U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Hydrogeologic Investigations of the Sierra Vista Subwatershed of the Upper San Pedro Basin, Cochise County, Southeast Arizona

Water-Resources Investigations Report 99–4197

Prepared in cooperation with the
ARIZONA DEPARTMENT OF WATER RESOURCES
and COCHISE COUNTY

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By D.R. Pool *and* Alissa L. Coes

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Tucson, Arizona
1999

U.S. DEPARTMENT OF THE INTERIOR
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Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8°C)+32$$

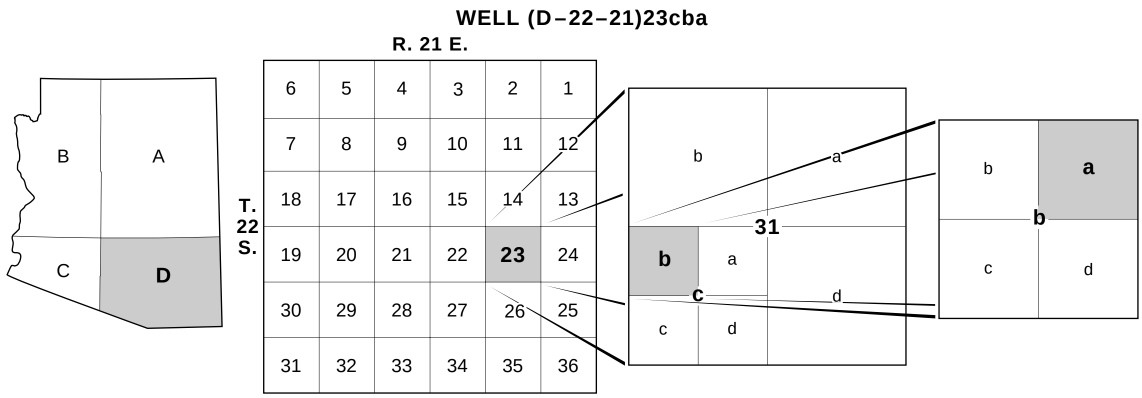
ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations lower than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

VERTICAL DATUM

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929; horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). **Altitude**, as used in this report, refers to distance above or below NGVD 29.

WELL-NUMBERING AND NAMING SYSTEM



Quadrant D, Township 22 South, Range 21 East, section 23, quarter section c, quarter section b, quarter section a

The well numbers used by the U.S. Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants and are designated by capital letters A, B, C, and D in a counterclockwise direction beginning in the northeast quarter. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes. In the example shown, well number (D–22–21)23cba designates the well as being in the NE1/4, NW1/4, SW1/4, section 23, Township 22 South, and Range 21 East.

Hydrogeologic Investigations of the Sierra Vista Subwatershed of the Upper San Pedro Basin, Cochise County, Southeast Arizona

By D.R. Pool *and* Alissa L. Coes

Abstract

The hydrogeologic system in the Sierra Vista subwatershed of the Upper San Pedro Basin in southeastern Arizona was investigated for the purpose of developing a better understanding of stream-aquifer interactions. The San Pedro River is an intermittent stream that supports a narrow corridor of riparian vegetation. Withdrawal of ground water will result in reduced discharge from the basin through reduced base flow and evapotranspiration; however, the rate and location of reduced discharge are uncertain.

The investigation resulted in better definition of distributions of silt and clay in the regional aquifer; changes in seasonal precipitation, runoff, and base flow in the San Pedro River; sources of base flow; and regional water-level changes. Regional ground-water flow is separated into deep-confined and shallow-unconfined systems by silt and clay. Precipitation, runoff, and base flow declined at the Charleston streamflow-gaging station from 1936 through 1997 for the months of June through October. Base flow at the Charleston station during 1996 and 1997 was primarily supplied by ground water recharged near the San Pedro River during recent major runoff and by minor contributions from the regional aquifer. The decline in base flow, about 2 cubic feet per second, has several probable causes including declining runoff and recharge near the river during June through October and increased interception of ground-water flow to the river by wells and phreatophytes. Water levels in wells throughout the regional aquifer generally declined at rates of 0.2 to 0.5 feet per year between 1940 and the mid-1980s, which corresponded with a period of below-average winter precipitation. Water levels in wells in the Fort Huachuca and Sierra Vista areas declined at rates that were faster than regional rates of decline through 1998 and caused diversion of ground-water flow that would have discharged along perennial stream reaches.

INTRODUCTION

The Sierra Vista subwatershed lies within the Upper San Pedro Basin of southeastern Arizona (**fig. 1**) and includes about 950 mi^2 that extends from the international boundary with Mexico to about 27 mi north near Fairbank, Arizona. The subwatershed is bounded on the west by the Huachuca Mountains and on the east by the Mule Mountains and Tombstone Hills, which are at altitudes of about 5,000 to 9,500 ft and 5,000 to 7,400 ft above sea level, respectively. The subwatershed is drained by the San Pedro River, which is an intermittent stream that flows perennially near Hereford and from south of Highway 90 into the Boquillas area. The altitude of the San Pedro River ranges from about 3,780 ft at the streamflow-gaging station near Tombstone to about 4,300 ft at the international boundary. Tributary streams are ephemeral except for the Babocomari River, which is perennial near the San Pedro River.

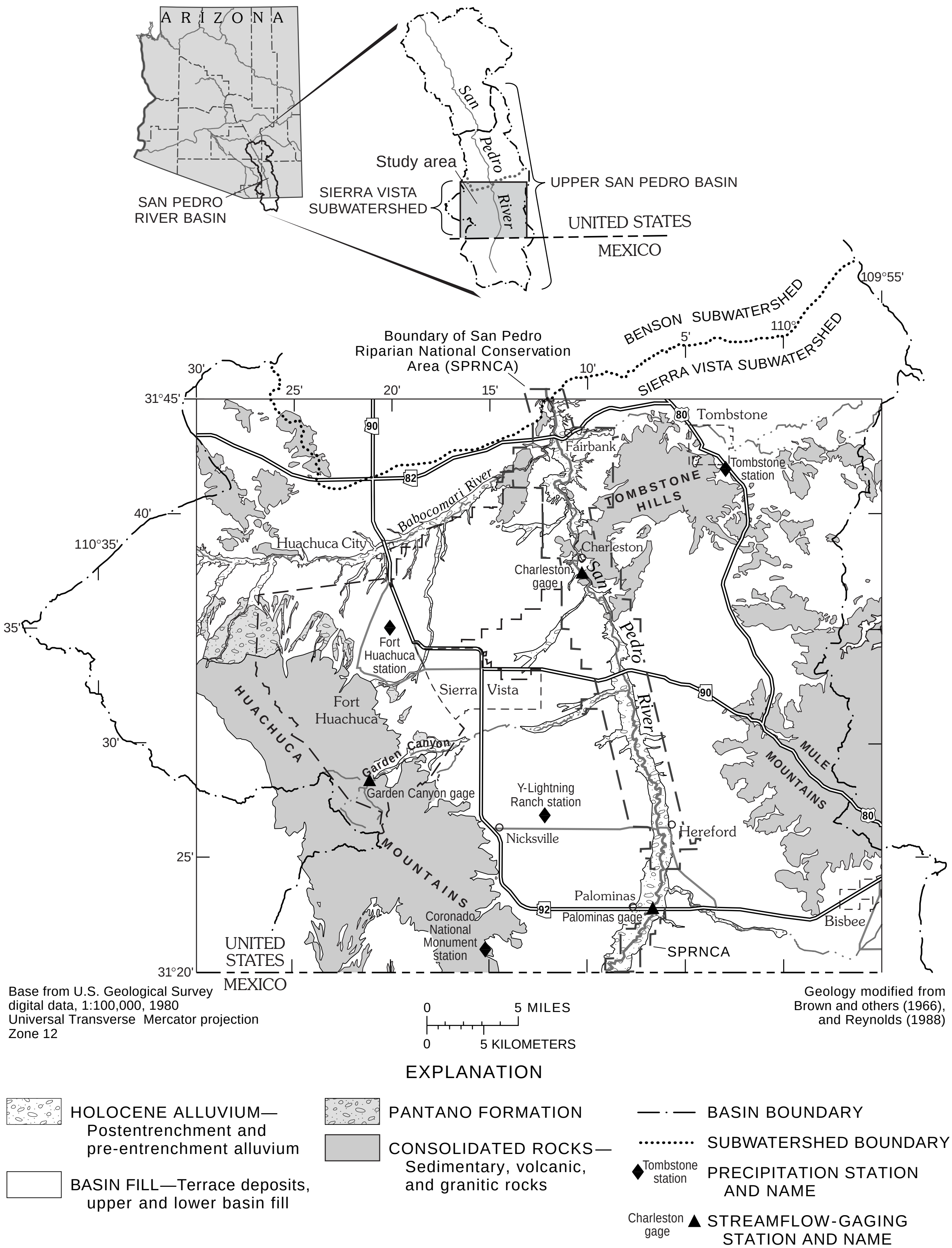


Figure 1. Location of study area and precipitation and streamflow-gaging stations in the Sierra Vista subwatershed of the Upper San Pedro Basin, Arizona.

Streamflow and shallow ground water support a narrow corridor of riparian vegetation that is a few hundred feet wide along the flood plain of the river. Riparian vegetation includes phreatophytes, which are plants that can draw shallow ground water. Important phreatophytes in the area include cottonwood, willow, and mesquite. The riparian area is a valued resource that supports several endangered species and is an important habitat for migratory birds. Most of the riparian area has been protected by designation as the San Pedro Riparian National Conservation Area (SPRNCA), which is managed by the Bureau of Land Management.

Increasing demands are being placed on the water supply in the Sierra Vista subwatershed by a growing population and may result in decreasing amounts of water available to the perennial-stream reaches and riparian vegetation. Base flow of perennial-stream reaches is supplied by ground-water flow from upgradient recharge areas. Ground water also is the primary source of water for many uses including: (1) riparian areas outside of the river; (2) agricultural, private, public, and industrial uses; and (3) supply for the military installation at Fort Huachuca. Basic water-budget analysis shows that ground-water withdrawals for upgradient uses will result in a reduction in natural discharge from the basin through reduced base flow and evapotranspiration by plants. The amount of the reduced discharge will be equivalent to the withdrawal assuming inflow to the ground-water system does not change; however, the rate and location of reduced discharge is not well known because of a lack of basic information about the hydrogeologic system in the basin. Improved knowledge of interactions between the stream and ground-water systems is needed for informed water-resources decisions. A cooperative investigation was begun in 1994 between the U.S. Geological Survey, Arizona Department of Water Resources, and Cochise County to address these needs.

The rate and location of reduced ground-water discharge to base flow caused by ground-water withdrawals are determined by the location of the ground-water withdrawals, hydraulic properties of the aquifer, and distribution of recharge and discharge. Generally, withdrawals from wells closest to the river will result in reduced base flow sooner and at a greater rate than withdrawals farther from the stream. Hydraulic properties of primary importance are transmissivity and storativity, which describe the ability of the aquifer to transmit and store water, respectively. These properties are controlled by aquifer geometry, or width and thickness, and aquifer stratigraphy—primarily the distribution of sand and gravel layers with respect to silt and clay layers. Sand and gravel layers readily transmit water and accept and release water from storage. Silt and clay layers transmit water poorly and limit the storage capacity of the aquifer. Distributions of recharge and discharge also are important because ground-water withdrawals that capture major flow paths between the recharge and discharge areas will reduce discharge sooner than withdrawals outside major flow paths. Improved knowledge of the aquifer geometry, stratigraphy, and ground-water flow paths will provide information needed to better manage the water supply of the basin so that the effects of upgradient ground-water withdrawals on base flow and ground-water availability in the riparian area are minimized.

Purpose and Scope

A hydrogeologic study of the Sierra Vista subwatershed of the Upper San Pedro Basin was done for the purpose of building on existing information to produce a better understanding of the hydrogeologic framework, stream-aquifer interactions, and the rate and location of decreased base flow caused by ground-water withdrawals. Better definition of the hydrogeologic system should result in improved estimates of the effect of ground-water use on the stream.

Improved understanding of the hydrogeologic system was developed through the analysis of precipitation, streamflow, geophysical, hydrochemical, and water-level data. Precipitation records from several stations in the basin were analyzed to determine whether trends in precipitation correlate with trends in recharge and streamflow. Streamflow records at the gaging station at Charleston were analyzed to determine trends in runoff and winter and summer base flow for the period of record. Geophysical data were collected to augment existing information on aquifer geometry and stratigraphy to depths of a few hundred feet in areas near the river and east of Sierra Vista. The hydrochemistry of ground water in the basin was studied to better define ground-water flow paths, distributions of recharge, and sources of base flow in the San Pedro River. Historical water-level data were analyzed and water levels were monitored in several wells to provide information on the response of the aquifer to changes in climate, ground-water withdrawals, and river flow. This report documents the results of data collection and analysis.

METHODS

Trends in seasonal precipitation and runoff were investigated using daily value records from four precipitation stations and the streamflow-gaging station at Charleston (**fig. 1**). The precipitation record for 1897 to 1997 from the weather station at Tombstone provides the only long-term continuous data for precipitation in the area. A more general precipitation record for a larger part of the basin is available beginning in 1956 when several more stations were activated. For months that had missing precipitation values, the average value for the month from the remaining record was used in the analysis. The streamflow record at the Charleston station provides annual data beginning in 1905. Several years of streamflow data are missing before 1936, but the remaining record is complete through 1997.

Base flow of the San Pedro River, the portion of flow supplied by ground-water discharge to the stream, was analyzed using records from the streamflow-gaging station at Charleston. Base flow during winter and summer was estimated by applying the method of Wahl and Wahl (1988) to the record from 1936 to 1997. The method uses average daily flow values to separate base flow from the portion of streamflow supplied by surface runoff. Winter base flow was estimated using the record from November 15 to December 15 of each year. This period was used because it is assumed to be about 1 month after evapotranspiration has stopped, after the first fall freeze, and before most winter runoff occurs. Summer base flow was estimated using the record from June of each year. The least precipitation and maximum rates of evapotranspiration occur during June, which contributes to the lowest base flows of the year.

Geophysical methods that were used included surveys of electrical resistivity and seismic refraction. Surveys were done within about 2 mi of the San Pedro River (pl. 1) because information on the distribution of silt and clay and aquifer geometry, which probably influences stream-aquifer interactions, was lacking in the area. Electrical resistivity is a measure of the ability of the earth to resist the flow of an electric current and is useful for delineating saturated silt and clay from saturated sand and gravel. Silt and clay is less electrically resistive than sand and gravel and more readily transmits an electrical field. Common electrical-resistivity values are about 10 ohm-m for saturated silt and clay and 20 to 50 ohm-m for saturated sand and gravel. Electrical resistivity was measured at the land surface and in boreholes for the purpose of defining the extent of silt and clay layers. Seismic-refraction surveys were used to define the structure of subsurface layers that transmit pressure waves at greater velocity than overlying layers. The subsurface materials generally are more densely compacted with depth and, therefore, normally transmit pressure waves at increasingly greater velocity with depth. The primary target of the seismic surveys was to delineate the top of the conglomerate and bedrock, which are high-velocity layers compared to the unconsolidated materials.

Electrical-resistivity surveys were made in several areas using two methods—vertical-electrical soundings (VES) and electromagnetic (EM) surveys. Seven VES were done to provide information on subsurface resistivity to depths of as much as 1,000 ft. EM surveys provided reconnaissance information for the upper 150 ft of materials in three areas.

The VES, or Schlumberger array, uses a direct-current electrical field that flows between two electrodes inserted into the ground. The resulting potential field is measured using two other electrodes that are inserted in the ground colinear with the current electrodes. Apparent resistivity is calculated using Ohm's law and a geometric factor that accounts for electrode spacing. To conduct a sounding, the spacing between electrodes is increased to measure the apparent resistivity of deeper materials. A VES results in several measurements of apparent resistivity at successively greater electrode spacings. The set of measurements are simulated to produce a layered-earth model of subsurface resistivity. For this study, spacings between the distant electrodes ranged from 3,281 to 5,905 ft. The simulated data sets produced well-constrained subsurface models of electrical resistivity to depths of 600 to 1,000 ft.

The EM surveys measure apparent resistivity of the earth through the measurement of a secondary electrical field that is induced in the ground by a primary time-varying magnetic field. The method uses transmitter and receiver coils that are carried by one or two persons. The spacing and orientation of the coils is increased to detect the electrical field from deeper materials. EM surveys for this project used EM31 and EM34 instruments manufactured by GEONICS LIMITED. Survey results were simulated to produce layered-earth models of resistivity to depths of about 150 ft.

The seismic-refraction method requires subsurface layers that transmit pressure waves at increasing velocity with depth. In basins, such as in the Upper San Pedro Basin, the sediments normally are more compacted and cemented with age and depth. The velocity contrast between layers produces a refracted pressure wave that is detected by geophones laid out along a line at the surface. Targets for the surveys were the tops of the upper basin fill, lower basin fill, Pantano Formation, and bedrock. The water table also may be a good refractor where the sediments are poorly consolidated sands and gravels.

Seismic-refraction surveys were made in three areas (**pl. 1**) using two sources of energy to produce the pressure-wave signal. A sledge hammer was used as the signal source for shallow investigations of the upper 100 ft of materials. Two-part explosives provided the signal source for the deeper investigations to depths of 500 to 600 ft. The surveys used a 24-channel digital seismograph manufactured by EG&G. Shallow investigations were done in the Boquillas, Lewis Springs, and Cottonwood areas, and deep investigations were done in the Lewis Springs and Cottonwood areas.

Geophysical logs of nine test wells (TW1–TW9) at Fort Huachuca (pl. 1) that were drilled from 1971 to 1973 were useful in estimating the resistivity and seismic velocity of subsurface layers in the Upper San Pedro Basin. The wells span the region of Fort Huachuca from near the Huachuca Mountains to the central part of the basin and range in depth from about 800 to 1,500 ft. Geophysical logs included natural gamma radiation, density, porosity, sonic velocity, and electrical resistivity. The electrical-resistivity and sonic-velocity logs were the most useful to this project. Electrical-resistivity logs generally contrast the saturated silt and clay from sand and gravel intervals. Sonic-velocity logs contrast the intervals of low-velocity silt and clay from high-velocity sand and gravel and higher-velocity conglomerate, bedrock, and caliche layers. Geologic and particle-size logs, which included interpreted breaks between units, were also available for the test holes. EM and natural gamma logs were also collected at wells MW5, MW6, and MW7 on the East Range of Fort Huachuca and at three monitor wells at Lewis Springs—BLM2, BLM5, and BLM6 (pl. 1). The monitor wells are shallow—115, 347, 220, 180, 200, and 180 ft—respectively, in comparison to the test wells, but provided comparative data in the eastern part of the basin and near the river.

Water levels were monitored at several wells (**pl. 2**) beginning in the spring of 1995 to monitor the aquifer response to ground-water withdrawals, changes in river stage, and natural recharge. Water levels were recorded hourly at several wells using submerged pressure transducers vented to the atmosphere. Barometric pressure also was recorded hourly at Lewis Springs. Well sites generally were visited on a quarterly or more frequent basis and tapedown measurements of depth to water were performed as a check of the transducer record.

Hydrochemical methods were used in this investigation to help define sources of ground water to base flow in the San Pedro River and ground-water flow paths. Ground water that is recharged at different locations should have different hydrochemical signatures. Base flow will have a signature that is a mixture of the water types from the various source areas. The relative amounts of ground water from each source area can be estimated provided enough information is available and changes in hydrochemistry along flow paths is accounted for or is minimal.

The primary hydrochemical characteristics applied to the investigation were general physical characteristics, common ions, several minor and trace constituents, the radioactive isotope of hydrogen (tritium, ^{3}H), and stable isotopes of oxygen ($^{18}O/^{16}O$) and hydrogen (^{2}H(deuterium)/^{1}H). Changes in the physical characteristics and common ions along flow paths are used to understand geochemical processes that occur between recharge and discharge areas. Water samples were analyzed for several minor and trace constituents for the purpose of determining if any of the elements could be used as natural tracers of water from particular sources. Tritium data are used to determine the presence of water that was recharged since 1953 when large amounts of ^{3}H were released to the atmosphere during above ground testing of nuclear weapons. Variations in the stable-isotope composition of water may be indicative of sources of recharge because the amounts of each isotope in ground water are dependent on the temperature and source of precipitation and the isotopic signature of the water does not change unless evaporation occurs through exposure of the water to the atmosphere. Water that is precipitated and recharged at a high elevation will have relatively greater amounts of the lighter isotopes of oxygen and hydrogen, ^{16}O and ^{1}H, than water that is recharged at a lower elevation. The amounts of stable isotopes in ground water may be useful for determining source areas because there is little chance for ground water to evaporate before it reaches the river and elevation differences in the San Pedro Valley should produce a significant range of values in stable-isotope ratios.

This study required definition of the distribution of common ions and stable isotopes in ground water and base flow of the San Pedro River. Thirty-one wells were sampled to characterize the chemistry of ground water in the basin (see table on **pl. 3**). The regional aquifer was characterized using samples from 18 wells. The shallow aquifer along the San Pedro River was characterized by samples from 13 shallow wells and drive-point wells. Three springs also were sampled—one that flows from carbonate rocks in Garden Canyon and two that flow from alluvial sediments about 1 mi west of the San Pedro River near Lewis Springs. Several of the wells were sampled repeatedly for determining the variability of ground-water chemistry. Base flow in the river was repeatedly sampled at Palominas, Lewis Springs, and Charleston.

U.S. Geological Survey ground-water and surface-water sampling protocols and procedures were followed to minimize measurement bias and variability. All wells were purged prior to sampling. Samples for some mineral characteristics and mineral and trace constituents were filtered using a 0.45-micrometer in-line cartridge filter during collection; mineral and trace constituents were preserved with 1 milliliter (mL) of nitric acid (70 percent) in a 250 mL sample. Temperature, pH, dissolved oxygen, and specific conductance were measured in the field prior to sampling. Alkalinity, total dissolved solids, and general-mineral and trace constituents were analyzed by the USGS National Water-Quality Laboratory in Arvada, Colorado; the stable isotopes of oxygen and hydrogen were analyzed at the USGS Isotope Fractionation Project Laboratory in Reston, Virginia; tritium was analyzed at the USGS Water-Quality Laboratory in Menlo Park, California. The abundance of stable-isotopes of hydrogen and oxygen are reported relative to the Vienna Standard Mean Ocean Water (VSMOW) that is prepared and distributed by the International Atomic Energy Agency. Values are reported in per mil units ($^{0}/_{00}$) using delta (δ) notation.

PRECIPITATION

Variations in the spatial and temporal distribution of precipitation can result in variations in surface runoff and aquifer recharge that could result in variations in base flow of the San Pedro River. Some studies have noted no significant variations in annual precipitation in the Upper San Pedro Basin (Hereford, 1993; Sharma and others, 1997); however, Rojo and others (1999) noted below-average annual precipitation for 1935 through 1982, and Hereford (1993) noted seasonal variations in precipitation patterns and rainfall intensity that are consistent with recent studies of regional precipitation patterns (Harrington, Cerveny, and Balling, 1992; Swetnam and Betancourt, 1998). Seasonal and annual precipitation in the basin were analyzed as part of this investigation because of the possible variations that may affect recharge and streamflow.

Hereford (1993) described the seasonal distribution of precipitation in the Sierra Vista subwatershed on the basis of the precipitation record at Tombstone. A distinct wet season occurs during mid-June through mid-October or early November that includes the greatest average-daily rainfall, rainfall intensity, and rainfall probability. Wet-season precipitation also is reflected by greater streamflow and flood frequency at the streamflow-gaging station at Charleston. Low-intensity precipitation occurs as rainfall and snowfall during early December through early to late March. Early April through early June is dominated by drought or near drought conditions.

General trends in annual precipitation in the Sierra Vista subwatershed during the 20th century can be inferred from the record of precipitation at the Tombstone precipitation station, altitude 4,540 to 4,610 ft, beginning in 1897 (**fig. 2**A). Annual precipitation averaged 13.9 in., but varied between 8 and 24 in. A least-squares linear fit to the annual data indicates a slight decreasing trend of about 1 in. during the period of record. A 5-year moving average of the annual data indicates that above-average precipitation generally occurred before about 1940 and during the early and mid-1980s; below-average precipitation generally occurred from about 1940 through about 1980; and annual precipitation was about average after the mid-1980s.

Trends in seasonal precipitation at the Tombstone station are slightly different from trends in annual precipitation (figs. 2B,C,D). Precipitation during the wet season, June through October, generally is several inches greater than precipitation during the winter months, November through February, and spring months, March through May. Average wet-season precipitation at the Tombstone station from 1897 through 1997 was 9.6 in., but precipitation during these months varied greatly on an annual basis from about 4 to 16 in. Average winter precipitation was 3.2 in., but precipitation from November through February varied annually from less than 1 in. to more than 8 in. Spring precipitation generally was about 2 in. or less and showed no significant trends. Only wet-season precipitation shows a long-term trend on the basis of a least-squares linear fit to the data. The decrease of about 1 in. of wet-season precipitation over the period of record accounts for the similar trend in annual data. Short-term trends in seasonal precipitation are indicated by the 5-year moving averages of the data. Wet-season precipitation generally was above average for a few years around 1930, during the mid-1950s, and during the mid-1980s (fig. 2C). Short periods of below-average wet-season precipitation occurred around 1900, 1940, 1980, and after 1990; which was the period with the lowest continuous 5-year average, less than 8 in. Above-average winter precipitation occurred for extended periods during about 1904 through 1920, from about 1930 through the early 1940s, and after the mid-1970s (fig. 2D). An extended period of below-average winter precipitation occurred during the mid-1940s through the mid-1970s.

An estimate of basin-wide precipitation is available for 1956 to 1997 using data from the Tombstone precipitation station and three additional stations—Fort Huachuca, Y-Lightning, and Coronado National Monument (**figs. 3**A,B, C,D). Precipitation was greater at the Fort Huachuca, Y-Lightning, and Coronado National Monument stations with respect to the Tombstone station because of generally higher altitude— 4,670, 4,550, and 5,240 ft—respectively; and proximity to the Huachuca Mountains. The average annual precipitation at the four stations for 1956 to 1997 was about 16.1 in. (fig. 3*E*). Trends in seasonal precipitation at the four stations are similar to the trend at the Tombstone station for the same period. Data from each station displays a general trend of increasing winter precipitation and decreasing wet-season precipitation; however, precipitation during individual seasons may vary greatly among the stations. Winter precipitation after the mid-1970s was greater than precipitation during 1956 through the mid-1970s. Wet-season precipitation generally was below average during about 1980 and during the early to mid-1990s. The most significant changes in seasonal precipitation have occurred at the station at Coronado National Monument where the increase in winter precipitation has nearly replaced the decrease in wet-season precipitation during the early to mid-1990s.

SURFACE WATER

Streamflow has been monitored at three streamflow-gaging stations along the San Pedro River in the Sierra Vista subwatershed that include Palominas, Charleston, and Fairbank (**fig. 1**). The Charleston station has the longest period of record of annual data beginning in 1905, but the station was moved several times before 1942. Continuous records of average daily flow values are available for 1936–97. Streamflow records from the Charleston station have been used as an indicator of hydrologic change in the basin by many investigators (Freethey, 1982; Putman and others, 1990; Vionnet and Maddock, 1992; Hereford, 1993; Corell and others, 1996; Sharma and others, 1997; Rojo and others, 1999). The current station is about 9 mi upstream of the northern extent of the Sierra Vista subwatershed and includes a drainage area of 1,234 mi^2, of which 696 mi^2 is in Mexico.

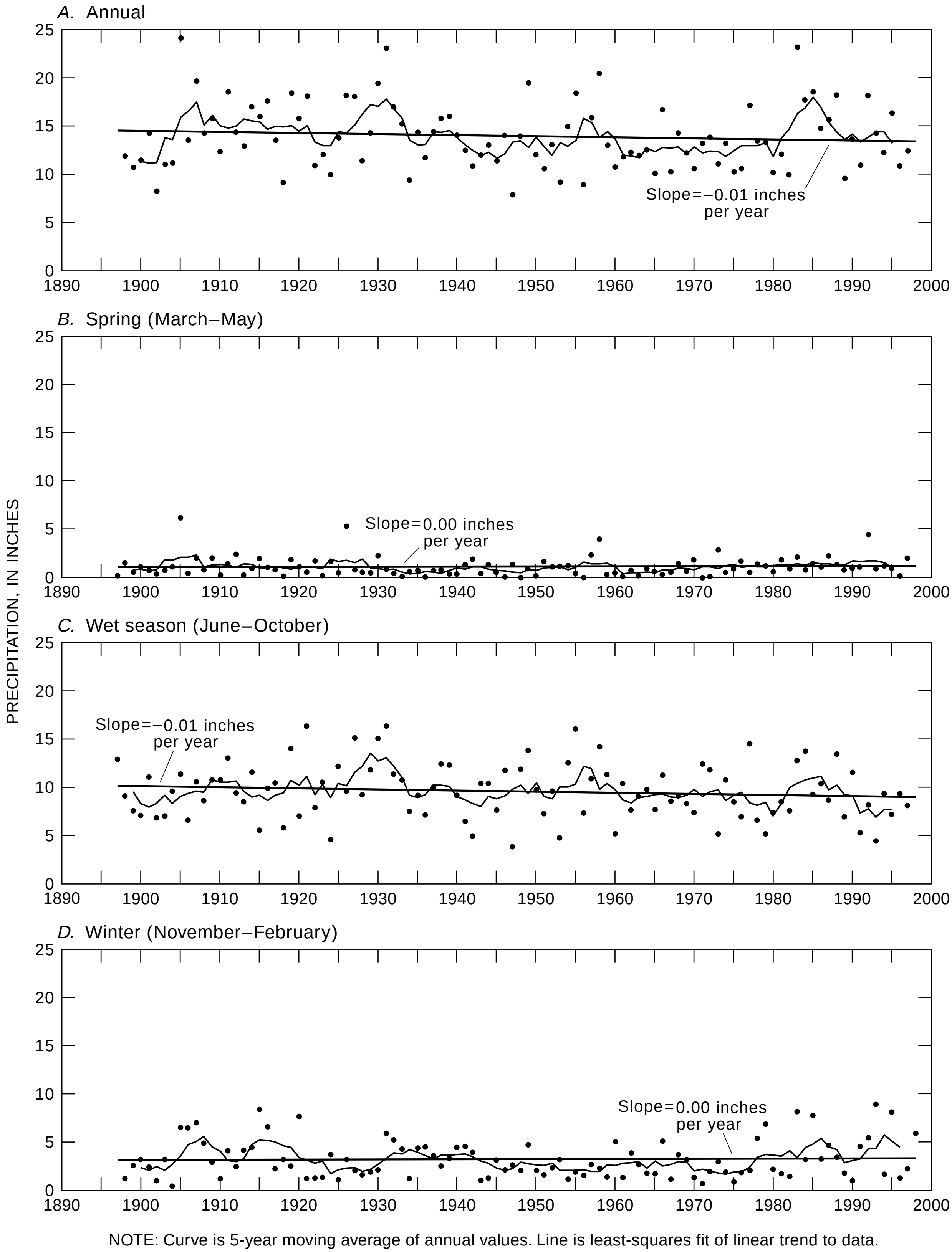


Figure 2. Annual and seasonal precipitation at Tombstone, 1897–1997. *A*, Annual. *B*, Spring (March–May). *C*, Wet season (June–October). *D*, Winter (November–February).

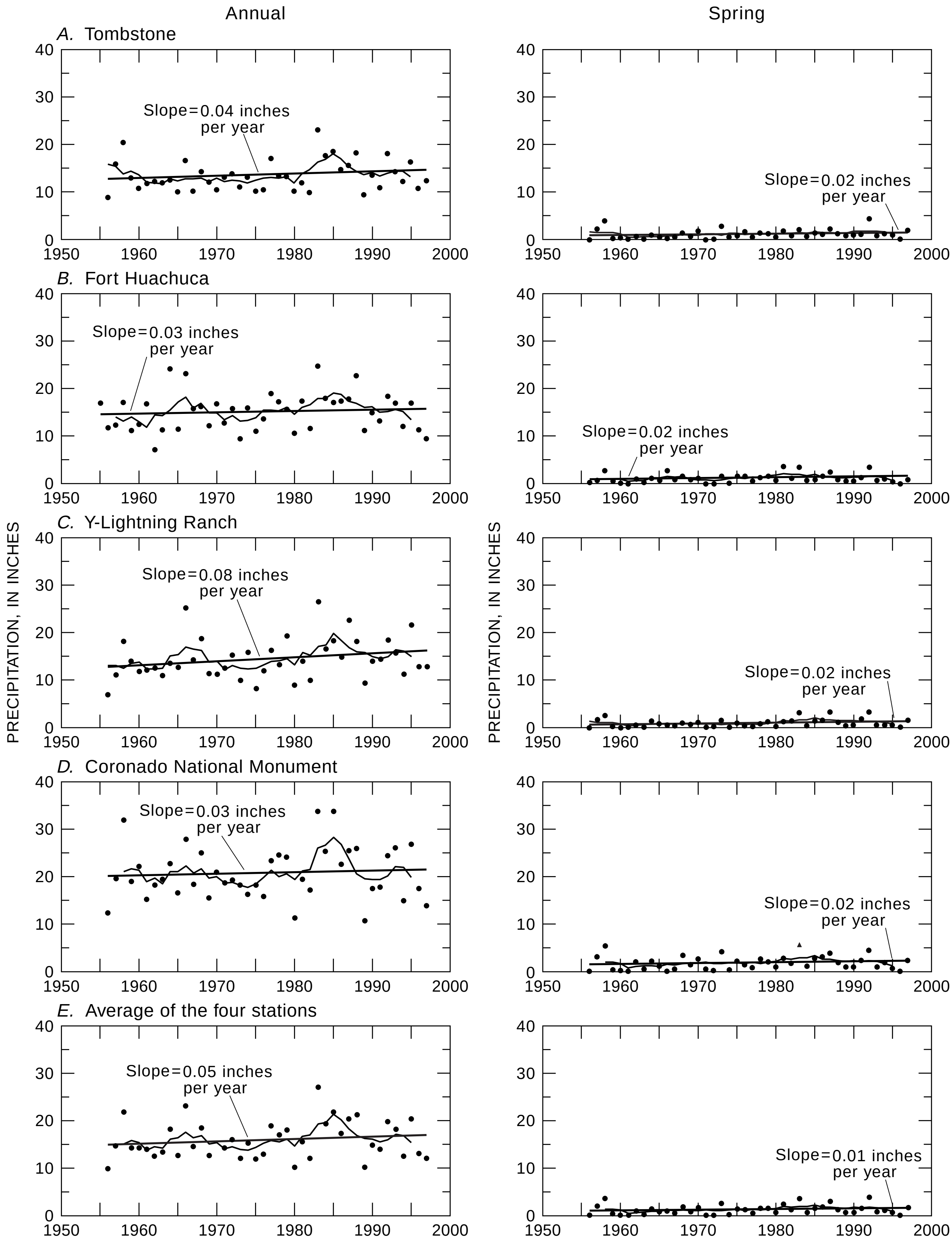


Figure 3. Annual and seasonal precipitation at four precipitation stations in the Sierra Vista subwatershed, 1956–97. *A*, Tombstone. *B*, Fort Huachuca. *C*, Y-Lightning Ranch. *D*, Coronado National Monument. *E*, Average of the four stations—Tombstone, Fort Huachuca, Y-Lightning Ranch, and Coronado National Monument.

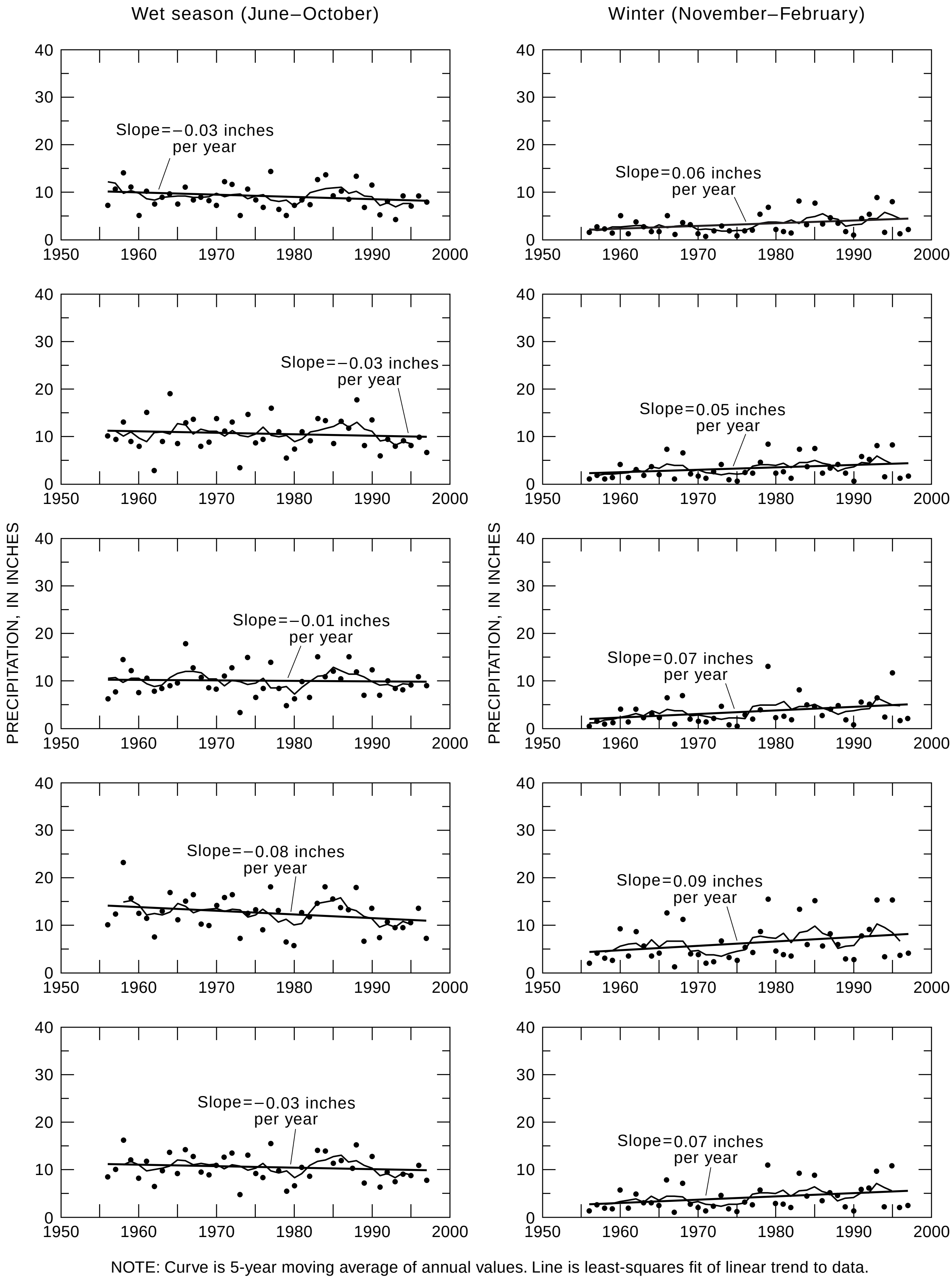


Figure 3. Continued.

The drainage area includes the Mule Mountains and the southern part of the Huachuca Mountains. Two major tributaries—the Babocomari River and Walnut Gulch—and several small ephemeral streams enter the river downstream from the Charleston station and drain the northern half of the Sierra Vista subwatershed—an area of 496 mi^2—which includes the Tombstone Hills, the northern part of the Huachuca Mountains, much of the town of Sierra Vista, and most of Fort Huachuca.

Runoff

Annual and wet-season runoff in the San Pedro River at the Charleston station have declined since the mid-1910s (**figs. 4**A,B). Winter runoff, however, has not declined, but was greatest in the 1910s and during the late-1980s through mid-1990s (fig. 4C). Annual- and seasonal-runoff values are highly variable, but a trend of decreasing annual and wet-season runoff with time is evident in the plots of the 5-year moving averages (figs. 4A,B). Annual runoff declined from more than 45,000 acre-ft before 1935 to about 30,000 acre-ft during the 1960s through early 1970s and less than 20,000 acre-ft during the mid-1990s. Short periods of above-average annual runoff occurred after 1935 and during the 1950s, late-1970s, and early to mid-1980s. Most of the decline in annual runoff was caused by declines in wet-season runoff from more than 40,000 acre-ft before 1935 to less than 10,000 acre-ft during the early and mid-1990s. Some of the decline in wet-season runoff may be explained by declining wet-season precipitation (**fig. 2**), especially during the period of extremely low wet-season precipitation in the early 1990s. Earlier declines may be related to changes in precipitation and runoff characteristics caused by changes in land use and vegetation.

In addition to the decline in wet-season runoff at the Charleston station, the percentage of the volume of wet-season precipitation that flows past the station has also declined (**fig. 5**A). The volume of precipitation above the station was estimated on the basis of precipitation at the Tombstone station multiplied by the drainage basin area above the Charleston streamflow-gaging station. The actual volume of precipitation in the basin probably is much greater than the estimated value, but errors in the estimate should be nearly constant through time provided spatial variations in precipitation are insignificant. The percentage of wet-season precipitation that is transmitted as surface runoff past the Charleston station varies greatly on a yearly basis, but the 5-year moving average has declined from more than 5 percent before the late-1950s to as low as 1 percent during the early and mid-1990s (fig. 5A). In contrast, the percentage of winter precipitation that flows past the Charleston station has not declined (fig. 5B), but has varied with winter precipitation (fig. 2D). The absence of a decline in the percentage of winter precipitation volume as runoff indicates that an increase in capture of precipitation and surface flow has occurred during the wet season. Possible mechanisms of capture during the wet season include increased direct capture through increased vegetation, increased recharge, more frequent occurrence of low-intensity rainfall, and increased surface-water diversions.

The basinwide reduction in the percentage of wet-season precipitation that runs off as surface flow also has occurred on a smaller scale above the streamflow-gaging station in the Garden Canyon drainage basin (**fig. 1**). The drainage basin is an area of 8.38 mi^2 at the southern boundary of Fort Huachuca and the altitude ranges from 5,400 to 8,600 ft. The gaging station was operated from October 1959 to June 1965 (early period) and from December 1993 to 1997 (late period). About 6,400 acre-ft of runoff flowed past the Garden Canyon station during the early period and an additional 50 acre-ft/yr was estimated to have flowed past the station through a pipeline (Brown and others, 1966) for use at Fort Huachuca. Precipitation at Fort Huachuca was 76.4 in. during the early period. About 3,100 acre-ft of runoff flowed past the station during the late period; flow in the pipeline was not measured. Precipitation at Fort Huachuca was 48.7 in. during the late period. The percentage of precipitation that flowed past the station in Garden Canyon declined from about 20 to 15 percent between the early and late gaging periods assuming that flow through the pipeline was similar for the two periods and precipitation at Fort Huachuca is representative of the Garden Canyon drainage basin.

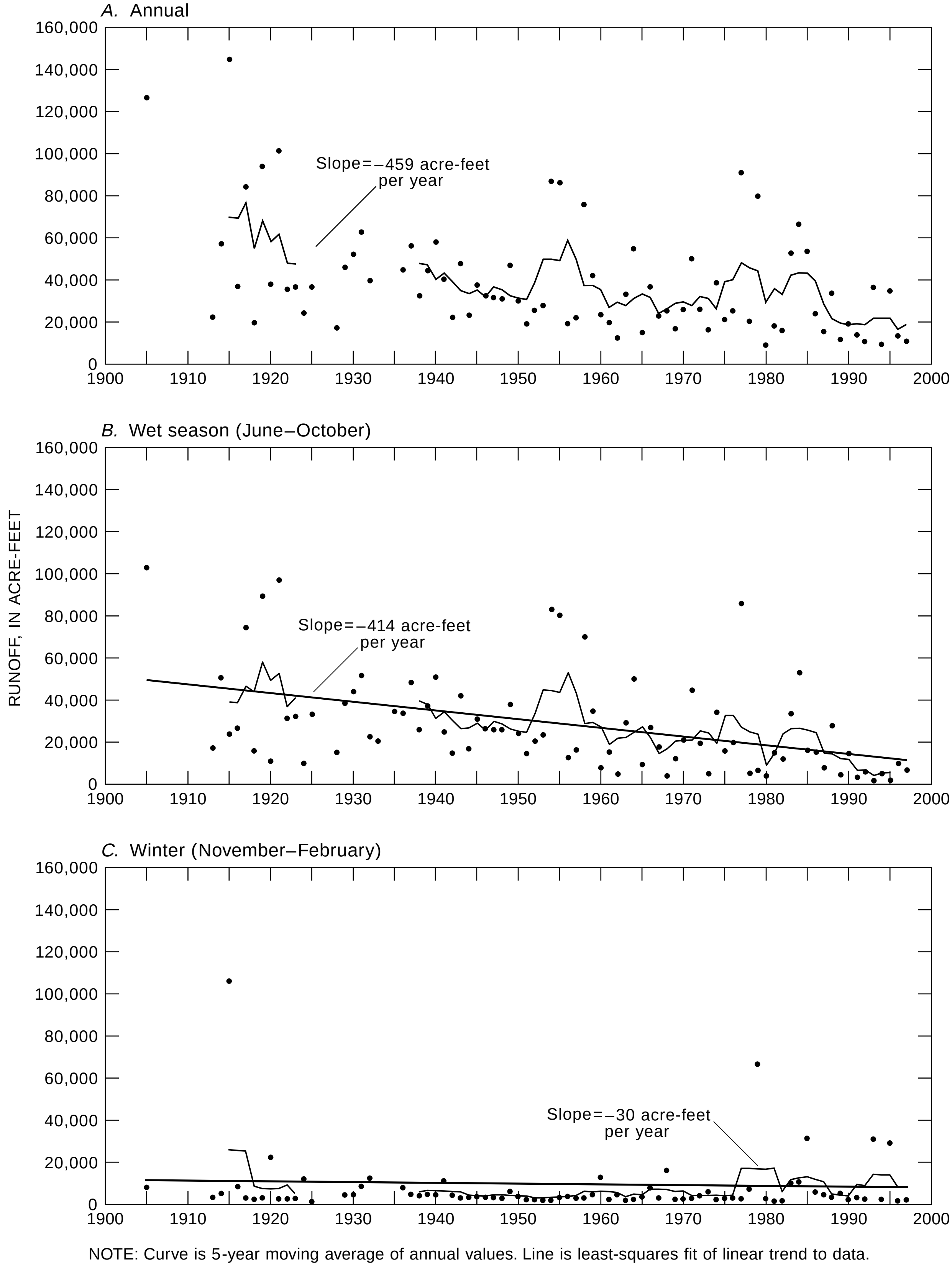


Figure 4. Annual, wet-season, and winter runoff at the streamflow-gaging station at Charleston, 1905–97. *A*, Annual. *B*, Wet season (June–October). *C*, Winter (November–February).

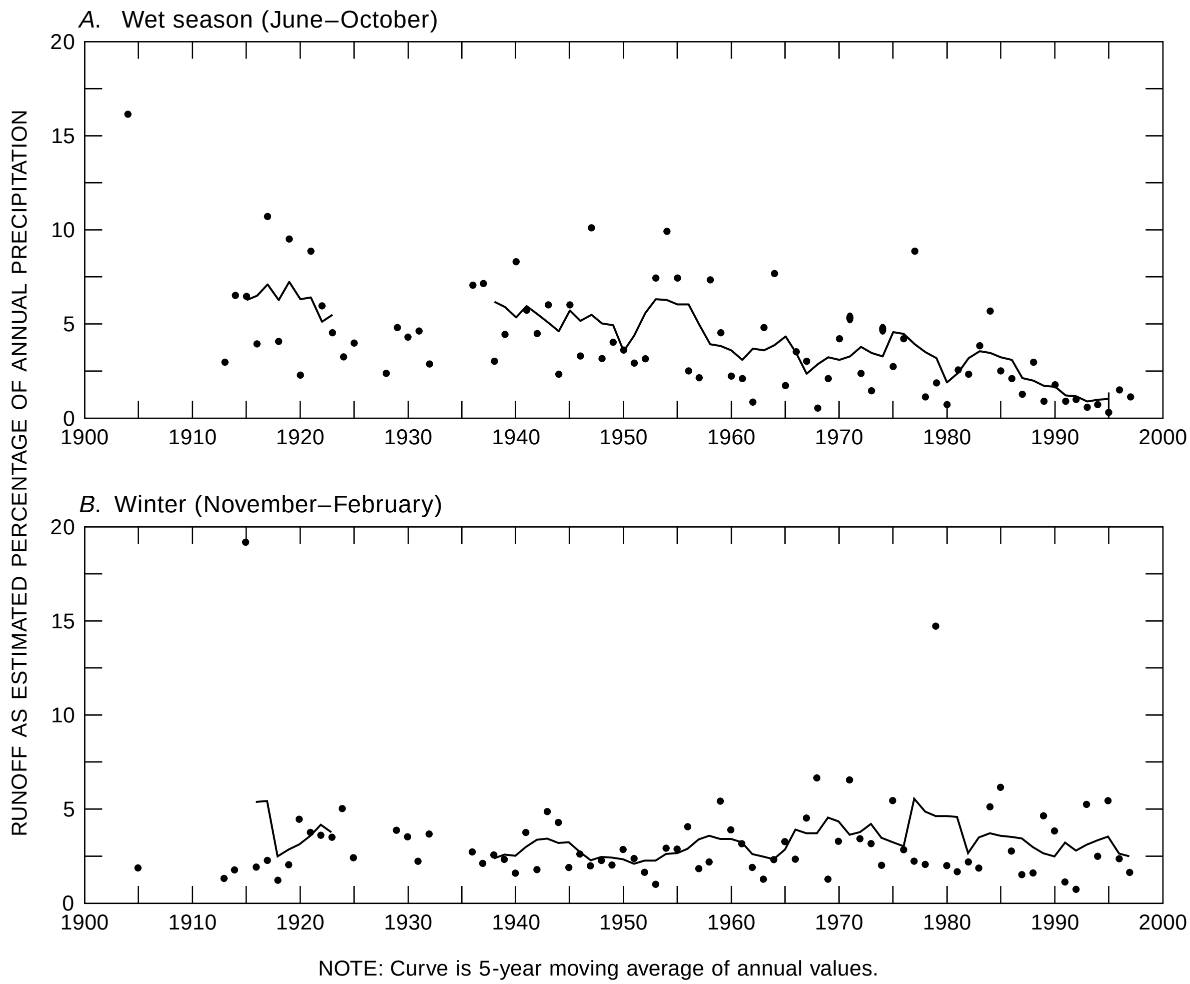


Figure 5. Wet-season and winter runoff as estimated percentage of annual precipitation volume above the streamflow-gaging station at Charleston, 1905–97. *A*, Wet season (June–October). *B*, Winter (November–February).

Reduced runoff from the Garden Canyon drainage basin during 1994 through 1997 relative to the period 1959 through 1965 was caused by less runoff in response to wet-season precipitation during the late period. Annual and winter precipitation were similar for the two periods, but wet-season precipitation was greater during the early period than during the late period. Precipitation during the wet season of the early period averaged 10.9 in., but during the late period averaged slightly less, 9.1 in. Precipitation during the winter was 2.8 and 3.1 in. for the early and late periods, respectively. Runoff during the wet seasons of 1959 through 1965, was 2,884 acre-ft or 12 percent of the precipitation volume, but during the late period runoff was only 492 acre-ft or 4 percent of the precipitation volume. Winter runoff during the early and late periods was 2,378 acre-ft and 1,980 acre-ft, respectively; and 31 and 35 percent of the precipitation volume, respectively. A decrease in the percent of wet-season precipitation that runs off as surface flow may be caused by decreased rainfall duration and intensity and increased vegetation, which were not investigated during this study.

Variations in the relation between precipitation and runoff in southeastern Arizona during the 20th century have been noted by two previous studies. Hereford (1993) and Webb and Betancourt (1992) noted changes in the annual peak flow of the San Pedro and Santa Cruz Rivers, respectively. Both studies attributed the changes in runoff characteristics, in part, to changes in precipitation patterns.

Hereford (1993) attributes a decline in annual peak flows at the Charleston streamflow-gaging station after 1955 to a reservoir effect, which delays runoff. Another possible cause of the decline in annual peak flows is the change in annual precipitation patterns after 1951, which may have resulted in increased vegetation growth. Long-term changes in annual precipitation were not evident in Herefords (1993) analysis, but the pattern of wet-season precipitation, June 15 to October 15, changed about 1951. Before 1951, precipitation during wet seasons tended to alternate yearly from above-average precipitation followed by a year of below-average precipitation. After 1951, several years of wet seasons with above-average precipitation tended to be followed by several wet seasons with below-average precipitation. The later pattern was considered to be more favorable for the establishment and growth of vegetation. Low-intensity rainfall also was cited as favorable for vegetation growth. The period 1954 to 1967 was particularly conducive to vegetation growth because of a higher frequency of low-intensity rainfall (Hereford, 1993). Other possible causes of reduced annual peak flows are increased channel width and sinuosity and changing land-use patterns (Hereford, 1993). The rate of channel widening, which followed channel incision during the early 1900s, reduced greatly by the mid-1950s and may have correlated with the establishment of a vegetated and stabilized channel.

Changes in annual precipitation and peak flows also have been noted in the nearby Santa Cruz Basin where the occurrence of peak flows following heavy precipitation during fall and winter storms was more frequent during 1960 to 1986 in comparison to 1930 to 1960 (Webb and Betancourt, 1992). Hereford (1993) notes that a similar pattern is not evident in the San Pedro Basin, however, the only annual winter floods on record have occurred since 1961. A total of 10 annual floods have occurred during the winter months of 1961 through 1997.

Mechanisms that may have contributed to declining wet-season runoff at the Charleston gaging station include reduced precipitation duration and intensity, increased vegetation, and increased streamflow infiltration along ephemeral reaches of the San Pedro River and tributary streams. Low-intensity rainfall and increased capture of surface flow by vegetation would result in reduced recharge and eventual reductions in the discharge of ground water to the San Pedro River as base flow. Conversely, increases in streamflow infiltration would eventually result in increased discharge of ground water to the San Pedro River as base flow. Increased capture of surface flow probably has resulted from the increased length of ephemeral stream reaches and may have been enhanced by changes in vegetation during the period of record. Streamflow infiltration along increased lengths of ephemeral stream reaches was likely promoted by water-level decline near the river caused by ground-water withdrawals and increased evapotranspiration. The reservoir effect noted by Hereford (1993) also may have contributed to increased recharge along ephemeral reaches of the San Pedro River. The predominant vegetation change in the basin since 1973 has been an increase in mesquite woodland that has replaced or fragmented areas of grasslands and desert scrub (Kepner, 1999). Net effects of the observed vegetation change on rainfall and runoff characteristics in the basin are poorly understood. Amounts of surface flow intercepted by each mechanism and effects on base flow are difficult to quantify without detailed information on each mechanism. The large volume of intercepted precipitation during the late 1980s through the mid-1990s indicates that a basinwide mechanism, such as changes in wet-season rainfall intensity or vegetation, however, is the dominant cause of reduced wet-season runoff during that period.

Base Flow

Base flow of the San Pedro River at the Charleston streamflow-gaging station is supplied by surface discharge of ground water that flows from the regional aquifer and Holocene alluvium above the station. Almost all the ground water in areas upstream from the station must discharge to the stream above the station because only small amounts of ground water can flow through the thin layer of Holocene alluvium overlying crystalline rock near the station (**pl. 1**, hydrogeologic section C–C'). Base flow varies seasonally depending on rates of ground-water withdrawal near the stream by wells and phreatophytes and surface-water use by plants and diversions. Base flow generally is at a minimum during the summer, which is the period of greatest rates of seasonal ground-water withdrawals near the stream. Changes in summer and winter base flow that occur over a period of several years or more can be caused by downcutting of the river, aggradation of sediments in the river, or long-term changes in ground-water recharge or withdrawals. Long-term changes in summer base flow also can result from changes in seasonal use of surface water and ground water near the stream. Both summer and winter base flow may be affected by long-term changes in the seasonality of precipitation.

Base flow at the Charleston streamflow-gaging station was estimated for the summer and winter of each year from 1936 through 1997 using the method of Wahl and Wahl (1988) (figs. 6A,B). Summer base flow was estimated using flow values during June of each year. Winter base flow was estimated using average daily flow values for November 15 to December 15 of each year. Significant runoff during or preceding the estimating periods is apparent in many of the base-flow estimates and resulted in base-flow values that probably include a runoff component. Several summer base-flow estimates also are influenced by runoff, especially those of 1937, 1938, 1941, 1972, and 1979. Several winter base-flow values that are greater than about 15 ft^3/s also probably are influenced by runoff. Changes in base flow that are of significance to changes in the ground-water system are best determined using years with the lowest estimated base-flow values that occur during periods not influenced by runoff.

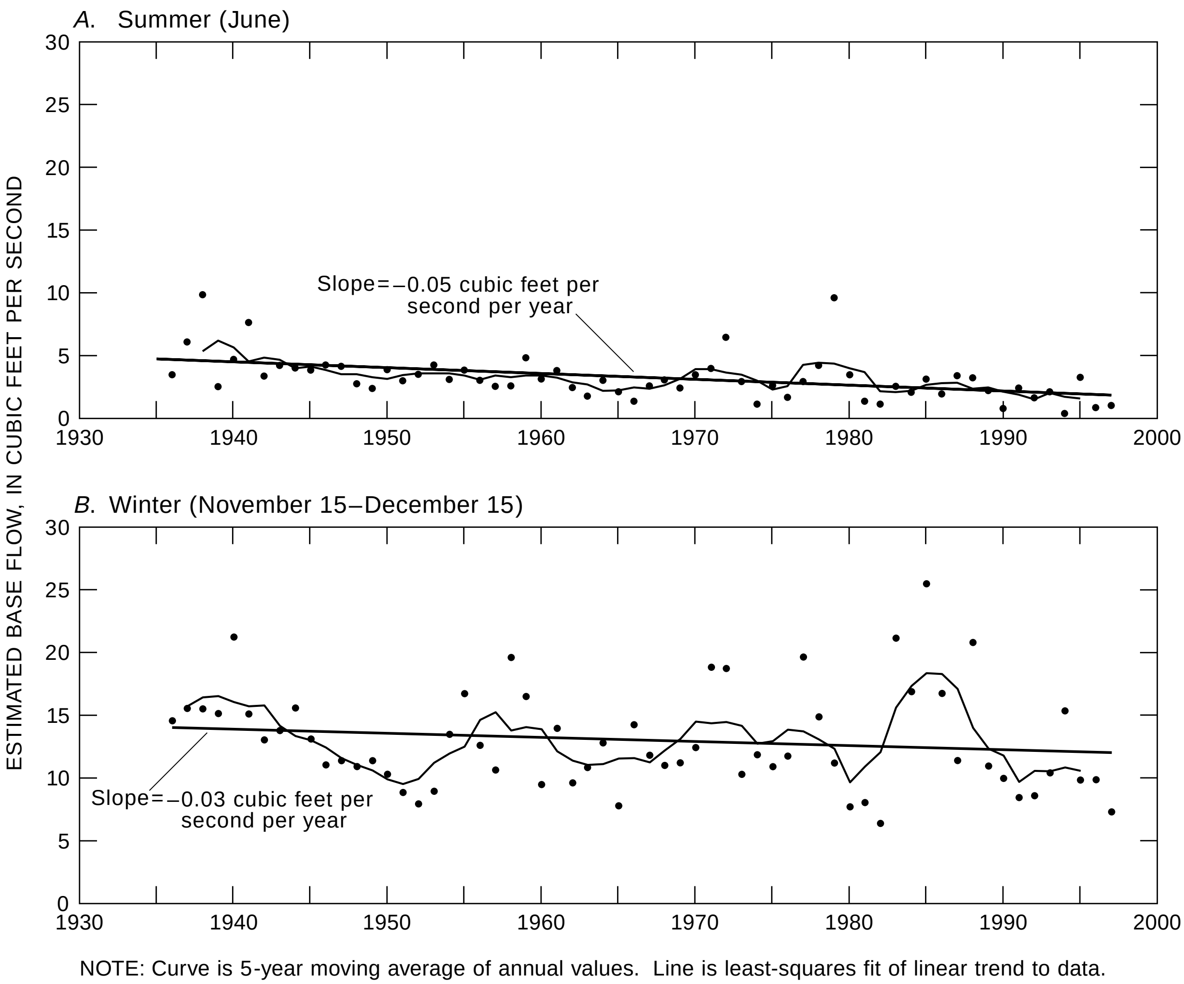


Figure 6. Estimated summer and winter base flow at the streamflow-gaging station at Charleston, 1936–97. *A*, Summer (June). *B*, Winter (November–December 15).

Annual summer base flow has declined during the period of record (**fig. 6**A). The average summer base flow for the period 1936 to 1997 was 2.9 ft^3/s, exclusive of several years that included significant amounts of runoff during June—1937, 1938, 1941, 1972, and 1979. Summer base flow declined from about 2.5–5.0 ft^3/s before 1963 to 1.0–4.0 ft^3/s during 1963 through 1982 and 0.4–3.3 ft^3/s after 1982. Overall decline in summer base flow has been about 2.0 ft^3/s during 1936 through 1997. Declines in summer base flow that occurred after about 1962 without a similar decline in winter base flow indicate that depletions in summer base flow may be caused by an increase in seasonal use of ground water by phreatophytes and vegetation that can access surface water, or declines in summer precipitation relative to winter precipitation.

Annual values of winter base flow are highly variable, but display no long-term trend during the period of record (fig. 6B). The average winter base flow for the period 1936 to 1997 was 10.9 ft^3/s exclusive of years with estimates of more than 15 ft^3/s. Winter base flow before 1951 declined from 15 to 8 ft^3/s and has varied with precipitation and runoff since that time. Minimum flows of about 7 to 8 ft^3/s have occurred several times since 1950—in 1952, 1965, 1980–82, and 1997. The lowest estimated value of winter base flow, 6.4 ft^3/s, was for 1982. The decline in winter base flow before 1951 may be related to several causes that include: (1) long-term water-level decline caused by growth and establishment of phreatophytes as the stream channel stabilized before about 1955 (Hereford, 1993), (2) long-term water-level decline caused by ground-water withdrawals for irrigation in the Palominas area, and (3) declines in annual and seasonal precipitation before about 1950 (**fig. 2**). No clear trends in winter base flow are apparent after the early 1950s, although the frequency of base flow below about 9 ft^3/s may have increased.

Trends in summer and winter base flow at the Charleston streamflow-gaging station are closely related to trends in wet-season runoff on the basis of the 3-year moving average of each (**fig. 7**). The long-term trend of decreasing wet-season runoff is similar to the long-term trend of decreasing summer base flow. Wet-season runoff declined from about 35,000 acre-ft/yr during about 1940 to about 5,000 acre-ft/yr during the mid-1990s, and summer base flow declined from about 5 to 6 ft^3/s to less than 2 ft^3/s during the same period. Short-term trends in wet-season runoff also are similar to short-term trends in base flow during the winter and summer. High wet-season runoff during a 3-year or longer period generally is followed by a similar period of high winter and summer base flow that begins during or after the initial high wet-season runoff. Notable exceptions to the relation have occurred. Periods of high wet-season runoff before 1970 were not followed by pronounced increases in summer base flow, and a period of increased wet-season runoff during the mid-1960s was not followed by increased base flow during the winter or summer. Increased base flow during the winter and summer also followed periods of high winter runoff after the mid-1970s.

Similarity of trends in wet-season runoff and summer base flow suggests that infiltration of wet-season surface flow may be an important source of summer base flow. High annual variability of summer and winter base flow suggests that much of the recharge probably occurs in the Holocene alluvium where ground-water flow paths to the river are short. Summer base flow may have become more dependent on infiltration of wet-season runoff after 1970. Infiltration of winter surface flow may also be an important source of base flow during periods of low wet-season precipitation and runoff. High winter base flow in 1994 and high summer base flow in 1995 (fig. 6) probably was influenced by discharge of ground water that recharged during high runoff during the winters of 1993, 1994, and 1995, because summer runoff during the same years was very low (**fig. 4**).

GROUND WATER

The general hydrogeologic framework of the Upper San Pedro Basin is well known from previous investigations (Brown and others, 1966). More detailed information has resulted from data gathered through the drilling of test and production wells at Fort Huachuca during the early 1970s and geophysical surveys conducted during this study. The primary aquifer is permeable alluvial deposits of basin fill that overlie relatively impermeable crystalline and sedimentary rocks. Ground water generally flows from recharge areas near the mountains through sand and gravel layers in the basin fill toward the San Pedro or Babocomari Rivers. Ground water discharges near the two streams as base flow, small springs near the San Pedro River, evapotranspiration through phreatophytes, and ground-water outflow across the subwatershed boundary. A part of the ground-water flow is intercepted upgradient from the San Pedro and Babocomari Rivers by pumped wells and phreatophytes where depths to water are shallow along ephemeral streams.

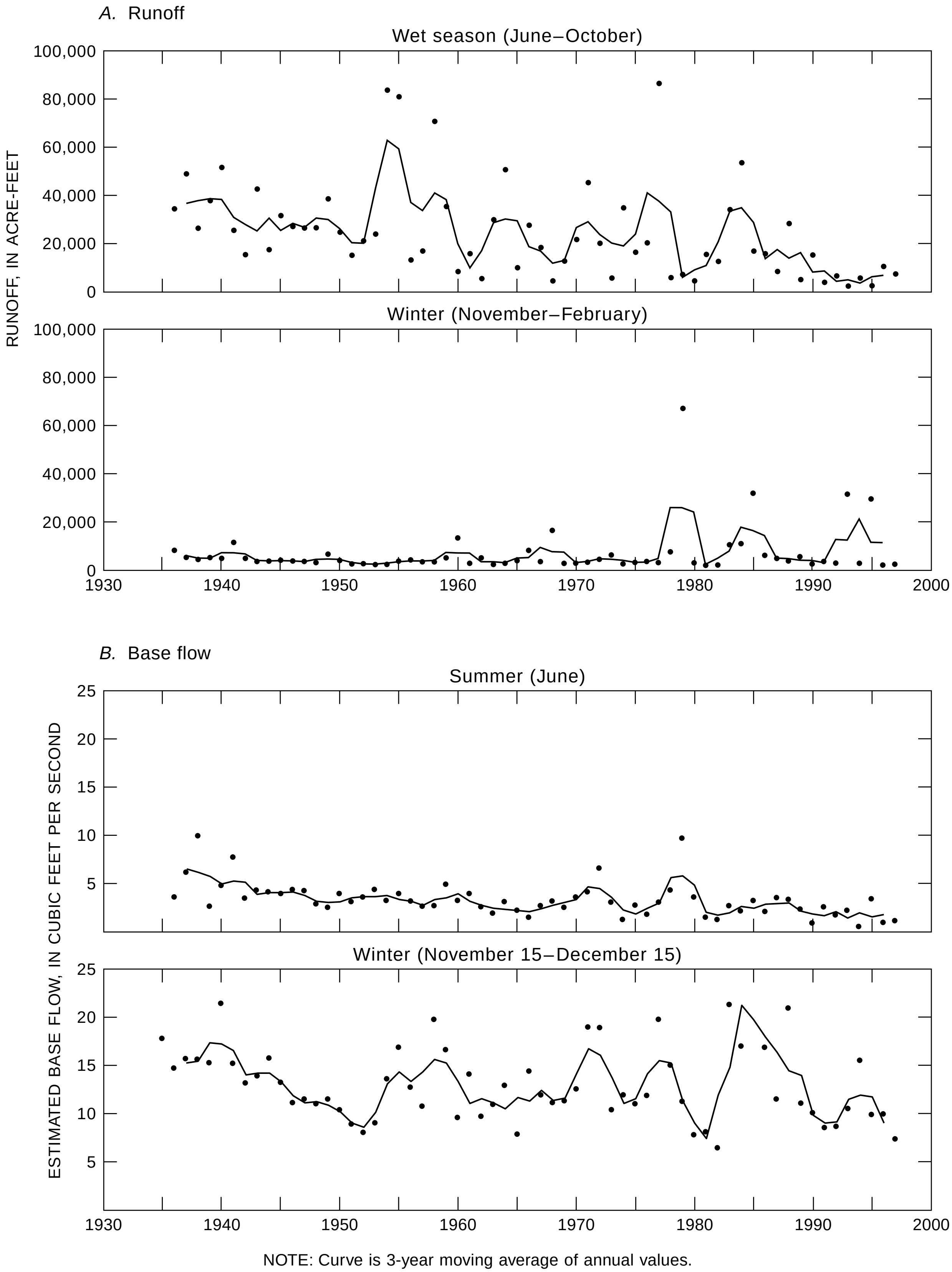


Figure 7. Wet-season and winter runoff and summer and winter estimated base flow at the streamflow-gaging station at Charleston, 1936–97. *A*, Runoff. *B*, Base flow.

Aquifers

The primary regional aquifer includes upper and lower basin fill, described by Brown and others (1966), that accumulated in the structural depression between mountain ranges during the Miocene through early Pleistocene ages (fig. 8). Secondary aquifers include Pleistocene terrace and alluvial deposits that generally coincide with the flood plains of the San Pedro and Babocomari Rivers and tributary streams. Prebasin-fill sediments and Mesozoic and Paleozoic limestones that crop out in the mountains in places also are secondary aquifers. Other rocks that crop out in the mountains and hills surrounding the basin are not known to be significant aquifers and include pre-Miocene granitic and volcanic rocks and Mesozoic sedimentary rocks of mudstone, quartzite, and conglomerate.

Ground water is transmitted primarily through layers of permeable sand and gravel within the basin fill, terrace, and alluvial deposits; however, silt and clay layers of poor permeability also occur. The distribution of the silt and clay layers significantly influences the ground-water flow system. Silt and clay layers limit the storage capacity of the aquifer, cause confined ground-water flow conditions in underlying sand and gravel layers, and limit the downward percolation of infiltrated surface water to the aquifer.

The Pantano Formation may be an important water-bearing unit locally and yields water through fractures to many wells in the Sierra Vista area. The unit is described as semiconsolidated brownish-red to brownish-gray conglomerate (fig. 8; Brown and others, 1966). The Pantano Formation is structurally disturbed by faulting and is tilted as much as 45 degrees to the southwest. The unit is separated from older rocks by a low-angle fault at the base of the Huachuca Mountains, named the Nicksville fault by Drewes (1980) (pl. 1, hydrogeologic section A–A').

STRATIGRAPHIC UNIT	LITHOLOGIC DESCRIPTION	THICKNESS, in feet	PHYSICAL CHARACTERISTICS: SONIC VELOCITY, in feet per second	PHYSICAL CHARACTERISTICS: RESISTIVITY, in ohm-meters	GEOLOGIC AGE	
POSTENTRENCHMENT ALLUVIUM	Sand and gravel	Less than 20	2,000–5,500	10–50	0–110 years	HOLOCENE
PRE-ENTRENCHMENT ALLUVIUM	Clay, silt, and fine sand	20	2,000–5,500	10–50	110–8,000 years	
TERRACE DEPOSITS	Clay, silt, sand, and gravel	50–100	2,000–5,500	10–50	0–700,000 years	PLEISTOCENE-HOLOCENE
UPPER BASIN FILL	Clay, silt, sand, and gravel	Less than 400	5,000–6,500 (caliche is greater than 10,000)	7–23	700,000–3,000,000 years	PLIOCENE-PLEISTOCENE
LOWER BASIN FILL	Clay, siltstone, silt, sand, and gravel	150–350	Silt and clay 5,000–6,500 Sand and gravel 7,000–9,000	10–30		MIOCENE-PLIOCENE
PANTANO FORMATION	Siltstone and conglomerate	Greater than 3,000	10,000–16,000	10–30		MIOCENE
CONSOLIDATED ROCKS	Granite, limestone, mudstone, quartzite, conglomerate, and volcanic rocks	Not applicable	Greater than 10,000	Generally greater than 100, mudstone may be much less		PRE-MIOCENE

Figure 8. Stratigraphic column and physical characteristics of geologic units in the Sierra Vista subwatershed of the Upper San Pedro Basin.

Gravity studies (Halverson, 1984; Gettings and Houser, 1995) indicate that the Pantano Formation probably is several thousand feet thick in two structural depressions along the west-central part of the basin. The two depressions are separated by an east-west-trending ridge in the subsurface near Sierra Vista. The electrical resistivity of the Pantano Formation generally is 20–30 ohm-m but includes a low-resistivity interval of about 10 ohm-m in several wells. The low-resistivity intervals correlate with descriptions of cuttings that indicate greater percentages of silt and clay and siltstone. Sonic velocity of the Pantano Formation generally ranges from 10,000 to 16,000 ft/s.

The lower basin fill is an important water-bearing unit throughout most of the basin. The unit unconformably overlies the Pantano Formation and consists of interbedded gravel and sandstone of variable cementation (Brown and others, 1966). Thickness of the lower basin fill ranges from about 150 to 350 ft on the basis of information from the Fort Huachuca test wells and monitor well MW7 (**pl. 1**, hydrogeologic section A–A'), which fully penetrate the unit. The upper 50 to 100 ft of the unit at test wells and monitor wells at Fort Huachuca is predominantly 10 ohm-m silt and clay, which transitions downward to 20 to 30 ohm-m sand and gravel. The lower basin fill at test well TW9 (pl. 1, hydrogeologic section A-A') includes a 100 ft interval of less than 10 ohm-m siltstone that is not found in the other well logs but probably correlates with much thicker layers of 10 ohm-m materials in two vertical-electrical soundings—Charleston Road and Murray Springs (pl. 1, hydrogeologic section B–B'). The lower basin fill near Lewis Springs averages about 30 ohm-m, but individual beds of 2 to 5 m in thickness range from 15 to 60 ohm-m on the basis of electric logs of wells BLM 2, 5, and 6 (pl. 1). The 15 ohm-m beds probably are clayey and silty sands. The 60 ohm-m beds probably are gravel or caliche. Sonic velocity of the lower basin fill ranges from 5,000 to 6,500 ft/s in silt and clay intervals to 7,000 to 9,000 ft/s in sand and gravel intervals.

The upper basin fill lies above a depth of 400 ft in all wells and is the primary water-bearing unit near the basin margins and near the international boundary with Mexico (**fig. 8**). The unit is conformable with the lower basin fill and consists of weakly cemented and compacted soft reddish-brown clay, gravel, sand, and silt (Brown and others, 1966). The upper basin fill includes a permeable fan-gravel facies near the mountains that grades laterally to a poorly permeable silt and clay facies with interspersed sand and caliche beds near the basin center. The unit is primarily a confining bed of silt and clay where it is saturated between Sierra Vista and the San Pedro River (pl. 1, hydrogeologic section A–A') and between Hereford and Highway 90 along the San Pedro River (pl. 1, hydrogeologic section C–C'). The upper basin fill is an important aquifer where the fan-gravel facies is saturated. Sand beds within the silt and clay facies may also transmit substantial amounts of water provided individual beds are sufficiently interconnected; however, the extent of individual beds is not well known because of a lack of detailed subsurface information. The upper basin fill is equivalent to the St. David Formation of Gray (1965) which crops out extensively north of the study area near St. David.

The saturated part of the upper basin fill generally is thickest near the basin center and thinnest near areas of bedrock outcrop and ranges from 5 ft at TW3 to 188 ft at TW9 (pl. 1, hydrogeologic section A-A'). The unit is above the water level in TW1 and TW2, which penetrate the fan-gravel facies (pl. 1, hydrogeologic section A–A'). The base of the upper basin fill is estimated to be close to the water level at MW7 (pl. 1, hydrogeologic section A–A').

The average electrical-resistivity of the saturated part of the unit at each well ranges from 7 ohm-m at MW5 (pl. 1) to 13 ohm-m at TW3 and TW8 (pl. 1, hydrogeologic section A–A'), which indicates the occurrence of a large amount of silt and clay. Average resistivity at wells BLM 2, 5, and 6 (pl. 1, hydrogeologic section C–C') is 18 to 23 ohm-m, which indicates less silt and clay. Sonic velocity of the upper basin fill generally ranges from 5,000 to 6,500 ft/s with a few high-velocity layers of 10,000 ft/s or more in unsaturated sediments. These high-velocity zones probably are intervals of generally dry caliche.

The unsaturated part of the upper basin fill generally is more electrically resistive than the saturated part and averaged 16 to 26 ohm-m except for TW1 and TW2, which averaged 73 and 161 ohm-m, respectively (pl. 1, hydrogeologic section A–A'). Some unsaturated intervals are as low as 10 ohm-m, which indicates that some of the silt and clay has retained significant amounts of water. A difference in the sonic velocity of saturated and unsaturated upper basin fill was not apparent in the logs except for a few high-velocity layers in several wells that probably are dry caliche.

Pleistocene terrace deposits of clay, silt, sand, and gravel are locally important water-bearing units where depths to water are shallow and can be subdivided into older and younger units (**fig. 8**). The older terrace deposits are unconformable with the upper basin fill and form a veneer of alluvium that is thin near the mountains but may be as much as 50 to 100 ft thick in erosional channels that parallel the current San Pedro River drainage (Brown and others, 1966). Late-Pleistocene lakebed deposits of silt, clay, and marl (Haynes, 1968) are included within the older terrace deposits. Younger terrace deposits are stream alluvium along the channels and flood plains of drainages. The older terrace deposits rarely are saturated outside of the flood plains of the Babocomari and San Pedro Rivers. The younger terrace deposits are saturated where depths to water are shallow near the San Pedro and Babocomari Rivers and along some major drainages near the base of the mountains. Alluvial-fan deposits within the older terrace deposits are locally important water-bearing units south of Hereford near the San Pedro River (pl. 1, hydrogeologic section C–C').

Local-confining conditions may result where the late-Pleistocene lakebed deposits occur near the San Pedro River. The deposits occur between altitudes of 4,050 and 4,190 ft (Haynes, 1968), primarily within current drainage channels. Repeated erosion cycles have removed much of the lakebed deposits along tributary washes, however, much of the deposits may remain in the subsurface south of Highway 90 along the San Pedro River. The lakebed deposits may directly overlie the silt and clay beds of upper basin fill and would be indistinguishable from upper basin fill on the basis of electrical-resistivity surveys. An intervening interval of sand and gravel of a few meters thickness, noted by Haynes (1968), could provide an important conduit for the transmission of water between the two layers of poor permeability.

Holocene alluvium along the San Pedro and Babocomari Rivers is a locally important water-bearing unit (fig. 8). The unit unconformably overlies lower basin fill and volcanic rocks in the Charleston area and upper basin fill above and below Charleston and along the Babocomari River. The oldest deposits of Holocene alluvium are clay, silt, and fine sand, having interbedded coarse-sand and pebble to cobble gravel that were deposited before entrenchment of the river, which occurred about 1890 (Hereford, 1993). Deposits of pre-entrenchment alluvium are as much as 20 ft thick and 1 mi wide. The post-entrenchment alluvium is sand and gravel deposited subsequent to entrenchment of 3 to 33 ft within a narrow channel in the flood plain and pre-entrenchment alluvium. The greatest entrenchment was 16 to 33 ft downstream from Lewis Springs; however, entrenchment of 3 to 16 ft occurred upstream from Lewis Springs (Hereford, 1993). Thickness of the postentrenchment alluvium is only a few feet. Width of the deposits has increased since entrenchment from a narrow channel to as much as 100 to 500 ft in the Hereford area; most of the widening occurred before 1955 (Hereford, 1993). Width of the postentrenchment alluvium in a 1.2-mile reach downstream from Hereford increased from an average of 114 ft in 1908, to 536 ft in 1955, and 645 ft in 1986.

The postentrenchment alluvium is highly permeable. Pre-entrenchment alluvium transmits water but is poorly permeable in comparison to the overlying postentrenchment alluvium and underlying deposits of sand and gravel within the upper basin fill. A layer of pre-entrenchment alluvium between the more permeable units may restrict the ability of ground water to flow between the river and the basin-fill aquifer in many areas. Unfortunately, the distribution of pre-entrenchment alluvium is not well known. A good hydraulic connection between the basin fill and river probably occurs in areas of greatest incision of the river below Highway 90, where much of pre-entrenchment alluvium may have been removed.

The electrical and seismic properties of the Holocene alluvium and terrace deposits are estimated from surface-electrical and surface-seismic surveys because the borehole logs did not provide information from the upper few tens of feet of the subsurface. The resistivity of saturated pre-entrenchment alluvium and postentrenchment alluvium are highly variable, ranging from 10 ohm-m silt and clay to 50 ohm-m sand and gravel; however, the postentrenchment alluvium tends to be more electrically resistive than the pre-entrenchment alluvium. Seismic velocity of the deposits ranges from less than 2,000 ft/s in unsaturated sediments to 5,500 ft/s below the water table.

Ground-Water Flow System

Ground water in the Sierra Vista subwatershed generally flows from recharge areas near the mountains through sand and gravel of the upper and lower basin fill to discharge areas along the San Pedro and Babocomari Rivers (**pl. 2**). Ground water discharges near the two streams as base flow, small springs near the San Pedro River, and evapotranspiration through phreatophytes. Some ground water discharges from the subwatershed as ground-water flow through alluvial deposits of basin fill and Holocene alluvium in the Boquillas area. A part of the ground-water flow is intercepted upgradient from the San Pedro and Babocomari Rivers by pumped wells and phreatophytes where depths to water are shallow along ephemeral streams. Withdrawal of ground water from aquifer storage has created a cone of depression in the heavily pumped area near Sierra Vista.

The distribution of water-level altitudes in wells during January 1998 (Arizona Department of Water Resources, unpub. data, 1998) defines the regional ground-water flow system (pl. 2). Water-level gradients toward the San Pedro River indicate that ground water discharges to the river. Water-level gradients are steep near the Huachuca Mountains and within about 2 mi west of the San Pedro River. Steep water-level gradients are indicative of areas of low transmissivity where silt and clay predominate or where the aquifer is thin. Steep gradients near the base of the Huachuca Mountains result from shallow bedrock that limits the aquifer thickness and may result in local perched aquifers that are poorly connected to the regional-aquifer system. Steep gradients west of the San Pedro River coincide with the silt and clay facies of the upper and lower basin fill and a thinning of the aquifer near the Tombstone Hills.

Ground water primarily flows horizontally; however, significant vertical-hydraulic gradients and vertical ground-water flow occurs near discharge areas along the San Pedro River, recharge areas along the mountain fronts, losing reaches of the Babocomari and San Pedro Rivers, and in heavily pumped areas. Upward flow occurs along gaining reaches of the San Pedro River between Charleston and Hereford. Downward flow occurs along losing reaches of the San Pedro River north of Charleston and south of Hereford and at places between Hereford and Lewis Springs. Downward flow also occurs along losing reaches of the Babocomari River near Huachuca City in an area coincident with a local perched aquifer. Vertical-hydraulic gradients are not documented throughout most of the basin because of few closely spaced pairs of shallow and deep wells, however, water levels in a deep well and a shallow well at Fort Huachuca indicate that significant vertical hydraulic-head gradients occur. Well (D-21-20)13cbb1 (TW8; pl. 1) is 1,500 ft deep with several screened intervals and no casing below 1,305 ft. Nearby well (D-21-20)13cbb2 is 468 ft deep with 105 ft of screened interval below a depth of 238 ft. The water-level altitude in the shallow well was about 35 ft below the water-level altitude in the deep well for several pairs of measurements made during the late 1970s. Water levels in the shallow well have not been measured since that time. Greater differences in hydraulic head probably occur between specific water-bearing zones because the water level in the deep well represents a composite of water levels in many intervals.

Most ground-water flow occurs through permeable sand and gravel within the upper and lower units of basin fill, terrace deposits, and Holocene alluvium near the San Pedro and Babocomari Rivers. The primary regional aquifer in the northern part of the basin includes upper and lower units of basin fill. Most wells in the southern part of the basin produce water from the upper basin fill, however, significant amounts of ground water may flow through the lower basin fill. The Pantano Formation is locally an important water-bearing unit in the vicinity of Sierra Vista where wells produce water from fractures. Elsewhere in the basin, the ability of the Pantano Formation to transmit water is not well known. Terrace deposits and the Holocene alluvium are the most permeable water-bearing units in the subwatershed and are important conduits for the transport of ground water near the San Pedro and Babocomari Rivers.

Silt and clay layers within the upper and lower units of basin fill split ground-water flow in the regional aquifer into deep- and shallow-flow systems (**pl. 1**, hydrogeologic sections A–A', B–B', and C–C'). Flow in the deep system is primarily through sand and gravel in the lower basin fill. Ground water in the shallow system primarily flows through layers of sand and gravel in the upper basin fill, terrace deposits, and Holocene alluvium. Ground water from the deep system must flow through the shallow system before reaching discharge areas along the San Pedro and Babocomari Rivers. The shallow system also discharges to several small springs and areas of riparian vegetation west of the river where the tops of the silt and clay layers intersect the land surface in washes. Flow in the northern part of the basin is primarily through the deep system (pl. 1, hydrogeologic section A–A'), however, some ground water may also be transmitted through sand layers that are interlayered with the silt and clay in the upper basin fill. Ground-water flow in the southern and central parts of the basin occurs in both the shallow and deep systems (**pl. 1**, hydrogeologic sections B–B' and C–C'). In the vicinity of hydrogeologic section B–B', ground water flows northeastward from the Huachuca Mountains and is separated into shallow- and deep-flow systems by the silt and clay layers. The shallow- and deep-flow systems merge again into a single flow system downgradient from the silt and clay layers.

Near the San Pedro River, ground water flows from the regional aquifer toward the river and downgradient parallel to the river through the Holocene alluvium. Ground-water flow between the regional aquifer and the Holocene alluvium is restricted by pre-entrenchment alluvium, which is less permeable than the postentrenchment alluvium. Entrenchment may have cut through the pre-entrenchment alluvium, in places, resulting in a good hydraulic connection between the regional aquifer, postentrenchment alluvium, and the river. Areas of greatest entrenchment below Lewis Springs are more likely to have a good hydraulic connection between the regional aquifer and river. The occurrence of a good hydraulic connection below Lewis Springs is supported by seepage data, which indicate that ground-water discharge to the river is greater below Lewis Springs than between Hereford and Lewis Springs (S.G. Brown and B.N. Aldridge, hydrologists, U.S. Geological Survey, written commun., 1973).

Ground-water flow near the river is also influenced by the local distribution of transmissivity. The greatest influence occurs where the regional aquifer is thin near areas of shallow conglomerate or bedrock, such as near Lewis Springs (**pl. 2**, hydrogeologic section D–D'). Transmissivity near Lewis Springs is greatest west of the river because the base of the basin fill dips to the west, which results in greater aquifer thickness west of the river. The distribution of transmissivity results in a ground-water flow system that is asymmetric about the river with the lowest hydraulic head in the regional aquifer occurring west of the river.

Changes in the Ground-Water Flow System

The ground-water flow system has changed primarily because withdrawals from wells have intercepted much of the flow that would otherwise discharge as base flow or evapotranspiration along the Babocomari and San Pedro Rivers (pl. 2). Other significant changes include water-level variations in response to precipitation and mountain-front recharge and regionally declining water levels before the mid-1980s. Despite these changes, the ground-water flow system in January 1998 was similar to the predevelopment system except for areas near Sierra Vista where withdrawals from wells have removed ground water from aquifer storage and caused diversion of pre-development ground-water flow paths. Directions of ground-water flow and hydraulic gradients outside of the Sierra Vista area have not changed significantly since pre-development; however, ground-water withdrawals near Palominas and Huachuca City have caused water levels to decline beneath the river level resulting in losing stream reaches.

The distribution of water levels in wells during January 1998 (pl. 2) indicate that ground-water withdrawals in the vicinity of Fort Huachuca and Sierra Vista have intercepted and diverted ground-water flow paths. Flow paths north of about Garden Canyon have been diverted to supply wells, and ground water in this area no longer flows to discharge areas along the Babocomari and San Pedro Rivers. Most of the diverted flow would have eventually discharged in areas north of the Charleston streamflow-gaging station as base flow to streams, ground-water underflow, and evapotranspiration by phreatophytes. Unfortunately, long-term streamflow records that could confirm reductions in base flow are not available along the Babocomari River or the San Pedro River above the Charleston station. Continued withdrawal of ground water from aquifer storage and expansion of the cone of depression will eventually divert ground-water flow that discharges above the Charleston station and result in diminished base flow at the station.

Long-Term Water-Level Monitoring

Changes in water levels in wells have occurred throughout the basin since water-level data were first routinely collected in the early 1940s. Water levels in wells near the mountains have varied in response to precipitation and recharge. A regional water-level decline of 0.3 to 0.5 ft/yr occurred though the mid-1960s (Brown and others, 1966) and continued in parts of the basin until the early 1980s. Greater rates of water-level decline have occurred in the heavily pumped part of the aquifer in the Fort Huachuca-Sierra

Vista area. Water-level changes also have occurred near the San Pedro River, but water-level data have not been routinely collected in the area. As a result, relations between the ground-water flow system and flow in the river before the mid-1990s are difficult to define in detail. Long-term monitoring of water levels in much of the basin, however, provide sufficient information to assess causes of the regional water-level changes.

Water Levels in Wells near the Mountains

Water levels in wells near the mountain fronts vary in response to precipitation and recharge. Records are available for two well sites near the mountains; wells (D-23-21)06ccc1 and (D-23-21)06ccc2 and well (D-22-20)26abb1 (**pl. 2**). The wells are close to major drainages near the Huachuca Mountains—Carr Canyon, and Garden Canyon—and have shallow water levels indicative of aquifers that are perched or have a poor hydraulic connection to the regional-aquifer system. Water levels may vary 20 ft or more between yearly measurements, but trends in depth to water of a few years or more correlate with trends in annual precipitation. The large variations in water levels occur because water levels recover quickly in response to periods of above-average recharge and decline gradually during periods of below-average recharge. Water levels recover when rates of recharge to the local aquifer exceed rates of outflow. Water levels decline when local recharge rates are less than outflow rates from the local aquifer.

Water-level variations in wells (D-23-21) 06ccc1 and (D-23-21)06ccc2 (pl. 2) indicate that rates of recharge near the Huachuca Mountains were greater during the late 1970s through early 1990s than during 1940 through the mid-1970s. The wells are adjacent to an ephemeral stream that drains the highest altitudes of the Huachuca Mountains. Water levels recover as much as 20 or 30 ft to near the land surface in response to streamflow, but water levels also decline when streamflow and recharge is infrequent. Infrequent recharge before 1969 resulted in annual water-level variations of 10 to 20 ft or more and water levels rose overall about 15 to 20 ft between 1943 and 1969. Most of the water-level rise occurred during periods of above-average wet-season precipitation during the mid-1950s to late 1950s and above-average winter precipitation during the mid-1960s as shown by data from the precipitation stations at Fort Huachuca, Y-Lightning Ranch, and Coronado National Monument (**figs. 3**B,C,D). Water levels declined during a period of below-average winter precipitation from 1969 to 1976 and recovered in response to above-average precipitation in the late 1970s. Water levels declined during a brief period of below-average precipitation in the early 1980s but recovered and remained high during an extended period of above-average precipitation in the mid-1980s through early 1990s. Recharge rates were sufficient to maintain high water levels and a local balance between recharge and discharge through about 1993. Precipitation after 1993 generally was below average with the exception of 1995 and rates of recharge were insufficient to maintain water levels until 1998.

Well (D-22-20)26abb1 is near Garden Canyon Wash, which drains a part of the Huachuca Mountains that is lower in altitude than near wells (D-23-21)06ccc1 and (D-23-21)06ccc2 (pl. 2). The water-level record at well (D-22-20)26abb1 is less complete than the records at wells (D-23-21)06ccc1 and (D-23-21)06ccc2 but displays similar trends. Frequent water-level measurements during 1995–98 indicate that water levels declined from about 20 ft below land surface in 1995 to more than 80 ft below land surface in 1997 before a recovery of about 15 ft in 1998. Water-level variations at well (D-22-20)26abb1 are greater than at wells (D-23-21)06ccc1 and (D-23-21)06ccc2, which indicates smaller storage volume within the local aquifer or greater variations in recharge rates.

Water Levels in Wells in the Regional Aquifer

Water levels in wells in the regional aquifer have declined throughout most of the period of record. Records available for several wells that are widely spaced throughout the regional aquifer (pl. 2) indicate that water levels generally declined before the mid-1960s or early 1980s. Water levels generally were stable or recovered after the early 1980s except for local areas near Fort Huachuca and Sierra Vista and near the San Pedro River. Regional water-level trends appear to correlate with precipitation and probably are caused by changes in recharge rates. Local changes near Fort Huachuca and Sierra Vista and near the San Pedro River are influenced by local changes in rates of ground-water withdrawals.

Well (D-19-23)35acd (pl. 2) is near Tombstone and has a deep water level indicative of the regional aquifer. The water level rose about 20 ft after the wet period during the mid-1980s similar to the trend in wells (D-23-21)06ccc1, (D-23-21)06ccc2, and (D-22-20)26abb1 (**pl. 2**) near the Huachuca Mountains. Water-level data are not available to assess the effects of precipitation after 1994.

Regional water-level declines before the early 1980s are evident in long-term hydrographs of water levels in several wells throughout the basin (pl. 2). Most of the wells are several miles from the Fort Huachuca-Sierra Vista and Palominas areas and should be minimally affected by ground-water withdrawals in those areas. Wells (D-23-22)18bbb and (D-22-21)23cba (pl. 2) are 3 to 4 mi west of the San Pedro River and several miles southeast of Sierra Vista. Hydrographs of water levels at the wells indicate similar rates of water-level decline of about 0.3 ft/yr before the early to mid-1980s, which were followed by a slight water-level recovery or stable water levels. Well (D-24-23)06aaa1 (pl. 2) is several miles east of the San Pedro River near Greenbush Wash and data from the well show a slightly greater rate of water-level decline. Water levels in wells farther north— wells (D-21-21)22ddc, (D-21-21)27cbd, and (D-21-21)27caa—have overall rates of water-level decline similar to wells (D-23-22)18bbb, (D-22-21)23cba, and (D-24-23)06aaa1 (pl. 2) before the mid-1960s, which were followed by a slight water-level recovery. The water level at well (D-20-20)02ddd (pl. 2), which is north of the Babocomari River, has declined only a few feet since data collection began about 1960.

The early water-level declines at wells throughout the regional aquifer correlate well with the precipitation records. Precipitation and recharge before the mid-1960s were insufficient to maintain water levels. Recovery of water levels at wells (D-21-21)22ddc, (D-21-21)27cbd, and (D-21-21)27caa (pl. 2) during the mid-1960s may indicate that greater rates of recharge occurred near those wells with respect to other areas at that time. Increased recharge rates did not affect water levels in other areas until several years of above-average precipitation during 1983 through 1988.

The effects of ground-water withdrawals in the Fort Huachuca-Sierra Vista area are evident in the hydrographs of water levels at wells (D-21-21)29cca and (D-21-21)31bdc (pl. 2). Rates of water-level decline were about 0.5 ft/yr before about 1980 at well (D-21-21)29cca and greater than 1 ft/yr at well (D-21-21)31bdc after about 1980. Rates of water-level decline in the Fort Huachuca-Sierra Vista area that are greater than the rates of decline at most other wells in the regional aquifer probably are caused by ground-water withdrawals in the area. Divergence of rates of water-level decline at well (D-21-21)31bdc from rates of decline at wells (D-21-21)22ddc, (D-21-21)27cbd, and (D-21-21)27caa after the 1960s also may be related to different aquifer lithology in the two areas. Water levels in wells (D-21-21)22ddc, (D-21-21)27cbd, and (D-21-21)27caa may be representative of the shallow ground-water flow system overlying the silt and clay facies of the upper and lower basin fill. Water levels at wells (D-21-21)29cca and (D-21-21)31bdc probably are representative of water levels in the ground-water flow system west of the silt and clay facies where a shallow ground-water flow system does not occur. Lack of water-level decline in the shallow ground-water flow system after the 1960s may be the result of a poor hydraulic connection with the deep ground-water flow system through the silt and clay (**pl. 1**, hydrogeologic sections A–A’ and B–B’).

Water Levels in Wells near the San Pedro River

Records of long-term water-level changes near the San Pedro River are poor with the exception of those for the Palominas area. Water levels declined with incision of the river before 1908, but there are no data to document the effect on the ground-water system. Amounts of water-level decline near the river probably were similar to the amount of incision, 16 to 33 ft downstream from Lewis Springs and 3 to 16 ft upstream from Lewis Springs (Hereford, 1993). River incision and water-level declines near the river probably resulted in increased hydraulic gradients between the regional aquifer and the river that dissipated as water levels in the regional aquifer declined.

The history of ground-water withdrawals for irrigation in the Palominas area is poorly documented, but previous investigations have assumed that significant withdrawals began in the area during the 1940s (Freethey, 1982; Vionnet and Maddock, 1992; and Corell and others, 1996). Water-level declines probably resulted from the ground-water withdrawals but were not documented by measurements. Monitoring of water levels at well (D-23-22)33dcd2 (pl. 2) began near the river at Palominas in 1954 and water levels have declined only a few feet since that time. Declines have been sufficient to lower water levels beneath the river in the area and convert a perennial stream reach to ephemeral.

Water levels in the regional aquifer near the San Pedro River at Highway 90 have risen since the mid-1980s when agricultural withdrawals ceased in the area. Water levels at well (D-22-22)06dac (pl. 2) rose about 8 ft over the period 1985 to 1998. Water levels in the well are representative of a composite of several intervals of upper and lower basin fill throughout the cased well depth of 715 ft. The difference in hydraulic head between the regional aquifer and the river has increased from about 19 to 27 ft and probably has resulted in greater rates of ground-water flow from the regional aquifer to the Holocene alluvium and the river. An apparent lack of increased base flow at the Charleston gaging station during the period of water-level recovery (**figs. 7**A,B) indicate that (1) the recovery of water levels in the regional aquifer may have helped maintain base flows that would have otherwise declined or (2) that the rate of ground-water flow from the regional aquifer to the river between Highway 90 and the Charleston station from 1985 to 1998 was relatively minor in comparison to other sources of base flow in the reach.

Analysis of Long-Term Water-Level Change

Water-level records indicate four types of long-term water-level changes: (1) periodic decline and recovery near the mountains, (2) decline of 0.5 to more than 1 ft/yr in the Fort Huachuca-Sierra Vista area during the period of record, (3) regional decline of 0.3 to 0.5 ft/yr during 1940 through the mid-1960s or early 1980s followed by a period of no decline or slight recovery, and (4) recovery near the San Pedro River after the mid-1980s. Variations near the mountains are related to variations in precipitation and rates of recharge. The highest rates of water-level decline in the regional aquifer are caused by ground-water withdrawals in the Fort Huachuca-Sierra Vista area. Regional water-level decline before the mid-1980s could be caused by variations in recharge rates or regional response to incision of the river. Water-level recovery near the San Pedro River after the mid-1980s probably is related to a decrease in agricultural withdrawals, but some of the recovery may be caused by increased recharge rates.

The proximity of the Babocomari and San Pedro Rivers to the wells—(D-20-20)02ddd, (D-21-21)22ddc, (D-21-21)27cbd, and (D-23-22)33dcd2—in which the lowest rates of regional water-level decline occurred before the mid-1980s indicates that the regional water-level decline is not related to changes near the rivers. The greatest rates of decline occur at wells (D-21-21)29cca, (D-22-21)23cba, (D-23-22)18bbb, and (D-24-23) 06aaa1 and are likely closer to the source of the decline. Proximity of the mountains to the greatest rates of water-level decline suggests that the regional declines are probably related to variations in recharge rates near the mountains. Below-average precipitation during 1940 to 1982 probably resulted in below-average rates of recharge. Periods of above-average rates of recharge probably occurred during wet periods in the mid-1950s to late 1950s, mid-1960s, late 1970s, and mid-1980s through early 1990s. The later wet period resulted in significantly greater recharge rates that persisted for nearly a decade on the basis of water levels at well (D-23-21)06ccc2. Stabilization or recovery of regional water levels after the early 1980s probably is related to the increased recharge rates during the mid-1980s through early 1990s. Water-level stabilization and recovery east of Sierra Vista during wet periods of the mid-1950s to late 1950s and mid-1960s may be caused by greater amounts of ephemeral stream recharge in the area or low-storage capacity of the aquifer. The occurrence of the silt and clay facies of upper basin fill in the area indicates that low-storage capacity probably contributed to the greater water-level response.

Water-level recovery near the San Pedro River at well (D-22-22)06dac after the early 1980s probably is related to both greater recharge rates and retirement of irrigated crop land within the SPRNCA. Greater water-level recovery at this well with respect to well (D-23-22)33dcd2 near Palominas probably is related to the continuation of some irrigation near Palominas and more extensive occurrence of the silt and clay facies of upper and lower basin fill and lower aquifer- storage capacity in the vicinity of well (D-22-22)06dac.

Recent Water-Level Monitoring

Water levels were monitored in several wells beginning in the spring of 1995 for the purpose of determining aquifer response to ground-water withdrawals, stage of the San Pedro River, and recharge (**pl. 2**). Data were collected at wells at Fort Huachuca and near Lewis Springs and the San Pedro River. Bimonthly tapedowns were conducted at many of the wells by personnel at Fort Huachuca and hourly data were collected at four additional wells. Hourly water levels and river stage were collected near Lewis Springs. The period of record was dominated by water-level declines in wells at Fort Huachuca. Water levels in wells at Lewis Springs varied seasonally with evapotranspiration and streamflow and displayed no long-term trends.

Water Levels in Wells in the Regional Aquifer

Water levels in the regional aquifer declined 1 to 2 ft from 1995 to 1998 in several test and monitor wells at Fort Huachuca (pl. 2). All the wells are more than 1 mi west of the San Pedro River. The test wells were installed in the early 1970s to depths ranging from 700 to 1,500 ft and are open to large thicknesses of aquifer through perforated casing and uncased holes. Water levels in the test wells had declined 11 to 18 ft during the early 1970s through 1995. Several monitor wells, which penetrate 20 to 150 ft of the aquifer, were installed in 1994 and are much shallower than the test wells.

Several trends are apparent in the recent water-level records. The water-level trends are caused by changes in the spatial and temporal distribution of ground-water withdrawals and recharge in the Fort Huachuca-Sierra Vista area. Short-term water-level changes caused by ground-water withdrawals at nearby supply wells are displayed in the record from TW4 (pl. 2) where seasonal pumping at nearby supply wells has caused variations of about 1 to 1.5 ft. Records at the other wells also reflect changes caused by withdrawals at the same supply wells to various degrees; however, water levels at these wells also may be influenced by variations in recharge and withdrawal at other supply wells at greater distances.

The first year of record has three primary trends that are spatially separated (pl. 2). Little or no water-level decline in wells near the Babocomari River until the spring of 1995 is illustrated by the water-level record at TW6. Water levels in wells farther south—MW3 as an example—had decline rates of about 0.5 ft/yr that continued throughout the period of record. Rates of water-level decline at the eastern most wells were more than 1 ft/yr through the winter of 1996 at MW7 and through the summer of 1996 at MW5. The lack of water-level decline during the first year of record at wells nearest the Babocomari River may be the result of recharge along the ephemeral part of the Babocomari River after floods during November and December of 1993 and the winter of 1994–95.

Water levels after the spring of 1996 have two primary trends (pl. 2). Water levels declined at a rate of 0.75 to 1 ft/yr at all but three wells—TW4, MW5, and MW7. Water levels at wells TW4, MW5, and MW7 declined through the winter or spring of 1997 before recovering 0.5 ft at MW5 and MW7 and 1 ft at TW4. Similarity of water level trends at MW5 and MW7 with trends at TW4 indicate that the screened intervals at MW5 and MW7 may be hydraulically connected to the primary producing zone at supply wells near TW4.

Water Levels in Wells near Lewis Springs

Water levels at seven wells near the river at Lewis Springs varied about 1 ft seasonally in response to evapotranspiration and river stage but did not display any long-term rises or declines (pl. 2). The wells are aligned along a transect perpendicular to the river and include a shallow, 6 ft, drive-point well in the river bank, three shallow wells (BLM1, 3, and 4) ranging in depth from 25 to 40 ft, and three deep wells (BLM2, 5, and 6) ranging in depth from 180 to 200 ft. Water levels in all the wells responded to river stage and evapotranspiration.

Ground-water flow near the well transect at Lewis Springs is northward and toward the stream in the deep- and shallow-flow systems. Flow in the Holocene alluvium is primarily northward but with a slight downward gradient toward the river (MacNish and others, 1998). Ground water in the deep system flows northward and upward from the lower basin fill through the upper basin fill and to the Holocene alluvium and the river. Flow is asymmetric about the river with the lowest hydraulic head at BLM6, which is the well farthest west of the river (pl. 2, hydrogeologic section D–D’). The asymmetry is consistent with geophysical surveys that indicate greater aquifer thickness and probable greater transmissivity west of the river.

Some changes in the deep ground-water flow system occurred during the monitoring. The head difference between BLM5 and BLM6 increased several tenths of a foot between the initial measurement in March 1995 and the spring of 1997 but varied only a few hundredths of a foot from the spring of 1997 to the spring of 1998. The increased head difference before the spring of 1997 is consistent with the effects of ground-water withdrawals or reduced recharge west of the river. The increased head difference also correlates with the greatest rates of water-level decline at MW5 and MW7 that occurred before the fall of 1997. This correlation is consistent with the effect of ground-water withdrawals in the Fort Huachuca-Sierra Vista area but could also be related to changes in recharge rates. However, lack of an increasing difference in hydraulic head between BLM5 and BLM6 after the spring of 1997 is not consistent with continued ground-water withdrawals and continued water-level decline at other wells in the regional aquifer. A longer period of data collection is needed to determine the causes of variations in head differences in the deep-flow system near Lewis Springs.

Water Budget

The ground-water budget in the Sierra Vista subwatershed includes three main components—recharge, storage, and discharge. Rates of recharge and storage change are difficult to directly estimate because both occur over large areas. Discharge primarily occurs through base flow to streams, well withdrawals, and evapotranspiration by phreatophytes. Rates of discharge from wells and streams can be accurately measured because the flow of water occurs at discrete sites; however, discharge through evapotranspiration occurs across large areas and must be estimated through indirect methods. Discharge also occurs through ground-water outflow from the subwatershed, but estimates of ground-water outflow are small in comparison to the three primary discharge mechanisms (Freethey, 1982; Vionnet and Maddock, 1992; Corell and others, 1996). Recharge can be indirectly estimated as equivalent to discharge provided that the ground-water system is in a state of equilibrium (steady state) where no changes in storage occur. The ground-water system in the Sierra Vista subwatershed has been assumed to have been in steady state before extensive ground-water withdrawals from wells began about 1940 (Freethey, 1982; Vionnet and Maddock, 1992; Corell and others, 1996); therefore, estimates of steady-state recharge for about 1940 are dependent on the accuracy of discharge estimates and the validity of the steady-state assumption.

Previous investigations have estimated discharge through base flow, ground-water outflow, evapotranspiration, and ground-water withdrawals. Freethey (1982) estimated that predevelopment ground-water base flow to streams was about 8,300 acre-ft/yr, but base flow declined to about 5,900 acre-ft/yr during the late 1970s. The same study estimated that predevelopment evapotranspiration rates were about 7,800 acre-ft/yr before ground-water development and declined to about 6,200 acre-ft/yr in the late 1970s. Ground-water outflow from the subwatershed in the Fairbank area has been estimated as 300 to 400 acre-ft/yr (Freethey, 1982; Corell and others, 1996). Significant ground-water withdrawals are estimated to have begun around 1940 with 2,000 to 5,000 acre-ft/yr of withdrawals (Freethey, 1982; Corell and others, 1996). Maximum withdrawals peaked in the early 1980s at more than 15,000 acre-ft/yr and had declined to about 11,000 acre-ft/yr by 1991 (Corell and others, 1996).

Input to the ground-water system in the Sierra Vista subwatershed includes recharge and ground-water flow from Mexico. Steady-state water-budget methods can be used to estimate the rate of annual recharge as equivalent to the estimated rates of discharge during predevelopment. The areal and temporal distribution of recharge, however, is difficult to determine. As a result, most investigators have adopted a simplified concept of the recharge distribution that includes recharge near the mountain fronts as a constant rate of infiltration of surface flow through the channels of ephemeral streams. This process is known as mountain-front recharge. Recharge probably also occurs along ephemeral streams below the mountain fronts and losing reaches of the San Pedro and Babocomari Rivers. Rates of recharge probably vary in time as well as in response to changes in precipitation rates and capture of surface flow and soil moisture by vegetation. This study has developed information relevant to the areal and temporal distribution of recharge on the basis of geochemical and precipitation data.

Estimates of annual input to the ground-water system include about 12,500 acre-ft (Freethey, 1982) to about 15,000 acre-ft (Corell and others, 1996) of mountain-front recharge and 3,000 acre-ft of ground-water flow from Mexico (Freethey, 1982; Corell and others, 1996). Since development, simulated input to the ground-water system increased by about 1,700 acre-ft/yr (Freethey, 1982) through induced infiltration of streamflow along the San Pedro and Babocomari Rivers and increased ground-water inflow from Mexico. The largest part of mountain-front recharge has been estimated to occur along the base of the Huachuca Mountains. Freethey (1982) estimated 5,500 acre-ft/yr of recharge along the base of the Huachuca Mountains and 4,300 acre-ft/yr in the Babocomari Valley, which is dominated by recharge along the north and west sides of the Huachuca Mountains. Recharge also occurs along the base of the Mule Mountains and Tombstone Hills, 2,750 acre-ft/yr (Freethey, 1982), and along ephemeral streams, although few estimates exist for this mechanism. Corell and others (1996) estimate 1,000 acre-ft/yr of ephemeral-stream recharge along Greenbush Wash.

Rates of mountain-front recharge probably vary with precipitation. Anderson and others (1992) developed an empirical relation (eq. 1) between precipitation and mountain-front recharge on the basis of the water budget for many basins in Arizona.

$$\mathrm{Log}Q = -1.40+0.98(\log P) \qquad (1)$$

where

Q = the annual rate of mountain-front recharge, in acre-feet; and

P = the volume of precipitation in excess of 8 in., in acre-feet.

This relation is general and does not account for several factors that influence recharge, such as geology, slope, vegetation, and soils. The relation, however, can be used to evaluate the influence of the observed long-term trends in precipitation on rates of mountain-front recharge in the Sierra Vista subwatershed. Variations in mountain-front recharge rates can be estimated considering the average annual precipitation in the basin as 16.1 in. on the basis of data from four precipitation gages from 1956 to 1997 (**fig. 3**). Annual precipitation from 1956 to 1982 was about 0.8 in. below average (15.3 in.), and annual precipitation from 1983 to 1997 was about 1.4 in. above average (17.5 in.). Application of annual rates of precipitation during the early and late periods to equation 1 indicates that mountain-front recharge in the Sierra Vista subwatershed could be expected to vary about 3,700 acre-ft/yr between the wet and dry period, which is 30 to 23 percent of the estimated recharge rate of 12,500 to 15,000 acre-ft/yr. Mountain-front recharge throughout the basin, inclusive of the part in Mexico, may be expected to vary about 6,200 acre-ft/yr between the wet and dry periods. Short-term variations in annual mountain-front recharge could be much larger, considering that mountain-front recharge in any year could be expected to be about 3 in. above or below average; however, long-term trends in recharge of decades length are more likely to result in significant variations in base flow of the San Pedro River than trends of a few years length. Rates of mountain-front recharge before 1983 that were 70 to 77 percent of later rates compare favorably with regionally declining water levels during 1940 through the early 1980s followed by stable or slight recovery of water levels.

HYDROCHEMISTRY

Chemistry of water in the Sierra Vista subwatershed was investigated to better define ground-water flow paths and to help quantify the sources of base flow in the San Pedro River above the streamflow-gaging station at Charleston. Ground-water and surface-water samples were analyzed for several chemical constituents including ions of calcium, magnesium, sodium, potassium, chloride, sulfate, fluoride, and bicarbonate; field parameters of temperature, specific conductance, alkalinity, and pH (see table on pl. 3). Many samples also were analyzed for tritium and stable isotopes of hydrogen and oxygen. The availability of wells provided a good areal distribution of samples west of the San Pedro River; however, few wells were accessible east of the San Pedro River. Seasonal and longer-term trends in the chemistry of base flow were analyzed using repeated samples of flow in the San Pedro River at four locations, which included near Hereford and near Lewis Springs (Highway 90), and the streamflow-gaging stations at Palominas and Charleston.

Ground water in the regional aquifer can be divided into three spatial categories that have different recharge sources and water chemistry— the regional aquifer west of the San Pedro River, the regional aquifer east of the San Pedro River and in Mexico, and the Holocene alluvium along the San Pedro River. Water in the regional aquifer west of the San Pedro River is depleted in heavy isotopes relative to water from the regional aquifer east of the San Pedro River and water that has flowed from the regional aquifer in Mexico. The two chemical signatures of water in the regional aquifer represent two important recharge sources that contribute to base flow of the San Pedro River—recharge near the Huachuca Mountains and recharge near the Mule Mountains and in Mexico. Ground water in the Holocene alluvium is a mixture of water from all recharge sources and has variable chemistry but is generally more enriched in heavy isotopes and has greater concentrations of some common ions and higher specific conductance than water in the regional aquifer. Sources of water in the Holocene alluvium include ground-water flow from all parts of the regional aquifer and recharge through infiltration of streamflow. An estimation of the relative contribution to base flow from each of the three recharge sources—near the Huachuca Mountains, near the Mule Mountains and in Mexico, and along the San Pedro River—was derived from the chemistry of base flow in the river at several locations during March 1996 and March 1997.

Common Ions

Ground water in the Sierra Vista subwatershed is predominantly a calcium bicarbonate type (**pl. 3**, fig. A, table 1), but concentrations of major ions change along ground-water flow paths through interaction of the water with grains of sediment that compose the aquifer. Primary flow paths include flow through the regional aquifer to the San Pedro River from areas of recharge near the mountains at the basin margins and flow from south to north through the Holocene alluvium along the San Pedro River.

Changes in the common-ion chemistry of ground water along flow paths in the regional aquifer are characterized by analyses of water samples from wells west of the San Pedro River (pl. 3). The distribution of common ions follows a pattern of high concentrations of calcium and magnesium in samples near the mountains to high concentrations of sodium and potassium in samples near the river. Reactions that possibly account for the observed changes include calcite precipitation, dolomite dissolution, and cation exchange (Coes, 1997). Similar trends probably occur east of the river, but data are sparse.

Water in the Holocene alluvium and streamflow in the San Pedro River generally are a calcium bicarbonate type, but concentrations of calcium and magnesium tended to be lower than concentrations in samples from the regional aquifer and concentrations of sodium, potassium, chloride, and sulfate tended to be greater than concentrations in samples from the regional aquifer (pl. 3). No spatial trends in the distribution of common ions are evident in water samples from the Holocene alluvium and San Pedro River, but concentrations of chloride, sulfate, and bicarbonate tended to vary with changes in amounts of surface-water runoff. The greatest variations in concentrations of common ions tended to occur in wells that draw water from the postentrenchment alluvium and at the Palominas well, which is near the Palominas streamflow-gaging station. The Palominas well is 91.5 ft deep and probably penetrates the pre-entrenchment alluvium; however, water in the well may be derived from the overlying postentrenchment alluvium. Variations in the concentration of common ions in samples from the Palominas well were greater than at any other well that has been repeatedly sampled (pl. 3).

Specific Conductance

Specific conductance of surface water and ground-water was variable, but the data indicate some temporal and spatial trends. Specific conductance of runoff in the San Pedro River varied between 235 to 610 µS/cm during the investigation, but generally was low (pl. 3, fig. F1). Specific conductance of base flow in the San Pedro River averaged 558 µS/cm and generally decreased downstream from Palominas to Charleston (pl. 3, fig. D3). Specific conductance of ground water in the Holocene alluvium also generally decreased downstream (pl. 3, fig. C3), but values were highly variable and ranged from 342 to 1,121 µS/cm and averaged about 550 µS/cm. Specific conductance of water in the regional aquifer varied across the subwatershed from 281 to 533 µS/cm, but commonly was above 400 µS/cm in water from wells in areas near outcrops of sedimentary rocks in the Huachuca and Mule Mountains and near the international boundary (pl. 3; Barnes, 1997). Specific conductance in most of the regional aquifer west of the San Pedro River was below 400 µS/cm and averaged 338 µS/cm. Specific conductance in the regional aquifer east of the river is poorly defined because of a lack of sampled wells; however, values from the two wells sampled for this project and from four previously sampled wells (Barnes, 1997) ranged from 390 to 519 µS/cm and averaged 445 µS/cm. Some reduction in specific conductance may occur through chemical reactions along ground-water flow paths in the regional aquifer. Variations in the specific conductance of ground water in the Holocene alluvium with time probably are minimal because the water does not flow through the alluvium for a long enough period of time for significant chemical reactions to occur.

The cause of high specific conductance in the Holocene alluvium is poorly understood. Possible mechanisms that may contribute to high specific conductance include infiltration of surface flow that is high in total dissolved solids, evaporative concentration, dissolution of gypsum in the regional aquifer near or south of Palominas, or dissolution of sedimentary rocks in Mexico. Continuous record of the specific conductance at the Charleston streamflow-gaging station during September 1996 through September 1998 (**pl. 3**, fig. F1) indicates that runoff was not a likely source of the high specific-conductance values in the Holocene alluvium during that period, because values in runoff generally were less than 300 µS/cm. Values of more than 600 µS/cm, however, were measured in several runoff samples collected during the investigation and values of 800 to 1,200 µS/cm also have been measured in samples collected from runoff before this study (U.S. Geological Survey, unpub. data, 1977–93). Evaporative concentration of streamflow during the summer months may be an important source of high specific conductance in the water samples from the Holocene alluvium. Evaporative concentration probably occurs during dry intervals between periods of runoff; especially in ephemeral stream reaches such as near Palominas and between Hereford and Highway 90. The concentrated surface water could infiltrate the alluvium during the initial stages of runoff and may explain the high value of specific conductance (1,121 µS/cm) in a water sample collected at the Palominas well in December 1994 following flood runoff during November 1994. Other evidence of evaporative concentration includes increased specific conductance during extreme low flows of July 1997 (pl. 3, fig. F1). Dissolution of gypsum in the subsurface near or south of Palominas could contribute to high specific conductance. Gypsum is reported in the driller's log of well (D-23-22)10cab near Hereford in the depth interval of 102 to 154 ft. Gypsiferous soils have been reported by the U.S. Department of Agriculture (McGuire, 1997). Dissolution of sedimentary rocks in Mexico probably occurs and may contribute to high specific conductance in the Holocene alluvium.

Specific conductance of water samples from the pre-entrenchment alluvium and base flow tend to decrease with distance downgradient from the international boundary, which indicates mixing with regional-aquifer water of lower conductance (pl. 3, figs. C3 and D3). Specific conductance of water samples from the pre-entrenchment alluvium during base flow conditions in 1996 and 1997 decreased from an average of about 650 µS/cm near Palominas to values similar to those of the regional aquifer at the Cottonwood #1 well (about 330 µS/cm) (pl. 3, fig. C3). Specific conductance of samples from the pre-entrenchment alluvium increased downgradient from the Cottonwood #1 well, which may indicate a greater contribution of flow from the regional aquifer near the Mule Mountains. Specific conductance of samples from the post-entrenchment alluvium was variable and displayed no particular spatial trend. A declining trend in the specific conductance of base flow with downgradient distance is displayed by data from samples collected during March 12 and 13, 1996; March 25, 1997; and June 24, 1997 (pl. 3, fig. D3). Specific conductance during March 1996 and March 1997 declined from about 600 µS/cm at Palominas and Hereford to about 500 µS/cm at Charleston. Specific conductance in base flow during June 1997 declined from about 500 µS/cm at Hereford to about 425 µS/cm at Charleston.

Stable Isotopes

The distribution of the stable isotopes of hydrogen (^{2}H(deuterium)/^{1}H) and oxygen ($^{18}O/^{16}O$) in water sampled during 1994 through 1997 in the Sierra Vista subwatershed was spatially variable in ground water and varied with time at surface water, spring, and some ground-water sites (see table on pl. 3). The distribution of the stable isotope values is bounded by values from runoff in the San Pedro River and springflow in the Huachuca Mountains after winter and summer storms (pl. 3, fig. B). The most depleted values, less than –70 $^{0}/_{00}$ δ2H and –10 $^{0}/_{00}$ $\delta^{18}O$, occurred in samples from springs in the Huachuca Mountains and runoff in the San Pedro River after winter precipitation during November and December of 1994. The most enriched values, greater than –50 $^{0}/_{00}$ δ^{2}H and –7 $^{0}/_{00}$ δ^{18}O, occurred in samples from runoff in the San Pedro River after summer precipitation in 1994.

Stable isotopes of hydrogen and oxygen in the regional aquifer are spatially variable across ground-water flow paths originating from the Huachuca Mountains (**pl. 3**). Values of δ^{2}H and δ^{18}O range from about –58 to –70 $^{0}/_{00}$ and from about –8.3 to –9.6 $^{0}/_{00}$, respectively. The distribution of values is coincident with ground-water flow paths determined from the water-level distribution (**pl. 2**). Water that is depleted in heavy isotopes occurs along flow paths that originate from the base of Huachuca Mountains near Nicksville, which is coincident with the highest altitudes and greatest amount of winter precipitation (Coes, 1997). Ground water that is more enriched in heavy isotopes occurs along flow paths that originate from the southern and northern parts of the Huachuca Mountains, which are lower in altitude than the Huachuca Mountains near Nicksville. Values do not vary greatly along flow paths, which indicates that little recharge from water enriched in heavy isotopes occurs downgradient from the mountains. Results of repeated samples at most wells in the regional aquifer varied about 1 $^{0}/_{00}$ δ^{2}H and 0.1 $^{0}/_{00}$ δ^{18}O (see table on pl. 3), which indicates little variation in the source of water to the wells. The greatest variation occurred in repeated samples from the Antelope Run #3 well where values varied about 1.5 $^{0}/_{00}$ δ^{2}H and 0.24 $^{0}/_{00}$ δ^{18}O. Small variations in the source of water to the well and values of stable isotopes in the sources may occur because the well is near a source of periodic recharge along the Garden Canyon drainage.

Ground water that originates from the Mule Mountains is isotopically similar to ground water that originates in Mexico on the basis of δ^{2}H and δ^{18}O; values range from about –55.1 to –57.8 $^{0}/_{00}$ for δ^{2}H and –7.6 to –8.3 $^{0}/_{00}$ for δ^{18}O (pl. 3). Ground water in the two areas is enriched in the heavier isotopes relative to water that originates near the Huachuca Mountains because of the lower altitudes of the Mule Mountains and the mountains in Mexico.

The isotopic composition of ground water in the Holocene alluvium is complex (see table on pl. 3). Values average –57.9 $^{0}/_{00}$ δ^{2}H and –8.2 $^{0}/_{00}$ δ^{18}O, which are similar to values in water that originates near the Mule Mountains and Mexico. The isotopic composition of water in the postentrenchment alluvium tends to be similar to the composition of river water and varies with runoff. The isotopic composition of water in the pre-entrenchment alluvium between Hereford and Lewis Springs is similar to the composition of regional-aquifer water from the Huachuca Mountains. Near Palominas and north of Lewis Springs the isotopic composition of water in the pre-entrenchment alluvium is similar to the composition of regional-aquifer water from the Mule Mountains and Mexico (pl. 3, figs. C1 and C2). Stratification is apparent at wells ESF16 and ESF24 (see table on pl. 3), which are at the same location but are finished at depths of 16 and 24 ft, respectively. Water from the two wells had significantly different isotopic values, –57.7 $^{0}/_{00}$ δ^{2}H and 8.17 $^{0}/_{00}$ δ^{18}O and –52.8 $^{0}/_{00}$ δ^{2}H and 7.71 $^{0}/_{00}$ δ^{18}O, respectively, when the wells were sampled concurrently during base–flow conditions in March 1997.

The isotopic composition of base flow of the San Pedro River is less variable than the isotopic composition of runoff (pl. 3, fig. B). The average value of 23 samples of base flow from several locations is –54.1 $^{0}/_{00}$ δ^{2}H and –7.5 $^{0}/_{00}$ δ^{18}O, but values vary from –59.5 to –47.9 $^{0}/_{00}$ δ^{2}H and –8.1 to –6.9 $^{0}/_{00}$ δ^{18}O. Samples collected at several locations during March 1996 and March 1997 indicate base flow is depleted in heavy isotopes downgradient from Highway 90 (pl. 3, figs. D1 and D2). Downgradient depletion probably is caused by dilution through mixing with regional-aquifer water that recharged near the Huachuca Mountains and is depleted in heavy isotopes. Downgradient mixing of base flow with water from the regional aquifer is consistent with downgradient increases in base flow of several cubic feet per second and downgradient decreases in specific conductance (pl. 3, fig. D3). The downgradient trend in the stable isotope composition of base flow during June 1997 is not similar to the March 1996 and 1997 trends, but is similar to the spatial distribution of stable isotopes in water from the Holocene alluvium. The low rates of flow during June 1997, about 0.5 ft^3/s at each sample site, and similarity of the spatial distribution of stable isotopes in base flow with the spatial distribution in water from the Holocene alluvium (pl. 3, figs. C1 and C2) indicate that the base flow probably was replaced by ground water from the Holocene alluvium as it moved downgradient. Replacement probably occurs through infiltration of base flow in seasonal losing reaches that develop in response to near stream evapotranspiration, withdrawal from wells, and ground-water flow to the stream from the Holocene alluvium in gaining reaches. The spatial distribution of losing and gaining reaches during June probably is more complex than can be described by data from the few sample sites used for this investigation.

Temporal Trends

Values of specific conductance and stable isotopes displayed long-term and seasonal trends in repeated samples of ground water in the Holocene alluvium and base flow in the San Pedro River during August 1994 through June 1998 (**pl. 3**, figs. F1 and F2). Long-term trends were evident in the data from repeated samples from the pre-entrenchment alluvium. Long-term trends were not evident in data from repeated samples from the postentrenchment alluvium, but values varied with changes in runoff in the San Pedro River. Seasonal and long-term variations in base-flow samples collected at the Charleston streamflow-gaging station indicate variations in the sources of ground water that maintain base flow. Long-term variations in sources of base flow probably resulted from a general lack of major runoff and streamflow infiltration to the Holocene alluvium during the investigation. Seasonal variations in sources of base flow probably resulted from seasonal changes in the length of gaining stream reaches upstream from the Charleston station.

Variations in the seasonality of precipitation during the investigation (**figs. 4** and **5**) resulted in variations in the isotopic composition of runoff in the San Pedro River (pl. 3, fig. B) and recharge to the Holocene alluvium. Major winter precipitation and runoff that was most likely depleted in heavy isotopes preceded the study during 1992–93 and occurred at the beginning of the study in 1994–95. Summer precipitation and runoff that was enriched in heavy isotopes was significant during 1994, 1996, and 1997, but was minimal during 1995. Seasonal variations in the isotopic composition of runoff in the San Pedro River are reflected in the extreme values of stable isotopes in samples of runoff at Palominas during August and December 1994 (see table on pl. 3). Runoff during August 1994 was enriched in heavy isotopes, –38.3 $^0/_{00}$ δ^2H and 5.4 $^0/_{00}$ $\delta^{18}O$. Runoff during December 1994 was depleted in heavy isotopes, –83.8 $^0/_{00}$ δ^2H and –11.1 $^0/_{00}$ $\delta^{18}O$. The specific conductance of runoff also varied but displayed no apparent seasonal trends.

Repeated samples of ground water from several shallow wells and drive-point wells in the pre-entrenchment alluvium generally displayed a long-term trend of enrichment in heavy isotopes reflecting the lack of recharge from infiltration of winter surface flow and predominance of recharge from infiltration of summer surface flow during 1996. Repeated samples at well BLM4, which is in the pre-entrenchment alluvium near Highway 90, displayed a trend of increasing enrichment in heavy isotopes during December 1994 through July 1996 (pl. 3, fig. F2). Repeated samples at other shallow wells in the pre-entrenchment alluvium display similar changes (see table on pl. 3). Enrichment of heavy isotopes in the pre-entrenchment alluvium during the investigation probably was caused by the diminishing influence of recharge that occurred from surface flow during the winter of 1994–95 and recharge of surface flow enriched in heavy isotopes during the summer of 1996.

Specific conductance of base flow at the Charleston streamflow-gaging station varies seasonally as the relative ground-water contributions to base flow from the regional aquifer and Holocene alluvium change (pl. 3, fig. F1). Specific conductance of base flow generally peaks during the winter at more than 500 µS/cm and decreases to as low as 400 µS/cm during the summer. Low base flow, generally less than 2 ft^3/s, at the Charleston station during the summer probably is influenced by a source of water from the regional aquifer that discharges to the river near the station and is low in specific conductance. A notable exception occurred during July 1997 when low flows, less than 0.5 ft^3/s, corresponded with elevated values of specific conductance of more than 500 µS/cm, which may have resulted from evaporative concentration. Higher rates of base flow, about 10 ft^3/s, during the winter are strongly influenced by water sources that are at greater distances from the station and high in specific conductance, which include ground water in the Holocene alluvium and ground water in the regional aquifer east of the river and in Mexico. Long-term trends were not evident in the values of specific conductance for base flow during the investigation.

Long-term trends in values of stable isotopes in base flow at the Charleston streamflow-gaging station (pl. 3, fig. F2) may be caused by changes in the seasonality of runoff and recharge to the Holocene alluvium. Stable isotopes in base flow generally became more enriched in heavy isotopes during the investigation similar to isotopes in the Holocene alluvium. Base flow that was sampled before runoff that occurred during July and August of 1996 was the most depleted in heavy isotopes. The runoff during July and August of 1996 was enriched in heavy isotopes.

The overall enrichment in heavy isotopes in base flow during the period of the investigation probably was caused by decreasing contributions of ground water from the Holocene alluvium during the winter of 1994–95 and greater contributions during the summers of 1996 and 1997.

Stable-isotope values in base-flow samples collected at three sites—Highway 90, the streamflow-gaging station at Palominas, and the streamflow-gaging station at Charleston—display seasonal variations that indicate possible evaporative enrichment in heavy isotopes during summer base flow. Four base-flow samples collected during June 1995 and June 1996 at these three sites had the lowest stable-isotope values of any base-flow samples and the values plot well below the global meteoric water line (see table on **pl. 3** and fig. B). The stable-isotope values also plot well below those of many samples from the Holocene alluvium and samples from the regional aquifer east of the river, indicating that ground water in those two areas is not a likely source of a large portion of the base flow. The stable-isotope values, however, are consistent with a source of water from the regional aquifer west of the river that is enriched in heavy isotopes. The base-flow samples probably represent a combination of sources from both regional-aquifer areas and the Holocene alluvium that are enriched in heavy isotopes. Samples of base flow collected at Highway 90 and Charleston during June 1997 were more enriched in heavy isotopes than the earlier samples, indicating that a significant change had occurred in the source of base flow throughout much of the stream reach. The enrichment in heavy isotopes is consistent with a significant source of water originating from infiltration of runoff during the summer of 1996. Values of stable isotopes in several base-flow samples from Hereford did not vary as greatly as values from the base-flow samples for the other three sites. The lack of variability in stable-isotope values indicates a consistent source of water that maintains base flow in the gaining reach above Hereford.

Base Flow Mass-Balance Analysis

Mass-balance analysis of conservative hydrochemical constituents can be used to estimate the average contribution of ground water to base flow in the San Pedro River between sample sites. The source of the contribution can be evaluated on the basis of observed concentrations of the constituents in known sources. Basic assumptions of the mass-balance analysis include: base flow is accurately measured, surface-water contributions do not occur between sample sites, evaporation from the water surface is minimal, and the river does not have losing reaches between the sites. Sources of base flow in the San Pedro River can be estimated using two conservative constituents—stable isotopes of hydrogen and stable isotopes of oxygen. Stable–isotope data are useful in evaluating the contribution to base flow from the regional aquifer west of the San Pedro River. The regional aquifer in this area contains water that is depleted in heavy isotopes relative to other sources of water to the river. Specific conductance also can be considered a conservative constituent because changes in specific conductance caused by chemical reactions in the river should be minimal. Specific conductance is useful in evaluating contributions to base flow from sources of water with high values, such as the Holocene alluvium, relative to sources of water with low values, such as the regional aquifer.

Contributions of conservative chemical constituents to base flow from ground-water discharge was calculated as the unknown value in equation 2.

$$Q_{Rout}C_{Rout} = Q_{Gin}C_{Gin} + Q_{Rin}C_{Rin} \qquad (2)$$

where

Q_{Rout} = the river discharge at the downstream end of a reach, in cubic feet per second;

C_{Rout} = the concentration of the conservative chemical constituent in the discharge at the downstream sample site;

Q_{Gin} = the ground-water discharge to the river in the reach between sample sites, in cubic feet per second;

C_{Gin} = the concentration of the conservative chemical constituent in ground- water discharge to the river in the reach between sample sites;

Q_{Rin} = the surface-water inflow at the upstream end of the reach, in cubic feet per second; and

C_{Rin} = the concentration of the conservative chemical constituent in surface- water inflow at the upstream end of a reach.

Concentrations of each constituent are in terms of δ^{2}H, deuterium content in per mil; δ^{18}O, oxygen-18 content in per mil; and specific conductance in microsiemens per centimeter.

Mass-balance analysis was applied to the analytical results of samples collected from the San Pedro River at three locations during March 1996 and March 1997. Both periods should be representative of base-flow conditions because significant runoff had not occurred for more than 5 months before the sampling periods (**pl. 3**, fig. F3). Samples of base flow during March 12 and 13, 1996, were collected at Palominas, near the Highway 90 bridge, and at the streamflow-gaging station at Charleston. Samples of base flow during March 25, 1997, were collected at Hereford, near the Highway 90 bridge, and at the streamflow-gaging station at Charleston. Base-flow samples also were collected at three sites during June 1997, but flow rates were only about 0.5 ft^3/s at each site (fig. D4). Losing reaches probably occurred during June 1997 between the three sample sites and samples may have been enriched in heavy isotopes as a result of evaporation. Results of mass-balance analysis indicate that ground-water contributions to base flow between Palominas and Charleston during both March periods were strongly influenced by sources derived from infiltration of runoff into the Holocene alluvium. Contributions to base flow from the regional aquifer west of the San Pedro River occurred mainly between Highway 90 and the streamflow-gaging station at Charleston and were a minor part of the overall ground-water contributions.

During March 12 and 13, 1996, the river gained 8.9 ft^3/s from ground-water discharge between Palominas and the Charleston streamflow-gaging station; 5.3 ft^3/s was gained between Palominas and the Highway 90 bridge, and 3.6 ft^3/s was gained below the Highway 90 bridge (figs. D4 and E4). Specific conductance of base flow declined in the downgradient direction from 604 µS/cm at Palominas, to 560 µS/cm at Highway 90, and 519 µS/cm at Charleston (pl. 3, fig. D3) by gaining ground water from the regional aquifer, which has low specific conductance (pl. 3, fig. E3). Values of stable isotopes in base flow were similar at Palominas and Highway 90; however, base flow was more depleted in heavy isotopes at Charleston (pl. 3, figs. D1 and D2), which indicates contribution below Highway 90 from the regional aquifer west of the river. Mass-balance analysis indicates that the ground-water contributions to base flow between Palominas and Highway 90 have an average specific conductance of 545 µS/cm and average stable-isotope values of –52.8 $^{0}/_{00}$ δ^{2}H and –7.52 $^{0}/_{00}$ δ^{18}O (pl. 3, figs. E1–E3). Similarity of the isotopic compositions of ground-water contributions to base flow and ground water in the Holocene alluvium indicates that the ground-water contributions to base flow between Palominas and Highway 90 were derived primarily from the Holocene alluvium. Ground-water contributions to base flow between Highway 90 and Charleston have an average specific conductance of 438 µS/cm and average stable-isotope values of –62.1$^{0}/_{00}$ δ^{2}H and –8.39 $^{0}/_{00}$ δ^{18}O. The source of the ground-water contribution in the reach is ambiguous on the basis of the mass-balance analysis because the stable-isotope values are similar to values for the regional aquifer west of the river, but the specific-conductance values are much higher than values in the regional aquifer. The apparent ambiguity could be caused by a large contribution of water to base flow from the Holocene alluvium that received recharge from surface flow during the winter of 1994–95 that was depleted in heavy isotopes.

During March 25, 1997, the river gained 7.4 ft^3/s from ground-water discharge to base flow between Hereford and the Charleston gaging station; 2.4 ft^3/s was gained between Hereford and the Highway 90 bridge, and 5.0 ft^3/s was gained below Highway 90 (figs. D4 and E4). Down-gradient changes in values of specific conductance and stable isotopes during March 25, 1997, were similar to changes that occurred during March 12 and 13, 1996 (pl. 3, figs. D1–D3); however, base flow during the later period was more enriched in heavy isotopes than base flow during the early period, which indicates that a significant change in the source of base flow occurred between the two periods. Specific conductance of base flow during March 25, 1997, declined in the downgradient direction from 583 µS/cm at Hereford, to 543 µS/cm at Highway 90, and 497 µS/cm at Charleston (pl. 3, fig. D3). Values of stable isotopes in base flow were similar at Hereford and Highway 90; –50.9 $^{0}/_{00}$ δ^{2}H and –6.94 $^{0}/_{00}$ δ^{18}O and –51.2 $^{0}/_{00}$ δ^{2}H and –7.11 $^{0}/_{00}$ δ^{18}O, respectively; but base flow was more depleted in heavy isotopes at Charleston, –53.5 $^{0}/_{00}$ δ^{2}H and –7.54 $^{0}/_{00}$ δ^{18}O (pl. 3, figs. D1 and D2). Ground-water contributions to base flow between Hereford and Highway 90 had an average specific conductance of 483 µS/cm (pl. 3, fig. E3) and average stable-isotope values of –51.7 $^{0}/_{00}$ δ^{2}H and –7.37 $^{0}/_{00}$ δ^{18}O (pl. 3, figs. E1 and E2), indicating that the 2.4 ft^3/s of ground-water contributions was derived primarily from the Holocene alluvium, which is isotopically similar to ground-water contributions in the Palominas to Highway 90 reach during March 1996. The source of ground-water contributions to base flow between Highway 90 and Charleston during the later period, however, was much different in comparison to the early period on the basis of stable-isotope values. Average specific conductance of the 5.0 ft^3/s of ground-water contributions below Highway 90 during March 25, 1997, was 442 µS/cm, which is similar to values during March 12 and 13, 1996 (**pl. 3**, fig. E3). Average stable-isotope values of ground-water contributions in the reach during March 1997, however, indicate enrichment in heavy isotopes with respect to values from the March 1996 samples, –56.3 $^0/_{00}$ δ^2H and –8.06 $^0/_{00}$ $\delta^{18}O$. The values of stable isotopes in the ground-water contributions to base flow between Highway 90 and Charleston require significant input from a post-March 1996 recharge source that is enriched in heavy isotopes. The most likely source of heavy isotopes is surface flow that infiltrated during the summer of 1996; however, evaporative enrichment of ground water from other sources could have contributed to the enriched values in base flow. Enrichment of heavy isotopes in ground-water contributions to base flow between Highway 90 and Charleston between March 1996 and March 1997 indicate that the increase in base flow of 1.4 ft^3/s over the period probably resulted from discharge of ground water from the Holocene alluvium that infiltrated from surface flows in the summer of 1996.

FUTURE DATA NEEDS

This investigation of the hydrogeologic system in the Sierra Vista subwatershed has resulted in an improved conceptual model of the system but has raised new questions that need to be answered before the system can be better understood. Important findings include silt and clay layers within the aquifer, significant declines in surface-water runoff, and the occurrence of significant recharge along the river during 1994 through 1998. The finding of silt and clay layers in the aquifer that influence ground-water flow and stream-aquifer interactions points to a need for better definition of the distribution of silt and clay and better definition of vertical ground-water flow.
The cause of declining runoff needs to be better understood. Possible causes that need to be investigated include several possible anthropogenic causes and changes in climate and vegetation. Ground-water recharge through infiltration of San Pedro River streamflow needs to be better understood and quantified, including changes that have occurred and where and when recharge occurs in the current system. The cause of high specific-conductance values in the Holocene alluvium and rates of ground-water use in riparian areas also need to be determined. Some of these needs will be met through current investigations, such as the Semi-Arid Land-Surface-Atmosphere (SALSA) Program of the Agricultural Research Service, the Southwest Ground-Water Resources Program of the U.S. Geological Survey, and ongoing monitoring conducted by multiple parties. Other needs will have to be answered by new programs.

SUMMARY AND CONCLUSIONS

Investigation of the hydrogeologic system in the Sierra Vista subwatershed resulted in improvements in the pre-existing conceptual model of the system and better understanding of changes that have occurred. Improvements in the conceptual model of the hydrogeologic system include better definition of the distribution of silt and clay layers in the regional aquifer and better definition of the source of water in base flow of the San Pedro River. Important changes in the system have occurred that include geologic changes, changes in precipitation, changes in the distribution of ground-water withdrawals, and diminishment of summer base flow and annual runoff at the Charleston streamflow-gaging station. Effects of the changes on the hydrologic system include variations in water levels, ground-water flow, recharge, and discharge. The new information will result in improved ground- water flow models and more reliable estimates of the effects of ground-water withdrawals on discharge.

Precipitation in the Sierra Vista subwatershed generally occurs during two seasons, but variations in the seasonal distribution of precipitation have occurred. Precipitation during the wet season, June through October, generally is greater than precipitation during the winter months of November through February. Drought conditions are common during the spring months of March through May. Periods of above-average wet-season precipitation occurred during the late 1920s, mid-1950s, and early to mid-1980s, but a general decreasing trend in wet-season precipitation occurred after the late 1950s. The lowest continuous 5-year average of wet-season precipitation, less than 8 in., occurred from 1991 through 1995. Trends in winter precipitation are dominated by an extended period of below-average precipitation during the mid-1940s through mid-1970s. Spring precipitation generally was about 2 in. or less throughout the record but has increased overall since about 1960.

Variations in the seasonal distribution of precipitation resulted in important hydrologic effects. Before 1960, annual precipitation totals were clearly dominated by amounts of wet-season precipitation. After 1960, most precipitation continued to occur during the wet season, but there was a trend to a more equal distribution of precipitation during the wet season and winter. The changes in seasonal distribution of precipitation resulted in decreased wet-season runoff after about 1960 and reduced rates of mountain-front recharge during the winters of the mid-1940s through mid-1970s.

Annual runoff in the San Pedro River at the streamflow-gaging station at Charleston has declined significantly during the period of record from more than 45,000 acre-ft before 1935 to less than 20,000 acre-ft during the mid-1990s. Most of the decline in annual runoff occurred as a result of declines in wet-season runoff from more than 40,000 acre-ft before 1935 to less than 10,000 acre-ft during the early and mid-1990s. Winter runoff, however, has varied with precipitation. Some of the decline in wet-season runoff may be explained by declining summer precipitation; however, the percentage of wet-season precipitation that flows past the Charleston gaging station has declined while the percentage of winter precipitation that flows past the station has not changed significantly. Absence of a decline in the percentage of winter precipitation that flows past the Charleston station indicates that an increase in capture of precipitation and surface flow may have occurred during the wet season. Similar changes in rainfall and runoff relations have occurred in a small upland basin in the Huachuca Mountains—Garden Canyon—which suggests that the reduced wet-season runoff may have occurred basinwide. Possible mechanisms for increased capture of precipitation during the wet season include increased direct capture through increased vegetation, more frequent occurrence of low-intensity rainfall, increased surface-water diversions, and increased recharge resulting from increased ground-water withdrawals by phreatophytes and by wells.

Winter and summer base flow at the streamflow-gaging station at Charleston displayed similar declining trends before about 1951, but winter base flows have displayed no particular trend since 1951; however, summer base flows have declined. Winter base flow varies greatly on an annual basis, but values generally declined from 15 to 8 ft^3/s before 1951 and varied with precipitation and runoff thereafter. Minimum values of winter base flow, about 7 to 8 ft^3/s, occurred several times after 1950. Conversely, summer base flows have declined from 2.5– 5 ft^3/s before 1963, to 1.0–4 ft^3/s during 1963 to 1982, and 0.4–3.3 ft^3/s after 1982. Decline in both winter and summer base flow before 1951 may be related to several causes that include: (1) growth and establishment of phreatophytes as the stream channel stabilized before about 1955, (2) declining annual and seasonal precipitation, and (3) ground-water withdrawals for irrigation in the Palominas area. Similarity of the long-term trends of decreasing wet-season surface flow and decreasing summer base flow suggests that infiltration of wet-season surface flow may be an important source of base flow. Infiltration of winter surface flow also may be an important source of base flow, especially during periods of low wet-season precipitation and runoff. Ground-water withdrawals by wells and variations in water use by phreatophytes may have caused changes in winter and summer base flows after 1951, but the effects probably are masked by the effects of variations in infiltration of surface flow.

Entrenchment of the San Pedro River during the early part of the 1900s resulted in hydrologic effects that were largely unrecorded. Initial hydrologic effects included increased base flow of the river that dissipated as water levels in the regional aquifer declined and a new hydraulic connection between the regional aquifer and the river was established. Entrenchment probably resulted in a better hydraulic connection between the regional aquifer and the river because of the removal of pre-entrenchment alluvium, which is primarily silt and sand of moderate hydraulic conductivity, and deposition of sand and gravel of a greater hydraulic conductivity within an inner flood plain. The hydraulic connection between the regional aquifer and the river probably continued to increase through the early 1950s as the width of the inner flood plain increased.

The occurrence of silt and clay layers in the regional aquifer causes a low storage capacity in the aquifer, separates the ground-water flow into deep- and shallow-flow systems, and restricts interaction between the regional aquifer and the river. Ground water flows under confined and semiconfined conditions in sand and gravel layers beneath layers of silt and clay. Ground-water withdrawals from confined parts of the aquifer result in water-level declines that are more extensive than declines caused by withdrawals from unconfined parts of the aquifer. Both the upper and lower basin fill include extensive silt and clay facies in the basin center surrounded by sand and gravel facies near crystalline rocks at the basin margins.The silt and clay facies of the upper basin fill is interspersed with sand layers. The silt and clay facies of the lower basin fill is massive silt and clay and occurs across a more narrow area than the silt and clay facies of the upper basin fill. In general, the silt and clay facies of both units occur west of the San Pedro River and north of Lewis Springs and underlies the river south of Lewis Springs, which results in a poor connection between the regional aquifer and the San Pedro River in the area. The southern extent of the silt and clay facies is not well known, however, confined conditions are known to exist in the Palominas area (Konieczki, 1980).

A period of below-average precipitation between 1932 and 1982 resulted in water-level declines of 0.2 to 0.5 ft/yr in the regional aquifer. The greatest rate of decline occurred in wells near the mountains, which indicates mountain-front recharge was insufficient to maintain water levels. Declining water levels in much of the basin were mitigated by greater rates of annual precipitation and recharge during wet periods in the mid-1960s and mid-1980s. Water levels continued to decline in the area of extensive ground-water withdrawal in the Fort Huachuca-Sierra Vista area and resulted in diversion of ground water from flow paths that would have terminated at the river. Most of the diverted flow would have eventually discharged along the Babocomari River and along the San Pedro River downstream from the streamflow-gaging station at Charleston but has been diverted to discharge at pumped wells.

Analysis of ground-water samples throughout the basin allowed identification of three sources of ground water—water that recharged the Holocene alluvium near the river, recharge to the regional aquifer in Mexico and east of the river near the Mule Mountains, and recharge to the regional aquifer west of the river near the Huachuca Mountains. Ground water in the Holocene alluvium is distinguished on the basis of values of specific conductance, which are greater than values in water from the regional aquifer. Ground water recharged near the Huachuca Mountains is distinguished on the basis of stable-isotope values that are different than values for samples from other areas. Values of specific conductance and stable isotopes from water recharged into the Holocene alluvium and near the Huachuca Mountains were sufficiently different than values for other sources of ground water to allow a general estimation of the relative amounts of water contributed from those sources in base flow during March 1996 and March 1997. Ground water from the Holocene alluvium that infiltrated near the river during surface flows was the primary source of base flow in the San Pedro River at the Charleston streamflow-gaging station during March 1996 and March 1997. Ground-water discharge from the regional aquifer contributed a minor part of the base flow at Charleston during the sample period.

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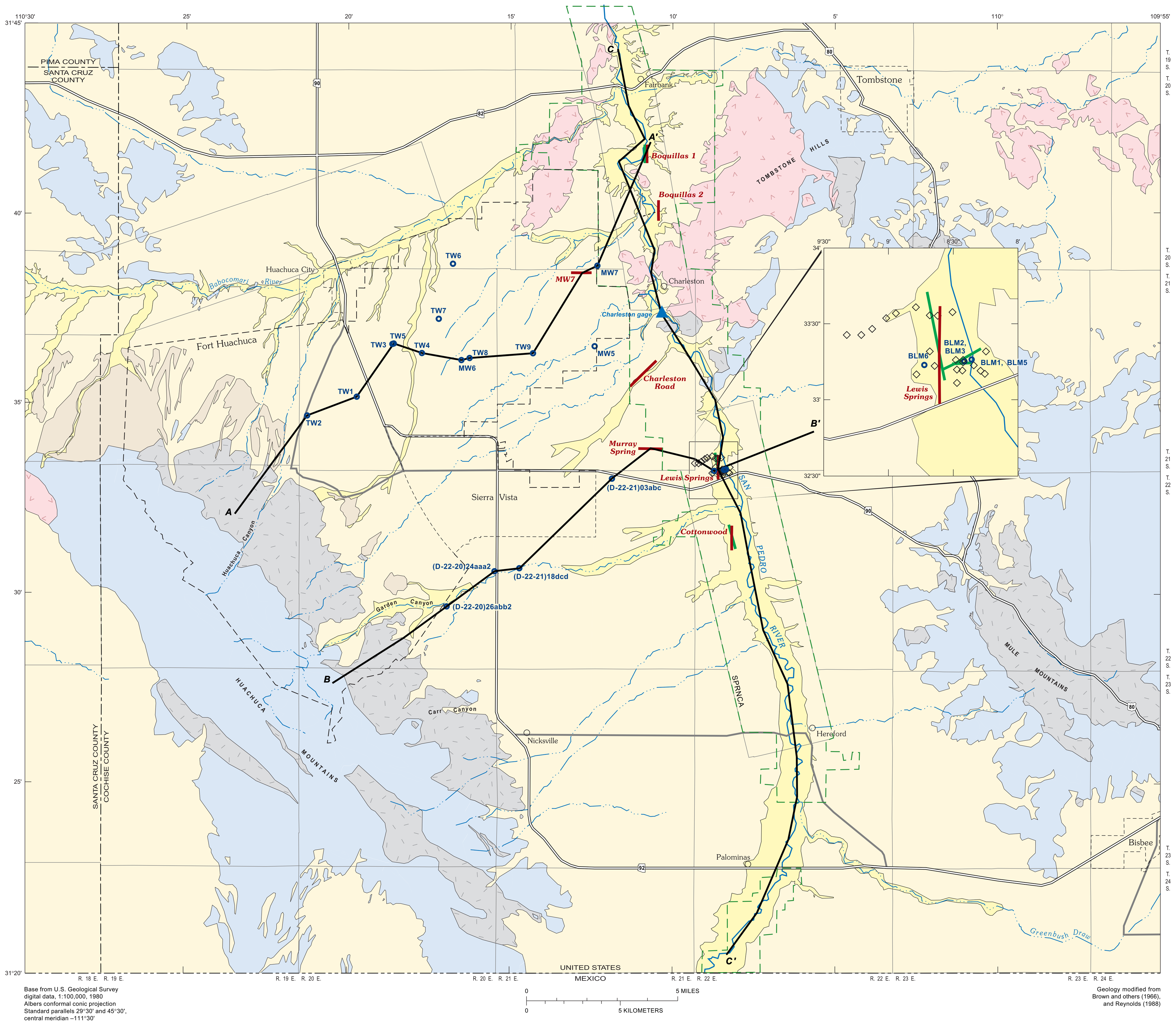

Base from U.S. Geological Survey digital data, 1:100,000, 1980
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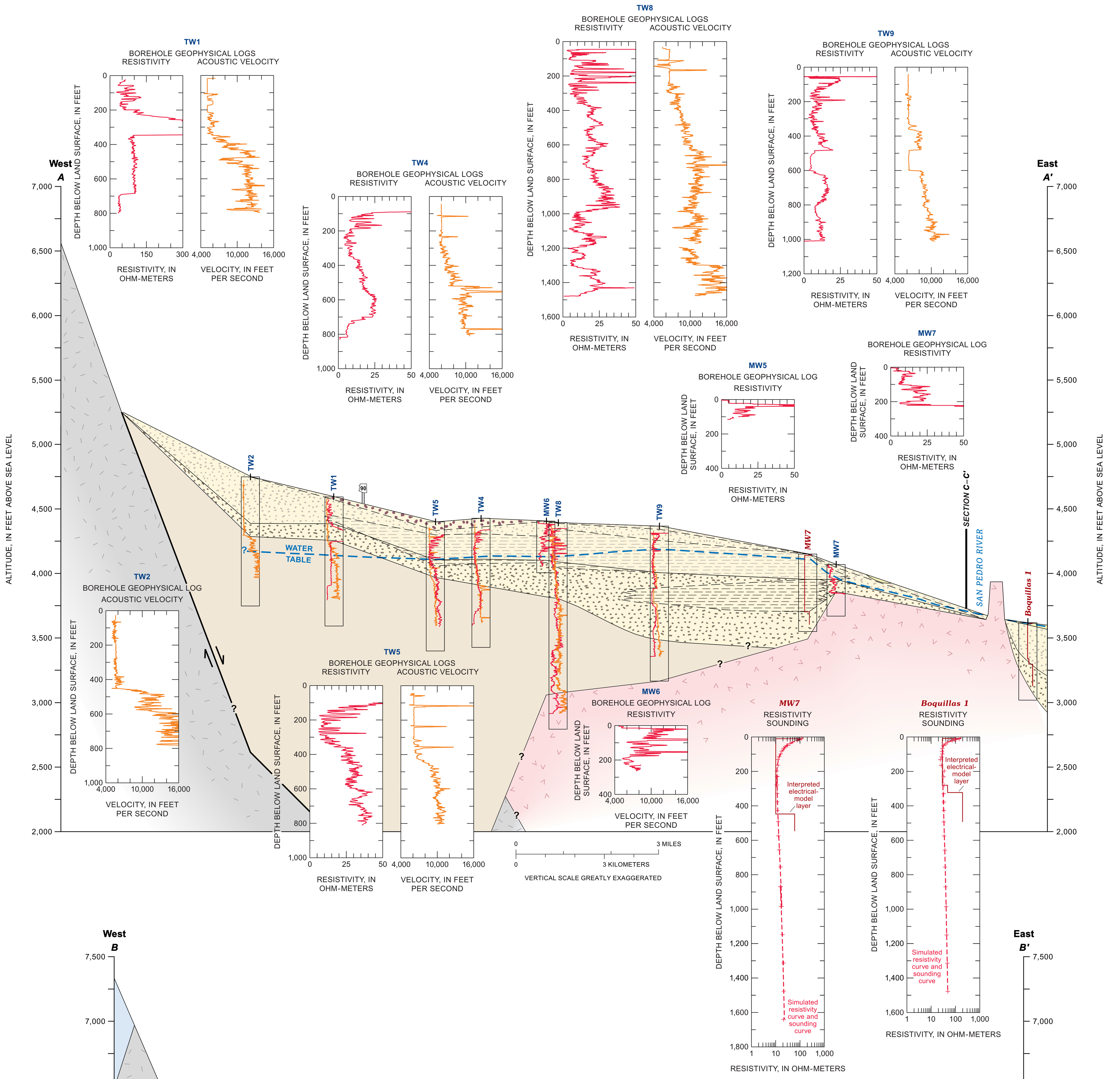
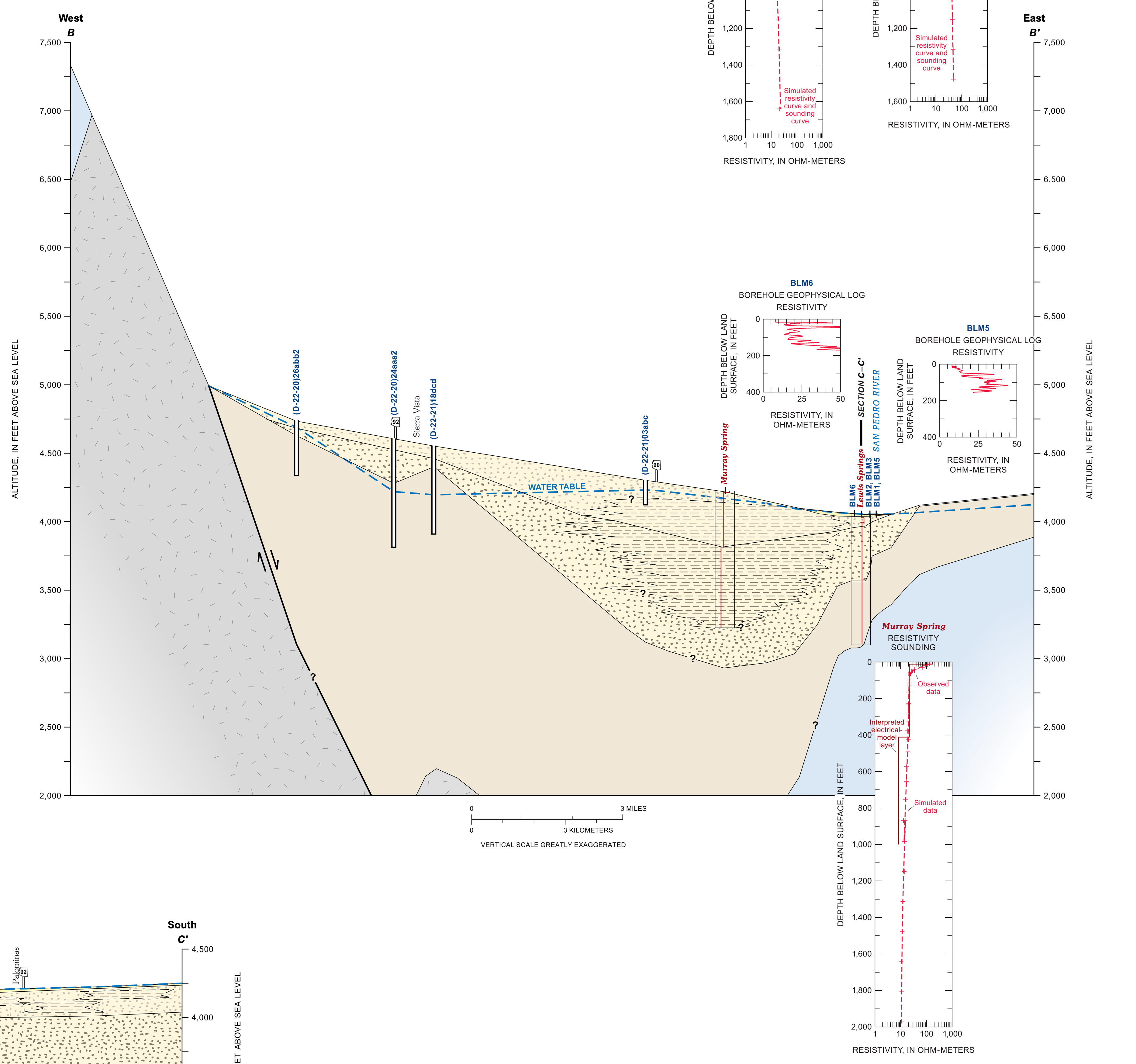
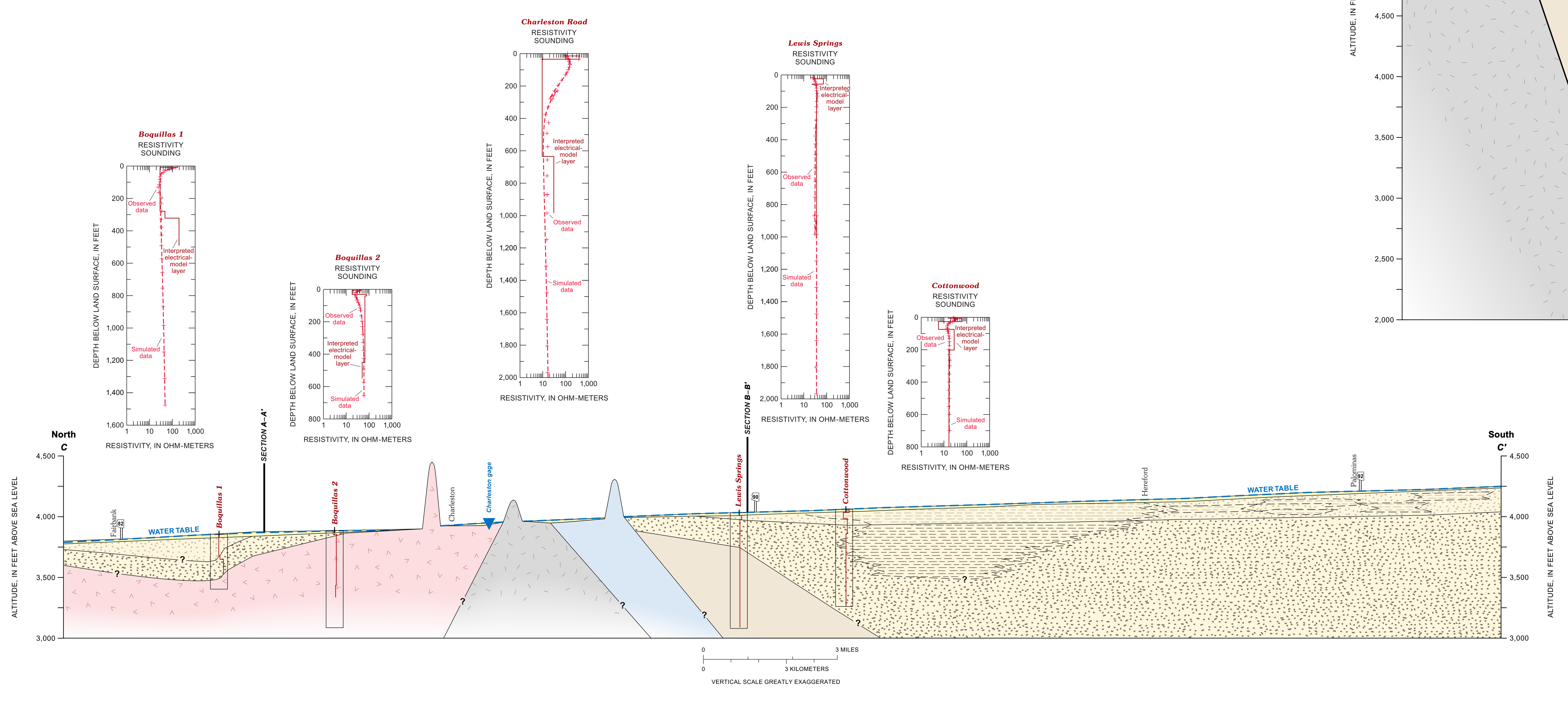
Geology modified from Brown and others (1966), and Reynolds (1988)







EXPLANATION

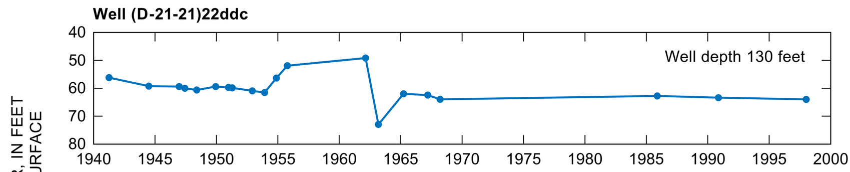
- SAND AND GRAVEL / SILT AND CLAY — UPPER BASIN FILL
- SAND AND GRAVEL / SILT AND CLAY — LOWER BASIN FILL
- HOLOCENE ALLUVIUM
- TERRACE DEPOSITS
- BASIN FILL
- PANTANO FORMATION
- SEDIMENTARY ROCKS
- VOLCANIC ROCKS
- GRANITIC ROCKS
- CONTACT—Queried where uncertain
- FACIES CHANGE—Queried where uncertain
- B —— B' TRACE OF HYDROGEOLOGIC SECTION
- BOUNDARY OF SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA (SPRNCA)
- SEISMIC SURVEY LINE
- RESISTIVITY-SOUNDING SURVEY LINE
- RESISTIVITY-SOUNDING DATA
- WELLS WITH SUBSURFACE INFORMATION
- ELECTROMAGNETIC-SOUNDING SITE
- WELL WITH DRILLER'S LOG
- FAULT—Arrows indicate direction of throw

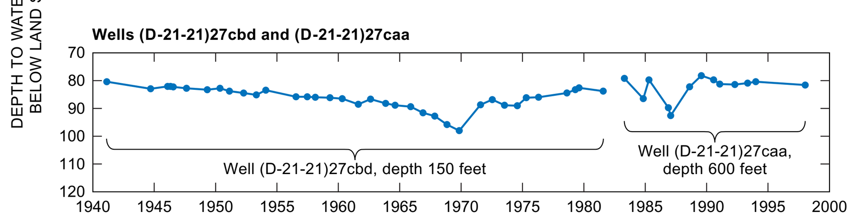
MAP SHOWING GEOLOGY, LOCATIONS OF HYDROGEOLOGIC SECTIONS AND GEOPHYSICAL DATA-COLLECTION SITES IN THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN, COCHISE COUNTY, SOUTHEAST ARIZONA

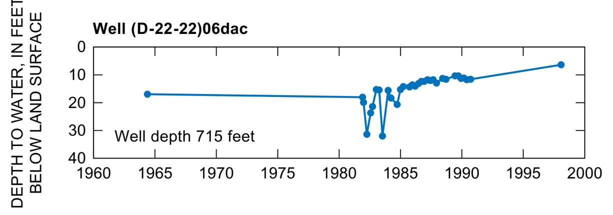
By D.R. Pool and Alissa L. Coes

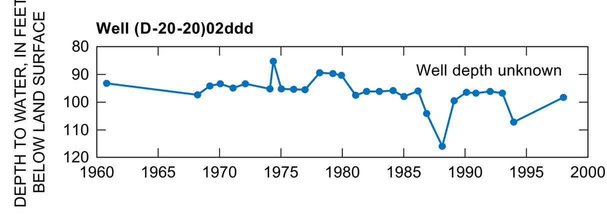
1999

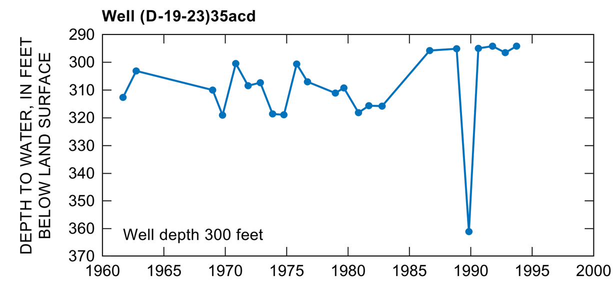
PREPARED IN COOPERATION WITH THE
ARIZONA DEPARTMENT OF WATER RESOURCES AND COCHISE COUNTY

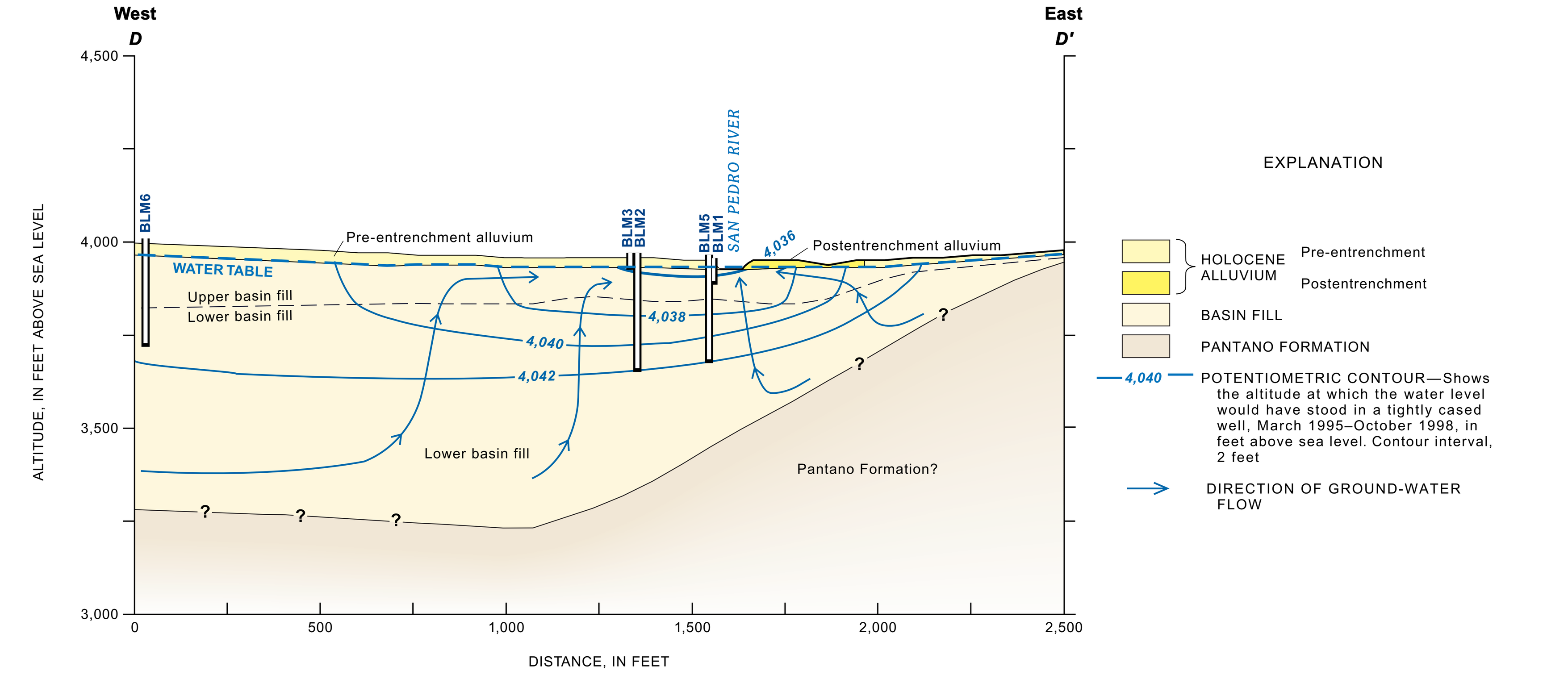


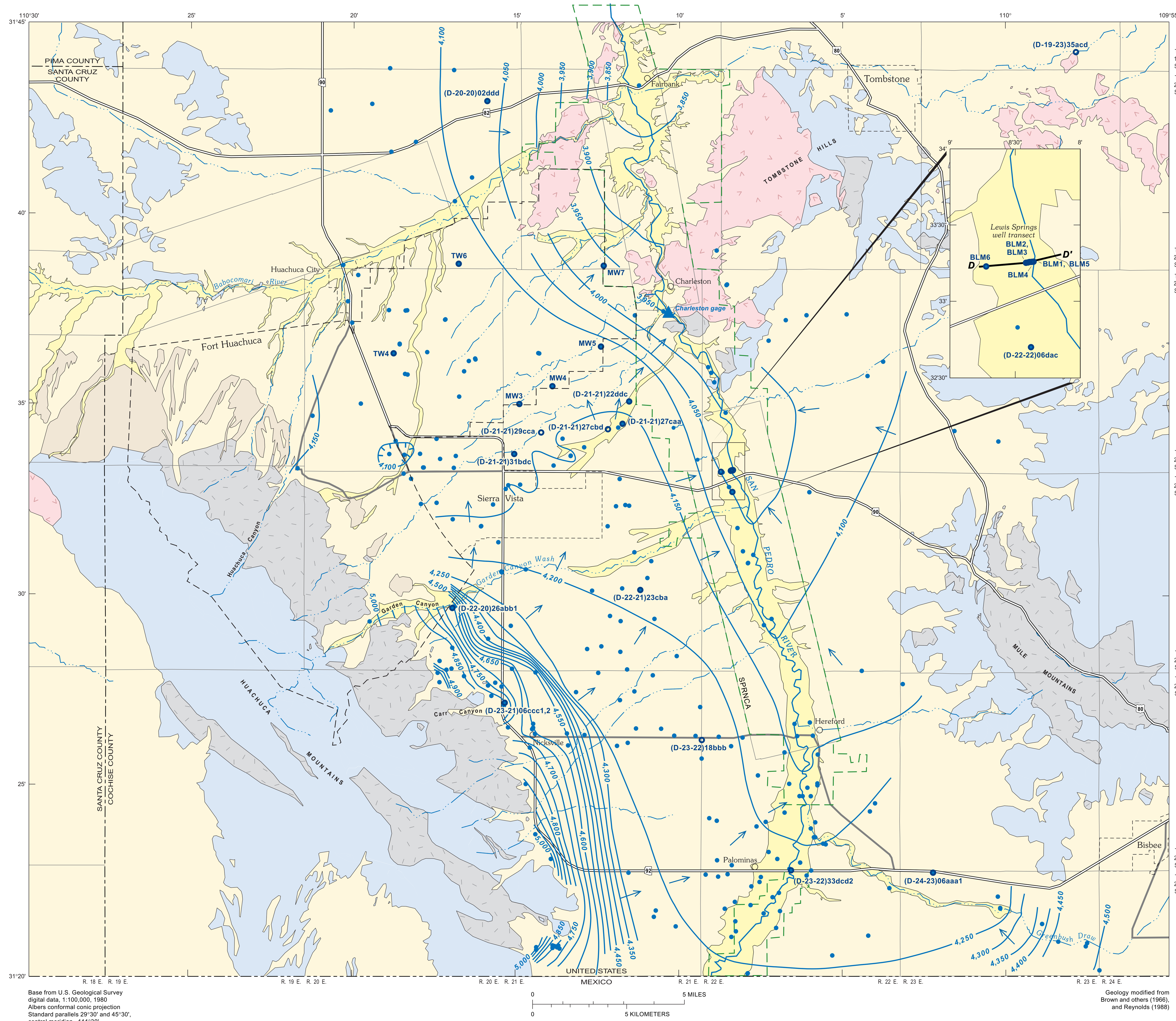






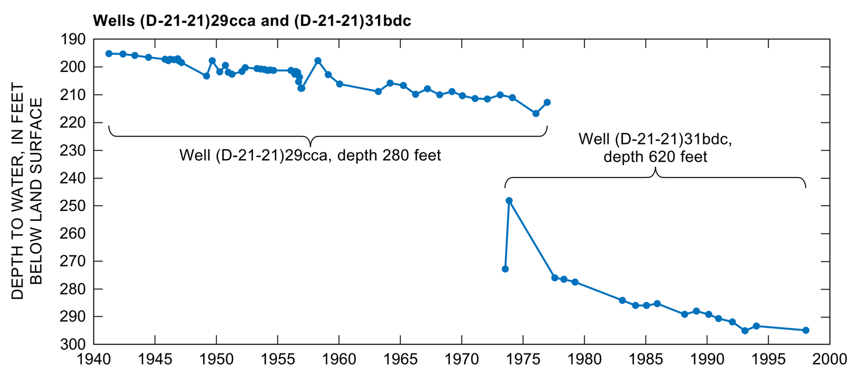


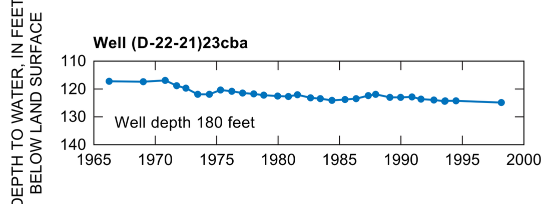


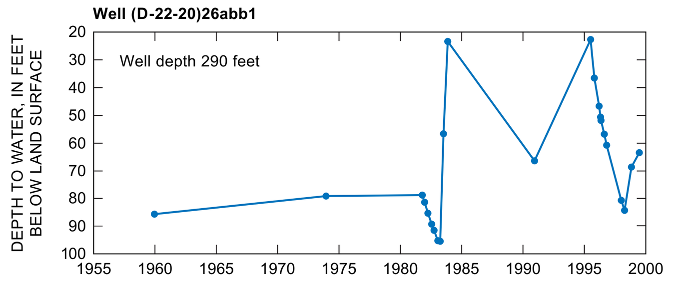


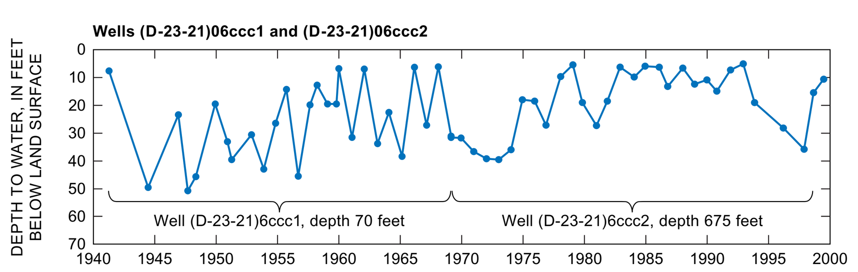
EXPLANATION

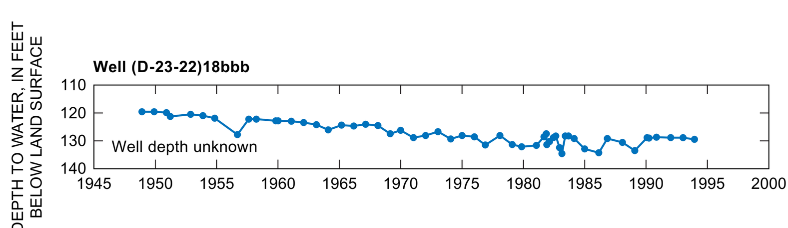
- HOLOCENE ALLUVIUM
- BASIN-FILL AND TERRACE DEPOSITS
- PANTANO FORMATION
- SEDIMENTARY ROCKS
- VOLCANIC ROCKS
- GRANITIC ROCKS
- BOUNDARY OF SAN PEDRO RIPARIAN NATIONAL CONSERVATION AREA (SPRNCA)
- 4,300 EQUIPOTENTIAL CONTOUR—Shows altitude of ground-water equipotential, January 1998, in feet above sea level. Contour interval 50 feet
- DIRECTION OF GROUND-WATER FLOW
- MW5 WELL WITH HYDROGRAPH AND WELL DESIGNATION
- WELL WHERE WATER-LEVEL ALTITUDE WAS MEASURED IN 1998
- SPRING WHERE WATER-LEVEL ALTITUDE WAS MEASURED IN 1997

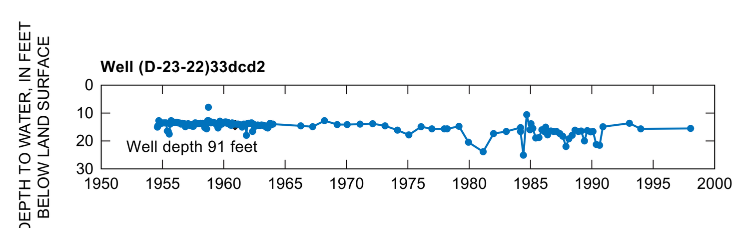


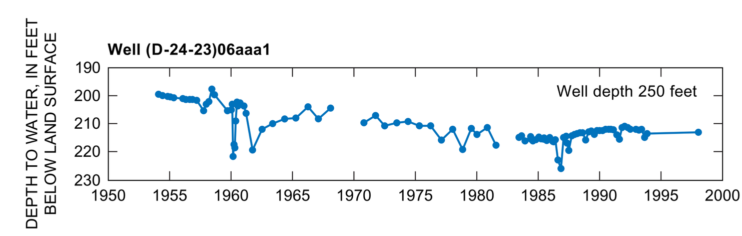


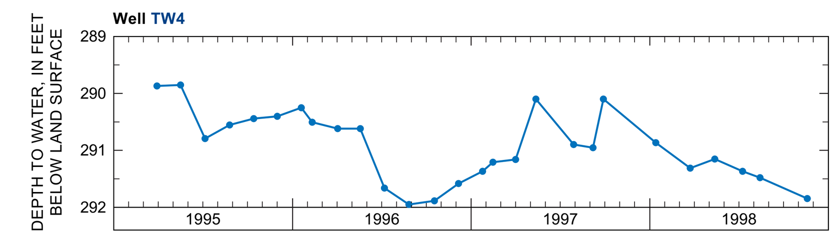


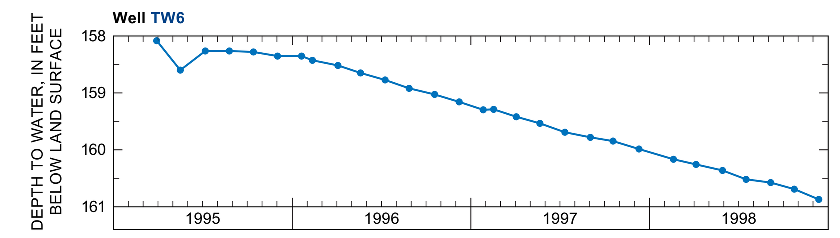


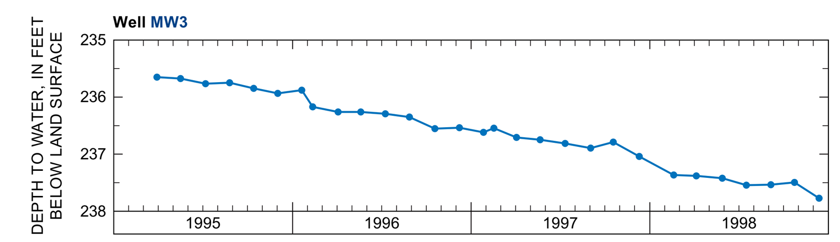


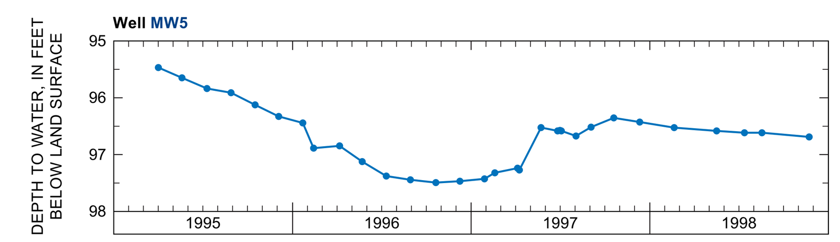


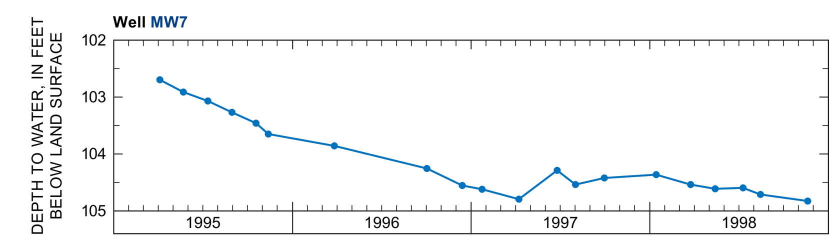


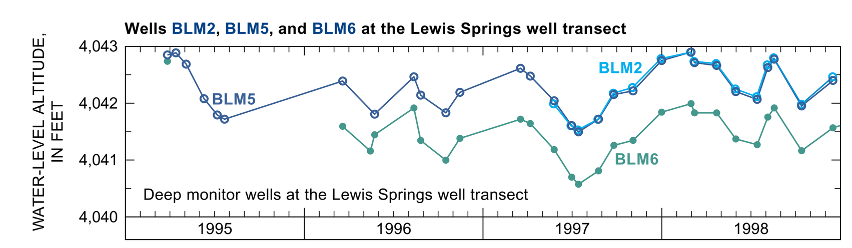


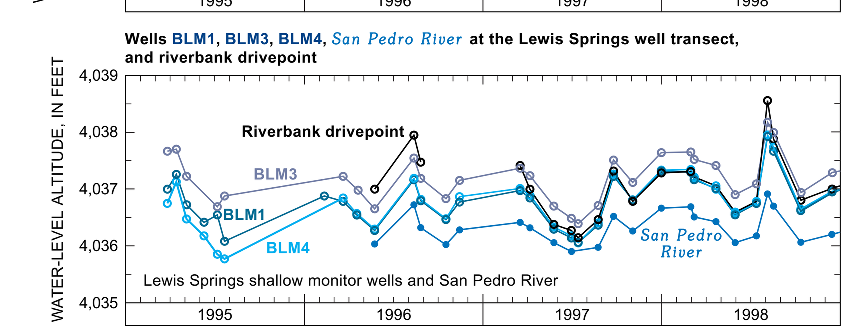


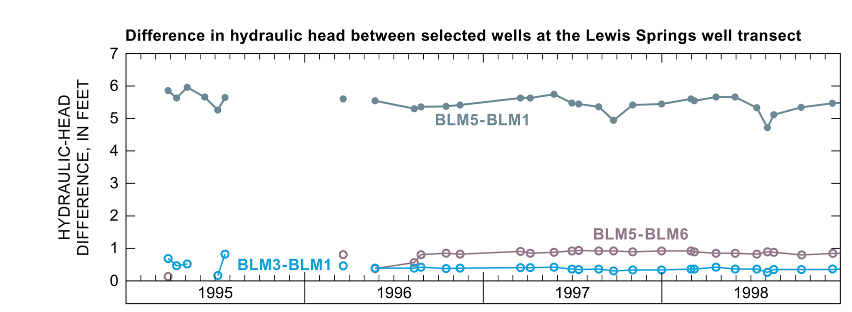












MAP SHOWING GROUND-WATER FLOW SYSTEM, WATER-LEVEL ALTITUDE IN WELLS DURING JANUARY 1998, AND HYDROGRAPHS OF WATER LEVELS IN SELECTED WELLS IN THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN, COCHISE COUNTY, SOUTHEAST ARIZONA

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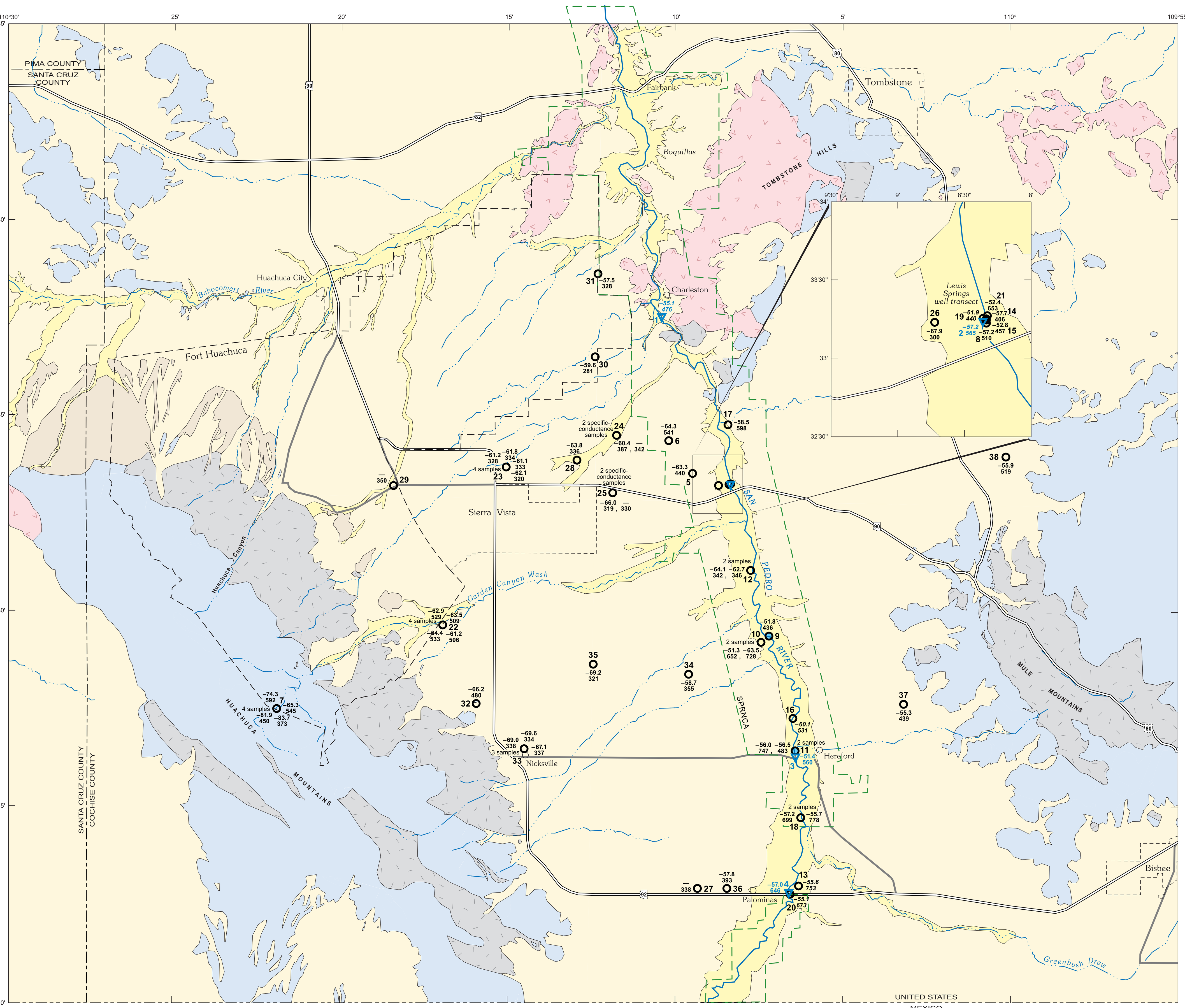
1999



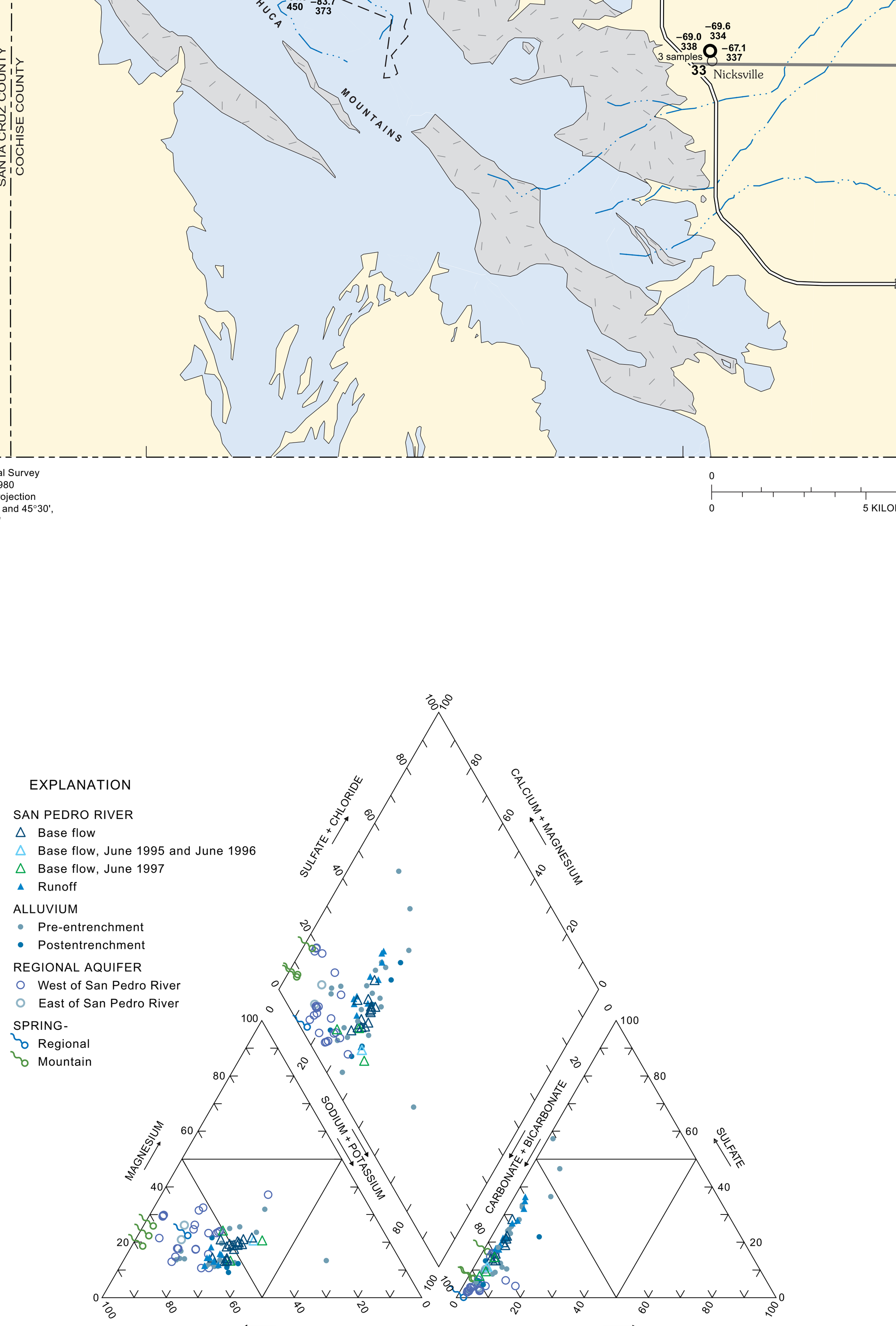


Figure A. Relative compositions of ground water and surface water in the Sierra Vista subwatershed.

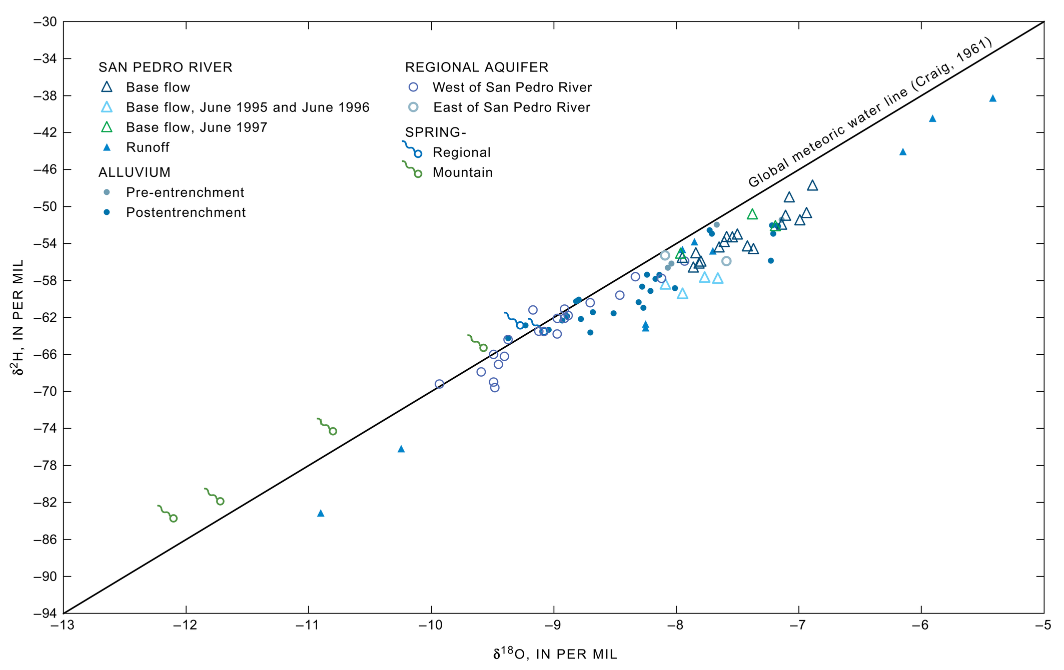


Figure B. Relation between δ^2H and $\delta^{18}O$ in water samples in the Sierra Vista subwatershed, August 1994 to April 1997.

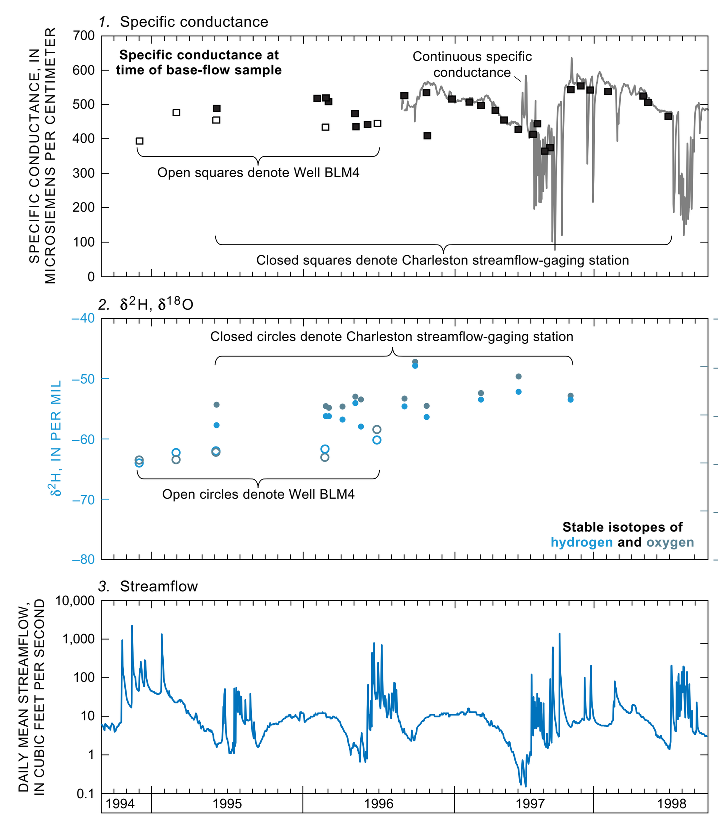


Figure F. Specific conductance, δ^2H, $\delta^{18}O$, and streamflow at the streamflow-gaging station at Charleston and at well BLM4, September 1994 through September 1998. *1*, Specific conductance at time of base-flow sample. *2*, δ^2H, $\delta^{18}O$ from samples of base flow. *3*, Daily mean streamflow.

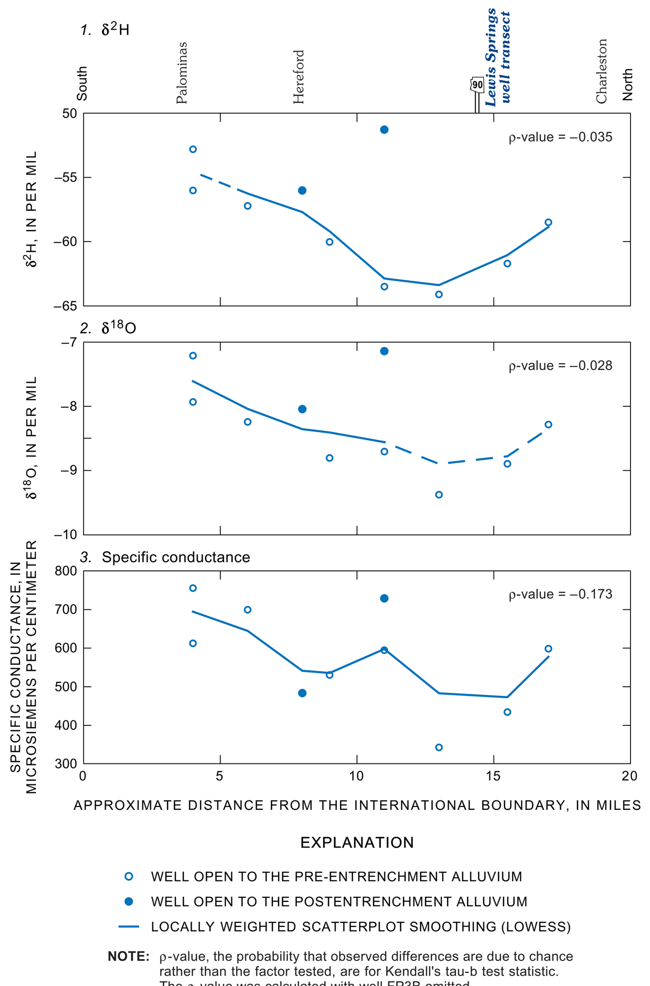


Figure C. δ^2H, $\delta^{18}O$, and specific conductance in the Holocene alluvium as a function of distance from the international boundary, Sierra Vista subwatershed, 1996 and 1997. *1*, δ^2H. *2*, $\delta^{18}O$. *3*, Specific conductance.

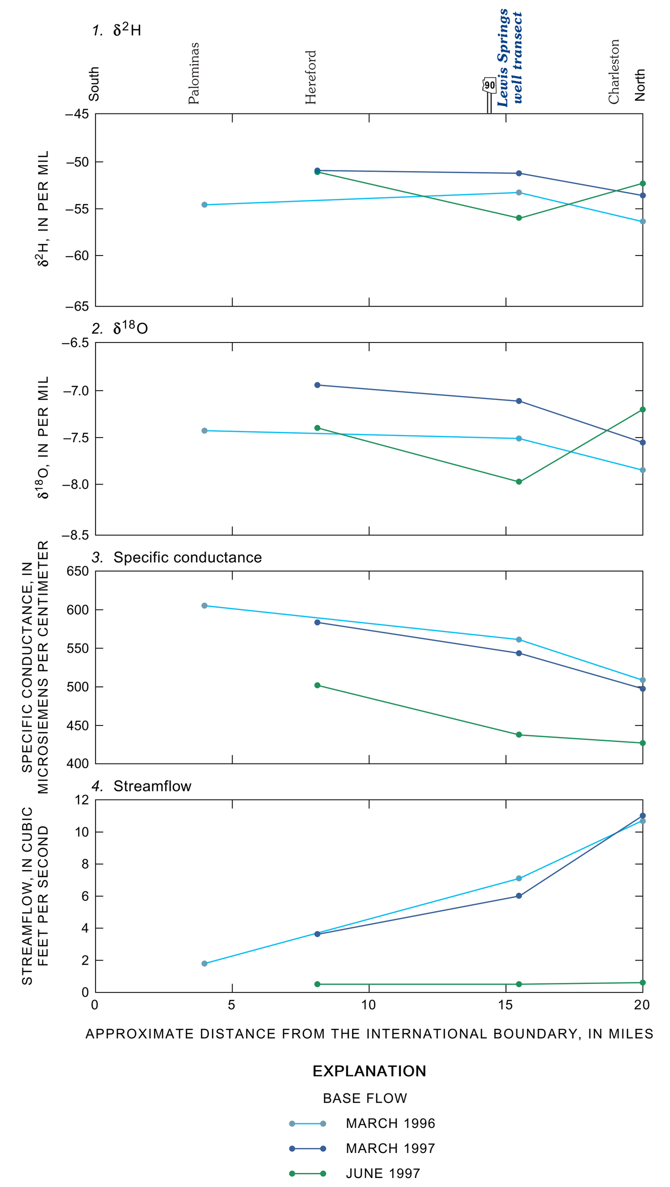
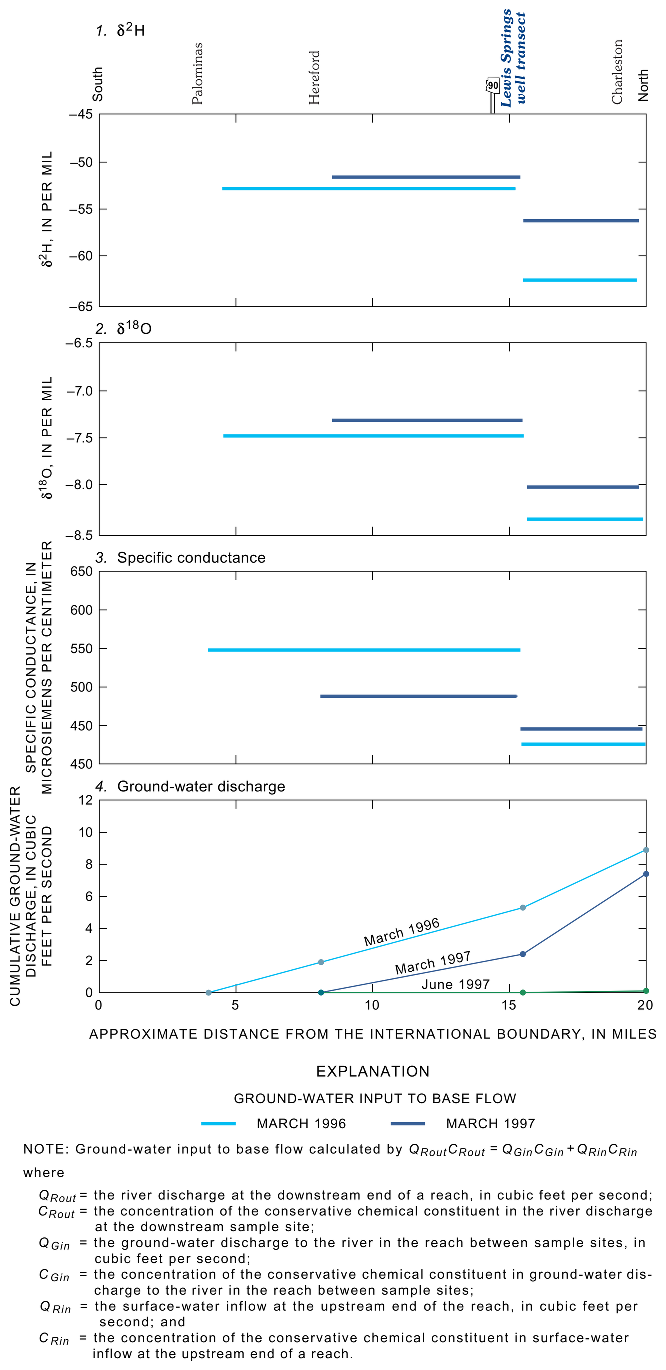


Figure D. δ^2H, $\delta^{18}O$, specific conductance, and streamflow in the San Pedro River as a function of distance from the international boundary, Sierra Vista subwatershed, on March 12 and 13, 1996, March 25, 1997, and June 24, 1997. *1*, δ^2H. *2*, $\delta^{18}O$. *3*, Specific conductance. *4*, Streamflow.



NOTE: Ground-water input to base flow calculated by $Q_{Rout}C_{Rout} = Q_{Gin}C_{Gin} + Q_{Rin}C_{Rin}$

where

Q_{Rout} = the river discharge at the downstream end of a reach, in cubic feet per second;
C_{Rout} = the concentration of the conservative chemical constituent in the river discharge at the downstream sample site;
Q_{Gin} = the ground-water discharge to the river in the reach between sample sites, in cubic feet per second;
C_{Gin} = the concentration of the conservative chemical constituent in ground-water discharge to the river in the reach between sample sites;
Q_{Rin} = the surface-water inflow at the upstream end of the reach, in cubic feet per second; and
C_{Rin} = the concentration of the conservative chemical constituent in surface-water inflow at the upstream end of a reach.

Figure E. δ^2H, $\delta^{18}O$, and specific conductance in ground water, and ground-water discharge that is contributing to base flow of the San Pedro River as a function of distance from the international boundary, Sierra Vista subwatershed, on March 12 and 13, 1996, and March 25, 1997. *1*, δ^2H. *2*, $\delta^{18}O$. *3*, Specific conductance. *4*, Ground-water discharge to the San Pedro River below Palominas on March 12 and 13, 1996, and below Hereford on March 25, 1997, and June 24, 1997.

Results of laboratory analysis of water samples from the San Pedro River and selected wells and springs, Sierra Vista subwatershed, southeast Arizona

[ft³/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; δ, per mil; TU, tritium unit; <, less than; >, greater than. Dashes indicate no data]

Site identifier	Station or well number	Site name	Sample description	Sample date	Discharge (ft³/s)	Temperature, field (°C)	pH, field	Specific conductance, field (µS/cm)	Specific conductance, laboratory (µS/cm)	Alkalinity, field (mg/L as $CaCO_3$)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Carbonate (mg/L as CO_3)	Calcium (mg/L as Ca)	Magnesium (mg/L as Mg)	Sodium (mg/L as Na)	Potassium (mg/L as K)	Chloride (mg/L as Cl)	Sulfate (mg/L as SO_4)	Fluoride (mg/L as F)	Hydrogen (per mil as δ^2H)	Oxygen (per mil as $\delta^{18}O$)	Tritium (TU)
				San Pedro River																			
1	09471000	Charleston	Base flow	06–22–95	2.4	26.0	8.2	488	---	---	---	244	0	---	---	---	---	---	---	---	-57.8	-7.77	---
do.	do.	Do.	do.	03–13–96	11.0	15.5	8.1	519	---	---	---	254	0	---	---	---	---	---	---	---	-56.2	-7.80	---
do.	do.	Do.	do.	03–20–96	11.0	18.0	8.4	508	---	214	---	246	7	50	12	41	1.9	9.6	44	0.6	-56.3	-7.83	---
do.	do.	Do.	do.	05–24–96	1.8	22.5	8.3	441	---	203	---	240	4	43	13	41	2.1	7.3	25	.7	-54.0	-7.61	---
do.	do.	Do.	do.	06–06–96	1.6	37.0	8.3	435	---	200	---	239	2	41	12	40	2.1	7.4	24	.7	-57.9	-7.66	---
do.	do.	Do.	Runoff	07–16–96	133	28.0	7.9	235	---	90	---	110	0	28	3.1	11	4.4	3.0	19	.2	-54.7	-7.95	---
do.	do.	Do.	do.	08–13–96	17	29.5	8.1	360	---	150	---	183	0	41	7.0	23	3.0	5.4	28	.4	-40.5	-5.91	---
do.	do.	Do.	Base flow	09–20–96	4.8	28.5	8.4	525	---	225	---	267	4	55	12	38	2.6	9.3	42	.6	-54.6	-7.65	---
do.	do.	Do.	do.	10–16–96	3.6	19.2	8.2	409	---	183	---	223	0	43	9.6	28	2.7	6.5	22	.5	-47.9	-6.89	---
do.	do.	Do.	do.	11–13–96	7.7	15.4	8.2	534	---	231	---	282	0	53	12	38	2.2	8.4	36	.7	-56.4	-7.81	---
do.	do.	Do.	do.	12–11–96	15	14.3	8.3	515	---	230	---	266	6	53	13	41	2.0	9.8	38	.7	-56.8	-7.86	---
do.	do.	Do.	do.	03–25–96	11	18.8	8.5	497	---	217	---	257	4	48	13	40	1.9	9.6	39	.6	-53.5	-7.54	---
do.	do.	Do.	do.	06–24–97	.6	28.1	8.2	427	---	197	---	240	0	35	11	39	2.2	7.4	20	.8	-52.2	-7.19	---
do.	do.	Do.	do.	10–29–97	6.2	25.0	8.4	542	---	242	---	283	6	56	14	42	2.5	11	36	.7	-53.5	-7.59	---
2	---	Highway 90	Runoff	09–02–94	<2.1	23.3	>6.8	476	---	---	---	237	0	57	11	27	3.4	7.4	42	.4	-44.1	-6.15	---
do.	---	Do.	do.	12–16–94	49	---	8.3	---	632	204	---	---	0	76	11	39	3.4	12	100	.3	-76.3	-10.24	---
do.	---	Do.	do.	03–16–95	25	14.0	8.1	610	---	---	---	261	0	71	12	42	2.8	12	85	.4	-62.8	-8.25	---
do.	---	Do.	Base flow	06–21–95	1.1	22.7	8.2	490	---	212	---	259	0	---	---	---	---	---	---	---	-58.5	-8.09	---
do.	---	Do.	do.	03–12–96	7.1	16.5	8.0	560	---	220	---	268	0	62	13	40	1.9	11	60	.4	-53.2	-7.50	---
do.	---	Do.	Runoff	07–17–96	38	26.5	7.8	356	---	136	---	165	0	43	5.7	18	4.8	5.4	32	.3	-54.9	-7.70	---
do.	---	Do.	Base flow	01–14–97	7.5	9.9	8.3	567	---	230	---	271	0	59	12	43	2.1	10	58	.4	-54.8	-7.37	---
do.	---	Do.	do.	03–25–97	6.0	14.4	8.1	543	---	222	---	270	0	57	13	44	1.7	11	54	.4	-51.2	-7.11	---
do.	---	Do.	do.	06–24–97	.5	19.5	7.8	437	---	205	---	250	0	46	13	26	1.6	5.8	17	.5	-55.8	-7.95	---
do.	---	Do.	do.	10–29–97	2.5	14.9	8.1	618	---	260	---	317	0	65	15	37	2.5	11	57	.5	-49.2	-7.08	---
3	---	Hereford	do.	01–14–97	5.3	9.6	8.2	587	---	227	---	270	4	64	9.3	45	2.0	11	65	.4	-51.7	-6.99	---
do.	---	Do.	do.	03–25–97	3.6	13.6	8.2	583	---	232	---	282	0	59	8.9	39	1.7	11	61	.3	-50.9	-6.94	---
do.	---	Do.	do.	06–24–97	.5	19.0	7.6	501	---	209	---	255	0	57	7.8	37	1.7	11	32	.4	-51.0	-7.38	---
do.	---	Do.	do.	10–29–97	1.5	15.0	8.3	568	---	224	---	273	0	64	8.9	42	2.2	13	52	.4	-52.1	-7.14	---
4	09470500	Palominas	Runoff	08–31–94	.4	26.5	>7.8	511	---	154	---	188	0	63	8.0	28	4.4	6.3	89	.3	-38.3	-5.42	---
do.	do.	Do.	do.	12–15–94	36	9.5	8.5	503	---	167	---	201	0	65	9.2	30	3.2	7.9	90	.2	-83.8	-11.11	---
do.	do.	Do.	do.	03–15–95	18	13.0	8.2	547	---	202	---	246	0	68	10	33	2.9	8.7	75	.3	-63.2	-8.25	---
do.	do.	Do.	Base flow	06–21–95	<.2	17.5	8.0	687	---	220	---	268	0	---	---	---	---	---	---	---	-59.5	-7.95	---
do.	do.	Do.	do.	03–12–96	1.8	10.0	7.9	604	---	220	---	268	0	74	9.9	40	2.4	8.1	86	.3	-54.5	-7.42	---
do.	do.	Do.	Runoff	07–15–96	816	25.2	7.8	236	---	83	---	102	0	26	3.2	13	4.7	3.1	23	.3	-53.9	-7.85	---
				Wells and springs																			
5	(D-21-21)36ddb	FP8 (drive point)	Basin-fill spring	03–24–97	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	-63.3	-9.11	---
6	(D-21-21)25cbc	Murray Springs (drive point)	do.	03–24–97	---	16.7	7.3	541	---	---	280	---	---	75	17	22	.2	4.6	.2	.3	-64.3	-9.43	<1.8
7	(D-23-19)01dbb	Garden Canyon Spring	Bedrock spring	08–30–94	---	15.0	>7.3	545	---	---	255	---	---	86	19	4.1	.4	3.1	50	.1	-65.3	-9.57	---
do.	do.	Do.	do.	12–17–94	---	2.4	7.3	373	---	192	---	234	---	67	9.7	3.2	.4	2.3	14	<.1	-83.7	-12.10	---
do.	do.	Do.	do.	03–14–95	---	16.5	7.2	450	---	214	---	261	---	71	13	3.6	.4	3.2	16	.1	-81.9	-11.72	---
do.	do.	Do.	do.	06–20–95	---	14.0	8.0	592	---	222	---	271	---	---	---	---	---	---	---	---	-74.3	-10.80	---
8	(D-22-22)05bbc	BLM (drive point)	Postentrenchment alluvium	09–02–94	---	22.1	7.2	510	---	250	---	305	---	57	14	27	1.5	5.9	16	.6	-57.2	-8.14	---
9	(D-22-22)33b2	FP3B	Postentrenchment alluvium	03–14–96	---	12.0	7.4	594	---	---	237	---	---	70	10	45	2.5	12	67	.3	---	---	---
do.	do.	Do.	do.	04–12–96	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	-51.3	-7.14	---
do.	do.	Do.	do.	07–18–96	---	---	7.6	436	---	183	---	223	---	43	6.5	33	2.8	3.4	29	.5	-51.8	-7.67	---
10	(D-22-22)33b3	FP3C	Pre-entrenchment alluvium	03–14–96	---	16.5	7.2	728	---	---	269	---	---	94	13	47	2.6	16	110	.3	-63.5	-8.70	---
do.	do.	Do.	do.	07–18–96	---	---	7.4	652	---	246	---	301	---	75	11	44	2.7	13	77	.3	-58.7	-8.01	---
11	(D-23-22)09d	Hereford #1	Postentrenchment alluvium	03–14–96	---	22.0	7.3	483	---	---	236	---	---	57	6.0	40	1.1	11	13	.6	-58.0	-8.04	---
do.	do.	Do.	do.	07–17–96	---	27.4	7.8	747	---	151	---	184	---	87	11	59	1.6	25	52	.5	-56.5	-8.07	---
12	(D-22-22)17c	Cottonwood #1	Pre-entrenchment alluvium	03–13–96	---	21.0	8.2	342	---	---	---	---	---	---	---	---	---	---	---	---	-64.1	-9.37	---
do.	do.	Do.	do.	07–18–96	---	27.4	7.3	346	---	176	---	214	---	24	14	28	1.6	3.6	4.1	.6	-62.7	-9.23	---
13	(D-23-22)33dda	Domestic Palominas	do.	03–14–96	---	15.0	8.3	755	---	---	258	---	---	99	12	50	2.2	12	130	.3	-56.0	-7.93	---
do.	do.	Do.	do.	07–16–96	---	29.8	7.25	750	---	252	---	307	---	87	11	49	2.4	11	130	.4	-55.1	-7.84	---
14	(D-22-22)05bbb2	ESF16	do.	03–24–97	---	17.5	7.8	406	---	---	204	---	---	47	11	27	1.6	5.5	12	.5	-57.7	-8.17	<1.8
15	(D-22-22)05bbb	ESF24	do.	03–24–97	---	18.3	7.7	457	---	---	---	---	---	---	---	---	---	---	---	---	-52.8	-7.71	---
16	(D-23-22)09b	FP1	do.	01–10–96	---	17.7	7.3	---	547	---	246	---	---	84	10	22	.7	16	26	.3	-61.3	-8.68	---
do.	do.	Do.	do.	03–13–96	---	16.0	7.3	530	---	---	---	---	---	---	---	---	---	---	---	---	-60.0	-8.80	---
do.	do.	Do.	do.	04–12–96	---	---	7.5	---	513	---	236	---	---	78	9.8	22	.6	14	23	.2	-60.1	-8.82	---
do.	do.	Do.	do.	07–17–96	---	27.5	7.6	532	---	222	---	271	---	73	9.2	23	.8	15	33	.3	-59.0	-8.21	---
17	(D-21-22)30d	FP2	do.	03–11–96	---	16.0	6.9	598	---	252	---	307	---	---	---	---	---	---	---	---	-58.5	-8.28	---
18	(D-23-22)22ccc	FP4	do.	03–14–96	---	14.5	7.4	699	---	---	269	---	---	82	11	56	2.3	12	95	.3	-57.2	-8.24	---
do.	do.	Do.	do.	07–16–96	---	16.4	7.8	778	---	288	---	352	---	81	12	61	2.6	12	96	.4	-55.7	-7.23	---
19	(D-22-22)06aaa4	BLM4	do.	12–16–94	---	19.6	8.0	393	---	158	---	193	---	19	6.7	58	2.9	15	20	.8	-63.2	-9.04	---
do.	do.	Do.	do.	03–16–95	---	---	7.6	476	---	204	---	249	---	39	14	39	3.1	16	27	.7	-62.2	-8.93	---
do.	do.	Do.	do.	06–21–95	---	35.5	7.5	454	---	210	---	256	---	---	---	---	---	---	---	---	-62.0	-8.78	---
do.	do.	Do.	do.	03–12–96	---	26.5	7.6	434	---	194	---	237	---	44	14	28	1.7	5.5	22	.6	-61.7	-8.89	---
do.	do.	Do.	do.	07–17–96	---	21.7	7.4	445	---	190	---	232	---	37	13	28	1.7	5.3	20	.7	-60.2	-8.31	---
20	(D-23-22)33dcd2	Palominas Well	do.	08–31–97	---	19.0	<7.3	514	---	196	---	239	---	63	7.3	35	1.5	7.2	44	.3	-51.9	-7.22	---
do.	do.	Do.	do.	12–15–94	---	19.0	6.9	1,210	---	268	---	327	---	160	18	77	2.4	39	270	.3	-61.4	-8.51	---
do.	do.	Do.	do.	03–15–95	---	---	7.5	770	---	208	---	254	---	84	12	59	2.1	32	140	.3	-60.8	-8.27	---
do.	do.	Do.	do.	06–21–95	---	19.0	7.3	529	---	214	---	261	---	---	---	---	---	---	---	---	-52.0	-7.17	---
do.	do.	Do.	do.	03–12–96	---	18.5	7.3	612	---	226	---	276	---	80	9.1	39	1.7	9.0	73	.4	-52.8	-7.21	---
do.	do.	Do.	do.	07–15–96	---	---	7.3	494	---	214	---	247	---	58	6.9	34	1.5	7.1	36	.4	-51.9	-7.18	---
21	(D-21-22)32ccc	ENF19	Regional aquifer	03–24–97	---	22.0	7.6	653	---	---	236	---	---	140	22	39	1.9	6.4	300	.6	-52.4	-7.73	<1.8
22	(D-22-20)26abb1	Antelope Run #3	do.	09–14–94	---	19.4	7.1	509	---	202	227	---	---	70	19	5.1	.4	6.3	44	.1	-63.5	-9.12	---
do.	do.	Do.	do.	12–16–94	---	17.1	7.4	506	---	232	---	283	---	76	21	5.5	.5	6.3	41	<.1	-61.2	-9.17	---
do.	do.	Do.	do.	03–16–95	---	17.5	7.3	533	---	234	---	286	---	73	20	5.1	.5	7.3	44	.1	-64.4	-9.37	---
do.	do.	Do.	do.	06–22–95	---	19.0	7.4	529	---	228	---	278	---	---	---	---	---	---	---	---	-62.9	-9.13	---
23	(D-21-21)31bdc	Bella Vista #5	do.	09–01–94	---	24.4	>7.4	333	---	154	---	188	---	35	10	19	.8	3.3	5.5	.2	-61.1	-8.91	---
do.	do.	Do.	do.	12–15–94	---	23.7	7.5	320	---	165	---	201	---	37	10	19	.8	3.3	4.1	.2	-62.1	-8.91	---
do.	do.	Do.	do.	03–15–95	---	23.7	7.4	328	---	164	---	200	---	36	10	19	.8	3.4	4.8	.2	-62.1	-8.97	---
do.	do.	Do.	do.	06–22–95	---	24.5	7.6	334	---	168	---	205	---	---	---	---	---	---	---	---	-61.8	-8.88	---
24	(D-21-21)27caa	Bella Vista B	do.	09–01–94	---	22.4	>7.3	342	---	154	---	188	---	37	14	12	.8	6.5	5.6	.1	---	---	---
do.	do.	Do.	do.	03–25–97	---	21.3	7.8	387	---	---	170	---	---	46	16	14	.9	25	8.7	.1	-60.4	8.70	<1.8
25	(D-22-21)03abc	Bella Vista C	do.	09–01–94	---	21.5	>7.2	319	---	146	---	178	---	46	7.4	11	.8	6.7	4.6	.1	---	---	---
do.	do.	Do.	do.	03–25–97	---	22.0	7.6	330	---	---	160	---	---	46	7.4	11	.8	7.2	4.9	.1	-66.0	-9.49	<1.8
26	(D-22-22)06abd	BLM Well #6	do.	03–28–95	---	22.0	7.7	300	---	140	---	171	---	17	13	21	1.8	4.2	9.3	.9	-67.9	-9.59	---
27	(D-23-22)31ccb	Cochise Water Co. Well	do.	09–14–94	---	23.6	7.3	338	---	---	163	---	---	40	6.5	19	1.1	5.5	9.0	.2	---	---	---
28	(D-21-21)33bda	Douglas	do.	08–15–96	---	23.6	7.5	336	---	---	162	198	---	40	11	12	.8	3.2	6.4	---	-63.8	-8.97	---
29	(D-22-20)03bbb2	Ft. Huachuca Prod. Well 2	do.	08–31–94	---	24.1	>7.5	350	---	158	---	193	---	39	10	17	.9	8.8	7.2	.2	---	---	---
30	(D-21-21)16aaa	MW5	do.	04–30–97	---	25.4	7.5	281	---		159	---	---	41	10	12	1.3	4.3	7.0	.2	-59.6	-8.46	<1.8
31	(D-20-21)33ddc	MW7	do.	04–30–97	---	23.6	7.4	328	---	---	155	---	---	43	7.5	16	1.2	2.7	3.9	.2	-57.6	-8.33	<1.8
32	(D-23-20)01acc2	Long	do.	07–24–96	---	19.9	7.3	480	---	193	---	236	---	71	13	7.7	.7	7.2	37	---	-66.2	-9.40	---
33	(D-23-21)07dda	Nicksville #16	do.	03–17–95	---	21.0	7.3	334	---	151	---	184	---	44	4.5	20	.6	6.2	8.2	.3	-69.6	-9.48	---
do.	do.	Do.	do.	06–20–95	---	21.1	7.4	337	---	152	---	185	---	---	---	---	---	---	---	---	-67.1	-9.45	---
do.	do.	Do.	do.	07–16–96	---	22.8	7.6	338	---	149	---	182	---	41	4.4	21	.7	6.1	8.4	.3	-69.0	-9.49	---
34	(D-22-21)36dba	Diaz	do.	09–01–94	---	21.7	>7.3	355	---	165	---	201	---	53	6.8	13	.9	5.1	9.4	.1	---	---	---
35	(D-22-21)33aaa	Paul	do.	07–10–96	---	22.5	7.4	321	---	---	166	202	---	47	5.2	11	.7	3.1	3.1	---	-69.2	-9.93	---
36	(D-23-22)31dda	Overbey	do.	06–24–96	---	22.1	7.6	393	---	---	149	182	---	47	8.0	17	1.4	16	11	---	-57.8	-8.12	---
37	(D-23-23)06bcc2	Hansford	do.	06–26–96	---	28.5	7.3	439	---	---	439	228	---	55	14	12	1.9	6.5	21	---	-55.3	-8.09	---
38	(D-21-23)33aaa	Griffin	do.	10–23–96	---	21.1	7.3	519	---	---	248	303	---	72	14	17	2.0	9.9	8.8	---	-55.9	-7.59	---

MAP SHOWING HYDROGEOCHEMISTRY, PLOTS OF SELECTED CHEMICAL CONSTITUENTS, AND ANALYSIS OF SOURCES OF WATER IN BASE FLOW OF THE SAN PEDRO RIVER IN THE SIERRA VISTA SUBWATERSHED OF THE UPPER SAN PEDRO BASIN, COCHISE COUNTY, SOUTHEAST ARIZONA

By D.R. Pool and Alissa L. Coes

1999