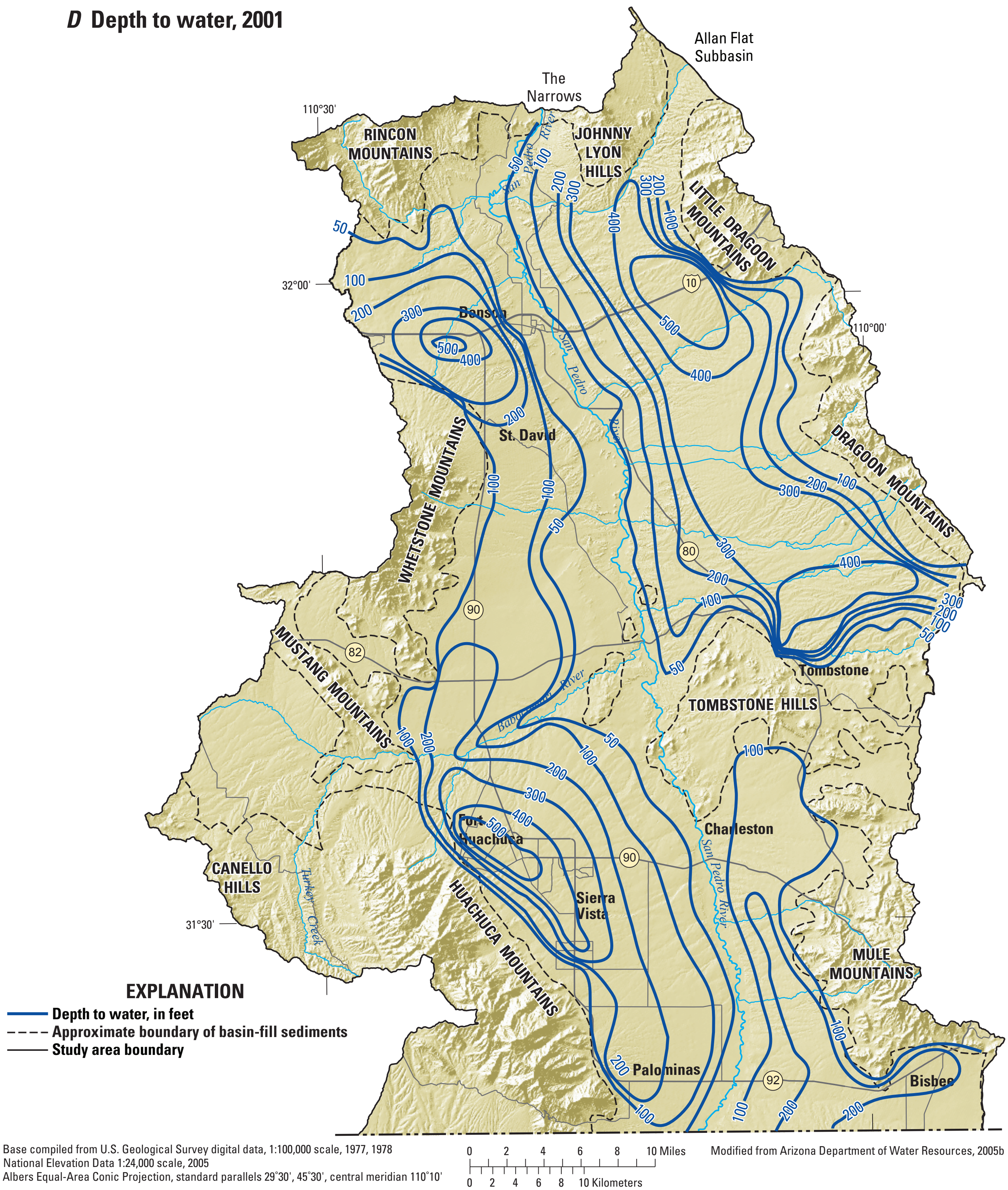

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Locally, however, groundwater withdrawals have resulted in depressed water levels near Benson and Sierra Vista and in the extreme southeastern part of the subbasin. These locales are detectable through comparison of water-level measurements made in a common set of wells for 1990 and 2001 (fig. 4*C*; Arizona Department of Water Resources, 2005b). In a few areas of the basin along the San Pedro River, however, water levels rose during the period 1990–2000 (fig. 4*C*; Arizona Department of Water Resources, 2005b). Another change to the groundwater system besides water-level changes is attributed to the effects of irrigation, specifically, the process of recharging excess water from the surface while pumping from wells completed deep within the aquifer serves to redistribute water from deeper to shallower zones in the aquifer system.

Areas with shallow depths to water can be more susceptible to contamination than areas with deeper water levels, especially where vertical gradients are not upward in the aquifer and in unconfined areas. Depths to water typically are less than 100 ft along the basin-fill margins, increase to several hundred feet toward the center of the basin, and then decrease to less than 100 ft along the basin axis (figs. 2 and 4*D*; Arizona Department of Water Resources 2005b). Areas of confined groundwater with upward gradients occur along the San Pedro River in the Palominas-Hereford area, and also in the St. David-Pomerene area (fig. 1).

Effects of Natural and Human Factors on Groundwater Quality

The quality of water in the basin-fill aquifer system in the Sierra Vista subbasin, which is affected by both natural and human-related factors, was cooperatively investigated by the U.S. Geological Survey's (USGS) National Water Quality Assessment (NAWQA) Program and the Arizona Department of Environmental Quality (ADEQ) in a 1996–97 study that sampled 39 wells. The results of this study were published in several reports. Coes and others (1999) provided a basin-wide assessment of general chemical parameters, major ions, nutrients, and trace constituents relative to location, depth, land use, and geology. Gellenbeck and Anning (2002) build on information from Coes and others (1999) by providing an assessment of pesticides and volatile organic compounds (VOCs) in the Sierra Vista subbasin and other areas. Cordy and others (2000) synthesized water-quality data from the Sierra Vista Subbasin, the West Salt River Valley, and the Upper Santa Cruz Basin. The following summary draws from these reports.

For the purposes of generalizing water-quality information, the Sierra Vista subbasin may be divided into four quadrants, with the east-west dividing line running roughly along the Sierra Vista and Benson subwatershed delineation (fig. 1) and the north-south line following the San Pedro River. A total of 39 wells in the subbasin were sampled during 1996–97, with each quadrant represented. Twenty of the wells were completed in unconfined basin-fill aquifer, 5 in confined basin-fill aquifer, 13 in water-bearing bedrock, and 1 in both water-bearing bedrock and unconfined basin-fill aquifer. Nineteen wells were sampled by the USGS, and 20 were sampled by the ADEQ. Coes and others (1999) determined that the datasets from the two agencies were comparable on the basis of replicate samples, and used both datasets in their analysis (fig. 5). Samples collected by the two agencies were analyzed for major ions, nutrients, and trace elements; those sampled by the USGS were additionally analyzed for tritium, pesticides, and VOCs. Groundwater in the Sierra Vista subbasin is, in most locations, suitable for all general human uses; relatively few sites had water in which any U.S. Environmental Protection Agency (USEPA) specific primary and secondary maximum contaminant levels (MCLs) were exceeded (fig. 5; U.S. Environmental Protection Agency, 2009).

Groundwater in the Sierra Vista subbasin is predominantly a calcium bicarbonate type, and generally is alkaline and of low salinity. Water in samples from 38 of the 39 wells had a pH above 7.0, and the median value was 7.4 standard pH units (table 2). Dissolved-solids concentrations are generally low—the median concentration in all wells was 262 mg/L, and the concentrations in samples from only two wells exceeded the USEPA secondary drinking-water standard of 500 mg/L (fig. 5). Sulfate concentrations in samples from these same two wells also exceeded the USEPA secondary drinking-water standard of 250 mg/L for sulfate.

Major-ion chemistry of the well samples was spatially correlated by quadrants (Coes and others, 1999). Sodium concentrations were higher in the northern half of the study area and were highest in the northeastern quadrant. Potassium concentrations were also generally higher in the northeastern quadrant than in other areas. Sodium concentration was related to aquifer type; concentrations were lower in unconfined areas of the aquifer than in the confined part in the St. David-Pomerene area. Sodium was also more concentrated in water-bearing bedrock units. Chloride concentrations were higher in water-bearing bedrock than in the basin-fill units. The spatial distribution of these ion concentrations are likely related to the varied mineralogy of the rocks in the mountains surrounding the Sierra Vista subbasin. Specifically, the higher concentrations of sodium and potassium in the northeastern quadrant are likely controlled by sodium- and potassium-bearing intrusive rocks of the Dragoon and Little Dragoon Mountains. Similarly, high concentrations of sulfate in the northwestern quadrant are likely related to deposits of gypsum interbedded with siltstone and dolomite in the Whetstone Mountains.

Figure 5. Elevated concentrations and detections of selected compounds in groundwater samples from the Sierra Vista subbasin, Arizona, 1996–97.

Table 2. Summary of groundwater-quality data, Sierra Vista subbasin, Arizona, 1996–97.

[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 (1999) and Gellenbeck and Anning (2002)]

	Number of wells	Minimum reporting level		Percentiles				
		Highest	Lowest	10th	25th	50th (median)	75th	90th
pH (standard units)	39	N/A	N/A	7.2	7.3	7.4	7.6	7.9
Dissolved oxygen (mg/L)	19	N/A	N/A	1.7	3.5	5.0	6.1	6.5
Dissolved solids (mg/L)	39	10	1	174	222	262	316	419
Nitrate plus nitrite (mg/L as nitrogen)[1]	38	0.1	0.05	[2]0.02	0.47	0.78	1.40	3.9
Nitrogen ammonia (mg/L as nitrogen)[3]	38	0.1	0.015	[2]0.001	[2]0.003	[2]0.014	[2]0.030	[2]0.053
Arsenic (µg/L)[1]	39	10	1	[2]0.19	[2]0.48	[2]1.3	[2]3.5	[2]8.5
Barium (µg/L)[3]	39	100	1	[2]26	[2]36	[2]99	240	450
Fluoride (mg/L)[3]	39	0.2	0.1	0.2	0.2	0.5	1.0	2.7
Uranium (µg/L)	19	1	1	1.0	1.0	2.5	5.3	6.4

Notes on other constituents:

Trace constituents—More than 80 percent of the 39 wells were reported below the highest and lowest MRLs (in parentheses) for phosphorus (0.1 and 0.01 mg/L), iron (100 and 1 µg/L), lead (5 and 1 µg/L), manganese (50 and 1 µg/L), and selenium (5 and 1 µg/L). More than 100 percent of the 39 wells were reported below the highest and lowest MRLs (in parentheses) for antimony (5 and 1 µg/L), beryllium (1 and 0.5 µg/L), cadmium (1 and 1 µg/L), and silver (1 and 1 µg/L).

Pesticides—Of the 19 wells analyzed for 47 pesticide compounds, there were no pesticide detections.

Volatile organic compounds—Of the 19 wells analyzed for 87 compounds, there were 11 compounds detected amongst 14 wells. Compounds included 1,2,4 trimethylbenzene (10 wells), tetrachloroethylene (3 wells), chloromethane, dichlorodifluoromethane, and carbon disulfide (2 wells each), and bromodichloromethane, tribromomethane, benzene, chlorobenzene, acetone, and tetrahydrofuran (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]Summary statistics calculated using probability regression method (Cohen, 1959).

Of the 38 wells with nutrient analyses, concentrations were above the minimum reporting level (MRL) in 36 wells for nitrate plus nitrite (0.05 mg/L), but in only 11 wells for ammonia (0.015 mg/L), in 2 wells for phosphorus (0.01 mg/L) and in no wells for nitrite (0.010 mg/L). The low nitrite concentrations are likely a result of well oxygenated waters—all but one well had a dissolved-oxygen concentration greater than 1.0 mg/L. The median nitrate plus nitrite concentration was 0.78 mg/L, and 90 percent of the wells had concentrations less than 3.9 mg/L (table 2). The USEPA primary drinking-water standard for nitrate of 10 mg/L was not exceeded in any well. Statistical relations (using the Kruskall-Wallis test statistic) were found between the concentration of nitrate plus nitrite and well location. Specifically, concentrations were significantly higher in the southeastern quadrant than in the northeast quadrant. Both quadrants host minimal agricultural activity, and adequate data are not available to relate concentrations to sources.

With the exceptions of fluoride, arsenic, barium, and uranium, trace constituents were detected in filtered samples from fewer than 8 (20.5 percent) of the 39 wells (table 2). The median fluoride concentration was 0.5 mg/L, the USEPA secondary drinking-water standard for fluoride (2 mg/L) was exceeded in 7 wells (fig. 5). In one well, the concentration also exceeded the USEPA primary drinking-water standard for fluoride (4 mg/L). Fluoride concentrations were found to be higher in the northeastern quadrant than other parts of the subbasin and also higher in the confined parts of the St. David-Pomerene area (fig 5). Coes and others (1999) hypothesized that the cause of the higher concentrations was fluoride-bearing minerals in the Pinal Schist of the Dragoon, Little Dragoon, and Whetstone Mountains.

The median arsenic concentration is 1.3 µg/L, and the USEPA drinking-water standard for arsenic (10 µg/L) was exceeded in samples from 4 wells (fig. 5; Coes and others, 1999). For groundwater in southern Arizona, Robertson (1991) found a plausible arsenic source to be minerals in the basin-fill deposits that originated from hydrothermal sulfide and arsenide deposits in the surrounding mountains.

The median uranium concentration in samples was 2.5 µg/L; however, no samples exceeded the USEPA drinking-water standard for uranium of 30 µg/L (fig. 5; Tadayon and others, 1998). Manganese and iron concentrations were below the detection limit for most samples; however, concentrations in one sample from a well completed in bedrock exceeded the USEPA secondary drinking-water standard for these two constituents (fig. 5).

A comparison of major ion and trace constituent data for historical (1950–65) and 1996–97 conditions using the Wilcoxon rank-sum test found that no significant changes occurred between these periods in spite of a large increase in human population. This finding suggests that although exceptions occur locally, human activities have not had a widespread effect on groundwater chemistry in the subbasin.

Groundwater and surface waters in the Sierra Vista subbasin were sampled for analysis of pesticides and VOCs. Within the NAWQA studied basins in Arizona, the Sierra Vista subbasin represents a minimally developed basin as compared with other investigated areas (Gellenbeck and Anning, 2002). Consistent with this development status, analyses for a suite of 47 pesticides in water sampled from 19 wells in the Sierra Vista subbasin resulted in zero detections (table 2). Likewise, there were no detections for 86 pesticides that were analyzed in surface-water samples collected from the San Pedro River at the U.S. Geological Survey's stream-gaging station at Charleston (station number 09471000).

Detections of VOCs, however, belied the minimally developed designation of the basin. Eleven of 87 VOCs analyzed were detected in 14 (74 percent) of 19 groundwater samples (table 2; Gellenbeck and Anning, 2002). No VOC concentrations exceeded standards for those compounds established by the USEPA. The 14 samples in which VOCs were detected were from wells distributed about the subbasin (fig. 5) in areas of both urban land use and rangeland, suggesting anthropogenic impacts under a variety of land-use patterns. Detected compounds include:

1,2,4 trimethylbenzene (10 samples)	Tribromomethane (1 sample)
Tetrachloroethylene (PCE; 3 samples)	Benzene (1 sample)
Chloromethane (2 samples)	Chlorobenzene (1 sample)
Dichlorodifluoromethane (CFC-12; 2 samples)	Acetone (1 sample)
Carbon disulfide (2 samples)	Tetrahydrofuran (1 sample)
Bromodichloromethane (1 sample)	

Specific natural or human sources for the VOCs detected could not be identified; however, 1,2,4-trimethylbenzene is used in dyes and perfumes, as well as in trimetallic anhydride production. Tetrachloroethylene (PCE) and dichlorodifluoromethane may have been present in one well because of its location near a land fill. Two of the VOCs detected may have originated from natural sources—chloromethane and carbon disulfide can enter groundwater from fungi and, less likely for the Sierra Vista subbasin, from volcanic gases.

Tritium was detected in samples from 9 (47 percent) of 19 wells (fig. 5; Tadayon and others, 1998), although this occurrence was not discussed by Coes and others (1999) or by Gellenbeck and Anning (2002). The presence of tritium indicates a post-1953 recharge source for at least some component of the groundwater in those wells (See Section 1 of this report for a discussion of groundwater age and environmental tracers). Of the nine wells with tritium detections, seven also had one or more VOC detections (fig. 5). This indicates that areas with recent groundwater recharge can be expected to have a higher susceptibility to contamination. Other studies that have performed radioisotope dating (Wahi, 2005) found that the youngest waters were generally near the mountain fronts and that the ages increased toward the San Pedro River; this pattern fits the conceptual model of flow through the basin-fill aquifer. Wahi (2005) found uncorrected data indicated ages of greater than 18,000 radiocarbon years in deep wells near the basin center. In spite of these age patterns, the presence of VOCs in wells near the basin center suggests the presence of alternative, shorter transport pathways of anthropogenic chemicals to well screens that make the older groundwater vulnerable to contamination.

Summary

The Sierra Vista subbasin hosts a growing population as well as a substantial riparian ecosystem along the San Pedro River in southeastern Arizona. Groundwater is the primary source of water for the residents of the basin and it also sustains the baseflow and riparian ecosystem of the San Pedro River.

The subbasin has typical basin and range physiography and geology, and was formed in the grabens between block faulted mountain ranges. Miocene through early Pleistocene sediments eroded from the uplifted blocks and filled the basin. The basin fill includes the Pantano Formation, upper and lower basin-fill sediments, terrace deposits, and stream alluvium. The upper and lower basin-fill sediments hold the principal aquifer in the basin.

Under natural predevelopment conditions, the basin-fill aquifer in the Sierra Vista subbasin was primarily recharged along the mountain fronts, and groundwater flow was toward the San Pedro River where it discharged through the streambed or was removed through evapotranspiration.

Groundwater recharge and discharge increased as a result of water-resources development. Recharge increased primarily through greater stream losses, the infiltration of excess irrigation water, and artificial recharge. Discharge, which has nearly doubled in magnitude, increased primarily from groundwater pumping.

The general pattern of groundwater movement for predevelopment conditions is of flow from the bounding mountains toward the San Pedro River and downgradient with the river. While the general pattern of movement for modern conditions is about the same, groundwater withdrawals have resulted in locally depressed water levels near Benson and Sierra Vista, and in the extreme southeastern part of the subbasin.

Groundwater quality of the subbasin was cooperatively investigated by the U.S. Geological Survey's National Water-Quality Assessment Program and the Arizona Department of Environmental Quality in a 1996–97 study that sampled 39 wells. Groundwater in the Sierra Vista subbasin is, in most locations, suitable for all general human uses. The relatively few exceedences of U.S. Environmental Protection Agency standards include those of the primary maximum contaminant level (MCL) for fluoride (1 sample) and the secondary MCLs for pH (2 samples), both sulfate and dissolved solids (2 samples), fluoride (7 samples), and both iron and manganese (1 sample).

Variation in concentrations of major ions and trace constituents were attributed mostly to natural factors rather than human-related factors (table 3). Specifically, the presence and concentrations of major ions such as sodium, potassium, and sulfate, and trace elements such as fluoride were correlated with the occurrence of certain geological materials. The absence of pesticides in the water was attributed to the small amount of crop production in the subbasin. The frequent occurrence of volatile organic compounds in tandem with tritium detections (14 of 19 wells), however, emphasizes the vulnerability of the aquifer to contamination from sources at the land surface, especially in parts of the subbasin where there are pathways for recent recharge to enter the groundwater system.

Table 3. Summary of documented effects of natural and human-related factors on groundwater quality in the Sierra Vista subbasin, Arizona.

Groundwater-quality effect	Cause/source	General location(s)	Reference(s)
Primarily natural factors			
Spatial variation in major ion chemistry	Spatial variation in different geologic materials	Entire basin	Coes and others, 1999
Elevated concentrations of sodium and potassium	Mineralogy of volcanic and intrusive rocks in the Dragoon and Little Dragoon Mountains	Northeastern quadrant of subbasin	Coes and others, 1999
Elevated concentrations of sulfate	Gypsum deposits interbedded with siltstone and dolomite	Northwestern quadrant of subbasin	Coes and others, 1999
Elevated concentrations of nitrate	Unknown, but unlikely human causes	Southeastern and northeastern quadrants of subbasin	Coes and others, 1999
Elevated concentrations of fluoride	Fluoride bearing minerals in the Pinal Schist	Northeastern quadrant of subbasin and in confined parts of aquifer near St. David and Pomerene	Coes and others, 1999
Detections of chloromethane and carbon disulfide	Possibly from fungi or volcanic gasses	Not pervasive in any area	Coes and others, 1999
Primarily human-related factors			
Lack of pesticide detections in well samples	Relatively small amount of crop production compared with other basins in the southwestern United States	Entire basin	Gellenbeck and Anning, 2002
Occurrence of volatile organic compounds	Urban or agricultural use of volatile organic compounds	Areas susceptible to contamination, especially those that receive modern (post-1950) focused recharge, such as that along streams and irrigated areas	This study

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