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

Hydrogeology of the Upper and Middle Verde River Watersheds, Central Arizona

Scientific Investigations Report 2005–5198

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By Kyle W. Blasch, John P. Hoffmann, Leslie F. Graser, Jeannie R. Bryson, *and* Alan L. Flint

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Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

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Suggested citation:
Blasch, K.W., Hoffmann, J.P., Graser, L.F., Bryson, J.R., and Flint, A.L., 2006, Hydrogeology of the upper and middle Verde River watersheds, central Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5198, 102 p., 3 plates.

V. 2, May 04, 2007.

Contents

Compact Disc (in pocket at back of report)

Format: American Standard Code for Information Interchange (ASCII) and Microsoft Excel 2003
Operating system used: Windows XP Professional

Plates

In pocket at back of the report.

Figures

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Tables

Tables—Continued

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
gallons per day per foot [(gal/d)/ft]	0.0124	square meters per day (m^2/d)
feet squared per day (ft^2/d)	0.0929	meters squared per day (m^2/d)
feet squared per day (ft^2/d)	7.481	gallons per day per foot (gal/d)/ft

Conversion Factors and Datums—Continued

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

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Geodetic Datum of 1929 (NGVD of 29).

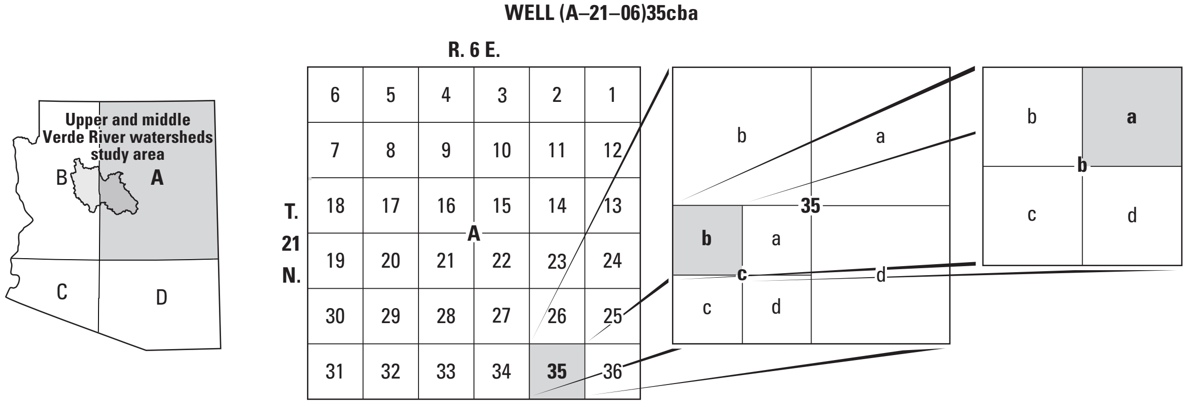
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27)

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

ARIZONA WELL-NUMBERING SYSTEM



Quadrant A, Township 21 North, Range 6 East, section 35, 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 (A–21–06)35cba designates the well as being in the NE1/4, NW1/4, SW1/4, section 35, Township 21 North, and Range 6 East.

Hydrogeology of the Upper and Middle Verde River Watersheds, Central Arizona

By Kyle W. Blasch, John P. Hoffmann, Leslie F. Graser, Jeannie R. Bryson, *and* Alan L. Flint

Abstract

The upper and middle Verde River watersheds in central Arizona are primarily in Yavapai County, which in 1999 was determined to be the fastest growing rural county in the United States; by 2050 the population is projected to more than double its current size (132,000 in 2000). This study combines climatic, surface-water, ground-water, water-chemistry, and geologic data to describe the hydrogeologic systems within the upper and middle Verde River watersheds and to provide a conceptual understanding of the ground-water flow system. The study area includes the Big Chino and Little Chino subbasins in the upper Verde River watershed and the Verde Valley subbasin in the middle Verde River watershed.

The Big Chino subbasin, in the upper Verde River watershed is 1,850 square miles in area. Within the subbasin, Big Chino Valley and Williamson Valley encompass about 570 square miles excluding the surrounding mountains and the western part of the Coconino Plateau. The valleys are filled with alluvial deposits eroded from adjacent uplands and interbedded basalt flows. Median thickness of the combined alluvial deposits and basalt flows is about 435 feet. The estimated volume of saturated basin-fill deposits within the valleys is about 155 million acre-feet. Beneath the basin-fill aquifer is a sequence of water-bearing Paleozoic formations that receive recharge where they crop out along the western boundary of the subbasin. Together, the basin-fill sediments and the Paleozoic formations constitute the regional aquifer in the Big Chino subbasin. Water-balance calculations indicate that about 1–2 percent of annual precipitation recharges the regional aquifer. Recharge occurs primarily along the Juniper and Santa Maria Mountains, Big Black Mesa, Granite Mountain, and Bill Williams Mountain. Average winter base flow at the Williamson Valley streamflow-gaging station (09502800) was 3.9 cubic feet per second during 1965–84 and 1.7 cubic feet per second during 2002–03. The decline is attributed primarily to climate fluctuations. Base flow at the Verde River near Paulden streamflow-gaging station (09503700) averages about 17,700 acre-feet per year. It currently (2003) is about equal to the long-term average but has declined at an annual rate of about 380 acre-feet per year since about the mid-1990s. Ground-water outflow from the Big Chino Valley occurs only as base flow in the Verde River. Declines in ground-water altitudes during the past 50 years are attributed primarily to ground-water withdrawals.

The Little Chino subbasin, in the upper Verde River watershed, is the smallest of the three subbasins in the study area and has had the greatest ground-water development. The regional aquifer underlying the subbasin is composed of sedimentary, volcanic, and basin-fill deposits of Quaternary and Tertiary age. Interfingering of less permeable units, such as lati-andesite, cemented alluvium, and trachyandesite, create confining conditions and artesian flow in some areas. The regional aquifer encompasses an area of about 310 mi^2, including Little Chino Valley and Lonesome Valley. Thickness of the basin-fill deposits generally ranges from about 100 to 800 feet; the estimated volume of the saturated basin-fill deposits in the Little Chino subbasin is 33 million acre-feet.

Winter precipitation is the primary source of recharge for the Little Chino subbasin as well as for other subbasins in the upper and middle Verde River watersheds. Water-balance calculations indicate that about 1–2 percent of annual precipitation recharges the regional aquifer in the Little Chino Subbasin. This amount may have been reduced since the predevelopment period (before 1940) by the construction of channel retention facilities along Granite Creek and its tributaries. During predevelopment times a larger volume of ground water flowed north across the southern boundary of the subbasin than flowed south. Recent numerical ground-water simulations indicate a greater flow of ground-water southward

across the boundary than northward. Discharge from Del Rio Springs has declined from about 2,800 acre-feet per year between 1940 and 1945 to about 1,000 acre-feet per year in 2003.

The 2,500-square-mile Verde Valley subbasin of the Verde River ground-water basin coincides with the middle Verde River watershed. The regional aquifer in the subbasin is composed predominantly of Paleozoic units present in the Coconino Plateau and of the basin-fill sediments, including the Verde Formation. The volume of saturated sediments, which are distributed primarily along the course of the Verde River, is about 112 million acre-feet. Recharge to the aquifer occurs predominantly along the Mogollon Escarpment and on the Coconino Plateau.

About 4 percent of the average annual precipitation results in recharge to the ground-water system; most of the recharge occurs from winter precipitation. Ground water discharges to the major tributaries and directly to the Verde River. Base flows in tributaries have declined in part because of climate fluctuations. Average winter base flow at the Verde River near Camp Verde streamflow-gaging station (09506000) was 148,600 acre-feet per year for 1936–44 and 1989–2003, but base flow declined at an annual rate of about 2,000 acre-feet per year during 1994–2003. Ground-water storage declines are almost entirely caused by ground-water pumping and reductions in natural channel recharge resulting from streamflow diversions. Storage declines are most evident in areas of municipal development where ground-water withdrawals are largest.

A geochemical mixing model was used to quantify fractions of ground-water sources to the Verde River from various parts of the study area. Most of the water in the uppermost 0.2 miles of the Verde River is from the Little Chino subbasin, and the remainder is from the Big Chino subbasin. Discharge from a system of springs increases base flow to about 17 cubic feet per second within the next 2 miles of the river. Ground water that discharges at these springs is derived from the western part of the Coconino Plateau, from the Big Chino subbasin, and from the Little Chino subbasin.

The relative component of base flow in the Verde River derived from the western part of the Coconino Plateau decreases in the downstream direction, as base flow increases, relative to the component from the Chino Valley subbasins. By river mile 22, the primary source area is the Big Chino subbasin, and the contribution from the western part of the Coconino Plateau is negligible. Ground-water discharge from the Verde Valley begins to contribute to base flow between river miles 22 and 30. The increases in base flow in this reach are primarily due to contributions from ground water that has recharge source areas at high altitudes along the Coconino Plateau and Black Hills. Ground water that has recharge source areas at low altitudes in the Verde Valley, and ground water from the Coconino Plateau and the Black Hills, also contribute to base flow between river miles 30 and 89.

Water quality in the study area generally is good for intended uses and shows little effects from human activities. Constituent concentrations in surface water and ground water generally were well below Federal and State regulations. Constituents exceeding U.S. Environmental Protection Agency Maximum Contaminant Levels or Action Levels include antimony, arsenic, fluoride, lead, nitrate, and selenium. Of these constituents, arsenic exceeded the MCL in the greatest number of samples, primarily owing to mineralogy of the Supai Group and the Verde Formation. Fluoride and sulfate concentrations exceeded the U.S. Environmental Protection Agency Secondary Maximum Contaminant Levels in a few samples.

Average water use in the Big Chino, Little Chino, and Verde Valley subbasins was about 12,000, 13,000, and 47,000 acre-feet per year, respectively, for 1990–2003. Agricultural and residential water use exceed other water uses; however, agricultural use within the Chino subbasins has decreased since the 1960s and 1970s.

Introduction

The upper and middle Verde River watersheds in central Arizona (fig. 1) are rich in natural beauty and cultural history, and are an increasingly popular destination for those seeking a temperate climate and opportunities for outdoor recreation. The region encompasses a diversity of terrain, including broad desert valleys, upland plains, forested mountain ranges, narrow canyons, and riparian areas along perennial streams. The river provides habitat for several threatened or endangered species. The watersheds are predominantly in Yavapai County, which in 1999 was determined to be the fastest-growing rural county in the United States (Woods and Poole Economics, Inc., 1999). The population of 132,000 in 2000 is projected to more than double by 2050. Such population growth will necessarily result in an increased demand on the region's water resources with ensuing consequences for instream, riparian, and other natural habitats. An understanding of the watersheds and their regional aquifers, surface-water bodies, and ground-water recharge and discharge areas is needed for informed water-management decisions. The influence of climate, geology, and topography on those components of the hydrologic system is also useful information for water-management decisions.

Figure 1. Locations of upper and middle Verde watersheds study area, central Arizona study area, structural provinces, and land ownership.

In 1999, the U.S. Geological Survey (USGS), in cooperation with the Arizona Department of Water Resources (ADWR), began a regional study of the hydrogeology of the upper and middle Verde River watersheds. In 2001, Yavapai County became an additional cooperator in the study. The study is part of the Rural Watershed Initiative (RWI), a program established by the State of Arizona that is managed by the ADWR and focuses on addressing water-supply issues in rural areas while encouraging participation from locally driven partnerships. Three RWI studies resulted from this cooperation: the upper and middle Verde River watersheds, the Coconino Plateau and adjacent areas, and the Mogollon Highlands (fig. 1). Results from the studies are intended to provide a description of the hydrogeologic framework and ground-water flow system needed for construction of a regional numerical ground-water flow model.

For this study the USGS has collected geologic and hydrologic data within the upper and middle Verde River watersheds from 1999 to 2005 to (1) describe the hydrogeologic units, (2) describe the interaction of ground water and surface water, (3) develop a conceptual model of ground-water flow systems, and (4) develop water budgets. Surface-water data were collected through March 31, 2004, ground-water level data were collected through May 2005 at some sites, and water-chemistry data were collected through 2003. Climate data were collected through 2003. Stable-isotope data for precipitation were collected during 2003–05. Data collected before the start of this study were included in some analyses.

Purpose and Scope

The purpose of this report is to describe the hydrogeologic framework, surface-water flow systems, and ground-water flow systems of the upper and middle Verde River watersheds, present a conceptual model of the occurrence and movement of water through the watersheds, and provide an estimated water budget for the watersheds and regional aquifers. This report is one of two reports on the upper and middle Verde River watersheds from this study. The first report is titled “Preliminary geophysical framework of the upper and middle Verde River watershed, Yavapai County, Arizona” (Langenheim and others, 2005). It presents basin-scale geophysical and geological data and defines the extent and depth of the Tertiary alluvial and volcanic deposits that make up the regional aquifers of the Big and Little Chino subbasins and the Verde Valley subbasin. In this second report the geologic interpretations presented in Langenheim and others (2005) are used with additional information to describe the hydrogeologic framework and present a conceptual model of the regional flow systems that will provide a basis for future hydrologic studies.

This report provides a comprehensive summary of the data available for the study area with a focus on the regional aquifers underlying the Big and Little Chino subbasins in the upper Verde River watershed and the Verde Valley subbasin in the middle Verde River watershed. Water budgets were estimated for pre-stress conditions (prior to 1940; Corkhill and Mason, 1995) and for transient conditions for calendar years 1990 through 2003. Data for this study were obtained from the U.S. Geological Survey National Water Inventory System (NWIS), the U.S. Department of Agriculture (USDA) Forest Service, the National Oceanic and Atmospheric Administration (NOAA), the ADWR Ground-Water Site Inventory (GWSI), the Arizona State Land Department (ASLD), Yavapai County, various municipalities, consulting companies, university data and reports, and private landowners.

Existing spatial data relating to geology, hydrology, hypsography, meteorology, land use, vegetation, water use, areal photography, and remotely sensed imagery were used to describe the study area. Water-bearing zones are described through discussion of ground-water movement, the interactions of surface water and ground water, hydraulic properties and characteristics, water chemistry, and isotope hydrology. Climate, land-use and land-development, vegetation, and water-use data are used in part to estimate water-budget components. Additional well and spring data collected during the study were used to supplement existing data. Information on additional data collection, analysis, and monitoring that would be useful in the development of a numerical ground-water flow model also is provided.

Acknowledgments

Tom Whitmer of the ADWR and John Munderloh of Yavapai County provided assistance and guidance throughout the study. Ed DeWitt of the USGS provided geologic expertise, including creation of the geologic sections. Bill Remick, Frank Corkhill, and Keith Nelson of the ADWR provided technical input and hydrologic data. Scott Izuka of the USGS, as well as Kim Mitchell, Frank Corkhill, and Tracey Carpenter of the ADWR, provided technical reviews. Staff of Prescott National Forest, Dead Horse Ranch State Park, and Yavapai Community College, and David Gipe of Paulden, Arizona, provided access to sites used for the installation of weather stations. Staff of the USDA Forest Service Natural Resources Conservation Service, Yavapai County, Arizona Public Service, Talking Rock Golf Course, Mingus Mountain Methodist Camp, and Camp Verde Water Company provided precipitation and weather data. Ann Harrington of Paulden, Arizona, provided access to field sites. Access to wells was also granted by Tina Swan, Mr. and Mrs. Goebel Pitzer, Carolyn Farnsworth, Dwayne Tischler, Mr. and Mrs. Edward Greuling, John Heidewald, Starr Bennett, Mr. and Mrs. Kenneth Clifton, Edward Bruhn, and Sally Strickland. Betsy Woodhouse, Cyndi Hayek, Ken Fossum, Henry Sanger, Elizabeth Leon, Julie Dufrenoy, Morning Dawn Johnson, and Doug Rautenkranz of the USGS provided field and analysis assistance. John Callahan of the USGS illustrated the figures and plates for this report.

Description of Study Area

Physiography.— The upper and middle Verde River watersheds, the study area for this report, are predominantly within the Transition Zone (Wilson and Moore, 1959) between the Colorado Plateau Structural Province and the Basin and Range Structural Province in Arizona (Fenneman, 1931); however, a small part of the study area is within the Colorado Plateau Province (fig. 1). The Colorado Plateau is a complex geologic area of deep carved canyons and flat-topped mesas formed by consecutive compressional mountain-building, erosional, and extensional-volcanic periods (Baars, 1983). The subprovince of the Colorado Plateau within the study area is the Coconino Plateau (fig. 1; Hunt, 1967), which consists of nearly flat-lying sedimentary units that are visible in the steep, exposed cliffs of the Mogollon Escarpment. The Basin and Range Province comprises mountainous regions of crystalline and consolidated sedimentary rocks separated by basins filled predominantly with unconsolidated alluvium derived from the surrounding mountains. These features are noticeable in the southern half of the study area (fig. 2). The Transition Zone has physiographic characteristics of both provinces that reflect episodes of both extension and compression that have created a region severely deformed by faulting and uplift and that contains rocks and alluvial sediments similar to those in the Colorado Plateau (Anderson and others, 1992).

Perennial streams in the study area include the Verde River, with headwaters approximately 2 mi southeast of Paulden, and its tributaries: Sycamore Creek, Oak Creek, Wet Beaver Creek, and West Clear Creek (fig. 3). Intermittent and ephemeral streams include Big Chino Wash, Pine Creek, Walnut Creek, Williamson Valley Wash, Little Chino Wash, Granite Creek, Hell Canyon, Bitter Creek, and Dry Beaver Creek. The altitude of the Verde River ranges from about 4,200 ft at its headwaters to about 3,000 ft near Camp Verde (fig. 3) at the downstream boundary of the study area. The river extends about 89 mi through the study area. Mountains surrounding the watersheds are the Bradshaw Mountains and Black Hills to the south, the Juniper Mountains and Santa Maria Mountains to the west, and the San Francisco Mountains to the north (fig. 2). These features, and parts of the Colorado Plateau, are primary hydrogeological boundaries for the study area that partly control the movement of surface water and ground water at the regional scale.

The upper and middle Verde River watersheds consist of three ground-water subbasins delineated by the State of Arizona (Arizona State Legislature, 2005; fig. 4*A*). The upper Verde River watershed consists of the Big Chino subbasin of the Verde River ground-water basin and the Little Chino subbasin of the Prescott Active Management Area. The Verde Valley subbasin of the Verde River ground-water basin coincides with the middle Verde River watershed.

Major features of the 1,850 mi² Big Chino subbasin are Big Chino Valley, Williamson Valley, Walnut Creek, and Big Black Mesa (figs. 1–4). The Little Chino subbasin includes Granite Creek, Little Chino Wash, and Lonesome Valley. It is the smallest of the subbasins at 310 mi^2. The 2,500 mi^2 Verde Valley subbasin extends from the Verde River near Paulden streamflow-gaging station (09503700) to the Verde River near Camp Verde gaging station (09506000; fig. 3). It includes Sycamore Creek, Oak Creek, Wet and Dry Beaver Creeks, and West Clear Creek (figs. 1–4).

Terminology.—The following explanation is provided to assist the reader.

- The “upper Verde River watershed” includes the Big Chino subbasin of the Verde River ground-water basin and the Little Chino subbasin of the Prescott Active Management Area.
- The “middle Verde River watershed” includes only the Verde Valley subbasin of the Verde River ground-water basin.
- “Big Chino subbasin” is shortened from the legal name “Big Chino subbasin of the Verde River ground-water basin.”
- “Verde Valley subbasin” is shortened from the legal name “Verde Valley subbasin of the Verde River ground-water basin.”
- “Little Chino subbasin” is shortened from the legal name “Little Chino subbasin of the Prescott Active Management Area.”
- A name ending in “subbasin” indicates the entire drainage, including the basin floor and the bounding mountains. For example, the Big Chino subbasin includes Williamson Valley, Big Chino Valley, the Juniper Mountains, the Santa Maria Mountains, Partridge Creek, Walnut Creek, and Big Black Mesa.
- A name ending in “valley” refers to the valley proper and the adjacent high-altitude areas. Minor drainages are included in references to some valleys.
- Ground-water source areas were delineated to identify sources of ground-water recharge on the basis of water chemistry (fig. 4*B*).

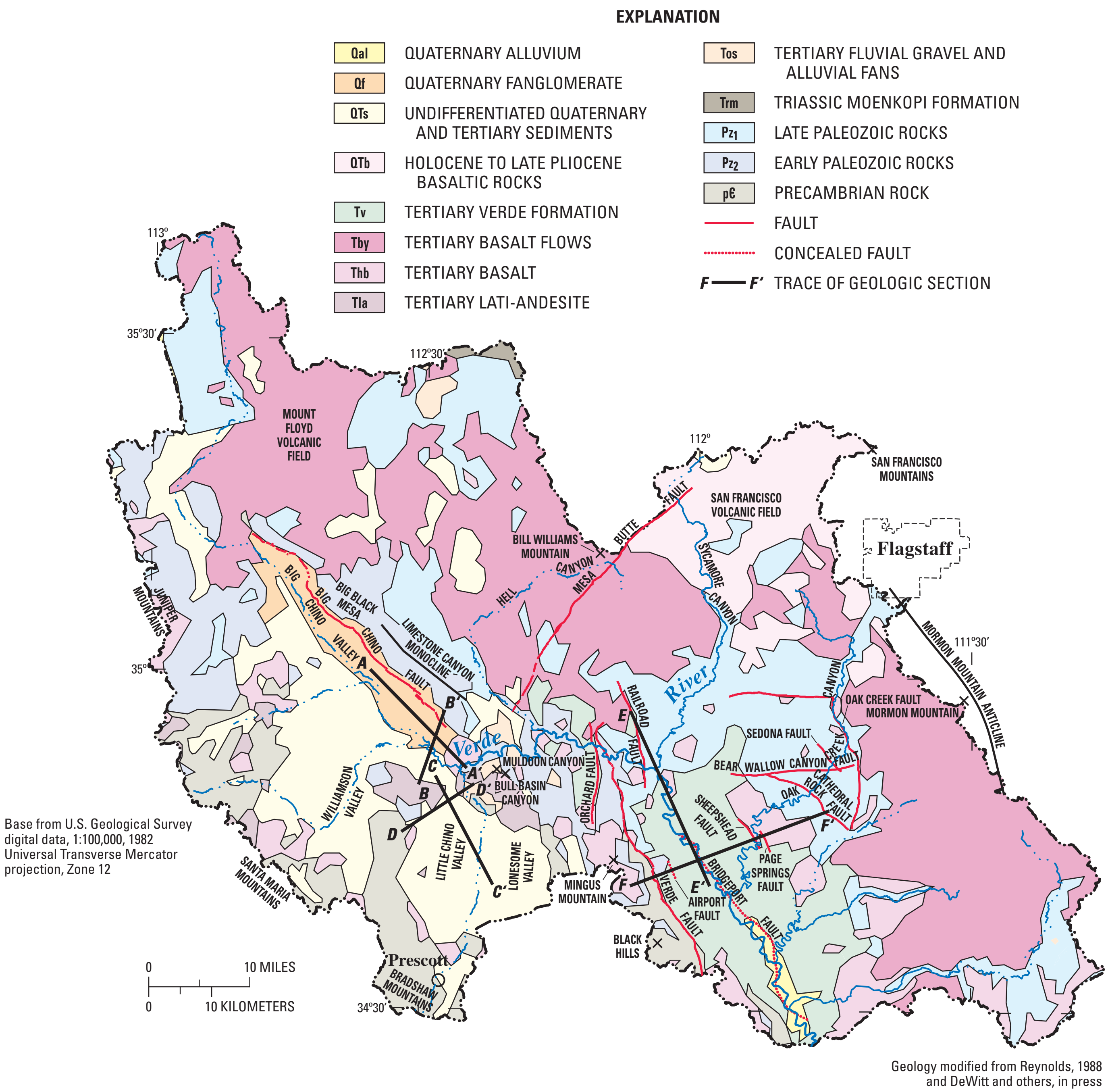
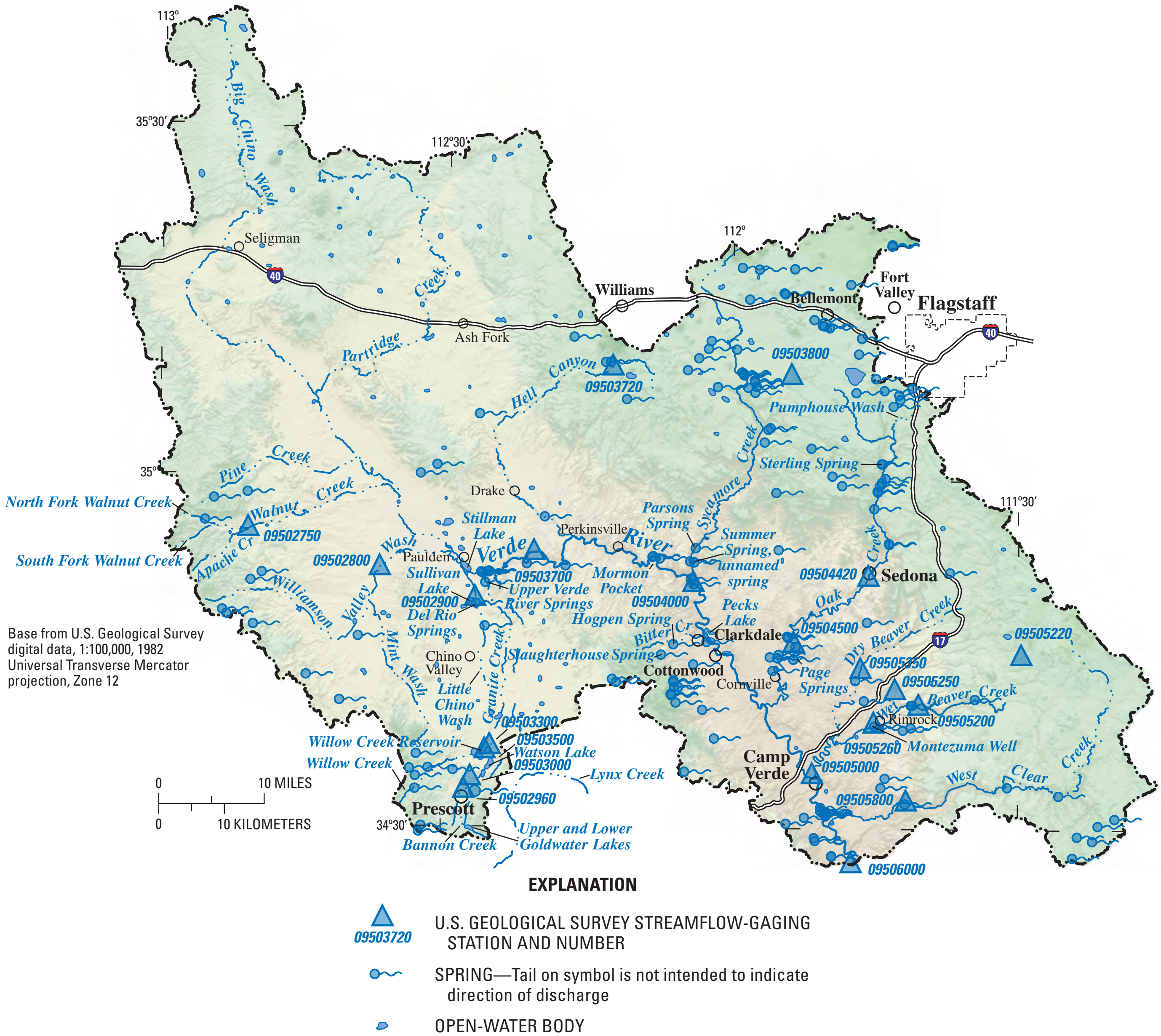


Figure 2. Generalized geology, geologic structures, and location of geologic sections, upper and middle Verde River watersheds, central Arizona.



Base from U.S. Geological Survey digital data, 1:100,000, 1982
Universal Transverse Mercator projection, Zone 12

Figure 3. Hydrography of the upper and middle Verde River watersheds including open-water bodies, the Verde River and its major tributaries, springs, and U.S. Geological Survey streamflow-gaging stations.

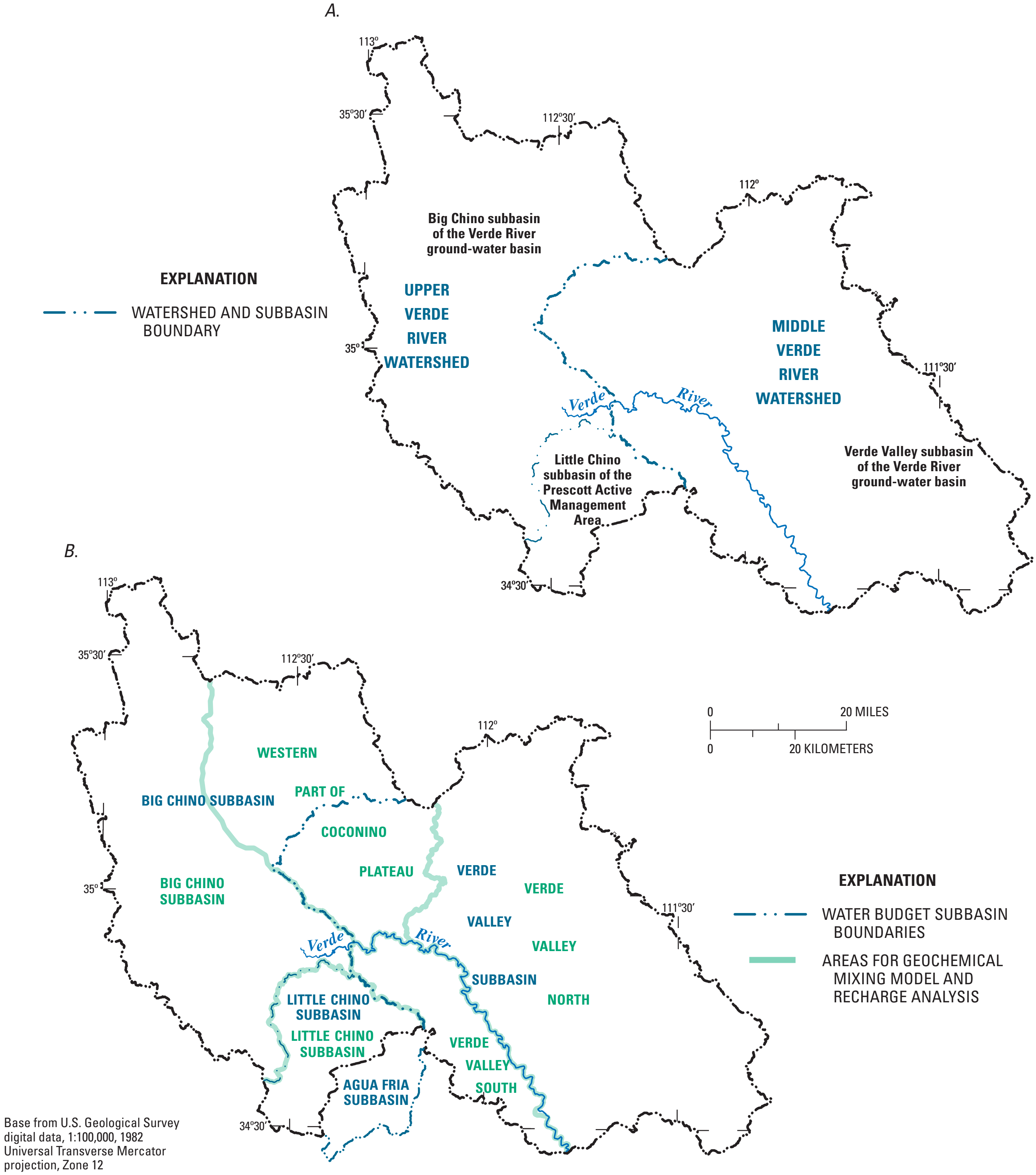


Figure 4. Hydrologic boundaries in the upper and middle Verde River watersheds. *A*, Watershed and subbasin boundaries defined by the State of Arizona; *B*, Subbasin boundaries and ground-water source area boundaries.

Climate.—The climate of the study area is primarily arid to semiarid and includes wide ranges in temperature and precipitation (fig. 5). Climate conditions are strongly correlated with altitude; moderate summers and severe winters occur at higher altitudes, and extreme summer heat and mild winters occur at lower altitudes. Microclimates also are common in the study area, as the slope and exposure of the mountains and deep canyons control the amount of solar radiation that reaches the land surface. The study area, like much of the Southwest, is also subject to extended dry periods or droughts. Collection of hydrologic data for this study corresponded with the transition from a wet period to the onset of a drought. Average annual precipitation ranges from about 10 inches in the basins to about 40 inches in the mountains and in the higher altitudes of the Coconino Plateau. In general, precipitation is distributed bimodally, between summer monsoons and winter frontal storms. Mean annual temperatures range from about 43°F to 63°F and are inversely correlative with altitude.

Vegetation.—The predominant type of vegetation in the study area is piñon-juniper woodlands, which account for 31 percent of the middle Verde River watershed and 62 percent of the upper watershed (fig. 6). Piñon-juniper woodlands and chaparral are primarily present in the middle altitudes (about 4,000–6,500 ft) of both watersheds. Desert scrub is the predominant vegetation type in the lower altitudes of the middle watershed and covers 8 percent of the watershed. Grasslands are the major vegetation type in the lower altitudes of the upper watershed and cover 28 percent of the watershed. Montane forests in the higher altitudes of the Bradshaw and Juniper Mountains in the upper watershed cover less than 4 percent of the watershed. Montane forests along the Mogollon Escarpment cover 41 percent of the middle watershed.

Population.—In 2000, the estimated population of the study area within Yavapai County and Coconino County was 132,000 (Arizona Department of Commerce, 2001). Approximately 50 percent of the population lives in the incorporated cities and towns of Prescott, Sedona, Cottonwood, Camp Verde, Chino Valley, Clarkdale, and Jerome.

Land Use.—Three-quarters of the land in Yavapai County is publicly owned (fig. 1); 38 percent is managed by the USDA Forest Service, 24.5 percent is managed by the State of Arizona, 11.5 percent is managed by the Bureau of Land Management, and less than 0.5 percent is managed by other public agencies. Private holdings account for about 25 percent of the land ownership, and the remaining 0.5 percent is accounted for by the Yavapai-Prescott Indian Reservation (Arizona Department of Commerce, 2001). Agriculture, cattle ranching, mining, and urban development are the largest land uses within the region.

Water Use.—The primary use of surface water in the study area is for irrigation of agricultural fields; numerous irrigation ditches downstream from the Verde River near Clarkdale streamflow-gaging station (09504000; fig. 3) divert water from the Verde River for this purpose. Ground water (including spring water) is the source for all domestic, municipal, industrial, and additional irrigation water use. Ground water is supplied for these uses primarily by private water companies, although a few municipal companies have been formed for this purpose. Additionally, thousands of private wells in the study area are used for domestic supply. Average annual ground-water withdrawals in the Big Chino, Little Chino, and Verde Valley subbasins during 1990–2003 was 7,900, 4,900, and 120 acre-ft, respectively. These values do not consider subirrigation and surface-water use. Residential water obtained from domestic wells and water providers totaled about 500, 7,900, and 9,700 acre-ft for the Big Chino, Little Chino, and Verde Valley subbasins, respectively, for the same time period.

Previous Investigations

The geology and hydrology of the study area have been studied by several investigators. Krieger (1965) provides a detailed discussion of the stratigraphy and structure, physiography, and mineral resources of Prescott and Paulden. Anderson and Creasey (1958) described the geology of the Jerome area (fig. 2); Lehner (1958) described the geology of the Clarkdale quadrangle; Twenter and Metzger (1963) summarized the geology of the Mogollon Rim in the Verde Valley area; and Anderson and Blacet (1972) described the bedrock in the northern part of the Bradshaw Mountains. Hydrologic investigations were primarily done for portions of the study area. Schwalen (1967) described ground water in the artesian area of Little Chino Valley and presented data for 1940–65. Matlock and others (1973) updated the work of Schwalen to include data for 1966–72. Levings (1980) described ground-water availability and water chemistry in the Sedona area. Owen-Joyce and Bell (1983) presented findings of a water-resource assessment in the Verde Valley near Camp Verde, Clarkdale, and Sedona. In 1980, the State of Arizona's Groundwater Management Act resulted in the declaration of Active Management Areas, of which the Prescott Active Management Area (PRAMA) was established. Numerous studies were conducted of the PRAMA that resulted in a map of ground-water conditions (Remick, 1983); a ground-water flow model that simulates both steady-state conditions (1940) and transient conditions (1940–93; Corkhill and Mason, 1995); and an updated ground-water flow model and extended simulation periods for examining forecasted predictions to 2025 (Nelson, 2002). Schwab (1995) constructed a water-level map for the study area including areas outside the PRAMA boundary.

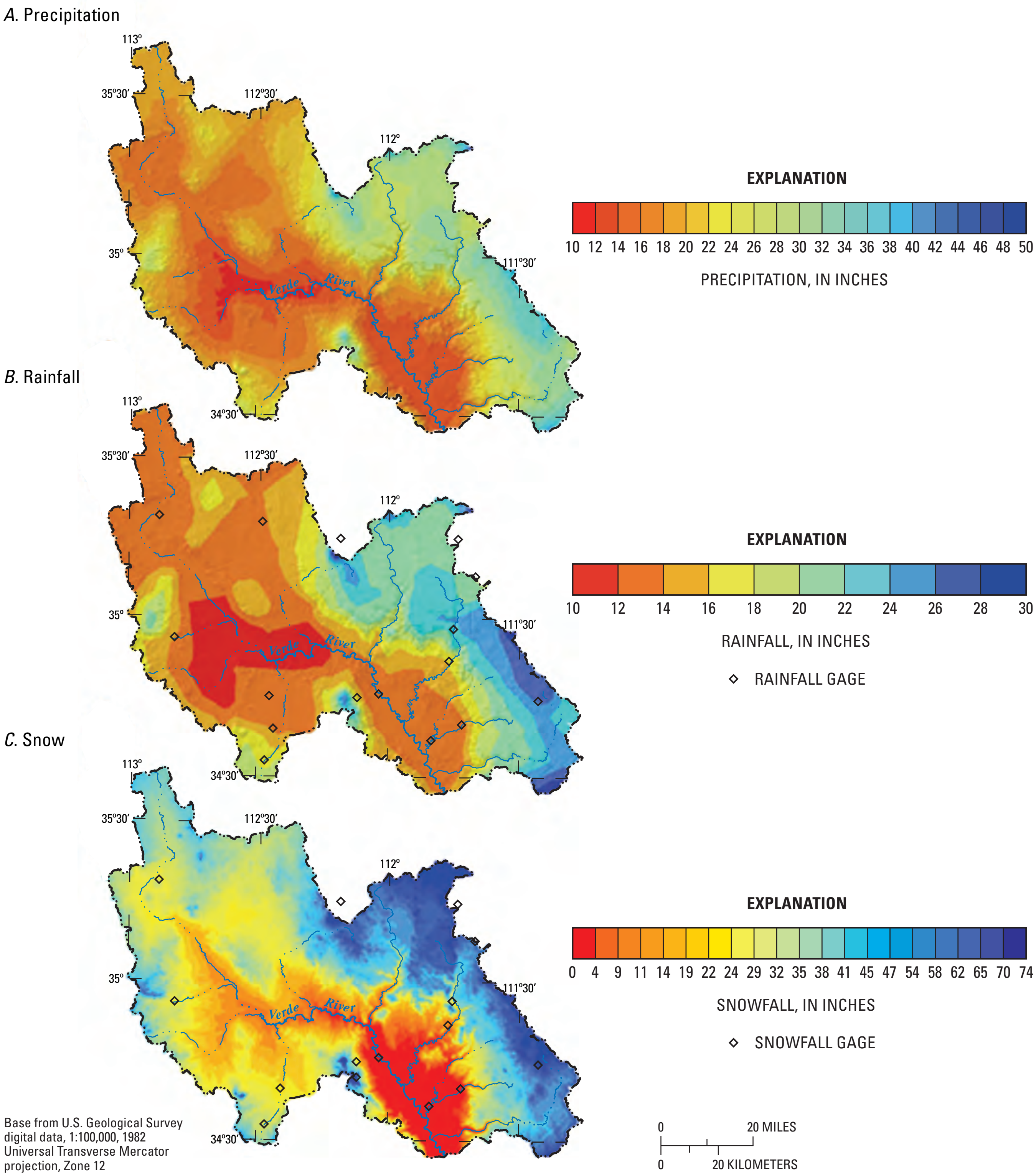
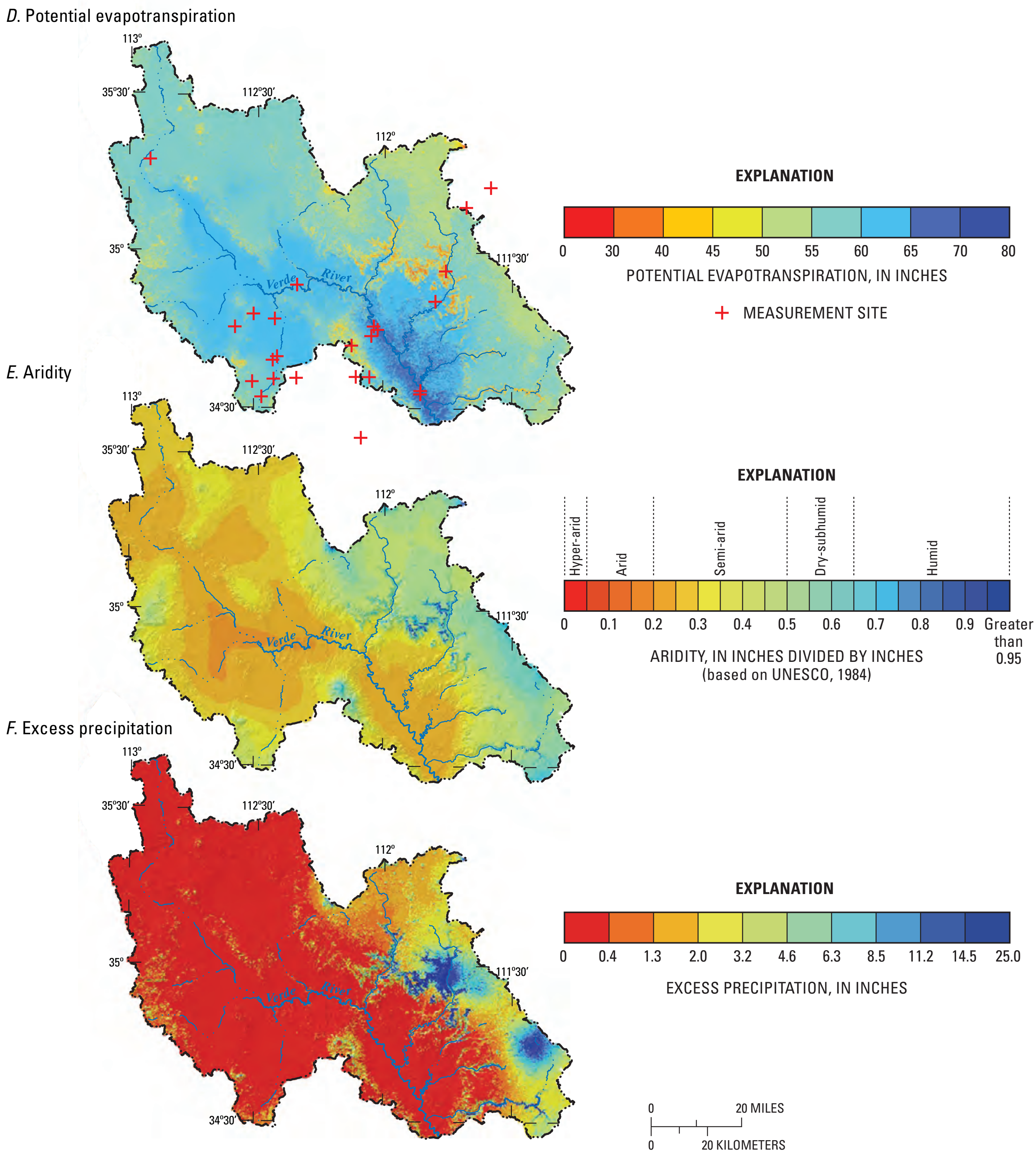


Figure 5. Distribution of average annual climatic values within the upper and middle Verde River watersheds, central Arizona. *A*, Total precipitation based on Parameter-elevation Regressions on Independent Slopes Model (PRISM) data for rainfall from 1971 to 2000 and National Oceanic and Atmospheric Administration (NOAA) data for snowfall from 1981 to 2003; *B*, Rainfall based on PRISM data from 1971 to 2000; *C*, Snowfall based on NOAA data from 1981 to 2003; *D*, Potential evapotranspiration based on data from 1971 to 2000; *E*, Aridity (UNESCO, 1984) based on data from 1971 to 2000; *F*, Excess precipitation based on data from 1971 to 2000.



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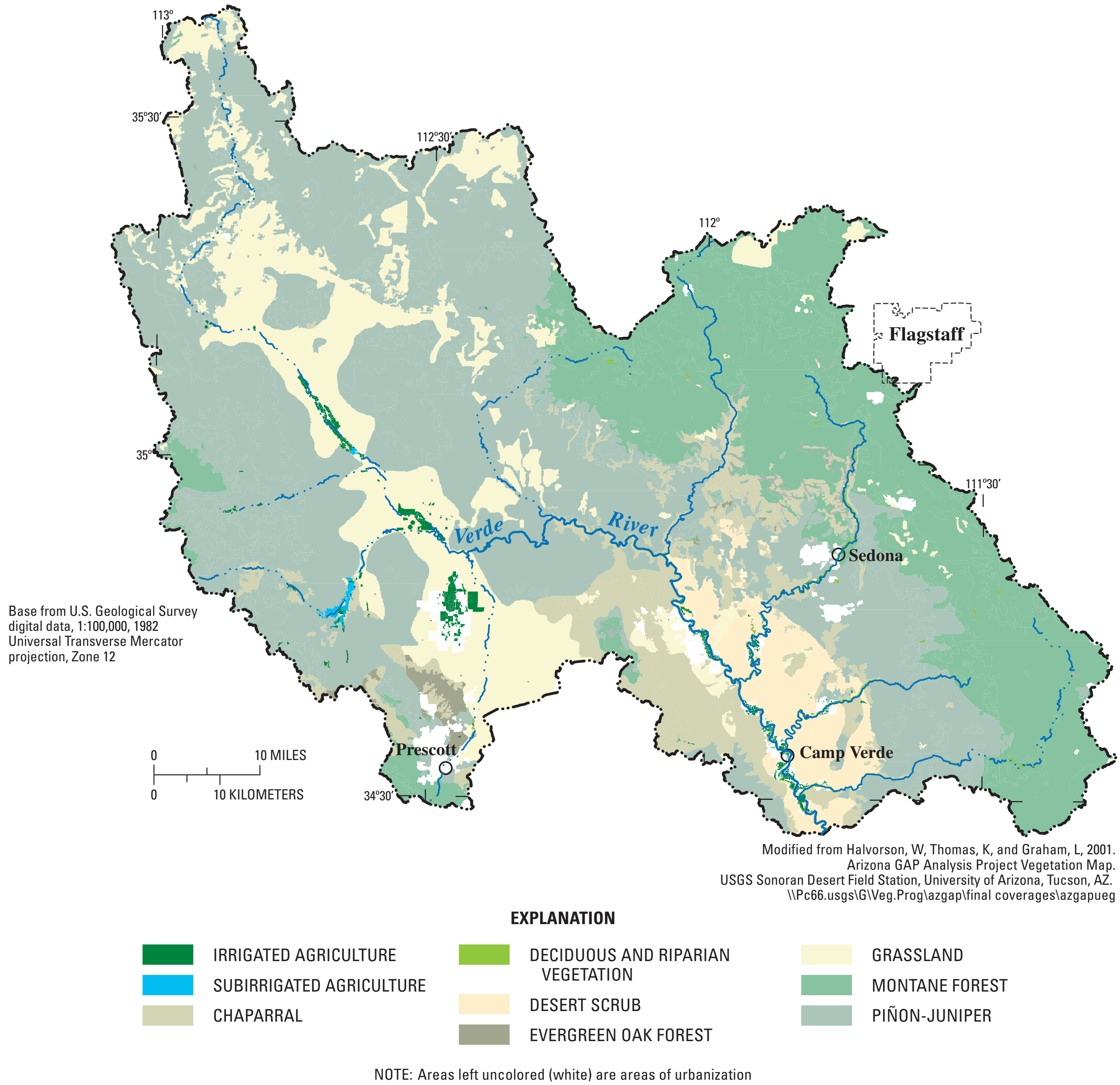


Figure 6. Vegetation, subirrigated agricultural areas, and irrigated agricultural areas within the upper and middle Verde River watersheds, central Arizona.

The Bureau of Reclamation (Ostenaa and others, 1993) conducted a hydrogeologic investigation of Big Chino Valley to identify potential sources of water for the city of Prescott. Knauth and Greenbie (1997) and Wirt and Hjalmarson (2000) used chemistry data to infer ground-water flow paths and source areas to the Verde River headwaters area. The ADWR (2000) compiled a summary of available water-resource data in the upper and middle Verde River watersheds. Langenheim and others (2005) calculated the depth of Tertiary alluvial sediments and volcanic deposits in Big Chino, Little Chino, Williamson, and Verde Valleys, and identified several new faults by using aeromagnetic and gravity surveys. Wirt and others (2005) described the geology, hydrogeology, and geochemistry of the Verde River headwaters area.

Climate

Climate records were compiled from multiple public and private agencies (appendices 1–4). Long-term temperature, rainfall, and snowfall data were obtained from the National Oceanic and Atmospheric Administration (NOAA) for climate analyses (Western Regional Climate Center, 2004). For the purposes of this report, analyses of annual statistics were limited to years in which records were complete for individual stations. The last full year of record considered in the analyses is 2003.

Temperature

Temperature records for the study area begin at the end of the 19th century and continue through to 2005. Mean annual temperatures for stations within the study area range from 43°F near Fort Valley (altitude 7,347 ft) to 63°F near the town of Cottonwood and Tuzigoot National Monument (altitude 3,470 ft), which is an increase of about 5°F per 1,000 ft decrease in altitude.

Long-term temperature trends were analyzed for five stations with the longest periods of record (Fort Valley, Jerome, Prescott, Seligman, and Williams). With the exception of Jerome, station temperatures have increased by about 1–3°F during the last 100 years. Temperature at the Jerome station has declined about 1°F during the past 100 years. Annual mean temperatures within the study area have increased since 1990, and temperatures during 1990–2004 were above the long-term mean temperature for 14 of 15 stations.

Precipitation

Average annual precipitation (rainfall and snowfall) varies spatially and temporally in the study area. The spatial distribution is primarily influenced by the direction of the approaching winds and orographic uplift of air masses. As a result precipitation amounts increase with increased altitude (fig. 5). Basins receive about 10 to 15 in., the slopes of the surrounding mountains receive about 15 to 30 in., and the crest of the mountains and the Coconino Plateau receive about 20 to 40 in. (fig. 5). The upper Verde River watershed (altitude 4,000–4,500 ft), however, receives less annual precipitation than the middle watershed (altitude 3,000–3,500 ft) because the middle watershed is surrounded by more abrupt and contrastively higher mountains than is the upper watershed.

Precipitation primarily occurs during two seasons. The first season is the summer monsoon (also known as the North American Monsoon, or the Southwestern, Arizona, or Mexican Monsoon), which typically begins in July and extends through September (fig. 7). During these months, moisture-laden air from the Gulf of Mexico and the Gulf of California migrates northward to the study area. Convective uplift caused by surface heating is combined with orographic uplift to create unstable atmospheric conditions. Intense rainfall, lightning, hail, and high winds are typically associated with the instability. Convective monsoon rainstorms are characteristically short lived (less than 1 hr), intense (greater than 1 in./hr), and localized (about 100 mi^2). The second season is December through March. During this season, winds typically are from the west, bringing with them moisture-laden air masses from the Pacific Ocean. Frontal storms, caused by cyclonic flow systems in the area are characteristically longer (12–48 hr), less intense (less than 0.25 in./hr), and more regional in extent (500 mi^2) than the summer convective storms.

Precipitation also can occur during October and November as a result of tropical disturbances from the Pacific Ocean. Although precipitation during this period can be a significant portion of the annual total, the atmospheric conditions that result in precipitation do not occur from year to year with regularity. Consequently, this period was not considered one of the primary seasons of precipitation in this study.

Currently, precipitation data for the upper and middle Verde River watersheds are collected by a multitude of agencies including Federal, county, municipal, private, and educational organizations. There are an estimated 110 active stations within and adjacent to the study area (appendix 1). NOAA stations, dating back to 1897, have the longest period of record in the watershed. There are currently 18 NOAA precipitation gages in the upper and middle watersheds. The longest NOAA records, from the late 1890s to the present, are for Fort Valley (023160), Jerome (024453), Prescott (026796), Seligman (027716), Walnut Creek (029158), and Williams (029359). The second oldest series of gages were activated on or about 1950. These include Beaver Creek (020670), Chino Valley (021654), Flagstaff AP (023010), Montezuma (025635), Oak Creek (026037), Sedona (027708), and Tuzigoot (028904).

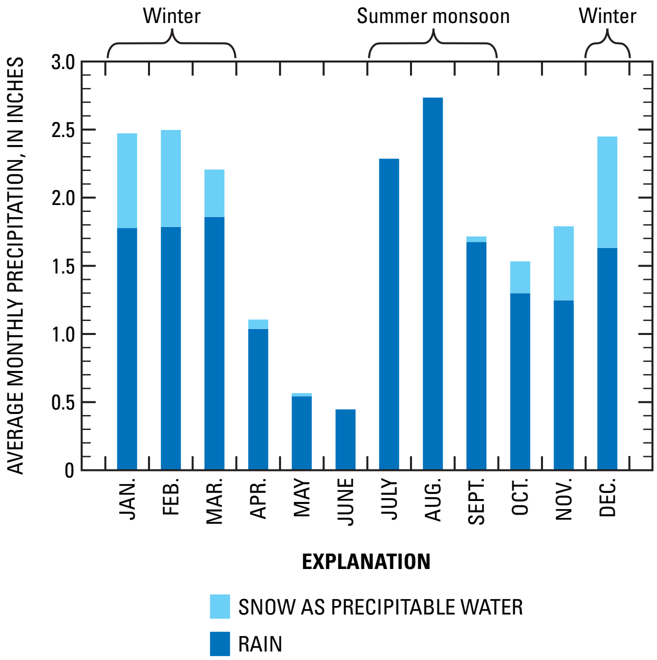


Figure 7. Average monthly precipitation at precipitation gages in the upper and middle Verde River watersheds, central Arizona (see figs. 5*B* and 5*C*).

Rain

On the basis of data from all NOAA gages in the study area, rainfall has been greater than the long-term average for periods of 30 to 40 years and less than the long-term average for periods of similar length (fig. 8*A*). Rainfall was greater than average from the beginning of the 20th century to 1940, less than average from 1940 through 1977, greater than average from about 1977 through about 1994, and generally drier than average from 1994 to 2004. The cyclical pattern in rainfall suggests that the current period of less-than-average rainfall could last at least for another decade.

The average annual rainfall for the study area is approximately 18 in./yr, and the total volume of rainfall is about 4.7 million acre-ft/yr. This volume was calculated by using annually averaged Parameter-elevation Regressions on Independent Slopes Model (PRISM) rainfall data from 1971 through 2000 for the study area (Daly and others, 1994; table 1). PRISM is an analytical procedure that calculates rainfall distributions by using measured rainfall and altitude data from climate stations. Long-term average annual rainfall is calculated by using data from NOAA stations for the 30-year period 1971–2000. These data were considered to be representative of long-term conditions because they reflect both wet and dry periods. Basin rainfall was calculated for a wet year (1992) and a dry year (2002) to characterize extremes in rainfall volumes (table 1). Comparison of PRISM data to altitude-rainfall relations by using the current network of stations indicates a difference of about ± 10 percent. This difference between methods is used as an estimate of uncertainty of the PRISM data.

Snow

Similar to rainfall, snowfall is directly correlated with altitude (fig. 5*C* and appendix 2). For example, from 1982 through 2003, average snowfall at Tuzigoot National Monument (altitude 3,470 ft) was 2 in./yr, while the average at Jerome (altitude 5,135 ft) was 9 in./yr and the average at Mingus Mountain (altitude 7,600 ft) was 92 in./yr.

The long-term record of snowfall indicates a period of greater-than-average snowfall from 1916 to 1955 and a period of less-than-average snowfall from 1955 to 2003 (fig. 8*B*). The water equivalent of snowfall is dependent upon the atmospheric conditions during which the snow was produced. An average snow water equivalent is 1 unit of water for each 10 units of snow depth. For higher altitudes, snowfall approaches 25 percent of the total annual precipitation, whereas in the low altitude basins, it is less than 5 percent. On average, snowfall is greatest during December at all gages; January and February are the second and third snowiest months, respectively (fig. 7).

An altitude-snowfall relation was created to estimate total snowfall for the study area using 22 years of record (1981–82 through 2002–03) for 15 gages. A single altitude-snowfall relation was developed owing to the small number of gages. The altitude-snowfall relation is

$$S_{pw} = 0.1(2x10^{-16}z^{4.5893}), \quad (1)$$

where S_{pw} is snowfall as precipitable water in inches using the snow water equivalent of 10 in. of snowfall to 1 in. of water, and z is altitude in feet. Snowfall accounted for about 695,000 acre-ft of precipitation per year (table 2), or about 16 percent, of the annual total precipitation in the study area during 1981–2002. The upper Verde River watershed receives about 20 percent less snowfall than the middle Verde River watershed on the basis of historic data; snowfall in the study area in 2002 and 2003 was less than historic averages (table 2).

Climate Oscillations

Three multiyear climate cycles, the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO), which are related to atmospheric pressures, sea surface temperature (SST) within the tropical and northern latitudes of the

Pacific and Atlantic Oceans, and atmospheric circulation patterns, have been shown to influence precipitation amounts on the Coconino Plateau including the adjacent Verde River watersheds (Enfield and others, 2001; Hereford and others, 2002; McCabe and others, 2004; fig. 9). ENSO cycles are about 4 to 7 years, whereas PDO and AMO cycles typically range from 20 to 70 years. Hereford and others (2002) calculated several statistically significant correlations between the ENSO and precipitation in the region. During periods of a strong El Niño (negative ENSO index), such as 1982 and 1993, there is increased precipitation during the winter and increased variability in precipitation during the summer (fig. 9*B*). During weak El Niño conditions, both winter and summer precipitation amounts are less than average. La Niña conditions (positive ENSO index), such as 1973–75, are associated with decreased winter precipitation and normal summer precipitation.

The PDO has a modest statistical correlation with precipitation in the study area (Hereford and others, 2002; McCabe and others, 2004; fig. 9*C*). Periods of positive PDO correspond with periods of greater-than-average annual precipitation, and periods of negative PDO correlate with periods of less-than-average annual precipitation. In contrast, periods of positive AMO, such as 1995–2004, are coincident with drought conditions in the study area (McCabe and others, 2004). Periods of negative AMO, such as 1915–25, are coincident with increased precipitation.

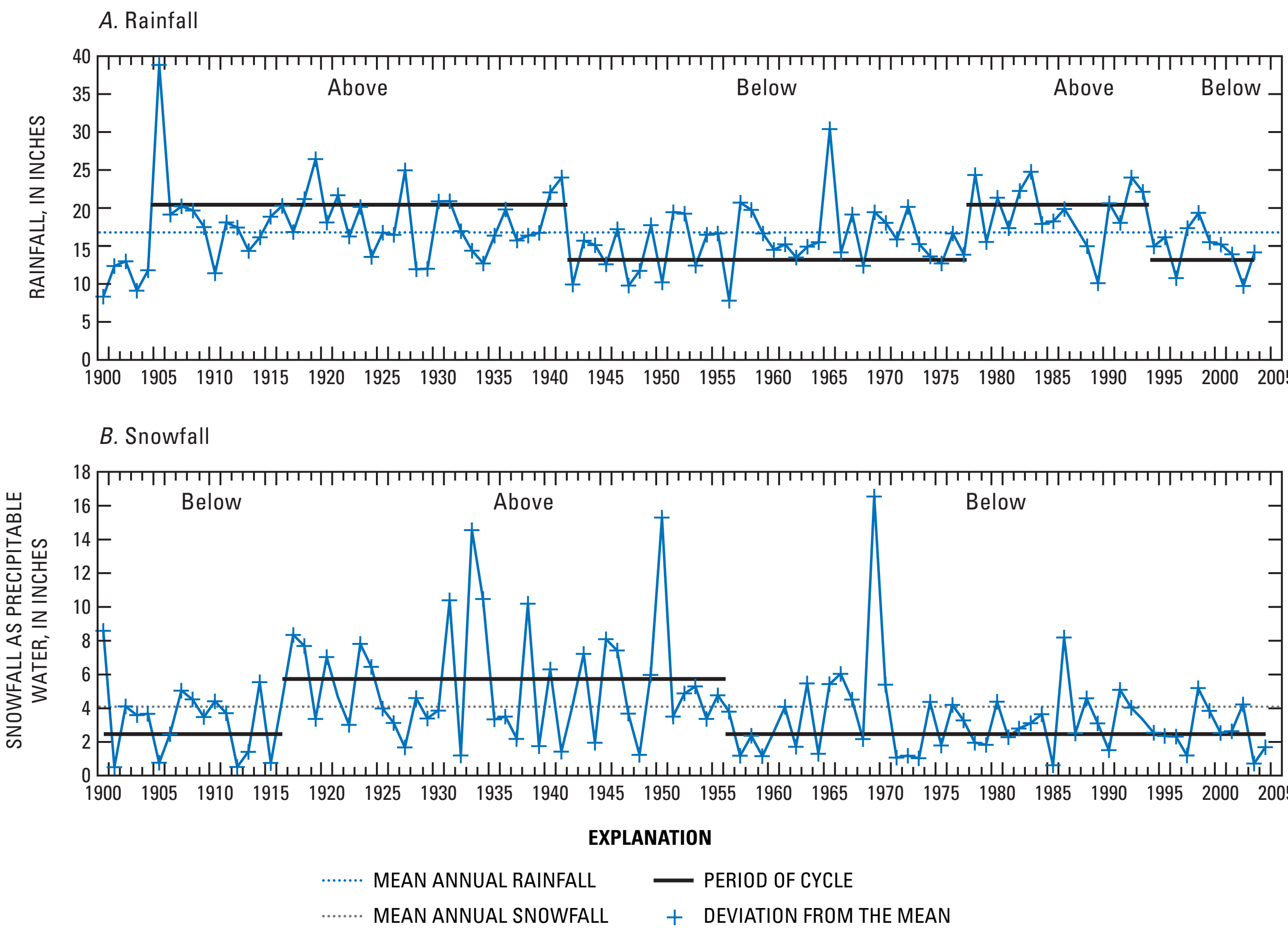


Figure 8. Comparison of annual deviations for rainfall at selected gages (see figure 5*B*) and snowfall from selected gages (see figure 5*C*) in the upper and middle Verde River watersheds with climate cycles. *A*, Rainfall; *B*, Snowfall.

Table 1. Rainfall in the upper and middle Verde River watersheds, central Arizona

Water-budget region	Rainfall (acre-feet per year) Average (1961–1990)	Rainfall (acre-feet per year) Average (1971–2000)	Rainfall (acre-feet per year) 1992	Rainfall (acre-feet per year) 2002	Rainfall (acre-feet per year) 2003
Upper Verde River watershed					
Big Chino subbasin	1,600,000	1,550,000	2,000,000	743,000	1,370,000
Little Chino subbasin	287,000	286,000	347,000	133,000	252,000
Middle Verde River watershed					
Verde Valley subbasin	3,050,000	2,850,000	3,960,000	1,490,000	2,410,000
Combined watersheds					
Combined watersheds	4,937,000	4,686,000	6,307,000	2,366,000	4,032,000

Table 2. Snowfall in the upper and middle Verde River watersheds, central Arizona

Water-budget region	Snowfall[1] (acre-feet per year) Average (1981–2002)	Snowfall (acre-feet per year) 1992	Snowfall (acre-feet per year) 2002	Snowfall (acre-feet per year) 2003
Upper Verde River watershed				
Big Chino subbasin	207,000	307,000	163,000	141,000
Little Chino subbasin	27,000	37,000	21,000	18,000
Middle Verde River watershed				
Verde Valley subbasin	461,000	597,000	285,000	248,000
Combined watersheds				
Combined watersheds	695,000	941,000	469,000	407,000

[1]Snowfall reported as precipitable water (10 inches of snowfall = 1 inch of precipitable water).

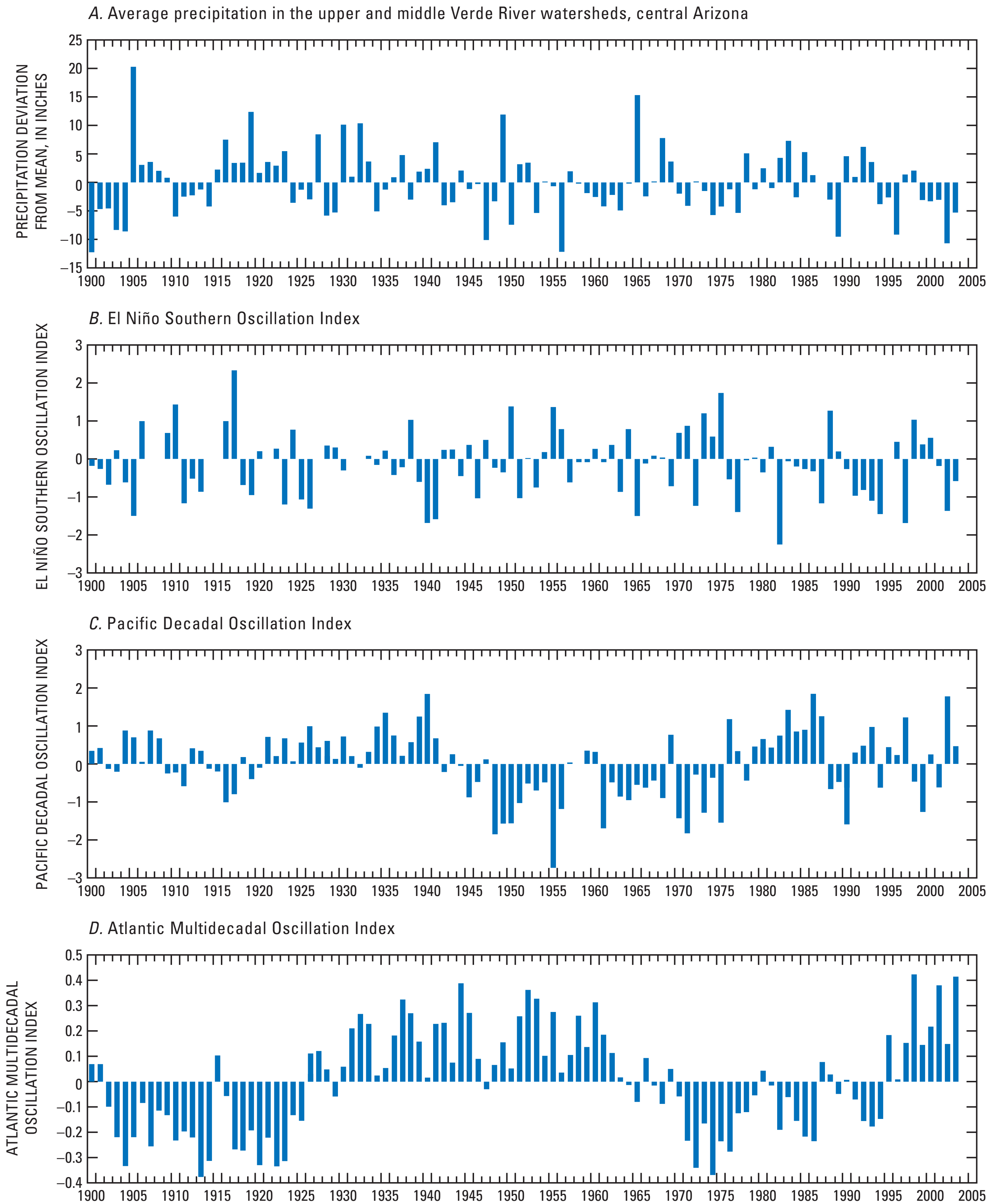


Figure 9. Comparison of annual deviations from the average for precipitation in the upper and middle Verde River watersheds with climatic cycles. *A*, Average precipitation in the upper and middle Verde River watersheds, central Arizona; *B*, El Niño Southern Oscillation Index; *C*, Pacific Decadal Oscillation Index; *D*, Atlantic Multidecadal Oscillation Index.

Surface Water

Streamflow

Surface water in the study area was assessed by using data from 21 streamflow-gaging stations. Streamflow statistics presented in this report are for the period of record ending March 31, 2004. For instance the period of record examined for Verde River near Paulden (09503700), is from the start of the record, July 17, 1963, to March 31, 2004 (appendix 3). Annual statistics are based on periods of record ending December 31, 2003. Several statistical techniques are commonly used to summarize streamflow data. In this report average annual streamflow is reported for the period of record. In addition, exceedance probabilities of different streamflows are reported. Exceedance probabilities are an estimate of the percentage of time that a specified streamflow was equaled or exceeded. One of the most commonly used percentiles is the 50th percentile, or median streamflow—the streamflow that is equaled or exceeded 50 percent of the time. The 10th, 50th, and 90th percentile streamflows for each gaging station are presented in this report.

The major streams in the upper Verde River watershed are the Verde River (perennial below the mouth of Granite Creek), Big Chino Wash, Little Chino Wash, Williamson Valley Wash, Walnut Creek, Granite Creek, Pine Creek, and Partridge Creek (pl. 1). In the middle Verde River watershed, the major streams are the Verde River, Hell Canyon, Sycamore Creek, Oak Creek, Bitter Creek, Dry Beaver Creek, Wet Beaver Creek, and West Clear Creek (pl. 1).

The Verde River and its tributaries provide habitat for several threatened or endangered species, such as the spikedace minnow and the Gila chub. The importance of the Verde River and its tributaries as a natural resource has prompted the USGS, in cooperation with other agencies, to monitor streamflow in the Verde River at four gaging stations: Verde River near Paulden (09503700), Verde River near Clarkdale (09504000), Verde River at Camp Verde (09505000), and Verde River near Camp Verde (09506000; fig. 3 and pl. 1). In addition to the gaging stations on the main stem of the Verde River, gaging stations have been operated on tributaries of the Verde River (pl. 1 and appendix 3).

Streamflow-Gaging Stations on the Verde River

The **Verde River near Paulden** streamflow-gaging station (09503700) is about 8 mi downstream from the mouth of Granite Creek (pl. 1) records flow from a drainage area of 2,507 mi^2. Streamflow upstream from the mouth is ephemeral to intermittent. Streamflow in the perennial reach is maintained by ground-water discharge. Average annual streamflow at the gaging station was 42.4 ft^3/s (30,700 acre-ft/yr) from 1964 through 2003, which equates to 12.2 acre-ft/yr per square mile of drainage area (table 3).

The **Verde River near Clarkdale** streamflow-gaging station (09504000) is about 31 mi downstream from the Verde River near Paulden streamflow-gaging station (09503700) and about 1 mi downstream from the mouth of Sycamore Creek (pl. 1). Flow in the reach between Verde River near Paulden and this gaging station increases owing to ground-water discharge and a larger drainage area (3,503 mi^2). Average annual streamflow was 169 ft^3/s (122,100 acre-ft/yr), which equates to 34.9 acre-ft/yr per square mile of drainage area (table 3).

Table 3. Average annual streamflow and selected annual exceedance-level streamflows at gaging stations on the main stem of the Verde River in the upper and middle Verde River watersheds for respective periods of record

[mi^2, square miles; ft^3/s, cubic feet per second; (acre-ft/yr)/mi^2, acre-feet per year per square mile. See appendix 3 for periods of record]

Streamflow-gaging station	Drainage area (mi^2)	Average annual streamflow (ft^3/s)	Average annual streamflow (acre-ft/yr)	Average annual streamflow per drainage area [(acre-ft/yr)/ mi^2]	90th percentile exceedance streamflow (ft^3/s)	50th percentile exceedance streamflow (ft^3/s)	10th percentile exceedance streamflow (ft^3/s)
Verde River near Paulden (09503700)	2,507	42.4	30,700	12.2	22	25	29
Verde River near Clarkdale (9504000)	3,503	169	122,100	34.9	72	82	183
Verde River near Camp Verde (09506000)	5,009	408	295,400	59	76	182	651

The **Verde River near Camp Verde** streamflow-gaging station (09506000) is about 50 mi downstream from the Verde River near Clarkdale streamflow-gaging station and about 6 mi downstream from the mouth of West Clear Creek (fig. 3 and pl. 1). The river drains an area of about 5,009 mi^2 at this gaging station, and the gaging station represents the most downstream point in the study area. Water flowing past this gaging station leaves the middle Verde River watershed. Streamflow in the reach generally increases owing to ground-water discharge and inflows from several perennial tributaries. It can also be increased by capture of overland flow. Several agricultural diversions along this reach result in decreased streamflow during summer. For the period of record 1935–45 and 1988–2003, average annual streamflow at the gaging station was 408 ft^3/s (295,400 acre-ft/year), which equates to 59 acre-ft/yr per square mile of drainage area (table 3).

The annual average streamflow for 1993, which was a wetter-than-average year associated with a strong El Niño, was the largest on record for all three Verde River gaging stations. The smallest annual average streamflow for the Verde River gaging stations occurred in 2002, which was a year of little precipitation. Average monthly streamflow for the gaging stations is greatest for February and March, as a result of winter precipitation and snowmelt, and is least for May, June, and July (fig. 10). Average streamflows for September and October also are large owing to runoff from monsoon storms

The range in streamflow magnitude increases in the downstream direction. For example, at Verde River near Paulden, streamflow exceeded 22 ft^3/s 90 percent of the time and 29 ft^3/s 10 percent of the time; however, at Verde River near Camp Verde, streamflow exceeded 76 ft^3/s 90 percent of the time and 651 ft^3/s 10 percent of the time during the period of record (table 3).

Streamflow-Gaging Stations on Verde River Tributaries

Tributaries in the upper Verde River watershed.— Streams in the upper Verde River watershed that flow into the Verde River or recharge the ground-water system upstream from the Verde River near Paulden streamflow-gaging station include Big Chino Wash and Little Chino Wash, which are ephemeral; Walnut Creek, Williamson Valley Wash, and Granite Creek, which all have perennial flow in their upper reaches and are ephemeral in downstream reaches; and Pine Creek and Partridge Creek, which are intermittent. Gaging stations have been operated on Williamson Valley Wash near Paulden (09502800), Walnut Creek near Ash Fork (09502750), Granite Creek at Prescott (09502960), Granite Creek near Prescott (09503000), Granite Creek below Watson Lake near Prescott (09503300), and Willow Creek near Prescott (09503500; fig. 3, pl. 1, appendix 3).

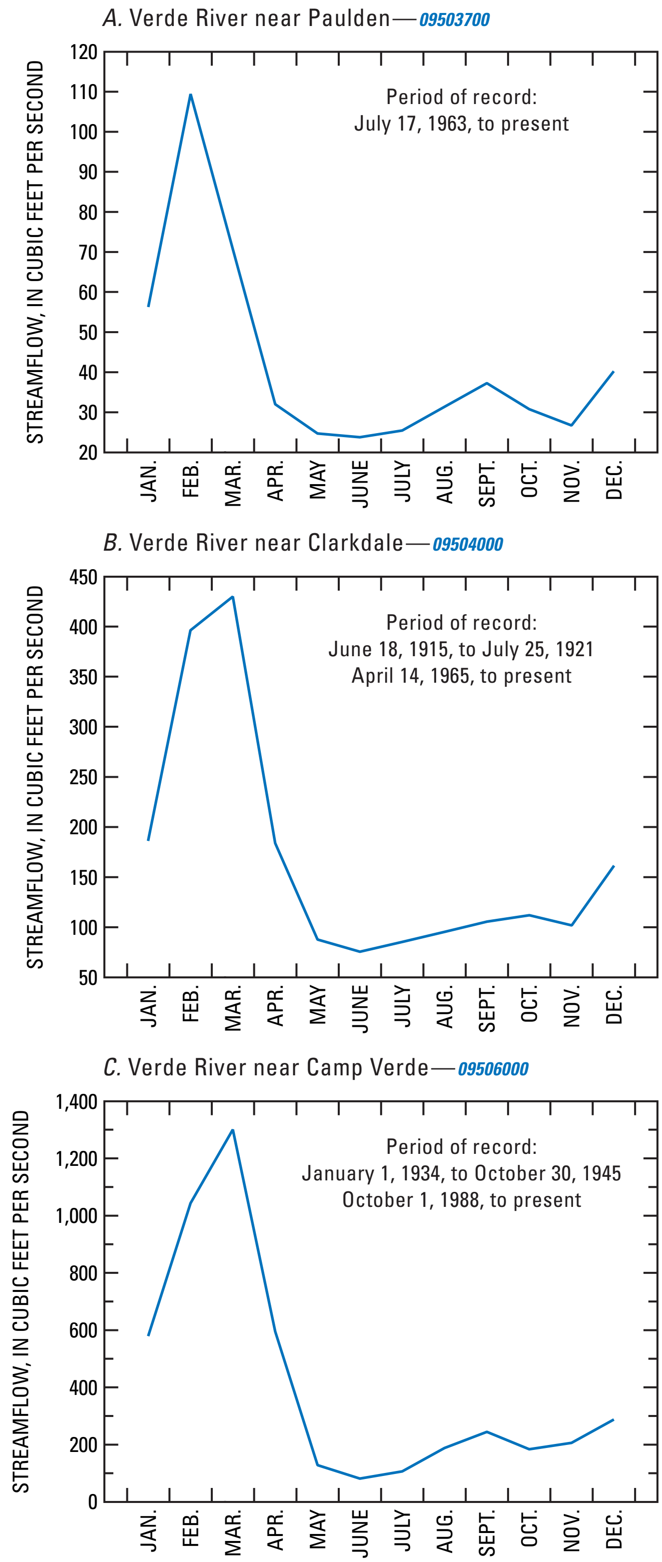


Figure 10. Average monthly streamflow at selected streamflow-gaging stations on the main stem of the Verde River in the upper and middle Verde River watersheds for the periods of record. *A*, Verde River near Paulden; *B*, Verde River near Clarkdale; *C*, Verde River near Camp Verde. Analysis period from beginning of record for each station until March 31, 2004.

Williamson Valley Wash near Paulden (09502800) and **Walnut Creek near Ash Fork (09502750)** are on the southwest side of Big Chino Valley and are the largest tributaries in the Big Chino subbasin. The gaging station on Williamson Valley Wash was in operation from March 1965 through September 1985, and was reactivated in August 2001 (fig. 3 and pl. 1). Average annual streamflow at the Williamson Valley Wash gaging station is about 14.2 ft^3/s, or 10,300 acre-ft/yr, for the period of record; however, streamflow is intermittent during the summer (fig. 11). The Bureau of Reclamation operated a streamflow-gaging station in Walnut Creek from September 1991 until September 1992 (Ostenaa and others, 1993). Average streamflow of Walnut Creek for approximately 1 year of record was about 1.9 ft^3/s, or about 1,400 acre-ft/yr (table 4).

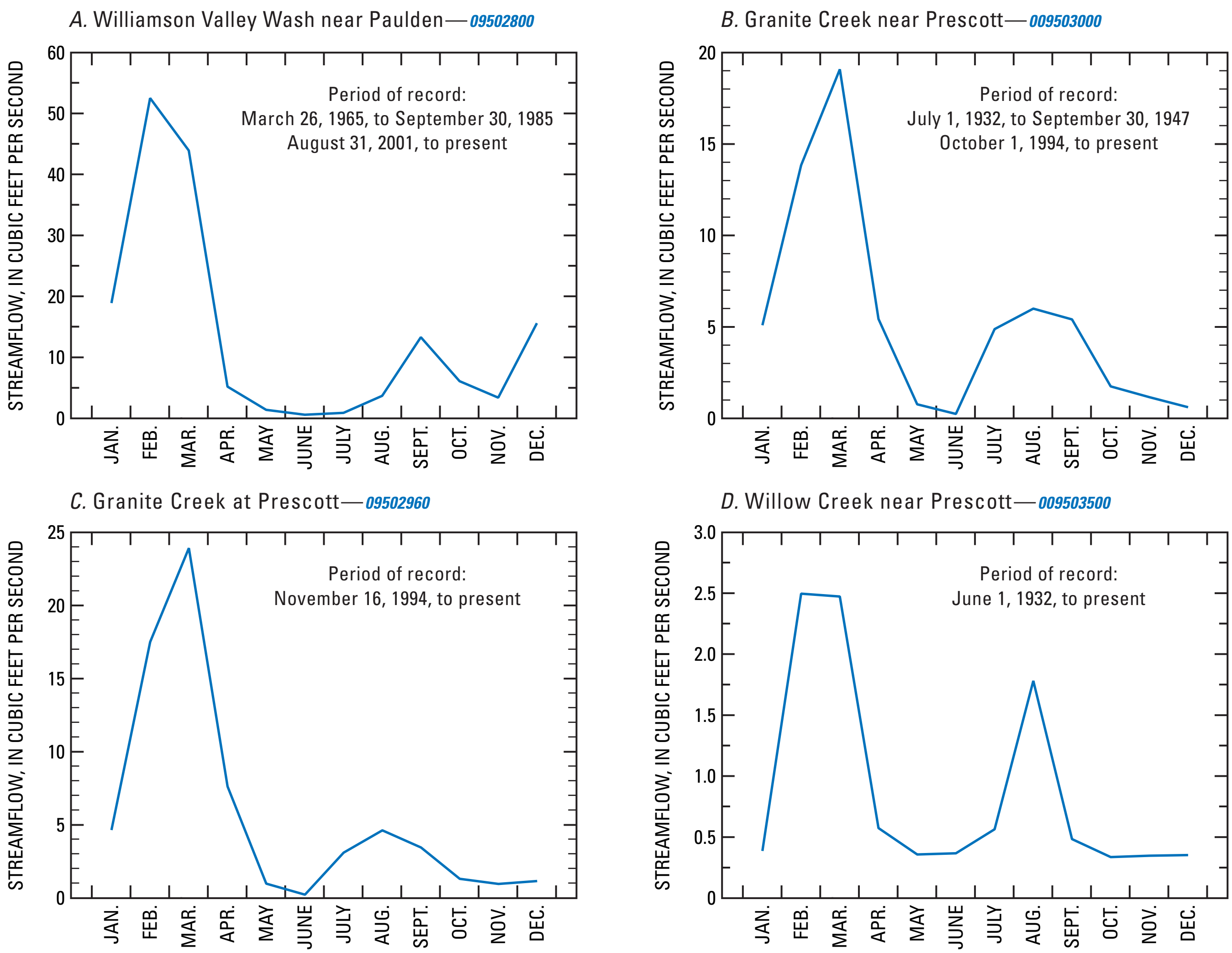


Figure 11. Average monthly streamflow at selected streamflow-gaging stations on tributaries of the Verde River in the upper Verde River watershed for the periods of record. *A*, Williamson Valley Wash near Paulden; *B*, Granite Creek near Prescott; *C*, Granite Creek at Prescott; *D*, Willow Creek near Prescott. Analysis period from beginning of record for each station until March 31, 2004, or until the end of record.

Table 4. Average annual streamflow and selected annual exceedance-level streamflows at gaging stations on tributaries of the Verde River in the upper Verde River watershed for respective periods of record

[mi², square miles; ft³/s, cubic feet per second; acre-ft/yr, acre feet per year; NC, not calculated]

Streamflow-gaging station	Drainage area (mi²)	Average annual streamflow (ft³/s)	Average annual streamflow (acre-ft/yr)	Average annual streamflow per drainage area [(acre-ft/yr)/mi²]	90th percentile exceedance streamflow (ft³/s)	50th percentile exceedance streamflow (ft³/s)	10th percentile exceedance streamflow (ft³/s)
Williamson Valley Wash (09502800)	255	14.2	10,300	40.3	0.13	1.7	6.5
Walnut Creek (09502750)	36	1.9	1,400	38.9	NC	NC	NC
Granite Creek at Prescott (09502960)	30	5.4	3,900	130	[1]0	.19	8.4
Granite Creek near Prescott (09503000)	36.3	5.8	4,200	115.7	[1]0	.22	10
Granite Creek below Watson Lake (0950330)	NC	.61	442	NC	[1]0	.04	.52
Willow Creek (09503500)	25.2	.9	650	25.8	NC	NC	NC

[1] Ephemeral streamflow; streamflow is present at least 90 percent of the year at these stations.

Three streamflow-gaging stations are operated in the uppermost part of Granite Creek, which is in the Little Chino Valley (pl. 1). The uppermost gaging station **(Granite Creek at Prescott, 09502960)** records flow from a drainage area of 30 mi². Flow occurred at this site about 90 percent of the time from November 1994 to 2003; periods of no flow primarily occur in the summer (fig. 11). Average annual streamflow is about 5.4 ft³/s, or about 3,900 acre-ft/yr. About 2 mi downstream from this gaging station is streamflow-gaging station **Granite Creek near Prescott (09503000)**, which records flow from a area of 36.3 mi². Flow occurred at this site about 69 percent of the time from July 1932 to September 1947 and October 1994 to 2003; periods of no flow have occurred primarily in June, July, and October. Average annual streamflow is about 5.8 ft³/s, or 4,200 acre-ft/yr. Downstream from this gaging station is the streamflow-gaging station **Granite Creek below Watson Lake (09503300)**. Streamflow upstream from gaging station 09503300 is regulated by the operation of diversions, Upper and Lower Goldwater Lakes, and Watson Lake (fig. 3). Average annual streamflow was about 0.6 ft³/s for October 1999 to 2003.

The **Willow Creek near Prescott** streamflow-gaging station (09503500) was near Prescott (pl. 1) and recorded flow from a drainage area of 25.2 mi². The gaging station was operated from June 1, 1932, to March 1937. During the approximately 5 years of record, average annual streamflow was about 0.9 ft³/s, or 650 acre-ft/yr.

Similar to the streamflow of the Verde River, average monthly streamflow in tributaries of the upper Verde River watershed is greatest in the winter and spring and least in the summer and fall (fig. 11). A secondary peak in average monthly streamflow caused by surface runoff during the monsoon season occurs at four tributary gaging stations in August or September. The peak occurs in August at gaging stations on Granite Creek and Willow Creek in the Little Chino subbasin and in September at the Williamson Valley Wash gaging station in the Big Chino subbasin.

Surface runoff from the Little Chino subbasin, Williamson Valley, and the upper reaches of Big Chino Wash reaches the Verde River infrequently. Surface runoff measured at the Verde River near Paulden gaging station is predominantly from the lower reaches of Granite Creek and from Big Chino Wash, and other tributaries. Occasionally, large-magnitude flows travel the full distance of the watershed.

Tributaries in the Middle Verde Watershed.— Major streams in the middle Verde River watershed that contribute streamflow to the Verde River or recharge the ground-water system are Sycamore Creek, Bitter Creek, Oak Creek, Dry Beaver Creek, Wet Beaver Creek, and West Clear Creek.

Sycamore Creek is 4.2 mi long from its headwaters near Parsons Spring (fig. 3) to its mouth at the Verde River. Perennial flow in the creek is sustained by several springs, including Parsons Spring, Summer Spring, and an unnamed spring. There are no gaging stations on Sycamore Creek; however, Owen-Joyce and Bell (1983) reported that base flow near the mouth ranged from 7.44 to 9.42 ft^3/s and averaged 8.5 ft^3/s for seven measurements made during 1956–77.

Bitter Creek drains part of the Black Hills near the town of Jerome (fig. 3). Discharge from several springs, such as Slaughterhouse and Hogpen Springs, produces intermittent flow in the creek. Drainage from the United Verde Mine also produced flow in the creek until the mine was closed in 1953 (Owen-Joyce and Bell, 1983). According to Owen-Joyce and Bell (1983), streamflow measured by the Arizona Department of Water Resources (ADWR) at the mouth of Bitter Creek in 1980 ranged from 1.4 to 4.7 ft^3/s (1,000 to 3,400 acre-ft/yr).

Oak Creek begins at Sterling Springs near the confluence of Sterling Canyon and Pumphouse Wash (pl. 1). The **Oak Creek near Sedona** streamflow-gaging station (09504420) is in the upper part of Oak Creek and records flow from a drainage area of 233 mi^2. It is about 16 mi downstream from the beginning of perennial flow in the creek, and its period of record for this study is October 1981 to March 2004 (fig. 12). **Oak Creek near Cornville (09504500)** is in the lower part of the creek and records flow from a drainage area of 355 mi^2. It is about 17 mi downstream from the Oak Creek near Sedona gaging station and about 17 mi upstream from the mouth of the creek. Its period of record for this study is July 1940 to March 2004 (fig. 12). There are several diversions upstream from the gaging station.

Average annual streamflow for Oak Creek near Sedona is about 81 ft^3/s (58,700 acre-ft/yr; table 5). Streamflow at the gaging station peaks in March owing to winter snowmelt and is at a minimum in May, June, and July (fig. 12). Average annual streamflow is about 85 ft^3/s (61,600 acre-ft/yr; table 5) at Oak Creek near Cornville. Seasonal streamflow patterns at this gaging station are similar to those at Oak Creek near Sedona (fig. 12 and pl. 1).

Wet Beaver Creek and Dry Beaver Creek join to form Beaver Creek about 9 mi upstream from the Verde River (pl. 1). The gaging station **Wet Beaver Creek near Rimrock (09505200)** is about 11 mi upstream from the confluence with Dry Beaver Creek. The drainage area for the gaging station is 111 mi^2. Perennial streamflow in Wet Beaver Creek begins at springs about 7 mi upstream from the gaging station. Average annual streamflow was about 31 ft^3/s (22,500 acre-ft/yr) for the period of record (table 5).

The streamflow-gaging station **Dry Beaver Creek near Rimrock (09505350)** is 14 mi upstream from the confluence of the creek with Wet Beaver Creek (pl. 1) and records flow from a drainage area of 142 mi^2. Dry Beaver Creek is ephemeral and flows primarily in response to precipitation and snowmelt. Average annual streamflow was 42.6 ft^3/s (30,900 acre-ft/yr) for October 1960 to 2003 (table 5). About 31 percent of this period had measurable streamflow.

The streamflow-gaging station **West Clear Creek near Camp Verde (09505800)** is 11 mi upstream from the mouth of the creek at the Verde River and 7 mi downstream from where perennial flow begins in the creek (pl. 1). The drainage area upstream from the gaging station is 241 mi^2. Average annual streamflow was 62.4 ft^3/s (45,200 acre-ft/yr) for December 1964 to 2003).

Average monthly streamflow in tributaries of the Verde River in the middle Verde River watershed peaks in March; peaks in average monthly flows attributed to the monsoon are difficult to discern on the hydrographs. Streamflow increases gradually from June through about November and decreases significantly in December. The absence of peak streamflow during the monsoon season, as compared to streamflow patterns in the upper Verde River watershed, is attributed to differences in the hydrologic systems upstream from the gaging stations. Streamflows in the middle Verde River watershed have a greater base-flow component throughout the year than flows in the upper Verde River watershed; therefore, total streamflow at gaging stations in the middle watershed generally is not greatly affected by surface runoff during the monsoon season. Additionally, localized storms in the upper watershed have a greater effect on runoff than localized storms in the middle watershed, because drainage areas within the upper watershed are smaller than those in the middle watershed. Furthermore, travel times for surface runoff to reach gaging stations are longer in the middle watershed than in the upper watershed, which provides more time for infiltration and evaporation. Finally, the absence of the monsoon peak is partially due to the generally higher hydraulic conductivity of exposed geologic units on the Coconino Plateau within the middle watershed compared to the conductivity of exposed geologic units in the Bradshaw Mountains in the upper watershed. Higher hydraulic conductivity enables greater infiltration of precipitation, which results in less surface runoff.

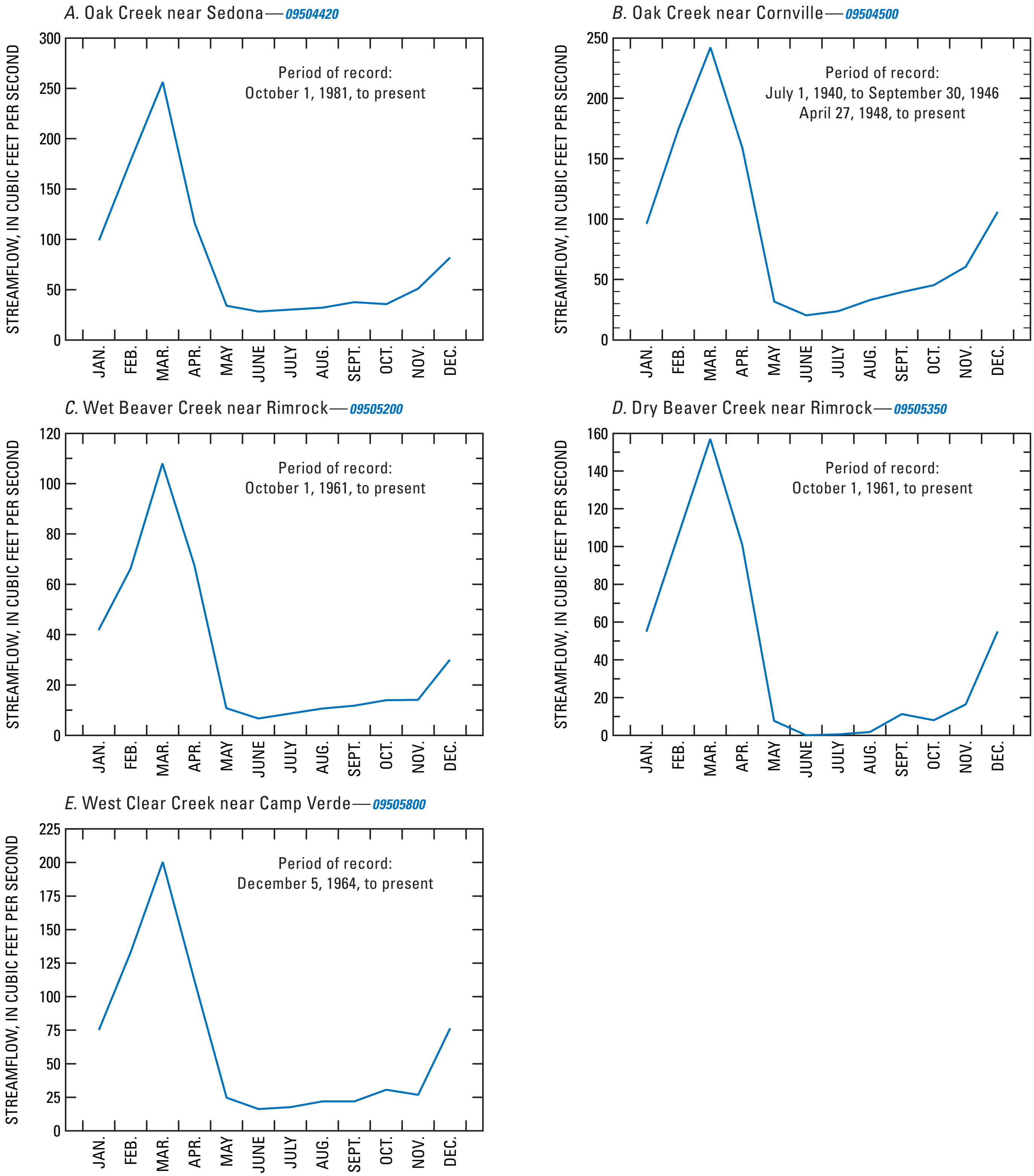


Figure 12. Average monthly streamflow at selected streamflow-gaging stations on tributaries of the Verde River in the middle Verde River watershed for the periods of record. *A*, Oak Creek near Sedona; *B*, Oak Creek near Cornville; *C*, Wet Beaver Creek near Rimrock; *D*, Dry Beaver Creek near Rimrock; *E*, West Clear Creek near Camp Verde. Analysis period from beginning of record for each station until March 31, 2004, or until the end of record.

Table 5. Average annual streamflow and selected annual exceedance-level streamflows at gaging stations on tributaries of the Verde River in the middle Verde River watershed for respective periods of record

[mi^2, square miles; ft^3/s, cubic feet per second; acre-ft, acre-feet; (acre-ft/yr)/mi^2, acre-feet per year per square mile. Note: 1 ft^3/s = 724.46 acre-feet per year]

Streamflow-gaging station	Drainage area (mi^2)	Average annual streamflow (ft^3/s)	Average annual streamflow (acre-ft/yr)	Average annual streamflow per drainage area [(acre-ft/yr)/mi^2]	90th percentile exceedance streamflow (ft^3/s)	50th percentile exceedance streamflow (ft^3/s)	10th percentile exceedance streamflow (ft^3/s)
Oak Creek near Sedona (09504420)	233	80.9	58,600	252	27	32	125
Oak Creek near Cornville (09504500)	355	85.1	61,600	174	18	32	134
Wet Beaver Creek (09505200)	111	31.3	22,700	205	6.3	7.3	53
Dry Beaver Creek (09505350)	142	42.6	30,900	218	0	0	90
West Clear Creek (09505800)	241	62.4	45,200	187	14	18	94

Base Flow

Perennial streamflow has two components—surface runoff and base flow. Surface runoff is derived from precipitation and snowmelt. Base flow is maintained by ground-water discharge to the river. Spatial and temporal trends in base flow are functions of recharge, evapotranspiration (ET), ground-water withdrawals, and the characteristics of the regional aquifer, such as ground-water flow direction.

For this study an automated base-flow separation technique was used to separate the base-flow component of streamflow from the surface-runoff component (tables 6 and 7). The method was automated by using the program HYSEP (Sloto and Crouse, 1996). The program uses one of the three following methods: fixed interval, sliding interval, or local minimum. The fixed-interval method was used in this study. Conceptually, this method uses an algorithm to draw the connecting lines between the low points of the hydrograph. The time interval used is proportional to the drainage area (Linsley and others, 1982) and can range from 3 to 11 days (Pettyjohn and Henning, 1979). The fixed-interval method assigns the smallest streamflow in each interval to all days in that interval starting with the first day of the period of record.

Selected streamflow data used in the base-flow separation analyses included data from stations on perennial reaches of the Verde River and its tributaries that are minimally affected by upstream diversions (figs. 13–15). Base-flow separation was done for average annual and average monthly values. Most of the base-flow separations use winter base-flow data because these are the least affected by diversions and ET.

Average annual base flow for the period of record (table 6) was derived by summing the average monthly values for the period of record (fig. 14) and dividing by the number of months used in the summation. In most years, all months of the years were used in the derivation of average annual base flow. For unusually wet years, such as 1973 and 1993, however, the automated program was unable to differentiate base flow from sustained high flows resulting from surface runoff or bank storage. Therefore, visual inspection of the analytical results was used to identify months in which the monthly average streamflow was at least 25 percent greater than the average base-flow values, and these monthly values were not used in the calculation. Typically, monthly values not used in the calculation were for late winter and early spring months when direct runoff was greatest and was sustained for a time period greater than the interval used in HYSEP.

Similar to the techniques used to summarize streamflow data, there are several statistical methods available for summarizing base-flow data. In this report, average annual base flow and winter base flow are reported for the periods of record. Cumulative departures from the average base flow are used to identify long-term trends in the data and describe the cumulative surplus or deficit of base flow. Cumulative departure is derived by adding successive monthly departures from the average annual base flow. Departure curves for multiple gaging stations were compared with one another after they were normalized by dividing the departures by the average annual base flow.

Table 6. Annual streamflow at selected gaging stations in the upper and middle Verde River watersheds for the period of record and for selected years

Streamflow-gaging station and period of record	Period of record: Average annual flow (acre-feet per year)			1992: Annual flow (acre-feet per year)			2002: Annual flow (acre-feet per year)			2003: Annual flow (acre-feet per year)		
	Total streamflow	Base flow component of total streamflow	Runoff component of total streamflow	Total streamflow	Base flow component of total streamflow	Runoff component of total streamflow	Total streamflow	Base flow component of total streamflow	Runoff component of total streamflow	Total streamflow	Base flow component of total streamflow	Runoff component of total streamflow
Verde River near Paulden (09503700) July 1963 to Mar. 2004	30,700	17,700	13,000	23,200	17,600	5,600	16,500	15,600	900	20,100	15,800	4,300
Verde River near Clarkdale (09504000) Apr. 1965 to Mar. 2004	122,100	57,200	64,900	139,700	58,200	81,500	54,600	52,100	2,500	68,300	51,700	16,600
Verde River near Camp Verde (09506000) Apr. 1934 to Sept. 1945, and Oct. 1988 to Mar. 2004[1]	295,400	138,800	156,600	394,200	160,800	233,500	100,300	83,000	17,300	199,500	118,800	80,600

[1]Long-term average annual flow at Verde River near Camp Verde is about 295,400 acre-feet per year; however, large-scale diversions exist upstream from the gaging station. A fraction of the runoff and base-flow components are diverted through irrigation canals upstream from the gaging station and is not accounted for in this table.

Table 7. Annual streamflow at selected gaging stations along tributaries in the upper and middle Verde River watersheds for the period of record and for selected years

[NC, not calculated]

Streamflow-gaging station and period of record	Period of record: Average annual flow (acre-feet per year)			1992: Annual flow (acre-feet per year)			2002: Annual flow (acre-feet per year)			2003: Annual flow (acre-feet per year)		
	Streamflow	Base flow	Runoff	Streamflow	Base flow	Runoff	Streamflow	Base flow	Runoff	Streamflow	Base flow	Runoff
Williamson Valley Wash[1] (09502800) Mar. 1965 to Sept. 1985, and Aug. 2001 to Mar. 2004	10,300	NC	NC	NC	NC	NC	1,500	NC	NC	2,400	NC	NC
Granite Creek at Prescott[1] (09502960) Nov. 1994 to Mar. 2004	3,900	400	3,500	NC	NC	NC	580	540	40	4,800	130	4,670
Granite Creek near Prescott[1] (09503000) July 1932 to Sept. 1947, and Oct. 1994 to Mar. 2004	4,200	800	3,400	NC	NC	NC	1,200	170	1,030	6,300	1,100	5,200
Del Rio Springs[1] (09504420) Jan. 1997 to Mar. 2004	1,300	1,300	30	NC	NC	NC	1,321	1,306	15	1,215	1,186	29
Oak Creek near Sedona (09504420) Oct. 1981 to Mar. 2004	58,700	23,000	35,700	84,000	22,000	62,000	22,600	21,700	900	48,900	21,600	27,300
Oak Creek near Cornville[1] (09504500) July 1940 to Sept. 1946, and Apr. 1948 to Mar. 2004	61,600	30,000	31,300	88,500	30,000	58,500	25,000	23,800	1,200	57,900	28,400	29,500
Wet Beaver Creek (09505200) Oct. 1961 to Sept. 1982, and Oct. 1991 to Mar. 2004	22,500	5,400	17,100	31,400	8,700	22,700	5,900	5,300	600	18,100	5,800	12,300
Dry Beaver Creek (09505350) Oct. 1960 to Mar. 2004	30,900	NC	NC	NC	NC	NC	580	NC	NC	23,300	NC	NC
West Clear Creek (09505800) Dec. 1964 to Mar. 2004	45,200	13,000	32,200	60,900	17,400	43,500	12,100	10,900	1,200	29,600	13,500	16,100

[1]Winter base flow only. Base-flow values shown represent winter values when diversions and evapotranspiration are at a minimum.

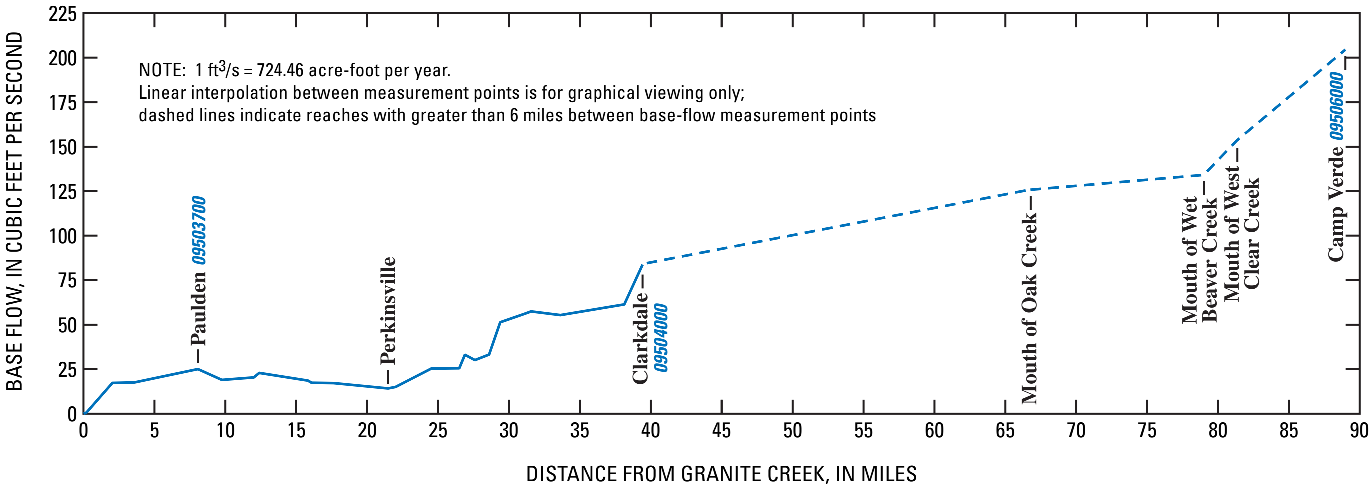


Figure 13. Base flow in the Verde River from the mouth of Granite Creek to the gaging station near Camp Verde (09506000).

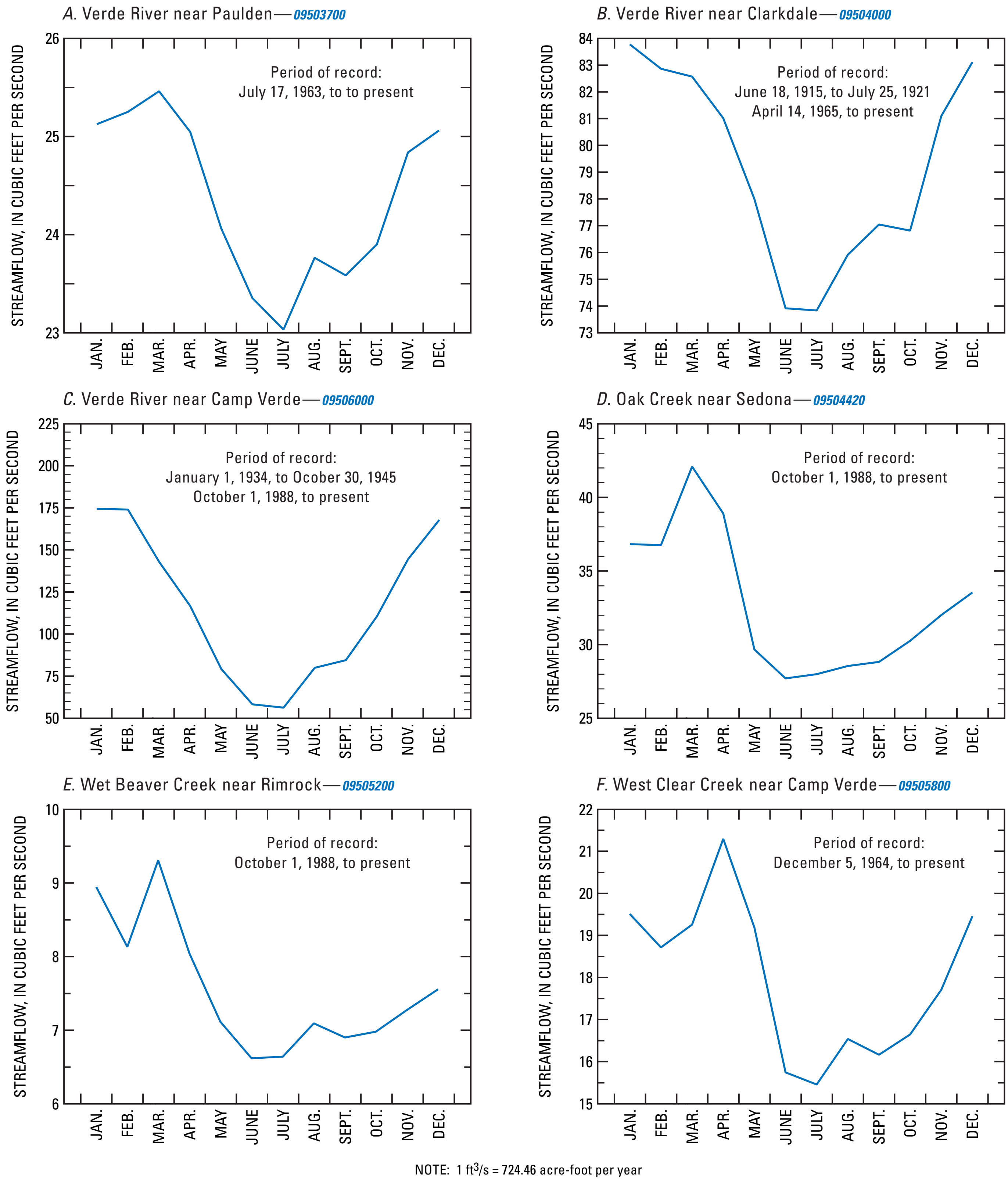


Figure 14. Average monthly base flow at selected gaging stations. *A*, Verde River near Paulden; *B*, Verde River near Clarkdale; *C*, Verde River near Camp Verde; *D*, Oak Creek near Sedona; *E*, Wet Beaver Creek near Rimrock; *F*, West Clear Creek near Camp Verde. Analysis period is from beginning of record for each station until March 31, 2004, or until the end of the record.

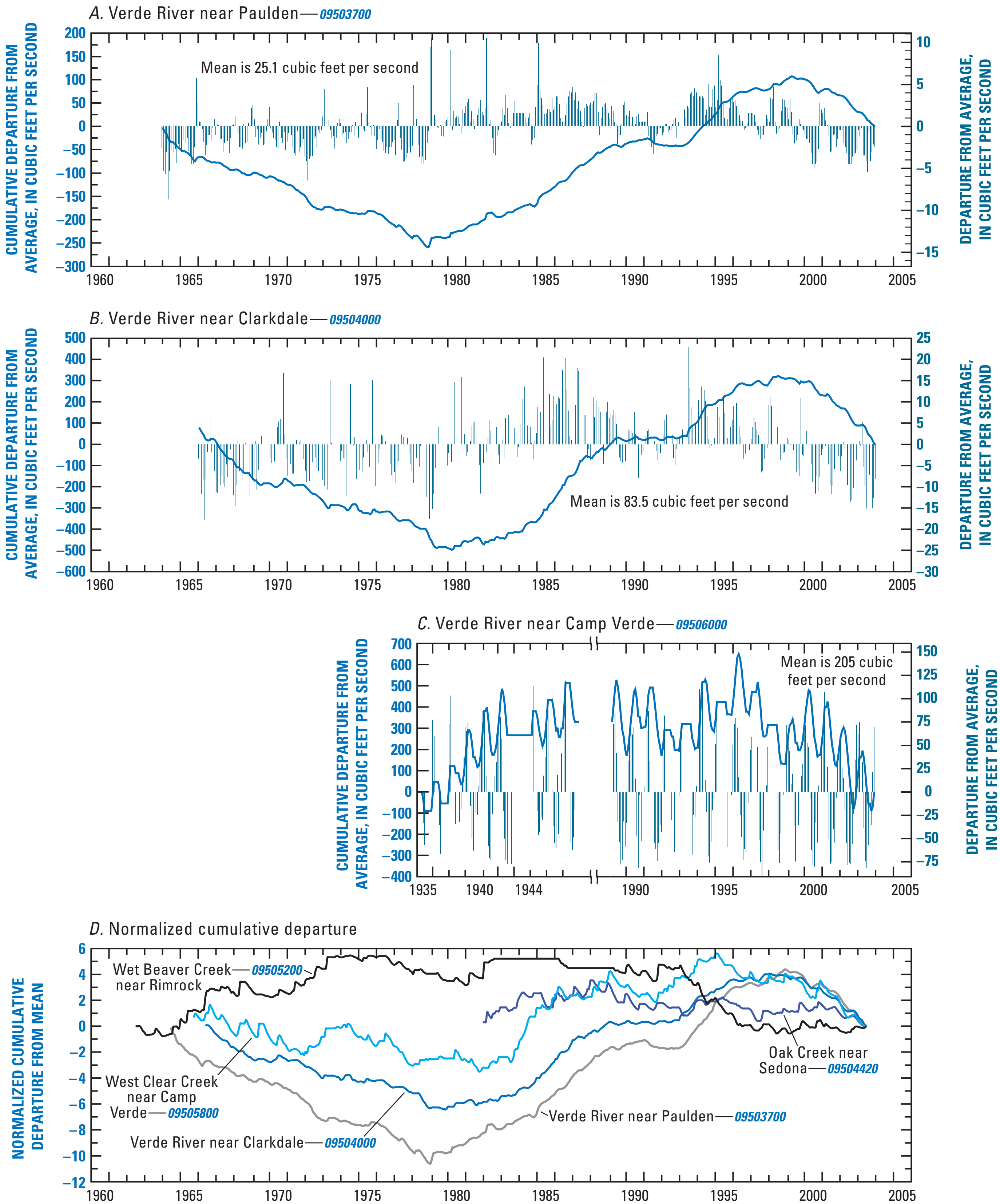


Figure 15. Cumulative departure from average winter base flow. *A*, Verde River near Paulden; *B*, Verde River near Clarkdale; *C*, Verde River near Camp Verde; *D*, Normalized cumulative departure for selected gaging stations.

Base-flow data are used to quantify the ground-water component of streamflow, to determine hydrologic budgets, and to aid in estimating ground-water recharge rates. Increases in base flow in a downstream direction result from additional inputs of ground water to the stream. Decreases in base flow result from evaporation, transpiration, infiltration losses, and diversions. Under steady-state conditions (assuming no change in aquifer storage), base flow, combined with losses due to ET and ground-water outflow, is equivalent to recharge and ground-water inflow. Change in base flow over time at a specific location is an indication that the magnitude of one or more water-budget components has changed. For instance, increased base flow can result from increased recharge, decreased ground-water withdrawals, and (or) decreased ET. Conversely, decreased base flow can result from decreased recharge, increased ground-water withdrawals, and (or) increased ET.

Discrete measurements indicate that base flow in the Verde River generally increases from about 1 ft^3/s (720 acre-ft/yr) at the mouth of Granite Creek to about 25 ft^3/s (18,100 acre-ft/yr) at Verde River near Paulden (09503700; fig. 13). Base flow between Granite Creek and the gaging station is maintained by ground-water discharge to the river from underlying Paleozoic sedimentary units. Base flow increases sharply downstream from the gaging station in the Mormon Pocket area (fig. 3) as additional ground water is discharged to the river from the Paleozoic units. Base flow then gradually increases and is about 79 ft^3/s (57,200 acre-ft/yr) at the Verde River near Clarkdale gaging station (09504000). Downstream from this station, base flow continues to increase as water enters the river from springs and from tributaries, such as Sycamore, Oak, Wet Beaver, and West Clear Creeks. Average winter base flow leaving the watershed is about 205 ft^3/s per year (148,500 acre-ft/yr), as measured at Verde River near Camp Verde (09506000).

Streamflow-Gaging Stations on the Verde River

Verde River near Paulden (09503700).—The river at the gaging station is in a well defined channel that is straight for several hundred feet both upstream and downstream from the station. Channel sediments consist of a veneer of stream alluvium overlying Tertiary fanglomerate and conglomerate. The south bank of the river is steeply dipping bedrock, whereas the north bank is a fairly flat, 450-ft-wide flood plain of coarse stream-channel deposits covered with grass and scattered tamarisk.

Average annual base flow at the Verde River near Paulden (09503700) gaging station for 1964–2003 is 24.4 ft^3/s (17,700 acre-ft/yr). This is nearly 0.6 ft^3/s less than the average winter base flow for the period (25.1 ft^3/s, or 18,200 acre-ft/yr; figs. 14 and 15*A*, table 8, pl. 1). For this study, winter base flow for each year was calculated by averaging the monthly average base flows for December, January, and February for the period of record. Anning (2004) calculated a time-weighted average standard error of 0.36 ft^3/s for the annual low-flow value measured at this station. The annual low-flow value is an approximation of annual base flow. The method Anning (2004) used to calculate the standard error for low-flow values was primarily based on that of Moss and Gilroy (1980) and accounts for (1) uncertainty in the periodic discharge measurements used to develop stage-discharge ratings, (2) uncertainty in the shifts that are applied to the stage-discharge ratings, and (3) changes in channel geometry and roughness characteristics that occur over time. The standard error for the average base flow for the period of record, computed as the time-weighted average standard error for the annual low-flow values divided by the square root of the number of years used to compute the value, is 0.057 ft^3/s, or about 0.23 percent of the average annual base flow.

Verde River near Clarkdale (09504000).—The gaging station at Verde River near Clarkdale (fig. 14*B*) is in a well defined canyon that is bounded on each side by consolidated Paleozoic deposits that are overlain by Tertiary basalts. The channel is straight for several hundred feet both upstream and downstream from the station and consists of a veneer of stream alluvium overlying the consolidated units of the Supai Group. Owing to the small cross-sectional area of stream alluvium, the component of base flow that passes the gaging station unrecorded as subflow in the stream alluvium likely is insignificant.

Average annual base flow at the gaging station for 1966–2003 is 79 ft^3/s (57,200 acre-ft/year), which is about 5 ft^3/s less than average winter base flow (table 8 and fig. 15*B*) for the period of record. Anning (2004) calculated a standard error of 0.78 ft^3/s for the annual low-flow value at this station. On the basis of this value, the standard error for the average base flow for the period of record is 0.12 ft^3/s, or about 0.16 percent of the average annual base flow.

Verde River near Camp Verde (09506000).— The streamflow-gaging station Verde River near Camp Verde (fig. 14*C*) was operated from 1934 to 1945, and was reactivated in 1988. Owing to the numerous diversions upstream from the gaging station, base flow measured at the gaging station underrepresents the amount of ground water that discharges to the river. Consequently, the determination of long-term trends in annual base flow is difficult. Trend analysis in this report is limited to data from winter months (December, January, and February), when streamflow diversions are generally reduced and ET is at a minimum. Base flow averaged 214 ft^3/s (155,000 acre-ft/yr) during the first part of the record (1934–45) and 199 ft^3/s (140,200 acre-ft/yr) during the second part (1989–2003).

Table 8. Summary statistics of annual and winter base flow at selected gaging stations in the upper and middle Verde River watersheds, central Arizona

[mi², square miles; ft³/s, cubic feet per second; acre-ft/mi², acre-feet per square mile; ft³/s/mi, cubic feet per second per mile; NC, not calculated]

Streamflow-gaging station	Period of record analyzed[1]	Drainage area (mi²)	Average annual base flow (ft³/s)	Average winter base flow (ft³/s)	Base flow per square mile of drainage area[2] (acre-ft/mi²)	Median winter base flow (ft³/s)	Standard deviation of winter base flow (ft³/s)	Average summer base flow (ft³/s)	Summer evapotrans-piration (ft³/s/mi)
Verde River gaging stations									
Verde River near Paulden (09503700)	1964–2003	2,507	24.4	25.1	7.3	24.9	1.9	23.3	0.23
Verde River near Clarkdale (09504000)	1966–2003	3,503	79	83.5	17.3	82.6	5.8	76.6	.17
Verde River near Camp Verde (09506000)	1934–1945, 1989–2003	5,009	NC	214 199	[3]28.8	203	16	NC	NC
Tributary gaging stations									
Del Rio Springs (09502900)	1997–2003	NC	1.75	2.05	NC	2.1	.2	1.5	NC
Williamson Valley Wash (09502800)	1965–1985 and 2001–2003	255	NC	3.7	10.6	2.5	2.5	0	NC
Granite Creek at Prescott (09502960)	1994–2003	30	NC	.6	13.3	.4	.5	NC	NC
Granite Creek near Prescott (095033000)	1933–1947 and 1995–2003	36.3	NC	1.1	22.0	.9	.9	NC	NC
Oak Creek near Sedona (09504420)	1981–2003	233	31.7	36.4	113	35.7	4.2	28.7	.48
Oak Creek near Cornville (09504500)	1940–2003	355	NC	41.8	82.8	NC	NC	NC	NC
Wet Beaver Creek (09505200)	1961–1982 and 1991–2003	111	7.4	8.4	54.8	7.8	1.7	7	.2
West Clear Creek (09505800)	1964–2003	241	18.2	19.9	59.8	18.6	3.8	15.5	.15

[1]Only complete years of data were analyzed.

[2]Based on winter base-flow analysis.

[3]Based on 1989–2003 record.

There is no apparent temporal trend in base flow during the first part; however, a downward trend began in about 1994 during the second part (pl. 1).

Streamflow-Gaging Stations on Verde River Tributaries

Williamson Valley Wash near Paulden (09502800).—Flow at the Williamson Valley Wash gaging station is intermittent and occurs during winter when the water table rises to intersect with the channel and during summer as a result of surface runoff (pl. 1). Base-flow separation analysis was done only for the winter months when streamflow is dominated by ground-water discharge. Average winter base flow is 3.7 ft^3/s (2,700 acre-ft/yr) for the period of winter record (1965–84 and 2002–03); however, it was 3.9 ft^3/s (2,800 acre-ft/yr) for the first part of the record and 1.7 ft^3/s (1,200 acre-ft/yr) for the second part. Most of the summer base flow is assumed to be lost to ET.

Del Rio Springs near Chino Valley (09502900).—Del Rio Springs is near the north end of Little Chino Valley and is a major discharge area for ground water that flows beneath the Little Chino subbasin. All flow measured at the gaging station, with the exception of a few high-flow, short-duration peaks (pl. 1), is base flow. An estimated 250 acre-ft of water that discharges from the spring each year is diverted upstream from the gaging station, and an estimated 150 acre-ft/yr is transpired by riparian vegetation between the springs outlet and the gaging station. Streamflow measurements made before the gaging station was installed indicate that total streamflow decreased from about 3.9 ft^3/s (2,800 acre-ft/yr) between 1940 and 1945, to about 2.5 ft^3/s (1,800 acre-ft/yr) in 1984 (Schwalen, 1967; Corkhill and Mason, 1995).

Streamflow continued to decrease after the gaging station was installed in 1997. Annual base flow during the period of record (1997–2003) averaged 1.75 ft^3/s (1,270 acre-ft/yr) but steadily declined from about 2 ft^3/s (1,450 acre-ft/yr) in 1997 to 1.4 ft^3/s (1,000 acre-ft/yr) in 2003. Winter and summer base flows have declined at a similar rate. Winter base flow generally is 0.6 ft^3/s greater than summer base flow. This difference was similar between 1939 and 1945, when winter flows were about 4 ft^3/s and summer flows were about 3.5 ft^3/s (Schwalen, 1967). Contributions from surface runoff and base flow are not available in these historical measurements; however, measured streamflow is presumed to predominantly represent base flow on the basis of recent streamflow records. The difference between winter and summer base flow at the gaging station is likely related to increased ET during summer (June-August); however, given the proximity of pumpage in the Little Chino subbasin, ground-water withdrawals during the summer may also contribute to the reduced base flow.

Granite Creek at Prescott (09502960) and ***Granite Creek near Prescott (09503000).***—Streamflow is diverted upstream from both gaging stations on Granite Creek; therefore, only winter base-flow values are evaluated for long-term trends. Average winter base flow at the upstream gaging station (09502960) is about 0.6 ft^3/s (400 acre-ft/yr) for the period of record (1994–2003) and has no apparent temporal trend (table 8 and pl. 1). Base flow at the downstream gaging station (09503000) has averaged 1.1 ft^3/s (800 acre-ft/yr) during the period of winter record (1933–47 and 1995–2003) and also has no apparent temporal trend (pl. 1).

Oak Creek near Sedona (09504420) and ***Oak Creek near Cornville (09504500).***—Diversions upstream from the gaging station Oak Creek near Sedona are minimal; thus, base-flow separation analysis was done for all months for this gaging station. Average annual base flow at the Oak Creek near Sedona gaging station for 1981–2003 is 31.7 ft^3/s (table 8), which is about 13 percent less than average winter base flow (36.4 ft^3/s, or 26,400 acre-ft/yr). Annual and winter base flow generally decreased 0.1 and 0.4 ft^3/s per year (70 and 290 acre-ft/yr per year), respectively, during 1981–2003 (pl. 1).

The Oak Creek near Cornville gaging station, about 17 mi downstream from the Oak Creek near Sedona gaging station, has been operated continuously since 1940. Owing to the number of diversions upstream from the gaging station, it is difficult to evaluate seasonal trends related to changes in natural streamflow. Average base flow for December, January, and February is 41.8 ft^3/s (29,400 acre-ft/yr) for the period of record (table 8). Although winter base flow has varied year to year owing to differences in upstream diversions, it has generally declined about 0.1 ft^3/s per year (70 acre-ft/yr per year), during the period of record (pl. 1).

Wet Beaver Creek near Rimrock (09505200).—Average annual base flow at the Wet Beaver Creek gaging station is about 7.4 ft^3/s for the period of record (1961–1982 and 1991–2003; table 8 and fig. 15*D*), which is less than the average winter base flow (8.4 ft^3/s or 6,100 acre-ft/yr). There was little to no decline in annual or winter base flow during the period of record.

West Clear Creek near Camp Verde (09505800).—Average annual base flow at the West Clear Creek gaging station (fig. 15*D*) is about 18.2 ft^3/s for the period of record (1965–2003; table 8). Average winter base flow is 19.9 ft^3/s (14,400 acre-ft/yr) for the period of record. There was little to no decline in annual or winter base flow during the period of record.

Trends in Base Flow.—Base flow generally was less than the long-term average during the 1960s and 1970s, greater the long-term average from the 1980s through the mid-1990s, and less than the long-term average from the mid-1990s through 2003 (fig. 15 and pl. 1). Flow has decreased at a rate of 0.5 ft^3/s per year (380 acre-ft/yr per year) at the Verde River near Paulden gaging station (09503700) since 1993, at a rate of about 1.4 ft^3/s per year (1,000 acre-ft/yr per year) at the Verde River near Clarkdale gaging station (09504000) since 1994, and at a rate of about 2.8 ft^3/s per year (2,000 acre-ft/yr per year) at the Verde River near Camp Verde gaging station (09506000) since 1994. Base flow also has declined at gaging stations on the Verde River tributaries; however, the declines generally started sooner in the tributaries than in the main stem of the Verde River, with the exception of Wet Beaver Creek (09505200) and West Clear Creek (09505800), where base flow has essentially been constant since the mid-1960s.

Subflow

Subflow is ground water flowing adjacent to streams and rivers in the stream-channel alluvium that is not measured by streamflow-gaging stations. Subflow at Verde River near Paulden (09503700) was estimated using Darcy's Law, which is represented as

$$Q = -KAI, \tag{2}$$

where Q is the ground-water flow (ft^3/s); K is the saturated hydraulic conductivity of the alluvium (ft/s); A is the cross sectional area of the aquifer (ft^2); and I is the hydraulic gradient of the water table (ft/ft). The estimated cross-sectional area was 13,500 ft^2 on the basis of an estimated saturated thickness of 30 ft and width of 450 ft. Thickness of the saturated alluvium was estimated on the basis of seismic-refraction surveys. It was assumed that the flood plain was saturated over its entire 450-ft width. The ground water was assumed to be in hydraulic connection with the river; therefore, the gradient of the water table was assumed to be the same as that for the surface of the Verde River (0.0058 ft/ft). The hydraulic conductivity of the alluvium was estimated to be about 300 ft/d, which is in the range of values derived for alluvial sediments in Arizona (Anderson and others, 1992). On the basis of these estimated values, the subflow through the flood plain at Verde River near Paulden (09503700) was estimated to be 0.27 ft^3/s (200 acre-ft/ yr). Although there could be error in this estimate that cannot be accounted for, the estimate is two orders of magnitude smaller than the base flow measured at the gaging station.

This same type of analyses was conducted near the mouth of Granite Creek, with the same conclusion that subflow adjacent to Granite Creek and the Verde River is negligible. Although subflow measured in the upper Verde River watershed during this study was small, Owen-Joyce (1984) estimated that subflow was 18 ft^3/s (13,000 acre-ft/yr), near the mouth of West Clear Creek.

Springs

The NWIS database contains records for springs in the upper and middle Verde River watershed; there are additional springs identified on USGS topographic maps for which no hydrologic or water-quality information is available in the database. Roughly half the springs in the database issue from Cenozoic rocks and half issue from Paleozoic rocks (particularly limestone formations) or, rarely, from Precambrian rocks. More than half the springs have recorded discharges of less than 0.02 ft^3/s (14 acre-ft/yr), and approximately 80 percent have discharges of less than 0.2 ft^3/s (145 acre-ft/yr). The largest springs in the study area are Page Springs, which has recorded discharges of 36 to 42 (26,100 to 30,400 acre-ft/yr)) 90ft^3/s (Twenter and Metzger, 1963; Levings, 1980), and Del Rio Springs, which had an average discharge of about 1.5 ft^3/s (1,100 acre-ft/yr) for 2003. Most springs (128) are in the middle Verde River watershed and issue from Paleozoic rocks.

Evapotranspiration

Only a fraction of the total volume of precipitation in the study area percolates through the subsurface and recharges the regional aquifer. The remaining amount returns to the atmosphere through the process of ET or leaves the study area as surface runoff. ET rates were calculated by using several techniques. Basin-scale potential ET (PET or ETo) and aridity were calculated by using techniques described by Flint and Childs (1987) and Flint and others (2004). Actual ET (AET) rates were calculated by using a technique described by Anderson (1976).

The AET rate is dependent upon two factors. The first factor is the vapor deficit between the land surface and the atmosphere. The combination of clear skies, warm temperatures, and unobstructed winds create ideal conditions for high vapor deficits at the land surface. The second factor is the soil water content. In semiarid environments, the vapor deficit commonly is high but the soil water content is low, resulting in low AET rates. These conditions change during the monsoon season (July-September) and the winter precipitation season (December-March). During the monsoon season, the increased humidity and frequent rainfall can result in saturated soils. As monsoon conditions are replaced by drier conditions, vapor deficits increase resulting in higher AET rates. Snowmelt also results in higher soil water contents and potential for increased AET rates.

Potential Evapotranspiration

Measurement of AET is difficult, and thus values are commonly inferred using surrogate measurements, such as potential evapotranspiration (PET), which can be defined as the quantity of water vapor the atmosphere can receive from an idealized, extensive, free-water surface under the existing climate conditions (Shuttleworth, 1993). Another surrogate is the reference crop evaporation (ETo), which is defined as the rate of evaporation from an idealized grass crop with a fixed crop height of 0.12 m and an albedo of 0.23 under existing climate conditions.

Weather data, including wind speed, air temperature, humidity, and solar radiation were available for 24 stations in the study area (appendix 4). Stations range in altitude from 3,111 ft near Camp Verde to 7,810 ft on top of Mingus Mountain within the Black Hills. Eleven stations are in the upper Verde River watershed, and 13 stations are in the middle Verde River watershed.

A computer model (SOLPET V1.0; Flint and others, 2004) was used to calculate reference crop evaporation for the study area (fig. 5*D*). The calculation of ETo is based on the Priestley-Taylor equation (Priestley and Taylor, 1972), which is considered appropriate for regional-scale applications in areas with heterogeneous land cover:

$$\mathrm{ETo} = \alpha S/(S + \gamma)(R_n - G), \tag{3}$$

where α is a coefficient set to 1.26, S is the slope of the temperature versus vapor deficit curve, γ is the psychometric constant, R_n is the net radiation, and G is the soil heat flux. Both S and γ are dependent on air temperature and can be estimated if air temperature is known.

Monthly air-temperature data from NOAA stations were used to calculate S and γ. Air temperature was also used to estimate G by using the method of Shuttleworth (1993), in which mean monthly air temperature is used as a surrogate for mean monthly soil temperature and increases or decreases in soil temperature are calculated as soil heat flux.

R_n is equal to incoming radiation minus outgoing radiation. Net long-wave radiation, L_n, is calculated by using air temperature as a surrogate for soil surface temperature and is input into the Stefan-Boltzman equation (long-wave energy is emitted from surfaces according to the equation $5.6697\mathrm{x}10^{-8}(\varepsilon)T^4$, where ε is the emissivity of the emitting surface and T is the temperature, in degrees Kelvin). The soil surface emissivity, ε_s, is about 0.98 (Lillesand and others, 2000), and the sky emissivity, ε_a, is calculated as a function of air temperature:

$$\varepsilon_a = 0.0000092(T_a^{\,2}), \tag{4}$$

where T_a is the air temperature in degrees Celsius. The soil surface emissivity and the sky emissivity are used in the Stefan-Boltzman equation to calculate net long-wave radiation as

$$L_n = 5.6697\mathrm{x}10^{-8}(\varepsilon_a - \varepsilon_s)T_a^{\,4}. \tag{5}$$

Net short-wave radiation, S_n, was calculated using a computer program modified from Flint and Childs (1987) that calculates solar radiation for each grid cell (30 m by 30 m). The solar radiation model, run on an hourly basis, uses data from the Digital Elevation Model (DEM; U.S. Geological Survey, 1999) for the study area to calculate slope, aspect, and topographic shading of direct-beam and diffuse sky radiation. In addition, the solar-radiation model accounts for variations in radiation attributed to ozone, precipitable water, albedo (for multiple scatter radiation), circumsolar radiation, and Angstrom's turbidity coefficient. Monthly values are used in the solar radiation model. Once incoming short-wave radiation, S_o, is modeled, S_n is calculated as the total incoming radiation minus that reflected owing to the albedo, α:

$$S_n = S_o(1 - \alpha). \tag{6}$$

The Arizona Meteorological Network (AZMET; Arizona Meteorological Network, 2005) includes a series of weather stations, mostly in southern Arizona, that are used to measure ETo. ETo values calculated for the basin analysis just described are almost identical to ETo values estimated by using data from the AZMET stations and the Penman-Monteith equation (Allen and others, 1998). Two AZMET stations were installed in Prescott and Flagstaff in November 2003. Results of the ETo basin model (SOLPET V1.0) were compared to monthly and cumulative monthly measurements of ETo from the AZMET stations determined from equations unique to each station (ETo AZ; Arizona Meteorological Network, 2005), the AZMET data using the Penman-Monteith equation (ETo Std; Arizona Meteorological Network, 2005), and the Arizona State ETo map (Yitayew, 1990; fig. 16). ETo calculations are consistent for the Prescott AZMET station, although ETo AZ is higher than ETo Std. The SOLPET ETo model is based on the Priestly-Taylor model, which is a variant of the Penman-Monteith model, so similar results are expected. There is also a good match between SOLPET ETo model results and data from the AZMET station in Flagstaff, although the ETo AZ is still higher than the ETo Std. The ETo for Flagstaff from the State map, however, which was constructed without the benefit of measured ETo data within the watershed, did not match well with the SOLPET ETo, ETo AZ, and ETo Std. Prescott is south of Flagstaff and closer to preexisting ETo stations in Maricopa County, which may explain why ETo values for Prescott from the State ETo map agree more closely with SOLPET ETo results than do values for the Flagstaff station.

An assessment of aridity was made for this study by using an international arid-land classification index (United Nations Educational, Scientific, and Cultural Organization, 1984). The method produces five classification indexes on the basis of the ratio of rainfall to ETo: hyper-arid (<0.05), arid (0.05–0.2), semiarid (0.2–0.5), dry-subhumid (0.5–0.65), and humid (>0.65). The upper and middle Verde River watersheds are centrally located in the mostly semiarid region of central Arizona (fig. 5*E*). Most of the study area is semiarid; the northern part of Williamson Valley and the southeastern parts of Big Chino Valley are arid. Higher altitudes are more humid than lower altitudes owing to higher precipitation rates and lower ETo rates. Parts of the study area along the Mogollon Escarpment and between the rim and the San Francisco Peaks range from semiarid to humid. Canyons within the study area, such as Oak Creek Canyon, can develop microclimates that generally are humid, especially if the canyons are sheltered from cross winds. The different aridity zones can be used as a means to determine differences in the availability of water for infiltration and recharge in the study area.

Actual Evapotranspiration

AET rates are calculated for riparian corridors, open-water bodies, and subirrigated agricultural lands, and are used in the water-balance equation (for ET). Riparian corridors

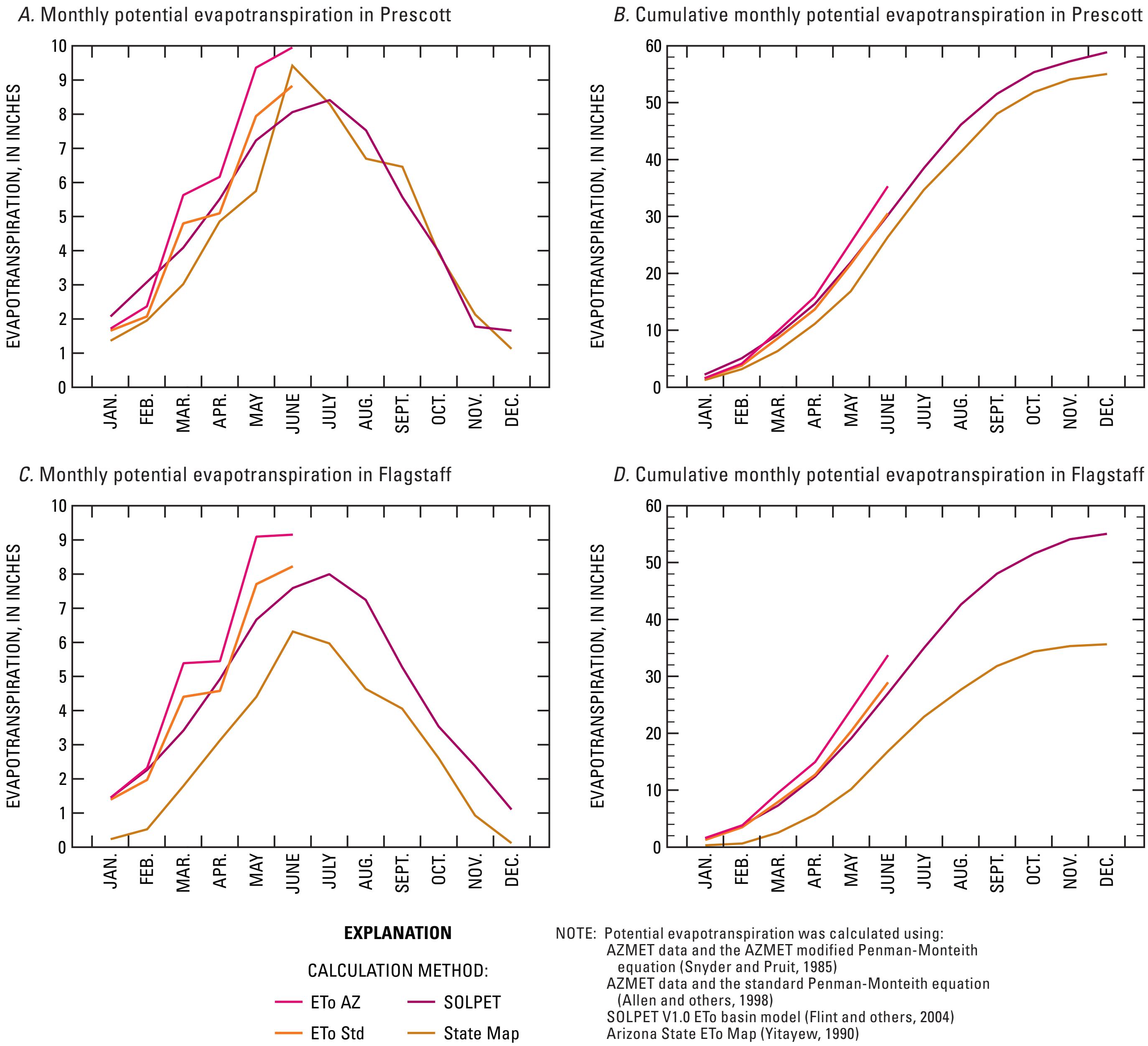


Figure 16. Monthly potential evapotranspiration (PET) and cumulative monthly PET for the Arizona Meteorological Network (AZMET) stations using different calculation methods. *A*, Monthly PET at the Prescott station; *B*, Cumulative monthly PET at the Prescott station; *C*, Monthly PET at the Flagstaff station; *D*, Cumulative monthly PET at the Flagstaff station.

along the Verde River and its tributaries are areas of significant evapotranspiration by riparian vegetation and evaporation from the river and tributaries. Ground-water levels in these areas commonly are above the land surface or just below the land surface within the rooting depth of riparian vegetation. Additionally, arid and semiarid atmospheric conditions within the region sustain a vapor deficit and a net upward flux of water vapor.

Anderson (1976) used multiple methods to infer AET rates within the Verde River watershed including a base-flow reduction analysis, an integration method, and a pan method. ET was estimated for this study by using the base-flow reduction method (table 9). This method utilizes the relation between seasonal base flow and vegetation activity. Vegetation requires more water during the growth seasons of spring and summer than during other times of the year. The removal of ground water by vegetation reduces base flow of the river. The base-flow reduction method has three primary assumptions. The first assumption is that during winter (December, January, and February) ET is nearly zero because vegetation is dormant and cold air is not conducive to storing large amounts of water vapor. The second assumption is that the difference between base flow in winter and base flow in spring, summer, and fall is attributed entirely to ET from vegetation and open-water bodies upstream from the measurement location. For large regional aquifers, such as those in the study area, discharge of ground water from springs to surface-water channels commonly is assumed to be constant throughout the year. The final assumption is that base flow can be accurately separated from surface runoff and bank storage. These assumptions are rarely applicable in developed land areas, such as those along Granite Creek, or for reaches that have significant bank storage.

Average annual and seasonal AET rates were calculated by using the seasonal base-flow values estimated by HYSEP. Results from this study were compared to AET rates estimated by Anderson (1976) for the same period (1961–73). Anderson (1976) used a manual technique to estimate base flow and AET rates.

AET rates estimated for 1961–73 are similar to those calculated by Anderson (1976) with the exception of rates for Wet Beaver Creek and West Clear Creek. AET rates were about 100 percent higher for Wet Beaver Creek and about 30 percent higher for West Clear Creek than those estimated by Anderson (1976). The differences in calculated AET are attributed to the differences in the base-flow separation methods used. Annually averaged AET rates

Table 9. Actual evapotranspiration (AET) within riparian corridors along the Verde River and its tributaries in the upper and middle Verde River watersheds, central Arizona, calculated by using base-flow reduction

[NC, not calculated]

Streamflow-gaging station or location	Period of record (1961–1973); values from Anderson (1976) (acre-feet per year)	Period of record (1961–1973); base-flow values from this study by using base-flow separation (acre-feet per year)	Period of record (1961–2003); base-flow values from this study by using base-flow separation (acre-feet per year)
Verde River near Paulden (09503700)	850	840	560
Verde River near Clarkdale (09504000)	3,290	2,980	2,970
Wet Beaver Creek near Rimrock (09505200)	340	730	480
West Clear Creek near Camp Verde (09505800)	1,250	1,600	1,040
Verde River near Camp Verde (09506000)	NC	NC	[1]6,500
Oak Creek (at mouth)	NC	NC	[2]2,800

[1]Calculated by using an average consumptive-use value determined from Verde River streamflow-gaging stations rather than by using base flow reduction.

[2]Calculated by using an average consumptive-use value determined from Verde River tributary streamflow-gaging stations rather than by using base flow reduction.

estimated for the entire period of record (1961–2003) are less than annually averaged AET rates for 1961–73 (table 9). The lower AET rates may partially be explained by the reduction in average annual precipitation in the watersheds for 1973–2003. The period of record available to Anderson (1961–73) was a wetter-than-normal period that likely resulted in increased vegetation growth and AET rates.

Annual consumptive use for the reach upstream from the Verde River near Camp Verde gaging station was calculated by using a consumptive-use rate for upstream gaging stations (table 10). The base-flow reduction method is not applicable here because the base-flow separation technique is not appropriate where streamflow is affected by diversions. The average consumptive-use rate of 73 [(acre-ft/mi)/yr] was multiplied by 89 mi (upstream reach length) to obtain an AET rate of 6,500 acre-ft/yr. AET along Oak Creek was calculated in a similar manner by using an average consumptive-use rate for tributary gaging stations. AET calculated at each gaging station includes ET from all upstream reaches. For example, average annual ET for the reach between Verde River near Clarkdale and Verde River near Paulden is 2,970 acre-ft minus 560 acre-ft, or a total of 2,410 acre-ft.

Table 10. Actual evapotranspiration within riparian corridors along the Verde River and its tributaries in the upper and middle Verde River watersheds per stream mile

Streamflow-gaging station or location	Length of riparian corridor upstream from gaging station (miles)	Evapotranspiration (acre-feet per year per mile)
Verde River near Paulden (09503700)	[1]8	70
Verde River near Clarkdale (09504000)	[1]39	76
Wet Beaver Creek near Rimrock (09505200)	7	69
West Clear Creek near Camp Verde (09505800)	[2]25	42
Verde River near Camp Verde (09506000)	89	[3]73
Oak Creek (at mouth)	51	[4]56

[1]Upstream tributary contributions not considered.

[2]To the mouth of Clover Creek.

[3]Value calculated as the average of values from upstream Verde River streamflow-gaging stations (0903700 and 09504000).

[4]Value calculated as the average of values from Verde River tributary streamflow-gaging stations (09505200 and 09505800).

The AET rates for Wet Beaver Creek and West Clear Creek are lower per mile than the AET rates for the reaches of the Verde River. This difference is attributed to differences in the type and distribution of vegetation upstream from the gaging stations.

Open Water.—Total surface area of open-water bodies (lakes, cattle tanks, recharge ponds, and other impoundment features) in the study area is approximately 3,900 acres (fig. 3). Actual evaporation from open-water bodies can be considered nearly equal to potential evaporation. Monthly evaporation rates were estimated by multiplying the surface area of the water body by the 30-year average monthly ETo rate for that locality and a coefficient to convert the ETo to PET (Shuttleworth, 1993). This value is considered conservative because most of the water bodies are not at full capacity year round. Average annual ETo is calculated as the sum of the average monthly rates. Average annual open-water body ET for the study area is about 30,800 acre-ft/yr (table 11).

Table 11. Evaporation from open-water bodies in the subbasins of the upper and middle Verde River watersheds, central Arizona

Subbasin	Open-water area (acres)	Open-water evaporation (acre-feet per year)
Big Chino Subbasin	900	7,300
Little Chino Subbasin	800	6,500
Verde Valley Subbasin	2,200	17,000
Total	3,900	30,800

Subirrigated Agricultural Lands.—AET rates from agriculture can be divided into AET from irrigated crops and AET from subirrigated crops (fig. 6). Irrigated crops typically do not have roots below the water table and require irrigation. Subirrigated crops have roots below the water table and are sustained by ground water extracted through their roots. AET for irrigated crops in the Big Chino subbasin, the Little Chino subbasin, and the Verde Valley subbasin was previously estimated to be 50 percent of the water applied as irrigation (Arizona Department of Water Resources, 2000; John Munderloh, Yavapai Water Coordinator, written commun., 2004).

Yavapai County surveyed 1,325 acres of subirrigated crops within Williamson Valley and Big Chino Valley consisting entirely of pasture grasses (John Munderloh, Yavapai Water Coordinator, written commun., 2004). AET from subirrigated crops was calculated by using two methods. One method uses average monthly ETo measurements, crop coefficients, and effective precipitation (table 12). The second method uses crop factors for pasture grasses and effective precipitation (table 12). Effective precipitation is the amount of moisture retained by the soils following precipitation and is influenced by factors such as slope of the agricultural field, soil properties, rainfall intensity, and rainfall frequency (U.S. Department of Agriculture Soil Conservation Service, 1970).

Average monthly ETo rates were derived using the SOLPET V1.0 ETo method described previously (table 12). Monthly ETo was multiplied by the monthly crop coefficient for pasture grasses (Shuttleworth, 1993) to obtain monthly AET. Effective precipitation was subtracted from AET to obtain the amount of water removed from the aquifer through AET. About 4,300 acre-ft of water per year is transpired from subirrigated crops (table 12).

The crop factor method used monthly crop factors to estimate AET (Arizona Department of Water Resources, 2000). Monthly effective precipitation values were subtracted from monthly crop factors to determine AET. About 2,600 acre-ft of water per year is transpired from the subirrigated crops (table 12). The AET estimates from the two methods are different because localized ETo is calculated from the first method and generalized crop coefficients are used in the second method. The average ETo from the two methods was used to develop water budgets in this study.

Hydrogeology

The hydrogeology of the Big Chino, Little Chino, and Verde Valley subbasins differ in physical dimensions, stratigraphy, and water-bearing units. The differences are attributed to the genesis of the subbasins and their location between the Colorado Plateau and Basin and Range structural provinces.

Hydrogeologic Units

The stratigraphic sequence in the study area includes Precambrian metamorphic and igneous rocks that are overlain by a sequence of Cambrian to Permian sedimentary rocks. This sequence of Paleozoic rocks is overlain in many parts of the study area by alluvial sedimentary and volcanic rocks that are Tertiary to Quaternary in age (fig. 17).

Table 12. Average monthly evapotranspiration (ET) from subirrigated crops comparing to calculation methods, upper and middle Verde River watersheds, central Arizona

[subirrigated crop acreage equals 1,325; NC, not calculated]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Method 1 (ETo)													
Reference crop evaporation (ETo), in inches	0	0	0	5.3	7.2	8.1	8.7	7.8	5.8	3.9	0	0	47
Crop coefficient[1]	0	0	0	1.04	1.034	1.035	1.03	1.0	1.0	1.025	0	0	NC
Actual evapotranspiration (AET), in inches	0	0	0	5.5	7.4	8.4	8.9	7.8	5.8	4.0	0	0	48
Effective precipitation, in inches	0	0	0	.75	.41	.41	2.3	2.9	1.42	1.0	0	0	9.2
AET from the aquifer, in inches	0	0	0	4.8	7	8	6.6	4.9	4.4	3.0	0	0	39
AET from the aquifer, in acre-feet	0	0	0	530	770	880	730	540	480	330	0	0	4,300
Method 2 (crop factor)													
Crop factor[2], in inches	0	0	0	4.6	4.8	4.6	4.8	4.8	4.6	4.8	0	0	33
Effective precipitation, in inches	0	0	0	.75	.41	.41	2.32	2.87	1.42	1	0	0	9.2
AET from the aquifer, in inches	0	0	0	3.9	4.4	4.2	2.5	1.9	3.2	3.8	0	0	24
AET from the aquifer, in acre-feet	0	0	0	430	480	470	270	210	350	420	0	0	2,600

[1]Based on average monthly humidity and wind speeds (Shuttleworth, 1992).

[2]Arizona Department of Water Resources (2000).

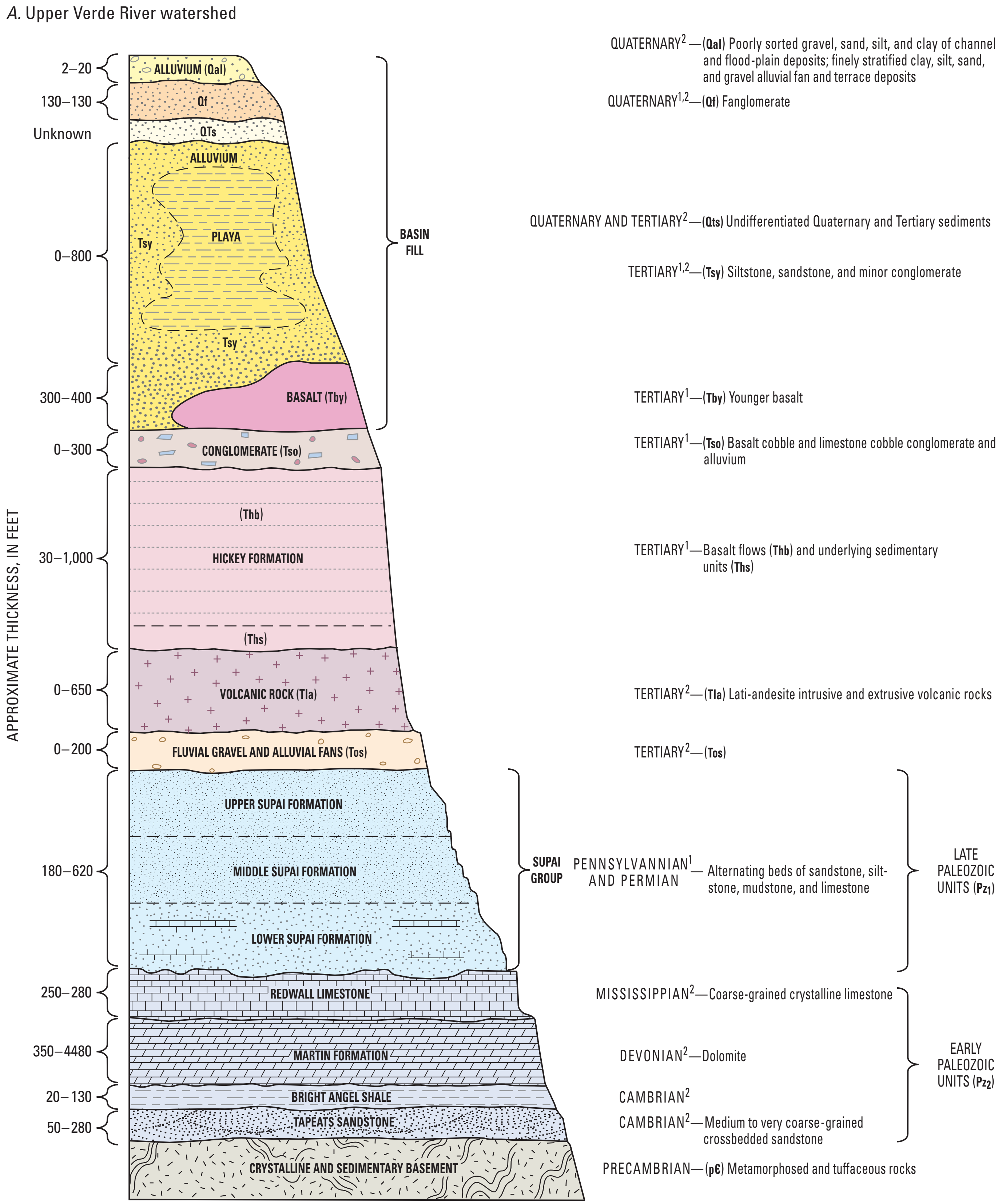


Figure 17. Generalized stratigraphic section for the upper and middle Verde River watersheds, central Arizona. *A*, Upper Verde River watershed; *B*, Middle Verde River watershed and adjacent Coconino Plateau.

B. Middle Verde River watershed and adjacent Coconino Plateau

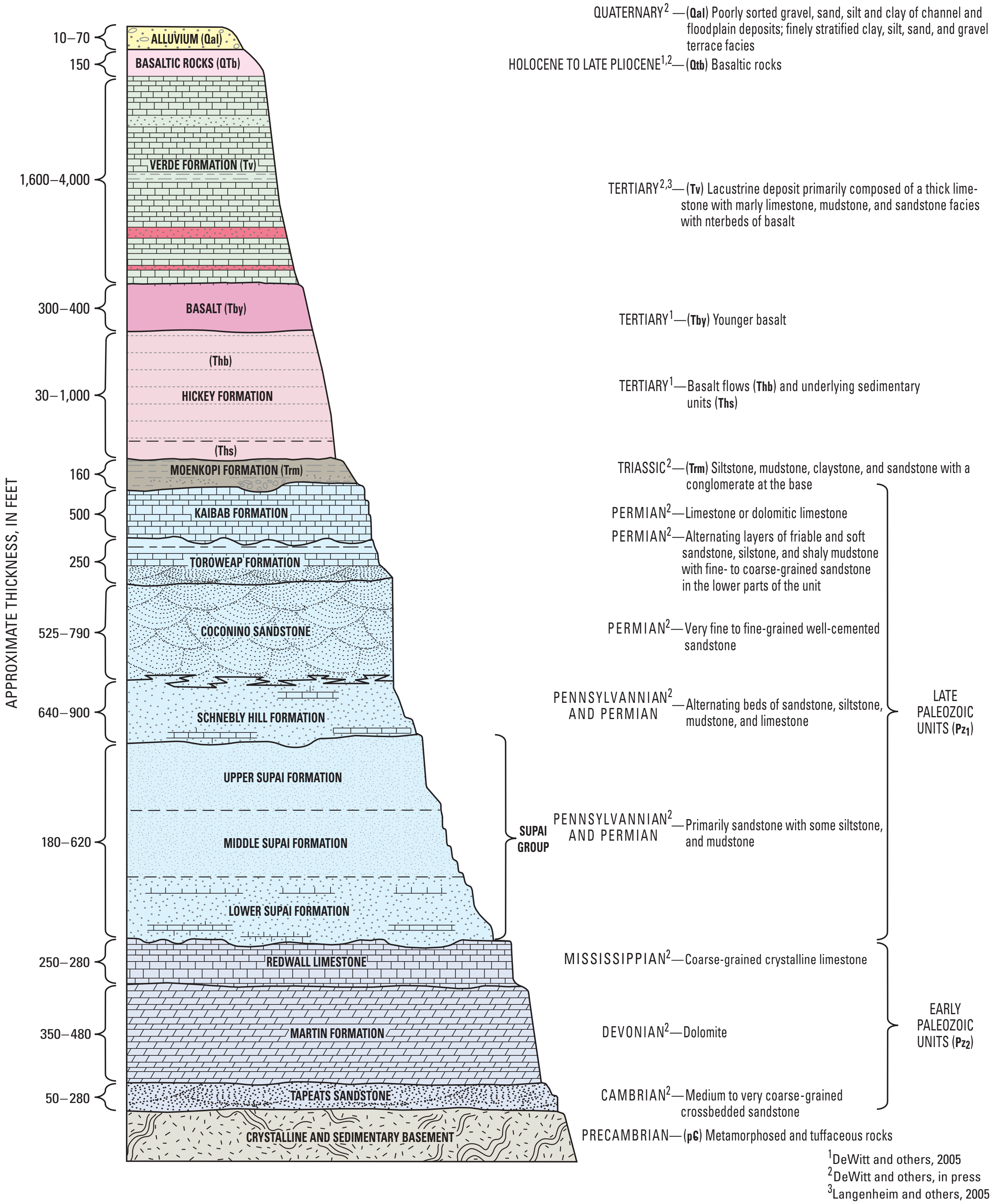


Figure 17. Continued.

Precambrian Basement

The Precambrian metamorphic rocks in the study area include regionally metamorphosed volcanic and sedimentary rocks that have been metamorphosed to a greenschist facies. The metamorphic rocks are intruded in places by Precambrian igneous units, which primarily include gabbro and granodiorites. One of these igneous units is the Mazatzal Group, a quartzite that unconformably overlies metamorphosed volcanic and sedimentary rocks. The Precambrian rocks are exposed throughout the study area in the mountain ranges and uplands, such as the Bradshaw Mountains in the southern part of the study area and the Juniper and Santa Maria Mountains in the western part. Precambrian rocks also are exposed in parts of the Black Hills, an upland area that separates Lonesome Valley from Verde Valley. Precambrian rocks also are exposed in isolated low-lying areas, such as the area near Del Rio Springs and the northern end of Big Chino Valley (figs. 2 and 17*A*).

In general, the Precambrian rocks do not store significant amounts of water and are not productive aquifers. Only in a few areas with significant fracturing is water found in quantities sufficient for withdrawal. Fractured and weathered granite between the Little Chino subbasin and the Big Chino subbasin in Williamson Valley (fig. 2), however, is capable of storing and transmitting water. Hundreds of wells in this area are completed in granite.

Paleozoic Rocks

The Paleozoic rocks comprise a sequence of nearly flat consolidated sedimentary units in the part of the study area in the Coconino Plateau structural province. The oldest unit in the sequence is the Cambrian Tapeats Sandstone. The Tapeats Sandstone lies unconformably on the Precambrian rocks and is exposed in isolated areas west of the town of Chino Valley, along lower Granite Creek, at the base of Big Black Mesa and the Juniper Mountains, and in Verde Valley near Muldoon Canyon. The Cambrian Bright Angel Shale is exposed in one isolated area at the base of the Juniper Mountains. The Devonian Martin Formation is exposed on Big Black Mesa, in the Juniper Mountains, and along the upper Verde River. The Mississippian Redwall Limestone overlies the Martin Formation and is exposed on Big Black Mesa, in the Juniper Mountains, and along the upper Verde River. The Pennsylvanian Supai Group overlies the Redwall Limestone and is exposed northwest of Big Black Mesa, in the Juniper Mountains, along the upper Verde River, and along the Mogollon Escarpment near Sedona. Overlying the Supai Group in the middle Verde River watershed are the Schnebly Hill Formation, the Coconino Sandstone, the Toroweap Formation, and the Kaibab Formation, all of Permian age. These formations are exposed at the surface in the northeastern part of the study area, near Sedona, and along the Mogollon Escarpment; some are exposed in the upper reaches of Sycamore Creek. Various components of the Paleozoic sequence may be partly or entirely absent, leaving a patchwork of exposed outcrops throughout the uplands (Krieger, 1965; Owen-Joyce and Bell, 1983; Ostenaa and others, 1993). Paleozoic units that yield water in the study area include the Tapeats Sandstone, the Bright Angel Shale, the Martin Formation, the Redwall Limestone, the Supai Group, the Schnebly Hill Formation, and the Coconino Sandstone.

The Tapeats Sandstone is a medium-grained to very coarse-grained crossbedded sandstone and, along with the Bright Angel Shale, has the smallest areal distribution of the Paleozoic formations in the study area. The formation typically is cemented with silica and is almost a quartzite. It ranges in thickness from 50 to 280 ft. The Bright Angel Shale contains particle sizes from clay to silt and ranges in thickness from 20 to 130 ft. It is thought to be saturated only beneath Big Chino Valley within the study area. Although the Tapeats Sandstone and Bright Angel Shale are likely saturated in the same areas that the Martin Formation is, little is known about their water-bearing properties in the study area because of the lack of deep-well data.

The Martin Formation is primarily a fine- to coarse-grained dolomite, although locally it contains interbeds of limestone, shale, and sandstone. Where present in the study area, the formation is about 350 to 480 ft thick and yields water to wells in the Sedona-Red Rock area, near the town of Drake, and in the Black Hills southwest of Perkinsville. The formation also is beneath Big Chino Valley owing to downward displacement on the west side of Big Chino Fault; however, no wells are known to produce water from the formation beneath Big Chino Valley. The Martin Formation is exposed along many parts of the Verde River and discharges ground water to the river.

The Redwall Limestone is a light-gray to gray, fine to coarse crystalline bedded limestone. Some beds within the formation are fractured, and the limestone typically contains solution cavities and caverns, some of which have collapsed. Those that have collapsed commonly are filled with conglomerate that is cemented with red, claylike sediment (Lehner, 1958, p. 530). In the study area, the Redwall Limestone ranges from about 250 to 280 ft in thickness and yields water to wells near the Clarkdale-Cottonwood area and the Sedona area.

The Supai Group is divided into three formations—the Upper, Middle, and Lower (Blakey, 1990). The Upper Supai Formation is a complex series of horizontally bedded reddish to brown sedimentary units that are mostly fine-grained sandstone, siltstone, and mudstone. The Middle Supai Formation is a grayish-orange, calcareous, very fine grained sandstone to siltstone. The Lower Supai Formation is a red to purple sandstone and siltstone, and gray limestone and dolomite. In some locations, the base of the formation contains conglomerate or breccia. The Supai Group is 180 to 620 ft thick in the study area and is exposed in the northeastern part of the area. It is generally the Middle Supai and Lower Supai Formations that are saturated in the study area. The Middle and Upper Supai Formations provide water to wells near

Sedona, Big Park, Oak Creek, and Page Springs, and north of Rim Rock. In some areas, these formations act as confining units to ground water in the underlying Redwall Limestone.

The Schnebly Hill Formation underlies, and in places interfingers, with the Coconino Sandstone and is exposed in the upper part of Oak Creek Canyon in the northeastern part of the study area. The formation comprises a sequence of reddish-brown to reddish-orange very fine grained to silty sandstone, mudstone, limestone, and dolomite (Blakey, 1990). The formation ranges in thickness from 640 to 900 ft. The Schnebly Hill Formation is partly saturated in the northeastern part of the study area where it is in hydraulic connection with the Coconino Sandstone.

The Coconino Sandstone is a white to tan to light brown, crossbedded, aeolian, fine-grained sandstone. It is about 625 to 790 ft thick and forms part of the regional aquifer in the northeastern part of the study area near Sedona. Outcrops of the formation can be seen along the Mogollon Escarpment and in the upper reaches of Oak Creek Canyon. Extensively fractured zones along faults are likely areas of high permeability and have the potential to yield significant quantities of water. The Coconino Sandstone is tapped by several wells in a small area in the northeastern part of the study area as well as in adjacent areas, such as Flagstaff. In Wet Beaver and West Clear Creeks, the formation is exposed in several deep canyons and discharges ground water to the creeks. The formation generally is above the water table west of Mesa Butte Fault.

Mesozoic Rocks

The Triassic Moenkopi Formation is present in the northeastern part of the study area and unconformably overlies the Kaibab Formation. The Moenkopi Formation is a sequence of mudstones, siltstones, sandstones, and gypsum, and lies above the water table throughout the study area.

Cenozoic Basin-Fill Sediments and Volcanic Rocks

Cenozoic sediments and volcanic rocks can be divided into two groups: those deposited before the Basin and Range structural disturbance and those deposited after the disturbance. Thick accumulations of basin sediments are associated with formation of the Basin and Range structural province and commonly are interbedded with Tertiary lava flows that entered the valleys from several locations. Tertiary sediments and volcanic rocks that are older than the Basin and Range disturbance are structurally deformed and regionally discontinuous, and are generally poor aquifers. Basin-fill sediments deposited in the structural depressions that resulted from the Basin and Range disturbance include permeable sequences of sand and gravel that are important aquifers. The basin-fill sediments include coarse-grained facies of sand and gravel along the basin margins and fine-grained facies of silt, clay, and evaporites in the basin center. Each of the subbasins contain water bearing Tertiary and Quaternary alluvial sediments and volcanic rocks (Arizona Department of Water Resources, 2000).

The Tertiary rocks in the upper Verde River watershed comprise volcanic rocks and alluvial deposits in low-lying valleys. Sedimentary rocks and volcanic rocks of andesite and lati-andesite were deposited prior to the Basin and Range structural disturbance (10–15 million years before present) and are poor aquifers. These rocks are primarily exposed at the north end of Little Chino Valley and were subjected to extensional tectonics characterized by low-angle faulting and rotation. Lati-andesite volcanic rocks commonly form dome-like structures that can protrude above land surface. Both extrusive flows and intrusive structures are preserved throughout the valley surface and can act as barriers to ground-water flow. In recent investigations, the dome-like structures were identified in the subsurface using geophysical techniques (Langenheim and others, 2005).

Older pre-basin fill sediments deposited in braided streams or in narrow stream valleys are structurally deformed and discontinuous in the study area. These older sediments are coarser grained than the overlying sediments and generally consist of well rounded Precambrian and Paleozoic clasts. Some of the older sediments are reworked fragments from Precambrian, Paleozoic, and Tertiary basalt units or angular fragments primarily from Precambrian, Paleozoic, and Tertiary lati-andesite units. Tertiary basalt and lati-andesite units are interbedded in the pre-basin fill Tertiary sediments.

Basin-fill sediments (Anderson and others, 1992) with interbedded basalt flows constitute the primary alluvial aquifer within the study area and were deposited during and following the Basin and Range structural disturbance. The basin-fill sediments include coarse-grained facies of sand and gravel along the basin margins and fine-grained facies of silt, clay, and gypsum in the basin centers. The younger Tertiary basalt flows in the area derived from eruptive centers nearby on the Colorado Plateau and flowed over the Mogollon Escarpment. These basalt flows are found in Big Chino Valley and the Verde River Valley east of Paulden (fig. 18; DeWitt and others, 2005). Basalt-cobble conglomerate and limestone-cobble conglomerate and alluvium are interbedded with the basalt flows in the basin-fill sediments. Basin-fill sediments include extensive fine-grained deposits of clay, silt, some sand, and minor gravel that generally becomes finer grained toward the valley center and in the downvalley direction. Included in the basin-fill sediments is a fine-grained silt and clay deposit that is lacustrine in origin (DeWitt and others, 2005). The playa deposit has been penetrated by drilling in Big Chino Valley and has an estimated surface area of about 50 mi^2 and a maximum recorded thickness of about 1,800 ft (DeWitt and others, 2005). The thickness of basin-fill sediments typically is several hundred feet but is a few thousand feet in some locations (Ostenaa and others, 1993; Langenheim and others, 2005; and DeWitt and others, in press).

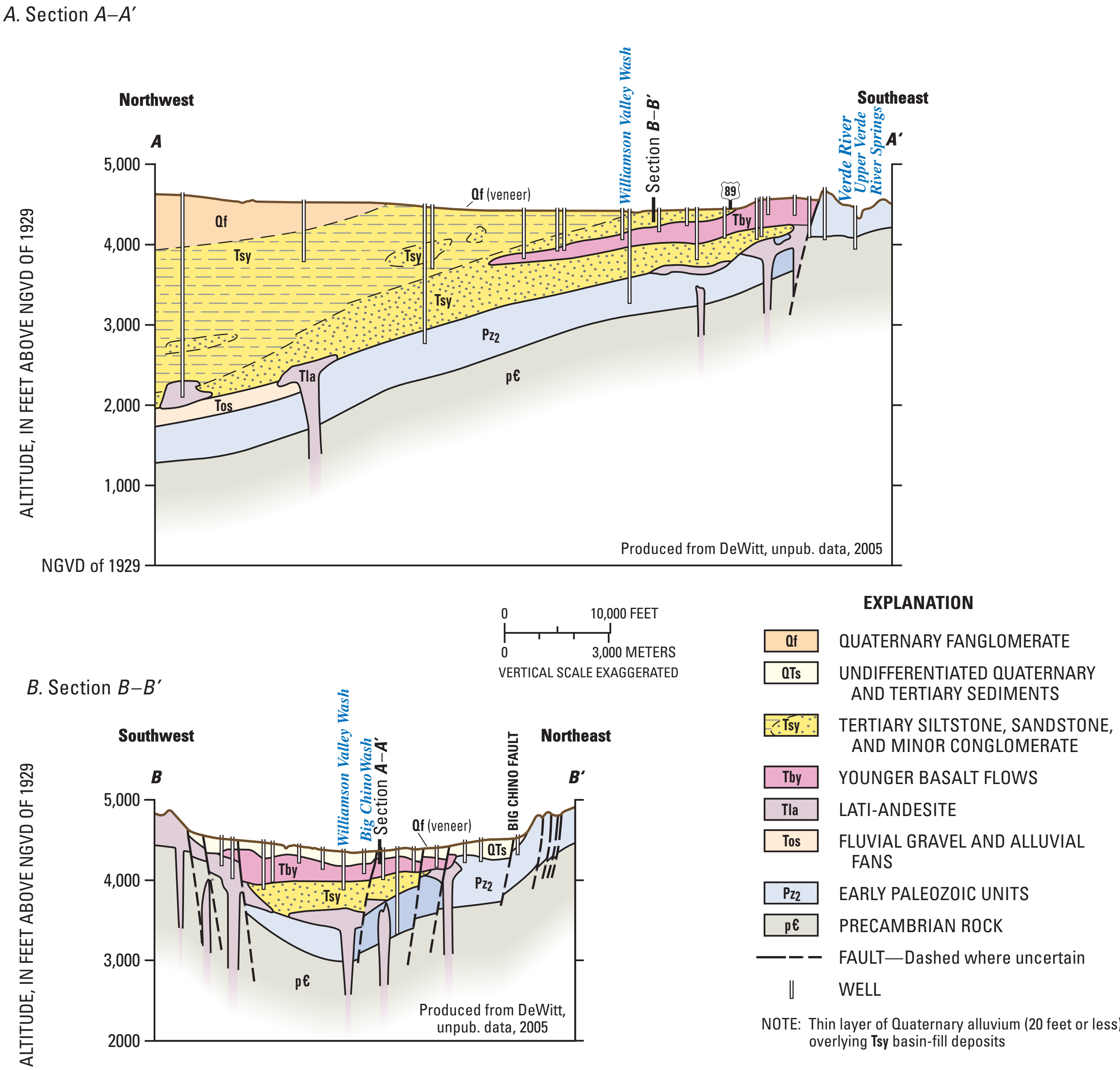


Figure 18. Generalized geologic sections of Big Chino Valley. *A*, Along the axis of the valley (A–A′); *B*, Across the axis of the valley (B–B′). See figure 2 for traces of sections.

The late-Tertiary Verde Formation, which consists of fluviolacustrine deposits (Jenkins, 1923) interbedded with gravel and basalt flows (figs. 2 and 17*B*). The formation formed in what is now the Verde Valley. It is exposed in the middle Verde River watershed northeast of the Black Hills and in an area southwest of the Mogollon Escarpment. It is a complex assemblage of six facies (Twenter and Metzger, 1963): upper, middle, and lower limestone facies; an undifferentiated limestone facies; and a sandstone and mudstone facies. The upper, middle, and lower limestone facies extend laterally from the thick undifferentiated limestone facies in the central part of the valley. The upper limestone facies generally extends to the basin margins or to where it interfingers with a sandstone facies. The upper limestone facies is separated from the middle limestone facies by the sandstone facies. The sandstone facies consists of sandstone and siltstone and thin interbeds of limestone. The middle limestone facies extends laterally from the thick limestone facies to the basin margins or to where it interfingers with clastic rocks of Verde Valley. The clastic rocks are the sandstone facies and the mudstone facies. Rocks in the mudstone facies are predominantly mudstone, claystone, and evaporites that extend to the bottom of the basin. The lower limestone facies interfingers with the mudstone facies. The limestone units are the most permeable units of the Verde Formation and are often confined beneath the mudstone units. The interbedded basalt flows generally are in the lower parts of the Verde Formation.

Quaternary sediments in the study area consist of alluvial fan deposits (fanglomerate), fine-grained alluvial sediments, terrace gravels, gravel, and recent stream alluvium. These sediments are exposed at land surface in Lonesome, Williamson, Little Chino, and Big Chino Valleys, and in major drainages throughout the study area.

Quaternary stream alluvium typically is highly permeable and locally yields water to shallow wells that is withdrawn for domestic and agricultural purposes. This unit is composed of unsorted, poorly bedded clay, silt, sand, pebbles, and cobbles, and typically is less than 30 ft thick. Owing to its limited areal coverage and thickness, the unit is not considered a primary aquifer. In addition, the unit is only partially saturated in many areas because generally it is above the water table except near major drainages.

On the part of the Coconino Plateau within the study area, Quaternary volcanic rocks overlie the Moenkopi and Kaibab Formations and are exposed at land surface. The volcanic rocks exposed in the northeastern part of the study area from Flagstaff to west of Williams are part of the San Francisco Volcanic Field (fig. 2) and comprise andesite, dacite, and basalt flows, and pyroclastic flows (Ulrich and others, 1984). Volcanic rocks associated with the volcanic field range from nearly 0 to 5,000 ft in thickness, and are 6.0 to 0.05 million years old (Nealy and Sheridan, 1989). The Mount Floyd Volcanic Field (fig. 2), in the northwestern part of the study area, ranges in age from 14.4 to 6.4 million years (McKee and McKee, 1972; Billingsley and others, 2005). Olivine basalt and red cinders (Goff and others, 1983), as well as rhyolite, rhyodacite, and obsidian units of the volcanic field (Billingsley and others, 2005) range in thickness from 0 to 2,000 ft (Bills and others, in press).

Geologic Structure and Aquifer Characteristics

The predominant structural features of the study area are the northwest- to north-trending valleys and mountains and normal faults that are typical of the Basin and Range structural disturbance, and pre-Basin and Range shear zones and folds. The northwest- to north-trending valleys are Big Chino, Williamson, Little Chino, Lonesome, and Verde Valleys (fig. 2), which were created by extensional faulting. The extensional faulting resulted in the downdropping of Paleozoic and Tertiary deposits that in many instances resulted in the juxtaposition of Precambrian crystalline rock against the younger deposits. The valley floors are gently sloping and consist of unconsolidated to consolidated Tertiary and Quaternary basin-fill sediments and Quaternary stream alluvium, which are typically underlain by gently dipping consolidated Paleozoic sedimentary rocks or Precambrian crystalline rocks (figs. 17–20).

The Big Chino subbasin has an area of about 1,850 mi^2 and comprises Big Chino Valley, Williamson Valley, Big Black Mesa, and the western part of the Coconino Plateau. Big Chino and Williamson Valleys cover an area of about 570 mi^2. This excludes the surrounding mountains and the western part of the Coconino Plateau. Big Chino Valley is a 28-mi-long northwest-trending valley in the northwesternmost part of the upper Verde River watershed. The valley is bounded on the northeast by Big Chino Fault and Big Black Mesa, and on the southwest by the Juniper and the Santa Maria Mountains (fig. 2). The basin underlying the valley was formed about 10 to 2 million years ago (DeWitt and others, 2005) by normal faulting in response to crustal extension during the Basin and Range disturbance. Normal faulting on the northeast and southwest sides of the valley created a graben (fig. 18), which has since filled with alluvial deposits eroded from adjacent uplands. Basalt flows also are interbedded with the alluvium (basin-fill sediments) in the upper part of the valley and in the lower part of the valley near Paulden. The graben ranges in width from about 2 mi at the northwest end of the valley to about 6 mi at the southeast end near Paulden.

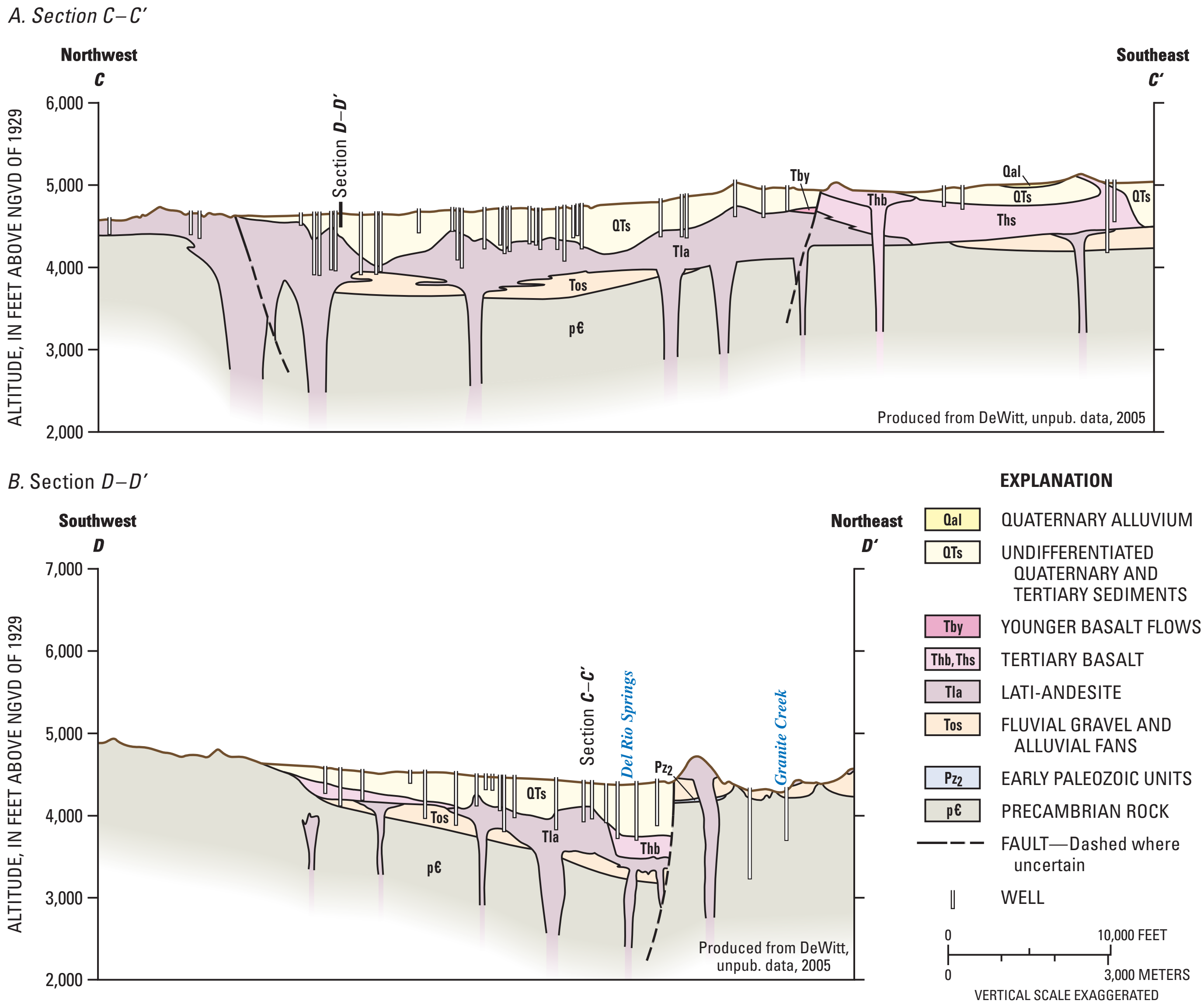


Figure 19. Generalized geologic sections of Little Chino Valley. *A*, Along the axis of the valley (C–C′); *B*, Across the axis of the Valley (D–D′). See figure 2 for traces of sections.

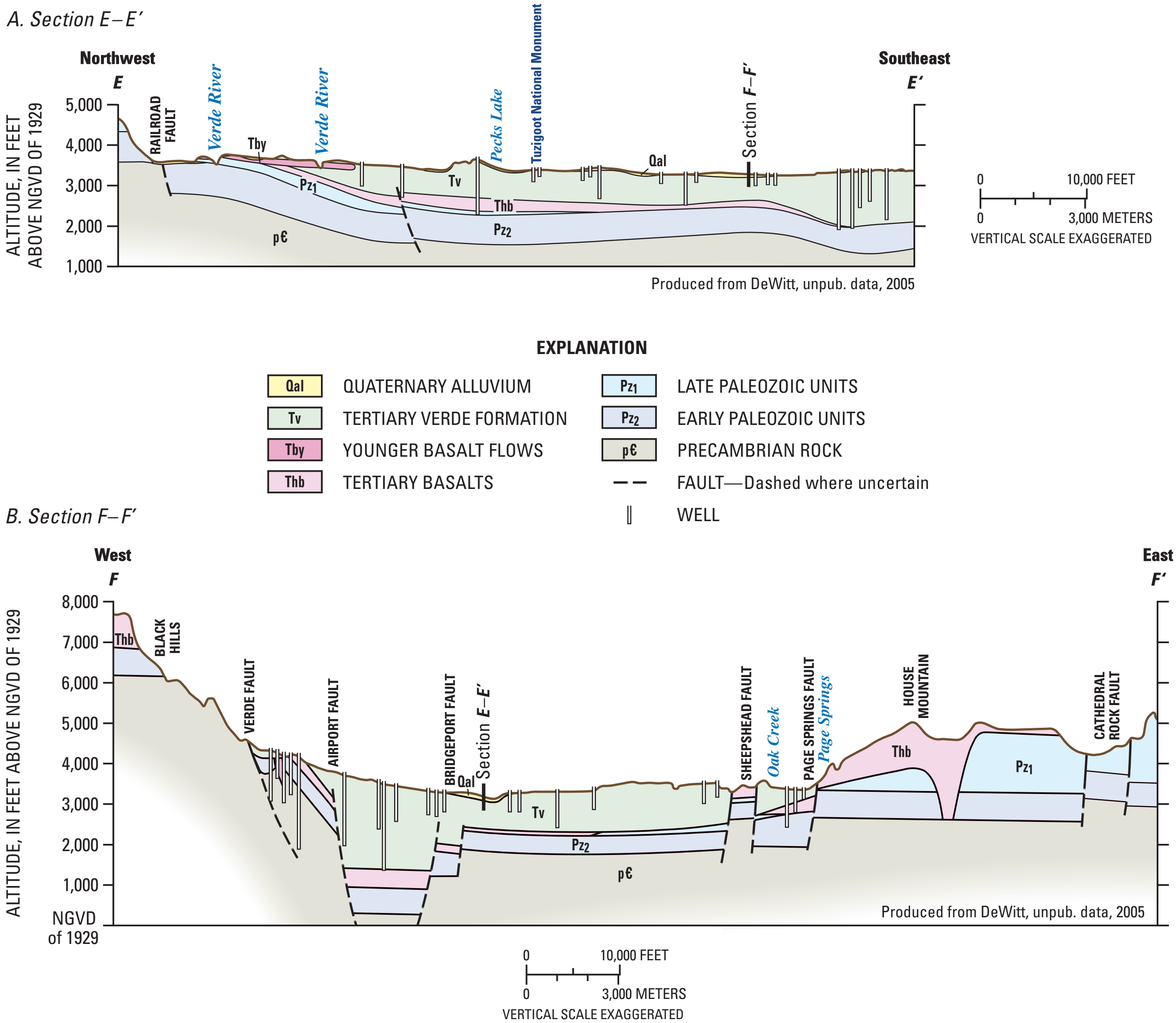


Figure 20. Generalized geologic sections of the Verde Valley. *A*, Along the axis of the valley (E–E′); *B*, Across the axis of the valley (F–F′). See figure 2 for traces of sections.

Thickness of the basin-fill sediments in Big Chino Valley is as much as 2,500 ft on the basis of interpreted logs from wells that partially penetrate the deposits (Ed DeWitt, research geologist, U.S. Geological Survey, written commun., 2005). The deepest part of the graben is the northeastern part adjacent to the Big Chino Fault.

Williamson Valley trends north and joins with the lower part of Big Chino Valley west of Paulden. Williamson Valley is about 10 mi wide and about 20 mi long, and is bounded on the south and southwest by the Santa Maria and the Juniper Mountains and on the east by the Sullivan Buttes. Its maximum depth, and thus the thickness of alluvium, is estimated to be 2,000 ft (Langenheim and others, 2005). The estimated volume of basin-fill sediments within Big Chino and Williamson Valleys is about 210x10^6 acre-ft on the basis of aeromagnetic and gravity data (table 13; Langenheim and others, 2005).

Table 13. Volume of total and saturated Tertiary alluvial and volcanic deposits in the upper and middle Verde River watersheds, central Arizona

Water-budget region	Total volume of sediment unsaturated and saturated (millions of acre-feet)	Total volume of sediment saturated (millions of acre-feet)
Upper Verde River watershed		
Upper Verde River watershed	280	188
Subbasins in the upper Verde River watershed		
Big Chino subbasin	210	155
Little Chino subbasin	70	33
Middle Verde River watershed		
Middle Verde River watershed	210	112
Subbasins in the middle Verde River watershed		
Verde Valley subbasin	210	112

The Big Chino Fault, which lies along the northeast margin of Big Chino Valley and the western margin of Big Black Mesa, is the largest documented fault in the Big Chino subbasin. Exposure of Cambrian and Precambrian rocks along the fault indicates a maximum displacement of about 3,500 ft. Displacement decreases southeastward to nearly zero near the town of Paulden.

Ground water in the Big Chino subbasin occurs in two primary aquifers. The upper aquifer consists of unconsolidated sedimentary deposits and interbedded volcanic rocks of Cenozoic age that fill the subbasin. This upper aquifer commonly is referred to as the Chino Valley Unit (Arizona Department of Water Resources, 2000). As described in the section titled “Cenozoic Basin-Fill Sediments and Volcanic Rocks,” a playa unit occurs within or overlies these sediments. Median thickness of the sedimentary deposits and volcanic rocks in the upper aquifer is about 435 ft. The upper aquifer is the major source of water for irrigation and domestic purposes. Ground water occurs under both unconfined and confined conditions in the subbasin. Confined conditions exist where buried coarse-grained sediments and volcanic rocks are layered with fine-grained sediments. The aquifer is unconfined in the remaining parts of the subbasin. The lower aquifer comprises Paleozoic rocks that underlie units of the upper aquifer everywhere within Big Chino Valley, in the northeastern part of Williamson Valley immediately adjacent to Big Chino Valley, in Big Black Mesa, and in the western part of the Coconino Plateau. Few water-level data are available for the Paleozoic rocks; however, it is assumed that a hydraulic connection exists between the upper and lower aquifers and the Paleozoic rocks in Big Chino Valley and Williamson Valley. Crystalline Precambrian rocks underlie the Paleozoic rocks in both valleys.

The Coconino multiple aquifer system (C aquifer) and the Redwall-Muav aquifer are the primary regional aquifers on the part of the Coconino Plateau within the study area (Cooley and others, 1969; Cooley, 1976). Both aquifers consist of multiple partly saturated to fully saturated Paleozoic units. The C aquifer comprises the Kaibab Formation, the Coconino Sandstone, the Schnebly Hill Formation, and units of the Supai Group (Bills and others, 2000). The Kaibab Formation is highly fractured and is exposed south of the San Francisco and Mount Floyd Volcanic Fields. Although the formation typically is unsaturated in these areas, except for perched zones, it provides a conduit for infiltration and percolation of precipitation and surface water (Bills and others, 2000; Wilkinson, 2000). The C aquifer is dry west of the Mesa Butte Fault and between Williams and Big Chino Valley. The Redwall-Muav aquifer underlies the C aquifer and comprises the Redwall, Temple Butte, and Muav Limestones in northern Arizona. The Temple Butte and Muav Limestones do not extend as far south as the study area. North of the Verde River and Big Chino Wash, the Martin Formation and Tapeats Sandstone underlie the Redwall Limestone and are considered part of the Redwall-Muav aquifer (Owen-Joyce and Bell, 1983).

Little Chino and Lonesome Valleys, adjacent to Big Chino Valley, also trend north (fig. 2). The basin underlying these valleys was created by tensional faulting, which also produced small normal faults along the perimeter and interior of the valleys. The combined area of the two valleys is about 210 mi^2, and the combined width is about 20 mi. The valleys are bounded on all sides by Precambrian crystalline and Tertiary volcanic rocks. Unlike Big Chino and Williamson Valleys, the alluvium in Little Chino and Lonesome Valleys is underlain predominantly by Tertiary basalt and latite volcanic rocks and only partially by Paleozoic rocks (fig. 19); the Paleozoic rocks are present only in the northernmost part of the valleys. The valleys narrow to the north amongst bounding

Precambrian crystalline and Tertiary volcanic rocks. Thickness of the basin-fill sediments generally ranges from about 100 to 800 ft (Ed DeWitt, research geologist, U.S. Geological Survey, written commun., 2005). The estimated volume of the basin-fill sediments in the Little Chino subbasin is 70x10^6 acre-ft (table 13; Langenheim and others, 2005).

The basin-fill aquifer in Little Chino Valley includes an assortment of alluvial and volcanic sediments (Matlock and others, 1973; Corkhill and Mason, 1995; Nelson, 2002; DeWitt and others, 2005). The alluvial units, composed of sedimentary, volcanic, and basin-fill deposits of Quaternary and Tertiary age, are described by Krieger (1967) and Wilson (1988). The geologic layering has resulted in an aquifer with heterogeneous properties. Interfingering of less permeable units, such as lati-andesite and Tertiary trachyandesite, with the pre-Basin and Range alluvial sediments creates artesian conditions near the town of Chino Valley as delineated by Schwalen (1967). Quaternary and Tertiary sediments are fine to coarse grained and vary in depth throughout the basin as a function of the underlying lati-andesite (DeWitt and others, 2005). Part of the alluvium in the western part of the Little Chino subbasin is less permeable than the surrounding sediments (Bill Remick, hydrologist, Arizona Department of Water Resources, written commun., 2005; pl. 3).

The Verde Valley subbasin is in the middle Verde River watershed and has an area of about 2,500 mi^2. Verde Valley is a northwest-trending valley also created by extensional faulting. The valley has an area of about 1,500 mi^2., and the estimated depth of the basin-fill sediments is 4,200 ft on the basis of aeromagnetic and gravity data. The deepest well known in the area was drilled to a depth of 2,078 ft in the south-central part of the valley and did not fully penetrate basin-fill sediments. The estimated volume of basin-fill sediments is 183x10^6 acre-ft (table 13; Langenheim and others, 2005).

The Verde Valley is bounded on the north and northeast by the Mogollon Escarpment and on the southwest by the Precambrian and Paleozoic rocks of the Black Hills (fig. 20). The Mogollon Escarpment serves as the boundary between the Colorado Plateau and the Transition Zone. It is a steeply sloping cliff that rises as much as 2,000 ft from the Verde Valley to an altitude of 7,500 ft on the Coconino Plateau.

The two major high-angle normal faults or fault zones in the middle Verde watershed are the Verde Fault zone along the southwest side of Verde Valley that separates Verde Valley from the Black Hills, and the Oak Creek Fault in the northeastern part of the study area. The Verde Fault zone is a series of northwest-striking faults throughout the Colorado Plateau and the Transition Zone and has subordinate faults mostly on the east side of the Verde Fault (Anderson and Creasey, 1958). The Verde Fault dips to the northeast; rocks on the northeast are displaced downward. The estimated maximum displacement along the fault is 1,850 ft or more (Anderson and Creasey, 1958, p. 80), which is the largest in the study area. The amount of displacement along the airport fault is similar, so that the cumulative displacement on the southwestern side of the graben is about 3,700 ft (Ed DeWitt, research geologist, U.S. Geological Survey, written commun., 2005). The Oak Creek Fault strikes north-south, and displacement along the fault is about 600–700 ft (Twenter and Metzger, 1963). Other normal faults in the area include the Sedona, Bear Wallow Canyon, and Cathedral Rock Faults; numerous subparallel unnamed faults are associated with these major faults.

Several monoclines associated with the Laramide Orogeny (60–80 million years before present) have been mapped on the Colorado Plateau (Davis, 1978). The Limestone Canyon Monocline exposed on Big Black Mesa in the northwestern part of the study area trends northwest; the Martin Formation and Redwall Limestone are exposed on the southwest limb, and the Supai Formation is exposed on the northeast limb (Krieger, 1965). Structural relief along the monocline is about 200 to 400 ft. Also in the northwestern part of the study area is a small, north-trending monocline along Bull Basin Canyon (Krieger, 1965). A significant fold in the northeastern part of the study area is the Mormon Mountain Anticline (fig. 2), which produces nearly 400 ft of displacement northeast of Sedona (Ed DeWitt, research geologist, U.S. Geological Survey, written commun., 2005). The anticline is near the northeastern boundary of the middle Verde River watershed. The regional dip of the Paleozoic sequence of sedimentary rocks is typically about 2–3 degrees to the north-northeast, except near monoclines where it can be steeper.

The Redwall-Muav aquifer, the C aquifer, the Verde Formation (basin fill), and the Quaternary stream-channel alluvium function as aquifers in the Verde Valley subbasin. The Redwall-Muav aquifer (primarily composed of the Supai Group in this subbasin) and the C aquifer occur in the northern part of the subbasin. The Verde Formation, which occurs throughout most of the subbasin south of the Mogollon Escarpment, is the primary water-bearing unit in the subbasin. The smallest, yet most permeable, of the aquifers comprises unconsolidated Quaternary alluvium along the stream channels. Although not considered an aquifer for the purposes of this report, the highly dissected and faulted consolidated rocks in the Black Hills in the southwestern part of the subbasin also yield water locally.

The Quaternary alluvial aquifer adjacent to the Verde River and its tributaries consists of unconsolidated stream-channel and flood-plain deposits of gravel, sand, silt, and clay. Width of this aquifer is generally less than 1 mi through most of the Verde Valley; however, the aquifer narrows to the width of the river in areas where the river has incised consolidated rocks, such as the thick sequences of basalt and Paleozoic sedimentary rocks near the Verde River near Camp Verde streamflow-gaging station (09506000). Thickness of the alluvium typically is about 60 ft and may exceed 100 ft (Owen-Joyce, 1984).

Hydrologic Properties of the Water-Bearing Units

Aquifer Test Data.—Knowledge of the hydrologic properties of the geological units that constitute the regional and localized aquifers within the upper and middle Verde River watersheds is essential for establishing a conceptual and numerical framework for the movement of water through the subsurface. Accurate estimates of aquifer properties, such as transmissivity and specific capacity, are important for development of wells and for simulating ground-water flow through aquifers. Formation lithology and degree of fracturing largely determine the magnitude and direction of these properties. Several aquifer tests have been conducted within the Big and Little Chino watersheds to support ground-water investigations (Water Resources Associates, 1990; Allen, Stephenson & Associates, 2001). During aquifer tests, a well is pumped for several hours to days while yield (volume per time) and change in water level (drawdown) in the pumped well and adjacent monitoring wells are recorded. The combined measurements of pumping and drawdown can be used to calculate aquifer properties.

Aquifer-test data are available for some of the water-bearing units within the study area. The test data were analyzed by using one of several analytical methods available (Thiem, 1906; Theis, 1935; Cooper and Jacob, 1946; Jacob, 1950; Neuman, 1975), and tests for which analyses have been published are summarized in this report. The analytical methods are used with the following assumptions: (1) the aquifer is underlain by an impermeable surface, (2) the aquifer is uniform in thickness and infinite in areal extent, (3) the aquifer is homogeneous and properties are isotropic, (4) all radial flow is toward the well, (5) laminar flow is maintained in the horizontal plane, (6) the aquifer does not receive any natural or incidental recharge during the test period, (7) the well and observation wells fully penetrate the layer being evaluated, (8) the diameter of the pumped well is infinitesimal, and (9) the water table or potentiometric surface has no slope before commencement of the test. The degree to which these assumptions are violated affects the accuracy of the estimated aquifer properties. Anomalous values could indicate violation of these assumptions or the presence of significant hydrologic features, such as boundaries created by zones of low hydraulic conductivity.

Aquifer tests were conducted in the Tertiary alluvium and basalt layers of Big Chino Valley by Water Resources Associates (1990; table 14). Analyses resulted in a range in transmissivity values of 19,100 to 334,000 ft^2/d. Ewing and others (1994; table 14) reanalyzed the test data and calculated a range in transmissivity values of 21,500 to 246,000 ft^2/d.

Published results are available for aquifer tests of the unconfined and confined alluvial and volcanic units in Little Chino Valley near Del Rio Springs (Allen, Stephenson, & Associates, 2001). Reported transmissivity values range from 51,000 to 73,500 ft^2/d and average 59,000 ft^2/d. Storativity values range from $1.2x10^{-8}$ to $7.17x10^{-5}$ and average $2.9x10^{-5}$.

Aquifer-test results reported for the Paleozoic units in the vicinity of Flagstaff indicate that variability in rock fracturing leads to wide ranges in hydraulic conductivity and storage coefficient (Bills and others, 2000). The largest transmissivity and hydraulic conductivity values correspond with areas of significant fracturing, and the smallest values are coincident with areas of little or no visible fracturing. Transmissivity values derived from drawdown data range from 13 to 4,700 ft^2/d and average 860 ft^2/d. Values derived from recovery data range from 1 to 630 ft^2/d and average 1,150 ft^2/d. Hydraulic conductivity values derived from drawdown data range from 0.0188 to 6.88 ft/d and average 1.6 ft/d. Values from analysis of recovery data range from 0.0188 to 10.6 ft/d and average 2.33 ft/d. Hydraulic conductivity values are predominantly less than 1.3 ft/d.

Data from aquifer tests near Leupp, Arizona, for a different USGS study indicate that hydraulic conductivity of the Coconino Sandstone ranges from 11 to 28 ft/d. Values range from 0.9 to 8 ft/d where the Coconino Sandstone interfingers with the Schnebly Hill Formation. The Upper Supai Formation had the smallest values (0.1 and 0.2 ft/d).

Levings (1980) completed four aquifer tests in the Sedona area (table 14). The aquifer test at well (A-16-04)27dcc indicated a transmissivity of 20 ft^2/d for the Verde Formation, and the test at well (A-15-04)12abd indicated a transmissivity of 50 ft^2/d for the combined Verde Formation and parts of the Supai Group. Transmissivity of the Supai Group at well (A-17-05)19aaa and the upper part of the Redwall Limestone at well (A-17-05)33ada were 10,000 and 16,000 ft^2/d, respectively.

Specific-Capacity Data.—Aquifer tests are costly and do not always provide accurate results. Thus, it is more common to estimate aquifer properties on the basis of specific-capacity values, which are more readily available (table 15). Specific capacity is computed by dividing well yield by drawdown at the pumped well. Specific-capacity values are representative of aquifer properties only within the vicinity of the pumped well.

Empirical equations can be used to estimate transmissivity on the basis of specific-capacity data (Theis and others, 1963; Driscoll, 1986, p. 1,021; Razack and Huntley, 1991; and Mace, 1997). The assumptions described for the aquifer tests similarly apply for the transformation of specific capacity into transmissivity. Several authors have reported specific-capacity values for the study area (Schwalen, 1967; Owen-Joyce and Bell, 1983; Navarro, 2002). A summary of specific-capacity values is presented on plate 2 for comparison of values among water-bearing units.

Table 14. Aquifer properties in the upper and middle Verde River watersheds, central Arizona, determined from aquifer tests

[ft)/day, feet squared feet per day; BLS, below land surface; ---, no data]

Principal water contributing unit	Saturated thickness (feet)	Static water level (BLS) (feet)	Well-casing diameter (inches)	Open or Screened interval (feet)	Average discharge (gallons per minute)	Test duration (hours)	Transmissivity, range (ft^2/day)	Transmissivity average , (ft^2/day)	Hydraulic conductivity range (feet per day)	Hydraulic conductivity average (feet per day)	Specific yield (dimensionless)	Storativity (dimensionless)	Specific storage (per foot)	Vertical to horizontal anisotropy (dimensionless)	Description	Data source
Tertiary alluvium (clay with coarse-grained layers, conglomerate, sand and gravel)	630	---	---	---	3,000	---	23,000 to 24,000	---	---	---	---	---	---	---	CV Ranch Big Chino Valley "pumped" well B(19-04)3bcd	Water Resources Associates, 1990
Tertiary alluvium (clay with coarse-grained layers, conglomerate, sand and gravel)	630	---	---	---	3,000	---	---	21,500	---	---	---	0.3	---	---	CV Ranch Big Chino Valley "pumped" well B(19-04)3bcd	Ewing and Others, 1994
Tertiary alluvium (clay with coarse-grained layers, conglomerate, sand and gravel)	630	---	---	---	3,000	---	19,000 to 330,000	---	---	---	---	.029 to .41	---	---	CV Ranch Big Chino Valley Observation Wells	Water Resources Associates, 1990
Tertiary alluvium (clay with coarse-grained layers, conglomerate, sand and gravel)	630	---	---	---	3,000	---	---	246,000	---	---	---	.015	---	---	CV Ranch Big Chino Valley Observation Wells	Ewing and Others, 1994
Tertiary alluvium and Tertiary basalt	19 56	---	---	---	5,000	---	190,000 to 210,000	---	---	---	---	---	---	---	B(17-02) "pumped" Well	Water Resources Associates, 1990
Tertiary alluvium and Tertiary basalt	19 56	---	---	---	5,000	---	361,000 to 481,000	---	---	---	---	.032 to .545	---	---	B(17-02)2dac Observation Well (3,480 ft from "pumped" well)	Water Resources Associates, 1990
Volcanic rock	---	---	---	None	2,000	64	51,000 to 74,000	59,000	---	---	---	1.20×10^{-8} to 7.17×10^{-5}	---	---	Well W-1 Little Chino Valley Bond Ranch near Del Rio Springs Confined	Allen, Stephenson, and Associates, 2001
Volcanic rock	---	---	---	None	800	4	800 to 97,000	26,200	---	---	---	7.45×10^{-8} to 4.95×10^{-4}	---	---	Well W-4 Little Chino Valley Bond Ranch near Del Rio Springs Confined	Allen, Stephenson, and Associates, 2001

See footnote at end of table.

Table 14. Aquifer properties in the upper and middle Verde River watersheds, central Arizona, determined from aquifer tests—Continuedv

Principal water contributing unit	Saturated thickness (feet)	Static water level (BLS) (feet)	Well-casing diameter (inches)	Open or Screened interval (feet)	Average discharge (gallons per minute)	Test duration (hours)	Transmissivity, range (ft^2/day)	Transmissivity average (ft^2/day)	Hydraulic conductivity range (feet per day)	Hydraulic conductivity average (feet per day)	Specific yield (dimensionless)	Storativity (dimensionless)	Specific storage (per foot)	Vertical to horizontal anisotropy (dimensionless)	Description	Data source
Coconino Sandstone	160	611 610 615	10 6 6	837 to 1,077 686 to 1,086 597 to 792	400	338	---	---	ND	28	0.06	---	$2x10^{-6}$	0.5	Near Leupp, Arizona 351023111062002 351022111061801 5T-533	John Hoffmann, hydrologist, U.S. Geological Survey, written commun., 2005
Coconino Sandstone interfingered with Schnebly Hill Formation	340	---	---	---	---	---	---	---	ND	8	---	---	---	---	---	---
Coconino Sandstone	455	223 to 227	6 10 2 2 2 2 2	388 to 425 696 to 1,076 250 to 270 694 to 714 240 to 260 680 to 700 1,150 to 1,170	780 to 800	---	---	---	ND	11	.05	---	$2x10^{-6}$	.17	Near Leupp, Arizona 351001110562601[1] 350957110562601[1] 350959110562303[1] 350959110562302[1] 350958110562201[1] 350958110562201[1] 350958110562201[1]	John Hoffmann, hydrologist, U.S. Geological Survey, written commun., 2005
CoconinoSandstone interfingered with Schnebly Hill Formation	420	---	---	---	---	---	---	---	ND	.9	---	---	---	---	---	---
Schnebly Hill Formation	---	---	---	---	---	---	---	---	ND	.2	---	---	---	---	---	---
Upper Supai Formation	---	---	---	---	---	---	---	---	ND	.2	---	---	---	---	---	---
Upper Verde Formation	---	---	6.63	60 to 80 240 to 260 358 to 388	37	47	---	20	---	---	---	---	---	---	(A-16-04)27dcc	Levings (1980)

See footnote at end of table.

Table 14. Aquifer properties in the upper and middle Verde River watersheds, central Arizona, determined from aquifer tests—Continued

Principal water contributing unit	Saturated thickness (feet)	Static water level (BLS) (feet)	Well-casing diameter (inches)	Open or Screened interval (feet)	Average discharge (gallons per minute)	Test duration (hours)	Transmissivity, range (ft^2/day)	Transmissivity average (ft^2/day)	Hydraulic conductivity range (feet per day)	Hydraulic conductivity average (feet per day)	Specific yield (dimensionless)	Storativity (dimensionless)	Specific storage (per foot)	Vertical to horizontal anisotropy (dimensionless)	Description	Data source
Verde Formation and Supai Formation	---	---	10	661 to 702 881 to 941	70	14	---	50	---	---	---	---	---	---	(A-15-04)12abd	Levings (1980)
Supai Formation and Redwall Limestone	---	---	8	0 to 622	87	49	---	10,000	---	---	---	---	---	---	(A-17-05)19aaa	Levings (1980)
Supai Formation and Redwall Limestone	---	---	8	---	708	29	---	16,000	---	---	---	---	---	---	(A-17-05)33ada1	Levings (1980)
Alluvium basalt sand, gravel, clay, shale, schist	---	50	12 10	50 to 422 Deepest 454	200 to 500	20	6 to 300	200	---	---	---	---	---	---	(B-17-2)22ba	Gookin and others (1977)

[1] U.S. Geological Survey ground water well site ID.

Table 15. Transmissivity of geologic units in the upper and middle Verde River watersheds calculated from specific-capacity data

[(gal/d)/ft, gallons per day per foot; ft^2/d. feet squared per day; ft, feet; gal/min, gallons per minute; ---, no data; NA, not applicable]

Well location	Well depth (feet)	Principal units and saturated thickness of materials, if known (feet)	Specific capacity [(gal/d)/ft]	Transmissivity (ft^2/d)	Drawdown (ft)	Average discharge (gal/min)	Source
A(14-5)17aac	---	Verde Formation	1,900	16	33	45	Twenter and Metzger, 1963
A(16-4)34abb	---	Verde Formation	430	4	121	40	U.S Geological Survey files, 1977
A(16-4)34abb	---	Verde Formation	16,300	250	42	470	Arizona Water Commission, 1979
A(20-08)18bcc	---	Coconino Sandstone and Supai Formation	2,000	19	431	600	Harshbarger and Associates, 1976
A(20-8)19aba	---	Coconino Sandstone and Supai Formation	2,880	14	342	701	Harshbarger and Associates, 1976
A(20-8)20dbc	---	Coconino Sandstone and Supai Formation	7,900	14	182	1,000	Harshbarger and Associates, 1976
B(15-1)26cbc1 (Observation)	611	Basalt 70	13,000	6,000 to 6,700	---	---	Woessner, 1998
B(15-1)26cbc2 (Production)	667	Alluvium 61 Basalt 110 Gabbro/Granodiorite?	13,000	770 to 1,600	---	---	Woessner, 1998
B(15-1)35acb (Test Well 1)	660	Alluvium 285	2,880 to 3,600	310 to 1,800	---	---	Woessner, 1998
B(16-2)14cba	690	Basalt 537	176,000	32,600	---	---	Woessner, 1998
B(16-2)14ccc	600	Basalt 400	213,000	39,600	---	---	Woessner, 1998
B(16-2)14cda	600	Basalt 419	127,000	24,000	---	---	Woessner, 1998
B(16-2)22dbb	548	Basalt 353	89,000	16,600	---	---	Woessner, 1998
B(16-2)22dbd	700	Basalt 493	42,000	7,800	---	---	Woessner, 1998
B(16-4)23bba	595	Alluvium 593	---	1,100	---	---	Southwest Ground-water Consultants, Inc., 2004
B(19-3)19cbd	500	Alluvium 197[1]	---	870	---	---	Southwest Ground-water Consultants, Inc., 2004
B(19-3)30bcb1	---	Alluvium	---	670	---	---	Southwest Ground-water Consultants, Inc., 2004
B(19-4)15aac	350	Alluvium 332[1]	---	3,100	---	---	Southwest Ground-water Consultants, Inc., 2004
B(19-4)15ada	---	Alluvium	---	870	---	---	Southwest Ground-water Consultants, Inc., 2004
B(20-4)30aad	600	Alluvium 598	---	2,300	---	---	Southwest Ground-water Consultants, Inc., 2004
B(20-4)32aca	---	Alluvium	---	2,100	---	---	Southwest Ground-water Consultants, Inc., 2004
B(20-4)32bba	602	Alluvium 512[1]	---	3,700	---	---	Southwest Ground-water Consultants, Inc., 2004

[1]Static water level estimated from water levels in nearby wells.

Razack and Huntley (1991) developed a relation for an alluvial ground-water basin in Morocco:

$$T=33.6(Q/(h_o-h))^{0.67}, \quad (7)$$

where T is the transmissivity (ft^2/d), Q is the pumping rate (ft^3/d), and h_o-h is the drawdown (ft). Mace (1997) developed a similar equation for the karstic Edwards aquifer near San Antonio, Texas:

$$T=0.76(Q/(h_o-h))1.08, \quad (8)$$

where T is the transmissivity (m^2/d), Q is the pumping rate (m^3/d), and h_o-h is the drawdown (m). Driscoll (1986) developed similar expressions on the basis of Jacob's nonequilibrium equation

$$Q/s = (T/264)\log((0.3(Tt))/(r^2S)), \quad (9)$$

where s is the drawdown (ft), Q is the well yield (gal/min), t is the period of pumping (d), T is the transmissivity (gal/d)/ft, r is the radius of the well (ft), and S is the storage coefficient.

Driscoll incorporated typical values into equation 9 (t=1 d, r = 0.5 ft, T = 30,000 (gal/d)/ft, and $S = 1x10^{-3}$ for a confined aquifer, and $S = 7.5x10^{-2}$ for an unconfined aquifer). Using these values, the transmissivity of a confined aquifer can be estimated as

$$T=Q/s(2,000), \quad (10)$$

and of an unconfined aquifer as

$$T = Q/s(1,500). \quad (11)$$

Within Big Chino Valley, specific-capacity values are largest for the water-bearing unit(s) near the junction of the valley with Williamson Valley and west of the community of Paulden where they are as much as 75,000 (gal/d)/ft. Near the terminus of Big Chino Valley, specific-capacity values (and thus transmissivity values) increase in variability. Specific-capacity values for the Tertiary volcanic rocks generally are smaller than those for the Paleozoic rocks. Specific-capacity values associated with the alluvial units in Williamson Valley are largest in the north central part of the valley where they range from 7,500 to 60,000 (gal/d)/ft. Values for Williamson Valley decline towards the boundaries of the valleys where they are less than 2,200 (gal/d)/ft.

Specific-capacity values for Tertiary rock units in Little Chino and Lonesome Valleys are in general lower than those in Big Chino Valley. The median value for wells near the town of Chino Valley is 7,200 (gal/d)/ft. Values tend to increase southward in part because of the discontinuity of confining units in the subsurface; values for unconfined conditions are higher than those for confined conditions. Values near Prescott range from 50 to 750,000 (gal/d)/ft; however, median values are about 1,600 (gal/d)/ft. In general, specific-capacity values within Lonesome Valley are less than those in Little Chino Valley; however, there are large ranges of values in both valleys and the ranges overlap.

In general, wells in Verde Valley have specific-capacity values between those of Little Chino Valley and those of Big Chino Valley (pl. 2). Most of these wells are completed in the Verde Formation or the unconsolidated Quaternary alluvium in areas adjacent to the Verde River and its major tributaries. Few specific-capacity data are available for the Paleozoic units within the middle Verde River watershed. Values range from 50 to 2,200,000 (gal/d)/ft; most values are within the range of 8,000 to 160,000 (gal/d)/ft. The large range is attributed to the degree of fracturing, faulting, and (or) solution-channel development.

Ground Water

Ground-Water Level Altitudes

The USGS National Water Information System (NWIS) database includes data for about 2,000 wells in the study area. Approximately three-fourths of the wells are completed in Cenozoic rocks, typically the Verde Formation in the middle Verde River watershed or volcanic rocks and (or) basin-fill sediments in the upper Verde River watershed. The remaining wells are completed in Paleozoic sedimentary rocks, with the exception of a few wells completed in Precambrian granite or gneiss. Well yields vary widely within each of the major water-bearing formations; values range from a few tens of gallons per minute to more than 1,000 gal/min, depending on the local degree of fracturing, faulting, and (or) solution-channel development. Depth to water is less than 200 ft in about 80 percent of the wells; depths are less than 55 ft in about 50 percent of the wells. In some parts of the upper Verde River watershed, water levels in confined parts of aquifers are above land surface. Water-level declines in recent years, however, have reduced the number of wells in which this occurs.

Directions of ground-water flow were estimated by using contours of water-level altitudes and assuming that aquifer properties were isotropic. Contours are primarily based on water-level data from April 2004 that were collected by the ADWR (pl. 3 and appendix 5). Several water-level altitudes from 2001 through 2005 are used where April 2004 data are not available. Many of the wells are clustered near population centers. Data gaps in sparsely populated areas prevent complete coverage of water-level contours in the study area.

Temporal changes in water levels are evaluated by examining hydrographs from selected wells distributed throughout the watershed. Selection of wells for hydrograph analysis was based on the location of the well within the watershed, the availability of a well description, and the period of water-level record.

Big Chino Subbasin.—Water-level data for 2004 indicate that ground water in the Big Chino subbasin flows southeastward through the basin-fill aquifer (pl. 3). It is likely that ground water flows downward from the basin-fill aquifer to the Paleozoic rocks and continues to move downvalley. In the lower part of Big Chino Valley near Paulden, ground-water movement continues southeastward within the basin-fill aquifer; however, movement also is probably upward from the Paleozoic rocks into the basin fill, although few data on vertical gradients are available for this area. Ground water in Williamson Valley flows north-northeastward in the basin-fill aquifer until it converges with ground-water flow from Big Chino Valley. Water then flows towards the terminus of the subbasin and eventually discharges to the Verde River.

Long-term water-level trends in the Big Chino subbasin differ spatially and temporally according to analysis of water-level measurements that extend back to the 1950s (pl. 3). According to Schwab (1995), synoptic water-level measurements made in Big Chino and Williamson Valleys in 1975 and 1992 indicate that water levels in most wells changed little or not at all. Measured water-level changes ranged from a decline of 5 ft to a rise of 40 ft. Water-level rises were associated with changes in irrigation practices in the central part of the valley. In 2004, depth to water ranged from flowing at land surface in Williamson Valley to about 250 ft below land surface near the eastern terminus of Big Chino Valley.

The water level in wells (B-17-02)06bbb, (B-17-02)S04dbc1, and (B-18-03)23bbc in the middle and lower part of Big Chino Valley rose gradually from the early 1950s though the early 1990s (pl. 3). Water levels declined from 1993 through 2003 at a rate of about 0.5 to 0.75 ft/yr. The patterns of water-level variations in the lower part of Big Chino are similar to those of base flow at the Verde River near Paulden (09503700) and Verde River near Clarkdale (09504000) streamflow-gaging stations (fig. 21 and pl. 1).

The water level at well (B-18-02)28aba at the northeastern terminus of Big Chino Valley (pl. 3) varies about 1 ft seasonally and had an overall decline of about 2–3 ft from March 2000 to June 2004. The water level at well (B-17-02)14cca near the junction of Big Chino Valley with the Little Chino subbasin varied about 2–3 ft seasonally and declined 1–2 ft from April 2000 through January 2004. Water levels at these wells are lowest during the summer months.

The volume of saturated Cenozoic alluvial and volcanic units in the Big Chino subbasin is about 155x10^6 acre-ft (table 13) on the basis of water-level data from 2004 (pl. 3) and estimated volume of Cenozoic sediments (Langenheim and others, 2005). The saturated thickness is greatest along the Big Chino Fault near Big Black Mesa (figs. 2 and 22).

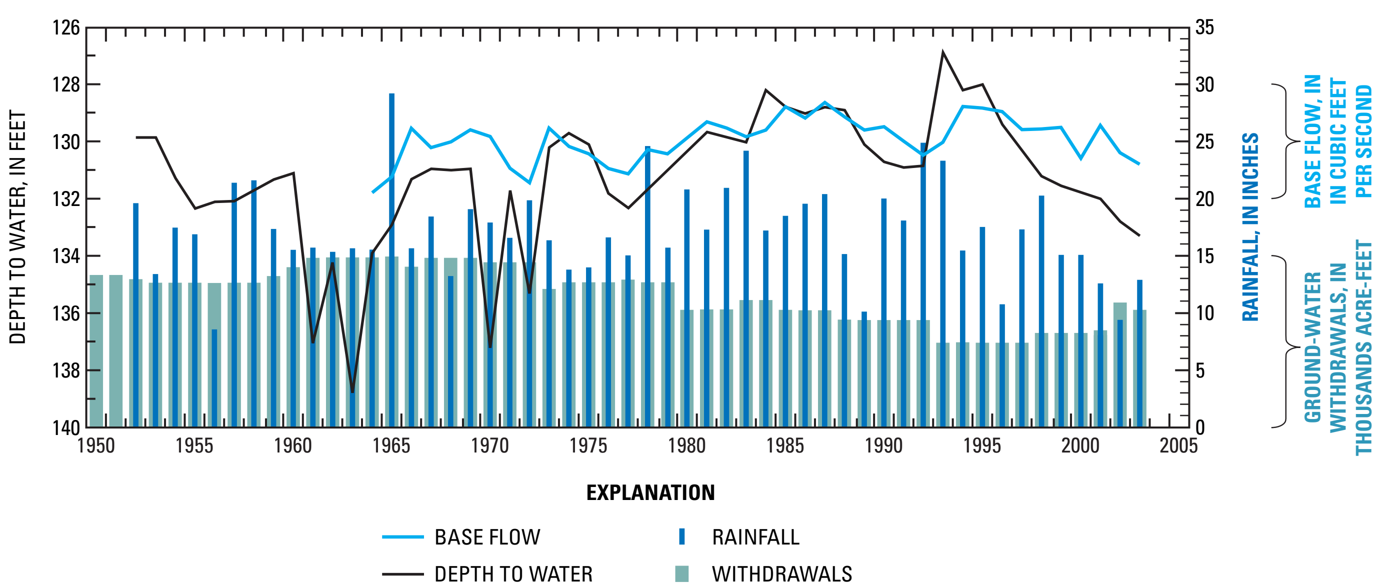


Figure 21. Water level in well (B-17-02)06bbb (Big Chino Valley), annual rainfall near Paulden, winter base flow at Verde River near Paulden (09503700), and annual ground-water withdrawals and diversions in Big Chino Valley (John Munderloh, Yavapai County Water Coordinator, written commun., 2004), Arizona, 1950–2003.

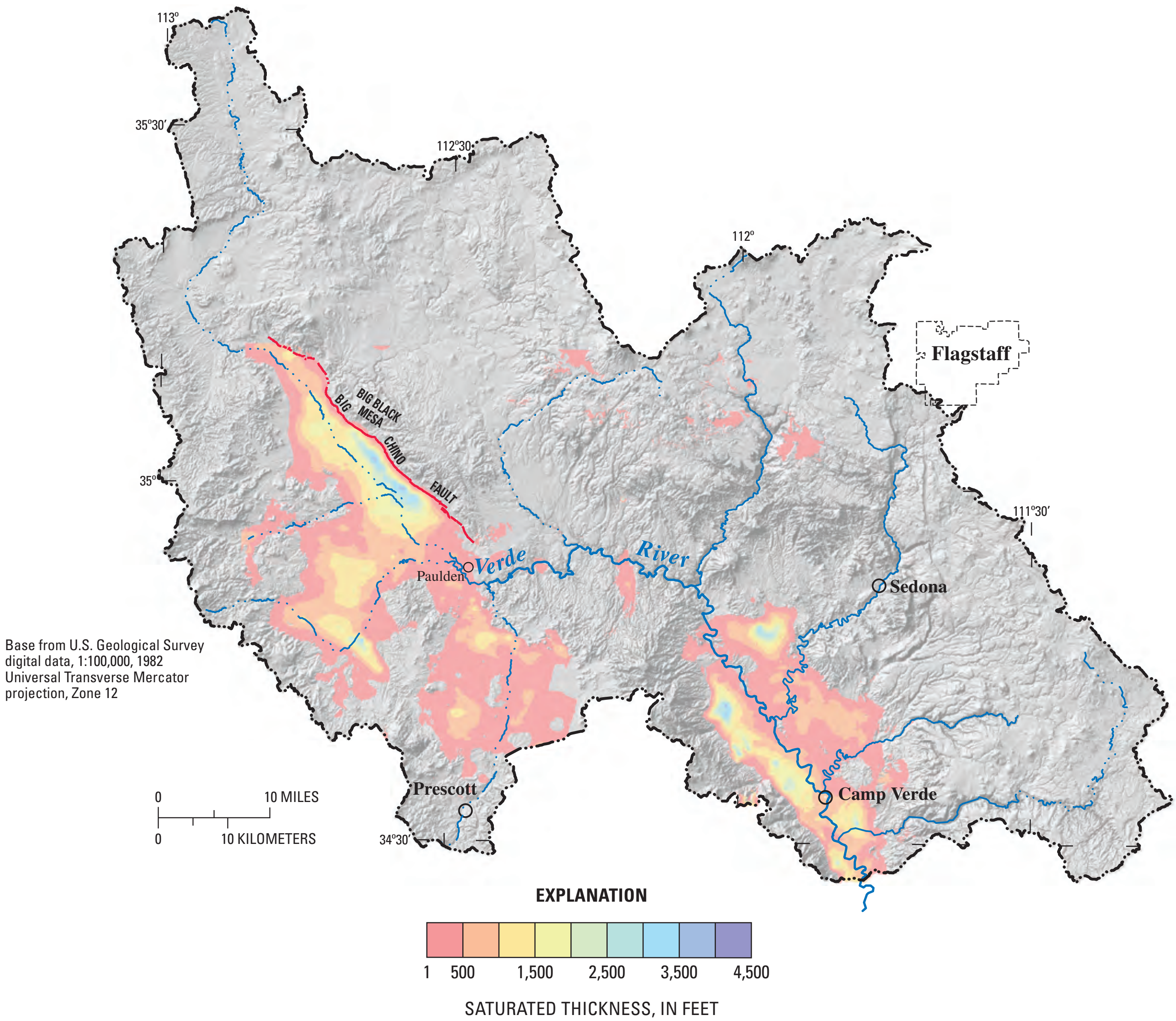


Figure 22. Thickness of saturated Cenozoic sediments and volcanic rocks, upper and middle Verde River watersheds, central Arizona. Thickness data from Langenheim and others, 2005.

Little Chino Subbasin.—Little Chino subbasin comprises Little Chino Valley and Lonesome Valley. Large irrigation demands in Little Chino Valley led to early investigations intended to understand and describe the occurrence of ground water in the area. Schwalen (1967) described the effects of agricultural pumpage on water levels. Water levels declined almost immediately following the onset of agricultural pumpage in the mid- to late 1930s. The declines averaged about 5 ft/yr between the mid-1950s and the mid-1960s. Water levels varied seasonally by about 15 to 35 ft and were lowest in the summer and highest in the winter. The largest seasonal variations were in the northern part of the confined area, whereas the smallest variations were in the southern part and were attributed to agricultural pumpage. Water levels in Lonesome Valley had similar declines, but the seasonal variations generally were small to nonexistent. Matlock and others (1973) updated the work of Schwalen (1967) and showed that the rate of water-level declines slowed to about 2 ft/yr between 1965 and 1972, and Corkhill and Mason (1995) showed that the rate of declines decreased after 1970 in many parts of the subbasin and water levels had stabilized or risen in some areas. They attribute these more recent trends to a decrease in cropped acreage and an increase in groundwater recharge from large floods. More recently, water levels in the subbasin have been monitored by ADWR's Prescott Active Management Area to fulfill monitoring requirements established in the 1995 Assured Water Supply rules (Arizona Department of Water Resources, 2003). A detailed description of the ADWR's monitoring program is provided in these annual reports. In summary, these reports show that between 2001 and 2002, water levels declined in 73 of the 84 wells measured and the declines ranged from less than 1 ft to 42 ft; the average decline was 4.0 ft and the median decline was 2.3 ft. In addition, between 2002 and 2003, water levels declined in 65 of the 85 wells measured and declines ranged from 0.3 to 10.0 ft, with an average decline of 2.5 ft and a median decline of 1.7 ft.

Continuous water-level recorders were installed in multiple wells throughout the northern half of the Little Chino subbasin for this study (pl. 3). Water levels declined 10 to 20 ft from 2000 through the beginning of 2005. Long-term rates of decline were fairly constant during the period of record. Seasonally, water levels fluctuate as much as 20 ft near the town of Chino Valley. Farther away from the town of Chino Valley, seasonal fluctuations are small. Water levels that fluctuate seasonally are lowest during the summer months.

The rates of ground-water declines have abated during the last several years, but the general direction of ground-water flow has not changed during this time. Water-level gradients indicate that ground water flows from the south towards Lonesome Valley. Ground-water flow in Little Chino valley is to the east and north through Lonesome Valley. On the western border of the subbasin, a zone of low permeability limits the rate of ground-water flow. Flow continues northward along the Black Hills to the east and toward the areas of natural discharge (pl. 3). Water-level altitudes are highest in the bordering mountains (generally 4,800 to 5,000 ft in 2004) and lowest in the subbasin bottoms (about 4,400 to 4,500 ft). Water-level altitudes within the subbasin are highest in the south-southwestern part (4,600 ft) and lowest in the northwestern part (4,400 ft); thus, regional ground-water flow is northward. Northeast of Prescott in the PRAMA, water-level altitudes are lower than in surrounding areas owing to ground-water withdrawals in Prescott Valley.

Ground water from the Tertiary sedimentary and volcanic units discharges naturally at Del Rio Springs and as ground-water flow to the Big Chino subbasin at the northern end of Little Chino Valley. Discharge at Del Rio Springs decreased from about 2,800 acre-ft/yr in the early 1940s to about 1,000 acre-ft/yr in 2003 (see section titled “Base Flow”). Withdrawals of ground water are a cause of the measured declines. Estimated ground-water flow to the Big Chino subbasin is 1,300 to 2,300 acre-ft/yr on the basis of numerical modeling methods, and the rate has generally declined over time (Corkhill and Mason, 1995; Nelson, 2002). Ground water flows out of the subbasin through basin-fill sediments (alluvium and basalt flows) in a narrow (about 1-mi wide) graben that is bounded on both sides by lati-andesite and crystalline Precambrian rocks of low permeability. Thickness of the basin-fill sediments is difficult to determine on the basis of drillers' logs; however, sediments are likely about 700 ft thick near Del Rio Springs and thin northward to about 200 ft. The median thickness is about 450 ft (Langenheim and others, 2005). Magnetic anomalies in the area indicate the probable presence of buried lati-andesite centers (Langenheim and others, 2005) where alluvium could be less than 200 ft thick. Ground-water flow continues predominantly northward towards Sullivan Lake and toward the upper reaches of the Verde River through the alluvium in the narrow graben. The presence of several small springs in the lower reaches of Granite Creek and in the Verde River upstream from the mouth of Granite Creek suggests that a small component of ground-water flow occurs in the stream alluvium along the creek and is likely maintained in part by water discharging from the Little Chino subbasin. The ground-water flow component likely is small owing to the small volume of alluvium overlying the crystalline basement rock.

Ground water also is withdrawn from the unconfined and confined parts of the regional aquifer through wells. Withdrawals from the unconfined parts generally serve domestic purposes, whereas withdrawals from the confined parts generally serve municipal, agricultural, and industrial purposes.

The volume of saturated Cenozoic alluvial and volcanic deposits in the Little Chino subbasin is about $33x10^6$ acre-ft (table 13) on the basis of water-level data from 2004 (pl. 3) and estimated volume of Cenozoic sediments (Langenheim and others, 2005). Saturated sediments are dispersed within the subbasin and are deepest towards the northern terminus of the subbasin (fig. 22).

Verde Valley Subbasin.—Regional movement of ground water in the subbasin is predominantly southwestward from the Mormon Mountain Anticline near the crest of the Mogollon Escarpment and southward from the Flagstaff area toward the Verde River (pl. 3). Ground water moves through the C and Redwall-Muav aquifers and ultimately discharges at springs and seeps within and along tributaries of the Verde River or flows into the Verde Formation and the Quaternary alluvium. It continues to flow through the Verde Formation and discharges to the Verde River or into the Quaternary alluvial aquifer adjacent to the Verde River. Ground water also flows northward from the crest of the Black Hills through highly faulted and dissected Precambrian and Paleozoic rocks of the Black Hills toward the Verde River. Portions of this flow discharge at springs along the middle altitudes of the Black Hills and support the community of Jerome. After ground water reaches the alluvial aquifer adjacent to the river, it flows southeasterly through the alluvial aquifer or through faults and fractures associated with the Verde Fault in various rock units.

The C aquifer receives recharge primarily at high altitudes along the Mogollon Escarpment from the upper reaches of West Clear Creek towards the San Francisco Peaks and in an area between the peaks and Bill Williams Mountain.

Units below the Kaibab Formation are exposed within the deeply incised stream channels in Sycamore Canyon and Oak Creek Canyon.

Where both the C and Redwall-Muav aquifers are saturated, lower, very fine grained units of the Supai Group can form an aquitard, which reduces the hydraulic connection between the aquifers. Portions of the aquifers are in hydraulic connection near the southern end of Verde Valley owing to faulting or fracturing of the aquitard. Confined conditions exist where the Supai Group overlies the Redwall-Muav aquifer and fracturing and faulting do not provide a conduit for flow. Only the Redwall Limestone, Martin Formation, and Tapeats Sandstone are saturated west of the Mesa Butte Fault. Recharge to the Redwall-Muav aquifer occurs primarily through faults and fractures within the overlying volcanic and sedimentary units.

Most of the ground water on the plateau flows northward toward the Little Colorado River or the Colorado River. A ground-water divide occurs along the Mogollon Escarpment in the northern part of the study area and from Williams southwestward toward Big Chino Valley (pl. 3). Water-level altitudes east of Partridge Creek (4,247 ft) and south of Ash Fork (4,249 ft) are higher than water-level altitudes west of Ash Fork (3,832 ft), in the vicinity of Williams (4,000–4,100 ft), and near the communities of Drake and north of Paulden (4,220–4,239). On the basis of these altitudes, a ground-water divide extends from near Bill Williams Mountain southwestward towards Big Black Mesa. Ground water flows northward away from the study area on the north side of the divide. South of the divide, ground water flows southward and discharges to springs that maintain base flow in the Verde River.

The Oak Creek Fault system has been identified as a particularly significant system influencing the transmission of water between aquifers and the surface (Levings, 1980). Vertical fault offsets cause permeable layers to abut less permeable layers causing vertical flow through the fault zone and ground-water discharge into Oak Creek (Levings, 1980). Langenheim and others (2005) identified a magnetic lineament coinciding with a normal fault mapped through Page Springs by DeWitt and others (in press). The proximity of the fault to Page Springs is an indication of a hydrologic connection between the Paleozoic rocks and the surface. Magnetic data are used to project this structure another 3–6 mi northwest and southeast of its mapped trace (Langenheim and others, 2005).

A ground-water divide occurs along the Mogollon Escarpment in the northeastern part of the study area and from Williams southwestward toward Big Chino Valley (Bills and others, 2000; Pierce, 2001; Hart and others, 2002; pl. 3). Ground water flows northward away from the study area on the north side of the divide. South of the divide, ground water flows southward and discharges to springs that maintain base flow in the Verde River, Sycamore Creek, Oak Creek, Wet Beaver Creek, and West Clear Creek (figs. 3 and 23 and pl. 3). Montezuma's Well on Beaver Creek also is a major point of discharge. An unknown amount of ground water flows southward from the regional aquifer to Verde Valley where it enters the Verde Formation (Owen-Joyce and Bell, 1983).

The location of the ground-water divide is a function of ground-water conditions within the upper and middle Verde River watershed and adjacent watersheds, including locations of recharge areas, aquifer properties, and locations of discharge areas. The divide is associated with ground-water mounding from recharge. Prior to ground-water development, the location of a ground-water divide changes primarily in response to long-term climate fluctuations. The location can also change as a result of large-scale ground-water withdrawals. Generally, ground-water pumping results in a shift of the divide away from the location of pumping. For complex ground-water systems, a numerical ground-water flow model may be required to predict migration of the ground-water divide induced by pumping.

Water is also perched within Quaternary and Tertiary alluvium and volcanic rocks overlying the Paleozoic rocks. These zones generally are small and discontinuous, and therefore are not suitable for long-term withdrawals. The most productive zones are in unconsolidated alluvium and volcanic rocks in the Bellemont area between Flagstaff and Williams and in volcanic rocks and the underlying Kaibab Formation near Bill Williams Mountain. Wells completed in these areas are less than 400 ft deep and have yields of about 50 gal/min or less. High yields in the Bellemont area likely are a result of an extension of a perched system near the San Francisco Mountains and enhanced fracturing (Don Bills, hydrologist, U.S. Geological Survey, written commun., 2004). Downward flow from the alluvium and volcanic layers is impeded by the low permeability of the underlying Paleozoic rocks. The zones around Bill Williams Mountain are less productive than the zones in the Bellemont area. Ground water is perched in the upper part of the Kaibab Formation between Flagstaff and Williams where downward flow of ground water is retarded as a result of the high chert content of the formation. Ground water in each of the perched zones flows downgradient and eventually discharges at springs or through wells, or moves vertically downward to deeper rock units.

Few long-term or recent water-level data are available for this part of the study area. Existing data, however, indicate that water levels generally are declining (Bills and others, in press).

Water levels in the alluvium adjacent to the river generally are higher than the river stage, which give rise to gaining stream conditions; however, Owen-Joyce (1984) identified ground-water flow away from the Verde River toward the Verde Fault in the vicinity of Camp Verde. She concluded that the Quaternary alluvial aquifer and regional aquifer are not hydrologically connected in all locations because she identified cascading water between the alluvial aquifer and the underlying Verde Formation in a well near Camp Verde.

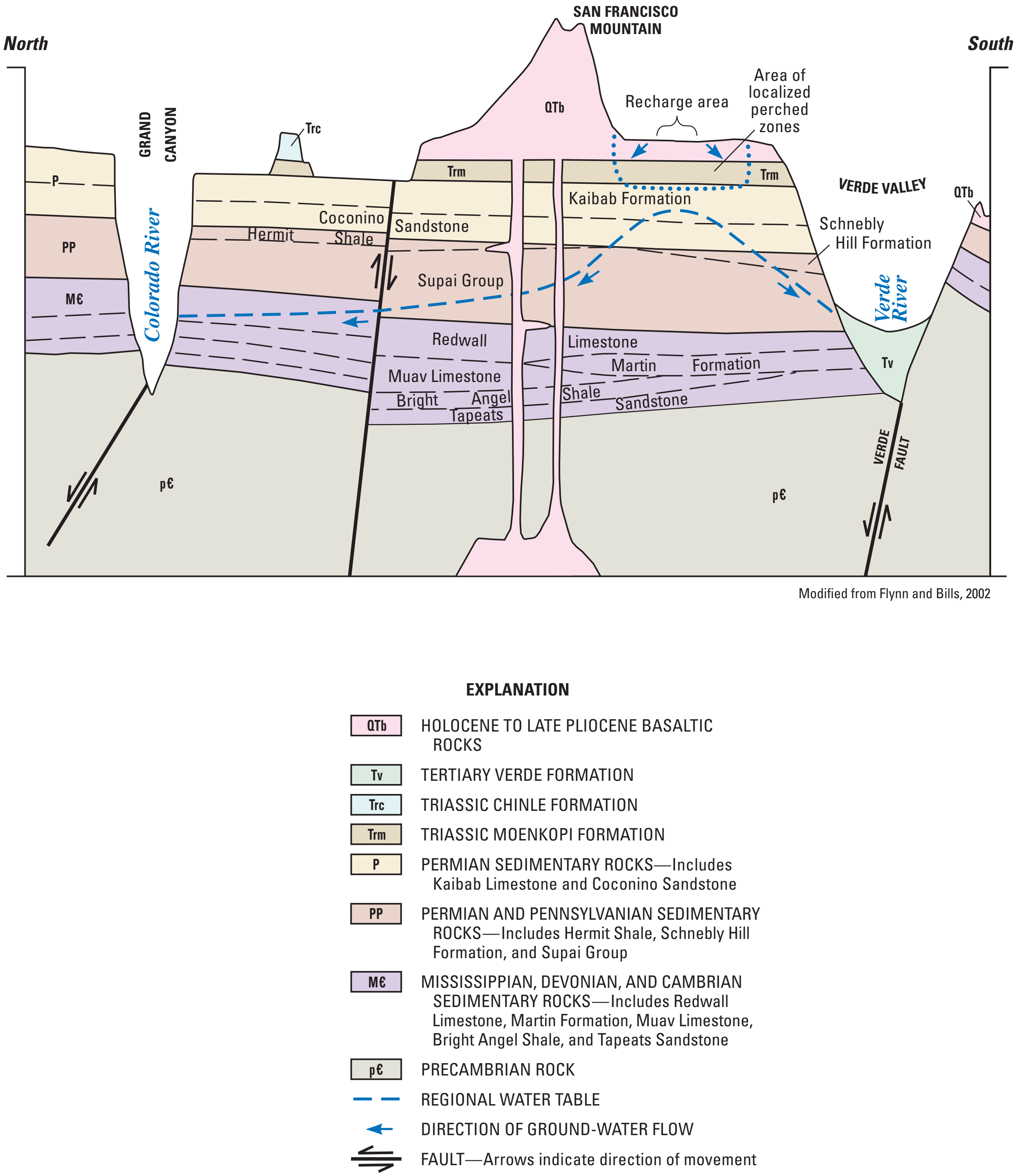


Figure 23. Generalized hydrogeologic section from the Verde River to the Colorado River, Arizona, showing the ground-water divide beneath the Coconino Plateau.

Depth to ground water within 8.5 mi of the Verde River varies from near land surface to hundreds of feet below land surface; the median depth is about 65 ft. Water levels in several wells completed in the Verde Formation declined about 30 to 40 ft during the past 40 years (for example, wells (A-15-03)12adb1 and (A-15-04)04ddc1 on pl. 3). Long-term data for wells adjacent to the Verde River and Oak Creek in the middle of the subbasin (for example, (A-15-04)04ddc1 and (A-15-03)12adb1, on pl. 3) indicate that water levels have declined since about the early to mid-1960s.

Seasonal water-level fluctuations, caused by changes in river stage, are common in wells completed in the Quaternary stream alluvium in Verde Valley (Owen-Joyce, 1984). Water levels in wells completed in the Verde Formation also vary seasonally (for example, wells (A-16-03)20ddc, (A-15-04)11aab, (A-14-05)32bbb1, and (A-15-05)36dab, pl. 3).

The volume of saturated Cenozoic units (Verde Formation and Quaternary stream alluvium) in the subbasin is about 112×10^6 acre-ft (table 13) on the basis of water-level data from 2004 (pl. 3) and estimated volume of Cenozoic sediments. The saturated thickness is greatest southwest of the Verde River (fig. 22).

Ground-Water Inflow and Outflow

Ground-water flow into or out of the subbasins was not measured, and it was assumed that water in the unsaturated zone is not transmitted between subbasins. Ground-water inflow to and outflow from each subbasin were estimated using Darcy's Law (eq. 2) where Q is flux of ground water (table 16). Saturated hydraulic conductivity of geologic units was estimated using a typical hydraulic conductivity value for the aquifer material. The cross-sectional area of the aquifer was estimated by using the depth to basement estimated on the basis of well logs and geophysical surveys. Because ground water is in hydraulic connection with the Verde River, hydraulic gradients were inferred from the slope of the river surface or from water-level altitudes.

Big Chino Subbasin.—Ground water flows into the Big Chino subbasin from the Little Chino subbasin north of Del Rio Springs. According to the simulation results from the PRAMA ground-water flow model (Nelson, 2002), ground-water inflow to the Big Chino subbasin from the Little Chino subbasin was about 3,000 acre-ft/yr before large-scale ground-water development began (table 16). Pumping in the Little Chino subbasin has reduced inflow to the Big Chino subbasin to about 1,800 acre-ft/yr in 1999 (Nelson, 2002, table 5). An unknown amount of ground water flows northward out of the Big Chino subbasin in response to the hydraulic gradient along the northern boundary of the subbasin.

Little Chino Subbasin.—A ground-water divide has been delineated south of the Little Chino subbasin in the Agua Fria subbasin on the basis of water-level altitudes in 1982 (fig. 4 and pl. 3; Remick, 1983). The offset of the ground-water divide from the surface-water divide is caused by ground water recharge along Lynx Creek. More recent water-level data (2004) indicate that the ground-water divide remains south of the surface-water divide. Ground-water north of the divide generally flows northwestward into the Little Chino subbasin; however, ground water also flows south into the Agua Fria subbasin near ground-water pumping in Prescott Valley (Frank Corkhill, Arizona Department of Water Resources, written commun., 2005).

Verde Valley Subbasin.—Ground-water flows into the subbasin from the Coconino Plateau west of the ground-water divide along the Mogollon Escarpment, and ground-water flows out of the subbasin from north of the divide in the northern part of the subbasin (pl. 3). The amount of ground-water flow into and out of the subbasin along the divide has not been estimated (table 16).

Estimated ground-water outflow through the alluvium and volcanic rocks at the southern end of the subbasin along the Verde River is about 100 acre-ft/yr (table 21).

Table 16. Ground-water inflow and outflow for the upper and middle Verde River watersheds, central Arizona

[NC; not calculated]

Subbasin	Predevelopment		Transient	
	Ground-water inflow (acre-feet per year)	Ground-water outflow (acre-feet per year)	Ground-water inflow (acre-feet per year)	Ground-water outflow (acre-feet per year)
Big Chino	3,000	0	1,800	0
Little Chino[1]				
Northern boundary	0	[1]-3,000	0	[1]-1,800
Southern boundary	[2]800	0	0	[2]-180
Verde Valley	NC	NC	NC	NC

[1]Nelson, 2002.

[2]Frank Corkhill, hydrologist, Arizona Department of Water Resources, 2005, written commun.

The estimate is derived from Darcy's Law and is based on (1) the assumption that the ground-water gradient is equal to the slope of the Verde River 3.5 mi upstream and downstream from the gaging station, (2) the saturated thickness of the combined alluvium and volcanic rocks perpendicular to the Verde River at the gaging station, and (3) estimated hydraulic conductivity values for basalt (Freeze and Cherry, 1981). Saturated thickness was calculated using water-level data from April 2004 and sediment-thickness data from Langenheim and others (2005). An unmeasured component of ground water also leaves the subbasin through faults and fractures associated with the Verde Fault zone south of the Verde River.

Storage Change

Changes in regional aquifer storage occur when inflow and outflow are not in balance. Changes in storage over time can be estimated by using one or more of several approaches: water-level changes for the regional aquifer, a numerical model, and geophysical measurements, such as microgravity. Well-calibrated transient numerical models provide a physically based means to estimate spatial storage changes using water-level data; however, only the Little Chino subbasin has been simulated through the use of a numerical model (Nelson, 2002).

The Big Chino subbasin has experienced both spatial and temporal changes in storage as indicated by historic water levels (fig. 21 and pl. 3). Storage changes are greatest near pumping centers and occur in response to seasonal and annual changes in recharge and withdrawals.

Water-level declines during the last 50 years have been greatest in Little Chino Valley, especially near the town of Chino Valley. Measured declines ranged from 25 to 60 ft near areas of substantial ground-water withdrawal since the mid-1950s. The alluvial sediments encompass an area of 135,000 acres (210 mi^2) and have an estimated specific yield of 0.075 on the basis of a numerical model (Nelson, 2002). Numerical simulations using the PRAMA model estimated about 4,100 acre-ft of storage change per year from 1990 to 2003.

Few long-term water-level data are available for the part of the Verde Valley subbasin between the Verde River near Paulden (09503700) and Verde River near Clarkdale (09504000) streamflow-gaging stations. Consequently, estimation of ground-water storage change for this area is difficult. With the exception of a few ranches, however, little development has occurred in the area. Changes in aquifer storage are assumed to be the result of climate fluctuations, and long-term storage change is assumed to be zero. Similar to the Big Chino subbasin, changes in storage are occurring within the the Verde Valley subbasin between the Verde River near Clarkdale (09504000) and Verde River near Camp Verde (09506000) streamflow-gaging stations (pl. 3). Changes in storage within the subbasin are primarily dependent upon the location of recharge, withdrawals, and the aquifer unit.

Geochemistry and Water Quality

Water-chemistry and -quality data, and parameters presented in this report are the product of multiple USGS investigations dating back to 1943. Data types are related to the various project objectives; therefore, the data presented in this study vary spatially and temporally. Data were collected during this study to supplement the historical data (fig. 24). Analyses are presented for precipitation, surface water, ground water, and spring water, and the data are available through the NWIS database.

Sample collection during this study followed protocols described in "National field manual for the collection of water-quality data" (U.S. Geological Survey, variously dated). Samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colorado, or at a laboratory participating in the USGS quality-assurance program. Samples were collected for analysis of major ions, trace elements, stable isotopes, and radioisotopes. Physical and chemical properties of water were measured in the field when samples were collected for major-ion and trace-element analyses, and when most of the samples were collected for stable-isotope and radioisotope analyses. Samples collected for major-ion and trace-element analyses were filtered through a 0.45-micrometer capsule filter into acid-rinsed bottles and preserved with nitric acid.

Ground-water samples were collected after field parameters stabilized to maximize the likelihood that samples represented the water-bearing units of interest. In general, stability was indicated when parameter values did not vary by more than 5 percent between successive measurements. Surface-water and spring-water samples were collected when base-flow conditions were predominant; therefore, analyses of these samples generally are indicative of the chemistry of water discharging from regional and local aquifers.

Precipitation samples were collected between summer 2003 and spring 2005 from 11 stations at altitudes ranging from 3,100 to 9,100 ft to determine variations in stable-isotope composition attributed to altitude and seasonality (fig. 24). Sample collection was timed to bracket the summer North American Monsoon and winter frontal-storm precipitation.

Precipitation samples were collected in 5-gal plastic buckets that were screened to limit contamination by plant material and contained a layer of mineral oil to prevent evaporation. Samples for stable-isotope analyses were collected in untreated 60-cm^3 glass bottles with polycone caps. Stable-isotope samples were analyzed by the USGS Isotope Fractionation Project Laboratory, Reston, Virginia, or at the Laboratory of Isotope Geochemistry-Environmental Isotope Research, University of Arizona, in Tucson.

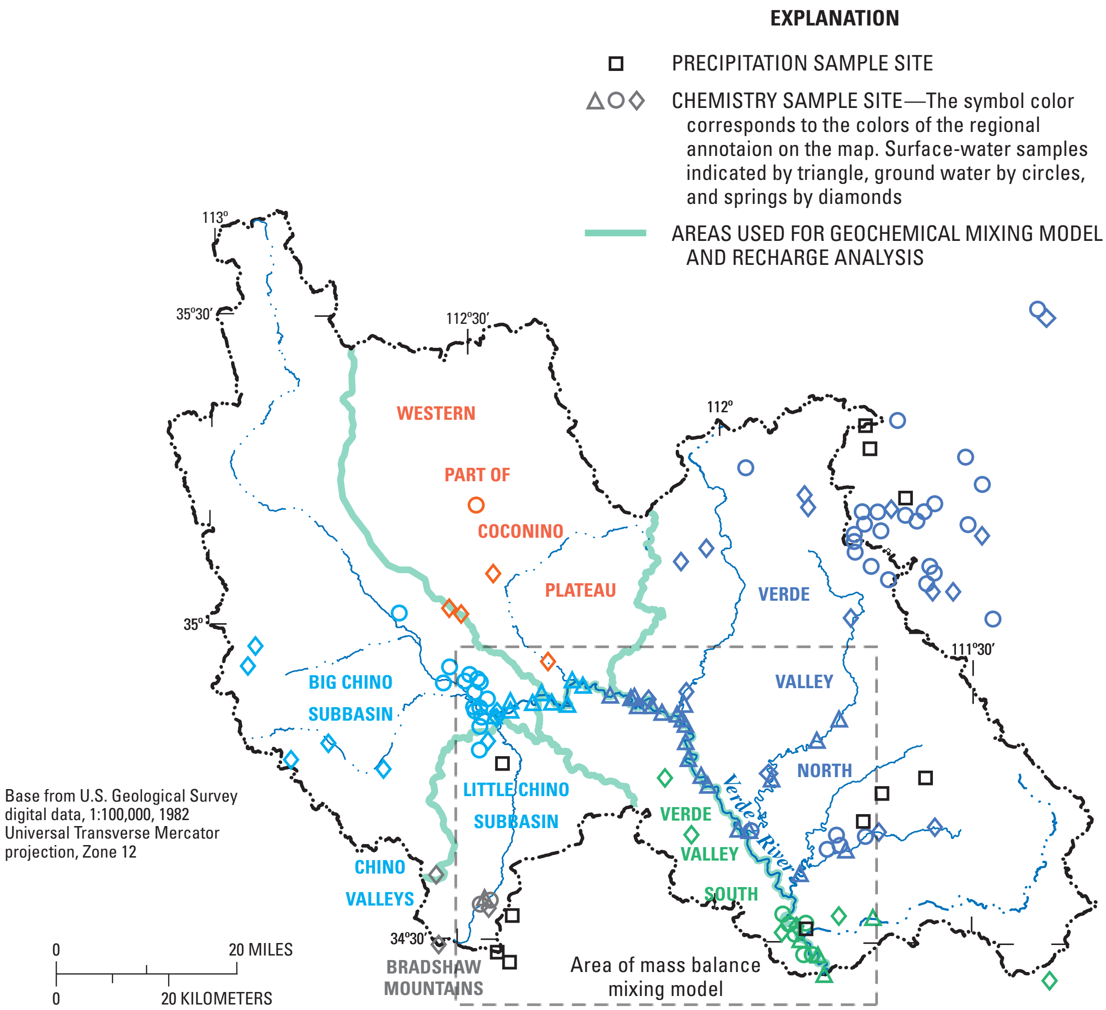


Figure 24. Locations of geochemistry and water-quality sampling sites in the upper and middle Verde River watersheds, central Arizona.

Ratios of heavier to lighter isotopes are reported as deviations from an international standard, Standard Mean Ocean Water (SMOW). Values are expressed in parts per thousand or per mil (‰) using delta notation:

$$\delta = \left(\frac{\mathrm{Rx\text{-}Rstd}}{\mathrm{Rstd}}\right)1{,}000, \qquad (12)$$

where

δ = delta notation,

Rx = ratio of isotopes measured in sample, and

$Rstd$ = ratio of same isotopes in the standard (VSMOW).

Fractions of regional and local source waters within the watershed were quantified with mass-balance calculations that incorporated stable-isotope values. The end-member isotope values were derived from average isotope values from specific geographic areas. The mixing-model equations use oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) data to characterize each end-member sample group.

Isotopic Composition of Precipitation

Stable-isotope compositions of precipitation are controlled primarily by prevailing temperature and moisture conditions of the atmosphere during rainfall and snowfall. Compositions throughout the study area are similar to those reported by the International Atomic Energy Agency (IAEA) for samples collected from a station in Flagstaff, Arizona (International Atomic Energy Agency/World Meteorological Organization, 2001; fig. 25). The IAEA operated the Flagstaff station as part of the Global Network of Isotopes in Precipitation (GNIP) database from 1962 to 1974, during which time temperature, precipitation, stable-isotope, and tritium data were collected.

$\delta^{2}H$ and $\delta^{18}O$ data worldwide are shown to be linearly correlated on a line defined by

$$\delta^{2}H = 8.13\delta^{18}O + 10.8 \text{ per mil}, \qquad (13)$$

which is termed the Global Meteoric Water Line (GMWL; Rozanski and others, 1993). This line was defined by using data from all stations in the GNIP database. A local meteoric water line also has been defined by using data from the IAEA station in Flagstaff and is defined by

$$\delta^{2}H = 6\delta^{18}O - 14 \text{ per mil}. \qquad (14)$$

Heavier (more positive) hydrogen and oxygen isotopic compositions ($\delta^{2}H$ and $\delta^{18}O$) are associated with warmer, lower altitude precipitation, whereas lighter (more negative) compositions are associated with cooler, higher altitude precipitation.

$\delta^{2}H$ and $\delta^{18}O$ data for samples collected during this study fall along the GMWL (fig. 25). Values for samples collected during the summer North American Monsoon ranged from -3 to -35 per mil for $\delta^{2}H$ and -0.8 to -6.1 per mil for $\delta^{18}O$. Values for winter precipitation were significantly lighter than those for summer precipitation and ranged from -56 to -83 for $\delta^{2}H$ and -8.3 to -11.8 per mil for $\delta^{18}O$ (figs. 25 and 26).

Isotope values for both summer and winter precipitation decrease with increasing altitude. On the basis of samples collected at altitudes of 3,100 to 9,100 ft, $\delta^{2}H$ and $\delta^{18}O$ values decrease -0.5 and -0.07 per mil per 100 ft of altitude increase, respectively (fig. 26). Isotope values as a function of altitude for winter are expressed as

$$\delta^{2}H = -79.65 - [0.5(z - 7{,}011)/100] \qquad (15)$$

and

$$\delta^{18}O = -10.92 - [0.07(z - 7{,}011)/100], \qquad (16)$$

where z is the land surface altitude, in feet, that the precipitation sample was collected. The values -79.65 and -10.92 in equations 15 and 16 are long-term average values of $\delta^{2}H$ and $\delta^{18}O$, respectively, measured at the IAEA station in Flagstaff at an altitude of 7,011 ft. These stable-isotope altitude gradients are similar to other gradients reported for the Southwest (Ingraham and others, 1998).

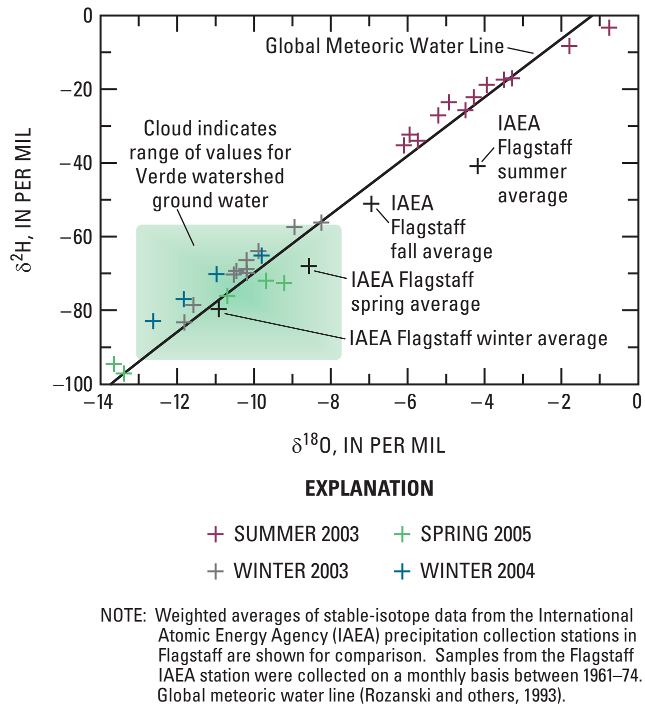


Figure 25. δ^2H and δ^{18}O values for precipitation samples collected from 11 locations in the upper and middle Verde River watersheds, central Arizona at altitudes of 3,000 to 9,000 feet above NGVD of 1929.

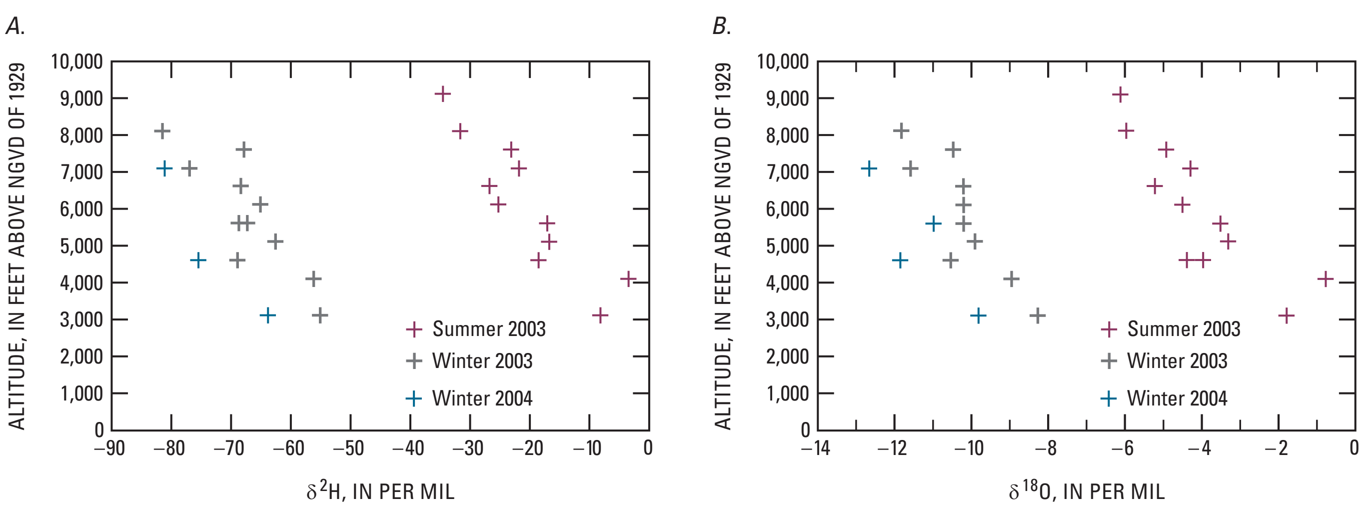


Figure 26. δ^2H and δ^{18}O values for winter and summer precipitation relative to altitude of sample collection, upper and middle Verde River watersheds, central Arizona. *A*, δ^2H; *B*, δ^{18}O.

Surface Water

Major Ions.—Surface water in the study area typically is a calcium bicarbonate water or a bicarbonate water, and major-ion chemistry varies spatially (fig. 27 and appendix 6). Water in the perennial reach of the Verde River near the mouth of Granite Creek is a calcium bicarbonate water. Downstream from this reach, near the upper Verde River springs (river mile 0.2 to 2), the percentage of sodium and potassium ions is greater and the percentage of calcium and magnesium ions is less (fig. 27). Dissolved sodium increases in the downstream direction between the springs and the Verde River near Paulden streamflow-gaging station (09503700, river mile 8). The major-ion chemistry changes abruptly between river miles 24 and 30. This reach includes Mormon Pocket where base flow increases and sodium and chloride concentrations decrease by about 60 percent. Between the towns of Clarkdale and Camp Verde (river miles 39 and 89), chloride and sulfate concentrations increase by 15 and 80 mg/L, respectively.

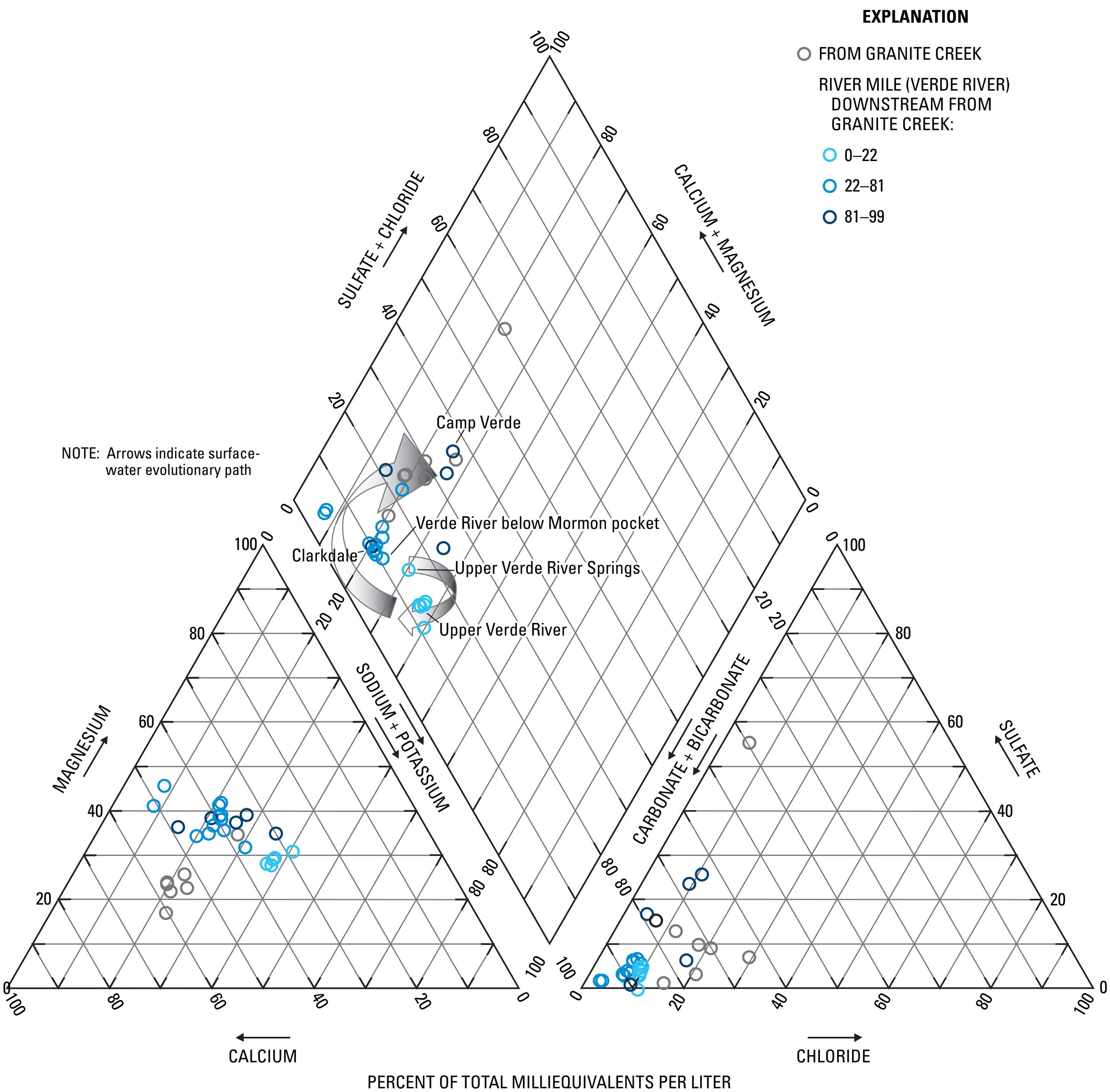


Figure 27. Relative ion composition of surface water in the upper and middle Verde River watersheds, central Arizona.

Major-ion chemistry of the Verde River tributaries varies Water in Granite and Oak Creeks is a calcium bicarbonate water. All other tributaries have bicarbonate water. Wet Beaver Creek contains slightly smaller percentages of calcium and carbonate and larger percentages of magnesium and sulfate than Granite Creek. Beaver Creek, downstream from the confluence of Wet and Dry Beaver Creeks, has larger percentages of sodium and bicarbonate than Wet Beaver Creek.

Trace Elements.—Trace elements in concentrations greater than laboratory detection limits were selenium, arsenic, boron, lithium, manganese, selenium, and strontium. Spatial variations in trace-element concentrations coincide with spatial variations in major-ion chemistry (fig. 28 and appendix 7).

Concentrations of dissolved selenium in surface water ranged from 0 to 8 µg/L. The highest concentration was measured in Oak Creek near the mouth (fig. 28*A*). Selected samples from Bitter Creek, Oak Creek, and the Verde River contained concentrations above detection limits.

Natural sources of arsenic predominantly include volcanic and lacustrine deposits (Hem, 1985). Arsenic concentrations were lowest in the upper Verde River watershed, where they ranged from 1 to 20 µg/L in samples from Granite Creek. Concentrations steadily increase from near the mouth of Sycamore Creek to the downstream end of the study area near Camp Verde (fig. 28*B*). In the middle Verde River watershed, concentrations ranged from less than the detection limit to 27 µg/L. The source of arsenic likely is the oxidized sulfides of the Verde Formation and Tertiary volcanic deposits (Robertson, 1991).

Dissolved boron concentrations ranged from 136 µg/L at the upper Verde River springs to 230 µg/L near the Verde River near Paulden streamflow-gaging station (09503700). The concentration in the river was 160 µg/L near the mouth of Sycamore Creek and decreased downstream (fig. 28*C*). Concentrations in Sycamore and Oak Creeks are less than concentrations in the river. Wet Beaver Creek had concentrations that were high (118–380 µg/L) compared with concentrations in other tributaries. As a result, boron concentrations in the Verde River generally increased from about 180 µg/L to 270 µg/L between Beaver Creek and the Verde River near Camp Verde streamflow-gaging station (09506000).

Concentrations of dissolved lithium ranged from 28 to 60 µg/L in the upper Verde River (fig. 28*D*) and from 13 to 33 µg/L in the middle Verde River. In Sycamore and Oak Creeks, concentrations ranged from 2 to 12 µg/L. The concentration was 37 µg/L in the Verde River immediately upstream from the mouth of West Clear Creek.

Concentrations of dissolved manganese in the Verde River ranged from 0 to 40 µg/L (fig 27*E*). Concentrations generally decreased downstream from the mouth of Sycamore Creek. Increases in concentrations occur from near Dead Horse Ranch State Park downstream to near Cottonwood. Concentrations decreased downstream from the mouth of West Clear Creek.

Concentrations of dissolved strontium in the upper Verde River ranged from 241 to 380 µg/L between the upper Verde River springs and Perkinsville, and ranged from 166 to 240 µg/L in the middle Verde River (fig 27*F*). Sycamore Creek had a concentration of 109 µg/L. The highest concentration in the Verde River immediately upstream from the mouth of West Clear Creek was 2,270 µg/L.

Stable Isotopes.—Stable isotopes provide a reference for determining the potential sources of base flow in the Verde River. For example, as hydrogen and oxygen isotopic compositions become lighter, the source water is inferred to change from that of a warmer, lower altitude region to that of a colder, higher altitude region. $\delta^{2}H$ and $\delta^{18}O$ values for surface waters in the study area range from -83 to -62 per mil and from -11.7 to -8.8 per mil, respectively, excluding outlier data (appendix 8).

Similar to major-ion chemistry, $\delta^{2}H$ and $\delta^{18}O$ values vary spatially within the upper and middle watersheds. $\delta^{2}H$ and $\delta^{18}O$ values for water discharging from the upper Verde River springs averaged -74 and -10.1 per mil, respectively. In the Verde River, $\delta^{18}O$ values become heavier between the upper Verde River springs area and Perkinsville (fig. 29); $\delta^{2}H$ and $\delta^{18}O$ values increase from about -73 to -71 per mil and from -10.2 to -9.4 per mil, respectively (appendix 8). The greatest change occurs downstream from Perkinsville at Mormon Pocket, where values decrease from about -73 to -77 per mil and -9.9 to -10.8 per mil. Values continue to decrease gradually to the mouth of Sycamore Creek and change little downstream from the creek. Water at the downstream end of the watershed near the Verde River near Camp Verde streamflow-gaging station (09506000) has slightly heavier $\delta^{2}H$ and $\delta^{18}O$ values than water in the reach between Mormon Pocket and the gaging station.

Stable isotope values were determined for several of the tributaries in the watershed during base-flow conditions. Samples from Williamson Valley Wash and Granite Creek had the heaviest compositions (-68 to -67 per mil for $\delta^{2}H$, and -9.2 to -9.3 per mil for $\delta^{18}O$), whereas samples from Sycamore and Oak Creeks had the lightest (-83 to -80 per mil for $\delta^{2}H$ and -11.7 to -11.4 per mil for $\delta^{18}O$). Samples from West Clear Creek had values between those from the other tributaries (about -77 to -74 per mil for $\delta^{2}H$, and -10.9 to -10.4 per mil for $\delta^{18}O$).

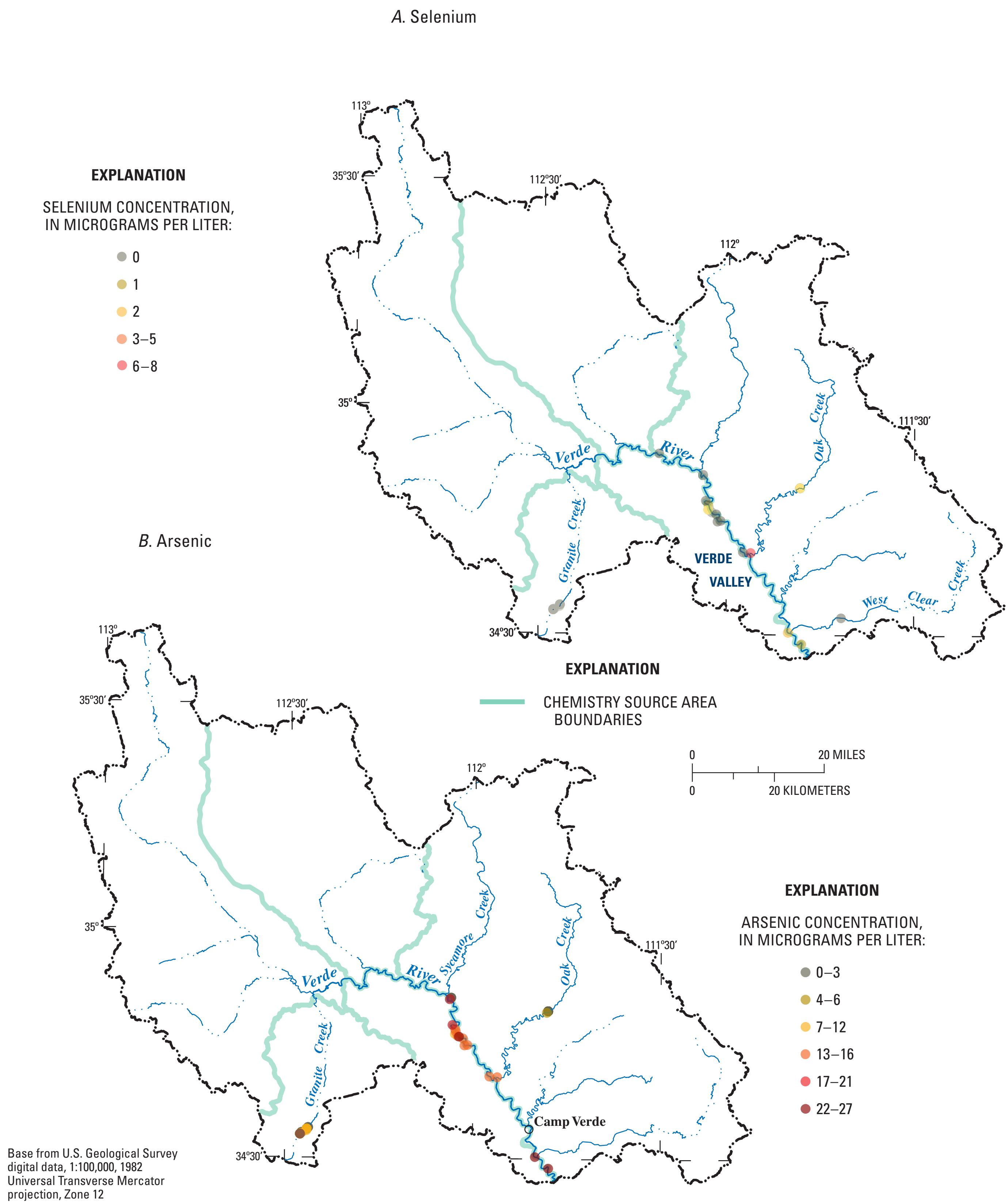
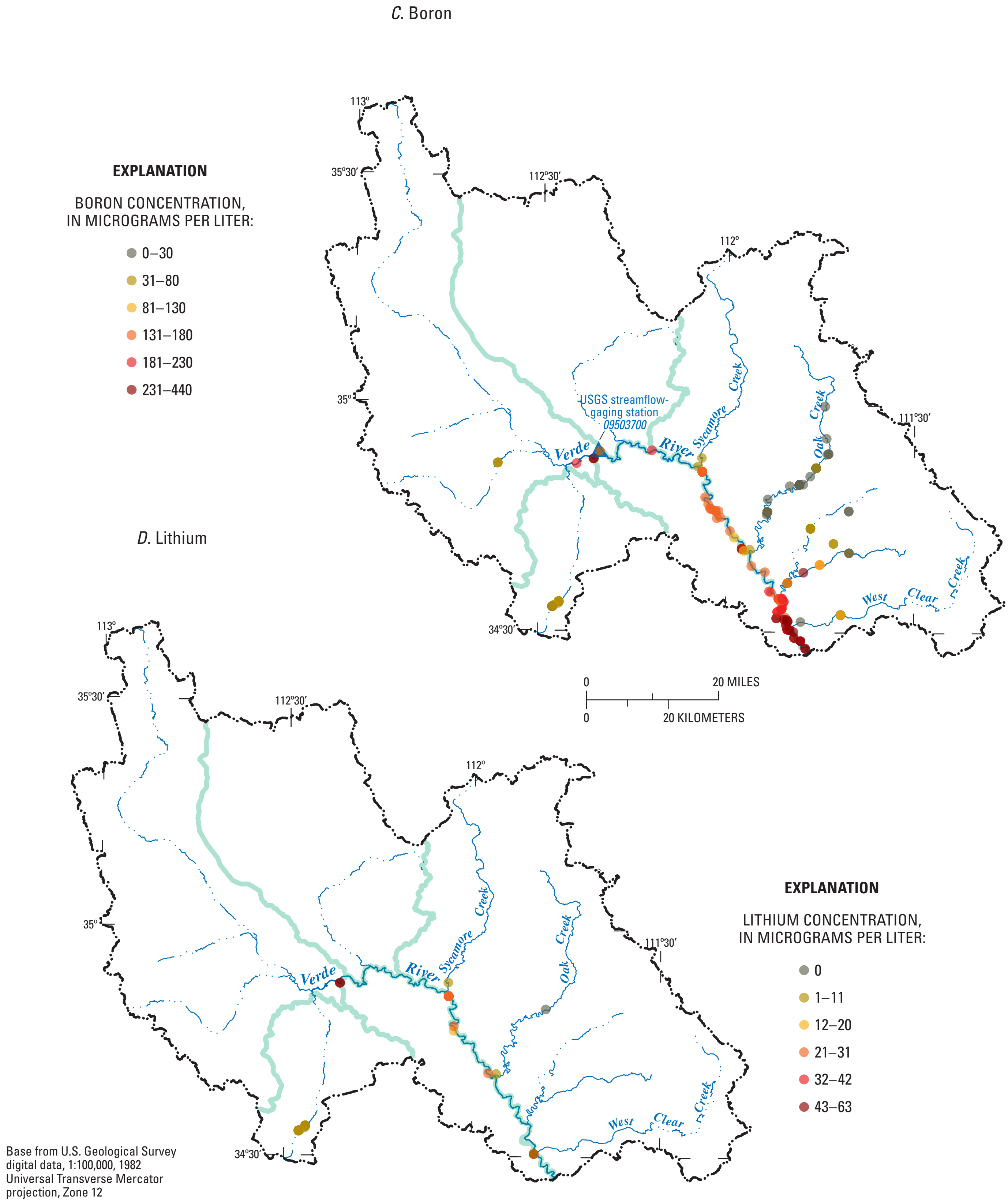


Figure 28. Concentrations of trace elements in surface water within the upper and middle Verde River watersheds, central Arizona. *A*, Selenium; *B*, Arsenic; *C*, Boron; *D*; Lithium; *E*, Manganese; *F*, Strontium.



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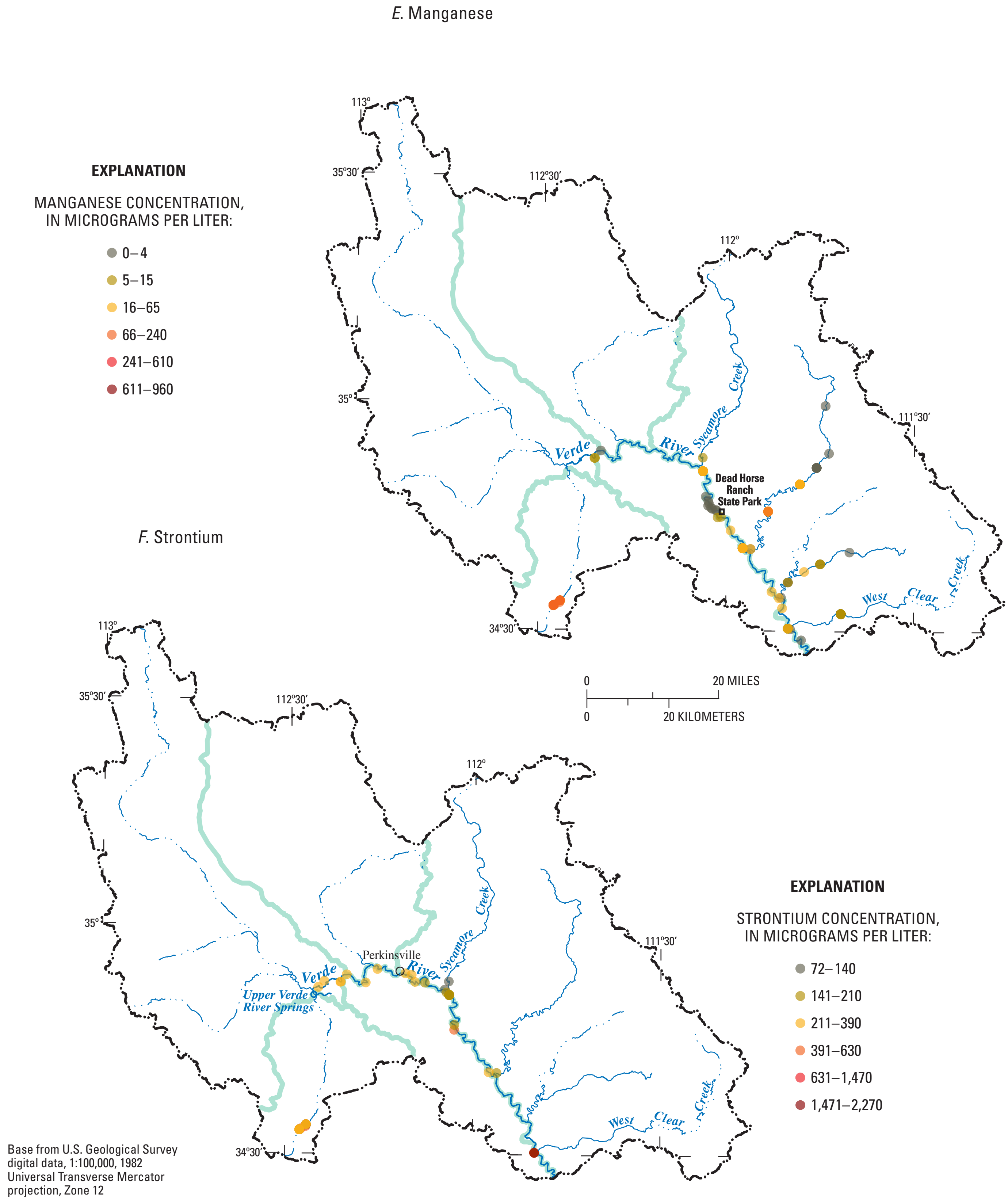

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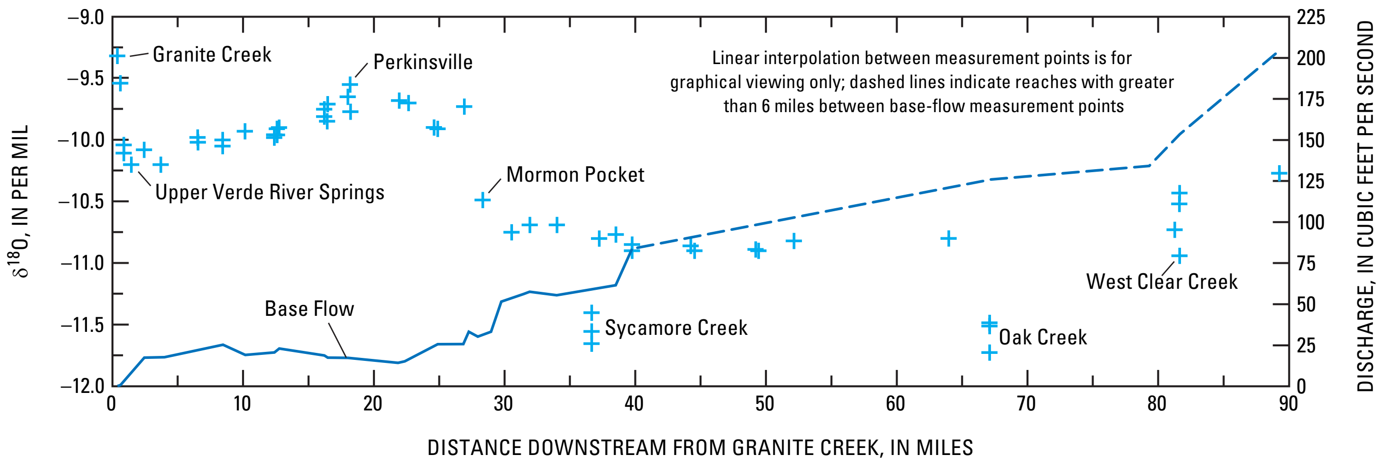


Figure 29. Base flow for the Verde River and $\delta^{18}O$ values for the Verde River, its tributaries, and springs discharging to the upper and middle Verde River watersheds, central Arizona.

Ground Water and Spring Water

Major Ions.—Proportions of anions and cations in ground water and spring water in the study area indicate that most of these waters are a bicarbonate type. Ground water from wells and springs in Big Chino Valley is predominantly a bicarbonate type and is distinctive in the study area because of its large sodium component (fig. 30). Major-ion chemistry of water in Big Chino Valley is similar to that of water in the reach of the Verde River between the upper Verde River springs and the Verde River near Paulden streamflow-gaging station (09503700). Ground water from the Bradshaw Mountains is generally a calcium bicarbonate type that is similar to that of Granite Creek. General major-ion chemistry of ground water in the Bradshaw Mountains is similar to that in Little Chino Valley, but water in the Bradshaw Mountains has slightly larger proportions of bicarbonate, calcium, and magnesium.

Waters within the western part of the Coconino Plateau and the part of the Coconino Plateau in the Verde Valley subbasin are also bicarbonate types; however, the Coconino Plateau within the Verde Valley subbasin generally has the largest proportion of bicarbonate, calcium, and magnesium, whereas the western part of the Coconino Plateau generally has the largest proportion of chloride and sulfate (fig. 30).

Three springs that discharge from different geologic units in the Verde Valley were sampled for major-ion analysis. The units include the Tertiary sedimentary rocks in the Black Hills, the Verde Formation, and the Coconino Sandstone. Water from the Black Hills contains the smallest percentage of bicarbonate and largest percentage of sulfate compared to water from the other two springs, and contains a large percentage of calcium, similar to that of ground water from Little Chino Valley and springs near the Bradshaw Mountains. Water from the Verde Formation has a large percentage of calcium and bicarbonate, consistent with the limestone lithology. Water from the Coconino Sandstone is similar to water from higher altitudes along the Coconino Plateau within the Verde Valley subbasin, although it has smaller percentages of bicarbonate and calcium.

Trace Elements.—Trace-element concentrations in ground water within the study area vary spatially. Concentrations of selenium, arsenic, boron, lithium, manganese, and strontium are discussed in this report. In general, trace-element concentrations are highest in the Big Chino Valley and Verde Valley south of the Verde River.

Concentrations of dissolved selenium in ground water ranged from 0 to 51 µg/L. The highest concentrations were measured in wells adjacent to the Verde River between the mouth of Wet Beaver Creek and West Clear Creek (fig. 31*A*). Concentrations in Little Chino Valley and along the Mogollon Escarpment ranged from 0 to 2 µg/L.

Arsenic concentrations are lowest in the higher altitudes of the Coconino Plateau in the Verde Valley subbasin (fig. 31*B*). The highest concentration was 506 µg/L, west of Paulden. Samples for the Chino Valley subbasins ranged from 0 to 506 µg/L. Tertiary volcanic rocks are the likely source of the high concentrations in the Chino Valley subbasins. Arsenic concentrations in the western part of the Coconino Plateau ranged from 0 to 16 µg/L. Ground water in the southern part of the Verde Valley generally had higher concentrations (0–220 µg/L) than ground water in the northern part (0–28 µg/L). Foust and others (2004) conducted a geostatistical analysis on data from 41 ground-water samples collected throughout Verde Valley and concluded that the primary sources of arsenic were the Verde Formation and the Supai Group.

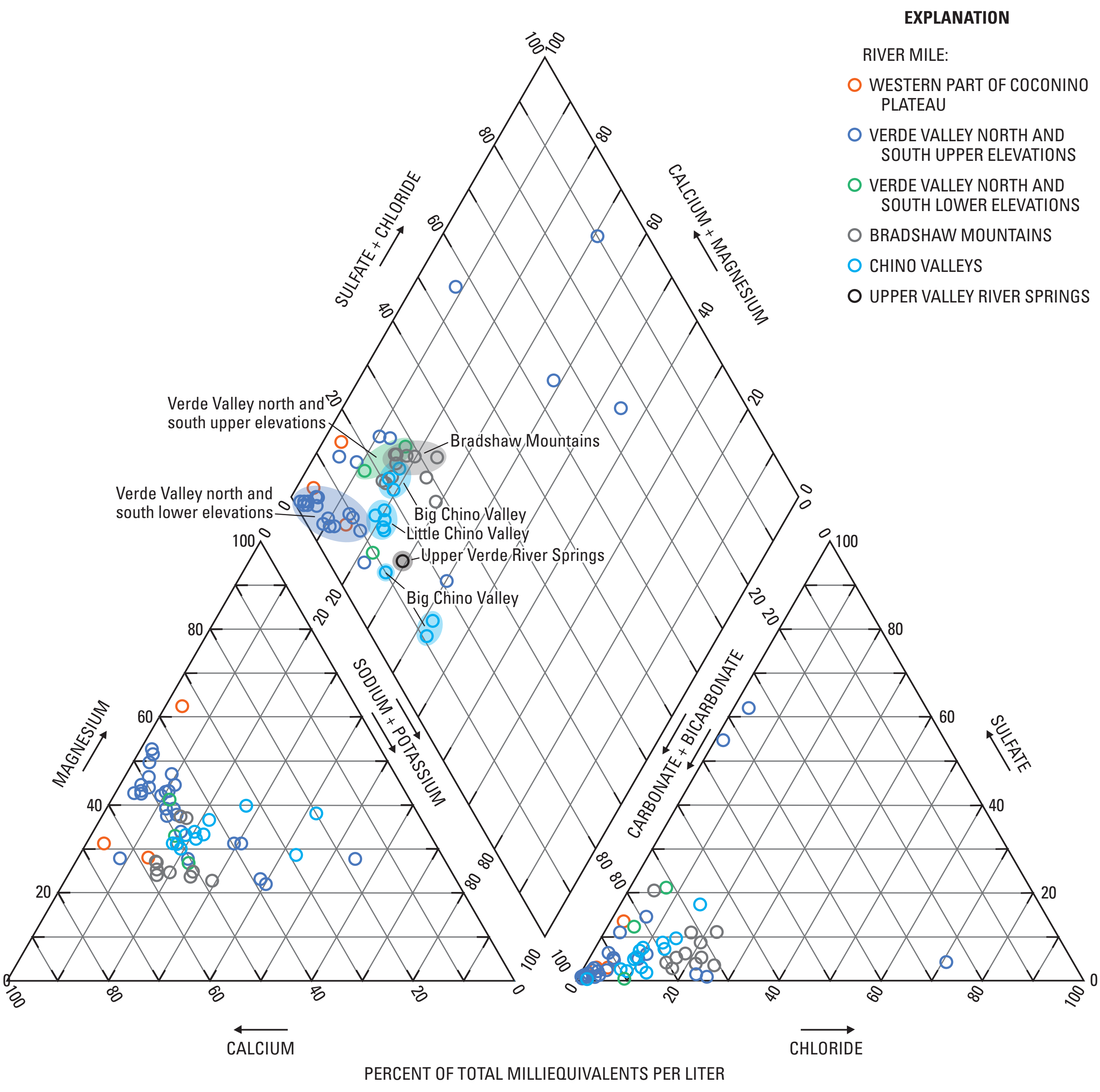


Figure 30. Relative ion composition of ground water in the upper and middle Verde River watersheds, central Arizona.

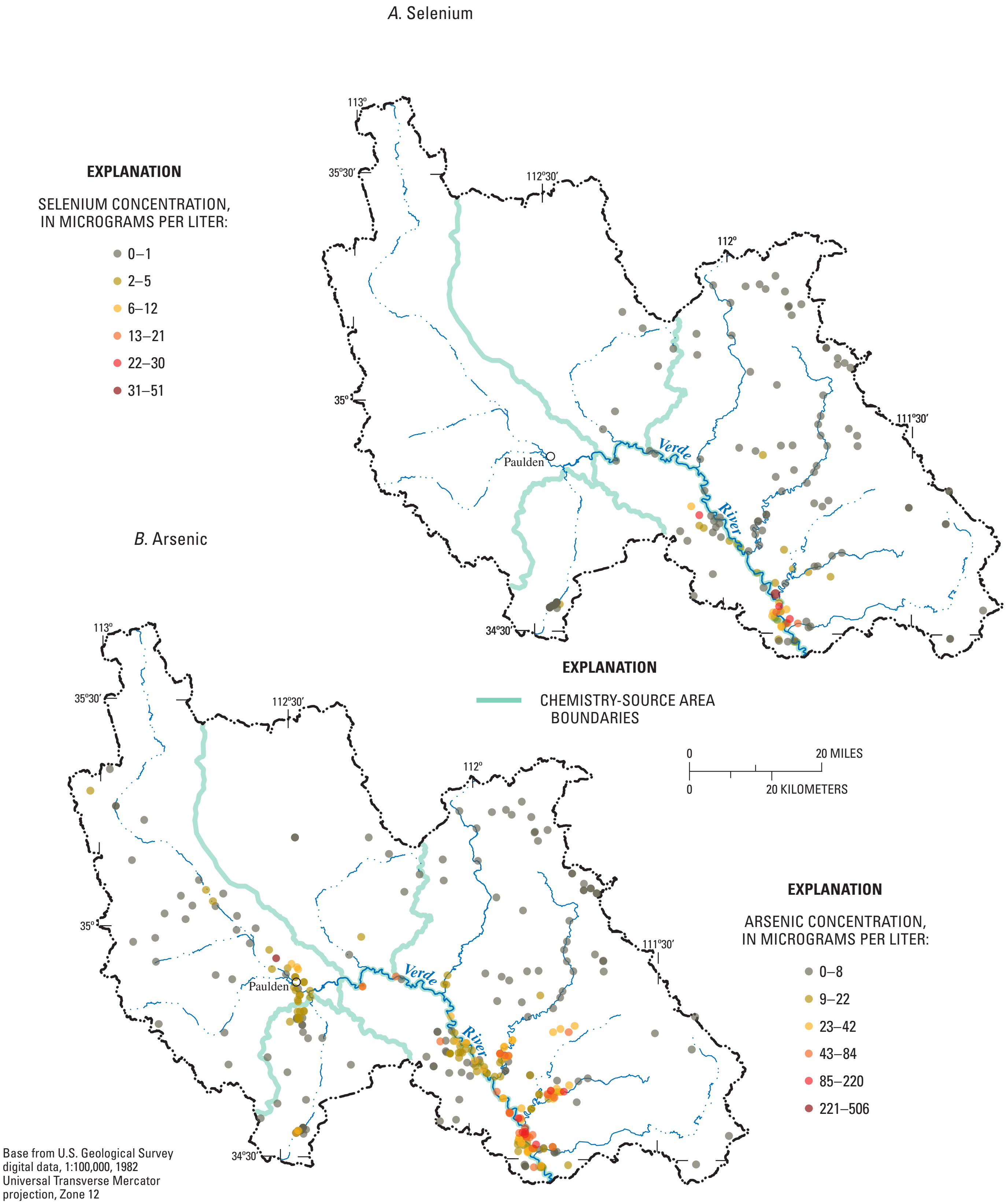


Figure 31. Concentrations of trace elements in ground water within the upper and middle Verde River watersheds, central Arizona. *A*, Selenium; *B*, Arsenic; *C*, Boron; *D*, Lithium; *E*, Manganese; *F*, Strontium.

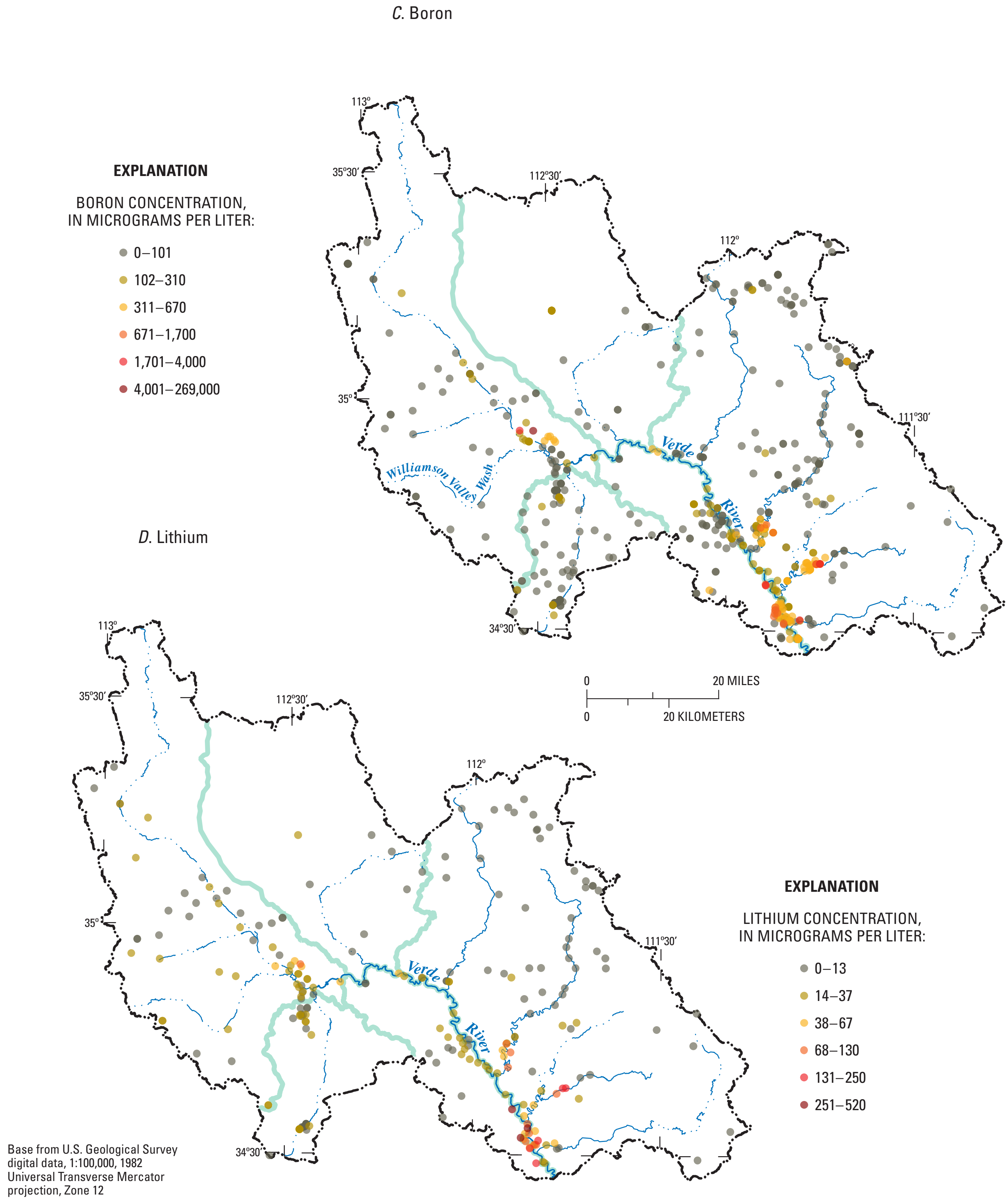


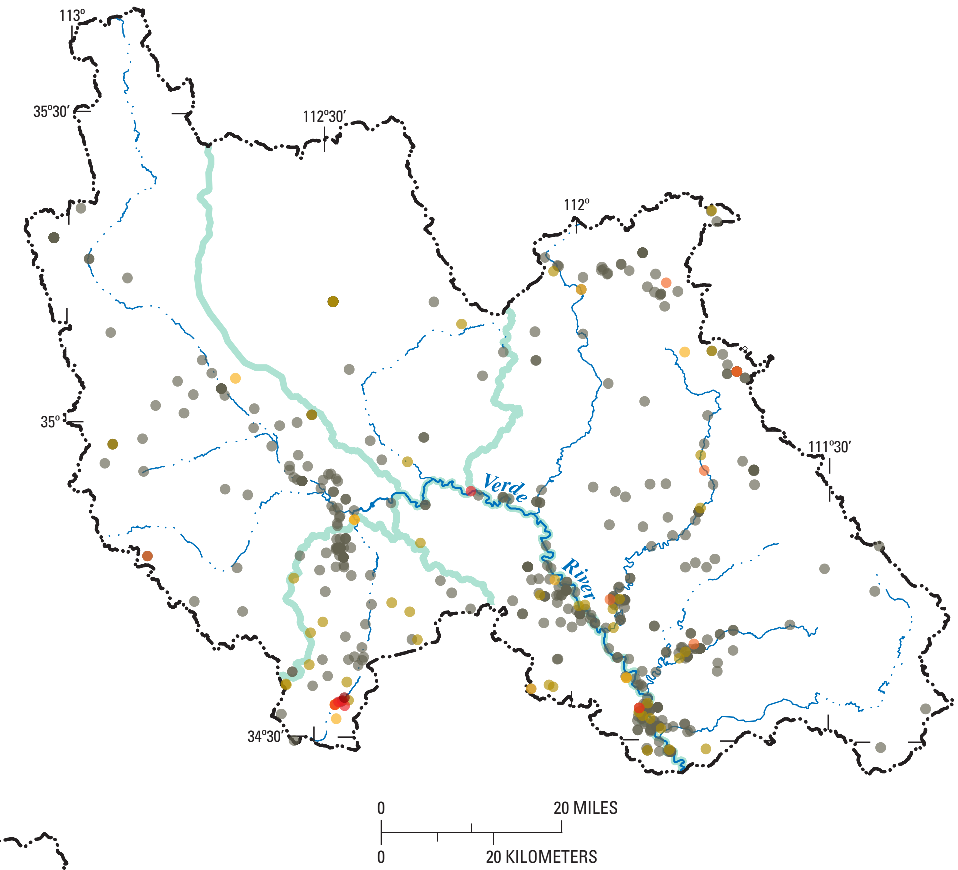
Figure 31. Continued.

E. Manganese

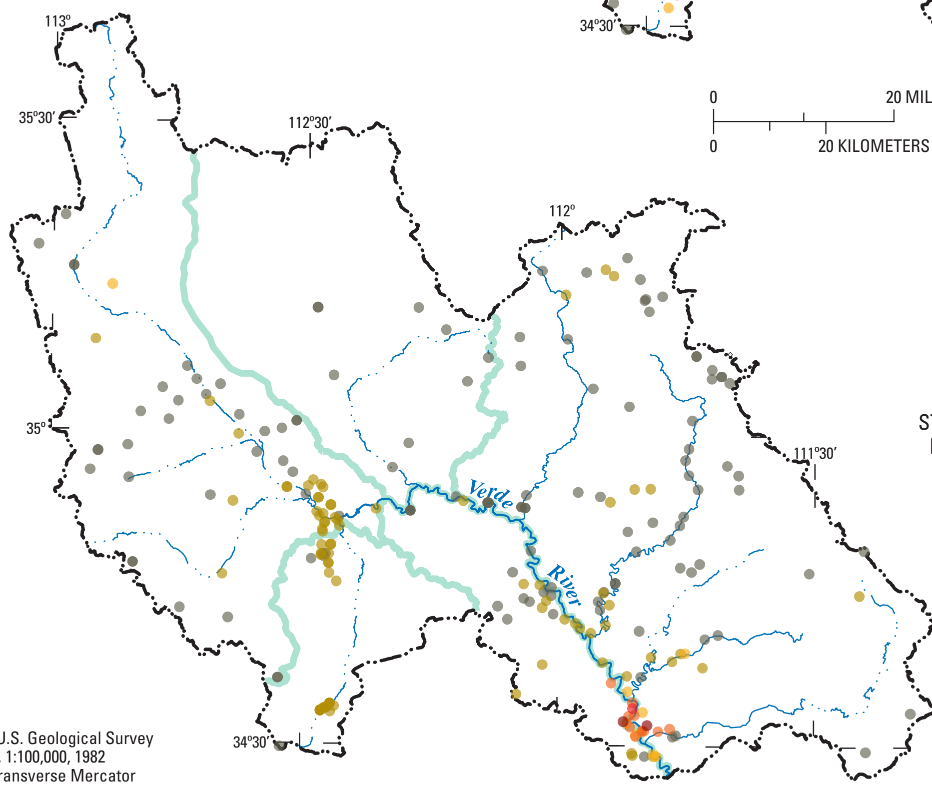
EXPLANATION

MANGANESE CONCENTRATION, IN MICROGRAMS PER LITER:

- 0–16
- 17–60
- 61–122
- 123–250
- 251–780
- 781–2,320



F. Strontium



EXPLANATION

STRONTIUM CONCENTRATION, IN MICROGRAMS PER LITER:

- 0–350
- 351–970
- 971–2,600
- 2,601–6,400
- 6,401–11,000
- 11,001–21,000

Base from U.S. Geological Survey digital data, 1:100,000, 1982
Universal Transverse Mercator projection, Zone 12

Figure 31. Continued.

Boron concentrations generally were highest in ground water from the lower altitudes of Verde Valley and in Big Chino Valley near the mouth of Williamson Valley Wash (fig. 31*C*). The average concentration in ground water from Big Chino Valley (127 µg/L) was higher than the average for Little Chino Valley (53.7 µg/L). Ground water from the higher altitudes along the Coconino Plateau had the lowest average concentration of boron in the study area (30 µg/L).

Similar to the average concentration of boron, the average concentration of lithium was highest in ground water from the lower altitudes of Verde Valley and Big Chino Valley (66.5 µg/L and 43.4 µg/L, respectively, fig. 31*D*). The average concentration in ground water from Big Chino Valley (18.6 µg/L) was higher than that for Little Chino Valley (13.1 µg/L). Ground water from the Coconino Plateau had the lowest average concentrations of lithium in the study area (3.5 µg/L).

Manganese concentrations generally were highest in ground water from the southern end of the Little Chino subbasin (fig. 31*E*) The average concentration in samples from other parts of the subbasin was 19.7 µg/L. Average concentrations for Verde Valley, Big Chino Valley, and the western part of the Coconino Plateau were 15 µg/L, 3 µg/L, and 4 µg/L, respectively.

Verde Valley had the highest average concentration of strontium (1,936 µg/L, fig. 31*F*). Average concentrations in Big Chino and Little Chino Valleys were similar (319 µg/L and 416 µg/L, respectively). Ground water from the Coconino Plateau had the lowest average concentration in the study area (169 µg/L).

Stable Isotopes.—Stable-isotope values for ground water and spring water plot between the GMWL and the local meteoric water line for the Flagstaff area (fig. 32). Outlier data were not included in interpretations of stable isotope patterns in ground water. δ^2H values ranged from -89 to -69 per mil, and $\delta^{18}O$ values ranged from -12.3 to -9.0 per mil. Similar to the patterns in major-ion and trace-element chemistry, δ^2H and $\delta^{18}O$ values can be grouped on the basis of sample location. For example, samples collected from the higher altitude parts of the Verde Valley on the Coconino Plateau had the lightest δ^2H and $\delta^{18}O$ values. δ^2H values ranged from -89 to -82 per mil and averaged -86 per mil, and $\delta^{18}O$ values ranged from -12.3 to -11.3 per mil and averaged -11.9 per mil. Samples from Little Chino Valley had the heaviest values: -72 to -66 per mil for δ^2H, and -10.1 to -8.8 per mil for $\delta^{18}O$. Average values were -70 per mil for δ^2H and -9.7 per mil for $\delta^{18}O$ (table 17).

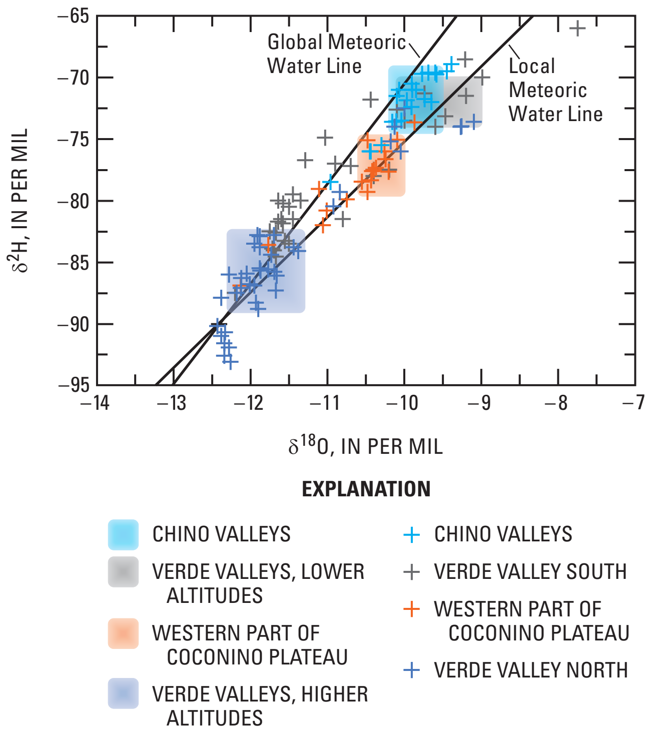


Figure 32. δ^2H and $\delta^{18}O$ values for ground water and springs, and stable-isotope value ranges for the four end-member regions within the upper and middle Verde River watersheds, central Arizona.

Table 17. Minimum, maximum, average, and standard deviation values for δ^2H and $\delta^{18}O$ ground-water and spring samples used in mass-balance mixing equations for the Verde River

[Average values are used as end members in mixing equations]

Part of study area	Minimum (per mil) δ^2H derived	Minimum (per mil) $\delta^{18}O$ derived	Maximum (per mil) δ^2H derived	Maximum (per mil) $\delta^{18}O$ derived	Average (per mil) δ^2H derived	Average (per mil) $\delta^{18}O$ derived	Standard deviation (per mil) δ^2H derived	Standard deviation (per mil) $\delta^{18}O$ derived
Western part of Coconino Plateau	-80	-10.6	-75	-10	-77	-10.4	1.4	0.15
Chino Valley	-75	-10.2	-69	-9.5	-72	-9.9	1.5	.19
Verde Valley north	-89	-12.3	-82	-11.3	-86	-11.9	1.8	.22
Verde Valley south	-74	-10.1	-70	-9	-72	-9.6	1.4	.4

Geochemical Mixing Model

A geochemical mixing model was used to quantify fractions of source waters from various ground-water regions to the upper and middle Verde River watersheds. Stable-isotope values for ground-water source areas are represented as end-member values in the mixing equations. The values are used in the mixing equations because they represent the most commonly used conservative tracers in the study area. δ^2H and $\delta^{18}O$ values remain constant if the water molecules are not subject to fractionation, such as through evaporation. Values for ground water subjected to evaporation plot away from the GMWL and were not used in the mixing-equation analysis.

Seasonality of Ground Water Recharge

The seasonal contribution of precipitation to recharge was calculated using a two-end-member mixing equation. Summer and fall stable-isotope values were combined into one group and used as a end member. The other end member represents isotope values for winter precipitation. Average stable-isotope values were calculated for each end member under the assumption that recharge contributions were the same for a given altitude range in the subbasin. This procedure likely results in average isotope values for each end member that are biased towards a lower altitude warmer (summer) signal. Thus, the results of this analysis are biased towards a greater summer ground-water recharge component.

The following two-end-member mass-balance mixing equations were used for the seasonal recharge contributions:

$$\delta^{18}O_{GW} = (\delta^{18}O_{SF}(f_{SF})) + (\delta^{18}O_{W}(f_{W})) \tag{17}$$

and

$$f_{SF} + f_{W} = 1, \tag{18}$$

where $\delta^{18}O_{GW}$ is the ground-water oxygen isotope value in per mil, f denotes the fraction of seasonal recharge, *SF* denotes summer and fall, and *W* denotes winter.

The isotope value at each altitude was then calculated using the measured gradients and calculated seasonal fraction according to the following equation:

$$\delta^{18}O(z) = (\delta^{18}O_{SF}(z) \times f_{SF}) + (\delta^{18}O_{W}(z) \times f_{W}), \tag{19}$$

where z is the altitude.

As much as 4 percent of ground-water recharge is from summer and fall precipitation. This small amount is likely related to high temperatures and active vegetation that are optimal conditions for high evapotranspiration rates. High intensity, short duration rainfall from summer monsoon storms also results in runoff rather than infiltration, which more commonly occurs from low intensity, longer duration frontal storms during the winter. In the analysis it was assumed that precipitation at all altitudes contributed equally to the average stable-isotope value for each seasonal end member. The assumption is biased towards values for lower altitudes because ground-water samples were collected at the lower-altitude terminus of the subbasins. This analysis provides a reasonable conclusion that the ground-water isotope values reflect a mixture of water from various altitudes primarily from winter recharge.

Source Water to the Verde River

Sources of water to the Verde River were differentiated on the basis of chemical and hydrologic characteristics described in the preceding sections of this report. End-member values used in the mass-balance mixing equations for the Verde River are derived from stable-isotope values for areas delineated for geochemical mixing model analysis (figs. 4 and 33 and table 18). Boundaries of the source areas generally coincide with subbasin boundaries; where they differ, watershed boundaries defined by the USGS Elevation Derivatives for National Applications (EDNA) database (U.S. Geological Survey, 2005) were used as the source-area boundaries. Representative data were chosen for each end member used in the mixing-model calculations so that each has a distinct range of stable-isotope values with minimal overlap between parts of the study area (fig. 32). Representative data were considered to be those that tended to cluster for a given area. Data for water subject to evaporation were removed from the analysis. Mixing equations defining the mixing model were applied to reaches of the Verde River.

The Chino Valleys end member comprises stable-isotope values from Big and Little Chino Valleys. For the purpose of quantifying source waters to the Verde River beyond the first reach, values from these two valleys are combined for two reasons: (1) differences in their stable-isotope values are small relative to the changes in values that occur along the Verde River, and (2) two conservative tracers limit the mixing equations to three components. Stable-isotope data for ground water in the western part of the Coconino Plateau are sparse. One end member is used to represent the higher altitudes of the Verde Valley subbasin, which includes a part of the Coconino Plateau in the eastern part of the study area. Values for samples collected above 6,900 ft in the Verde Valley north and south source areas are combined to create the Verde Valley higher altitude end member. Similarly, values for samples collected below 6,900 ft are combined to create the Verde Valley lower altitude end member.

Table 18. Mass-balance mixing equations used for each reach of the Verde River

[*f* represents the fraction of each end member in the measured sample and $\delta^{18}O$ and $\delta^{2}H$ are the corresponding compositions]

Reach	End members	Mass-balance mixing equation
1	Little Chino subbasin (LC) + Big Chino subbasins (BC)	$\delta^2H_S = (\delta^2H_{LC} \times f_{LC}) + (\delta^2H_{BC} \times f_{BC})$
		$f_{LC} + f_{BC} = 1$
2	Chino subbasins (CV) + Western part of Coconino Plateau (WCP)	$\delta^2H_S = (\delta^2H_{WCP} \times f_{WCP}) + (\delta^2H_{CV} \times f_{CV})$
		$f_{WCP} + f_{CV} = 1$
3	Upper Verde River surface water (USW)[1] + Verde Valley subbasin south (VVS) + Verde Valley subbasin north (VVN)	$\delta^{18}O_S = (\delta^{18}O_{USW} \times f_{USW}) + (\delta^{18}O_{VVS} \times f_{VVS}) + (\delta^{18}O_{VVN} \times f_{VVN})$
		$\delta^2H_S = (\delta^2H_{USW} \times f_{USW}) + (\delta^2H^{VVS} \times f_{VVS}) + (\delta^2H_{VVN} \times f_{VVN})$
		$f_{USW} + f_{VV} + f_{VVN} = 1$

[1]USW is a combination of CV and WCP contributions.

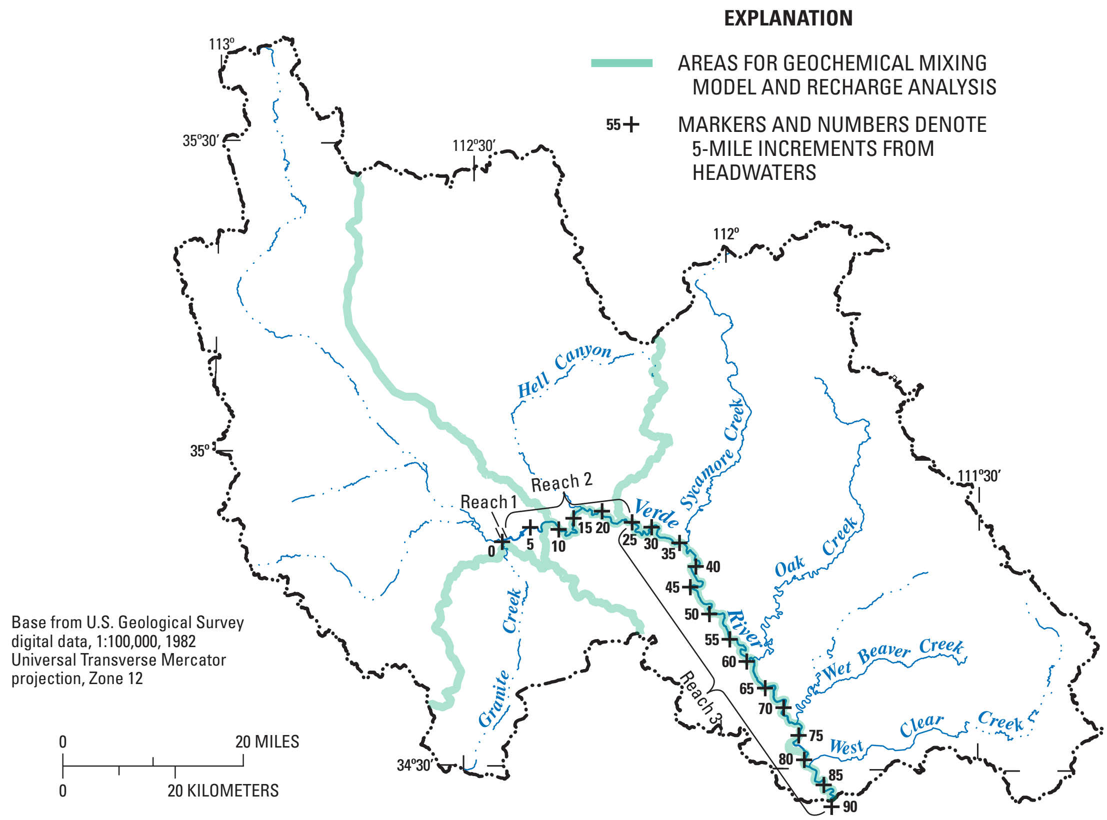
Three distinct reaches along the Verde River were identified on the basis of stable-isotope data and changes in base flow (figs. 29 and 33). Plausible end members for each reach were selected on the basis of the pertinent hydrologic system and were limited to combinations that resulted in positive percentages within one standard deviation of error.

Reach 1 (Little Chino Valley and Big Chino Valley, river mile 0 to 0.2).—Water in reach 1 is similar in major-ion and isotopic composition to both water from Little Chino Valley (figs. 27 and 30, table 17) and a sample from Granite Creek collected upstream from the mouth. Base flow along this reach typically is less than 1 ft^3/s. δ^2H and $\delta^{18}O$ values decrease from -67.1 and -9.31 per mil, respectively, in Granite Creek, to -69.2 and -9.6 per mil, respectively, in the Verde River. Similarity between stable-isotope values from Big and Little Chino Valleys precludes accurate quantification of ground-water contributions from each region by using mass-balance mixing equations with δ^2H and $\delta^{18}O$ data.

Reach 2 (Chino Valleys and the western part of the Coconino Plateau, river mile 0.2 to 22).—Water in reach 2 comprises water from the Chino Valleys and the western part of the Coconino Plateau (table 18 and fig. 33). Reach 2 includes the upper Verde River springs, which cause base flow to increase from 1 ft^3/s to 17 ft^3/s within the first 2 mi of the reach. Water from reach 1 is diluted in the first mile with roughly equal contributions of water from the Chino Valleys and the western part of the Coconino Plateau. Base flow increases to 25 ft^3/s during the first 8 mi. During this section of the reach, the relative contribution from the Chino Valleys increases compared to that from the western part of the Coconino Plateau. Base flow declines from about 25 ft^3/s to 15 ft^3/s between river miles 8 and 22. Verde River stable-isotope values are indicative of evaporation along this section of the reach (fig. 29). The contribution from the western part of the Coconino Plateau decreases and is negligible when compared to contributions from the Chino Valleys downstream from river mile 12. The contribution from waters having end-member δ^2H and $\delta^{18}O$ values could vary by ±27 percent on the basis of error analysis.

Reach 3 (Upper Verde River surface water and Verde Valley higher altitudes, and Verde Valley lower altitudes, river miles 22 to 89).—An upper Verde River end member, incorporating all previous end-member inputs (Little Chino subbasin, Big Chino subbasin, western part of the Coconino Plateau), is used with water from the Verde Valley higher altitude and Verde Valley lower altitude end members for the mixing model for this reach. Base flow increases from 15 ft^3/s to 25 ft^3/s between river miles 22 and 25. In this part of the reach, surface water from reach 2 is the predominant source. Between river miles 25 and 30, base flow increases from 25 ft^3/s to 55 ft^3/s, and the relative contribution from the Verde Valley higher altitude source area increases from negligible to about half. The contributions from the Verde Valley lower and higher altitude source areas remain about equal until the end of the reach. Between river miles 40 and 67, base flow increases from 84 ft^3/s to 126 ft^3/s. It also increases from 153 ft^3/s to 204 ft^3/s downstream from the mouth of West Clear Creek between river miles 81 and 89. By the end of the reach, about half of the water is from the Verde Valley lower altitude source area. The contribution from waters having end-member δ^2H and $\delta^{18}O$ values could vary by ±9.8 percent on the basis of error analysis.

A. Reaches



B. Base-flow contributions

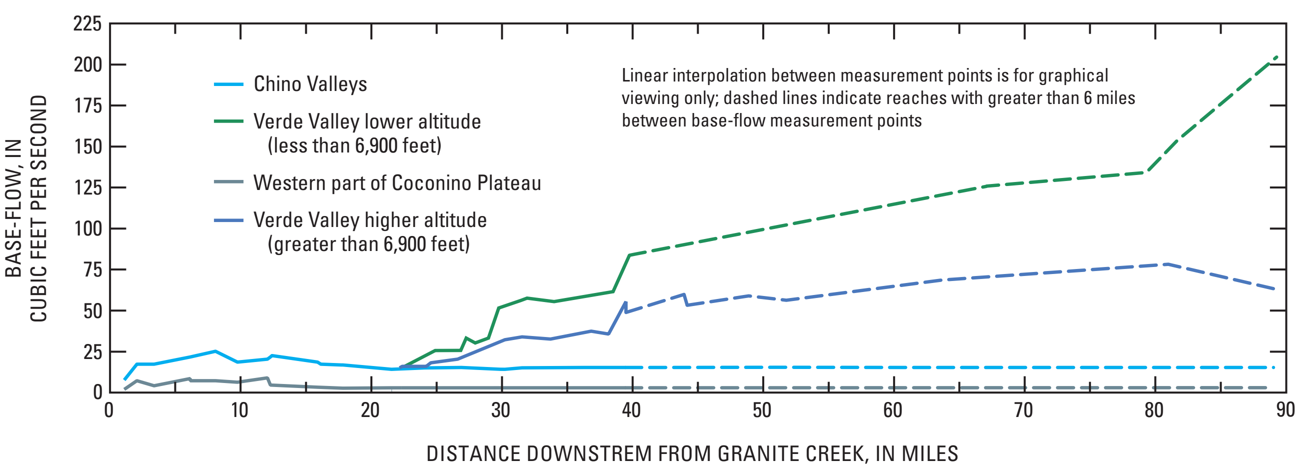


Figure 33. *A*, Three distinct reaches along the Verde River identified on the basis of water chemistry and variations in base flow; *B*, Cumulative base flow partitioned from source areas to the Verde River.

Source Water to the Upper Verde River Springs

Major-ion data indicate that water discharging at the upper Verde River springs is a mixture of ground water from the western part of the Coconino Plateau, from Big Chino Valley, and from Little Chino Valley. It is most similar to ground water from Big Chino Valley (fig. 30). On the basis of inverse geochemical modeling (PHREEQC; Parkhurst and Apello, 1999), Wirt and others (2005) estimated that contributions to the springs from the basin-fill and Paleozoic rock aquifers of Big Chino Valley are about 81 percent, contributions from the western part of the Coconino Plateau are 19 percent, and contributions from the Little Chino subbasin are negligible.

Water Quality

Water quality in the upper and middle Verde River watersheds is generally good for most uses and reflects little evidence of human activities. Constituent concentrations in surface water and ground water in the study area generally were well below Federal and State regulations with the exception of several inorganic compounds, including arsenic.

Results of water analyses were compared to Primary and Secondary Drinking-Water Regulations of the U.S. Environmental Protection Agency (USEPA; U.S. Environmental Protection Agency, 2003). Primary Drinking-Water Regulations include Maximum Contaminant Levels (MCLs) that are enforceable standards. MCLs apply to inorganic, organic, and radionuclide constituents. Secondary Drinking-Water Regulations include Secondary Maximum Contaminant Levels (SMCLs) that are nonenforceable guidelines based on aesthetic properties of drinking water. Analytical data from surface-water samples also were compared to State of Arizona water-quality standards that are based on designated stream uses (Arizona Department of Environmental Quality, 1996).

Surface Water

Water-quality standards established by the Arizona Department of Environmental Quality (ADEQ) are dependent on the designated use or uses of water in a particular water body or stream reach. The standards are divided into two main categories: (1) Human Health and Agriculture designated use criteria and (2) Aquatic and Wildlife designated use criteria. Human Health and Agriculture criteria are set at levels safe for ingestion, body contact, irrigation, and livestock watering. Aquatic and Wildlife criteria are set at levels considered safe for aquatic organisms and other wildlife that are supported by surface water. With the exception of arsenic, surface-water samples from the study area met water-quality standards for all 143 analytes. The U.S. Environmental Protection Agency (USEPA) MCL for arsenic will change from 50 µg/L to 10 µg/L on January 23, 2006. All surface-water samples from the Verde River collected between the mouth of Sycamore Creek and the Verde River near Camp Verde gaging station (09506000) had concentrations that exceeded 10 µg/L. The Verde River and its tributaries are maintained by ground-water discharge and reflect the quality of ground water within the study area.

Ground Water

Ground water throughout most of the study area meets USEPA Primary Drinking-Water Regulations with the exception of several inorganic constituents (table 19). Concentrations of antimony, arsenic, fluoride, lead, nitrate, and selenium exceeded the MCLs in some samples. Inorganic constituents naturally occur in the environment and also can be released by agricultural (nitrate and nitrite, for example) and industrial activities (antimony and asbestos, for example). Of these constituents, arsenic exceeded the standard in the greatest number of samples. The change in the MCL will result in an increased number of wells that are unsuitable as sources of drinking water if no actions are taken to reduce concentrations in the distribution systems.

Arsenic is prevalent throughout the study area, especially west of Paulden and in the Verde Valley. Ninety percent of ground-water samples from Verde Valley south of the Verde River had arsenic concentrations that exceeded 10 µg/L. Arsenic concentrations in rock samples from the Verde Formation ranged from 7 to 88 parts per million (Robertson, 1991).

Arsenic typically is associated with either reduced sulfide compounds or oxidized arsenate compounds. Arsenic compounds in ground-water systems of southern Arizona are derived from hydrothermal sulfides and arsenide compounds in material that is deposited in the subbasins from the surrounding mountains (Robertson, 1991). Arsenic enters ground water when sulfide compounds are oxidized, forming arsenates (As^{5+}); arsenic can also enter the ground water in slightly reduced environments as arsenite (As^{3+}; Hem, 1985). Throughout the study area, arsenic occurs most commonly as arsenate owing to the stability of As^{5+} in oxygenated water having a pH between 7 and 11 (Robertson, 1991).

Multiple constituents in ground-water samples from the study area exceeded SMCLs (table 20). Concentrations of fluoride and sulfate exceeded the SMCLs more than any other constituent, and most of these samples were from Big and Little Chino Valleys and Verde Valley.

Table 19. Comparison of selected constituent concentrations in ground water from the upper and middle Verde River watersheds to U.S. Environmental Protection Agency National Primary Drinking Water Regulations

[TT, treatment technique]

		U.S. Environmental Protection Agency National Primary Drinking Water Regulations			
Constituent	**Concentration range (milligrams per liter)**	**Maximum Contaminant Level (milligrams per liter)**	**Percent of samples exceeding Maximum Contaminant Level**	**Maximum Contaminant Level Goal (milligrams per liter)**	**Percent of samples exceeding Maximum Contaminant Level Goal**
Antimony	0–0.007	0.006	0.05	0.006	0.05
Arsenic	0–0.506	[1].010	8.4	0	18.92
Barium	0–2	2	0	2	0
Beryllium	0–0.0012	.004	0	.004	0
Cadmium	0–0.003	.005	0	.005	0
Chromium	0–0.04	.1	0	.1	0
Copper	0–0.23	TT[2]	[3]0	1.3	0
Fluoride	0–22.5	4	1.19	4	1.19
Lead	0–0.04	TT[2]	[3].22	0	2.55
Nitrate	0–67	10	.65	10	.65
Nitrite	0–0.89	1	0	1	0
Selenium	0–0.051	.05	.05	.05	.05

[1]Compliance required beginning on January 23, 2006, decreased from previous standard of 0.050 milligrams per liter.

[2]Copper action level 1.3 milligrams per liter; lead action level 0.015 milligrams per liter.

[3]Percentage of samples exceeding action level.

Table 20. Comparison of selected constituent concentrations in ground water from the upper and middle Verde River watersheds to U.S. Environmental Protection Agency National Secondary Drinking Water Regulations

		U.S. Environmental Protection Agency National Secondary Drinking Water Regulations	
Constituent/property	**Concentration range (milligrams per liter)**	**Secondary Maximum Contaminant Level (milligrams per liter)**	**Percent of samples exceeding Secondary Maximum Contaminant Level**
Aluminum	0–0.08	0.05–0.2	0.1
Chloride	.4–6,720	250	2.14
Copper	0–0.23	1	0
Fluoride	0–22.5	2	4.34
Iron	0–15	.3	1.09
Manganese	0–2.32	.05	2.19
pH	5.6–10.8	6.5–8.5	1.25
Silver	0–0.003	.1	0
Sulphate	0–64,700	250	5.36
Zinc	0–6.5	5	.05

Conceptual Model of Hydrologic System

A conceptual model of the occurrence and flow of water within the upper and middle Verde River watersheds was developed through an understanding of the hydrologic processes within the subbasins. These hydrologic processes are governed by basic laws of physical transport and the interaction of water movement between the surface features and the underlying geologic units. Climatic, hydrologic, and geologic data described in previous sections were assimilated into watershed and regional-aquifer water budgets that provide a description of surface and subsurface flow systems. The water budgets describe the flow of water into, out of, and between these systems. The conceptual model incorporates the storage and flow information from the water budget into a cohesive hydrologic flow model.

Water Budgets

The importance of water-resource allocation in the upper and middle Verde River watersheds is evident by the number of historical water-budget investigations. These investigations were completed for the upper watershed by the ADWR in 2000 (Arizona Department of Water Resources, 2000) and Yavapai County in 2004 (John Munderloh, Yavapai County Water Coordinator, written commun., 2004). Water budgets for the middle watershed were developed by Owen-Joyce and Bell (1983), the ADWR (Arizona Department of Water Resources, 2000), and Yavapai County (John Munderloh, Yavapai County Water Coordinator, written commun., 2004). Only cursory comparisons of the budgets are appropriate between studies because of the variability in complexity, boundaries considered, and available data incorporated into each budget. Several of the investigations assumed no change in storage within the regional aquifer and a balance between inflows and outflows. These assumptions were not used for all of the subbasins described in the water-budget analysis for this study.

Water budgets were developed for the subbasins in the upper and middle Verde River watersheds and for the regional aquifers in the subbasins. Water-budget terms were estimated by using historical data to quantify the conceptual relation between the water-budget terms. Several water-budget terms were not estimated if there were insufficient data available. There is uncertainty associated with all water-budget terms; when possible, an estimated uncertainty (error) value is provided. Water-budget terms were rounded to four significant digits to facilitate comparison only and are not indicative of the actual precision.

Water Budgets for subbasins in the Upper and Middle Verde River Watersheds.— Water-balance equations are based on the law of conservation of mass, which states that the sum of the water entering a system minus the water exiting a system is equal to the change in storage. The water-balance equation used for each of the subbasins is

$$P+IR+GW_{in}+BF_{in}+RO_{in}-ET-GW_{out}-BF_{out}+RO_{out}-WU=\Delta S, \quad (20)$$

where P is precipitation (rainfall and snowfall); IR is incidental and artificial recharge; GW_{in} is ground-water flow into the subbasin; BF_{in} is the base flow into the subbasin from tributaries and streams; RO_{in} is runoff into the subbasin from tributaries and streams; ET is evaporation from open-water bodies and transpiration from riparian vegetation and subbasin vegetation; GW_{out} is ground-water flow out of the subbasin; BF_{out} is base flow out of the subbasin; RO_{out} is runoff out of the subbasin; WU is water used for agricultural, municipal, industrial, and domestic purposes; and ΔS is change in storage of surface water and ground water.

Average annual water budgets for the subbasins were developed by using data from different periods of record (table 21). Longer periods of record were used to improve accuracy in the estimated water-budget terms and to reduce anomalies caused by short-term variabilities in climate. Water-budget terms based on shorter periods of record are noted. Basin evapotranspiration was calculated as the remainder from the subbasin water-balance equation (potential eq. 20). Error associated with the basin evapotranspiration is potentially large because it includes potential error from the other water-budget terms and because not all components of the water-balance equation were calculated.

Regional-Aquifer Budgets.—Ground-water budgets compiled by the ADWR (Arizona Department of Water Resources, 2000) are the most comprehensive to date for the regional aquifers underlying the upper and middle Verde River watersheds; therefore, they were used as baselines for this study. Methods used in this study to calculate water-budget components are in some cases different from those used by the ADWR. Annual water budgets were developed for regional aquifers in the subbasins (table 22, appendix 9). The water-balance equation used for the water budgets is

$$R+IR+GW_{in}+BF_{in}-ET-GW_{out}-BF_{out}-WU=\Delta S, \quad (21)$$

where R is natural recharge; IR is incidental and artificial recharge; GW_{in} is ground-water flow into the aquifer; BF_{in} is base flow entering the subbasin; ET is evaporation and transpiration from riparian, open-water, and subirrigated areas connected to the regional aquifer; GW_{out} is ground-water flow out of the aquifer; BF_{out} is ground water leaving the aquifer as base flow; WU is water used for agricultural, municipal, industrial, and domestic purposes; and ΔS is change in aquifer storage. The primary difference between the subbasin and regional-aquifer water budgets is that the regional-aquifer water budgets consider only waters directly entering and leaving the aquifer. Natural recharge, incidental and artificial recharge, and water use are discussed in the following sections; all remaining terms in the water-balance equations were discussed in previous sections of this report.

Table 21. Average annual water budgets for subbasins in the upper and middle Verde River watersheds, central Arizona, for various periods of record

[Values are in acre-feet per year. Negative values indicate water is removed from or leaves the subbasin. Terms in brackets are estimated error as ± percent. Terms in parentheses refer to terms in water-balance equations. Detailed annual water budgets are included in appendix 9]

Water-budget component	Big Chino subbasin	Little Chino subbasin[1]	Verde Valley subbasin
Total inflow	**1,763,880**	**320,550**	**3,364,200**
Rain[2] (P)	1,550,000[10]	286,000[10]	2,850,000[10]
Snow[3] (P)	207,000	27,000	461,000
Base flow in[4] (BF_{in})	[4a]180	0	18,100
Runoff in[5] (RO_{in})	Not Calculated[5a]	0	15,800
Ground-water in[6] (GW_{in})	[6a]2,400	0	Not Calculated[6b]
Incidental and artificial recharge[7] (IR)	4,300	7,550	19,300
Total outflow	**-1,763,880**	**-324,650**	**-3,364,200**
Open-water evaporation[8] (ET)	-7,300	-6,500	-17,000
Vegetation evapotranspiration[9] (ET)	-560	[9a]0	[9b]-10,800
Basin evapotranspiration[10] (ET)	-1,710,320	-301,370	-2,996,100
Base flow out[11] (BF_{out})	-18,100	[11a]-1,800	[11b]-137,200
Runoff out[12] (RO_{out})	-15,800	Not Calculated[12a]	[12b]-156,600
Ground-water out[13] (GW_{out})	Not Calculated[13a]	[13b]-1,980	[13c]-100
Water use and subirrigation[14] (WU)	[14a]-11,800	-13,000	[14b]-46,400
Change in storage (ΔS)	[15a]**Not Calculated**	[15b]**-4,100**	[15a]**Not Calculated**

[1]The Little Chino subbasin is considered a tributary subbasin to the Big Chino subbasin.

[2]Calculated by using PRISM 30-year average values from 1971 to 2000 (Daly and others, 1994). Estimated uncertainty described earlier in report, see precipitation.

[3]Calculated by using NOAA snow gages in area for the period of record from 1981–2002 (fig. 5*C* and appendix 2).

[4]Runoff and base-flow separation calculated by using HYSEP; 30-year average values (1971–2000); estimated uncertainty described earlier in report, see base flow.

[4a]Base flow from Del Rio Springs minus diversions, channel infiltration, and evapotranspiration.

[5]Runoff and base-flow separation calculated by using HYSEP; 30-year average values (1971–2000).

[5a]Runoff into subbasin, such as from Granite Creek, not calculated.

[6]14-year average values (1990–2003); does not include possible ground-water inflow through the northern boundary.

[6a]Nelson (2002) simulated 1,800 acre-ft/yr of ground-water flow from the Little Chino subbasin to the Big Chino Subbasin. About 600 acre-ft per year is derived from recharge of base flow downstream from the streamflow-gaging station at Del Rio Springs. This value was applied to the conceptual budget for 1990–2003. Possible ground-water inflow on the northern boundary of the subbasin not calculated.

[6b]Ground-water inflow that may occur along the Mogollon escarpment not calculated.

[7]Calculated on the basis of incidental recharge factors and water use; 14-year average values (1990–2003).

[8]Calculated by using basin monthly potential evapotranspiration values and open-water surface area; 30-year average values (1971–2000).

[9]Calculated by using gaging-station data and HYSEP base-flow separation; 43-year average values (1961–2003).

[9a]Evapotranspiration near Del Rio springs is included in base flow out.

[9b]Sum of base-flow reduction for Wet Beaver Creek, West Clear Creek, Oak Creek, and Verde River near Camp Verde.

[10]Basin evapotranspiration is estimated as a residual in this equation. Value incorporates errors from the other water-budget terms.

[11]Runoff and base-flow separation calculated by using HYSEP; 30-year average values (1971–2000).

[11a]Base flow from Del Rio Springs including diversions, channel infiltration, and evapotranspiration.

[11b]Runoff and base flow separation calculated by using HYSEP; 11-year average values (1989–2000).

[12]Runoff and base flow separation calculated by using HYSEP; 30-year average values (1971–2000).

[12a]Runoff out of subbasin, such as from Granite Creek, not calculated.

[12b]Runoff and base-flow separation calculated by using HYSEP; 30-year average values (1989–2000).

[13]14-year average values (1990–2003).

[13a]Ground-water flow out of the subbasin through the northern boundary not calculated.

[13b]Nelson (2002) simulated 1,800 acre-ft/yr of ground-water flow from the Little Chino subbasin to the Big Chino Subbasin. This GW_{out} value includes the water that leaves the Little Chino subbasin as base flow from Granite Creek. Wirt and others (2005) reported a base flow of 360 acre-ft/yr; however, the base flow can vary. In order to determine the flows across the subbasin boundary, the Arizona Department of Water Resources did a Zone Budget (Harbaugh, 1990) analysis of the 1998 model results. Frank Corkhill, hydrologist, Arizona Department of Water Resources, written commun., 2005.

[13c]Ground-water flow out of the southern boundary calculated. Ground-water flow out of the northern and eastern boundaries not calculated.

[14]Ground-water use values detailed in appendix 9; 14-year average values (1990–2003).

[14a]Includes approximately 3,400 acre-ft of water evapotranspired from subirrigated agriculture.

[14b]Includes approximately 33,900 acre-ft of surface water per year.

[15a]Change in storage occuring; consult water level altitudes on pl. 3

[15b]Nelson (2002) simulated an average 4,000 acre-ft/yr of ground-water storage change from 1990 to 2003.

Table 22. Average annual water budgets for regional aquifers in the upper and middle Verde River watersheds, central Arizona, 1990–2003

[Values are in acre-feet per year. Negative values indicate water is removed from or leaves the subbasin. Terms in parentheses refer to terms in water-budget equations. Terms in brackets are estimated error as ± percent. Detailed annual water budgets are included in appendix 9]

Water-budget component	Big Chino subbasin	Little Chino subbasin[1]	Verde Valley subbasin
Total inflow	**30,300**	**12,620**	**167,470**
Base flow in[2] (BF_{in})	[2a]180	0	17,900
Natural recharge[3] (R)	23,420	5,070	130,270
Incidental and artificial recharge[4] (IR)	4,300	7,550	[4a]19,300
Ground water in[5] (GW_{in})	[5a]2,400	0	Not Calculated[5b]
Total outflow	**-30,300**	**-16,720**	**-167,470**
Agricultural irrigation[6] (WU)	-7,900	-4,900	-120
Agricultural subirrigation (WU)	[7]-3,400[25]	0	0
Domestic (WU)	-300	-1,300	-1,900
Water providers (WU)	-200	-6,600	-7,800
Golf course irrigation (WU)	-30	0	-1,500
Industrial use (WU)	-10	-140	-1,150
Base flow out[8] (BF_{out})	-17,900	[8a]-1,800[1]	[8b]-144,100
Vegetation evapotranspiration[9] (ET)	-560	[9a]0	[9b]-10,800
Ground water out[10] (GW_{out})	Not Calculated[10a]	[10b]-1,980	[10c]-100
Change in storage (ΔS)	**Not Calculated**[11a]	[11b]**-4,100**	**Not Calculated**[11a]

[1]The Little Chino subbasin is considered a tributary subbasin to the Big Chino subbasin.

[2]Base-flow separation calculated by using HYSEP; 14-year average values (1990–2003).

[2a]Base flow from Del Rio Springs minus diversions, channel infiltration, and evapotranspiration.

[3]Natural recharge is estimated as a residual in this equation. Includes components such as mountain-block, mountain-front, basin, and channel recharge. This value does not consider storage losses in the system.

[4]Calculated on the basis of incidental recharge factors and water use; 14-year average values (1990–2003).

[4a]Includes recharge from diverted surface water applied as irrigation.

[5]14-year average values (1990–2003).

[5a]Nelson (2002) simulated 1,800 acre-ft/yr of ground-water flow from the Little Chino subbasin to the Big Chino Subbasin. About 600 acre-ft/yr is derived from recharge of base flow downstream from the streamflow-gaging station at Del Rio Springs. This value was applied to the conceptual budget for 1990–2003. Possible ground-water inflow on the northern boundary of the subbasin not calculated.

[5b]Ground-water inflow that may occur along the Mogollon escarpment not calculated.

[6]Ground-water use values detailed in appendix 9; 14-year average values (1990–2003).

[7]Includes approximately 3,400 acre-ft of water evapotranspired from subirrigated agriculture.

[8]Base-flow separation calculated by using HYSEP; 14-year average values (1990–2003).

[8a]Base flow from Del Rio Springs including diversions, channel infiltration, and evapotranspiration.

[8b]Base-flow values based only on winter base-flow values.

[9]Calculated by using gaging-station data and HYSEP base-flow separation; 43-year average values (1961–2003).

[9a]Evapotranspiration near Del Rio springs is included in base flow out.

[9b]Sum of Wet Beaver Creek, West Clear Creek, Oak Creek, and Verde River near Camp Verde.

[10]14-year average values (1990–2003).

[10a]Ground-water flow out of the subbasin through the northern boundary not calculated.

[10b]Nelson (2002) simulated 1,800 acre-ft/yr of ground-water flow from the Little Chino subbasin to the Big Chino Subbasin. This GW_{out} value includes the water that leaves the Little Chino subbasin as base flow from Granite Creek. Wirt and others (2005) reported a base flow of 360 acre-ft/yr; however, the base flow can vary. In order to determine the flows across the subbasin boundary, the Arizona Department of Water Resources did a Zone Budget (Harbaugh, 1990) analysis of the 1998 model results (Frank Corkhill, hydrologist, Arizona Department of Water Resources, written commun., 2005).

[10c]Ground-water flow out of the southern boundary calculated. Ground-water flow out of the northern and eastern boundaries not calculated.

[11a]Changes in storage occuring; consult water level altitudes on pl. 3

[11b]Nelson (2002) simulated an average 4,000 acre-ft/yr of ground-water storage change from 1990 to 2003.

Annual water budgets were developed for the regional aquifers for 1990–2003. During this period, 1992, 2002, and 2003 represent high, low, and medium precipitation years, respectively. Natural recharge was calculated as the remainder from the regional aquifer water-balance equation (eq. 21). Error associated with natural recharge is potentially large because it includes potential error from the other water-budget terms and because not all components of the water-balance equation were calculated.

Natural Recharge

The amount of ground-water recharge (*R* in the water-balance equation) is dependent upon the location, rate, and accumulation of precipitation within the subbasins. Recharge is divided into two types: diffuse and focused. Recharge of precipitation through the basin floor and mountain block are considered diffuse recharge. Water infiltrating stream channels along the mountain front and within the basin and through collection ponds is considered focused recharge because precipitation and surface runoff are concentrated within these features. Focused recharge is advantageous because water held within focused recharge features is more likely to infiltrate and less likely to evaporate compared to water associated with diffuse mechanisms, such as basin recharge.

Channel recharge was not estimated owing to limited streamflow data; however, data are available for estimating streambed infiltration for some channels. Hydraulic conductivity values for channel sediments are useful in determining potential rates of natural recharge. The soil survey of the western part of Yavapai County (Wendt and others, 1976) estimated the hydraulic conductivity of channels on the basis of sediment characteristics. Values in Williamson Valley ranged from about 0.4 to 12 ft/d. Navarro (2002) measured channel permeability along Mint Wash by using a Guelph permeameter and soil classification information. Measurements were as low as about 0.4 ft/d; however, the highest values exceeded the measurement capability of the instrument (10 ft/d).

Basin recharge, or water infiltrating directly through the basin soils and percolating to the regional aquifer, is small compared to other recharge components in a semiarid and arid climate (Scott and others, 2000). Consequently, basin recharge is assumed to be small in these watersheds.

Mountain-block recharge is defined as precipitation infiltrating through the thin soils of the mountain block and percolating through the geologic strata of the mountain directly to the water table (Wilson and Guan, 2004). Mountain-front recharge occurs as portions of overland flow along mountain slopes infiltrates through alluvial and bedrock stream channels near the transition from the mountain range to the basins (Wilson and Guan, 2004) and percolates to the water table. Mountain-block and mountain-front recharge can be significant components of recharge; however, they are difficult to measure. For the purposes of this study, they were combined as a single value.

Natural recharge areas within the subbasins were identified using two methods: excess precipitation and stable-isotope composition. The first method relies on climatic data to identify areas having suitable atmospheric conditions for generation of precipitation and subsequent infiltration. It is based on the assumption that recharge occurs when the precipitation rate exceeds the evapotranspiration rate. In all arid and semiarid parts of the study area, average annual ET exceeds average annual precipitation. On shorter time scales, however, precipitation in excess of ET results in water that does not return to the atmosphere (excess precipitation; fig. 5*F*). For this study, average monthly ETo rates were subtracted from average monthly precipitation rates to determine monthly excess precipitation. Because excess values for individual precipitation events were not available, monthly excess rates were summed to determine annual excess rates. This method cannot adequately calculate actual recharge values because recharge is more likely to occur on event timescales rather than monthly time scales; however, the method is appropriate for identifying recharge areas and determining relative magnitudes of recharge within the study area. A more detailed explanation and extension of this concept is presented by Flint and others (2004).

The second method for identifying recharge areas is based on stable-isotope values for ground water sampled near discharge areas of the subbasins that was assumed to be a mixture of water from the various recharge areas. Relations among stable-isotope values, precipitation, and altitude are used to identify likely areas of recharge. Average annual precipitation for 50-ft intervals of land-surface altitude was calculated by multiplying the total average annual precipitation for that interval by the total area of the interval within the subbasin. Isotopic values were calculated for each altitude interval using the locally derived isotope-altitude relations. These values were weighted by a fraction equivalent to the precipitation for the altitude interval divided by the total precipitation for all altitudes in the subbasin. Average stable-isotope values for each of the subbasins were calculated by summing the weighted isotopic values for each altitude interval and assuming that recharge from precipitation is uniform across the subbasin.

The average stable-isotope values for precipitation were heavier than the average values for ground water for all subbasins. If the ground water is assumed to be well mixed, the lighter isotope values for ground water indicate that recharge is more likely to be from precipitation at higher altitudes than from precipitation at lower altitudes. Isotope values for precipitation at lower altitudes were removed from inclusion in the calculation of the average value for the subbasin until the average value equaled the average measured isotope value for the ground-water samples (fig. 34). Remaining altitudes are considered the predominant altitudes for recharge. Although the solution obtained in this manner is not unique, it is considered sufficient for identifying likely source areas of recharge because higher altitudes receive more precipitation, and that mountain-block, mountain-front, and channel recharge are more likely where precipitation occurs. One standard deviation of error was added to the average isotope value to estimate the likely lower altitude boundary for the recharge source areas (fig. 34).

Predicted recharge-source areas from the two methods are similar (figs. 5*F* and 34), although recharge could actually occur downstream from the inferred locations. The two methods provide further evidence that recharge in the basins is likely small compared to recharge at other locations. The percentage of the predicted recharge-source area within the upper Verde River watershed is smaller than that within the middle Verde River watershed. This is primarily attributed to the larger high-altitude area within the Verde Valley compared to that within the Big and Little Chino subbasins.

The stable-isotope method indicated that the recharge-source area in the Little Chino subbasin ranges in altitude from about 4,900 ft to 7,900 ft and constitutes about 76 percent of the subbasin. Available water in the mountain blocks, mountain fronts, and basin channels recharges the ground-water system at these altitudes or downstream from these altitudes. The mountain block in the Little Chino subbasin is composed of Precambrian granitoid surfaces that are fairly impermeable (DeWitt and others, 2005). Consequently, only a small portion of excess precipitation may be recharging in fracture zones within the mountain block. Ground-water stable-isotope data did not indicate evaporative effects; thus, recharge in the subbasin is predominantly derived from infiltration of water on the mountain front and in the basin channels before significant evaporation occurs.

In contrast to the Little Chino subbasin, only a small recharge-source area was identified in the Big Chino subbasin (18 percent of subbasin). This area is primarily in the Juniper Mountains, the Santa Maria Mountains, and Granite Mountain, and ranges from about 5,900 to 7,700 ft in altitude. The small source area relative to the subbasin area indicates that the higher altitudes must receive more precipitation and (or) have a higher recharge potential than lower altitudes. Results from the excess-precipitation analysis indicate that the western boundary of the subbasin and Big Black Mesa have the highest recharge potential. These are areas where excess precipitation is greatest and permeable Paleozoic sedimentary units are exposed.

In the part of the Verde Valley subbasin south of the Verde River, the stable-isotope method indicated that the recharge-source area ranges from about 6,200 to 7,900 ft in altitude, which corresponds to about 8 percent of that part of the subbasin. This area coincides with the Black Hills, which is the most suitable recharge area indicated by the analysis of climate and geologic data. A layer of permeable Paleozoic sedimentary units are at the crest of the Black Hills, whereas soils at lower altitudes are underlain by impermeable Precambrian rocks.

Mountain-front and mountain-block recharge-source areas for the part of the Verde Valley subbasin north of the Verde River, as estimated from the stable-isotope method, range from about 7,200 to 13,000 ft in altitude, which constitutes 15 percent of that part of the subbasin. This area coincides with zones of high precipitation and low evapotranspiration as indicated by estimates of excess precipitation. In this area Cenozoic volcanic rocks overly Paleozoic sedimentary units.

It is not possible to quantify recharge from source areas by using either the excess-precipitation or stable-isotope method. Additional hydrologic information is required to determine rates of recharge and ground-water flow rates from the source areas. Also, the stable-isotope method identifies the predominant recharge-source areas; however, recharge could be occurring at many locations in the subbasin, but at a significantly lower rate than that occurring at the areas identified. These other areas could be important for recharge of perched or isolated aquifers but are not considered important for the recharge of the regional aquifer.

The annual rates of natural recharge mechanisms, such as channel recharge, mountain-block recharge, and mountain-front recharge, were not directly measured during this study. Instead, recharge rates were estimated on the basis of subbasin water-budget terms and residuals of the regional-aquifer water budgets (table 22). Changes in storage were not considered in the Big Chino and Verde Valley subbasins.

Long-term average data (table 21) were used to estimate the percentage of recharge from precipitation for each subbasin by summing total rainfall, snowfall, and runoff in and subtracting runoff out and ET and dividing this quantity by total rainfall and snowfall for the subbasin. The ratio was multiplied by 100 to obtain a percentage (table 23). Recharge to the regional aquifer was calculated as a residual by using equation 21 and includes mountain-front, mountain-block, channel, and basin recharge components. The difference in recharge values in table 23 is caused by differing time periods of data and uncertainties in the water-budget terms. Additionally, the water budgets in tables 21–23 do not consider that the terms represent hydrologic processes operating at different time scales. A greater percentage of annual precipitation recharges ground water in the middle Verde River watershed than in the upper Verde River watershed.

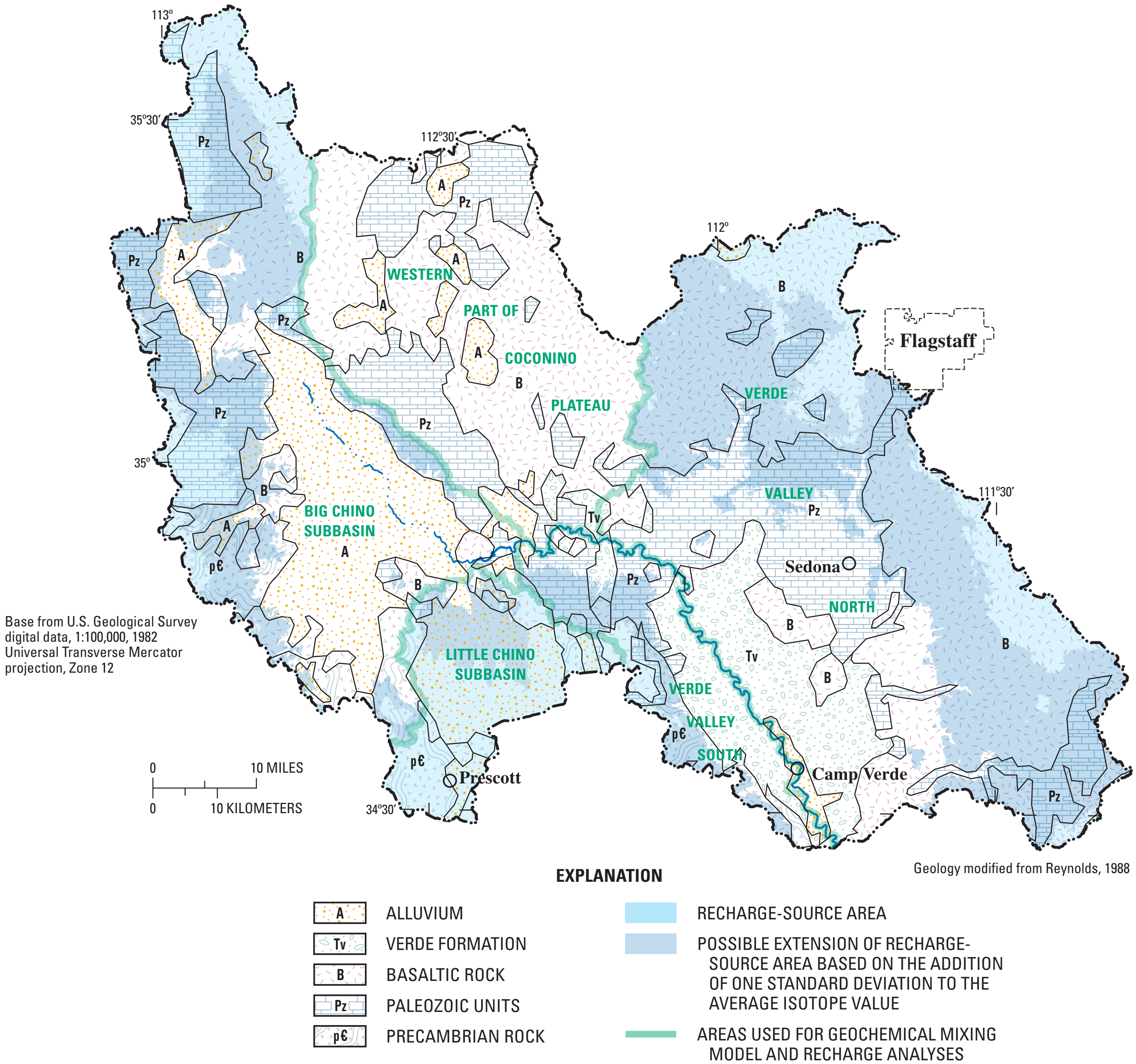


Figure 34. Potential recharge source areas in the upper and middle Verde River watersheds, central Arizona, delineated on the basis of $\delta^{2}H$ and $\delta^{18}O$ data.

Table 23. Estimated recharge in the Big Chino, Little Chino, and Verde Valley subbasins

	Subbasin water budget		Regional aquifer water budget	
Subbasin	**Average annual recharge (acre-feet per year)[1]**	**Recharge from precipitation (percent)[2]**	**Average annual recharge (acre-feet per year)[3]**	**Recharge from precipitation (percent)[2]**
Big Chino[4]	22,980	1.3	23,300	1.3
Little Chino[4]	5,130	1.6	5,100	1.6
Verde Valley[4]	146,300	4.4	130,300	3.9

[1]Recharge derived from subbasin budgets as rainfall + snowfall + runoff in - runoff out - evapotranspiration calculated at the land surface.

[2]Average annual rainfall from 1971–2000 and average annual snowfall from 1981–2002.

[3]Recharge is calculated as a residual in table 22 and is a combination of channel, basin, mountain-front, and mountain-block recharge.

[4]Changes in storage are not considered.

Incidental and Artificial Recharge

Incidental recharge (*IR* in the water-balance equation, eq. 21) results from human activities such as irrigation related to agriculture, golf courses, and green belts, and the use of septic systems. Recharge has not been measured for most of these activities in the study area. Previous protocols of the ADWR, Bureau of Reclamation, and Yavapai County were used as a basis for estimating incidental recharge. Agricultural irrigation recharge, golf course irrigation recharge, and industrial recharge were assigned recharge coefficients. These coefficients were as large as 0.5 (50 percent of water applied) for agriculture irrigation, 0.2 for golf-course irrigation, and 0.2 for industrial use (appendix 9). These coefficients are not based on actual measurements and likely are not uniform within the study area.

The estimate of recharge from septic systems was based on several considerations: the number of households not connected to sewer systems, the estimated number of individuals per household, and the estimated per capita water use. In addition, all water entering a home is assumed to discharge through the septic system. About 35 percent of the water that enters septic systems was estimated to recharge the aquifer. This number is based on the knowledge that some leach fields are above the plant rooting depth and in some locations the water table is close to land surface.

Artificial recharge in the study area includes the use of infiltration ponds and lagoons. Recharge was estimated from the amount of water discharged from wastewater-treatment plants (effluent) and delivered to artificial lagoons or channels. Annual recharge from effluent is about 3,000 acre-ft in the Little Chino subbasin and about 1,000 acre-ft in the Verde Valley subbasin. As more households are added to centralized sewer systems, the amount of artificial recharge could increase, but the incidental recharge from septic systems would thereby decrease.

Water Use

For the purposes of this study, water use is the amount of water withdrawn for agricultural, domestic, and industrial purposes. For the regional-aquifer budget, water use is the amount of ground-water withdrawn. In some cases, water use is given as a combined total for ground-water withdrawal and surface-water diversions. Water-use data were collected from several municipalities, county agencies, and State agencies, as well as from direct users. Where annual water-use data were not available, values were estimated on the basis of known values from other years or from typical water-use coefficients. Average annual water use for the Big Chino, Little Chino, and Verde Valley subbasins during 1990–2003 was about 12,000, 13,000, and 13,000 acre-ft, respectively. Average annual water use in the Verde Valley subbasin was 47,000 acre-ft if surface-water diversions are included (table 21). The primary water uses in the subbasin are listed below.

Agricultural Use (WU).—Irrigation-withdrawal data for the Big Chino subbasin were obtained from the Yavapai County Water Advisory Committee report titled “Big Chino subbasin historical and current water uses and water use projections, Draft, February 2004” (John Munderloh, Yavapai County Water Coordinator, written commun., 2004). There are no current requirements for agricultural water users to meter and report their surface or ground-water usage. Thus, Yavapai County and the ADWR have estimated usage on the basis of aerial photography and typical consumptive-use values for croplands (fig. 6). Irrigation-withdrawal data for the Little Chino subbasin were retrieved from ADWR annual reports. Agricultural water use was calculated as the summation of the volumes reported by Irrigation Grandfathered Right holders. Irrigation-withdrawal data for the Verde Valley subbasin was obtained from the Yavapai County Water Advisory Committee and Bureau of Reclamation report titled “Water use projections Verde Valley Arizona, Draft, April 2003.”

Average annual water use in the Big Chino, Little Chino, and Verde Valley subbasins during 1990–2003 was 7,900, 4,900, and 120 acre-ft, respectively (table 22). These values represent decreases in agricultural withdrawals since the peak withdrawals in the 1960s and 1970s.

Water Providers (WU).—The State of Arizona requires that nonmunicipal water providers report usage if they serve 15 or more connections or 25 or more people. Additionally, nonmunicipal providers inside the PRAMA must report annual withdrawals to the State. Withdrawal records for these providers in the Big Chino subbasin and the Verde Valley subbasin were obtained from the Arizona Corporation Commission. Withdrawal records for nonmunicipal providers in the Little Chino subbasin were obtained from the PRAMA. Reported water withdrawals generally cannot be separated into residential, commercial, and industrial uses. Furthermore, some of the entities receiving water augment their usage with water from private wells.

Municipal providers are required to meter and report water use only within Active Management Areas. The city of Prescott and the town of Prescott Valley are the only municipal water providers in the Little Chino subbasin. Municipal water-use data from 1990 through 1997 were obtained from the ADWR (2000). Municipal water-use data from 1998 through 2003 data were obtained from the ADWR annual reports. As of 2004, there were no municipal water providers in the Big Chino subbasin. The town of Jerome is the only municipal provider in the Verde Valley subbasin and acquires its water from springs. Municipal water use are likely to increase in the future as several towns in the Little Chino subbasin and the Verde Valley subbasin are considering or are in the process of acquiring water from private water providers and developing municipal supply capabilities. Combined average annual water use for nonmunicipal and municipal providers in 1990–2003 was about 200, 6,600, and 7,800 acre-ft for the Big Chino, Little Chino, and Verde Valley subbasins, respectively (table 22 and appendix 9).

Domestic Use (WU).—Domestic water use was calculated for each subbasin on the basis of the number of domestic wells and estimated water use per household. It was assumed that each well was associated with only one household. Domestic use (indoor and outdoor use) was calculated by using the following equation:

$$\text{Annual domestic use (in acre-ft)} = [(\text{number of wells})(\text{average number of people per household})(\text{GPCD})(365)]/325{,}851, \qquad (22)$$

where the number of wells was determined by querying the ADWR database (fig. 35), the average number of people per household was 2.35 for 1990 and 2.33 for 2000 (Arizona Department of Economic Security, 2001), GPCD is gallons per capita per day, and 325,851 is the number of gallons in an acre-ft.

A study by Mayer and others (1999) and the Arizona Municipal Water Users Association (1999) estimated that the average indoor household use for the Western United States was about 62 GPCD. Since passage of the 1992 Energy Policy Act, which set water-use standards for toilets, shower heads, and faucets, the average household GPCD has declined. The average indoor water use for a household that incorporates the conservative fixtures mentioned above as well as conservative fixtures for clothes washers and dishwashers is about 43 GPCD. The combined indoor and outdoor water use in the Big Chino and Little Chino subbasins is 97 GPCD on the basis of water-provider information from 1990–97 (Arizona Department of Water Resources, 2000). This value is less than that for other Arizona cities (Mayer and others, 1999; Arizona Municipal Water Users Association, 1999). Combined indoor and outdoor use in the Verde Valley subbasin is 133 GPCD (Arizona Department of Water Resources, 2000). Average annual domestic water use in 1990–2003 was about 300, 1,300, and 1,900 acre-ft for the Big Chino, Little Chino, and Verde Valley subbasins, respectively (table 22 and appendix 9).

Golf Courses (WU).—The Big Chino subbasin has one golf course, which used about 450 acre-ft of ground water for irrigation in 2003 (appendix 9). The Little Chino subbasin has three golf courses that irrigate exclusively with effluent. Volumes of effluent applied to golf courses were obtained from the city of Prescott's annual recharge and reuse reports as well as from the Verde River Watershed Study (Arizona Department of Water Resources, 2000).

The 11 golf courses in the Verde Valley subbasin are maintained through a combination of ground water, surface water, and effluent. Water-use data were acquired from the Arizona Department of Water Resources (2000) and the Yavapai County Water Advisory Committee and Bureau of Reclamation report titled "Water use projections Verde Valley Arizona, Draft, April 2003." Currently, there are no requirements outside of the PRAMA to monitor and report water usage on golf courses; however, individual courses voluntarily submit usage amounts. Average annual ground-water use for 1990–2003 was about 1,500 acre-ft (table 22 and appendix 9).

Industrial Use (WU).—The Big Chino subbasin has one industrial water user (Arizona Department of Water Resources, 2000). The Little Chino subbasin has multiple industrial facilities that use a combination of ground water and effluent. Facilities inside the PRAMA are required to meter and report water use from wells. The Verde Valley subbasin currently has four industrial water users. Water-use data were acquired from the Arizona Department of Water Resources (2000) and the Yavapai County Water Advisory Committee and Bureau of Reclamation report titled "Water use projections Verde Valley Arizona." Average annual industrial ground-water use for 1990–2003 was 10, 140, and 1,150 acre-ft for the Big Chino, Little Chino, and Verde Valley subbasins, respectively (appendix 9).

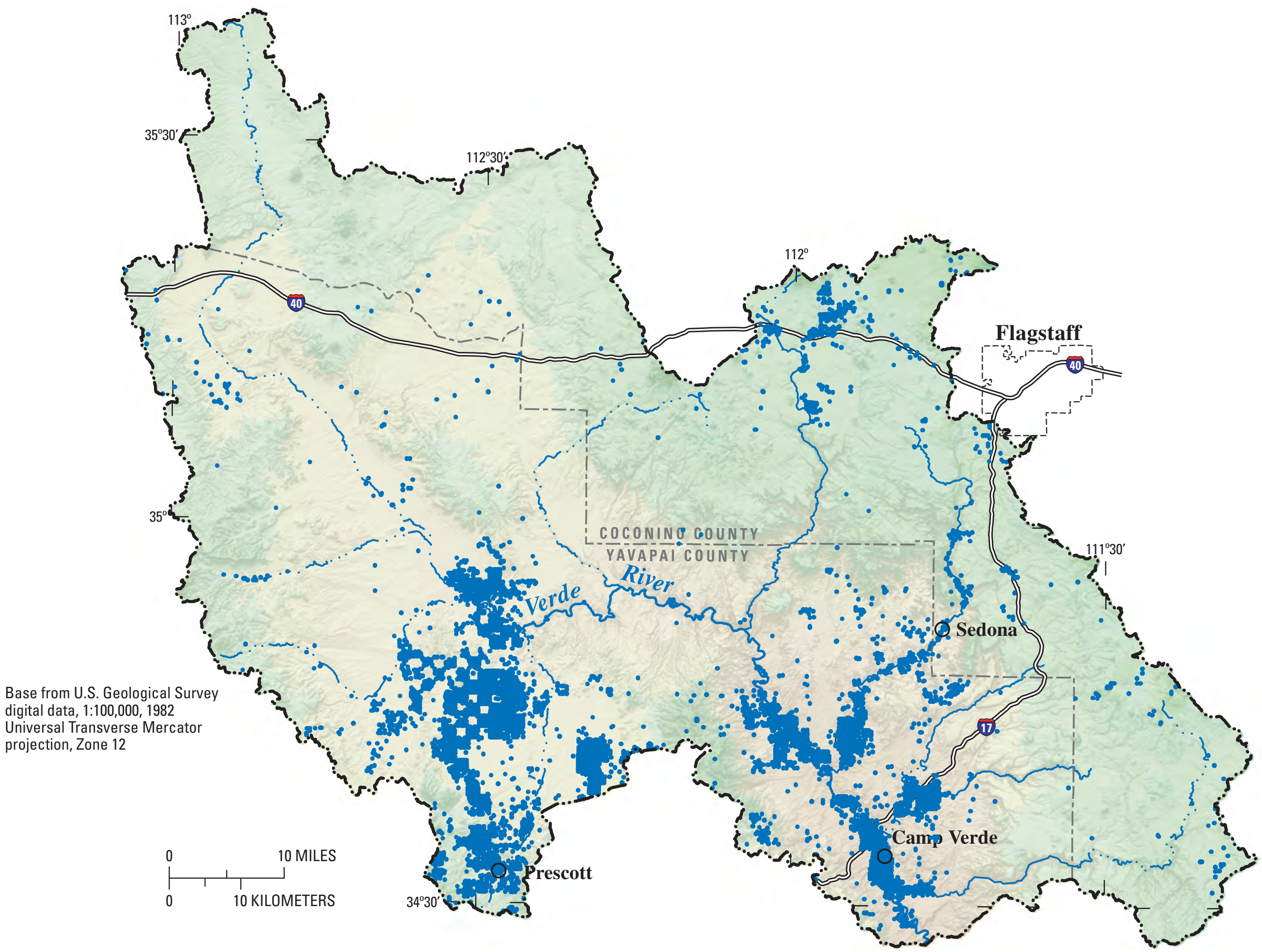


Figure 35. Locations of domestic wells within the upper and middle Verde River watersheds, central Arizona.

Conceptual Flow Systems

Upper Verde River Watershed

Big Chino Subbasin.— The Big Chino subbasin is the second largest subbasin in the study area (1,850 mi^2). The regional aquifer in Big Chino Valley is composed of an upper part, which consists of unconsolidated basin-fill sediments and interbedded volcanic rocks, and a lower part, which consists of Paleozoic rocks. North and northwest of Big Chino Valley, the Redwall-Muav aquifer, which consists of the Redwall Limestone, the Martin Formation, and the Tapeats Sandstone (Owen-Joyce and Bell, 1983), is partially connected to the regional aquifer in the Big Chino Valley. Ground water from the Redwall-Muav aquifer likely flows into Big Chino Valley west of Big Black Mesa near Partridge Creek and east of Big Black Mesa near the Verde River headwaters. Ground water flows northward into Big Chino Valley from the Little Chino subbasin near Del Rio Springs. This inflow is estimated to be about 2,400 acre-ft/yr.

Average annual rainfall for 1971–2000 was about $1.55x10^6$ acre-ft, and average annual water equivalent for snowfall during 1981–2002 was about 207,000 acre-ft. Within Big Chino Valley, the Juniper Mountains, Santa Maria Mountains, and Big Black Mesa were identified as predominant locations for recharge on the basis of stable-isotope and climate data. Within these areas, the Paleozoic rocks along the northern edge of the Walnut Creek drainage and underlying the Juniper Mesa Wilderness may be the most suitable units for recharge. Steep ground-water gradients in this area indicate the potential for high-magnitude ground-water flow. Paleozoic rocks also are exposed on Big Black Mesa. Springs discharging on the south side of Big Black Mesa have stable-isotope values similar to those of springs at higher altitudes within the subbasin.

Excess-precipitation estimates for the western part of the Coconino Plateau indicate that the highest potential for recharge is near Bill Williams Mountain. The direction of ground-water flow in the western part of the Coconino Plateau is dependent upon the location of the ground-water divide north of Big Black Mesa. Water-level altitudes east of Partridge Creek (4,247 ft) and south of Ash Fork (4,249 ft) are higher than water-level altitudes west of Ash Fork (3,832 ft), in the vicinity of Williams (4,000–4,100 ft), and near the communities of Drake and north of Paulden (4,220–4,239 ft). On the basis of these altitudes, a ground-water divide extends from near Bill Williams Mountain southwestward towards Big Black Mesa. Ground water in recharge areas south of the divide flows through Paleozoic rocks and discharges at the eastern end of Big Chino Valley and directly to the Verde River. Contributions to base flow in the Verde River from ground water in the western part of the Coconino Plateau occur primarily within the first 6 mi downstream from the mouth of Granite Creek. Ground water north of the divide flows northward out of the Big Chino subbasin.

Ground-water recharge originating in the northwestern part of the subbasin near Partridge Creek is likely less than recharge occurring in the eastern part of the subbasin near Bill Williams Mountain on the basis of decreased excess precipitation. Additional information on recharge, water-level altitudes, and aquifer properties are needed to determine the magnitude and direction of ground-water flow.

Channel recharge occurs within the tributaries and main stem of Big Chino Wash in Big Chino Valley. Mint Wash and Williamson Valley Wash are the predominant avenues for channel recharge in Williamson Valley. Navarro (2002) estimated that channel permeability along Mint Wash ranged from 0.4 ft/d to more than 10 ft/d on the basis of permeability measurements and soil classification information. Channel recharge also occurs downstream from Del Rio Springs where surface water from the springs enters the subbasin.

Recharge has been altered from predevelopment conditions as a result of diversions and containment features along stream channels. Infiltration of streamflow that originates in the Juniper Mountains recharges the ground-water system along Apache Creek and Walnut Creek. Streamflow in Apache Creek declined during 2000–2004 (David Moore, Prescott National Forest, written commun., 2005). The decline is attributed primarily to diversions and to ground-water capture.

Ground water occurs under both unconfined and confined conditions. Within the upper part of the regional aquifer, confined conditions exist where buried coarse-grained sediments and volcanic rocks are layered with fine-grained sediments. Few water-level data are available for the Paleozoic rocks; therefore, ground-water conditions within the lower part of the aquifer cannot be determined with certainty.

Over much of its extent, the Redwall-Muav aquifer is confined by overlying rock units, including parts of the Supai Group. Erosion of overlying rock units within the study area, however, has exposed the aquifer and created unconfined conditions (Bills and others, in press). Ground-water north of Big Chino Valley and south of the ground-water divide flows through this aquifer and eventually discharges to Big Chino Valley and the Verde River primarily through the Martin Formation.

Average annual discharge from the subbasin for 1964–2003 is about 30,700 acre-ft. Average annual base flow at Verde River near Paulden (09503700) is about 17,700 acre-ft/year for 1964–2003. Patterns in base flow variations are similar to those in water levels in well (B-17-02)06bbb in Big Chino Valley, and are likely related to changes in climate and (or) ground-water withdrawal (fig. 21). Periods of high base flow and water levels are associated with periods of increased precipitation and (or) smaller ground-water withdrawals. Conversely, periods of low base flow and low water levels are associated with periods of decreased precipitation and (or) larger ground-water withdrawals.

Average annual evaporation from open-water bodies within the subbasin was about 7,300 acre-ft for 1971–2000, and another 600 acre-ft is transferred to the atmosphere each year primarily from riparian vegetation along the Verde River (from the mouth of Granite Creek to the terminus of the subbasin at Verde River near Paulden, 09503700). Average annual ET in the subbasin is about 1.71×10^6 acre-ft. Average annual ground-water withdrawal in the subbasin during 1990–2003 was about 12,000 acre-ft (table 22). The largest ground-water withdrawals are for agriculture.

Agricultural withdrawals from the regional aquifer have altered the hydrology of the subbasin from predevelopment conditions. Although agricultural withdrawals are decreasing from historical highs, ground-water withdrawals for domestic use within the subbasin are increasing. Because State regulations permit the transportation of water from the subbasin to the PRAMA, the regional aquifer within Big Chino Valley is being considered as a water source by communities within the PRAMA that are concerned about water supply.

The ground-water residence time was calculated for the regional aquifer in Big Chino Valley from the ratio of total saturated sediments to total ground-water outflows for the predevelopment period. Ground-water residence time is about 6,000 years but likely ranges from about 1,000 to 10,000 years owing to the potential error in estimated saturated thickness of the aquifer. Water storage in the Paleozoic rocks was not considered in estimating the residence time.

Little Chino Subbasin.—The Little Chino subbasin is at the upstream end of the upper Verde River watershed and has an area of about 310 mi^2. The basin-fill aquifer in Little Chino and Lonesome Valleys includes an assortment of younger Tertiary and Quaternary alluvial and volcanic sediments. About 313,000 acre-ft of water enters the Little Chino subbasin annually as precipitation. On average, rain contributes about 286,000 acre-ft of water and snow contributes the remaining 27,000 acre-ft (table 21). This equates to an areal average precipitation of about 19 in./yr.

On the basis of stable-isotope data from ground water sampled at the northern end of the subbasin, the aquifer in the subbasin receives recharge from precipitation at altitudes of about 4,900–7,900 ft. Ground water is recharged almost exclusively from winter precipitation. Precipitation infiltrates through localized fracture zones at these altitudes or through the channels that drain these areas. Mint Wash, Granite Creek, Willow Creek, and Little Chino Wash are the predominant channels that drain higher altitudes. Postdevelopment channelization, diversions, and construction of permanent instream reservoirs on these channels likely have reduced channel recharge compared to recharge during the predevelopment period.

Predevelopment for the Little Chino subbasin has been identified as a quasi-steady state period on the basis of known hydrologic values for 1940 (Nelson, 2002). Recharge for predevelopment conditions was 8,600 acre-ft/yr. Estimated postdevelopment recharge for 1990–2003 is about 12,600 acre-ft/yr on the basis of the PRAMA model simulations (Nelson, 2002). The increase in recharge is attributed to increases in incidental and artificial recharge.

Ground-water flow is almost exclusively towards the junction with the Big Chino subbasin. A ground-water divide occurs south of the subbasin in the Agua Fria subbasin. Historically, ground water flowed northward from the divide into the Little Chino subbasin. Water-level altitudes measured in 2004 do not indicate a significant shift in the ground-water divide; however, pumping in Prescott Valley causes some water in the Little Chino subbasin to flow southward into the Agua Fria subbasin.

Natural outflow from the Little Chino subbasin occurs at the northern terminus of the subbasin where geologic constrictions force water to the surface or near the surface. Outflow from the subbasin is in the form of ground-water flow to the Big Chino subbasin and discharge from Del Rio Springs. According to Corkhill and Mason (1995), the discharge from Del Rio Springs averaged about 2,400 acre-ft/yr from 1984–89. In 2003, discharge from Del Rio Springs was 1,050 acre-ft; about 10 percent of this amount flows out of the subbasin as surface flow. The remaining amount is diverted for agriculture. Approximately 1,800 acre-ft of water leaves the subbasin each year as ground-water flow north of the town of Chino Valley (Nelson, 2002). An additional 600 acre-ft of water leaves as ground-water flow as a consequence of diversions of base flow downstream from Del Rio Springs.

Ground water from the Little Chino subbasin discharges to the Verde River within the first 0.2 mi of the river downstream from the mouth of Granite Creek. Ground water from the Little Chino subbasin is isotopically and chemically similar to water in lower Granite Creek and Stillman Lake, a semi-impeded reach of the Verde River (Wirt and others, 2005).

Evaporation from open-water bodies within the subbasin, primarily surface-water impoundments, accounts for about 6,500 acre-ft of water leaving the system each year. ET from riparian vegetation primarily occurs in the vicinity of Del Rio Springs where the water table is higher than the rooting depth (Nelson, 2002). Continuing ground-water withdrawals could cause a lowering of the water table below the rooting depth, which would result in reduced ET near Del Rio Springs. The amount of water returned to the atmosphere from the subbasin surface was calculated as a residual from the subbasin water-balance equation (eq. 20). About 302,000 acre-ft of water per year is returned to the atmosphere.

Average annual ground-water withdrawal in the subbasin was about 13,000 acre-ft for 1990–2003. Withdrawals were largest for municipal and domestic uses. Losses in ground-water storage, or overdraft, within the subbasin average about 4,100 acre-ft/yr on the basis of numerical modeling simulations (Nelson, 2002).

The ground-water residence time was calculated for the regional aquifer in Little Chino and Lonesome Valleys from the ratio of total saturated sediments to total ground-water outflows for the predevelopment period. Ground-water residence time is about 3,500 years but likely ranges from about 1,000 to 10,000 years owing to the potential error in estimated saturated thickness of the aquifer.

Middle Verde River Watershed

Verde Valley Subbasin.—The Verde Valley subbasin is in the middle Verde River watershed and has an area of about 2,500 mi^2. The Redwall-Muav aquifer, the C aquifer, the Verde Formation (basin fill), and the Quaternary stream-channel alluvium function as aquifers in the subbasin. The Redwall-Muav aquifer (primarily composed of the Supai Group in this subbasin) and the C aquifer occur in the northern part of the subbasin. The Verde Formation, which occurs throughout most of the subbasin south of the Mogollon Escarpment, is the primary water-bearing unit in the subbasin.

Average annual rainfall for 1971–2000 was about $2.85x10^6$ acre-ft, and average annual water equivalent for snowfall during 1981–2002 was about 461,000 acre-ft (table 21). North of the Verde River, precipitation infiltrates permeable volcanic units and the upper units of the C aquifer. Ground water from the C aquifer discharges into Sycamore Creek, Oak Creek, Wet and Dry Beaver Creeks, and West Clear Creek. Discharge to the Redwall-Muav aquifer occurs where there is significant fracturing, faulting, or solution features in the less permeable units of the aquifer, such as the Supai Group. Precipitation directly infiltrates into the Redwall-Muav aquifer where the aquifer is exposed along the northwestern boundary of the subbasin. Discharge from the Redwall-Muav aquifer occurs directly into the Verde River and through Parsons, Summer, and unnamed springs in the perennial reach of Sycamore Creek and near Mormon Pocket. Discharge from Page Springs coincident with the Page Springs Fault maintains flow in Oak Creek (Langenheim and others, 2005; Bills and others, in press). Ground water that does not discharge to springs or stream channels is transmitted to the Verde Formation at lower altitudes in the subbasin. South of the Verde River, precipitation infiltrates the Paleozoic rocks in the higher altitudes of the Black Hills. Ground water percolates downward through fractures, faults, and solution features, and is impeded at the contact between the Paleozoic rocks and the less permeable crystalline basement. Spring discharge is much more prevalent at this contact than at any other contact in the Black Hills. Discharge from several of these springs is diverted for water supplies for the town of Jerome. Multiple perched aquifers underlying the slopes of the Black Hills have formed in part by vertical and horizontal displacement of permeable and impermeable units along faults.

Average annual surface-water inflow to the subbasin, measured at Verde River near Paulden (09503700), was about 30,700 acre-ft/yr for 1964–2003. Base flow accounts for about 60 percent of this value or about 17,700 acre-ft/yr.

Water leaves the subbasin primarily as streamflow and ET. Average annual streamflow at Verde River near Camp Verde (09506000) was about 295,400 acre-ft/yr for the periods 1935–43 and 1989–2003. Base flow exiting the subbasin south of Camp Verde was about 138,800 acre-ft/yr during these periods. Vegetation and open-water ET are about 10,800 acre-ft/yr and 17,000 acre-ft/yr, respectively. Average annual ET along the riparian corridors between Verde River near Paulden and Verde River near Clarkdale was about 2,400 acre-ft during 1961–2003. Average annual ET from the basin surface was $3.0x10^6$ acre-ft for this period.

Water use was about 47,000 acre-ft/yr during 1990–2003. Unlike most parts of the study area, irrigation water within the Verde Valley subbasin is obtained from diversions on the Verde River and its tributaries rather than from ground-water withdrawals. Water providers and domestic use accounted for the largest ground-water withdrawals in the subbasin (9,700 acre-ft/yr for 1990–2003).

Ground-water inflow primarily occurs along the northeastern boundary of the subbasin, and ground-water outflow occurs along the northern and southern boundaries of the subbasin. Ground water flows into the subbasin from the Coconino Plateau southwest of the ground-water divide along the Mogollon Escarpment, and ground-water flows out of the subbasin from north of the divide in the northern part of the subbasin (pl. 3). The amount of ground-water flow into and out of the subbasin along the divide has not been estimated. Ground-water outflow through the Cenozoic alluvium and volcanic rocks at the southern end of the subbasin along the Verde River is about 100 acre-ft/yr; however, an unquantified portion likely exits the subbasin through the Verde Fault south of the river.

Ground water that is recharged by precipitation at higher altitudes along the Mogollon Escarpment maintains base flow in the Verde River and its tributaries within the subbasin. Average annual streamflow at Verde River near Clarkdale (09504000) is about 122,000 acre-ft/yr, of which about 57,200 acre-ft/yr is base flow. Base flow increases by about 39,600 acre-ft/yr within the reach between the gaging stations. Stable-isotope data indicate that the source of the base flow typically is derived from altitudes above

6,900 ft. Most of the water discharges to the river between Perkinsville and the mouth of Sycamore Creek from the Martin Formation.

Oak Creek is the predominant tributary of the Verde River between Verde River near Clarkdale and Verde River near Camp Verde (09506000). Average measured winter base flow of Oak Creek near Cornville (09504500) is 30,500 acre-ft/yr, which is more than double the average winter base flow of the second largest tributary, West Clear Creek. Dry Beaver Creek is unique in the subbasin because it is ephemeral and yet adjacent to Wet Beaver Creek and Oak Creek, both of which are perennial. Additionally, there are fewer springs along Dry Beaver Creek than along other tributaries of the Verde River. Bills and others (2000) estimated the age of water from wells completed in the upper units of the Paleozoic formations near Flagstaff from modern to about 7,000 years. Bills and others (in press) estimated the age of water from springs in the Verde Valley subbasins in the lower Paleozoic formations to range from modern to approximately 4,600 years.

Study Limitations and Considerations for Future Data Collection and Analyses

The hydrologic investigation described in this report provides the most comprehensive baseline set of hydrologic and geochemical data for 1998 through 2004. The data were collected by many different public and private agencies, which have distinct measurement systems, data-collection protocols, and quality-assurance procedures.

Although the data collected provide a significant improvement to the understanding of water flow within the watersheds and supplements existing evidence for previously held assumptions, significant data gaps still remain. The data gaps preclude a definitive understanding and quantitative assessment of recharge, ground-water flow paths, and aquifer storage. Gaps exist in periods of record and in areal distribution. Predevelopment conditions are difficult to determine because of the lack of historical records. Water-level data are lacking in areas outside of population and agricultural centers (pl. 3). Consequently, water-table altitudes are uncertain in these areas.

The primary limitation in constructing a numerical model from the information gathered in this study will be the uncertainty in aquifer extent and properties. Although describing the extent of the Tertiary sediments and volcanic rocks is a significant step in describing the regional aquifers, information on the Paleozoic rocks is still lacking. This is particularly significant in the Big Chino and Verde Valley subbasins. Collection of aquifer-property data is difficult and expensive, but is necessary to determine ground-water flow rates and connectivity among water-bearing units.

Another limitation is the lack of data on mountain-front and mountain-block recharge, channel recharge, and incidental recharge. Of the recharge mechanisms within the watersheds, channel recharge and incidental recharge are the easiest to measure. Additional measurements of streamflow would reduce uncertainty in channel-recharge estimates. Streamflow data for Mint Wash, Partridge Creek, and Walnut Creek would be particularly useful. Finally, comprehensive water-use data are needed to numerically discern between climate and human-induced stresses on the ground-water system.

Summary

The upper and middle Verde River watersheds in central Arizona are predominantly in Yavapai County, which in 1999 was determined to be the fastest growing rural county in the United States. Geologic and hydrologic data were collected and analyzed to provide an understanding of regional aquifers, their recharge mechanisms, potential ground-water flow paths, and primary ground-water discharge points. The Little Chino subbasin has changed the most from predevelopment conditions. Data for the Big Chino subbasin and the Verde Valley subbasin indicate less basin-wide effects from development, but localized effects are just as significant. Overdraft of the regional aquifers is occurring as ground-water outflows from all three subbasins are greater than inflows.

Regional aquifers within the watersheds are combinations of Paleozoic sedimentary, volcanic, and alluvial units. Median thickness of the combined volcanic and alluvial sediments in the subbasins ranges from about 400–450 ft. The volume of saturated volcanic and alluvial sediments in the subbasins ranges from about $100 \text{x} 10^6$ to $200 \text{x} 10^6$ acre-ft; however, there is little information on volumetric water storage, availability, and water quality. Additional water is stored in the Paleozoic sedimentary rocks.

Changes in precipitation and temperature during the 20th century likely have contributed to changes in ground-water levels and base flow. Annual precipitation fluctuates at decadal and shorter time scales in response to changes in global air circulation patterns. Temperature increased about 1 to 3°F during the 20th century at four stations and decreased about 1°F at one station.

Aquifers primarily receive recharge from infiltration and percolation of winter precipitation at higher altitudes of the study area. Excess water at the soil surface from increased precipitation, decreased ET, and decreased potential for runoff during the winter increases the potential for deep infiltration of precipitation. Areal distribution of recharge within the subbasins was estimated by using excess-precipitation and stable-isotope methods. Aquifers within the Big Chino and Verde Valley subbasins receive most of their recharge from the higher altitudes in the subbasins, whereas the aquifer in the Little Chino subbasin receives most of its recharge from mid- and high altitudes. The ratio of recharge to precipitation, however, is smaller in the Big Chino and Little Chino subbasins than in the Verde Valley subbasin.

A geochemical mixing model was used to quantify fractions of source waters to the Verde River from different parts of the study area. Different source areas were identified for river reaches on the basis of water chemistry and base flow. Within the first 0.2 mi of the river downstream from the mouth of Granite Creek, base flow is predominantly maintained by ground water from the Little Chino subbasin. From 0.2 to river mile 22, ground water from Big Chino Valley and the western part of the Coconino Plateau discharges to the river. Most of the water discharging to this reach is from Big Chino Valley. Ground water that discharges to the river downstream from river mile 22 is primarily recharged at higher altitudes of the Verde Valley subbasin. In the downstream direction, the lower altitudes of the Verde Valley subbasin increasingly become the predominant recharge area.

Base flow begins in the upper Verde River watershed in an area referred to as the upper Verde River springs and increases in the downstream direction. It increases to about 17,700 acre-ft/yr within the first 8 mi as measured at the Verde River near Paulden streamflow-gaging station (09503700), to 57,200 acre-ft/yr at river mile 39 as measured at the Verde River near Clarkdale gaging station (09504000), and to 148,600 acre-ft/yr (winter base flow) at river mile 89 as measured near the outlet of the middle Verde River watershed at the Verde River near Camp Verde gaging station (09506000).

Annual base flow gradually increased at most gaging stations from the mid-1960s to the early to mid-1990s, but has decreased at most gaging stations since the early to mid-1990s. Base flow increased as a result of greater than average precipitation and decreased in part as a result of less than average precipitation. Flow has decreased about 380 acre-ft/yr per year at Verde River near Paulden (09503700) since 1993; about 1,000 acre-ft/yr per year at Verde River near Clarkdale (09504000) since 1994; and about 2,000 acre-ft/yr per year at Verde River near Camp Verde (09506000) since 1994. Base flow of Verde River tributaries also has declined; however, the declines generally started sooner in the tributaries than in the main stem of the river with the exception of Wet Beaver Creek (09505200) and West Clear Creek (09505800), in which base flow has varied little since the mid-1960s.

Ground-water withdrawals in the upper and middle Verde River watersheds are increasing. Average withdrawals from 1990–2003 were 13,000 acre-ft/yr for the Little Chino subbasin, 12,000 acre-ft/yr for the Big Chino subbasin, and 13,000 acre-ft/yr for the Verde Valley subbasin. Agricultural and residential water use account for the largest water withdrawals, although agricultural withdrawals have decreased since the peak withdrawals in the 1960s and 1970s. Water-level declines were greatest near population centers.

Water quality in the study area generally is good for most intended uses of the water, and there is little evidence of effects from human activities. Constituent concentrations in surface water and ground water generally were well below Federal and State regulations. Constituents exceeding USEPA Maximum Contaminant Levels for drinking water include antimony, arsenic, fluoride, lead (action level), nitrate, and selenium. Of these constituents, arsenic exceeded the standard in the greatest number of samples. Arsenic is a common element in the study area, particularly in rocks of the Supai Group and the Verde Formation in the Verde Valley and in the Tertiary volcanic rocks near Paulden. On January 23, 2006, the MCL for arsenic will change from 50 micrograms per liter to 10 micrograms per liter. The change in the MCL will result in an increased number of wells that are unsuitable as sources of drinking water if no actions are taken to reduce concentrations in the distribution systems.

References Cited

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998, Crop evapotranspiration: Guidelines for computing crop requirements: Irrigation and Drainage Paper No. 56, FAO, Rome, Italy.

Allen, Stephenson, & Associates, 2001, Hydrogeology study, The ranch at Del Rio Springs, town of Chino Valley, Arizona, October 25, 2001.

Anderson, C.A., and Blacet, P.M., 1972, Precambrian geology of the northern Bradshaw Mountains: U.S. Geological Survey Bulletin 1336, p. 176–177.

Anderson, C.A., and Creasey, S.C., 1958, Geology and ore deposits of the Jerome area, Yavapai County, Arizona: U.S. Geological Survey Professional Paper 308, 185 p.

Anderson, T.W., 1976, Evapotranspiration losses from flood-plain areas in central Arizona: U.S. Geological Survey Open-File Report 76–864, 91 p.

Anderson, T.W., Freethey, G.W., and Tucci, Patrick, 1992, Geohydrology and water resources of alluvial basins in south-central Arizona and parts of adjacent States: U.S. Geological Survey Professional Paper 1406-B, 67 p.

Anning, D.W., 2002, Standard errors of annual discharge and change in reservoir content data from selected stations in the lower Colorado River streamflow-gaging station network 1995–99: U.S. Geological Survey Water-Resources Investigations Report 01–4240, 81 p.

Anning, D.W., 2004, Uncertainty in low-flow data from three streamflow-gaging stations on the upper Verde River, Arizona, *in* Sehlke, Gerald, Hayes, D.F., and Stevens, D.K., eds., Critical transitions in water and environmental resources management: World Water and Environmental Resources Congress 2004, June 27–July 1, 2004, Salt Lake City, Utah, electronic book, p. 1–8.

Arizona Department of Commerce, 2001, Arizona Department of Commerce county profiles, accessed October 15, 2005, at http://www.commerce.state.az.us/Communities/county_profiles.asp.

Arizona Department of Economic Security, 2001, Arizona Department of Economic Security, accessed January 20, 2005, at http://www.de.state.az.us/links/economic/webpage/index.html

Arizona Department of Environmental Quality, 1996, Arizona Administrative Code, Title 18—Environmental Quality, Chapter 11: Department of Environmental Quality Water Quality Standards, 60 p.

Arizona Department of Water Resources, 1991, Management plan for the second management period 1990–2000, Prescott Active Management Area: Arizona Department of Water Resources, 216 p.

Arizona Department of Water Resources, 2000, Verde River watershed study: Arizona Department of Water Resources, Phoenix, Arizona, v.p.

Arizona Department of Water Resources, 2003, Prescott Active Management Area 2002–2003—Hydrologic monitoring report: Phoenix, Arizona Department of Water Resources, 21 p.

Arizona Meteorological Network, 2005, AZMET Arizona Meteorological Network, accessed June 1, 2005, at http://ag.arizona.edu/azmet/.

Arizona Municipal Water Users Association, 1999, Final report on the participation of the Arizona municipal water users association in the American Water Works Association Research Foundation's North American Residential End User Study: Arizona Municipal Water Users Association, 30 p.

Arizona State Legislature, 2005, Arizona Revised Statutes, Title 45–404 and 45–411: Arizona State Legislature, Phoenix, accessed June 15, 2005, at http://www.azleg.state.az.us/ArizonaRevisedStatutes.asp

Arizona Water Commission, 1979, Arizona State water plan: Arizona Water Commission Report.

Baars, D.L., 1983, The Colorado Plateau: Albuquerque, New Mexico, University of New Mexico Press, 279 p.

Billingsley, G.H., and Hendricks, J.D., 1989, Physiographic features of northwestern Arizona, *in* Elston, D.P., Billingsley, G.H., and Young, R.A. eds., Geology of Grand Canyon, northern Arizona (with a Colorado River guide), American Geophysical Union, Washington, D.C., chap. 4, p. 67–71.

Bills, D.J., Truini, Margot, Flynn, M.E., Pierce, H.A., Catchings, R.D., and Rymer, M.J., 2000, Hydrogeology of the regional aquifer near Flagstaff, Arizona, 1994–97: U.S. Geological Survey Water-Resources Investigations Report 00–4122, 143 p.

Bills, D.J., Flynn, M.E., and Monroe, S.A., in press, Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5222.

Blakey, R.C., 1990, Stratigraphy and geologic history of Pennsylvanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity: Geological Society of America Bulletin, v. 102, no. 9, p. 1189–1217.

Cooley, M.E., 1976, Spring flow from pre-Pennsylvanian rocks in the southwestern part of the Navajo Indian Reservation, Arizona: U.S. Geological Survey Professional Paper 521-F, 15 p.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., and Hardt, W.F., 1969, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah—*with a section on* vegetation by O.N. Hicks: U.S. Geological Survey Professional Paper 521-A, 61 p., 9 plates.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphic method for evaluating formation constants and summarizing well-field history: Transactions, American Geophysical Union, v. 27, no. 4, p. 526–534.

Corkhill, E.F., and Mason, D.A., 1995, Hydrogeology and simulation of ground water flow, Prescott Active Management Area, Yavapai County, Arizona: Arizona Department of Water Resources Modeling Report, no. 9, 143 p.

Daly, C., Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, no. 33, p. 140–158.

Davis, G.H., 1978, Monocline fold pattern of the Colorado Plateau, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the Western United States: Geological Society of America Memoir 151, p. 215–233.

DeWitt, Ed, Langenheim, V.E., Force, Eric, Vance, Kelly, and Lindberg, P.A., in press, Geologic map of the Prescott National Forest and headwaters of the Verde River, Yavapai and Coconino Counties, Arizona—With a digital database by Doug Hirschberg, Guy Pinhassi, and Nancy Shock: U.S. Geological Survey Miscellaneous Investigations Map.

DeWitt, Ed, Langenheim, V.E., and Wirt, Laurie 2005, Geologic framework of aquifer units and ground-water flow paths, Verde River headwaters, north-central Arizona: U.S. Geological Survey Open File Report 2004–1411-B, p. 24.

Driscoll, F.G., 1986, Groundwater and wells (2d ed.): St. Paul, Minnesota, Johnson Division, 1021 p.

Enfield, D.B., Mestas-Nunez, A.M., and Trimble, P.J., 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S.: Geophysical Research Letters, v. 28, no. 10, 2077–2080.

Ewing, D.B., Osterberg, J.C., and Talbot, W.R., 1994, Groundwater study of the Big Chino Valley—Technical Report, Section I of III, Perspective: U.S. Bureau of Reclamation.

Fenneman, N.M., 1931, Physiography of the Western United States: New York, McGraw-Hill, 534 p.

Flint, A.L., and Childs, S.W., 1987, Calculation of solar radiation in mountainous terrain: Journal of Agricultural and Forest Meteorology, v. 40, p. 233–249.

Flint, A.L., Flint, L.E., Hevesi, J.A., and Blainey, J.B., in press, Fundamental concepts of recharge in the Desert Southwest—A regional modeling perspective: American Geophysical Union Monograph, Washington, D.C.

Flynn, M.E., and Bills, D.J., 2002, Investigation of the geology and hydrology of the Coconino Plateau of northern Arizona—A project of the Arizona Rural Watershed Initiative: U.S. Geological Survey Fact Sheet 113–02, 4 p.

Foust, R.D., Mohapatra, P., Comton-O’Brien, A.M., and Reifel, J., 2004, Groundwater arsenic in the Verde Valley in central Arizona, USA: Applied Geochemistry, v. 19, no. 2, p. 251–255.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 305 p.

Goff, F.E., Eddy, A.C., and Arney, B.H., 1983, Reconnaissance geologic strip map from Kingman to south of Bill Williams Mountain, Arizona: Los Alamos, New Mexico, Los Alamos National Laboratory, LA-9202-Map, 5 sheets.

Harbaugh, A.W., 1990, A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 90–392, 46 p.

Harshbarger and Associates, 1976, Lake Mary aquifer report, City of Flagstaff, Arizona, 89 p.

Hart, R.J., Ward, J.J., Bills, D.J., and Flynn, M.E., 2002, Generalized hydrogeology and ground-water budget for the C aquifer, Little Colorado River Basin and parts of the Verde and Salt River Basins, Arizona and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02–4026, 47 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hereford, Richard, Webb, R.H., and Graham, Scott, 2002, Precipitation history of the Colorado Plateau region, 1900–2000: U.S. Geological Survey Fact Sheet 119–02, 4 p.

Hidalgo, H.G., in press, Climate precursors of multidecadal drought variability in the Western U.S.: Water Resources Research.

Hunt, C.B., 1967, Physiography of the United States: San Francisco, W.H. Freeman and Company, 630 p.

Ingraham, N.L., Caldwell, E.A., and Verhagen, B.T., 1998, Arid catchments, *in* Kendall, Carol, and McDonnell, J.J., eds., Isotope tracers in catchment hydrology: Amsterdam, Elsevier, p. 435–466.

International Atomic Energy Agency/World Meteorological Organization, 2001, Global Network of Isotopes in Precipitation, The GNIP Database, accessed June 25, 2004, at http://isohis.iaea.org

Jacob, C.E., 1950, Flow of groundwater, *in* Rouse, H. ed., Engineering Hydraulics: New York, John Wiley and Sons, p. 321–386.

Jackson, J.A., 1997, Glossary of geology (4th ed): Alexandria, Virginia, American Geological Institute, 769 p.

Jenkins, O.P., 1923, Verde River lake beds near Clarkdale, Arizona: American Journal of Science, 5th ser., v. 5, no. 25, p. 65–81.

Knauth, L.P., and Greenbie, M., 1997, Stable isotope investigation of ground-water-surface-water interactions in the Verde Rivers headwaters area: Arizona State University Department of Geology report in fulfillment of Arizona Water Protection Fund Grant #95–001, administered by Arizona Department of Water Resources, 28 p.

Krieger, M.H., 1965, Geology of the Prescott and Paulden quadrangles, Arizona: U.S. Geological Survey Professional Paper 467, 127 p.

Langenheim, V.E., Hoffmann, J.P., Blasch, K.W., DeWitt, Ed, and Wirt, Laurie, 2002, Preliminary report on geophysical data in Yavapai County, Arizona: U.S. Geological Survey Open-File Report 02–352, 28 p.

Langenheim, V.E., DeWitt, Ed, and Wirt, Laurie, 2005, Preliminary geophysical framework of the upper and middle Verde River watershed, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 2005–1154, 43 p.

Lehner, R.E., 1958, Geology of the Clarkdale quadrangle, Arizona: U.S. Geological Survey Bulletin 1021-N, p. 511–592.

Levings, G.W., 1980, Water resources in the Sedona area Yavapai and Coconino Counties, Arizona: Arizona Water Commission Bulletin 11, 37 p.

Lillesand, T.M., and Kiefer, R.W., 2000, Remote sensing and image interpretation (4th ed.): New York, John Wiley and Sons, 724 p.

Linsley, R.K., Kohler, M.A., and Paulhus, J.L., 1982, Hydrology for engineers (3d ed.): Net York, McGraw-Hill, 508 p.

Mace, R.E., 1997, Determination of transmissivity from specific-capacity tests in a karst aquifer: Ground Water, v. 35, no. 5, p. 738–42.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production: Bulletin of the American Meteorological Society, v. 78, p. 1069–1079.

Matlock, W.G., Davis, P.R., and Roth, R.L., 1973, Groundwater in Little Chino Valley, Arizona: Agricultural Experiment Station, University of Arizona, Technical Bulletin 201, 19 p.

Mayer, P., 1999, Residential end uses of water study: American Water Works Association Research Foundation, 90 p.

Mayer, P.W., DeOreo, W.B., Kiefer, J.C., Opitz, E.M., Dziegielewski, Benedykt., and Nelson, J.O., 1999, Residential end uses of water: American Water Works Association, Denver, Colorado.

McCabe, G.J., Palecki, A.P., and Betancourt, J.L., 2004, Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States: Proceedings of the National Academies of Science, v. 101, no. 12, p. 4136–4141.

McKee, E.D., and McKee, E.H., 1972, Pliocene uplift of the Grand Canyon region—Time of drainage adjustment: Geologic Society of America Bulletin 83, p. 1923–1932.

Menges, C.M., and Pearthree, P.A., 1983, Map of neotectonic (latest Pliocene-Quaternary) deformation in Arizona: Arizona Bureau of Geology and Mineral Technology, Open-File Report 83–22, 48 p.

Metzger, D.G., 1961, Geology in the relation to availability of water along the south rim, Grand Canyon National Park, Arizona: U.S. Geological Survey Water-Supply Paper 1475–C, 33 p.

Moss, M.E., and Gilroy, E.J., 1980, Cost-effective stream-gaging strategies for the Lower Colorado River—The Blythe field office operations: U.S. Geological Survey Open-File Report 80–1048, 112 p.

National Climatic Data Center, 2005, Arizona Climate Summaries, accessed January 20, 2005, at http://www.ncdc.noaa.gov/oa/ncdc.html

Navarro, L.F., 2002, Characterization and ground-water flow modeling of the Mint Wash/Williamson Valley area, Yavapai County: Flagstaff, Northern Arizona University, unpublished master's thesis, 158 p.

Nealy, D.L., and Sheridan, M.F., 1989, Post-Laramide volcanic rocks of Arizona and northern Sonora, Mexico, and their inclusions, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 609–647.

Nelson, Keith, 2002, Application of the Prescott Active Management Area groundwater flow model, planning scenario 1999–2025, Modeling Report No. 12: Arizona Department of Water Resources Hydrology Division, September 2002, 49 p.

Neuman, S.P., 1975, Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response: Water Resources Research, v. 11, p. 329–342.

Ostenaa, D.A., Schmischal, U., King, C.E., Jr., and Wright, J.W., 1993, Ground water study of the Big Chino Valley, U.S. Bureau of Reclamation, Denver, Colorado, v.p.

Owen-Joyce, S.J., 1984, Hydrology of a stream-aquifer system in the Camp Verde area, Yavapai County, Arizona: Arizona Department of Water Resources Bulletin 3, 60 p.

Owen-Joyce, S.J., and Bell, C.K., 1983, Appraisal of water resources in the upper Verde River area, Yavapai and Coconino Counties, Arizona: Arizona Department of Water Resources Bulletin 2, 219 p.

Parker, J.T.C., and Flynn, M.E., 2000, Investigation of the geology and hydrology of the Mogollon Highlands of central Arizona—A project of the Arizona Rural Watershed Initiative: U.S. Geological Survey Fact Sheet 159–00, 4 p.

Pettyjohn, W.A., and Henning, Roger, 1979, Preliminary estimate of ground-water recharge rates, related streamflow and water quality in Ohio: Ohio State University Water Resources Center Project Completion Report Number 552, 323 p.

Pierce, H.A., 2001, Structural controls on ground-water conditions and estimated aquifer properties near Bill Williams Mountain, Williams, Arizona: U.S. Geological Survey Water-Resources Investigations Report 01–4058, 41 p.

Pool, D.R., and Schmidt, Werner, 1997, Measurement of ground-water storage change and specific yield using the temporal-gravity method near Rillito Creek, Tucson, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97–4125, 30 p.

Priestley, C.H.B., and Taylor, R.J. 1972, On the assessment of surface heat flux and evaporation using large-scale parameters: Monthly Weather Review, v. 100, no. 2, p. 81–92.

Razack, M., and Huntley, David, 1991, Assessing transmissivity from specific capacity data in a large and heterogeneous alluvial aquifer: Ground Water, v. 29, no. 6, p. 856–861.

Remick, W.H., 1983, Maps showing groundwater conditions in the Prescott Active Management Area, Yavapai County, Arizona—1982: Arizona Department of Water Resources, Hydrologic Map Series Report Number 9.

Reynolds, S.J., 1988, Geologic map of Arizona: Tucson, Arizona Geological Survey Map M–26, scale 1,000,000, 1 sheet.

Robertson, F.N., 1991, Geochemistry of ground water in alluvial basins of Arizona and adjacent parts of Nevada, New Mexico, and California: U.S. Geological Survey Professional Paper 1406–C, 90 p.

Rozanski, K., Araguás-Araguás, L. and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation, *in* Swart, P.K., Lohman, K.C., McKenzie, J., and Savin, S., eds., Climate change in continental isotopic records: American Geophysical Union, Geophysical Monograph 78, p. 1–36.

Scott, R.L., Shuttleworth, W.J., Keefer, T.O., and Warrick, A.W., 2000, Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest: Water Resources Research, v. 36, no. 8, p. 2233–2247.

Schwab, K.J., 1995, Maps showing groundwater conditions in the Big Chino sub-basin of the Verde River Basin, Coconino and Yavapai Counties, Arizona—1992: Arizona Department of Water Resources Hydrologic Map Series Report no. 28.

Schwalen, H.C., 1967, Little Chino Valley artesian area and ground-water basin: Arizona Agricultural Experiment Station Technical Bulletin 178, 63 p.

Shuttleworth, W.J., 1993, Evaporation, *in* Maidment, D.R., ed., Handbook of hydrology: New York, McGraw-Hill, p. 4.1–4.53.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP: A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96–4040, 46 p.

Southwest Ground-water Consultants, Inc., 2005, Big Chino Ranch hydrology study, City of Prescott Public Works Department, 138 p.

Thiem, G., 1906, Hydrologische methoden (Hydrologic methods), J.M. Gebhardt, Leipzig, 56 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: Transactions American Geophysical Union, v. 16, p. 519–524.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissivity of aquifers from the specific capacity of wells: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331–341.

Twenter, F.R., and Metzger D.G., 1963, Geology and ground water in Verde Valley—The Mogollon Rim region Arizona, Geological Survey Bulletin 1177, 132 p.

Ulrich, G.E., Billingsley, G.H., Hereford, Richard, Wolfe E.W., Nealey, L.D., and Sutton, R.L., 1984, Map showing geology, structure, and uranium deposits of the Flagstaff 1°x2° quadrangle, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I-1446, scale 1:250,000.

United Nations Educational, Scientific and Cultural Organization, 1984, Map of the world distribution of arid regions. Paris, France.

U.S. Department of Agriculture Soil Conservation Service, 1970, Irrigation Water Requirements, Technical Release No. 21, (rev. 1970), 88 p.

U.S. Environmental Protection Agency National Primary Drinking Water Standards, 2003, National Primary Drinking Water Standards: U.S. Environmental Protection Agency Report EPA 816-F-03-016, June 2003, 6 p.

U.S. Geological Survey, Elevation derivatives for national applications, 2005, accessed June, 15, 2004 at http://edna.usgs.gov/.

U.S. Geological Survey, EROS Data Center, 1999, National elevation dataset, Sioux Falls, South Dakota, accessed June 15, 2004, at http://edc.usgs.gov/products/elevation/dem.html

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1-A9, http://pubs.water.usgs.gov/twri9A

Water Resources Associates, 1990, Hydrogeology investigation of Big Chino Valley, Yavapai County, Arizona: Phase II, consultants report for City of Prescott, City Attorney's Office, Prescott, Arizona, February 5, 1990, 3 vols.

Wendt, G.E., Winkelaar, P., Wiesner, C.W., Bither, R.A., Whitney, B.A., and Larson, K.N., 1976. Soil survey of Yavapai County, Arizona, western part, United States Department of Agriculture Soil Conservation Service and Forest Service, 121 p.

Western Regional Climate Center, 2004, Western Regional Climate Center Historical Climate Information, accessed June 15, 2004, at http://www.wrcc.dri.edu/CLIMATEDATA.html.

Western Resource Advocates, 2003, Smart water—A comparative study of urban water use across the Southwest: Boulder, Colorado, Western Resource Advocates, 178 p.

Wilkinson, R.W., 2000 Water resources of Bellemont Park, Coconino County, Arizona: Flagstaff, Northern Arizona University, unpublished master's thesis, 198 p.

Wilson, E.D., and Moore, R.T., 1959, Structure of Basin and Range province in Arizona, *in* Heindl, L.A., ed., Southern Arizona Guidebook II: Tucson, Arizona Geological Society, p. 89–97.

Wilson, J.L., and Guan, Huade, 2004, Mountain-block hydrology and mountain front recharge, *in* Hogan J.F., Phillips, F.M., and Scanlon, B.R., eds., Groundwater recharge in a desert environment—The Southwestern United States: Washington, D.C., American Geophysical Union, Water Science and Application Series, v. 9, p. 113–147.

Wilson, R.P., 1988, Water resources of the northern part of the Agua Fria area Yavapai County, Arizona: Arizona Department of Water Resources Bulletin 5, 109 p.

Wirt, Laurie, DeWitt, Ed, and Langenheim, V.E., 2005, Geologic framework of aquifer units and ground-water flowpaths, Verde River headwaters, north-central Arizona: U.S. Geological Survey Open-File Report 2004–1411.

Wirt, Laurie, and Hjalmarson, H.W., 2000, Sources of springs supplying base flow to the Verde River headwaters, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 99–0378, 50 p.

Woods and Poole Economics, Incorporated, 1999, 1999 Arizona State Profile report, January: Washington, D.C., 220 p.

Woessner, W.W., 1998, Evaluation of two groundwater models of the Prescott Active Management Area: ADWR Model (1995) and Southwest Ground-water Consultants, Inc. Model (1998): Arizona Department of Water Resources, 29 p.

Yitayew, Muluneh, 1990, Reference evapotranspiration estimates for Arizona: Tucson, University of Arizona, Arizona Agricultural Experiment Station, Technical Bulletin 266.

Glossary

Albedo The ratio of reflected/scattered to incident electromagnetic radiation power by a surface or body (for example, cloud or ground surface).

Alluvium (alluvial, adj.) A general term for clay, silt, sand, gravel, or similar unconsolidated detrital material, deposited during comparatively recent geologic time by a stream or other body of running water.

Aquifer Rock and (or) sediment in a formation, a group of formations, or part of a formation that is sufficiently permeable to store and transmit economic quantities of water to wells and springs.

Aquifer, confined An aquifer that lies between layers of less permeable rock (lower hydraulic conductivity) and in which ground water is confined under pressure significantly greater than atmospheric pressure. Static water levels in wells that penetrate a confined aquifer are higher than the top of the aquifer. Synonym: *artesian aquifer*.

Aquifer, perched An aquifer containing *perched ground water*.

Aquifer, regional An aquifer that functions regionally as a water-yielding unit. Synonym: *pumping test*.

Aquifer test A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. An aquifer test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Synonym: *pumping test*.

Aquifer, unconfined An aquifer in which there are no confining beds between the zone of saturation and the ground surface. There is a water table in an unconfined aquifer. Synonym: *water-table aquifer*.

Aridity A measure of dryness for climate calculated as the ratio of precipitation rate to potential evapotranspiration rate.

Artesian aquifer An aquifer that functions under hydrostatic pressure. See *aquifer, confined*.

Artificial recharge See *recharge, artificial*.

Base flow The water in a stream that comes from ground water as seepage or spring water. This water sustains the stream during periods of no precipitation.

Base-flow recession The declining rate of discharge of a stream fed only by base flow for an extended period. Typically, a base-flow recession will be exponential.

Conceptual model A working understanding of a hydrologic system constructed by means of description, statistical data, or analogy of a phenomenon or process that can not be observed directly, or is difficult to observe directly.

Confined aquifer See *aquifer, confined*.

Consumptive Use The water which is no longer available for use because it has evaporated, transpired, been incorporated into products and crops, or consumed by man or livestock during its use.

Darcy's law An equation that can be used to compute the quantity of water flowing through a saturated aquifer in a given time equal to the negative hydraulic gradient multiplied by the hydraulic conductivity of the system.

Discharge The volume of water flowing in a stream channel or through an aquifer cross-section in a given period of time. Stream discharge is the combination of base flow and surface runoff.

Drawdown The lowering of the water level in a well as a result of withdrawal. The difference between the static (undisturbed) water level and the water level in a pumped well.

Ephemeral stream A stream which flows only at certain times of the year when the channel receives water exclusively from surface-water sources, such as rainfall and snowmelt. See *intermittent streams* and *perennial streams*.

Evaporation The process by which water passes from the liquid to the vapor state.

Evapotranspiration The sum of *evaporation* and *transpiration*.

Evapotranspiration, actual The evapotranspiration that actually occurs under given climatic and soil-moisture conditions.

Evapotranspiration, potential The evapotranspiration that would occur from a well-vegetated surface if water was not a limiting factor.

Flow duration curve A graph showing the percentage of time that the given flows of a stream were equaled or exceeded. It is based on a statistical study of historical streamflow records.

Global meteoric water line (GMWL) an equation that correlates the average relationship between the stable isotopes of oxygen and hydrogen in meteoric waters throughout the world. See *meteoric water line*.

Ground water Water contained in pores below the water table in unconfined aquifers, and in confined aquifers.

Ground water, confined The water contained in a confined aquifer. Pore-water pressure is greater than atmospheric pressure at the top of the confined aquifer.

Ground-water divide The divide is represented by a high in the water table or other potentiometric surface from which ground water moves away in both directions.

Ground-water flow The movement of water through openings in rocks and sediments; it occurs in the saturated zone and the unsaturated zone.

Ground-water storage Water naturally detained in an aquifer, artificial impoundment of water in an aquifer, or the water so impounded.

Ground water, unconfined The water in an aquifer where there is a water table.

Head The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point in an aquifer. The National Geodetic Vertical Datum of 1929 is used in this report. See *potentiometric surface*.

Homogeneity (homogeneous, adj.) The property of a parameter whose values are unchanged over space.

Humidity, absolute The amount of moisture in the air as expressed by the mass of water per unit volume of air.

Humidity, relative Percent ratio of the absolute humidity to the saturation humidity for an air mass.

Humidity, saturation The maximum amount of moisture that can be contained by an air mass at a given temperature.

Hydraulic conductivity A coefficient of proportionality describing the rate at which water can move through a permeable medium. Hydraulic conductivity describes the ability of aquifer material to transmit water.

Hydraulic gradient The change in head per unit of distance in a given direction. The direction is that which yields a maximum change in head per unit of distance.

Hydrogeologic framework The conceptual understanding of the surface and subsurface geologic structure and geometry controlling the movement of ground water and associated energy and chemical constituents.

Hydrograph A graph that shows some property of ground water or surface water as a function of time.

Infiltration The process of water moving from the land surface into the soil or rock.

Intermittent stream A stream which flows only at certain times of the year when the channel receives water from a ground-water source and surface-water sources. See *ephemeral streams* and *perennial streams*.

Isotope An atom having the same atomic number as another atom but having a different atomic weight (or a different mass number). One of two or more species of the same chemical element having the same number of protons in the nucleus, but having a different number of neutrons. Isotopes of an element can have different chemical and physical properties.

Isotropic A condition in a geologic structure in which a hydraulic property, for example hydraulic conductivity, is the same in all directions. Antonym: *anisotropic*.

Lacustrine Pertaining to, produced by, or formed in a lake or lakes.

Lithologic log A record of rock and soil types and strata encountered in a borehole from the land surface to the bottom. See *well log*.

Local meteoric water line (LMWL) See *meteoric water line*.

Meteoric water line (MWL) The relationship between stable isotopes of oxygen and hydrogen in meteoric water. Local meteoric water lines are calculated for given areas; variations from this model are due to isotope effects of kinetic fractionation**.** See global meteoric water line.

Overland flow Precipitation that does not infiltrate into the land surface during a rain or snowmelt event, but instead moves over the land surface

Perched ground water Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

Percolation The downward movement of water through the unsaturated zone.

Perennial stream A stream that flows continuously.

Porosity The ratio of the volume of void spaces in rock or sediment to the total volume of the rock or sediment.

Porosity, effective The volume of the void spaces through which water or other fluids can travel in rock or sediment divided by the volume of the rock or sediment.

Porosity, primary The porosity that represents the original pore openings when a rock is formed or sediment is deposited.

Porosity, secondary The porosity that has been caused by fractures, weathering, diagenesis, and dissolution in a rock formation or sedimentary deposit.

Potentiometric surface An imaginary surface representing the head of ground water. The water table is a type of potentiometric surface. The potentiometric surface for a confined aquifer is the level to which water would rise in a well yielding water from that aquifer at the depth of the screened or open interval.

Potentiometric surface map A contour map of the potentiometric surface of a particular hydrogeologic unit.

Pumping test See *aquifer test*.

Radiation The process of emitting, transmission, and absorption of energy in the form of waves or particles

Radioisotope An unstable isotope of an element that decays or disintegrates, emitting radiation.

Recharge The inflow of water to the aquifer or zone of saturation. Recharge occurs as the water reaches the water table in an unconfined aquifer. Recharge used as a noun refers to the actual water that flows into the aquifer or zone of saturation.

Recharge, artificial The process by which water can be injected or artificially added to an aquifer. Dug basins, drilled wells, or simply the spread of water across the land surface are all means of artificial recharge. See *recharge, incidental*.

Recharge, basin Recharge from infiltration through basin sediments.

Recharge, channel Recharge from seepage through stream-channel sediments.

Recharge, incidental Recharge of water as a result of human activity. Examples of activities that can lead to incidental recharge include irrigation, septic tank use, and discharge of effluent from waste-water treatment plants. See *recharge, artificial*.

Recharge, mountain-block Recharge of precipitation percolating through fractures in the rocks of the mountains.

Recharge, mountain-front Recharge of precipitation seeping through the basin and stream-channel sediments near the foot of the mountains surrounding the basins.

Riparian corridor The vegetation zone immediately adjacent to springs, creeks, streams, rivers, and canals.

Saturated zone The zone in which the voids in the rocks or sediments are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

Specific capacity An expression of the productivity of a well, obtained by dividing the rate of discharge by the drawdown of the water level within the well.

Specific yield The volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table.

Standard Mean Ocean Water (SMOW) See *Vienna Standard Mean Ocean Water*.

Storage, ground water See *ground-water storage.*

Storativity The volume of water that a saturated confined aquifer releases from storage per unit surface area of aquifer per unit decline in hydraulic head normal to that surface.

Stream, gaining A stream or reach of a stream, where flow increases because of an influx of ground water.

Stream, losing A stream or reach of a stream that loses water by seepage into the ground.

Subflow Water flowing in shallow, highly permeable stream-channel alluvium. (Note: This is not the same as the State of Arizona's legal definition.)

Subirrigated crop Crop in which the water table is above the rooting depth.

Surface runoff Runoff that travels over the soil surface to the network of stream channels.

Transmissivity The ability of the entire thickness of an aquifer to transmit water. It is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer. Formally, transmissivity is the rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient.

Transpiration The process by which plants take up water through their roots and give off water vapor through stomata in their leaves.

Unconfined aquifer See *aquifer, unconfined*.

Unsaturated zone A subsurface zone containing water under pressures less than atmospheric. This zone is above the saturated zone (Lohman and others, 1972).

Vienna Standard Mean Ocean Water (VSMOW) An isotopic water standard defined in 1968 by the International Atomic Energy Agency. VSMOW serves as a reference standard for comparing hydrogen and oxygen isotope ratios, mostly in water samples. Very pure, distilled VSMOW water is also used for making high accuracy measurement of water's physical properties and for defining laboratory standards since it is considered to be representative of "average ocean water."

Water budget An accounting of the inflow to, outflow from, and storage changes in an aquifer or watershed.

Water table The surface in an unconfined aquifer below which the rocks are saturated with water. The water table is the level at which water stands in wells that penetrate the uppermost part of an unconfined aquifer.
See *potentiometric surface*.

Water-table map A specific type of potentiometric-surface map for an unconfined aquifer; it shows lines of equal elevation of the water table.

Well log See *lithologic log*.

Xerophyte A desert plant capable of existing by virtue of a shallow and extensive root system in an area of minimal water.

Yield The maximum pumping rate that can be supplied by a well without lowering the water level in the well below the pump intake (Freeze and Cherry, 1979).