Prepared in cooperation with the
ARIZONA DEPARTMENT OF WATER RESOURCES

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Scientific Investigations Report 2005–5222

U.S. Department of the Interior
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Hydrogeology of the Coconino Plateau and Adjacent Areas, Coconino and Yavapai Counties, Arizona

By Donald J. Bills, Marilyn E. Flynn, and Stephen A. Monroe

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Figures

Tables

Supplemental Data

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre	4,047	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60°F (in Hg)	3.377	kilopascal (kPa)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	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	meters per day (m/d)
	Transmissivity	
gallons per day per foot [(gal/d)/ft]	0.0124	square meters per day (m^2/d)

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 National Geodetic Vertical Datum of 1929 (NGVD of 29).

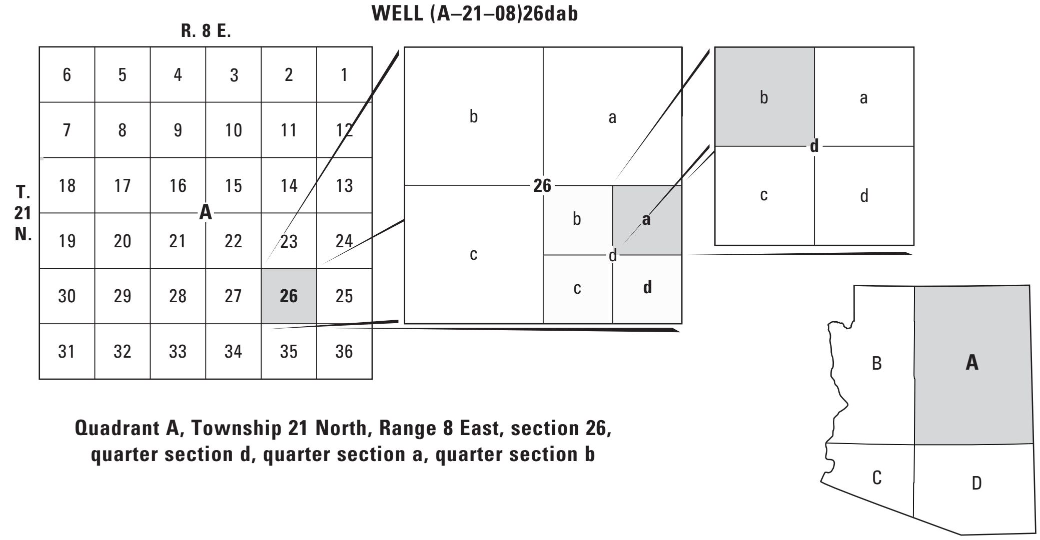
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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). Radioactivity is expressed in picocuries per liter (pCi/L).

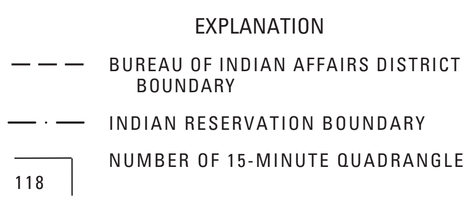
Arizona Well-Numbering System

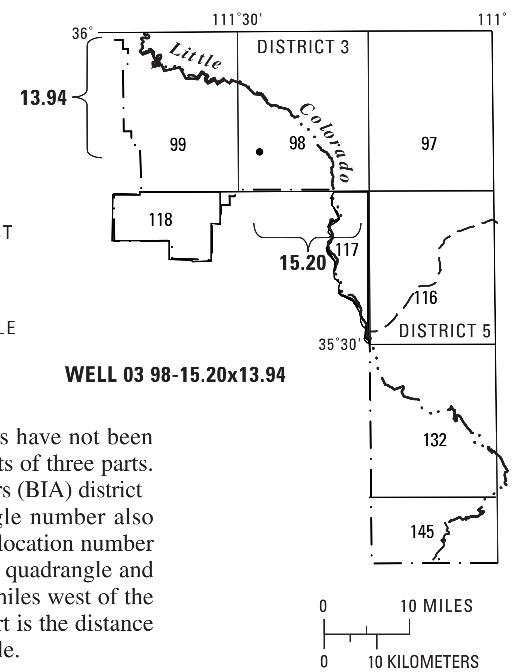


Quadrant A, Township 21 North, Range 8 East, section 26, quarter section d, quarter section a, quarter section b

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–21–08)26dab designates the well as being in the NE1/4, NW1/4, SE1/4, section 26, Township 21 North, and Range 8 East.

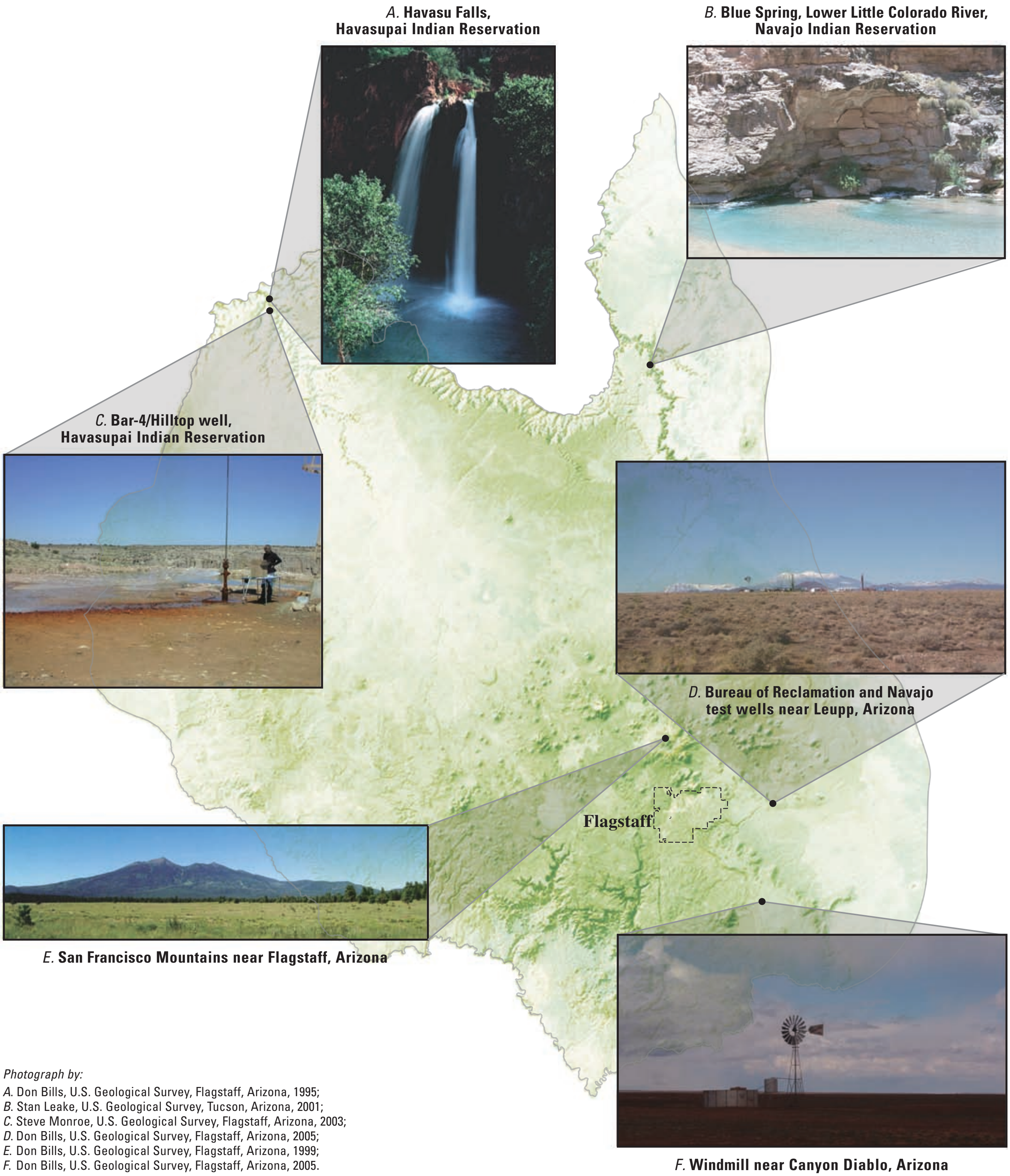
WELL-NUMBERING SYSTEM,
NAVAJO RESERVATION, ARIZONA





WELL 03 98-15.20x13.94

In the Navajo Reservation, where public land surveys have not been made, the local identifier is a filed number that consists of three parts. The first part is formed from the Bureau of Indian Affairs (BIA) district number. The second part is the 15-minute quadrangle number also assigned by the BIA. The third part is the quadrangle location number and indicates the position of a site within a 15-minute quadrangle and consists of two parts. The first part is the distance in miles west of the northeast corner of the quadrangle, and the second part is the distance in miles south of the northeast corner of the quadrangle.



Collage of photographs of the study area.

Hydrogeology of the Coconino Plateau and Adjacent Areas, Coconino and Yavapai Counties, Arizona

By Donald J. Bills, Marilyn E. Flynn, and Stephen A. Monroe

Abstract

Two large, regional ground-water flow systems occur in the Coconino Plateau and adjacent areas: the C aquifer and the Redwall-Muav aquifer. The C aquifer occurs mainly in the eastern and southern parts of the 10,300-square-mile Coconino Plateau study area, and the Redwall-Muav aquifer underlies the entire study area. The C aquifer is a water-table aquifer for most of its occurrence with depths to water that range from a few hundred feet to more than 1,500 feet. In the western part of the Coconino Plateau study area, the C aquifer is dry except for small localized perched water-bearing zones decoupled from the C aquifer to the east. The Redwall-Muav aquifer underlies the C aquifer and ranges from at least 3,000 feet below land surface in the western part of the Coconino Plateau study area to more than 3,200 feet below land surface in the eastern part of the study area. The Redwall-Muav aquifer is a confined aquifer for most of its occurrence with hydraulic heads of several hundred to more than 500 feet above the top of the aquifer in the western part of the study area and more than 2,000 feet above the top of the aquifer in the eastern part of the study area near Flagstaff. In the eastern and northeast parts of the area, the C aquifer and the Redwall-Muav aquifer are in partial hydraulic connection through faults and other fractures.

The water discharging from the two aquifers on the Coconino Plateau study area is generally of good quality for most intended uses. Water from sites in the lower Little Colorado River Canyon had high concentrations of most trace elements relative to other springs, rivers, and streams in the study area. Concentrations of barium, arsenic, uranium, and lead, and gross alpha radioactivity were greater than U.S. Environmental Protection Agency Maximum Contaminant Levels for drinking water at some sites. Ground water discharging to most springs, streams, and wells on the Coconino Plateau and in adjacent areas is a calcium magnesium bicarbonate type and has low concentrations of the major dissolved constituents. Ground water discharging from the Redwall-Muav aquifer to springs in the lower Little Colorado River Canyon is a mixture of water from the C aquifer and the Redwall-Muav aquifer and is a sodium chloride type with high concentrations of most major dissolved constituents. Concentrations of sulfate and chloride in ground water discharging from the Redwall-Muav aquifer at springs near the south rim of Grand Canyon increase toward the west. Water samples from the Verde River above Mormon Pocket had higher concentrations of most dissolved constituents than samples from springs that discharge from the Redwall-Muav aquifer at Mormon Pocket and in Sycamore Canyon.

Water-chemistry data from C aquifer wells and springs in the Flagstaff area indicate that ground-water ages in the aquifer range from 7,000 years to modern and that samples were a mix of younger and older waters. Ground-water ages for the Redwall-Muav aquifer are estimated to range from 22,600 to 7,500 years, and low tritium values indicate that this water is older than water discharging from the C aquifer. Tritium and carbon-14 results indicate that ground water discharging at most springs and streams is a mixture of young and old ground waters, likely resulting from multiple flow paths and multiple recharge areas.

Ground-water withdrawals in the study area increased from about 4,000 acre-feet per year prior to 1975, to about 20,000 acre-feet per year in 2003. About two-thirds of the water withdrawn is from the C aquifer and about one-third is from the Redwall-Muav aquifer. In the study area, most development of the C aquifer has occurred near Flagstaff. Development of the Redwall-Muav aquifer is more extensive in Verde Valley where water-bearing zones of the aquifer are closer to land surface. In recent years, however, development of the Redwall-Muav aquifer in the study area has increased in response to population growth and the attendant increase in demand for new water supplies accelerated by a continuing drought.

Ground-water budget components for the C aquifer and Redwall-Muav aquifer combined were quantified by using measured and estimated discharge values from springs, a base-flow analysis of streams, and a flownet analysis for constant-head boundary areas. Two water-budget conditions were evaluated: one for predevelopment or steady-state conditions and one for transient conditions in 2002. For the predevelopment water budget, the average annual precipitation

available to the study area is estimated to be about 8,700,000 acre-feet. A recharge rate of about 302,000 acre-feet per year was calculated as the residual of the ground-water budget. Ground-water discharge of about 300,000 acre-feet per year was calculated from stream-flow gaging station data and spring flow measurements and estimates. About 223,000 acre-feet of the average annual ground-water discharge occurs at the northern boundary of the study area, and about 77,000 acre-feet occurs at the southern boundary. Evapotranspiration from the watershed is estimated to be about 8,198,000 acre-feet per year on the basis of the water-budget computation.

For the transient water budget calculated from 2002 water-year conditions, annual precipitation available to the study area is estimated to be about 4,350,000 acre-feet. Because of the drought and continuing high evapotranspiration rates, it was assumed that no recharge occurred during the 2002 water year. Discharge in the water budget was increased by 20,000 acre-feet for the transient budget to account for current ground-water withdrawals. This results in a net loss of about 313,000 acre-feet of ground water from storage or a decline in the water table of the regional flow systems of about 0.05 feet when applied to the entire study area. Actual water-level declines for the drought period 1998–2004 were more than 200 feet near municipal well fields and a few tens of feet or less in observation wells in the rest of the study area. Ground-water discharge at some springs and base flow of some streams also declined during this period.

Introduction

The water resources of the Coconino Plateau study area in northern Arizona are under increasing pressure from development (fig. 1). The population of this arid to semiarid region continues to grow, and the number of visitors to the numerous national and state parks and monuments in the region continues to increase each year. Residents, local and tribal governments, water-facilities managers, Federal interests, and environmental groups within the region recognize the potential consequences of increased ground-water development attendant to population growth. Public input has identified the sustainability, protection, and maintenance of springs and seeps and associated riparian habitat on the plateau as major issues that have broad support. Concerns about the effects of water development on regional springs, surface-water and riparian resources, and the availability and sustainability of regional water supplies have led to the organization of several action groups. In 2001, one of these groups, the North Central Arizona Regional Water Supply Study (NCARWSS), requested that the U.S. Geological Survey (USGS), in cooperation with the city of Williams, compile existing water-resources data, collect additional data and identify data gaps for the study area (Bills and Flynn, 2002). The study area, which included the plateau and parts of adjacent physiographic regions, encompassed about 10,300 mi^2.

Before the study described in this report began, little was known about the regional ground-water flow systems of the Coconino Plateau study area. One report prepared for the Tusayan growth environmental impact statement has indicated a direct relation between ground-water withdrawals and spring flows in discharge areas of the regional flow system (Kaibab National Forest, 1999; Errol L. Montgomery and Associates, 1999). Regional stakeholders agreed that an improved understanding of the regional hydrogeologic system was needed to address the concerns of water supply and ground-water sustainability. In order to develop a conceptual hydrogeologic framework for the Coconino Plateau study area, a comprehensive effort was needed to identify data gaps, collect additional data, and evaluate the data. In 2000, the Arizona State Legislature established the Arizona Rural Watershed Initiative (ARWI) program to help rural areas develop locally driven partnerships to address water-supply issues on a regional scale (fig. 2). In 2002 the Arizona Department of Water Resources (ADWR) and the Technical Advisory Committee (TAC) of the NCARWSS requested that the USGS continue its investigation of water resources in the study area. The TAC consisted of representatives from the ADWR, Coconino County, the city of Flagstaff, the city of Williams, the National Park Service (NPS), the Navajo Nation, the Hopi Tribe, the Havasupai Tribe, and the Grand Canyon Trust. The continued investigation involved interpretation of data compiled by Bills and Flynn (2002), and the compilation of additional data that could be used for the development of the hydrogeologic framework, hydrogeologic conceptual model, and water budget to provide a better understanding of the occurrence and movement of ground water in the region.

There are two regional ground-water-flow systems on the Coconino Plateau: the C aquifer and the Redwall-Muav aquifer. The C aquifer, which overlies the Redwall-Muav aquifer, comprises the Kaibab Formation, the Coconino Sandstone, and rock units of the Supai Group mainly in the eastern and southern parts of the plateau. The Redwall-Muav aquifer, named for its primary water-bearing units, the Redwall Limestone and Muav Limestone, occurs throughout the study area and was the principal focus of this study.

The Redwall-Muav aquifer is a regional aquifer system that is contained in several mainly limestone formations buried deep beneath the Coconino Plateau and adjacent areas. Because of the availability of other ground-water resources closer to land surface in most of the study area, the water resources of the Redwall-Muav aquifer were not developed on the plateau until the last decade. The water-bearing potential of the Redwall-Muav aquifer has historically been inferred from the few large, regional springs that either discharge into the Grand Canyon near the northern boundary of the plateau or discharge into Verde Valley near the southern boundary.

Figure 1. Location and geographic features of the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

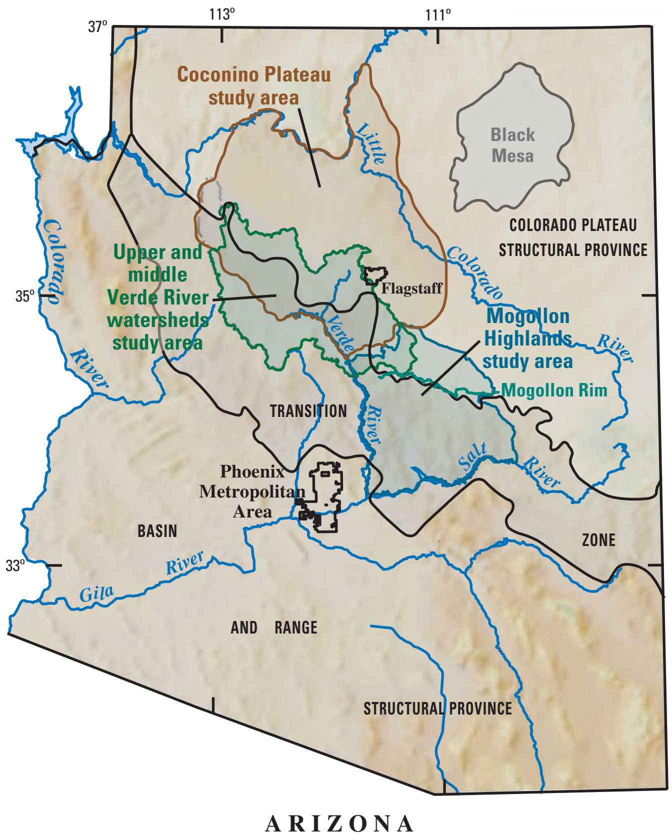


Figure 2. U.S. Geological Survey Rural Watershed Initiative study areas in north-central Arizona.

As growth and development and a continuing drought in the study area increase stress on shallower aquifers, development of deep wells to withdraw water from the Redwall-Muav aquifer is a more frequently chosen option. Interest in development of the Redwall-Muav aquifer and concerns about the sustainability of spring and seep flows in discharge areas have increased the need for water-resources and natural-resource managers to better understand the relation of the Redwall-Muav aquifer to other water resources. The water supply to the highly valued riparian environments in these discharge areas need to be understood for effective resource management and protection.

Formation of the NCARWSS was the first attempt by local stakeholders to identify and address regional water issues for this part of Arizona. The paucity of basic hydrogeologic information was identified by the group as an impediment to regional planning that lead to the compilation of hydrogeologic data by Bills and Flynn (2002). For this study, the USGS, in cooperation with the ADWR, collected additional data in the Coconino Plateau study area to add to the data base developed by Bills and Flynn (2002) and evaluated this information to (1) describe the hydrogeologic units, (2) describe the interaction of ground water and surface water, (3) develop a conceptual model of the ground-water flow systems, and (4) develop water budgets for predevelopment and current conditions.

The hydrogeologic data contained in this report and additional data from this study are available, for the most part, in Bills and Flynn (2002) or Monroe and others (2005), or in unpublished form from Ronald Antweiler (hydrologist, U.S. Geological Survey, Boulder, Colo.) or the USGS Arizona Water Science Center in Tucson, Arizona, or by accessing the Arizona Water Science Center Web page at http://az.water.usgs.gov.

Purpose and Scope

This report presents findings from a hydrogeologic investigation of the Coconino Plateau area conducted between 2001 and 2004. The report describes the hydrogeologic framework and ground-water flow systems, presents a conceptual model of the occurrence and movement of water, and provides estimated water budgets. The boundaries of the Redwall-Muav aquifer and other aquifers and water-bearing zones are further defined through discussions of ground-water movement, the interactions of surface water with ground water, and the various water-bearing zones, hydraulic properties and characteristics, water chemistry and geochemistry, and isotope hydrology. This report also provides information on the amount and variability of flow in the discharge areas of the regional flow system that support riparian habitat. Climate, land use and development, vegetation, and water-use data are used to evaluate the estimated water-budget data. Information on future data collection, analysis, and monitoring that could be used in conjunction with this report to develop a numeric ground-water flow model also is provided.

The focus of this report is the Redwall-Muav aquifer; however, information also is provided on other aquifers and water-bearing zones that interact with the Redwall-Muav aquifer. Estimated water budgets were calculated for steady-state (predevelopment) and transient conditions. The predevelopment water budget was based on data prior to 1975, and the transient water budget was based on data for the 2002 calendar year. Because precipitation in the 2002 water year was 50 percent or less of the average annual precipitation at most data collection sites in the study area, the transient water budget should not be considered representative of transient conditions in general.

Data compiled in Bills and Flynn (2002) were supplemented with additional data and information compiled from September 2001 to September 2004. The source of these data and information include, USGS National Water Information System (NWIS), the NPS, the U.S. Department of Agriculture (USDA) Forest Service, the U.S. Census Bureau, the Western Regional Climate Center, the National Atmospheric Deposition Program, the ADWR Ground-Water Site Inventory (GWSI), the Arizona Geological Survey (AZGS), the Arizona State Land Department (ASLD), Native

American governments, published reports, engineering and environmental consultants, universities, and private landowners. The USGS databases contain most of the information evaluated in this report.

Existing spatial data describing the Coconino Plateau and adjacent areas included geology, hydrology, hypsography, meteorology, land use, vegetation, water use, aerial photography, and remotely sensed imagery. Available point data included the location of wells and springs, well-construction and spring-development data, well logs, aquifer characteristics at wells and springs, water usage, water chemistry, temperature, water levels, and stratigraphy.

Acknowledgments

Members of the NCARWSS-TAC provided input at several group meetings during the course of the study. The cities of Williams and Flagstaff, several private water companies, and land owners provided access to well data and information. Spring data from remote locations on the Havasupai Indian Reservation and the south rim of the Grand Canyon were graciously provided by the Havasupai Indian Tribe and the NPS, respectively. John Rihs, hydrologist, NPS, helped prepare and obtain research permits for the sampling of springs and streams in Grand Canyon National Park. George Billingsley, geologist, USGS, shared his insight and provided perspective on the geology and structure of the study area. Many USGS hydrologists, hydrologic technicians, and volunteers assisted with the collection of data and water samples, sometimes under extremely harsh field conditions.

Methods of Investigation

This hydrogeologic evaluation is the result of analysis of data compiled by Bills and Flynn (2002), Monroe and others (2005), and Ronald Antweiler, hydrologist, U.S. Geological Survey (written commun., 2004), supplemented with data provided by the Havasupai Tribe and the NPS, and data collected from September 2001 to September 2004. These data were analyzed primarily to develop a hydrogeologic framework, a conceptual model, and water budgets. Water-quality and water-chemistry data were evaluated to refine our understanding of the hydrogeologic framework and conceptual model. Methods described in the following sections are those used during the period of this study. Data and information used from previous studies were obtained through various methods that generally are documented in the published reports from those studies.

Hydrogeologic Framework

Evaluation and analysis of the hydrogeologic framework is based on data available from reports that describe the geology of the area, in particular Billingsley (1987, 2000), Billingsley and Hendricks (1989), Billingsley and others (2000, 2006), Ulrich and others (1984), Weir and others (1989), Wolfe and others (1987a, 1987b), Newhall and others (1987), Goff and others (1983), Blakey (1990), Sorauf and Billingsley (1991), and Reynolds (1988), and supplemented with lithologic data from selected new wells, other holes of opportunity, and selected unsurveyed springs. Data from about 600 wells developed in the C aquifer, 47 wells developed in the Redwall-Muav aquifer, 18 springs discharging from the C aquifer, and 35 springs discharging from the Redwall-Muav aquifer were used to develop and define the hydrogeologic framework.

Water Chemistry

Water-chemistry data for selected springs, streams, and wells that discharge water from the Redwall-Muav aquifer in the central and western parts of the Coconino Plateau study area were used to refine the hydrogeologic framework and evaluate water quality (table 1, and supplemental data). Data describing the C aquifer near Flagstaff and the Redwall-Muav aquifer were included in the analyses. These data primarily were from sites in major discharge zones of both aquifers that were identified in previous studies (Bills and Flynn, 2002; Monroe and others, 2005; Ronald Antweiler, hydrologist, U.S. Geological Survey, written commun., 2004). Data were also available for samples collected from additional springs, streams, and wells in the study area. These data included field measurements of pH, specific conductance, dissolved-oxygen concentration, temperature, alkalinity, and discharge. Laboratory data were available for major ions, nutrients, trace elements, radioactive constituents, and stable and radioactive isotopes (table 1). Not all types of data were available for some sites. The USGS and other researchers have studied the hydrochemistry and isotope hydrology of parts of the Coconino Plateau during recent years (Ronald Antweiler, hydrologist, U.S. Geological Survey, written commun., 2004). This study incorporates data from these studies. Chemical data for all sites are provided in the section titled “Supplemental Data” at the end of this report.

Field and Laboratory Methods

Water-sample collection during this study at springs, streams, and wells followed methods described in Monroe and others (2005). Data from other USGS studies included in this report were collected according to protocols described in the USGS National Field Manual for the Collection of Water-Quality Data (Wilde and others, 1998) and USGS protocols in effect at the time of sample collection.

Selected spring samples collected in the western part of the Grand Canyon and along the Mogollon Rim during 2001–03 were collected as close as possible to the point of discharge owing to extremely difficult access. The remaining spring samples were collected at the point of discharge. Spring discharge was measured by using a pygmy meter or a Parshall flume, or was measured volumetrically, as physical conditions required (Rantz and others, 1982).

Table 1. Sources of water-chemistry data for sample sites, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

[--- indicate no data; USGS, U.S. Geological Survey]

Areas	Springs	Streams	Wells	Precipitation	Data collection dates	Data source
Flagstaff	4	---	25	---	1996–1997	Bills and others, 2000
Little Colorado River Canyon	3	1	---	---	2001–2002	USGS, unpublished data; Howard Taylor, U.S. Geological Survey, written commun., 2005
Grand Canyon National Park	26	8	---	---	2000–2002	Monroe and others, 2005; Ronald Antweiler, U.S. Geological Survey, written commun., 2004
Havasupai Indian Reservation	2	---	2	---	1994–2002	USGS, unpublished data
Hualapai Indian Reservation	2	2	---	---	1993–2002	USGS, unpublished data
Upper Verde River	12	25	1	---	1991–2003	USGS, unpublished data
Miscellaneous Coconino Plateau wells	---	---	5	---	2000–2003	USGS, unpublished data; Ronald Antweiler, U.S. Geological Survey, written commun., 2004
Precipitation, Flagstaff and Grand Canyon National Park	---	---	---	3	1962–2004	International Atomic Energy Agency, 2001; National Atmospheric Deposition Program, 2003; USGS unpublished data

Depth-integrated stream samples were collected in 2003 from the Little Colorado River at river mile 3.1 (3.1 mi upstream from the confluence with the Colorado River). Methods used for measuring stream discharge were based on stream size and physical conditions and included the Price AA current meter, the Price pygmy meter, and the Parshall flume (Rantz and others, 1982).

Water samples were collected from wells during 2001–03. Samples were collected after purging a minimum of three casing volumes of water from each well as temperature, pH, and specific conductance were monitored. Samples were collected after confirming that successive measurements of these field properties showed negligible change. Air and water temperature, pH, specific conductance, and dissolved-oxygen concentration were measured on site by using calibrated instruments. Alkalinity was determined in the field by fixed end-point or incremental titration (Radtke and others, 1998).

Samples were analyzed for selected constituents at several laboratories. Water samples were analyzed for concentrations of major ions, nutrients, and trace elements at USGS research laboratories in Boulder, Colorado, by using procedures described by Mitko and Bebek (1999, 2000), Garbarino and Taylor (1979), Taylor (2001), Roth and others (2001), Brinton and others (1996), and Antweiler and others (1996). The USGS National Water Quality Laboratory in Denver, Colorado, analyzed water samples for major ions, nutrients, trace elements, radioactive constituents, and stable and radioactive isotopes. Water samples were analyzed for deuterium/hydrogen ($^{2}H/^{1}H$) and oxygen-18/oxygen-16 ($^{18}O/^{16}O$) at the USGS Isotope Fractionation Project Laboratory in Reston, Virginia. Rock samples and well cuttings were analyzed for carbon-13/carbon-12 ($^{13}C/^{12}C$) at the University of Colorado in Boulder. Water samples were analyzed for tritium (^{3}H), and water and rock samples were analyzed for strontium-87/strontium-86 ($^{87}Sr/^{86}Sr$) at USGS research laboratories in Menlo Park, California. Bulk mineralogy and clay-fraction analysis of rock samples and well cuttings were completed at Northern Arizona University in Flagstaff.

Isotope Constituent Analyses of Water, Rock Samples, and Well Cuttings

Stable isotopes of oxygen, hydrogen, carbon, and strontium were measured relative to internationally agreed-upon standards (International Union of Pure and Applied Chemistry, 1994). For oxygen and hydrogen, the deviation of the sample from the standard mean is expressed by the delta notation ($\delta^{18}O$, $\delta^{2}H$) in per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW; Coplen, 1988, 1994; International Union of Pure and Applied Chemistry, 1994). Oxygen-isotope values were determined by using the carbon dioxide equilibration technique described by Epstein and Mayeda (1953). Hydrogen-isotope values were determined by using a hydrogen equilibration technique at 30°C to measure ^{2}H activity (Coplen and others, 1991). $\delta^{18}O$ and $\delta^{2}H$ values are reported in per mil.

Analyses of $^{13}C/^{12}C$ in water, crushed rock samples, and well cuttings were done by an isotope-ratio mass-spectrometric technique (Clark and Fritz, 1997) after conversion of inorganic carbon to carbon dioxide by addition of hydrochloric acid. $^{13}C/^{12}C$ results ($\delta^{13}C$) are reported in per mil relative to the Vienna Peedee belemnite standard (Coplen, 1994). These data are necessary to correct ^{14}C results for ground-water dating applications. ^{14}C isotopic activities were measured by accelerator mass spectrometry according to methods described in Beukens (1992). All ^{14}C determinations are reported in percent modern carbon (pmc) normalized to the 1950 National Bureau of Standards (National Bureau of Standards, 1984) oxalic acid standard (Stuiver and Polach, 1977; Wigley and Muller, 1981), with accompanying 1 sigma error in pmc.

Strontium isotopic analyses of water, crushed rock samples, and well cuttings were performed using solid-source mass spectrometry (Taylor, 2000; Bullen and others, 1996). Rock samples were leached in a 0.1 normal (N) hydrochloric acid solution before analysis for strontium isotopes. This procedure normalized $^{87}Sr/^{86}Sr$ results for natural and analytical fractionation to 8.37521. Strontium values are given as ratios ($^{87}Sr/^{86}Sr$; Monroe and others, 2005).

Water samples were analyzed for tritium, the radioactive isotope of hydrogen, by using a liquid-scintillation counting technique (Kendall and Caldwell, 1998) after preconcentration by an electrolytic-enrichment procedure. Results are reported in picocuries per liter (pCi/L) and tritium units (TU; 1 TU=1 ^{3}H per 1,018 hydrogen atoms; Fritz and Fontes, 1980; Clark and Fritz, 1997).

X-ray Diffraction Analyses of Rock Samples and Well Cuttings

Bulk mineralogy and the clay mineral fraction of samples representing the major stratigraphic units near the Bright Angel Fault in Grand Canyon and of well cuttings from Dogtown Well No. 1 and Rodeo Grounds Well were determined by using X-ray diffraction techniques (Schultz, 1964; Moore and Reynolds, 1997). Physical grain-size techniques were used to determine particle-size distribution for the rock samples. Results of the X-ray diffraction and grain-size analyses were compared with descriptions of similar rock units in the region (Rod Parnell, professor and Todd Loseke, graduate student, Northern Arizona University, written commun., 2002).

Isotopic Geochemical Approach

Stable isotopes of oxygen and hydrogen were used to help determine sources of recharge to aquifers. During evaporation, the isotopes in water fractionate. The lighter oxygen (^{16}O) and hydrogen (^{1}H) molecules preferentially move from the liquid phase to the gas phase leaving behind the heavier ^{18}O and ^{2}H molecules. This action will affect the isotopic signature of the water by making the isotope ratios more positive indicating enrichment in the heavier water molecules. The ratios are unaffected by low-temperature geochemical processes in ground-water systems (Clark and Fritz, 1997). Craig (1961) developed a relation between $\delta^{18}O$ and $\delta^{2}H$ for meteoric waters known as the global meteoric water line (GMWL). Regional variations in $\delta^{18}O$ and $\delta^{2}H$ may be caused by differences in latitude, altitude, or temperature. For this study, a local meteoric water line (LMWL) was developed using $\delta^{18}O$ and $\delta^{2}H$ data from precipitation samples collected by the NPS at the National Atmospheric Deposition Program National Trends Network Monitoring Location AZ03, Grand Canyon National Park, Coconino County, Arizona, between 1989 and 2003 (Pendall, 1997; Harvey, 2000; National Atmospheric Deposition Program, 2003). $\delta^{18}O$ and $\delta^{2}H$ data for wells and springs in the study area were compared with both the GMWL and LMWL to determine possible recharge and mixing of waters from different parts of the ground-water flow systems.

Residence time of ground water was estimated by converting ^{14}C values in pmc to time (years) by using a method known as Conventional Radiocarbon Age (Stuiver and Polach, 1977). The Conventional Radiocarbon Age method is used for the conversion without considering either isotopic dilution or fractionation from water and carbonate-rock interactions. This approach biases the adjusted ground-water age to be artificially older. A better estimate of ground-water residence time using ^{14}C data requires adjustment to account for the influence of isotopic dilution and fractionation along flow paths. Because ground water in the Redwall-Muav aquifer is contained primarily in carbonate rocks, ground-water residence times were adjusted by using methods described in Monroe and others (2005) that account for the influence of isotopic dilution and fractionation.

$^{87}Sr/^{86}Sr$ data were analyzed to aid in determining ground-water flow paths and water-rock interactions. Geologic units have distinct $^{87}Sr/^{86}Sr$ values, and strontium enters water through dissolution of minerals from these units during chemical weathering. This relation allows the use of strontium isotopes as a tracer in many ground-water systems (Faure, 1986). Dissolution rates are dependent on chemical processes and the minerals that are present. The $^{87}Sr/^{86}Sr$ values in ground water reflect the strontium ratios of the host rock but may differ slightly if the ground-water flow path involves multiple rock units.

Tritium data were used to help determine ground-water residence time and ground-water mixing at time scales of less than 50 yr. Low concentrations of cosmogenic tritium occur as background in natural waters. Anthropogenic tritium was produced by thermonuclear tests that began in 1952. Thermonuclear tritium levels peaked in about 1963 before atmospheric thermonuclear testing was banned. Tritium has a half-life of 12.3 yr, and the radioactive decay of tritium with the known levels of tritium in the environment make it possible to use tritium to determine the age of modern ground water and to approximate the time of recharge. In continental regions, tritium values of less than 0.5 TU indicate recharge prior to 1952. Values of 0.5 TU to 10 TU indicate possible mixing of pre–1952 and post-bomb waters, and values greater than 10 TU represent recharge less than 50 yr ago (Mazor, 2004).

Statistical Analyses

Water-chemistry data were statistically analyzed by using principal components analysis (PCA) and Q-mode agglomerative hierarchical cluster analysis (HCA) with S-Plus statistical software (Insightful Corporation, 2002). Theobjective of the statistical analysis was to identify patterns of similarity or differences among major-ion data collected from springs, streams, and wells. PCA is a mulitvariate statistical technique that does not require a normally distributed data set and is used to reduce the number of dimensions present in large data sets (e.g. the major-ion data), replacing them with a smaller set of variables (i.e. their principal component axis; Everitt and Dunn, 1992). The new variables describe the structure of the data matrix with each of the principal components representing a proportion of the total variance; the first few components typically account for most of the variability in the data set. The principal components are orthogonal, independent, uncorrelated, and explain all the variance of the original data. PCA was used to determine the minimum number of variables that contain the maximum amount of information and to identify relations among variables (Brown, 1998; Guler and others, 2002). PCA produces two matrices: a scores matrix and a loadings matrix (Kreamer and others, 1996). Within each component, the contribution of each of the major ion concentrations is represented by a loading value. Scores are used to represent individual sites as a function of major ion concentration.

The data were classified into distinct groups by using Q-mode HCA (Guler and others, 2002). The term Q-mode is used to describe parameter-based clustering, and in this case, water-chemistry parameters were used. The data for the springs, streams, and wells were standardized before cluster analysis was performed.

Agglomerative hierarchical algorithms proceed by combining or dividing existing groups, producing a hierarchical structure displaying the order in which groups are merged or divided. Agglomerative methods start with each observation in a separate group and proceed until all observations are in a single group (Insightful Corporation, 2001).

Conceptual Model and Water Budget

The hydrogeologic framework and information from wells, springs, and water chemistry provided the basis for developing a conceptual model of the occurrence and movement of ground water. Data for the study were stored in the USGS NWIS data base and then copied to Microsoft Access and Geographic Information System (GIS) data bases to facilitate organization, sorting, and evaluation.

Data used to develop water budgets were compiled through September 2004. The predevelopment period for the C aquifer and the Redwall-Muav aquifer was assumed to be pre-1975 and 1990 respectively; however, data through 2000 were included for springs that were used to calculate average annual discharge. This approach was deemed reasonable owing to the paucity of data for the area and the lag times between recharge and discharge of 100 yr or more for most areas. Meteorologic, land-use, vegetation, surface-water, and water-use information were used to evaluate other water-budget components and to establish the boundaries of riparian zones in discharge areas that could be influenced by increased water-resource development.

All data for this evaluation were examined for accuracy, precision, redundancy, errors, and representativeness. As much as possible, activities of this study were coordinated with those of other groups to take advantage of data collection and evaluation by other stakeholders involved in the NCARWSS. Activities of the other groups included (1) Havasupai tribal spring inventories, (2) NPS/AWPF (Arizona Water Protection Fund) and NPS/USGS inventory of Grand Canyon water resources along the south rim, (3) ADWR-ARWI evaluation of water resources in adjacent basins, and (4) academic research of water resources on the Coconino Plateau.

Description of Study Area

The Coconino Plateau is a sub-province of the Colorado Plateau south of the Colorado River in north-central Arizona (fig. 1; Hunt, 1967). The study area is about 10,300 mi^2 in size, including all of the Coconino Plateau and parts of the Little Colorado River and Verde River Basins where large regional discharges of water occur. The boundaries of the study area extend about 160 mi north of latitude 34°30’ N and about 170 mi west of longitude 111° W. The boundaries of the study area are the Colorado River on the north, the Aubrey and Chino Valley Faults on the west, the Verde River and Wet Beaver Creek on the south, and the Echo Cliffs Monocline and western edge of the Black Mesa Basin on the east (fig. 1; pl. 1). These features are the primary hydrogeologic boundaries representing physical controls on the regional movement of surface water and ground water in the study area.

Physiography

The Coconino Plateau has several physical characteristics that set it apart as a sub-province at the southern edge of the Colorado Plateau. Most of the 5,000 mi^2 Coconino Plateau extends above 5,000 ft in altitude and steep drops in altitude as a result of geologic structure, erosion, or both occur at all of the margins of the Coconino Plateau. The southern third of the Coconino Plateau is covered by volcanic rocks of the San Francisco and Mount Floyd Volcanic Fields. The interior of the plateau is a Cenozoic upland composed of nearly flat-lying Paleozoic and younger consolidated sediments (Billingsley and Hendricks, 1989; Beus and Morales, 1990). Thickness of the consolidated sedimentary rocks ranges from about 5,000 ft at the northern end of the plateau to about 8,000 ft at the southern end. Erosion of these sediments on the plateau has exposed a land surface characterized by low-relief hills and mesas, broad mature valleys, and several internal drainages with no free-flowing streams. Between uplift of the plateau and the more recent volcanic activity, thousands of feet of Mesozoic rocks were removed by Laramide erosion (Hunt, 1967). The hills and mesas are the scattered remnants of these rocks protected by local downwarping or lava cap rocks. The altitude of the study area ranges from about 1,740 ft at the mouth of National Canyon in Grand Canyon to 12,633 ft at the top of San Francisco Mountain. Total relief for the study area is more than 10,500 ft.

The Coconino Plateau study area is defined by large altitude changes at its margins. At the northern boundary of the study area, the Colorado River has exposed more than 5,000 ft of Precambrian and Paleozoic rocks that underlie the study area (pl. 1). These rocks are exposed in young, deeply dissected canyons near the south rim of Grand Canyon, suggesting recent and continuing erosion (Beus and Morales, 1990). Most of these young, steep drainages are aligned on joints and faults (Billingsley, 2000; Weir and others, 1989), are small in area, and have ephemeral streamflow. Where they intersect water-bearing zones in the rock, the drainages are discharge zones for local and regional ground-water flow northward toward the canyon. Near the southern boundary of the study area, more than 3,000 ft of Paleozoic and younger rock units dipping to the north are exposed along the Mogollon Escarpment above the Verde River Valley. The Mogollon Escarpment is a steep erosion scarp about 2,000 ft high that trends generally northwest-southeast through the study area (Pierce, 1984). Referred to as the Mogollon Rim locally, it is less well defined to the northwest where it blends into a Transition Zone between the Colorado Plateau and the Basin and Range Physiographic Province (pl. 1). In this part of the study area, most of the Paleozoic rocks are overlain by younger unconsolidated sediments and volcanic rocks. Northwest- to north-striking faults with several hundred feet of offset (upward on east side) parallel the extended trace of the Mogollon Rim and continue to define the northwestern edge of the Mogollon Rim (Pierce, 1984) and hence, the southwestern and western boundaries of Coconino Plateau. The eastern edge of the study area is less well defined by a series of parallel to subparallel monoclines and faults that separate the Coconino Plateau from the Black Mesa Basin to the east (fig. 1; pl. 1). These include the Echo Cliffs Monocline, the Black Point Monocline, and the Mesa Butte and Cedar Ranch Faults. The combined offset of these features is more than 3,000 ft (upward on west side), which represents a significant barrier to westward flow of ground water from the Little Colorado River Valley and Black Mesa Basin to the east.

The southern part of the study area is covered by San Francisco and Mount Floyd Volcanic Fields that overlie Paleozoic, Triassic, and younger sedimentary rocks (pl. 1; Billingsley and Hendricks, 1989). The age of the San Francisco Volcanic Field is 0.05–6.0 million years before present (mega-annum, Ma), and the field has a linear age trend, older to younger, from west to east (Nealey and Sheridan, 1989). A recent age determination for the Mount Floyd Volcanic Field agrees with the 7.03 Ma determined by McKee and McKee (1972). The age of Red Butte, an isolated volcanic intrusion about 10 mi south of the Grand Canyon, is 9.0 Ma (Wolfe and others, 1987a).

The sedimentary rocks of the Coconino Plateau slope gently to the south and southwest and to the east and northeast toward the Cataract Syncline (pl. 1). The mature valleys that have developed on the interior of the Coconino Plateau have few well-defined streams and no free-flowing water. Many of these valleys have been filled to depths of 100 ft or more with gravels and other erosional materials from surrounding uplands (Billingsley and others, 2000, 2006). These drainages generally follow the regional slope to the south and southwest away from the Grand Canyon before turning east and northeast into the structural trough of the Cataract Syncline.

The lack of free-flowing water on the Coconino Plateau study area is attributed to the permeability of sedimentary and volcanic rocks at land surface over much of the area. The exceptions to this drainage pattern are a few oversized drainages, such as Cataract Canyon, Canyon Diablo, Sycamore Canyon, and the Little Colorado River, that may have had more prominent rivers or streams in wetter periods before the deposition of volcanic rocks (Elston and Young, 1989; Holm, 2000). Cataract Canyon, in particular, almost divides the Coconino Plateau in half along the axis of the Cataract Syncline. The canyon is a superimposed meandering tributary of the Colorado River that likely began its downcutting 9 to 6 m.y. ago coincident with that of the Colorado River (Billingsley and others, 2006).

The overall drainage pattern of the study area is interrupted in places by areas of internal drainage. Mechanisms leading to the formation of internal drainage include (1) dissolution of gypsum in the Kaibab Formation, (2) dissolution of older limestones, (3) development of tectonically young faults and grabens that interrupt normal drainage, and (4) collapse structures associated with breccia pipe development (Billingsley and others, 2006). These internal drainage features are frequently filled with Quarternary sediments that can trap water (pl. 1). As a result, these areas may have a significant effect on the regional occurrence and movement of ground water.

Climate

The climate of the study area is semiarid to arid with spatial and temporal extremes of temperature and precipitation. The broad range of climate is strongly correlated with altitude resulting in moderate summers and severe winters at higher altitudes and intense summer heat and mild winters at lower altitudes. Microclimates also are common in the study area, as the slope and exposure of mountains and deep canyons control the amount of solar radiation that reaches land surface.

The Coconino Plateau study area, like much of the Southwest, is also subject to extended dry periods or droughts. Drought cycles on the plateau can be documented for hundreds of years into the past and provide some insight for the dry period that began concurrent with this study. Mesoscale changes in climate on the plateau have resulted in differential erosion and deposition; abandonment of Pueblo settlements in the 13th century and again in the 16th century; and most recently, drought periods of the 1930s and 1950s, and the current dry period, which began in 1998 (Cook and others, 2004; McCabe and others, 2004).

Average annual temperature ranges from 43ºF at Fort Valley on the southwest flank of San Francisco Mountain to 68ºF at the bottom of Grand Canyon (Sellers and others, 1985). Winter extremes of subzero temperatures can occur in deep canyons and, more commonly, in higher altitude areas of the mountains on the plateau. Summer temperatures commonly exceed 100ºF on the plateau and 110ºF in many of the deep canyons.

Average annual precipitation ranges from 5.5 in. at Cameron at the eastern edge of the study area to 27.7 in. at Junipine north of Oak Creek Canyon (fig. 3; Sellers and others, 1985). Precipitation is strongly correlated with altitude; generally less than 15 in./yr falls at altitudes below 5,000 ft and more than 25 in./yr falls above 7,000 ft (fig. 3; Bills and Flynn, 2002).

Although the amounts of winter and summer precipitation are about equal (Sellers and others, 1985), the winter and summer wet periods have different effects on the occurrence and availability of water in the study area. In winter, large storm systems that originate in the Pacific Ocean pass over the State bringing rain and heavy snows to higher altitudes and less frequent rain and snow to lower altitudes. Deep snow accumulations in the mountains can result in significant spring runoff to lower elevations. Because of low evapotranspiration in winter, a greater portion of winter precipitation is available for runoff and infiltration than summer precipitation. Summer rainfall occurs as part of a thunderstorm or monsoon season that is controlled by moisture-laden air masses that move into Arizona from the Gulf of Mexico and the Gulf of California. In middle to late summer, the orographic effect of the high altitude of the study area results in frequent, intense, short-duration thunderstorms. The amount of precipitation derived from these thunderstorms is sporadic both spatially and temporally, but intense downpours can produce flash flooding and debris flows. The high summer temperatures also result in evaporation far in excess of precipitation (fig. 3). The ratio of annual evaporation to precipitation is about 2:1 at higher altitudes in the southern part of the study area and ranges from about 3:1 at lower altitudes in the western and northwestern parts to more than 8:1 in the eastern and northeastern parts of the study area (fig. 3). Intense but sporadic rains that last from one to several days can result in significant runoff, however, most of this runoff eventually evaporates or is transpired back to the atmosphere.

Vegetation and Land Use

Ponderosa pine forest with piñon and juniper pines and aspen and oak interspersed with many flat meadow areas that contain drought tolerant grasses and brush are the primary vegetation types at higher altitudes in the study area. Lower altitude areas are populated with a mix of sparse grasses, brush, and other high desert species (fig. 4). Riparian habitat throughout the study area consists of a diverse mix of cottonwood, ash, and sycamore with mixed native grasses and brush and exotic, invasive phreatophytes, such as tamarisk (salt cedar), willow, Siberian elm, and Russian olive. Pine forests cover about 53 percent of the study area, and high-altitude desert scrubs and grasses about 47 percent of the area (fig. 4).

Riparian habitats exist at springs, seeps, and short stream segments fed by springs. These riparian areas are among the least affected such areas remaining in Arizona, have national significance, and are linked to important components of Native American culture. Many of the springs issue from water-bearing zones in the Redwall and Muav Limestones into canyons of the greater Grand Canyon area that are approximately 3,000 ft below the mean altitude of the Coconino Plateau. These habitats support a species diversity that is about 100 to 500 times greater than that of the surrounding landscape (Grand Canyon Wildlands Council, 2004). Several of the riparian areas have national significance because of their location in Grand Canyon National Park (GCNP), yet little is known about the variability and sustainability of spring flows that sustain these areas. These springs and seeps, and the diverse biological habitat that they support, are a critical aspect of GCNP operations. Springs and seeps that discharge along the Mogollon Rim to the south also are critical to the health and maintenance of riparian habitat in these areas. Continued development of water resources and changes in climatic conditions in the study area threaten to upset the regional ground-water flow systems and the riparian areas that they support.

Since 1998, drought conditions in the Southwest have resulted in much less water being available to plants. The resultant stress makes the plants more susceptible to disease, insect outbreaks, and wildfires. From 1999 to 2003 about 45,300 acres of the Kaibab and Coconino National Forests have burned (Bruce Greco and Larry McCoy, forestry technicians, Coconino and Kaibab National Forests, written commun., 2004). Beginning in 2002, a pine bark beetle infestation triggered by the dry conditions threatened to kill as much as 75 percent of the forest if climate and water conditions did not improve dramatically (DeGomez, 2002). The amounts of surface water and ground water available for other uses are likely to change as the forest adjusts to these changing conditions.

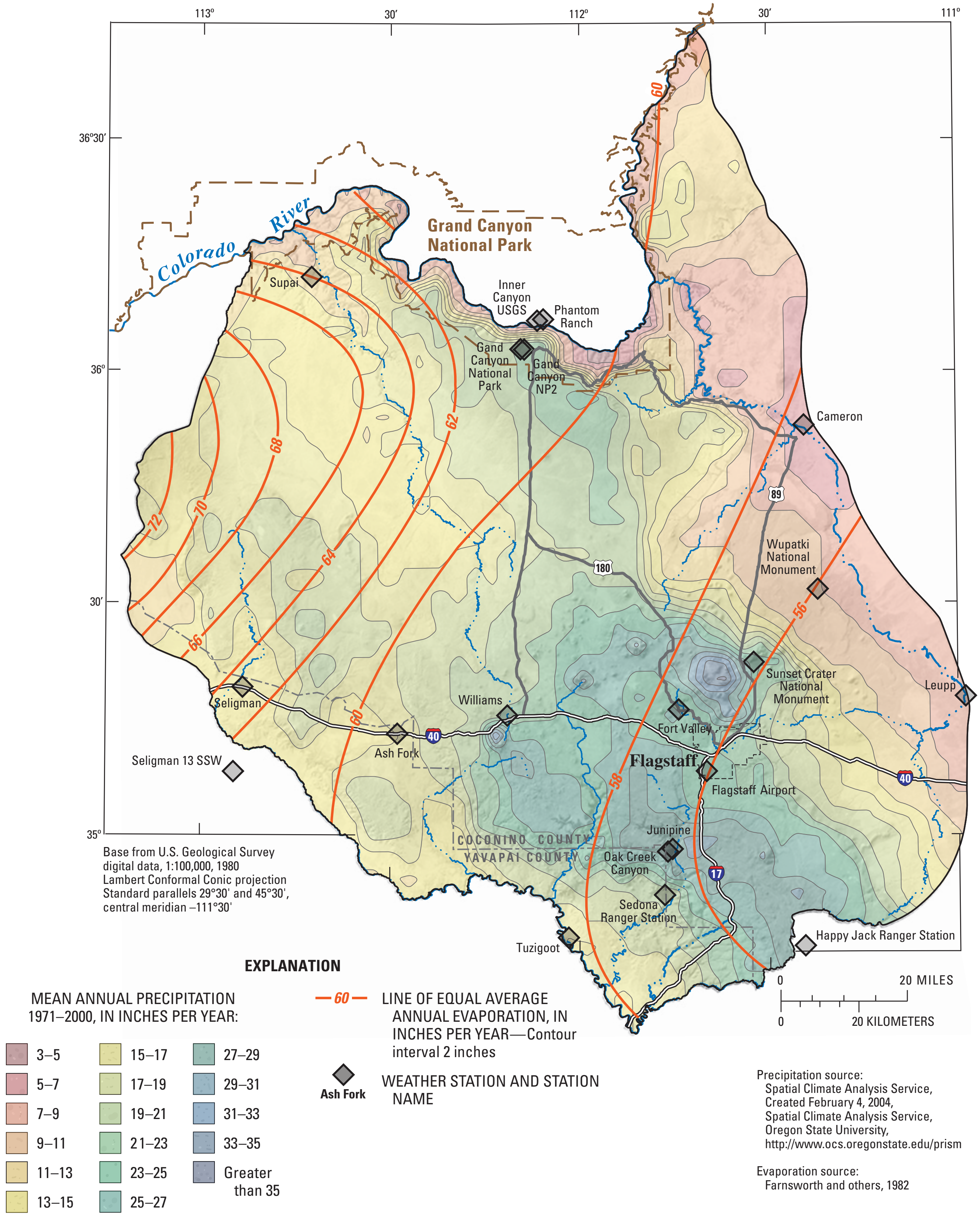


Figure 3. Mean and annual precipitation and average annual evaporation, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

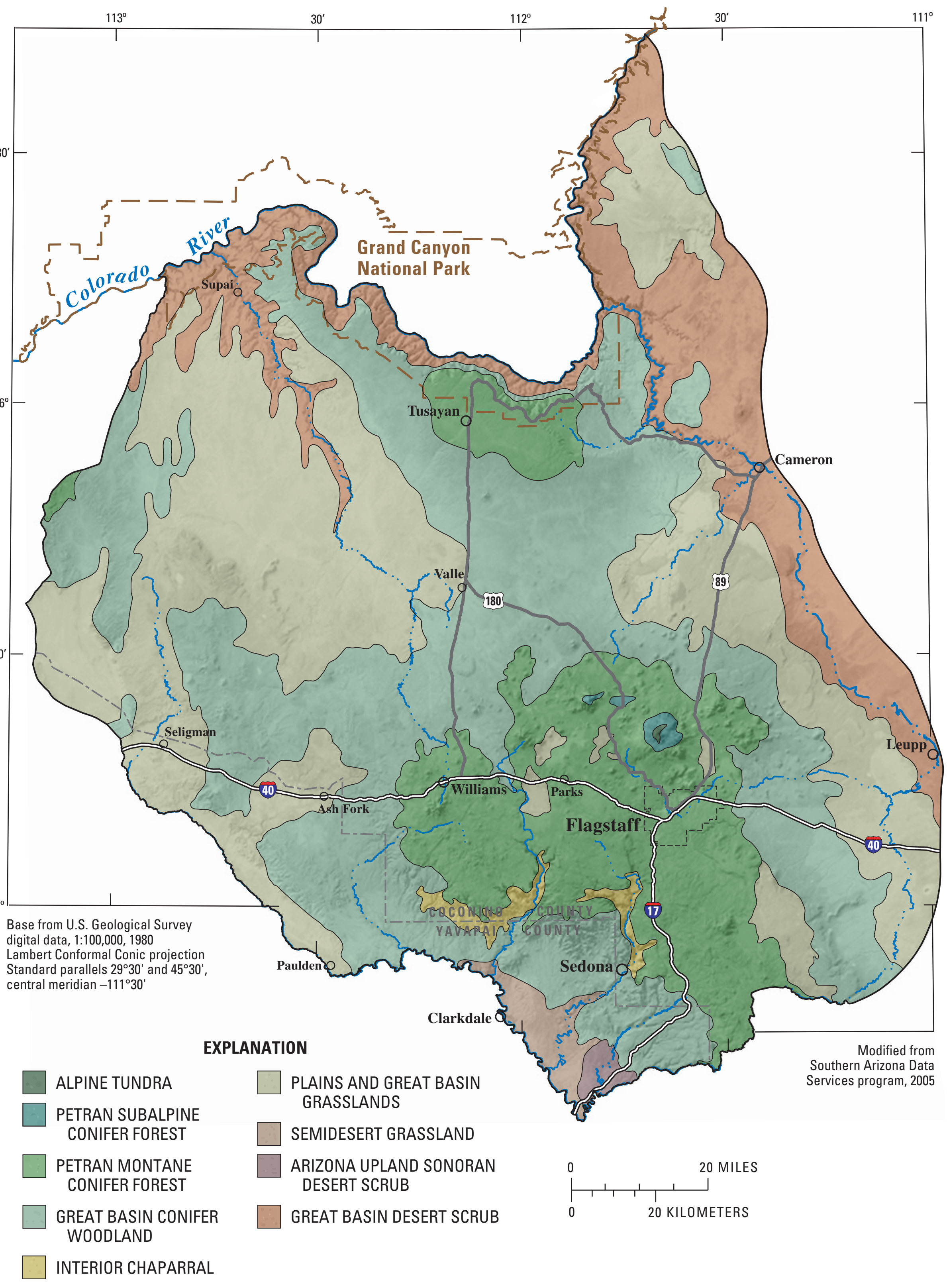


Figure 4. Vegetation types in the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

Arizona State Land Department and Bureau of Land Management (BLM), U.S. Department of the Interior, maps indicate that about 42 percent of the land in the study area is managed by the Federal Government and 20 percent is managed by three Indian reservations and other Native American trust lands (Southern Arizona Data Services Program, 2005). The remaining 38 percent is evenly split between State Trust and privately-owned land. Federal lands in the study area include parts of the Coconino, Kaibab, Prescott, and Tonto National Forests; GCNP; Sunset Crater, Wupatki, and Walnut Canyon National Monuments; and BLM lands (fig. 5). Indian reservation lands include the Havasupai Reservation and parts of the Hualapai Reservation west of Flagstaff, parts of the Navajo Reservation east of Flagstaff, and the Navajo and Hopi Trust lands west, south, and east of Flagstaff.

Population and Water-Resource Development

Rates of human population growth and development in the Coconino Plateau study area during the last decade have been equal to and in some cases have exceeded those for the rest of Arizona (Kasindorf and McMahn, 2001). The population of the plateau increased 20 percent from 1990 to 2000 and is currently (2001) about 78,000. About 80 percent of the population lives in the Flagstaff area (U.S. Census Bureau, 2001), about 5 percent of the population lives at the western end of the Navajo Reservation and on the Havasupai Reservation, and the remainder lives in smaller population centers, including Williams, Valle, Tusayan, Grand Canyon Village, Ash Fork, Seligman, and Parks, and in rural areas throughout the plateau.

The Verde Valley area south of the Mogollon Rim was one of the fastest growing areas in the United States in 1999 (Woods and Poole Economics, Inc., 1999). The current population of the area is more than 61,000 (U.S. Census Bureau, 2004) and, as with the population of the Coconino Plateau study area, is projected to more than double by 2050 (Heffernon and others, 2001; Rocky Mountain Institute and Planning and Management Consultants, Ltd., 2002).

Northern Arizona also attracts millions of visitors each year to enjoy one of the largest concentrations of national parks and monuments in the Western United States (Ghioto, 2001). Chief among these is GCNP, which has been designated a world heritage site and one of the seven natural wonders of the world (National Park Service, 2001). Although GCNP visitation fluctuates, the average annual rate has increased by about 6 percent since 1985, and at least 90 percent of this visitation occurs at the south rim of Grand Canyon (Ghioto, 2001). Visitation peaked at about 5 million people in 2000 and has since dropped off to about 4 million; however, it is rising again as foreign and domestic travel, and national park visitation patterns have begun to improve since September 11, 2001 (Arizona Daily Sun, 2004).

Communities near national parks and monuments have benefited from this tourism. The increases in population and development on this part of the plateau can be traced to the need to provide services to this increasing visitor base as well as to the expanding needs of the growing communities. Other communities on the plateau are faced with these same growth and development issues that place increasing pressure on the limited water resources of the region. Fresh, accessible water is one of the key issues facing northern Arizona during the next decade (Flagstaff, city of, 1996). Public input has identified the sustainability, protection, and maintenance of springs and seeps and associated riparian habitat of the study area as major issues that have broad support (Kaibab National Forest, 1999).

Water-resources development on the Coconino Plateau study area first focused on the use of springs and small empoundment of surface water in the mid to late 19th century and early 20th century to support small developing communities, the railroad, and timber industry. As the demand for municipal water supply grew in the mid 20th century, wells were developed in shallow perched-water bearing zones to depths of a few hundred feet, or to the C aquifer at depths of 1,200 ft or more. The first successful well was drilled into water-bearing zones in the Redwall and Muav Limestones in 1984 at a total depth of about 3,500 ft. Since that time about 12 wells have been drilled to this depth or deeper for public supply, commercial development, or industrial use. Little is currently known about the performance of these wells and the hydraulic characteristics of water-bearing zones in proximity of these wells.

Previous Investigations

Bills and Flynn (2002) compiled a data base for the study area on geology, hydrology, climate, and other water-resources information and reports available through September 2001. The more significant reports are mentioned here to provide a regional and historical perspective.

The geology of various parts of the study area was investigated in some detail through the middle of the 20th century beginning with investigations of Dutton (1882) and Darton (1910) who focused on the geology and structure of northern Arizona in their reconnaissance studies of the region. Robinson (1913) provided the first detailed study of the San Francisco Volcanic Field. The hydrogeologic study of the Navajo and Hopi Reservations by Cooley and others (1969) provided a geologic framework for northeastern Arizona that is the basis of all modern work in the region. The geology of the Grand Canyon has been investigated by hundreds, if not thousands, of natural and physical scientists. The Grand Canyon Natural History Association has compiled these investigations into a bibliography of the Grand Canyon and lower Colorado River as a ready reference to Grand Canyon geology (Spamer, 1990).

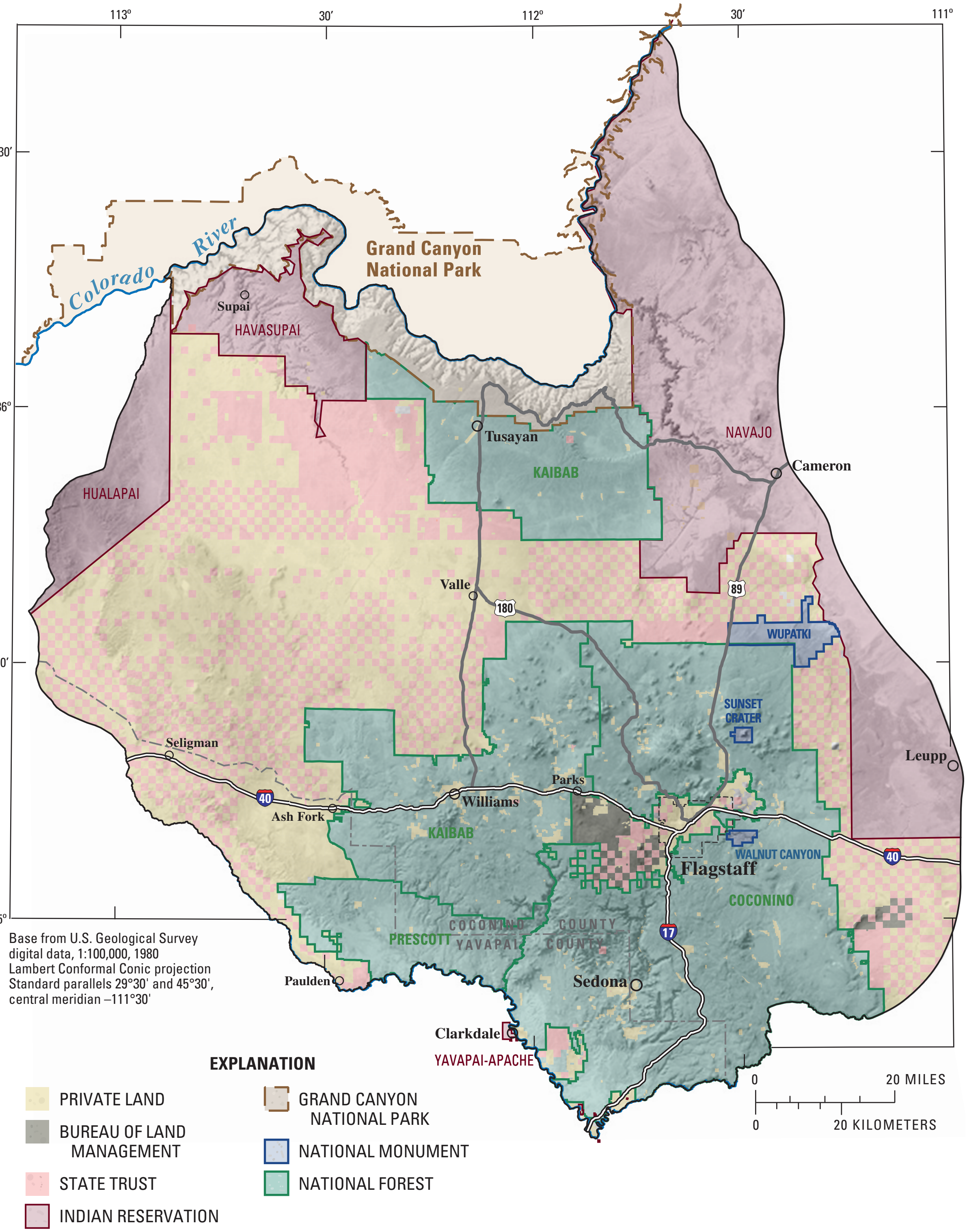


Figure 5. Land ownership in the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona (modified from Southern Arizona Data Services Program, 2005).

The surface geology and geologic structure of the Colorado and Coconino Plateaus south of Grand Canyon have remained largely overlooked until recent times (Huntoon, 1974; Huntoon and others, 1981; 1982; and 1986). Mineral exploration and, more recently, ground-water exploration and development are the topics of recent geologic studies on the Coconino Plateau.

Billingsley (1987) and Billingsley and others (2000) provided detailed geologic descriptions of the western part of the Coconino Plateau as part of regional mineral-resource studies. Wenrich and others (1994) conducted a hydrogeochemical survey to identify mineralized breccia pipes in the region.

Recently, there has been renewed interest in developing more detailed geology and structural information for the Coconino Plateau because of concerns about the effects of continuing ground-water development on the sustainability of spring resources in GCNP. Recent geologic investigations have focused on updating the Grand Canyon 30’ x 60’ quadrangle (Billingsley, 2000) and developing surface geology and structural information for the Valle and Cameron quadrangles (Billingsley and others, 2006; George Billingsley, geologist, U.S. Geological Survey, oral commun., 2004).

Geology and structural detail for the central part of the study area was described by Ulrich and others (1984) and Weir and others (1989). Detailed geologic and structural analysis of the upper and middle Verde Valley watersheds by the U.S. Geological Survey is ongoing as part of the ARWI (Blasch and others, 2006). The regional structural framework was also revisited recently by Gettings and Bultman (2005) for identification of important hydrologic structures based on regional geophysical surveys.

Although Dutton, Darton, and Robertson all commented on springs and ground-water potential in their geologic reconnaissance investigations, and Gregory (1916) conducted hydrographic reconnaissance as part of his study of the Navajo Country, the first detailed evaluations of ground water on the Coconino Plateau study area were not conducted until the 1960s (Akers, 1962; Metzger, 1961; Cosner, 1962; and Twenter and Metzger, 1963). Feth (1954) and Feth and Hem (1963) focused their investigations on the water-resources potential of national parks and monuments on and adjacent to the Coconino Plateau. Johnson and Sanderson (1968) completed the first systemic inventory of springs along the Colorado River from Lees Ferry to Lake Mead, including a discussion of Havasu Spring and Havasu Creek.

Cooley and others (1969) provided detailed discussions of the hydrogeology of the Navajo and Hopi Indian Reservations. Cooley (1976) also described, in detail, the hydrogeology of the lower Little Colorado River area, one of the principal ground-water discharge areas of the Coconino Plateau study area. Significant reports on the hydrology and hydrogeology for the more populated parts of the Coconino Plateau study area include investigations by the city of Flagstaff (Harshbarger and Associates and John Carollo Engineers, 1972, 1973; Montgomery, 1981; Harshbarger and Associates, 1976, 1977; Duren Engineering, 1983; Errol L. Montgomery and Associates, 1992, 1993), the State of Arizona (McGavock, 1968; McGavock and others, 1986; Levings, 1980; Arizona Department of Water Resources, 2000), and the USGS (Feth, 1953; Cosner, 1962; Appel and Bills, 1980; Owen-Joyce and Bell, 1983; Bills and others, 2000; Bills and Flynn, 2002; Hart and others, 2002; Monroe and others, 2005). Academic investigations that have contributed to the understanding of ground-water systems in parts of the Coconino Plateau include those of Goings (1985), Zukosky (1995), Fitzgerald (1996), Wilson (2000), and Kessler (2002).

Water-supply and water-sustainability issues on the Coconino Plateau study area have changed the focus of water-resource investigations away from localized studies to a more regional view of the hydrogeology and the capacity of regional systems to sustain water demands for people and ecosystems. The first of these regional studies was the Tusayan Growth Environmental Impact Statement and supplement released by the USDA Forest Service June 20, 1997, and July 17, 1998, that identified the protection of springs and seeps and associated riparian habitat in the greater Grand Canyon area as a major issue to be addressed by any new development in the area (Kaibab National Forest, 1999). A ground-water flow model developed by Montgomery and Associates for the environmental impact statement (Errol L. Montgomery and Associates, 1999) was used to predict the effects of ground-water withdrawals for proposed development on spring flows in the area. Although the model was based on a limited data set, one of the predictions of the model was that ground-water withdrawals would have a direct, although small, effect on spring flows.

Phase I of the NCARWSS, completed in September 1998, included the compilation of current and future demands for water, currently available water supplies and costs, and possible future water supplies available to the area (Arizona Department of Water Resources, 2000). More detailed water-demand and growth studies followed (Heffernon and others, 2001; Rocky Mountain Institute and Planning and Management Consultants, Ltd., 2002). One of the current and future water supplies identified for the area is ground water. There is also, however, a recognized lack of information about ground-water flow systems on the Coconino Plateau study area, their connectivity to surface-water resources in the area, and the variability and sustainability of these resources over time. Recent studies by Northern Arizona University suggest that spring-flow systems along the south rim of Grand Canyon may be more sensitive to changes in ground-water flow from natural and anthropogenic causes than previously recognized (Wilson, 2000; Kessler, 2002). The Bureau of Reclamation (BOR) North Central Regional Water Supply Appraisal Study (Kevin Black, hydrologist, BOR, written commun., 2006) report of findings indicate that there will be an unmet water demand by the year 2025.

Hydrogeology

The hydrologic system of the Coconino Plateau study area is characterized by a network of ephemeral streams, two main regional ground-water flow systems, and a precipitation record dominated by a cyclical pattern of wet and dry periods. Ephemeral streams originate on the mountain slopes of the San Francisco and Mount Floyd Volcanic Fields and drain north to the Colorado River and south to the Verde River. Several areas of internal drainage between the volcanic fields and the Colorado River influence surface-water/ground-water relations on the plateau. The regional ground-water flow systems are the C aquifer, which is mainly in the eastern half of the study area, and the Redwall-Muav aquifer, which underlies the C aquifer where the C aquifer is present and occurs throughout the study area. Zones of perched ground water are most common in the central and southern parts of the plateau in association with the volcanic fields but also occur in the consolidated sedimentary rocks west and northwest of these fields.

Precipitation Patterns

Changes in precipitation can affect the amount of water available to surface-water and ground-water reservoirs. Declines in precipitation during extended dry periods, if combined with constant or increased rates of evapotranspiration, result in less water available to recharge local and regional ground-water systems. This decrease in ground-water recharge can result in decreased spring flow and decreased ground-water discharge to streams. Alternatively, wet periods result in increased amounts of water available for ground-water recharge and can result in increased spring flows and ground-water discharge. The average annual precipitation value is useful for long-term comparisons; however, it is a poor indicator of water availability in a given year. A surplus of summer precipitation can offset a deficit in winter precipitation, but the summer rains, though important relief for water starved vegetation, provide little if any runoff and recharge to depleted surface-water and ground-water reservoirs owing to excessive evapotranspiration.

Annual and longer term precipitation patterns are evident in climate data for the Colorado and Coconino Plateaus. Winter storms (those occurring from October through April) provide about 60 percent of precipitation to the study area and summer storms about 40 percent (Western Regional Climate Center, 2004b). Extended wet and dry periods since the early part of the Holocene epoch are evident from precipitation records, tree-ring data, and geomorphology (Western Regional Climate Center, 2004b; Hereford and others, 2002; Swetnem and Betancourt, 1998; Hereford, 2002).

Throughout the Holocene, wet periods have resulted in the accumulation and deposition of sediments in stream channels and valleys. Dry periods are characterized by erosion: downcutting of channels and arroyo and gully development in channel sediments and valley margins. This record of extended wet and dry cycles is documented in the channels cut into talus and alluvial deposits of steep canyons and in the terrace deposits of larger drainages throughout the Southwest (Hereford, 2002).

Studies using tree-ring data correlated to the Palmer Drought Index have reconstructed a climate record for the Colorado Plateau back to the 900s (Cook and others, 2004). The reconstructed record indicates that periods of severe drought occur at least once per 100 yr and sometimes more often. Changes to drier conditions in the mid- to late 1400s and 1600s correlate with, and are at least partly responsible for, the abandonment of Pueblo settlements on and adjacent to the Coconino Plateau (Schlanger and Wilshusen, 1996).

The current drought in parts of the Western United States is the most severe since the 1950s and may be the most severe in the last 100 yr (Western Regional Climate Center, 2004b). The wet and dry cycles typical of the Southwest, with dry periods in the early 1930s, 1940s, 1950s and 1970s, are apparent in data from all the sites in the study area (figs. 6 and 7). A wet period began in the late 1970s and extended through the early 1990s. The early 1980s was among the wettest periods on record for northern Arizona (figs. 6 and 7). The annual precipitation has declined at all stations since about 1998. Hereford and others (2002) reported that the current precipitation pattern is similar to the regional drought of the 1930s to 1950s. The dry conditions in the mid- to late 1400s and 1600s, however, dwarf the current drought by comparison (Cook and others, 2004).

Geology

The Coconino Plateau study area is composed of Precambrian basement granites and metamorphic rocks, layered Paleozoic and Mesozoic rocks, Tertiary and late Cenozoic volcanic rocks, sedimentary rocks, and unconsolidated sediments, and Cenozoic to late Cenozoic unconsolidated sediments (pl. 1 and fig. 8). Structurally the plateau is characterized by large erosion escarpments and regional folds, faults, and other fractures that help to define the boundaries of the study area and further define the geologic framework (pl. 1). The sedimentary rocks generally are flat lying to gently dipping. Regional dips are 2 degrees to the southwest in most of the study area, 1 degree to the northeast in the southwestern part of the study area, and 1 to 5 degrees to the east or northeast in the eastern and northeastern parts of the study area. The Cataract Syncline in the western part of the study area and the Little Colorado River Valley in the eastern part are structural and erosional low areas separated by the uplands of the Kaibab Uplift in the central part of the Coconino Plateau study area (pl. 1). The Mogollon Rim, the result of uplift and cliff erosion, is a prominent transition from the Coconino Plateau and San Francisco Volcanic Field to the lower altitudes of Verde Valley.

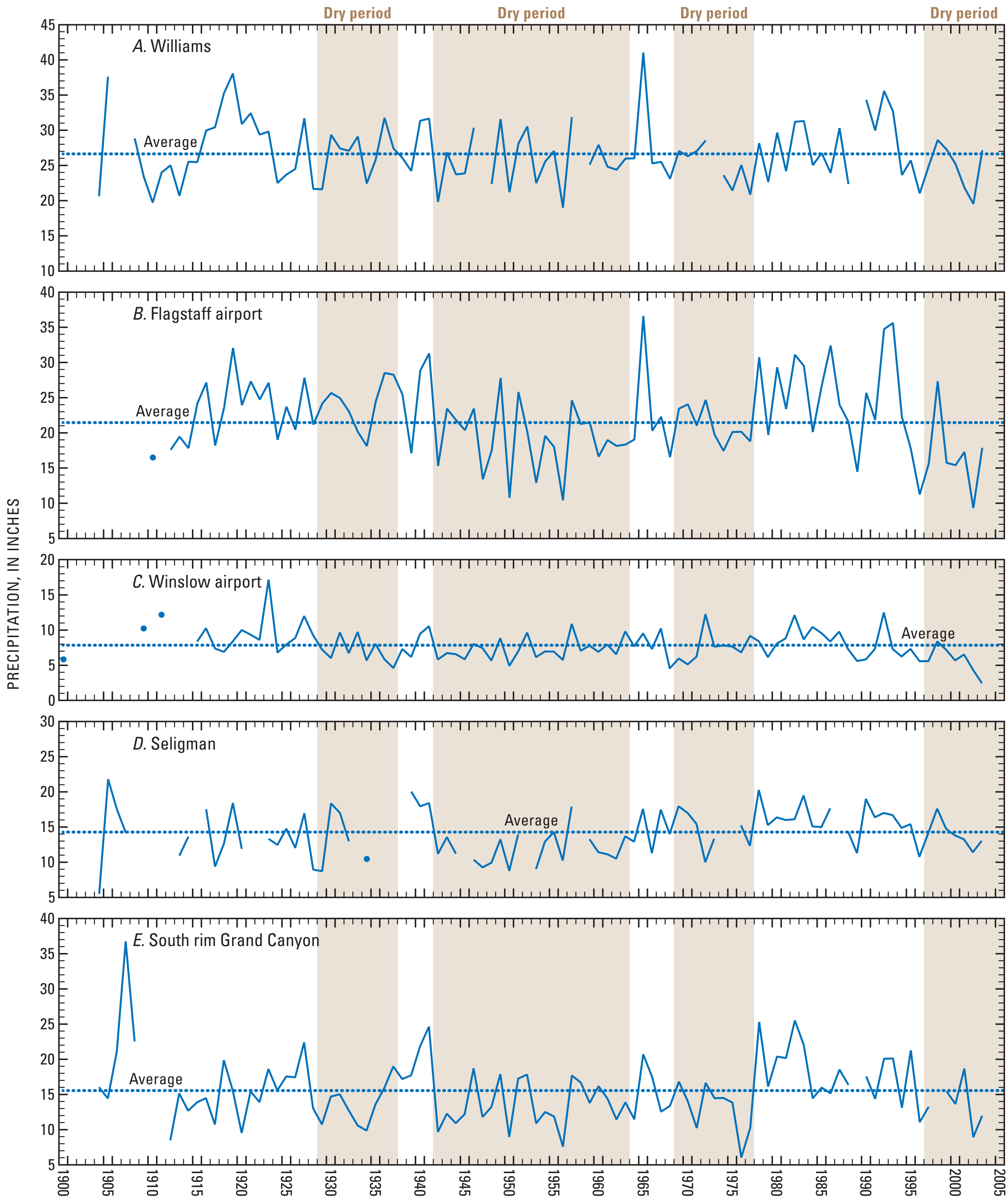


Figure 6. Annual and average precipitation for selected weather stations, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona: *A*, Williams; *B*, Flagstaff airport; *C*, Winslow airport; *D*, Seligman; *E*, South rim Grand Canyon.

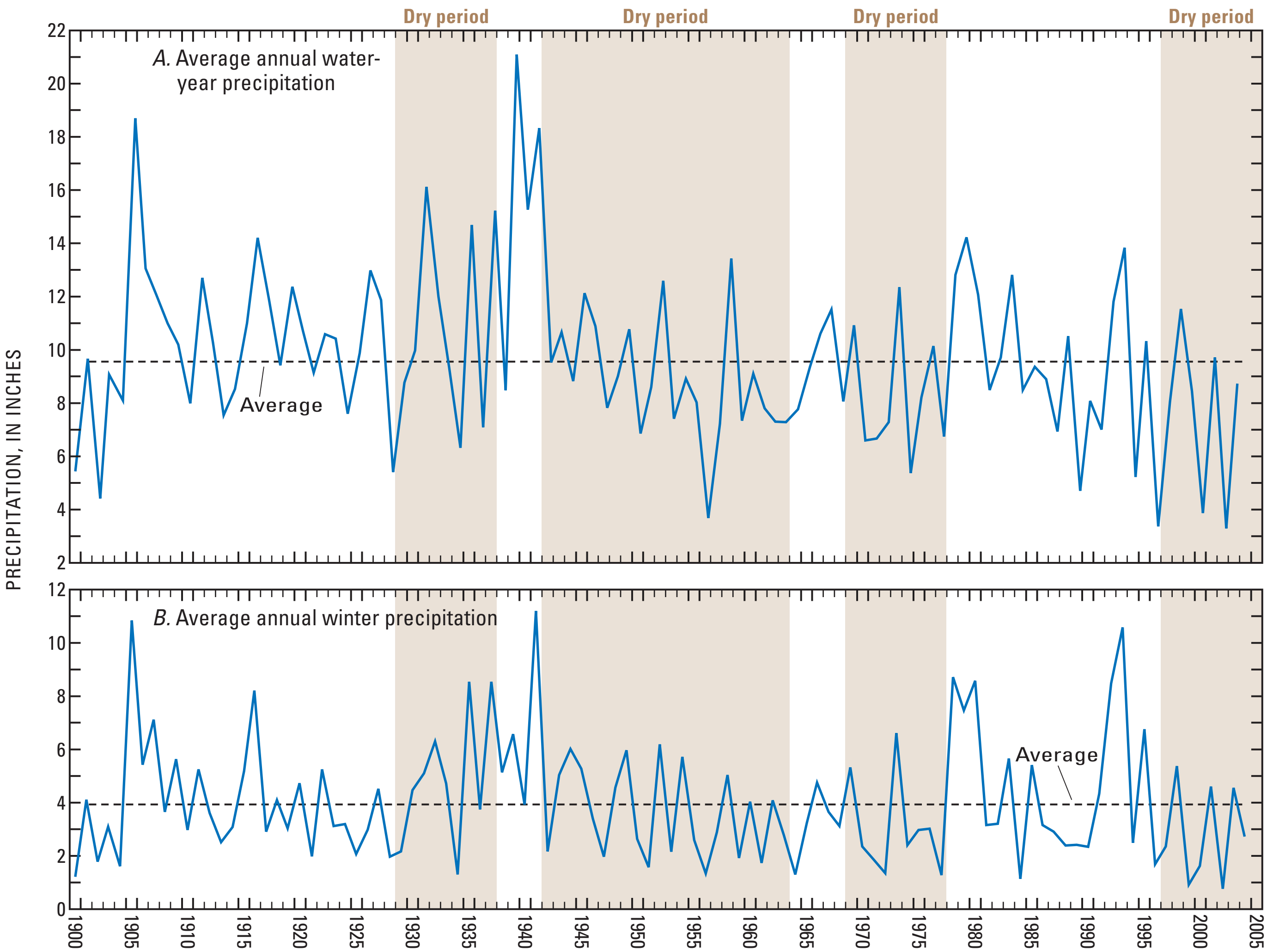


Figure 7. Average annual precipitation for all reporting weather stations, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona: *A*, Average annual water-year precipitation; *B*, Average annual winter precipitation (November–March). Data from National Climate Data Center (2004).

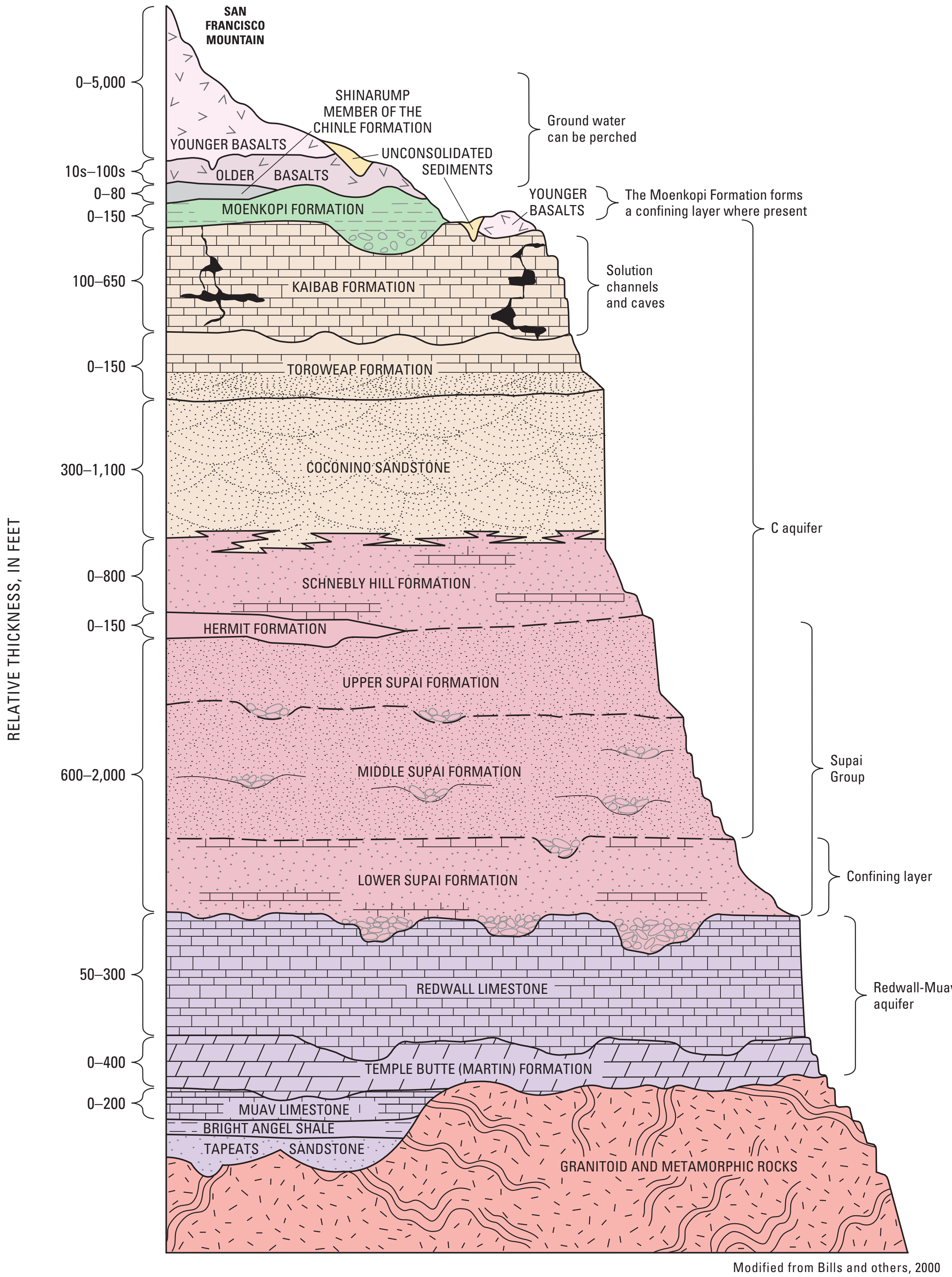


Figure 8. Generalized stratigraphic section of rock units in the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

Stratigraphy

The oldest rocks beneath the study area are Precambrian in age and are exposed north of the study area in the bottom of the Grand Canyon and south and west of the study area in the Verde and Chino Valleys (pl. 1). In the Grand Canyon area, the Precambrian rocks consist of metamorphic schists and gneisses, granites, and the Grand Canyon Supergroup. The Grand Canyon Supergroup is a collection of shale, sandstone, conglomerate, quartzite, and diabase units that were heavily eroded, faulted, and tilted prior to deposition of younger rock units (Elston, 1989). The Grand Canyon Supergroup and the metamorphic rocks are exposed in the Grand Canyon but do not appear in well cuttings from deep wells south of the canyon. Erosion has removed younger rocks in the Chino Valley and upper Verde River areas and along the Mogollon Rim, and the exposed Precambrian rocks in these areas consist of red to pink granite and granodiorite (pl. 1). They are consistent with intrusive granite complexes described by Conway and Silver (1989) and Cox and others (2002). Cuttings samples from deep wells throughout the study area that partly penetrate Precambrian rocks indicate that these rocks extend further under the Colorado Plateau than previously described. Before deposition of the Paleozoic sedimentary rocks, erosion of the Precambrian rocks formed a flat surface that has a general relief of a few tens of feet to about 500 ft (Hendricks and Stevenson, 1990). Huntoon (1989), however, documented scattered, isolated hills of Precambrian rocks as high as 1,200 ft buried by Paleozoic sediments in the western part of Grand Canyon.

Paleozoic rocks of the study area consist of the Tapeats Sandstone, Bright Angel Shale, Muav Limestone, Temple Butte/Martin Formation, Redwall Limestone, Supai Group, Hermit Formation, Schnebly Hill Formation, Coconino Sandstone, Toroweap Formation, Kaibab Formation, Moenkopi Formation, and the Shinarump Member of the Chinle Formation (pl. 1 and fig. 8). These consolidated sedimentary rock units are characterized by east-to-west facies changes, a general westward thickening of most units of about 1,000 ft, and a regional southwest dip of about 2 degrees (Billingsley, 2000; Billingsley and others, 2006). The Paleozoic rocks are sandstone, conglomerate, siltstone, mudstone, shale, limestone, and dolomite, and range in age from Cambrian to Permian (pl. 1 and fig. 8). They underlie almost the entire study area and are exposed in deep canyons along the Colorado River north of the study area (Beus and Morales, 1990) and the Mogollon Rim south and west of the study area (Twenter and Metzger, 1963). The Permian Kaibab Formation is the bedrock at land surface over much of the study area (Reynolds, 1988).

The Cambrian Tapeats Sandstone is the lowermost unit of the Paleozoic rocks and is composed mostly of brown and red-brown, medium- to coarse-grained feldspathic and quartz sandstone. The formation is predominantly a conglomerate at its base, grades to a medium sandstone near its top (Middleton, 1989; Billingsley, 2000), and is crossbedded to planar (Hereford, 1977). Overall thickness of the formation ranges from 0 to about 400 ft, and its contact with the overlying Bright Angel Shale is gradational where both units are present (Middleton, 1989; Billingsley, 2000). In Grand Canyon, the Tapeats Sandstone lies unconformably on the Precambrian rocks exposed in the canyon and is nearly continuous. The thickness of the Tapeats is controlled by relief of the underlying Precambrian surface, and in Grand Canyon, the Tapeats Sandstone thins and pinches out against the Precambrian highs (Middleton and Elliott, 1990; Billingsley, 2000). Near Payson, exposure of the Tapeats Sandstone is more discontinuous, and where it is exposed, it overlies granites and granite rubble. The Tapeats is also exposed discontinuously in the upper Verde Valley and Chino Valley areas, lying on granites and granite rubble. Here the Tapeats is stratigraphically equivalent to but much thinner than (about 260 ft or less where present) the Tapeats Sandstone of Grand Canyon (Hereford, 1977). Fossil evidence extends this correlation to the Payson area (Hereford, 1977). The Tapeats Sandstone is encountered only sporadically in wells, suggesting that it is discontinuous throughout much of the area and is confined to old channels and valleys on the Precambrian surface as suggested by past researchers (Hereford, 1977; Middleton, 1989; Middleton and Elliott, 1990).

The Cambrian Bright Angel Shale is an interbedded sandstone, siltstone, and shale (Middleton, 1989; Billingsley, 2000). The sandstones, in shades of brown and red, are most dominant near the bottom of the formation, which grades upward from a medium- to fine-grained sandstone to a shale. Greenish shale composed largely of clay with some chlorite and kaolinite (Middleton and Elliott, 1990) is the dominant composition. The Bright Angel Shale overlies and is gradational with the Tapeats Sandstone where the Tapeats is present and lies unconformably on the Precambrian rocks elsewhere (Middleton, 1989). It is 450 ft thick near the western end of Grand Canyon and thins southward and eastward. The formation is 350 ft thick along Bright Angel Creek, a few feet thick in the Chino Valley area, and altogether absent south and east of the Black Hills (Middleton and Elliott, 1990). Because the formation is rarely encountered in wells drilled in the study area, the channels and valleys on the Precambrian surface could be deeper than indicated. The upper contact of the Bright Angel Shale consists of complex intertounging with the overlying Muav Limestone (Middleton and Elliott, 1990).

The Cambrian Muav Limestone is composed of thin- to thick-bedded, dark-gray, fossiliferous limestone, silty limestone, dolomite, and mudstone with interfingering sandstone, siltstone, mudstone, and shale beds (Middleton and Elliott, 1990; Billingsley, 2000; Billingsley and others, 2006). Brown to orange-red sandstone, green to purplish-red siltstone and mudstone, and silty limestone are more common near the base of the formation. The Muav grades upward into a fine- to medium-grained, light- to dark-gray limestone and dolomite (Middleton, 1989). McKee and Resser (1945) described several horizons and members, including the Rampart Cave Member, which is significant in the context of this report as the principal point of discharge for many springs along the south rim of Grand Canyon. The limestone units of the Muav are correlative throughout the Grand Canyon, but are difficult to differentiate in well cuttings. Cuttings from wells drilled in the northern and western parts of the study area are similar in lithology to the Muav Limestone; however, in the central and southern parts of the study area, well cuttings appear more consistent with the Martin Formation. The southward depositional extent of the Muav Limestone probably is south of Grand Canyon (Middleton, 1989), but because the limestones in the Muav and Martin are so similar, the two formations may be stratigraphically equivalent. In a few wells, the Muav Limestone is absent and the holes bottom in granite. This configuration could be indicative of high areas in the surface of the Precambrian rocks. The Muav Limestone thickens westward; it is less than 200 ft thick in the eastern part of Grand Canyon and more than 600 ft thick in the western part of the canyon (Middleton and Elliott, 1990; Bilingsley, 2000). It is not present or not recognized in outcrops in Chino Valley, in the upper Verde Valley, or in the Payson area (Middleton, 1989).

The Devonian Temple Butte Formation includes purple to light-gray, dolomite, sandy dolomite, sandstone, mudstone, limestone, and conglomerate. These rocks fill channels eroded into the underlying Cambrian units (Beus and Morales, 1990). The formation is discontinuous along the south rim of Grand Canyon and thickens westward, but it is absent in wells in the study area and is not exposed at the southern and western margins of the plateau. The formation ranges from 50 to 275 ft thick where it is exposed (Billingsley, 2000). In the central and southern parts of the study area and along the Mogollon Rim, equivalent Devonian rocks are recognized as the Martin Formation (Tiechert, 1965).

The Devonian Martin Formation is a dolomite or limestone with local minor amounts of mudstone, sandstone, or sandy dolomite (Beus, 1989). Teichert (1965) defined two members of the formation in central Arizona: a thin basal member composed mostly of sandstone, silt, and sandy dolomite, and a limestone and dolomite member. In the study area, the Martin Formation is predominantly a light-gray to brownish-gray, fine-grained dolomite to medium-grained dolomite and limestone, and ranges in thickness from 0 to about 460 ft. The formation is absent in Grand Canyon. The presence of the Martin Formation directly overlying granite in some wells further supports the existence of scattered high areas in the surface of the Precambrian rocks. The Martin Formation crops out along the western, southern, and eastern margins of the Coconino Plateau study area and lies unconformably on lower Cambrian units or Precambrian rocks at the southern margin of the plateau and in wells throughout the study area.

The Mississippian Redwall Limestone is a massive, light-gray limestone and dark-gray to brown dolomite with thin beds and lenses of chert (Beus, 1989). Four members of the Redwall, the Whitmore Wash, Thunder Springs, Mooney Falls, and Horseshoe Mesa Members, were defined by McKee and Gutschick (1969). All the members are found in outcrops along the south rim of Grand Canyon and at the southern and western margins of the plateau (pl. 1). Total thickness of the Redwall Limestone ranges from about 450 ft in the southeastern part of the study area to about 750 ft in the northwestern part (Beus, 1989; Billingsley, 2000; Billingsley and others, 2006). In cuttings from wells throughout the study area, the Redwall Limestone is mainly a gray limestone with dolomite and, less commonly, chert. The formation lies unconformably on Devonian, Cambrian, or Precambrian rocks. In well cuttings, the upper part of the formation appears gradational with the Lower Supai Formation; however, significant pre-Supai erosion and weathering of the Redwall allows for intermixing of these two units at the contact (Beus, 1989; Billingsley and others, 2006).

McKee (1982) divided the Pennsylvanian to lower Permian Supai Group in the Grand Canyon area into four formations: the Esplanade Sandstone, the Wescogame Formation, the Manakacha Formation, and the Watahomigi Formation. The Supai Group of McKee can be traced from the Grand Canyon to the Mogollon Rim. More recently, Blakey (1990) provided a modified description of the Supai Group formations on the basis of his study of Pennsylvanian and Permian rocks in the Mogollon Rim region. Blakey's classification, used in this report, divides the Supai Group into three formations—the Lower Supai Formation, the Middle Supai Formation, and the Upper Supai Formation (pl. 1 and fig. 8). The Lower Supai Formation, which lies unconformably on the Redwall Limestone, consists of gray to purplish-red limestone, siltstone, mudstone, shale, and conglomerate, with chert lenses in the limestone. The Middle Supai Formation is a sequence of interbedded reddish-orange to reddish-brown fine-grained calcareous and cherty sandstone, siltstone, and mudstone. The Upper Supai Formation is a reddish-brown calcareous, planar to crossbedded, fine-grained sandstone with siltstone and mudstone. The Esplanade Sandstone of McKee (1982) is the dominant sandstone member at the top of the Upper Supai Formation and forms a prominent bench and erosion surface in the western part of Grand Canyon (pl. 1); however, it is considerably thinner on the Mogollon Rim and consists mostly of a red to reddish-brown mudstone. For those reasons, it is included in the Upper Supai Formation of Blakey (1990). The Supai Group in the Grand Canyon area is about 1,120 ft thick and generally thins eastward (McKee, 1982; Billingsley, 2000). In the middle of the study area the Supai Group is about 1,000 ft thick (Billingsley and others, 2006). In the Mogollon Rim area, it ranges from about 300 ft thick near Sedona to about 700 ft thick west and east of Sedona (Blakey, 1990).

The Permian Hermit Formation is a red to dark-red, thin-bedded siltstone and fine-grained sandstone that lies unconformably on the Supai Group in Grand Canyon (Billingsley, 2000). The thickness of the Hermit Formation in Grand Canyon ranges from about 850 ft near the western end of the canyon to less than 260 ft near the eastern end. At the Mogollon Rim, the thickness of the Hermit Formation is varied. The Hermit is difficult to differentiate from the underlying Upper Supai Formation in the central and eastern parts of the Mogollon Rim. Outcrops of the Hermit are 100 ft or less in the Sedona area, and the formation thickens to about 300 ft in the upper Verde Valley area (Blakey, 1990). Although outcrops of the Hermit Formation were recognized and described by Blakey (1990) on the flanks of Mt. Elden near Flagstaff, the formation is seldom identified in well cuttings as a distinct unit except in the western part of the study area.

The Permian Schnebly Hill Formation as described by Blakey (1990) occurs mostly in the central and southern parts of the study area and is not found in Grand Canyon or any of its tributaries to the south. The formation consists of orange to light red, fine-grained to very fine-grained sandstone, silty sandstone, and mudstone, and a distinct limestone marker bed near its base (Blakey, 1990). Throughout its occurrence, the formation lies unconformably on the Hermit Formation, where present, or on the Supai Group. In the Sedona area, the Schnebly Hill Formation is about 750 ft thick, and it thickens east and west along the Mogollon Rim to more than 1,500 ft (Blakey, 1990). The formation also thins sharply to the north and is not present in well cuttings north and northwest of Flagstaff.

The Permian Coconino Sandstone (Darton, 1910) is a distinct eolian quartz sandstone, fine- to medium-grained, well sorted, and white to tan in color. The formation is thickest (about 1,100 ft) in the Flagstaff area (Bills and others, 2000). In Grand Canyon, the formation forms prominent cliffs about 150 ft high in the western part of the canyon and more than 500 ft high in the eastern part (Billingsley, 2000). Along the Mogollon Rim, the formation is about 600 ft thick (Blakey, 1990). The Coconino Sandstone lies unconformably on the Hermit Formation in Grand Canyon and interfingers or is gradational with the Schnebly Hill Formation along the Mogollon Rim. The Coconino Sandstone has been identified in well cuttings throughout the study area. The interfingering with the Schnebly Hill Formation is especially prominent on an east-west line from Flagstaff to west of Williams.

The Permian Toroweap Formation occurs west of a line running from about Sycamore Canyon to Marble Canyon (Sorauf and Billingsley, 1991). The formation consists of red carbonate sandstone, redbeds, red silty sandstone and siltstone, limestone, and thin layers of gypsum (Sorauf and Billingsley, 1991). The formation ranges in thickness from 0 to about 380 ft and thickens westward. In the Flagstaff area, the transition from the upper part of the Coconino Sandstone to the Toroweap Formation is abrupt. East of Flagstaff, well data indicate that the formation is absent. The transition between the two formations becomes increasingly gradational northwestward from Flagstaff to the point at which it is difficult to distinguish the two formations (Sorauf and Billingsley, 1991).

The Late Permian Kaibab Formation (Sorauf and Billingsley, 1991) unconformably overlies the Toroweap Formation and is composed of two members: the lower Fossil Mountain Member and the upper Harrisburg Member. The Fossil Mountain Member is a light-grey, cherty, thick-bedded limestone to sandy limestone. The chert occurs in lenses or layers of interformational breccia. The Harrisburg Member is an interbedded sequence of light-red to grey limestone, dolomite, siltstone, sandstone, and gypsum (Sorauf and Billingsley, 1991). The frequency and amount of chert in well cuttings increase to the west of Flagstaff, and is rarely found in wells drilled east of Flagstaff. The formation thins from west to east and ranges in thickness from 100 ft to about 650 ft (Sorauf and Billingsley, 1991). It is exposed at land surface in much of the study area. Where exposed, the formation has well-developed fractures, many of which are widened by solution and sinkholes, and depressions caused by dissolution of gypsum.

The Triassic Moenkopi Formation (McKee, 1954) is composed of red to dark-red to reddish-brown, thin-bedded, siltstone, sandy siltstone, fine-grained to very fine-grained sandstone, mudstone, and gypsum. The formation lies uncomformably on the Kaibab Formation as a discontinuous erosion remnant throughout the study area and is best preserved where protected by overlying volcanic rocks. In much of the study area, the formation ranges in thickness from 0 to about 150 ft. At Red Butte, a complete section about 1,000 ft thick has been preserved (Billingsley and others, 2006).

The Triassic Shinarump Member of the Chinle Formation occurs as an erosion remnant mainly on the Coconino Plateau in the west-central part of the study area. The formation lies unconformably on the Moenkopi Formation and weathers to a veneer overlying rocks exposed at lower altitudes. The Shinarump Member is a white, coarse-grained sandstone to pebble conglomerate and has a thickness of 0 to 85 ft (Billingsley and others, 2006). Other rocks of the Chinle Formation occur along the eastern edge of the study area adjacent to and east of the Little Colorado River. The rocks are mostly multicolored, interbedded siltstone, claystone, fluvial sandstone, and limestone that dip shallowly to the east (Billingsley, 1987).

Tertiary and Quaternary sediments overlie Paleozoic and Triassic rocks throughout the study area. The Verde Formation, an unconsolidated to consolidated lakebed deposit, is the thickest of the Tertiary or Quaternary rock units and is present throughout Verde Valley. The Verde Formation is composed of light-gray, green, orange, or pink interbedded limestone, siltstone, sandstone, mudstone, and minor tuff, gypsum, and diatomite (Weir and others, 1989). It ranges in thickness from a few feet to more than 3,100 ft. Along the north and northeast edges of Verde Valley, the formation intertongues with volcanic rocks (Weir and others, 1989). The remaining Tertiary sediments are unconsolidated light-red, gray, and white, conglomerate, sandstone, gravel, silt deposits and local freshwater limestone deposits mainly in the central and western parts of the Coconino Plateau (Billingsley and others, 2006). Recent travertine deposits are found in some canyons and drainages along the northern and southern edges of the study area (Billingsley and others, 2006).

The Tertiary sediments are the result of Laramide erosion of north-flowing drainages in paleovalleys into a fluvial, freshwater environment. The deposits accumulated to an unknown thickness with the remnants partly preserved by overlying Tertiary volcanic rocks (Billingsley and others, 2006). Thickness of these deposits, where present, ranges from 60 to 180 ft.

Other unconsolidated alluvial, colluvial, glacial, and landslide deposits of Quaternary age are among the youngest deposits in the study area (Bills and others, 2000). These sediments occur as a veneer or as thicker discontinuous deposits throughout the study area. The alluvium consists of thin soils or thicker deposits of silt, clay, and fine sand in stream channels, lakebeds, grabens, and meadows. In the central and western part of the Coconino Plateau, these deposits are the source of extensive thin eolian sand-dune and sand-sheet deposits (Billingsley and others, 2006). These eolian deposits are normally stabilized by grassy vegetation during wet climate conditions, but the recent drought (1998 to present) has rendered these sand-dune and sheet-deposits unstable and subject to erosion (Billingsley and others, 2006). The colluvium is coarse-grained material confined to the steep slopes of canyons and mountainsides. Glacial outwash occurs in the Inner Basin of San Francisco Mountain and on the east and north slopes of the mountain. A few landslide deposits are on the southern flanks of the mountain and around the Mount Floyd Volcanic Field and Red Butte (Wolfe and others, 1987a, 1987b; Billingsley and others, 2006). Talus deposits and landslide deposits are common in tributary canyons of the Colorado River.

Quaternary travertine deposits are gray, white, and tan, massive, porous limestone deposited at old spring outlets at the base of either the Redwall or Muav Limestones along tributary canyons of the Colorado River. Many of these deposits are tens of feet to several hundreds of feet above the present river level and represent historical discharge zones for regional aquifers of the study area. Travertine continues to be deposited in the study area; massive deposits have accumulated in the Little Colorado River below Blue Spring, in Royal Arch Creek, and in Havasu Creek below Havasu Spring. These deposits range from 30 ft to more than 100 ft in thickness (Billingsley, 2000). Lesser amounts of travertine are accumulating at the outlets of minor springs in smaller tributaries of the Colorado River. Travertine deposits are not known to occur in the southern part of the study area along the Mogollon Rim or in the Big Chino or upper Verde Valleys despite the presence of several places where large amounts of ground water discharge from the Redwall and Muav Limestones or the Martin Formation. Travertine is being deposited south of the study area in the Fossil Creek and Tonto Creek drainages of the Mogollon Highlands (Parker and others, 2005).

The Tertiary to Quaternary volcanic rocks, grouped into six assemblages on the basis of age and geographic location, are (1) the Mormon Mountain Basalts, (2) the Mount Floyd Volcanic Field, (3) Red Butte, (4) Howard Mesa, (5) the San Francisco Volcanic Field, and (6) scattered young Tertiary intrusive rocks, pyroclastic deposits, and basalts.

The volcanic rocks in the southern one-third of the study area form a protective caprock over the more erodable sediments and sedimentary rocks. The Mormon Mountain Basalts are overlain by the San Francisco Volcanic Field and are exposed south and southwest of the San Francisco Volcanic Field in Verde Valley (Weir and others, 1989). These volcanic rocks are medium-gray to dark-gray, aphanitic to coarse-grained, locally vesicular basalts. They are 50 to 300 ft thick on the uplands, but thicken to more than 1,000 ft along the margins of Verde Valley and date from 15.4 to 5.5 Ma (Weir and others, 1989).

The Mount Floyd Volcanic Field is mostly gray to black flows of olivine basalt and red cinders (Goff and others, 1983). A study by Billingsley and others (2006) also has identified rhyolite, rhyodacite, and obsidian dikes, necks, and flows. McKee and McKee (1972) determined that the field ranges in age from 14.4 to 7.3 Ma. Billingsley and others (2006) recently determined a younger age for the field from samples of basalt and obsidian (6.7 and 6.4 Ma, respectively). Thickness of volcanic rocks of the field ranges from a few tens of feet to more than 2,000 ft near principal vents. Most basalt flows are from a few hundred feet to about 500 ft thick (Billingsley and others, 2006).

Red Butte is an isolated, dark gray, olivine-phyllic basalt flow and vent about 10 mi south of Grand Canyon (Billingsley and others, 2006). The structure dates from 9.7 to 8.9 Ma (Wolfe and others, 1987b; Reynolds, 1988) and is contemporaneous with the Mount Floyd Volcanic Field. The volcanic rocks are as much as 165 ft thick, and the vent is assumed to be covered by basalt or landslide deposits.

Howard Mesa is a dark-gray to black andesite north of Williams in the San Francisco Volcanic Field (Billingsley and others, 2006). The age of the flow is 2.1 Ma (Wolfe and others, 1987b). The flow is 200 ft or more in thickness, and its age and composition are significantly different from those of the surrounding volcanic rocks.

The San Francisco Volcanic Field is composed of andesitic and dacitic basalts, dacite and ryolitic domes, cinder cones, and pyroclasitc flows that range in age from 5 Ma to 900 yr before present. It covers about 5,000 square kilometers of the study area at the southern edge of the Coconino Plateau from east of Flagstaff to west of Williams (Ulrich and others, 1984). These volcanic rocks were deposited on an erosion surface of mainly Permian sediments and locally preserved Triassic sediments. The volcanic rocks of the field range in thickness from veneers of cinders to more than 5,000 ft of layered deposits at Bill Williams Mountain and San Francisco Mountain. The volcanic field follows a general northeast-to-east progression that is marked by the occurrence of hundreds of cinder cones and vents with the youngest rocks occurring at the eastern end of the field (Newhall and others, 1987; Wolfe and others, 1987a).

In addition to these principal volcanic rocks, scattered intrusive igneous rocks and pyroclastic flows occur throughout the study area. These rocks and flows are not connected to but probably are coincident with the principal volcanic rocks (Billingsley and others, 2006).

Tectonic History and Geologic Structure

Regional tectonic stresses created the geologic structure that has developed and shaped the landscape of the study area. Layered, predominantly ocean sediments were raised 10,000 to 15,000 ft by uplift resulting from two or more tectonic compressional events that began in the Cretaceous period (Shoemaker and others, 1978). Regional folding along a general northwest trend developed with this uplift. Continued periodic tectonic compressional and extensional stresses have resulted in folds, faults, and other fractures that have further modified the sediments (Nations, 1989; Jenny and Reynolds, 1989).

Patterns of northeast-, north-, and northwest-striking faults and other fractures currently dominate the structure of the study area (pl. 1; Gettings and Bultman, 2003). The extensional stresses that have weakened the regional sediments have enabled large amounts of intrusive and volcanic rocks to find their way to the surface in recent times (Wolfe and others, 1987a, 1987b). In addition, zones of weakness in the sedimentary bedrock are continuing to expand, lengthen, and deepen, in some areas into canyons, from continued interaction with water. Ground-water movement is dissolving rock deep in the subsurface creating preferential flow paths.

The oldest structures in the study area are vertical to near vertical fractures that have propagated upward from Precambrian basement rocks and strike north and northeast. These fractures are inferred to be related to reactivation of Precambrian normal faults under tension with reversal that has further resulted in development of monoclinal structures in younger rocks (Shoemaker and others, 1978; Wolfe and others, 1987a, 1987b). The monoclines overlying the deep-seated Proterozoic reverse faults were reactivated by late Cretaceous and early Tertiary compression commonly referred to as the Laramide Orogeny.

The Laramide Orogeny uplifted the Coconino Plateau and horizontally shortened it through development of folds on reactivated basement faults (Huntoon, 1974, 1990). The regional uplift, occurring in pulses, has raised the Precambrian surface more than 10,000 ft above its Early Cretaceous level (Huntoon, 1989). The erosion that accompanied the Laramide Orogeny has stripped most of the Mesozoic rocks from the surface of the Coconino Plateau and adjacent areas and left a few well-preserved drainages that have been minimally modified by the Pliocene incision of Grand Canyon (Huntoon, 1990). The three principal structural features of the Coconino Plateau that resulted are the Kaibab Uplift (Shoemaker and others, 1978), the Cataract Syncline (Krantz, 1989; Huntoon, 2003), and the Mesa Butte Fault (pl. 1; Babenroth and Strahler, 1945).

The Laramide Orogeny produced a regional dip of 1–2 degrees to the east and north (Naeser and others, 1989) and other large anticlines, synclines, and monoclines (Huntoon, 1989). The Black Point Monocline in the eastern part of the study area dips to the east-northeast and has several hundred feet of offset (Ulrich and others, 1984). The Mormon Mountain Anticline, with 5 degrees of local dip, trends northwest-southeast across the southern and southeastern part of the study area (pl. 1; Ulrich and others, 1984; Weir and others, 1989). The Aubrey Fault is a high angle, down-to-the-west normal fault with about 200 ft of offset at the north end of the fault and more than 500 ft of offset at the south end (pl. 1; Billingsley and others, 2000). The Aubrey Fault occurs along the axis of the Aubrey Monocline, which dips to the east (Billingsley and others, 2000). The Aubrey Fault and Monocline transition into the Toroweap Fault just beyond the northwestern boundary of the study area (Billingsley and others, 2000). The Aubrey and Toroweap Faults represent two of the many north-striking to northeast-striking, deep-seated regional fault systems reactivated during the Laramide Orogeny and, more recently, during Basin and Range extension (Huntoon, 2003).

The change from compressional stress to extensional stress at the onset of Basin and Range extension probably began by the middle Tertiary (Young, 1979) and has resulted in active faults and open fracture zones (Billingsley and others, 2006). Recent seismic activity (Fellows, 2000) indicates ongoing extensional stresses, which have resulted in the development of local extensional basins and extensional sags and closed basins (Huntoon, 1990, 2003). Aubrey Valley, east of the Aubrey Fault, is a closed topographic basin formed by extension (Billingsley and others, 2000). It is similar to other extensional basins on and around the edges of the Coconino Plateau, such as the Markam Dam area and Big Chino and Verde Valleys (Huntoon, 2003). Late Cenozoic volcanic activity of the Mount Floyd Volcanic Field and San Francisco Volcanic Field is further evidence of weakening and extension of the crust on the plateau.

The Colorado River was established in Grand Canyon by late Miocene, 9 to 6 Ma (Lucchitta, 1990). The downcutting through more than a mile of Paleozoic sediments and Precambrian rocks has progressed rapidly since that time. This rapid incision has lead to the dewatering of regional ground-water systems of the study area. Historical outlets are well marked by old travertine deposits along the south face of Grand Canyon well above the present river level (pl. 1).

The Mogollon Rim is a south-facing, mainly erosion escarpment that is retreating to the north (pl. 1; Elston, 1978; Pierce and others, 1979). It extends from the Aubrey Cliffs southeast across the central part of Arizona to the New Mexico border and is the result of at least two episodes of uplift: one preceding deposition of upper Cretaceous strata and another preceding fluvial deposition of nonmarine late Tertiary rim gravels that have evolved on the ancestral escarpment (Pierce and others, 1979; Pierce, 1984). Subsequent erosion of the plateau edge northward has removed most of the rim gravels and Cretaceous sediments. The rim has been subsequently segmented by more recent faulting, volcanism, and erosion into the landforms seen today (Pierce, 1984).

The Chino Valley Fault is part of the northwest-striking fault system that has developed during Basin and Range extension and helps to define the southern edge of the Coconino Plateau (pl. 1). The down-to-the-west Chino Valley Fault forms the eastern edge of a structural basin that is similar to but smaller than Verde Valley to the south (Hereford, 1977).

Verde Valley is a large structural basin coincident with the southern boundary of the study area. The valley is constrained to the east by the Mormon Mountain Anticline, which has about 1,500 ft of closure down to the west, and the Mogollon Rim, which has more than 2,000 ft of erosion slope westward into the valley. The Verde Fault Zone, a series of normal, parallel to subparallel faults with more than 3,000 ft of up-to-the-west displacement (Twenter and Metzger, 1963), forms the western boundary of the valley west of the Verde River adjacent to the study area. The ancestral Verde Valley of the late Tertiary had eroded into Paleozoic and Precambrian rocks before volcanic activity to the south blocked the outlet and allowed the basin to partly fill with more than 3,000 ft of sediments and volcanic debris. As uplift continued on the Verde Fault Zone to the west, erosion breached an outlet to the south exposing a pediment and several terraces along the channels of present-day streams and washes (Twenter and Metzger, 1963). The Oak Creek Fault in the north central part of Verde Valley is one of the many north-striking, high-angle normal faults that have been reactivated by recent Basin and Range extension. The west side of the fault is upthrown, and displacement ranges from about 400–500 ft at the north end on the San Francisco Volcanic Field to more than 700 ft at the south end near Sedona.

Ongoing erosion has produced the landscape of the modern Coconino Plateau and adjacent areas. Two mature north-flowing drainages, Cataract Creek and the Little Colorado River, dominate the study area. Isostatic rebound caused by the formation of Grand Canyon has resulted in the dramatic short, steep drainages of the south rim of the canyon that are just beginning to develop southward onto the plateau (Beus and Morales, 2003). Cenozoic volcanism has modified ancestral south-flowing drainages to fairly short, steep streams that flow northward to the Grand Canyon or southward into Verde Valley (Wolfe and others, 1987a, b; Nealey and Sheridan, 1989). Faults and monoclinal structures partly define the western, southern, and eastern boundaries of the study area.

Surface Water

The Coconino Plateau study area is nearly surrounded by large rivers. The Colorado River forms the boundary of the study area to the north, drains seven Western States, and has cut a channel through all the sedimentary rocks and into the largely impermeable basement granites and metamorphic rocks in Grand Canyon. At the southern and western boundaries of the study area, the Verde River originates in the Transition Zone between the plateau and the Basin and Range Province. The Verde River and its tributaries drain the south slope of the Mogollon Rim and have deeply incised the sedimentary rocks of the plateau as they flow southward. Several large sedimentary basins in the Transition Zone are roughly aligned on the course of the Verde River. The Little Colorado River flows along the eastern boundary of the study area and drains most of northeastern Arizona and parts of New Mexico. The Little Colorado River is not as deeply incised as the Colorado or Verde Rivers except north of Cameron where its downcutting has kept pace with that of the Colorado River.

Most of the major rivers and streams within the study area are ephemeral except for short perennial reaches that are sustained by ground-water discharge (pl. 2). Ephemeral streams flow only in response to runoff from precipitation and snowmelt. The Verde River, Oak Creek, and Wet Beaver Creek are perennial for most of their lengths. Havasu Creek and the lower part of the Little Colorado River are perennial owing to large spring flows. The Colorado River is a perennial river regulated by operations at Glen Canyon Dam. Drainage basin characteristics and streamflow of the principal streams in the study area are listed in table 2.

The largest stream entirely within the study area is Cataract Creek, which becomes Havasu Creek below Havasu Spring (pl. 2). The creek begins on the north slopes of Bill Williams Mountain at the western end of the San Francisco Volcanic Field and flows northward across the consolidated sediments of the Coconino Plateau. The channel is aligned along north-trending and northwest-trending structures, and for most of its length, it has cut a deep gorge in bedrock. Because the channel slopes steeply, only thin layers of coarse alluvium can accumulate along its bed. The drainage is ephemeral upstream from Havasu Spring, which sustains perennial flow in the creek downstream from the spring. Travertine dams downstream from the spring have resulted in the accumulation of fine-grained alluvium to a depth of 100 ft or more (Marx, 1995). The Havasu/Cataract drainage also contains closed basins in two types of areas: (1) on the flanks of volcanic fields where basalt flows and cinder fields have truncated established drainage to the north, and (2) in developing extensional basins that are a result of continuing Basin and Range tectonic stresses (Billingsley and others, 2006). These closed basins represent traps for surface-water runoff and could be areas of concentrated ground-water recharge.

Table 2. Drainage-basin characteristics of principal streams, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

[mi², square miles; ft, feet; mi, miles; ft/mi, feet per mile; in., inches; ft³/s, feet cubed per second; e, estimated; --- indicate no data]

Basin name	Drainage area, mi²	Non-contributing drainage area, mi²	Mean basin elevation, ft	Stream length, mi	Main channel slope, ft/mi	Forested area percent	Soil index	Mean annual precipitation, in.
Little Colorado River	26,946	368	6,200e	340	7.68	30	2.7	12
Cottonwood Spring Creek	3.92	0	4,532	3.64	64.0	---	---	---
Pipe Creek	8.48	0	5,363	3.81	56.7	---	---	---
Indian Gardens Creek	4.13	0	5,794	3.31	99.7	---	---	---
Horn Creek	1.66	0	4,377	1.99	76.3	---	---	---
Monument Creek	3.54	0	4,651	3.52	85.0	---	---	---
Hermit Creek	12.4	0	5,789	5.59	68.1	---	---	---
Boucher Creek	6.60	0	4,562	4.38	51.0	---	---	---
Royal Arch Creek	12.0	0	5,284	5.14	71.3	---	---	---
Olo Canyon	12.7	0	4,834	6.71	58.3	---	---	---
Matakatamiba Canyon	33.5	0	5,170	12.5	32.2	---	---	---
Havasu/Cataract Creek	3,020	209	6,087	128	4.63	---	---	---
National Canyon	170	0	5,871	42.1	10.7	---	---	---
Mohawk Canyon	87.8	0	5,945	26.7	16.3	---	---	---
Canyon Diablo/Walnut Creek	1,180	0	6,576	139	2.87	---	---	---
Hell Canyon	333	0	5,645	42.1	7.54	88	3	24.1
Sycamore Creek	477	0	6,816	53.1	8.55	---	---	---
Oak Creek	466	0	6,200	45.8	85.0	65	2.7	22.6
Wet Beaver Creek	302	0	6,320	51.4	13.4	45.5	2.9	24
Verde River	5,009	365	5,560	168	17.9	70	2.5	17.6

Stream type	Annual average flow, ft³/s	Runoff per square mile, ft³/s	Annual 7-day minimum flow, ft³/s	Maximum flow, ft³/s	Maximum date	Minimum flow, ft³/s	Minimum date	Remarks
Intermittent	about 420	0.02	200	about 120,000	9/20-21/1923	194	3/3/1991	River mile 13 to the mouth is perennial; supported by ground-water discharge
Intermittent	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	Perennial flow partially supported by return flow of NPS water-supply system to creek
Perennial	---	---	---	---	---	---	---	Perennial flow partially supported by return flow of NPS water-supply system to creek
Intermittent	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	
Intermittent	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	
Perennial	---	---	---	---	---	---	---	
Ephemeral/perennial	---	---	63	20,300	9/3/1990	61	5/1993; 4-5/1995	Perennial flow below Havasu Spring supported by ground-water discharge
Ephemeral	---	---	---	---	---	---	---	
Ephemeral	---	---	---	---	---	---	---	
Ephemeral	---	---	---	---	---	---	---	
Ephemeral	---	---	---	---	---	---	---	
Intermittent	---	---	---	---	---	---	---	
Perennial	90	0.19	---	26,400	2/19/1980	6	7/27/1940	
Perennial	90	0.3	6.4	16,000	1/8/1993	5.4	8/1962; 7/1967; 7-8/1993	
Perennial	465	0.09	---	119,000	2/20/1993	40	6/30/1990	

Table 3. Base-flow discharge estimates from springs and streams, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

[ID, identification; acre-ft, acre-feet; M, measured; E, estimated; 5 percent, good gaged record; 10 percent, good measurements made quarterly; 25 percent, good intermittent measurements; 50 percent, good estimates of flow; ---, indicate no data; UNLV, University of Nevada Las Vegas; USGS, U.S. Geological Survey; NAU, Northern Arizona University; NRCE, Natural Resources Consultant Engineers; NPS, National Park Service; misc. meas., miscellaneous measurements]

Site ID	Latitude	Longitude	Spring	Water-bearing zone	Annual flow, acre-ft	Method
360700111413701	36°07'00"	111°41'37"	Lower Little Colorado River, including Blue Spring	Redwall-Muav	159,300	M
360020111560401	36°00'21"	111°56'04"	Red Canyon Spring	Redwall-Muav	5	M
360025111571501	36°00'15"	111°57'04"	JT Spring	Redwall-Muav	1	M
---	---	---	Hance Spring	Redwall-Muav	29	E
360656111405801	36°06'56"	111°40'58"	Curtain Spring	Redwall-Muav	1.6	E
360128111591901	36°01'28"	111°59'19"	Cottonwood Springs	Redwall-Muav	45	M
09402430	36°02'32"	112°00'48"	Grapevine Springs	Redwall-Muav	320	M
---	36°04'30"	112°02'45"	Boulder/Lonetree Springs	Redwall-Muav	8	E
360100111582001	36°01'00"	111°58'20"	Miners/Sam Magee Springs	Redwall-Muav	0.3	E
360436112060401	36°04'36"	112°06'04"	Burro Spring	Redwall-Muav	12.5	M
360410112055700	36°04'10"	112°05'57"	Pipe Creek	Redwall-Muav	15.02	M
360415112060601	36°40'15"	112°06'06"	Indian Garden Springs	Redwall-Muav	700.0	M
360441112073201	36°04'39"	112°07'31"	Pumphouse Spring	Redwall-Muav	1.4	M
360450112083601	36°04'50"	112°08'36"	Horn Spring	Redwall-Muav	8.0	M
360439112094101	36°04'39"	112°09'41"	Salt Creek Spring	Redwall-Muav	8.0	E
---	36°05'08"	112°08'39"	Cedar Spring	Redwall-Muav	8.0	E
360455112111001	36°04'55"	112°11'10"	Monument Creek Springs	Redwall-Muav	180.0	M
09403043	36°04'51"	112°12'47"	Hermit Creek Springs	Redwall-Muav	560.0	M
360411112141701	36°04'11"	112°14'17"	Boucher East Spring	Redwall-Muav	9.4	M
360511112155501	36°05'23"	112°15'34"	Boucher Spring	Redwall-Muav	0.8	M
---	---	---	Travertine Canyon Spring	Redwall-Muav	8.0	E
360658112170701	36°06'58"	112°17'07"	Slate Canyon Spring	Redwall-Muav	0.2	M
360711112184601	36°07'11"	112°18'46"	Sapphire Spring	Redwall-Muav	1.4	M
360735112201601	36°07'35"	112°20'16"	Turquoise Canyon Spring	Redwall-Muav	1.4	M
360952112203501	36°09'52"	112°20'35"	Ruby Spring	Redwall-Muav	0.2	M
361141112211101	36°11'41'	112°21'11"	Serpentine Spring	Redwall-Muav	0.6	M
---	36°11'45"	112°27'10"	Royal Arch Canyon Springs	Redwall-Muav	360.0	M
361354112320001	36°13'54.3"	112°32'00.0"	Foster Canyon Spring 1	Redwall-Muav	0.4	M
361403112314201	36°14'03.5"	112°31'42.5"	Foster Canyon Spring 2	Redwall-Muav	0.8	M
361648112315101	36°16'48.4"	112°31'50.8"	Fossil Canyon Spring	Redwall-Muav	2.0	M
---	---	---	Spencer Canyon Spring	Redwall-Muav	2.0	M
---	---	---	Saddle Canyon above the falls	Redwall-Muav	8.0	E
---	36°23'19"	112°33'52"	140 Mile Canyon Springs	Redwall-Muav	40.0	E

Error, percent	Error, acre-ft[1]	Flow range based on percent error, acre-ft High	Flow range based on percent error, acre-ft Low	Percent of total flow[2]	Remarks
5	7,965	167,265	151,335	53.23	Average base flow, 09402300, 1990–93 and 2003 to present
25	1	6	4	0	Tadayon and others, 2001; McCormack and others, 2002; misc. meas.
25	0	1	1	0	Tadayon and others, 2001; McCormack and others, 2002; misc. meas.
50	15	44	15	0.01	USGS estimate of flow 2002–03
50	1	1	2	0	USGS estimate of flow 2002
10	5	50	41	0.02	Average base flow, 09402450, 1994–97; Goings, 1985; NPS,1994–96, 1999 (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000; misc. meas., seasonal weighted average
10	32	352	288	0.11	Average base flow, 09402430, 1994–96
50	4	12	4	0	Zukosky, 1995; NPS, 1997 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas., seasonal weighted average
25	0	0	0	0	Fitzgerald, 1996; NPS, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000; misc. meas., seasonal weighted average
10	1	14	11	0	Tadayon and others, 2001; McCormack and others, 2002; misc. meas.
10	2	17	14	0.01	Tadayon and others, 2001; McCormack and others, 2002; misc. meas.
10	70	770	630	0.23	Average base flow, 09403013 and 09403010, 1994–95; NPS 1997, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000; misc. meas., seasonal weighted average
25	0	2	1	0	Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas.
10	1	9	7	0	Goings, 1985; Fitzgerald, 1996; NPS, 1999, (John Rihs, hydrologist, NPS, written commun. 2000); Tadayon and others, 2000, 2001; misc. meas., seasonal weighted average
50	4	12	4	0	Goings, 1985; Fitzgerald, 1996; NPS, 1999, (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000; misc. meas., seasonal weighted average
50	4	12	4	0	Zukosky, 1995; misc. meas., seasonal weighted average
10	18	198	162	0.06	Goings, 1985; NPS, 1992–97 (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000, 2001; McCormack and others, 2002; mics. meas., seasonal weighted average
5	28	588	532	0.19	Average base flow, 09403043, 1994–97; Goings, 1985; Tadayon and others, 2000, 2001; McCormack, 2002; misc. meas., seasonal weighted average
10	1	10	9	0	NPS, 1994, 1996–98 (John Rihs, hydrologist, NPS, written commun., 2000); Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas., seasonal weighted average
25	0	1	1	0	McCormack and others, 2002; misc. meas.
50	4	12	4	0	Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas.
25	0	0	0	0	Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas.
25	0	2	1	0	McCormack and others, 2002; misc. meas.
25	0	2	1	0	McCormack and others, 2002; misc. meas.
25	0	0	0	0	McCormack and others, 2002; misc. meas.
25	0	1	0	0	McCormack and others, 2002; misc. meas.
25	90	450	270	0.12	USGS, 1989–93, unpublished misc. meas.; Tadayon and others, 2001; NPS, 1992–96 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas., seasonal weighted average
25	0	1	0	0	Tadayon and others, 2001; misc. meas.
25	0	1	1	0	Tadayon and others, 2001; McCormack and others, 2002; misc. meas.
25	1	3	2	0	McCormack and others, 2002; misc. meas.
50	1	3	1	0	Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas.
50	4	12	4	0	NPS, 1992–97 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas., seasonal weighted average
50	20	60	20	0.01	Tadayon and others, 2000, 2001; McCormack and others, 2002; misc. meas.

Table 3. Base-flow discharge estimates from springs and streams, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona—Continued.

Site ID	Latitude	Longitude	Spring	Water-bearing zone	Annual flow, acre-ft	Method
---	36°22'15"	112°38'55"	Olo Canyon Springs	Redwall-Muav	40.0	M
362038112401900	36°20'38"	112°40'19"	Matkatamiba Canyon Springs	Redwall-Muav	97.0	M
361303112411200	36°13'03"	112°41'12"	Havasu Spring	Redwall-Muav	4,700	M
361524112420400	36°15'24"	112°42'04"	Springs below Havasu Falls in-channel springs and gains, undifferentiated	Redwall-Muav	5,683	M
---	---	---	Haqbaqi Spring	Redwall-Muav[3]	645.7	E
---	---	---	Fern Spring and unnamed spring above Fern Spring	Redwall-Muav[3]	64.6	E
---	---	---	Crematory Spring	Redwall-Muav[3]	645.7	E
---	---	---	Beaver Spring	Redwall-Muav[3]	161.4	E
---	---	---	Manakaja Spring	Redwall-Muav	6.0	E
---	---	---	Spring near Manakaja Spring	Redwall-Muav	1.0	E
361518112523901	36°15'18"	112°52'39"	National Canyon Springs	Redwall-Muav	130.0	M
361310112580401	36°13'10"	112°58'04"	Mohawk Canyon Springs	Redwall-Muav	40.0	M
345644112193701	34°56'44"	112°19'37"	King Spring	Redwall-Muav	16.0	E
350535112263601	35°05'35"	112°26'36"	Meath Spring	Redwall-Muav	6.5	E
350107112305601	35°01'07"	112°30'56"	Storm Seep	Redwall-Muav	7.2	E
350022112324001	35°00'22"	112°32'40"	Pool Spring	Redwall-Muav	3.2	E
345235112172501	34°52'35"	112°17'25"	Duff Spring	Redwall-Muav	35.5	E
			Total Redwall-Muav		**216,221**	
361250112411600	36°12'50"	112°41'16"	IGE Spring (MP 5, Hualapai Canyon)	Supai Group	2.5	M
---	36°14'06"	112°41'40"	Greasy Spring	Supai Group	32.3	M
---	36°14'46"	112°40'15"	School House Springs	Supai Group	16.1	M
---	36°14'33"	112°44'40"	Little Coyote Springs	Supai Group	8.1	M
---	36°12'31"	112°40'56"	Window Spring	Supai Group	8.1	M
---	36°11'38"	112°39'49"	Putesoy Spring	Supai Group	1.6	M
---	36°11'42"	112°37'45"	Burro Spring	Supai Group	1	M
---	---	---	Ladder Spring	Supai Group	11.3	M
---	36°12'11"	112°42'10"	Grapevine Spring	Supai Group	8.1	M
---	---	---	Tenakma Spring	Supai Group	32.2	M
---	---	---	Santa Maria Spring	Supai Group	0.32	E
---	---	---	Fourmile Spring	Supai Group	---	---
			Total Supai Group		**121.6**	

Error, percent	Error, acre-ft[1]	Flow range based on percent error, acre-ft High	Low	Percent of total flow[2]	Remarks
25	10	50	30	0.01	USGS, 1990–92, unpublished misc. meas.; NPS, 1992–95, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas., seasonal weighted average
25	24	121	73	0.03	USGS, 1990–92, unpublished misc. meas.; NPS, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas.
5	2,350	49,350	44,650	15.71	USGS, gaged 09404110, 1990–present
5	284	5,967	5,399	1.90	USGS seepage investigation, 1995, and subtraction of gages 09404115, 09404112, 09404110, unpublished misc. meas.
25	161	807	484	0.22	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	16	81	48	0.02	NRCE, 1999; USGS, 1995, unpublished misc. meas.
25	161	807	484	0.22	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	40	202	121	0.05	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
50	3	9	3	0	NRCE, 1999, misc. meas.
50	1	2	1	0	NRCE, 1999, misc. meas.
25	33	163	98	0.04	USGS, 1984–85, 1989–93, 1995, unpublished misc. meas.; NPS, 1992–97 (John Rihs, hydrologist, NPS, written commun., 2000); misc. meas., seasonal weighted average
25	10	50	30	0.01	USGS, 1993, 1995, unpublished misc. meas.; Tadayon and others, 2001; McCormack and others, 2002; misc. meas., seasonal weighted average
50	8	24	8	0	USGS estimate of flow, 1994, 2000, and 2002
50	3	10	3	0	USGS estimate of flow, 2001
50	4	11	4	0	USGS estimate of flow, 2001
50	2	5	2	0	USGS estimate of flow, 2001
50	18	53	18	0.01	USGS estimate of flow, 1991
	11,400	**227,619**	**204,821**	**72.25**	
25	1	3	2	0	USGS, 1995, unpublished misc. meas.; NRCE, 1999, misc. meas.
25	8	40	24	0.01	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	4	20	12	0.01	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	2	10	6	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	2	10	6	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0	2	1	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0	1	1	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	3	14	8	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	2	10	6	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	8	40	24	0.01	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
50	0	0	0	0	NPS, 1993, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); seasonal weighted average
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	30.5	**152**	**91.1**	**0.04**	

Table 3. Base-flow discharge estimates from springs and streams, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona—Continued.

Site ID	Latitude	Longitude	Spring	Water-bearing zone	Annual flow, acre-ft	Method
---	---	---	Dripping Spring	Coconino-Kaibab	0.38	E
---	36°10'01"	112°43'58"	Willow Spring	Coconino-Kaibab	1	M
---	36°12'13"	112°34'32"	Topocoba Spring	Coconino-Kaibab	0.5	M
---	36°02'15"	112°34'07"	Highwall Spring	Coconino-Kaibab	0.5	M
---	36°04'54"	112°32'55"	Sinyella Spring	Coconino-Kaibab	0.5	M
---	---	---	Jwa Qwaw Gwa Spring	Coconino-Kaibab	1.6	M
---	---	---	Baaquithduuva Spring 1&2	Coconino-Kaibab	1.6	M
---	---	---	Qwaq Nonaa Spring	Coconino-Kaibab	0.25	E
---	---	---	Hmilt Biiwoo Spring	Coconino-Kaibab	0.4	E
---	35°04'02"	111°34'44"	Clark Spring	Coconino-Kaibab	10	M
---	34°04'01"	111°32'16"	Babbitt Spring	Coconino-Kaibab	4	M
352418111514901	35°24'18'	111°51'49"	Newman Spring	Coconino-Kaibab	1	M
---	35°02'25"	111°34'27"	Hoxworth Spring	Coconino-Kaibab	30	M
---	35°01'05"	111°35'07"	Babes Hole Spring	Coconino-Kaibab	0.5	M
			Total Coconino-Kaibab		**52.2**	
---	---	---	Volcanic Field Springs	Volcanic rocks	4,550	M
---	---	---	Inner Basin Springs	Volcanic rocks and glacial	1,448	M
---	---	---	Upper Sycamore Canyon	Volcanic rocks and alluvium	443	E
			Total San Francisco Peaks volcanic field		**6,441**	
---	---	---	Bill Williams Mountain volcanic field springs	Volcanic rocks	645	E
---	---	---	Mount Floyd volcanic field springs	Volcanic rocks	24	E
---	---	---	Mormon Pockets Springs	Redwall-Muav	15,928	M
---	---	---	Springs below Mormon Pockets	Redwall-Muav	6,516	M
---	---	---	Sycamore Canyon Springs, lower	Redwall-Muav	7,963	M
---	---	---	Spring at 09504000, Verde River near Clarkdale	Redwall-Muav	2,172	M
---	---	---	Oak Creek Springs, upper	Coconino-Kaibab	24,140	M
			Other boundary-dependent outflow			
---	---	---	Wet Beaver Creek Springs	Coconino-Kaibab[4]	5,370	M
---	---	---	West Clear Creek Springs	Coconino-Kaibab[4]	13,660	M
			Total spring discharge, Coconino Plateau		**299,253**	

[1]Errors less than 0.5 acre-ft were rounded to 0. Errors greater than 0.5 acre-ft were rounded to 1.0.

[2]Percent of total flow less than 0.01 percent were rounded to 0.

[3]Assumed to be Redwall-Muav.

[4]Assumed to be Coconino-Kaibab.

Error, percent	Error, acre-ft[1]	Flow range based on percent error, acre-ft High	Low	Percent of total flow[2]	Remarks
50	0.01	0.97	0.19	0	NPS, 1993, 1998 (John Rihs, hydrologist, NPS, written commun., 2000); seasonal weighted average
25	0.25	1.25	0.75	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0.12	0.75	0.38	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0.12	0.75	0.38	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0.12	0.75	0.38	0	NRCE, 1999; 2002–03 (Torrey Copfer, hydrologist, NRCE, written commun., 2003); misc. meas.
25	0.4	2	1.2	0	NRCE, 1999, 2000
25	0.4	2	1.2	0	NRCE, 1999, 2000
50	0.12	0.37	0.2	0	NRCE, 1999, 2000
50	0.2	0.6	0.2	0	NRCE, 1999, 2000
25	2.5	13	7.5	0	USGS, 1979, 1985, 1993–94, unpublished misc. meas.
25	1	5	3	0	USGS, 1979, 1985, 1993–94, unpublished misc. meas.
25	0.25	1.25	0.75	0	USGS, 1979, 1985, 1993–94, unpublished misc. meas.
25	7.5	38	23	0.01	USGS, 1979, 1985, 1993–94, unpublished misc. meas.
25	0.12	0.62	0.38	0	USGS, 1979, 1985, 1993–94, unpublished misc. meas.
	13.3	**65.5**	**38.9**	**0.02**	
25	1,138	5,688	3,413	1.52	USGS, unpublished misc. meas., 1970–85
25	362	1,810	1,086	0.48	Harshbarger and Associates and John Carollo Engineers, 1974; USGS unpublished misc. meas., 1970–79.
50	222	665	222	0.15	Tadayon and others, 2001; McCormack and others, 2002; unpublished misc. meas.
	1,721	**8,162**	**4,720**	**2.15**	Appel and Bills, 1981; Hart and others, 2002; Harsbarger and Associates and John Carollo Engineers, 1972, 1973, 1974; Harshbarger and Associates, 1976, 1977
50	323	968	323	0.22	USGS, unpublished misc. meas., 1970s, 2001–02
50	12	36	12	0.01	USGS, unpublished misc. meas., 1970s, 2001–02
25	3,982	19,910	11,946	5.32	USGS seepage investigations, 1977, 1999, 2000; unpublished misc. meas.
25	1,629	8,145	4,887	2.18	USGS seepage investigations, 1977, 1999, 2001; unpublished misc. meas.
25	1,991	9,954	5,972	2.66	USGS seepage investigations, 1999, 2001, 2003, 2004; unpublished misc. meas.
25	543	2,715	1,629	0.73	USGS gaged, 1917–21, 1965–2004
5	1,207	25,347	22,933	8.07	Average base flow, USGS gaged, 09504420, 1981–2004
5	269	5,639	5,102		Average base flow, USGS gaged, 09505200
5	683	14,343	12,977		Average base flow, USGS gaged, 09505800
	23,803	**323,054**	**275,452**	**100.00**	

Walnut Creek and San Francisco Wash drain most of the south and east flanks of San Francisco Mountain and the Mormon Mountain area to the south. They are ephemeral and drain to Canyon Diablo, which is also ephemeral and drains to the Little Colorado River (pl. 2). These streams cross volcanic rocks for most of their courses and are not deeply incised into the sedimentary rocks. The remaining streams that drain northward are short and have high gradients (32 to 99 ft per mi). They are deeply incised into the south rim of Grand Canyon, are ephemeral or intermittent, and drain to the Colorado River. The intermittent streams intersect water-bearing zones in the sedimentary rocks that support short reaches of flow (pl. 2 and table 3). In some streams, such as Hermit, Monument, Royal Arch, Olo, and Matkatamiba Creeks, the flow reaches the Colorado River.

The principal streams that flow southward to the Verde River are a mixture of ephemeral, intermittent, and perennial streams. Drainages that contain ephemeral flow, such as Hell Canyon, which begins on the south flanks of Bill Williams Mountain, cross porous volcanic rocks for most of their courses. Runoff occurring in this type of drainage rapidly infiltrates the channel bed. Drainages that contain intermittent flow, such as Sycamore Creek, which begins on the west flanks of San Francisco Mountain, cross volcanic rocks and cut deeply into the Paleozoic rocks of the Mogollon Rim. Sycamore Creek and other streams of this type can intersect several ground-water-bearing zones along their lengths and include short reaches of flow from the ground-water discharge. Near its mouth at the Verde River, Sycamore Creek cuts into the Redwall Limestone where springs sustain perennial flow. Perennial streams such as Oak Creek and Wet Beaver Creek are formed on geologic structure that has enabled them to cut rapidly and deeply into the sedimentary rocks of the Mogollon Rim where they intersect regional ground-water systems that sustain perennial flow.

Continuous-record streamflow-gaging stations operated by the USGS on Havasu Creek, the Little Colorado River, Oak Creek, Beaver Creek, and the Verde River can be used to measure stream base flow, which is a useful indicator of ground-water-discharge and discharge trends. In 2003, the USGS operated 10 continuous-record streamflow-gaging stations in the study area (Bills and Flynn, 2002). An additional five streamflow-gaging stations in the study area that were discontinued by the USGS are currently being operated by the NPS (John Rhis, National Park Service, oral commun., 2003). Data from 46 other discontinued USGS streamflow-gaging stations and from one seepage investigation on Havasu Creek were evaluated for this study (pl. 2; Bills and Flynn, 2002). Statistical summaries were obtained only for stations that had 10 yr of continuous record or more in order to derive any statistical significance from streamflow data. Only a few sites in the study area met that requirement. Records that are shorter than 10 yr, however, contain useful information on base flow (table 2 and fig. 9).

Data from the three streamflow-gaging stations on Havasu Creek indicate a general gain in base flow downstream to the mouth (pl. 2). Average annual winter base flow at Havasu Creek below Havasu Springs (09404110) is about 64 ft^3/s on the basis of 9 yr of record (fig. 9A). Average annual winter base flow at Havasu Creek above the mouth (09404115) is about 71 ft^3/s on the basis of 12 yr of record. This average is 11 percent greater than the average at station 09404110 (fig. 9B). A seepage investigation conducted from Havasu Spring to the mouth of Havasu Creek for the Havasupai Tribe showed that the creek loses about 14 percent of its flow from the spring to Havasu Falls and then gains 29 percent of its flow from Havasu Falls to the mouth (U.S. Geological Survey, unpublished data, 1995). Although some small springs issue from the Redwall Limestone at the base of Havasu Falls and downstream, most of the increase in flow is attributed to ground-water discharge through the streambed as the channel cuts deeper into the Redwall and Muav Limestones in the downstream direction.

Trends in annual winter base flows at Havasu Creek below Havasu Spring and Havasu Creek above the mouth could be related to variations in precipitation (figs. 5, 9A, and 9B). Base flow at both sites has a declining trend through the late 1990s that correlates with the below-average annual precipitation during the same period (figs. 6 and 7). Slightly above-average precipitation in 1999 and 2000 (fig. 7) could account for the increase in base flow in 2001–2003; however, base flow continued to decline after 2003. The combined water use in the Havasu Creek Basin for this same time period (late 1990s to 2004) represents less than one-tenth of a percent of the average annual winter base flow. Trends are not apparent in the base flow of other small drainages that drain the south rim of Grand Canyon and have intermittent or perennial flow with the exception of Cottonwood Spring located upstream from its juncture with Cottonwood Creek (pl. 2). The reach contained perennial flow from 1994 to 1998. From 1999 to 2003, the reach was dry for increasing periods of time during the summer.

The Little Colorado River upstream from Cameron is ephemeral to intermittent (pl. 2). Ground-water discharge from a collection of springs in the Redwall and Muav Limestones sustains perennial flow in the lower 13 mi of the river (Cooley, 1976). Blue Spring is the largest of these springs and has a flow of about 95 ft^3/s (Monroe and others, 2005). Average annual base flow at the mouth of the Little Colorado River calculated from five partial years of record is about 237 ft^3/s (pl. 2). Summer and winter base flows differ by about 10 percent; the difference is likely the result of differences in the amount of evapotranspiration in and near the channel during these seasons.

Oak Creek is perennial throughout most of its length (pl. 2). Spring flow begins at the head of Oak Creek Canyon as ground water is discharged from the C aquifer. Oak Creek continues to gain flow from ground-water discharge downstream to Sedona (Levings, 1980). Average annual winter base flow calculated from 23 yr of record (1982–2004) at the Oak Creek near Sedona streamflow-gaging station is about 32.4 ft^3/s (fig. 9C; Pope and others, 1998; U.S. Geological Survey, unpublished data, 1997–2003). Since 1982, base flow in Oak Creek has declined by about 10 percent. It is not known if this decline is caused by changes in climate or changes in water withdrawals.

Wet Beaver Creek also is perennial for most of its length (pl. 2). Flow increases near the headwaters where the channel intersects saturated rock of the C aquifer. The creek gains flow downstream to Verde Valley. Average annual winter base flow of Wet Beaver Creek calculated from 42 yr of record (1962–2004) is about 7.4 ft^3/s (fig. 9D; Pope and others, 1998; U.S. Geological Survey, unpublished data, 1997–2003). The winter base-flow data indicate wet and dry cycles, but a clear declining trend is not apparent.

The upper reaches of the Verde River are perennial. Base flow is sustained by ground-water discharge from the alluvial aquifers of Chino Valley northwest of the river and from the Redwall-Muav aquifer north of the river (pl. 2). Average annual winter base flow of Verde River near Paulden calculated from 42 yr of record (1962–2004) is about 25 ft^3/s (fig. 9E; Pope and others, 1998; U.S. Geological Survey, unpublished data, 1997–2003). Most of the base flow at this point in the drainage is the result of ground-water discharge from alluvial aquifers of Chino Valley that are heavily used for irrigation and municipal supply (Blasch and others, 2006; and Wirt and others, 2005). Annual winter base flow downstream at Verde River near Clarkdale calculated from 45 yr of record (1919–21, 1962–2004) is about 82 ft^3/s (fig. 9F; Pope and others, 1998; U.S. Geological Survey, unpublished data, 1997–2003). The more than threefold increase in base flow is attributed to ground-water discharge from the Redwall-Muav aquifer between Paulden and Clarkdale (Blasch and others, 2006). Winter base flows at Verde River near Paulden and Verde River near Clarkdale have a similar pattern and lag 1 to 2 yr behind precipitation (figs. 6 and 7). Since 1998, winter base flow at Verde River near Paulden has declined by about 12 percent and the winter base flow at Verde River near Clarkdale has declined by about 17 percent.

The base-flow components of all the intermittent and perennial streams of the study area are derived from ground-water discharge where the stream channels intersect local or regional ground-water systems. Changes in base flow indicate changes in aquifer storage, which can be affected by changes in recharge or by changes in ground-water withdrawals. Data for a few streams, such as Havasu Creek and Cottonwood Creek, indicate that changes in base flow likely result from changes in precipitation and recharge. Base flow at other sites, such as Oak Creek and the Verde River, may be affected by ground-water withdrawals, and the effects of recent variations in precipitation on base flow at these sites are not as apparent.

Ground Water

The ground-water systems of the Coconino Plateau study area are more complex than is indicated by the fairly simple layering of the sedimentary rocks that contain them. The complexity is due to variations in stratigraphy, lithology, and most importantly, geologic structure throughout the plateau.

Ground water on the plateau occurs in two primary aquifer systems—the C aquifer and the Redwall-Muav aquifer—and in perched zones in alluvium, volcanic rocks, the Kaibab Formation, the Coconino Sandstone, and the Supai Group. Other aquifers and water-bearing zones in the study area include the Big Chino aquifer and the Verde aquifer (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983) in the southern part of the study area and water-bearing zones in the Moenkopi and Chinle Formations in the central and northeastern part of the study area. Previous investigators have suggested that the Big Chino and Verde aquifers likely receive ground water from the aquifer systems on the Southern Colorado Plateau (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). The Big Chino and Verde aquifers are not an integral part of the regional ground-water flow systems on the plateau, however, they are the subject of a more comprehensive ongoing hydrogeologic study of the upper and middle Verde watersheds (Blasch and others, 2006). Water-bearing zones in the Moenkopi and Chinle Formations in the central and northeastern part of the study area are small, discontinuous, and hydraulically isolated from the regional ground-water flow systems of the study area (Farrar, 1979, 1980).

Perched Ground Water

Zones of perched ground water are common in the volcanic rocks of the San Francisco and Mount Floyd Volcanic Fields, and are less common in the consolidated sedimentary rocks of the plateau. Perched ground water typically is close to the land surface in unconsolidated alluvium and volcanic rocks south and west of San Francisco Mountain, surrounding Bill Williams Mountain, and in parts of the Mount Floyd area (Appel and Bills, 1981; McGavock and others, 1986; Bills and others, 2000; and Bills and Flynn, 2002). These perched zones generally are small and thus are unsuitable as long-term water supplies; however, they are used extensively to meet water demands for individual households. The depth to water varies from a few feet to more than 200 ft below land surface, and well yields typically are less than 20 gal/min (Bills and Flynn, 2002). Ground water in these zones flows downgradient and discharges at springs or migrates deeper into the subsurface. A few exceptions to these conditions occur in the Flagstaff and Williams areas.

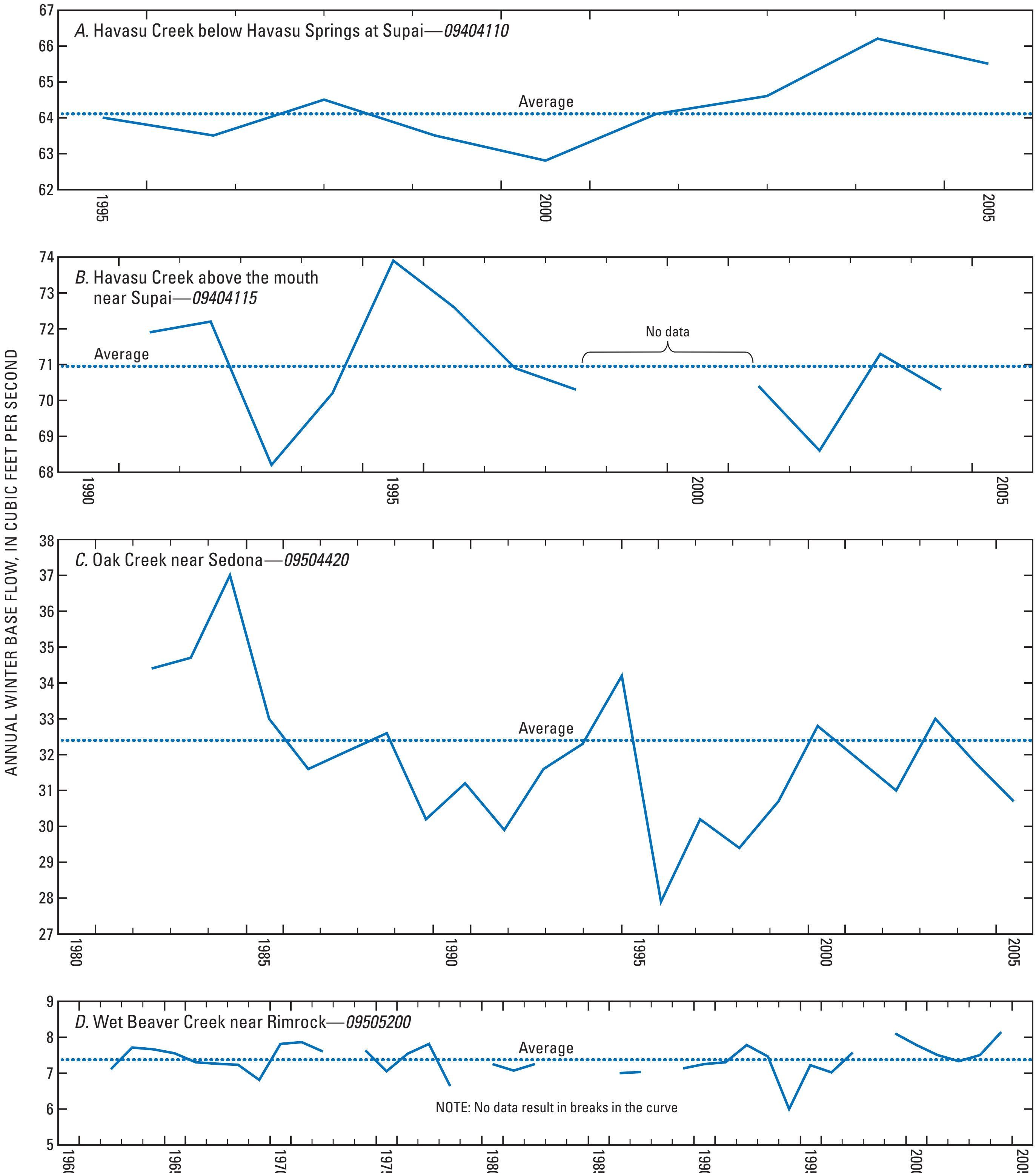

Figure 9. Annual winter base flow for selected streamflow-gaging stations, Coconino Platea study area, Coconino and Yavapai Counties, Arizona: *A*, Havasu Creek below Havasu Springs at Supai; *B*, Havasu Creek above the mouth near Supai; *C*, Oak Creek near Sedona; *D*, Wet Beaver Creek near Rimrock; *E*, Verde River near Paulden; *F*, Verde River near Clarkdale.

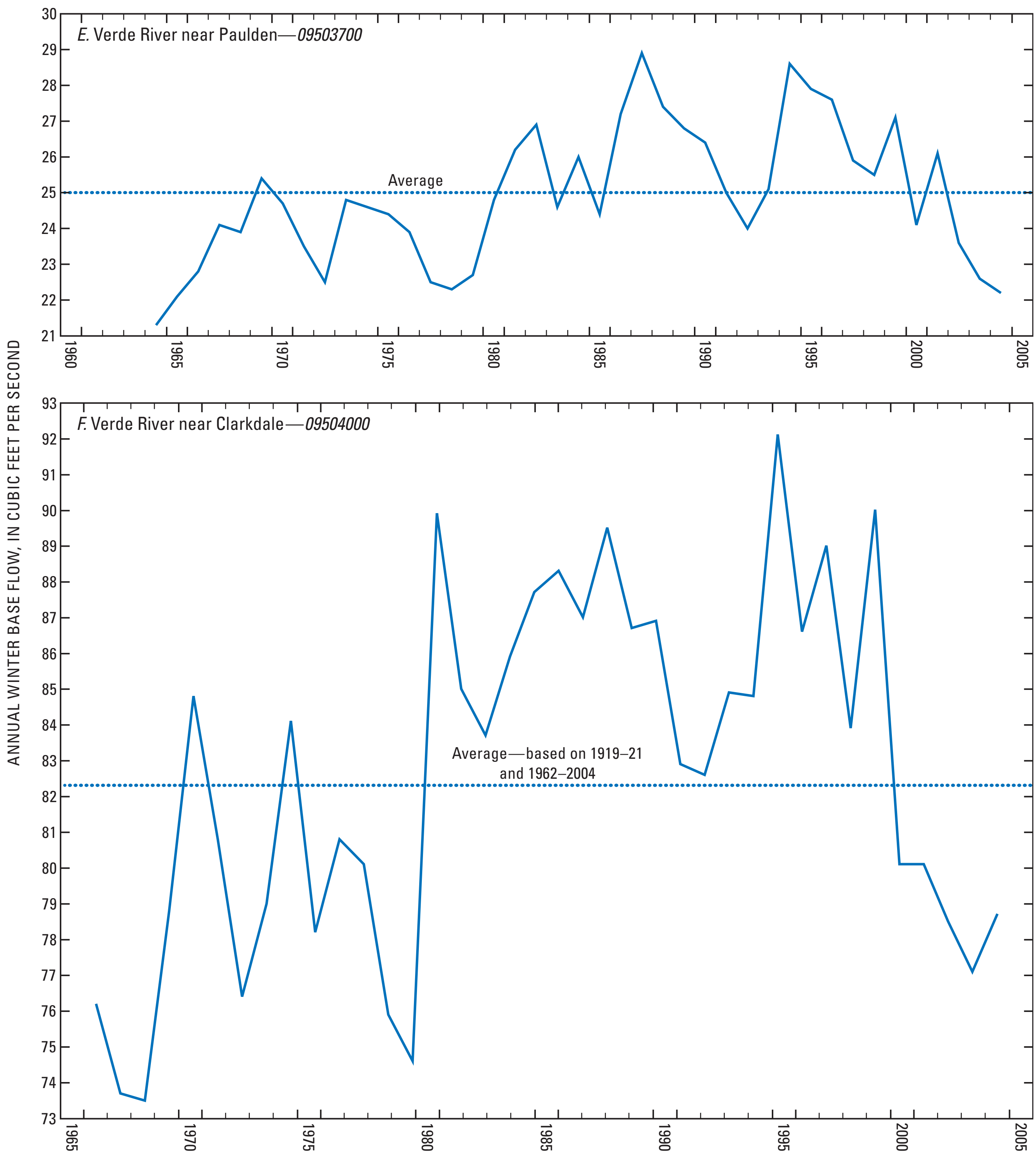

Figure 9. Annual winter base flow for selected streamflow-gaging stations, Coconino Platea study area, Coconino and Yavapai Counties, Arizona: *A*, Havasu Creek below Havasu Springs at Supai; *B*, Havasu Creek above the mouth near Supai; *C*, Oak Creek near Sedona; *D*, Wet Beaver Creek near Rimrock; *E*, Verde River near Paulden; *F*, Verde River near Clarkdale—Continued.

The Inner Basin of San Francisco Mountain contains a perched aquifer in glacial outwash and volcanic rocks. This aquifer has been fully developed by the city of Flagstaff; well yields range from 150 to 800 gal/min. Well yields are seasonally limited owing to the small areal extent of the aquifer and ground-water recharge that is predominantly from infiltration of snowmelt (Harshbarger and Associates and John Carollo Engineers, 1974).

In the Bellemont area between Flagstaff and Williams, a few shallow wells developed in unconsolidated volcanic rocks have had consistent yields of 50 gal/min in recent years, whereas other wells and springs in the area have gone dry (Lonnie McCleve, owner, Bellemont Truck Stop, written commun., 2003). One possible explanation for the consistent yields is that these wells are developed in a larger perched zone that extends to the flanks of San Francisco Mountain.

The city of Williams recently developed a municipal supply well in fractured volcanic rocks and the upper part of the Kaibab Formation on the northeast side of Bill Williams Mountain. The well yield was about 90 gal/min for 3 to 4 weeks before it declined to less than 10 gal/min. If the well is not pumped for about 3 months, it can be pumped again at the 90 gal/min rate for short periods of time (Dennis Wells, city manager, city of Williams, written commun., 2003). The well is developed in a fracture zone (Pierce, 2003) that likely channels ground-water flow to the well from a large area. The recent drought, however, limits the well's use as a source of municipal supply (Dennis Wells, city manager, city of Williams, written commun., 2003).

Less common throughout the Coconino Plateau study area is perched water in consolidated sediments. In the eastern part of the plateau and underlying the volcanic rocks of San Francisco Mountain north of Flagstaff, ground water does occur in interbedded sandstone of the Moenkopi Formation (Appel and Bills, 1981; McGavock and others, 1986; Bills and others, 2000; Thomas, 2003). Some of these zones are more extensive than those in volcanic rocks, but they are dependent on seasonal recharge, which occurs by the percolation of water from overlying units. The depth to water can range from 50 to more than 300 ft below land surface (Bills and Flynn, 2002). The only springs in the study area that discharge from the Moenkopi Formation occur in the Wupatki National Monument northeast of Flagstaff (Appel and Bills, 1981; Thomas, 2003). Most of the perched ground water in the Moenkopi Formation probably flows downgradient to fractures in a confining layer or to the edge of a confining layer where it then migrates deeper into the subsurface. Well yields from perched water zones in the Moenkopi Formation are limited by the poor permeability of the very fine-grained interbedded sandstone and typically are only a few gallons per minute.

Layers and lenses of chert and chert nodules become an increasingly significant component of the Kaibab Formation west of Flagstaff (Appel and Bills, 1981; and Sorauf and Billingsley, 1991). Ground water can become perched above these layers and lenses owing to their poor permeability. Based on well data, these perched zones appear to be most extensive between Flagstaff and Williams and north and northwest of Williams.

The depth to perched water in the Kaibab Formation can range from a few tens of feet to more than 500 ft below land surface (Bills and Flynn, 2002). The perched zones are recharged by ground water that has passed through overlying rock units and by direct infiltration where the Kaibab Formation is exposed at land surface (pl. 1). Ground water in these perched zones flows downgradient and discharges at seeps and springs, or it migrates deeper into the subsurface. The Kaibab Formation is highly fractured in much of the study area (pl. 1; Billingsley and others, 2000; Ulrich and others, 1984; and Billingsley and others, 2006). These outcrops of fractured rock play a significant role in transmitting water deeper into the subsurface.

Springs discharge ground water from the Kaibab Formation between Flagstaff and Williams and north of Williams. Discharge from these springs ranges from a few gallons per minute to more than 100 gal/min. Wells developed in perched zones in the Kaibab Formation have yields similar to this range. Only small seeps and two wells yield water from the Kaibab Formation along the south rim of the Grand Canyon (Metzger, 1961). The yield of springs and wells developed in the Kaibab Formation fluctuates seasonally, and some springs and wells have gone dry during extended periods of little to no precipitation (Metzger, 1961; McGavock and others, 1986; and Bills and others, 2000).

A few springs and wells discharge water from perched zones in the Coconino Sandstone or in sandstone beds of the Supai Group. Dripping Springs and Santa Maria Spring discharge 1 gal/min or less from the Coconino Sandstone and Supai Group, respectively, along the Hermit Trail at the western end of the south rim of Grand Canyon (Metzger, 1961). Several springs on the Havasupai Reservation along the Cataract Creek drainage and some of its tributaries also discharge water from the Coconino Sandstone and the Supai Group (table 3; Torrey Copfer, hydrologist, Natural Resources Consultant Engineers, written commun., 2003), but only a handful of wells are able to develop water from perched water-bearing zones in the Coconino Sandstone or the Supai Group on the Coconino Plateau west of the Mesa Butte Fault (Bills and Flynn, 2002). Ground water can be perched in the Coconino Sandstone where the formation is underlain by the very fine-grained Hermit Formation (pl. 1). It can also be perched in sandstone layers of the Upper and Middle Supai Formations that are not significantly fractured and are underlain by siltstone and mudstone of the Lower Supai Formation. Since neither the Coconino Sandstone nor the Supai Group crops out in the study area except in deep canyons and along the south rim of Grand Canyon, the perched zones receive recharge only by the downward migration of water from overlying units. The depth to perched water in these rock units on the Coconino Plateau generally is greater than 1,000 ft below land surface.

C Aquifer

Cooley and others (1969) defined the C multiple-aquifer system (C aquifer) as the sequence of rock units between the Kaibab Formation and the Supai Group inclusive. On the Coconino Plateau study area (fig. 8), this definition has been refined to include the Kaibab Formation, the Coconino Sandstone, the Schnebly Hill Formation, and the Upper and Middle Supai Formations, where they are partly or fully saturated and hydraulically connected (McGavock and others, 1986; Bills and others, 2000; Bills and Flynn, 2002). The Toroweap Formation, where present, is above the water table of the C aquifer in the study area and is not part of the aquifer. Previous investigators have referred to the aquifer as the Coconino aquifer (Mann, 1976; McGavock, 1968; McGavock and others, 1986), the C multiple-aquifer system (Cooley and others, 1969), the regional aquifer (Levings, 1980; Owen-Joyce and Bell, 1983; Bills and others, 2000), and the C aquifer (Hart and others, 2002). The term “C aquifer” is used in this report. Rock units of the C aquifer occur throughout northern Arizona and underlie the entire study area.

The Kaibab Formation, the uppermost rock unit of the C aquifer, crops out over large parts of the Coconino Plateau north of the San Francisco and Mount Floyd Volcanic Fields (pl. 1). Smaller outcrops are interspersed within and south and east of the San Francisco Volcanic Field. The formation is dry, except for perched ground water north of Williams, in areas where it crops out north of the volcanic fields. It is partly saturated in areas where it is interspersed within and south of the volcanic field. The other rock units of the C aquifer, the Coconino Sandstone, the Schnebly Hill Formation, and the Upper and Middle Supai Formations, crop out only in steep canyons or escarpments in the northern, southern, and western parts of the study area near ground-water discharge zones. Rock units of the aquifer are completely dry on the northwest side of the Mesa Butte Fault (pl. 3).

Water Level and Saturated Thickness

A map of the potentiometric surface of the C aquifer in the study area (pl. 3) was prepared on the basis of work by Hart and others (2002), Bills and others (2000), and Owen-Joyce and Bell (1983). The potentiometric surface represents a period of pre-stress prior to about 1980. Water-level data from new wells drilled from 1990 to 2004 was used to supplement and extend the potentiometric surface in those areas where there has been little or no water-level change as a result of ground-water withdrawals since about 1980.

Water-level trends for the C aquifer are varied in the study area; changes range from more than 100 ft of decline since 1983 near pumping centers for municipal supply, to a few feet of decline in areas where there is little ground-water withdrawal (pl. 2; Bills and Flynn, 2002). Water-level drawdown and recovery related to pumping are abrupt in withdrawal wells operated by the city of Flagstaff. The water level in the Skunk Canyon well, south of Flagstaff, had a declining trend from the late 1990s through about 2001 (pl. 2). This decline correlates well with the extended large withdrawals of ground water from the city of Flagstaff’s well fields in the dry years of the 1990s. Water levels in the NPS wells at Sunset Crater and Wupatki National Monuments declined about 5 to 20 ft from the 1950s and 1960s to present. This could be a delayed response to drier conditions earlier in the century. Since quarterly measurements began at these wells in the late 1990s, trends related to climate and (or) withdrawal are more apparent.

A ground-water mound is indicated by water-level data for the C aquifer south of Flagstaff near recharge areas on the Mogollon Rim. This ground-water mound forms a ground-water divide and influences the direction of ground-water flow in the aquifer. The ground-water divide is not fixed spatially nor temporally and can be affected by ground-water withdrawals. Ground water flows from the divide northward toward the Little Colorado River and from the divide southward to Verde Valley.

The hydraulic gradient of the aquifer in the study area ranges from about 40 to 100 ft/mi (pl. 3; Bills and others, 2000). The varied hydraulic gradient is a reflection of the varied flow conditions in the aquifer that are largely controlled by geologic structure. As ground water moves north and south to discharge areas, it is also migrating deeper into the subsurface along fractures and faults. North and west of Flagstaff, the Kaibab Formation, the Coconino Sandstone, and the Schnebly Hill Formation abruptly become unsaturated, and the underlying sandstone units of the Upper and Middle Supai Formations are saturated or partly saturated. Southward, the Kaibab Formation and the Coconino Sandstone become unsaturated as ground water moves downgradient toward Verde Valley in the sandstone units of the Schnebly Hill Formation and the Upper and Middle Supai Formations. West of Parks and on a northeast-southwest line extending to Cameron, the aquifer is unsaturated as ground water has migrated deeper into the subsurface. The aquifer also is unsaturated between Williams, Big Chino Valley, and the upper Verde Valley except for small perched zones mainly in the Kaibab Formation and the Upper and Middle Supai Formations. The saturated thickness of the aquifer ranges from 600 ft in the northeastern part of the study area to 2,200 ft in the southeastern part. Average saturated thickness is about 1,200 ft (Bills and others, 2000).

Recharge and Discharge

Recharge to the C aquifer occurs from direct infiltration of precipitation and infiltration of runoff mainly at higher altitudes along the Mogollon Rim and in the San Francisco Mountain area where the Kaibab Formation is exposed at land surface. A significant part of the recharge process is the interception of runoff by open fractures and solution channels developed on the Kaibab Formation surface (Bills and others, 2000; Wilkinson, 2000). The aquifer also is recharged by downward leakage of ground water from overlying perched zones and through the volcanic rocks of the San Francisco Volcanic Field. Small amounts of water are recharged to the aquifer from infiltration of treated municipal effluent along drainages in the Kaibab Formation near Flagstaff (Bills and others, 2000). A small amount of recharge occurs also as underflow along the eastern boundary of the study area. For the rest of the study area, the aquifer is topographically higher than adjacent areas that could contribute underflow.

Ground-water discharge from the C aquifer occurs as (1) spring flow in Verde Valley, (2) underflow to aquifers in Verde Valley, (3) downward leakage to the Redwall-Muav aquifer, (4) discharge from wells, and (5) evapotranspiration where the water table is at or near land surface (pl. 3). The aquifer discharges to springs along the Mogollon Rim in Sycamore Creek, Oak Creek, Wet Beaver Creek, and West Clear Creek (south of Wet Beaver Creek outside the study area) as well as directly to the Verde River north of Clarkdale (pl. 3; Bills and Flynn, 2002). Of these perennial reaches sustained by spring flow, Oak Creek is the largest and has a base flow of 28 ft^3/s. Montezuma's Well on Beaver Creek is a major spring outlet on this drainage (Konieczki and Leake, 1997).

Ground water from the aquifer that is not discharged as springs or withdrawn by wells flows southward into Verde Valley and becomes hydraulically connected to ground water in the Verde Formation (Owen-Joyce and Bell, 1983). Some of this ground-water flow also migrates downward through fractures and faults to become part of the underlying Redwall-Muav aquifer. In the northern part of the study area, ground water in the C aquifer that is not lost to evapotranspiration or withdrawn by wells migrates into the underlying Redwall-Muav aquifer through fractures and faults except for water in small perched zones.

Municipal and public supply wells discharge water from the C aquifer, in some cases in large amounts, near Flagstaff and in Verde Valley near Sedona. Most wells drilled into the Coconino Sandstone and the Upper and Middle Supai Formations north and west of San Francisco Mountain penetrated 2,000 ft or more of unsaturated rock. A few wells drilled north and west of Williams penetrated small perched zones in the Coconino Sandstone or in sandstone beds in the Upper and Middle Supai Formations at depths of about 1,200 ft to more than 2,000 ft below land surface.

Ground water discharges from the aquifer as evapotranspiration in a few riparian areas south of Flagstaff where the water table is in contact with the root zone of plants. The only ground water that discharges from rock units of the aquifer along the Colorado River and north and west of Williams are small seeps and springs that discharge from perched zones a thousand feet or more above the underlying Redwall-Muav aquifer.

Aquifer Properties and Well Yield

Aquifer properties—transmissivity, hydraulic conductivity, and storage coefficient—are important components of hydrogeologic assessments because they provide information useful for well development and prediction of aquifer response to stress. They also are important components of ground-water models because they are used to simulate ground-water flow. The properties are influenced by formation lithology and the type and degree of fracturing.

Aquifer properties (table 4) were determined from historical information and the analysis of field data collected during this study (Owen-Joyce and Bell, 1983; McGavock and others, 1986; Bills and others, 2000; Bills and Flynn, 2002). The data indicate that the C aquifer on the Coconino Plateau study area is anisotropic and unconfined except for a small part of the aquifer south of Flagstaff that is confined (Bills and others, 2000). Bills and others (2000) noted that transmissivity and hydraulic conductivity generally are higher at wells developed in the Coconino Sandstone or sandstone beds of the Upper and Middle Supai Formations and are lower in wells developed in the Kaibab or Schnebly Hill Formations. Transmissivity and hydraulic conductivity generally are higher where extensive fracturing occurs regardless of the lithology.

The storage coefficient and specific yield of the C aquifer are related to the lithology and geologic structure of the rock units. Values calculated for storage coefficient or specific yield from the few aquifer tests available for the study area (table 4) are consistent with those determined for the C aquifer underlying the Navajo and Hopi reservations (Cooley and others, 1969) and the Little Colorado River Basin (McGavock and others, 1986; Mann, 1976; Mann and Nemecek, 1983).

Well yields for wells developed in the C aquifer vary in the study area from about 1 to 1,700 gal/min (Bills and Flynn, 2002). Several factors contribute to this large range: (1) formation lithology, (2) degree and type of fracturing, (3) degree of secondary mineralization of the aquifer, (4) saturated thickness penetrated by the well, (5) well efficiency, and (6) pump design and lift. Bills and others (2000) showed that the degree and type of fracturing has the greatest effect on yields for wells developed in the C aquifer. In general, wells that yield less than 100 gal/min are not completed in or near faults or other fractures, and wells that yield greater than 100 gal/min are completed in or near faults and fractures.

Redwall-Muav Aquifer

The Redwall and Muav Limestones are the principal water-bearing rock units underlying the C aquifer in the study area. Because of the regional extent of these formations in northern Arizona, Cooley (1976) defined the Redwall and Muav Limestone multiple-aquifer system as the saturated to partly saturated and hydraulically connected Redwall, Temple Butte, and Muav Limestones. McGavock and others (1986) characterized the limestone aquifer in the area as consisting of several hydraulically connected limestone, sandstone, and shale units including the Tapeats Sandstone, the Bright Angel Shale, the Muav Limestone, the Temple Butte Limestone, the Martin Formation, and the Redwall Limestone. According to Owen-Joyce and Bell (1983), the regional aquifer in the Verde Valley area northeast of the Mogollon Rim consists of the Coconino Sandstone, the Supai Group, the Naco Formation, the Redwall Limestone, the Martin Formation, and the Tapeats Sandstone.

Table 4. Aquifer properties of the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

[discharge, in gallons per minute; drawdown and saturated thickness, in feet; transmissivity, in gallons per day per foot; hydrologic conductivity, in gallons per day per foot squared; specific yield, in percent; storage coefficient, dimensionless; and specific capacity, in gallons per minute per foot; >, less than; ---, indicate no data]

Source	Aquifer	Discharge	Saturated thickness	Transmissivity from drawdown	Transmissivity from recovery	Hydrologic conductivity from drawdown	Hydrologic conductivity from recovery	Storage coefficient/ Specific yield	Porosity, percent	Specific capacity	Number of tests
McGavock, 1968	C aquifer	1.0 to 1,000	>250	---	---	---	---	---	---	0.005 to 26.2	84
McGavock, 1968	Redwall-Muav aquifer	5.0 to 145	---	---	---	---	---	---	---	---	8
Cooley and others, 1969	C aquifer	200	---	35,000	---	42.0	---	0.00015 to 0.0074/---	0.01	13.3	1
Levings, 1980	C aquifer	5.0 to 225	---	10,000	---	---	---	---	---	0.1 to 118	51
Levings, 1980	Redwall-Muav aquifer	9.0 to 1,078	---	16,000	---	---	---	---	---	16.5 to 51.3	7
Bills and others, 2000	C aquifer	4.0 to 1,700	60 to 1,284	83.8 to 181,400	100 to 169,664	0.22 to 335	0.14 to 313	0.00001 to 0.01/0.0002 to 3.0	0.04 to 0.50	0.014 to 13.0	76
J.M. Montgomery, 1981	Redwall-Muav aquifer	35.0	559	20.0 to 40.0	---	---	---	---	---	0.07	1
Owen-Joyce and Bell, 1983	Redwall-Muav aquifer	0.4 to 1,078	---	---	---	---	---	---	---	---	15
Errol L. Montgomery and Associates, 1999	Redwall-Muav aquifer	5.0 to 89	600	---	---	---	---	---	---	---	8
City of Williams, written commun., 2002	Redwall-Muav aquifer	7.0 to 250	120 to 570	---	---	---	---	---	---	1.07 to >100	4

Northwest of the Mogollon Rim, the regional aquifer consists of the Redwall Limestone, the Martin Formation, and the Tapeats Sandstone (Owen-Joyce and Bell, 1983). In the Little Colorado River Basin, hydraulically connected water-bearing zones in the Redwall and Muav Limestones underlying the C aquifer have been referred to as the Redwall-Muav Limestone (Hart and others, 2002).

The Temple Butte Formation and other Devonian limestone rock units are exposed along the south rim of Grand Canyon and locally may be partly saturated in areas where ground water discharges from the Redwall-Muav aquifer (Huntoon, 1977). Well records indicate, however, that these rock units do not extend for significant distances south of Grand Canyon, and therefore they are not considered to be a significant part of the Redwall-Muav aquifer on the Coconino Plateau study area. The Bright Angel Shale and Tapeats Sandstone underlie the Redwall and Muav Limestones and are fully saturated where penetrated by wells. The Bright Angel Shale, however, is several hundred feet thick and composed of very fine-grained sediments that impede the downward migration of water near the south rim of Grand Canyon (Huntoon, 1977). The Bright Angel Shale and Tapeats Sandstone are believed to be hydraulically connected to the overlying Redwall and Muav Limestones through faults and fractures and where the Bright Angel Shale is thin in the central part of the study area (pl. 1). The Tapeats is hydraulically connected to the limestones where the Bright Angel Shale is absent in the central part of the study area.

For this report the term “Redwall-Muav aquifer” is used to describe this aquifer system as it occurs on the Coconino Plateau study area. Rock units of the aquifer on the plateau include the Redwall Limestone, the Temple Butte/Martin Formation, the Muav Limestone, and the Tapeats Sandstone (fig. 8).

The Redwall Limestone is the upper rock unit of the Redwall-Muav aquifer and occurs throughout the study area in the subsurface. The formation crops out in steep canyons and escarpments in the northern, southern, and western parts of the study area at or near locations of ground-water discharge (pl. 1). The Redwall Limestone is variably saturated in the study area. In a few places along the south rim of Grand Canyon, it is partly saturated to unsaturated where ground water migrates into lower units of the aquifer.

The Temple Butte Formation and the Muav Limestone underlie the Redwall Limestone along the south rim of Grand Canyon (pl. 1). South of Grand Canyon, the Temple Butte Formation abruptly thins to extinction, and the Muav and Redwall Limestones are in direct contact. The Muav Limestone is partly to fully saturated where it is penetrated by wells. It underlies most of the study area, thinning southward and eventually lapping onto the Martin Formation (pl. 1). The Martin Formation occurs mainly in the central and southern part of the plateau and thickens to the south as the Muav Limestone thins to extinction (pl. 1). The Martin Formation is fully saturated where it is penetrated by wells and only partly saturated in discharge areas to the south.

The Tapeats Sandstone occurs as a continuous unit along the south rim of Grand Canyon. South of Grand Canyon, it thins and is mainly present as an erosion remnant above Proterozoic rocks as fill in valleys and other low lying areas.

Water Levels and Saturated Thickness

The Redwall-Muav aquifer is confined throughout much of its occurrence by very fine-grained sediments in the overlying Lower Supai Formation and underlying Proterozoic granites and schists (pl. 1 and fig. 8). All the ground water in the Redwall-Muav aquifer is the result of downward leakage from overlying units through faults, fractures, or other geologic structures, such as breccia pipes. Some leakage also occurs through the bottom of the Redwall-Muav aquifer to underlying basement rocks that are heavily eroded or fractured.

A potentiometric surface map of the Redwall-Muav aquifer was developed on the basis of water-level data for wells and the altitude of springs that discharge from the aquifer (pl. 3). Because few wells are developed in the Redwall-Muav aquifer in the study area, water-level data from all of the Redwall-Muav aquifer wells were used to develop the potentiometric surface. Water-level data for Redwall-Muav aquifer wells are available for the 1940s to 2004 (Bills and Flynn, 2002; U.S. Geological Survey and Arizona Department of Water Resources, unpublished data). Most water-level data is from wells on the slope of the Mogollon Rim or in Verde Valley; almost no water-level data for the period before about 1980 are available for the rest of the Coconino Plateau study area. From the 1940s to 2004, water levels only varied in the range of a few feet throughout the study area. Trends resulting from the withdrawal of ground-water for municipal supply or from climatic changes are not apparent.

Two ground-water divides control, in part, the direction of ground-water flow in the Redwall-Muav aquifer (pl. 3). The ground-water divides are not fixed spatially or temporally and can be affected by ground-water withdrawals. One divide is aligned northeast and southwest parallel to the Mesa Butte Fault near the middle of the study area. It is horseshoe shaped with prongs extending northwest parallel to the south rim of Grand Canyon and northwestward from a point just south of Williams to near Seligman (pl. 3). On the northern end of the divide, ground water in the aquifer flows from the divide northeastward toward discharge areas on the Little Colorado River at and below Blue Spring and westward and northwestward toward discharge areas along the south rim of Grand Canyon and in Havasu Creek. On the southern end of the divide, ground water flows southward toward discharge areas in Big Chino Valley and the upper Verde Valley. A second ground-water divide in the aquifer is not indicated on plate 3 but is assumed to trend northwest-southeast parallel to the north side of the Mogollon Rim in the south-central part of the study area. From this ground-water divide, water in the aquifer flows northward and discharges in the lower part of the

Little Colorado River, and southward toward discharge areas along the Verde River between Clarkdale and Perkinsville, and along Beaver Creek.

The hydraulic gradient in the Redwall-Muav aquifer ranges from about 4.4 to 88 ft/mi in the study area. The large range in the gradient is a reflection of the varied flow conditions in the aquifer that are largely controlled by geologic structure, solution channel features in the subsurface, and topography. The gradient is higher near discharge areas along the south rim of Grand Canyon and south of the Mogollon Rim, and is lower in the interior of Havasu Creek/Cataract Canyon (pl. 3).

The static water level in wells developed in the Redwall-Muav aquifer is from 1 to several hundred feet above the top of the Redwall Limestone in most of the study area. It ranges from a few hundred feet to more than 2,900 ft below land surface. In ground-water discharge areas in the northern and southern parts of the study area, erosion has removed overlying rock units in steep canyons and escarpments exposing the aquifer to the atmosphere in small areas and creating unconfined or water-table conditions. The saturated thickness of the aquifer is roughly the same as the combined thickness of the Redwall and Muav Limestones and the Tapeats Sandstone. It ranges from about 640 to 2,000 ft and averages about 1,000 ft in the study area.

Recharge and Discharge

Recharge to the Redwall-Muav aquifer occurs almost entirely through faults, fractures, and other geologic structures, or by downward leakage from overlying units. Normal faults and their associated fractures occur throughout the study area and predominantly strike northeast to northwest (pl. 1). Recent analysis of surface geophysical data by Gettings and Bultman (2003) indicate that many of these structures are deep seated, penetrating both the C aquifer and the Redwall-Muav aquifer and bottoming in the basement granites and metamorphic rocks. Areas where significant faulting and fracturing occur are (1) along the Mesa Butte Fault zone; (2) in the Havasu Creek/Cataract Canyon area, especially in the Markham Dam area (pl. 1); (3) north of Mount Floyd roughly parallel with Farm Dam Draw; (4) along the Bright Angel and Vishnu Faults; (5) in the Cameron area coincident with several large monoclines; and (6) south of Flagstaff in association with developing extensional basins (pl. 1; Cooley, 1976; Ulrich and others, 1984; Billingsley, 2000; Bills and others, 2000; Billingsley and others, 2006).

Significant faults and fractures probably are present in the consolidated sediments underlying the San Francisco and Mount Floyd Volcanic Fields, but if so they are masked by the volcanic rocks. These volcanic fields are areas of significant recharge potential because their occurrence at higher altitudes is associated with increased precipitation and their porous soils allow rapid and deep infiltration. On the west side of Havasu Creek/Cataract Canyon, recharge potential is enhanced by the presence of large deposits of unconsolidated material—old lake bed and alluvial deposits that readily permit infiltration of precipitation and runoff. Infiltrating water percolates into the subsurface where fracture zones act as deep conduits to the aquifer (pl. 1). In the eastern and southeastern parts of the study area, ground water is recharged to the aquifer by downward leakage from the overlying C aquifer where very fine-grained sediments of the Lower Supai Formation have been faulted or fractured. This downward leakage is driven by higher head in the C aquifer that exceeds 1,000 ft in most of the area where the two aquifers overlap. Another part of the recharge process is the interception of runoff by open fractures and solution channels on the surface of the Kaibab Formation (Bills and others, 2000; Wilkinson, 2000) that occur throughout the study area (pl. 1).

The Redwall-Muav aquifer could receive recharge as underflow from the Black Mesa and Little Colorado River Basins; however, most of the flow from these areas likely discharges along the lower Little Colorado River or is impeded by the more than 500 ft of uplifted virtually impermeable basement granites along the Mesa Butte Fault (pl. 1). Recharge by underflow from north and south of the study area does not occur because the Redwall-Muav aquifer in the study area is topographically higher than these areas.

Ground-water discharge from the aquifer occurs as (1) spring flow along the lower Little Colorado River and in tributaries of the Colorado River along the south rim of Grand Canyon, (2) spring flow along the Verde River and its tributaries, (3) underflow into Verde Valley, (4) downward leakage into the Bright Angel Shale and Tapeats Sandstone, (5) discharge from wells, and (6) evapotranspiration where the water table in the aquifer is at or near land surface.

Metzger (1961) noted that springs issuing from the Redwall Limestone in the lower Little Colorado River and in Havasu Creek have large discharges, but that most other springs and seeps along the south rim of the Grand Canyon that issue from the Redwall and Muav Limestones have small discharges. The average flow of Blue Spring, one of dozens of outlets from the Redwall-Muav aquifer along the lower Little Colorado River, is about 95 ft^3/s, and the combined flow from all springs in this reach of the Little Colorado River is about 237 ft^3/s. Havasu Spring in Havasu Creek has a discharge of about 64 ft^3/s. Additional springs that discharge from the Redwall and Muav Limestones downstream to the mouth of Havasu Creek increase the base flow of the creek to about 71 ft^3/s. Numerous smaller springs and seeps discharge from the Redwall-Muav aquifer along the south rim of Grand Canyon (Monroe and others, 2005). These springs typically are about 3,000 ft below the surface of the Coconino Plateau. Smaller springs occur at the northwest end of the Grandview Monocline, in the Pipe Creek area on the Bright Angel and Vishnu Faults, in the Monument Creek area, in the Hermit Creek area, and in the area from Royal Arch Creek to Olo Canyon (pl. 2). The largest of these small spring flows, from Grandview Monocline to Olo Canyon, range from 0.67 to 1.11 ft^3/s and occur in the Pipe Creek area and along Hermit Creek. The rest of the spring flows in these areas are less than

0.22 ft^3/s. Other minor springs and seeps west of Pipe Creek typically have flow rates of less than 0.01 ft^3/s or just a few gallons per minute.

At the southern end of the Coconino Plateau study area, ground water discharges from the Redwall-Muav aquifer at springs along the upper reaches of the Verde River, along lower Sycamore Creek, and along the lower reaches of Oak and Beaver Creeks. The base flow of the Verde River increases from about 24 ft^3/s near Paulden to 78 ft^3/s near Clarkdale owing to discharge from springs in and north of the river, including those in lower Sycamore Creek. Spring flow from the Redwall-Muav aquifer to lower Oak Creek occurs mainly in the Page Springs area (pl. 2; Owen-Joyce and Bell, 1983). This spring issues from either the Verde Formation or the Supai Group (Owen-Joyce and Bell, 1983), but the main orifice is a solution channel in limestone rubble on the west-facing slope of a limestone unit that is consistent with Redwall Limestone lithology. Ground water from the aquifer that is not discharged as springs or withdrawn by wells, flows southward into Verde Valley and becomes hydraulically connected to ground water in the Verde Formation (Owen-Joyce and Bell, 1983). The amount of ground-water flow from the Redwall-Muav aquifer to the Verde Formation is unknown (Blasch and others, 2006).

Downward leakage from the Redwall-Muav aquifer to underlying rock units can occur throughout the Coconino Plateau study area where deep-seated faults and fractures through the entire sequence of Paleozoic rocks penetrate the Precambrian granites and metamorphic rocks. In the northern part of the study area, ground water migrates through faults and fractures in the Bright Angel Shale and the underlying Tapeats Sandstone into the underlying granite rubble, fractured granite, and fractured metamorphic rocks. Several small springs and seeps discharge from these Precambrian rock units several hundred feet to a thousand feet below the main discharge zone of the Redwall-Muav aquifer. Flow from these springs and seeps generally is less than 0.02 ft^3/s (10 gal/min). In the southern part of the study area, leakage from the aquifer can flow directly into the underlying granite rubble and fractured granites because the Bright Angel Shale is absent and the Tapeats Sandstone occurs only in low-lying areas of the erosion surface on the Precambrian rocks. Ground water from the Redwall-Muav aquifer can also flow laterally into permeable consolidated to unconsolidated valley-fill units in either Big Chino Valley or Verde Valley. The quantity of underflow in these areas is unknown.

Most wells developed in the aquifer in the study area are in smaller communities, such as Valle, Tusayan, Ash Fork, Drake, and Supai. A few municipal wells have been developed in the aquifer in Verde Valley near Sedona and in the Williams area.

Evapotranspiration (ET) can be a significant cause of seasonal variations in base flow. In the northern part of the study area, shallow ground water and spring flow support lush riparian habitat in the otherwise arid environment of the south rim of Grand Canyon. ET can account for as much as 10 percent of the base-flow component in Havasu Creek (Bills and Flynn, 2002). In the southern part of the study area, ET is estimated to be 7 to 10 percent of the base flow in the Verde River (Blasch and others, 2006).

Aquifer Properties and Well Yield

Data on aquifer properties and well yield—transmissivity, hydraulic conductivity, storage coefficient, and specific capacity—for the Redwall-Muav aquifer are lacking because few wells have been developed in this aquifer and even fewer usable aquifer-test data are available for analysis. Aquifer properties are affected by formation lithology and geologic structure. Structural development (faulting and fracturing) resulted in secondary permeability that greatly influences the occurrence and movement of ground water in the aquifer. Available data on aquifer properties for the study area were compiled from previous reports (table 4). These data compare well with data for the aquifer in areas adjacent to the Coconino Plateau (Owen-Joyce and Bell, 1983; Cooley and others, 1969). The data indicate that the aquifer is anisotropic and confined in much of the study area. Small parts of the aquifer are unconfined near discharge areas in the northern and southern parts of the study area (pl. 3). Well data indicate that transmissivity and hydraulic conductivity generally are greater in or near major fault or fracture zones. Wells drilled along extension faults and fractures typically penetrate zones of increased transmissivity owing to the solution-enhanced permeability (Errol L. Montgomery and Associates, 1999). Storage coefficients are not available for the Redwall-Muav aquifer; however, limited test data indicate that storage likely is influenced by structure. The storage coefficient probably is low in areas where data from wells drilled into unfractured or slightly fractured limestones indicate low transmissivity (Montgomery, 1981).

Yields from wells developed in the Redwall-Muav aquifer in the study area range from less than 1.0 to more than 1,000 gal/min (table 4). The same factors that contribute to the large range in yields from C aquifer wells also contribute to the large range in yields from the Redwall-Muav aquifer: lithology, degree and type of fracturing, saturated thickness penetrated by the well, and pump design and lift. In addition, dissolution of limestone and the widening of fractures by dissolution contribute significantly to the large range of well yields from the Redwall-Muav aquifer. One test well drilled into a zone of secondary fractures in the Redwall Limestone to the south of the Lake Mary and Anderson Mesa faults, south of Flagstaff, yielded only 35 gal/min (Montgomery, 1981). Recent wells drilled into the Redwall and Muav Limestones and the Martin Formation east of Williams along the Mesa Butte Fault zone yield 7.0 to 280 gal/min (Dennis Wells, city manager, city of Williams, written commun., 2004). Wells drilled in the Valle and Tusayan areas away from regional faults typically produce about 40 to 50 gal/min (Bills and Flynn, 2002). Well yields from the Redwall-Muav aquifer in Verde Valley range from less than 10 to about

1,100 gal/min (Owen-Joyce and Bell, 1983; Bills and Flynn, 2002). The correlation of higher well yields and regional geologic structure holds true in this area as well.

Ground-Water Development and Water Use

Until the 1950s, ground-water development on the Coconino Plateau study area consisted of a few shallow wells in perched water-bearing zones and developed, small to moderate-sized springs near population centers (McGavock and others, 1986). The amount of water withdrawn annually from wells and springs on the plateau through the end of the 1950s was estimated to be about 1,500 acre-ft. Most of the water from the developed springs was used by the city of Flagstaff (Harsbarger and Associates and John Carollo Engineers, 1972). Growth and development at the main population centers of Flagstaff and Sedona and the smaller communities along the main highways, coupled with drought conditions in the 1950s, early 1960s, and mid-1970s that reduced the water available from spring resources, forced the development of deep wells that penetrated the C aquifer or the Redwall-Muav aquifer. By 1970, the estimated annual ground-water withdrawal in the study area was about 2,600 acre-ft, and by 1975, estimated annual ground-water withdrawals had increased to about 5,200 acre-ft (McGavock and others, 1986). Almost all of this water was withdrawn from the C aquifer. More accurate accounting of ground-water withdrawals began in 1975 (table 5).

Ground-water development and withdrawals on the Coconino Plateau study area have increased steadily since 1975 (fig. 10). During the drought in the mid- to late-1970s, which caused a significant reduction in the amount of readily available surface water and perched ground water, withdrawals from C aquifer and Redwall-Muav aquifer wells increased nearly twofold (fig. 10). Ground-water use dramatically increased again during the period of below-average precipitation in the late 1980s. The decline in ground-water withdrawals in the early 1990s was partly the result of above-average precipitation and partly the result of increased water conservation measures and the use of treated effluent.

Since 1975, most of the increases in withdrawals from the C aquifer and the Redwall-Muav aquifer have been due to increased municipal use by the growing communities on the Coconino Plateau study area. Withdrawals for agricultural use, mainly from the C aquifer, represented about a third of the annual withdrawals from the mid-1970s to the mid-1980s, but have since declined to less than 1 percent on the basis of field observations. Most municipal and industrial use occurs in the Flagstaff and Sedona areas, the two largest communities in the study area. The city of Flagstaff currently accounts for about 9,000 acre-ft (Flagstaff Utility Department, 2004) or about half of the total water use in the study area (table 5). Most of this water comes from wells developed in the C aquifer. Withdrawals for industrial uses on the study area have remained fairly steady since about 1975; slight increases occurred in the late 1990s (table 5).

Ground-water withdrawals from the C aquifer accounted for 80 percent of the total withdrawals from 1975 to about 1983 (fig. 10). Almost all the withdrawals from the Redwall-Muav aquifer occurred in Verde Valley within the study area during this time, whereas withdrawals from the C aquifer occurred in the eastern, central, and southern parts of the study area. By early 1993, withdrawals from the Redwall-Muav aquifer had increased to about one-third of the total; almost all the withdrawals were in Verde Valley. Currently (2004), about two-thirds of the withdrawals in the study area are from the C aquifer and one-third is from the Redwall-Muav aquifer. From early 1990 to 2003, withdrawals in the study area have increased by more than 25 percent (fig. 10). As the demand for water increases in the western part of the study area, additional wells are being developed in the Redwall-Muav aquifer as the only viable source of ground-water supply owing to the lack of other reliable surface-water and ground-water resources in these areas.

Water Chemistry

Water-chemistry data provide important clues about the origins, occurrence, and flow paths of water in regional ground-water systems. Major-ion and trace-element data were used to distinguish ground water from different sources. Nutrient and selected trace-element data were used to indicate anthropogenic sources of ground-water recharge. Isotope and radiochemistry data were used to determine the origins of water in the ground-water system, trace the flow paths of water within the system, and determine the age of ground water in different parts of the system. All these water-chemistry data were used to develop a conceptual model and hydrogeologic framework for the regional ground-water system.

Quality of Water

Most sample analyses indicated that water from springs, streams, and wells on the Coconino Plateau study area is a calcium magnesium bicarbonate type. Water in the western part of Grand Canyon is a calcium magnesium sulfate type, and water discharging to the Little Colorado River Canyon is a sodium chloride type (fig. 11 and pl. 4). Water at springs and streams in the central part of Grand Canyon, springs near the Verde River, and springs and wells near Flagstaff had low concentrations of the major dissolved constituents.

The linear pattern of increasing sulfate and chloride proportions in relation to other major ions for sites near the south rim of Grand Canyon (fig. 11 and pl. 4) suggests mixing between chemical end members (Drever, 1997). Sulfate proportions increase westward from Monument Creek to Mohawk Canyon (fig. 12 and pl. 4). Similar increases in the proportions of calcium and magnesium also occur among sites near the south rim of Grand Canyon.

Table 5. Estimated annual ground-water withdrawals from the C aquifer and Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1975–2003.

[Data are in acre-feet per year; ---, indicate no data]

	C aquifer				Redwall-Muav aquifer						
Date	Public supply	Irrigation	Industrial	Recreation	Public supply	Irrigation	Industrial	Recreation	Total C aquifer	Total Redwall-Muav aquifer	Total
1975	2,709.7	660	17	---	711.7	---	---	---	3,386.7	711.7	[1]4,098.4
1976	2,505.9	1,230	117	---	784	---	50	---	3,852.9	834	[1]4,686.9
1977	5,370	2,161	117	---	772.7	---	50	---	7,648	822.7	[1]8,470.7
1978	3,930	1,985	117	---	801	---	50	---	6,032	851	[1]6,883
1979	3,130	382	117	---	800	---	50	---	3,629	850	[1]4,479
1980	2,233	671	323	---	896	---	50	---	3,227	946	[1]4,173
1981	4,999	572	312	---	917	32	50	---	5,883	999	[1]6,882
1982	4,457	613	314	---	986	32	50	---	5,384	1,068	[1]6,452
1983	4,561	919	140	---	1,211	32	80	---	5,620	1,323	[1]6,943
1984	5,260	922	155	---	1,989	32	80	---	6,337	2,101	[1]8,438
1985	4,445	498	155	---	2,016	32	80	---	5,098	2,128	[1]7,226
1986	4,219	2,360	139	---	2,211	32	80	---	6,718	2,323	[1]9,041
1987	3,798	1,167	132	---	2,345	32	80	---	5,097	2,457	[1]7,554
1988	4,924	1,951	141	---	2,650	30	80	---	7,016	2,760	[1]9,776
1989	11,540	1,934	139	---	2,834.2	20	80	---	13,613	2,934.2	[1]16,547.2
1990	11,294	1,785	138	---	2,817	20	80	---	13,217	2,917	[1]16,134
1991	8,302	1,800	132	---	4,216	30	85	---	10,234	4,331	[1]14,565
1992	7,696	1,875	134	---	4,121	30	85	---	9,705	4,236	[1]13,941
1993	8,850	625	137	---	4,739	30	85	---	9,612	4,854	[1]14,466
1994	---	---	---	---	---	---	---	---	---	---	---
1995	---	---	---	---	---	---	---	---	---	---	---
1996	---	---	---	---	---	---	---	---	---	---	---
1997	---	---	---	---	---	---	---	---	---	---	---
1998	---	---	---	---	---	---	---	---	---	---	---
1999	10,018	---	137	---	5,071	---	100	---	10,155	5,171	[2]15,326
2000	11,615	---	140	---	5,643	---	100	---	11,755	5,743	[2]17,498
2001	11,298	---	135	---	5,794	---	75	---	11,433	5,869	[2]17,302
2002	12,911	---	140	---	6,535	---	88	---	13,051	6,623	[3]19,674
2003	12,057	---	137	---	6,355	---	82	---	12,194	6,437	[3]18,631

[1]Annual U.S. Geological Survey Summary of Ground-Water Conditions in Arizona (for example, Anning and Duet, 1994).

[2]Hart and others, 2002.

[3]Compiled for this study.

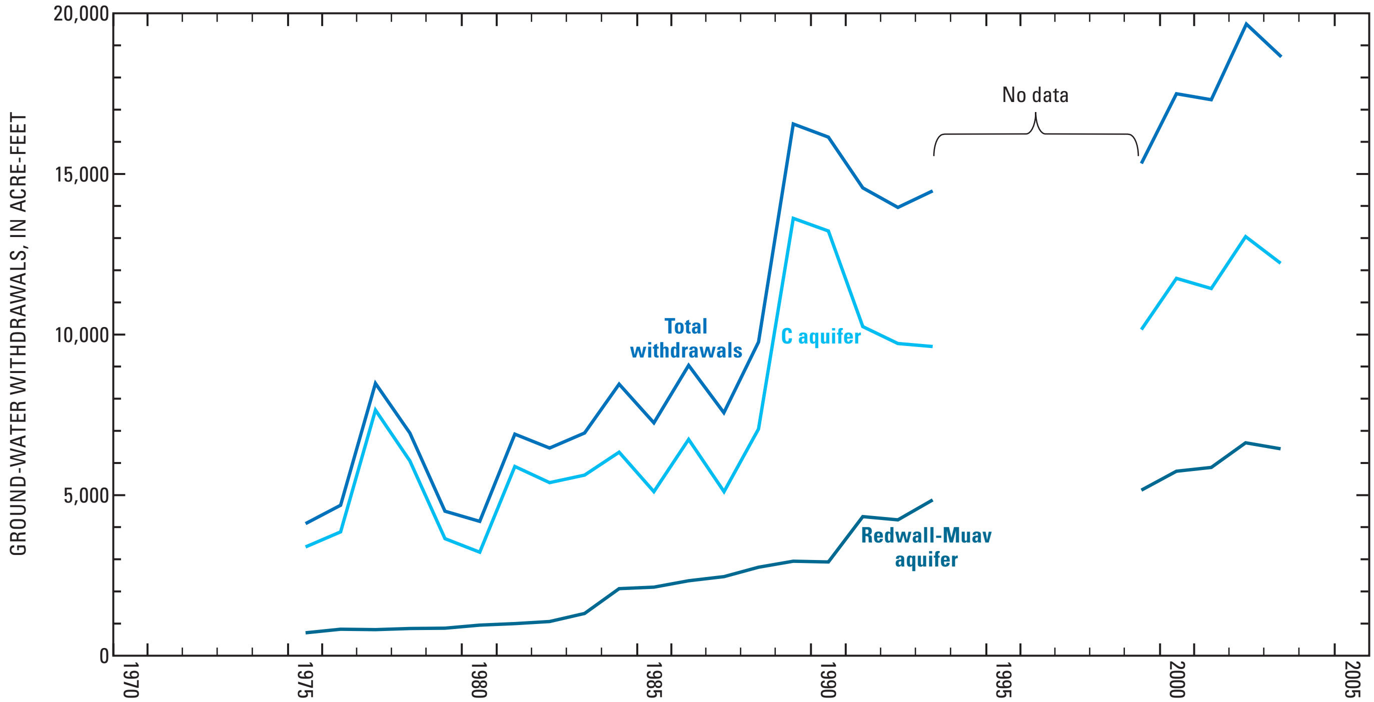

Figure 10. Annual and total ground-water withdrawals from the C aquifer and the Redwall-Muav aquifer in the Coconino Plateau study area, Arizona, 1975–2003.

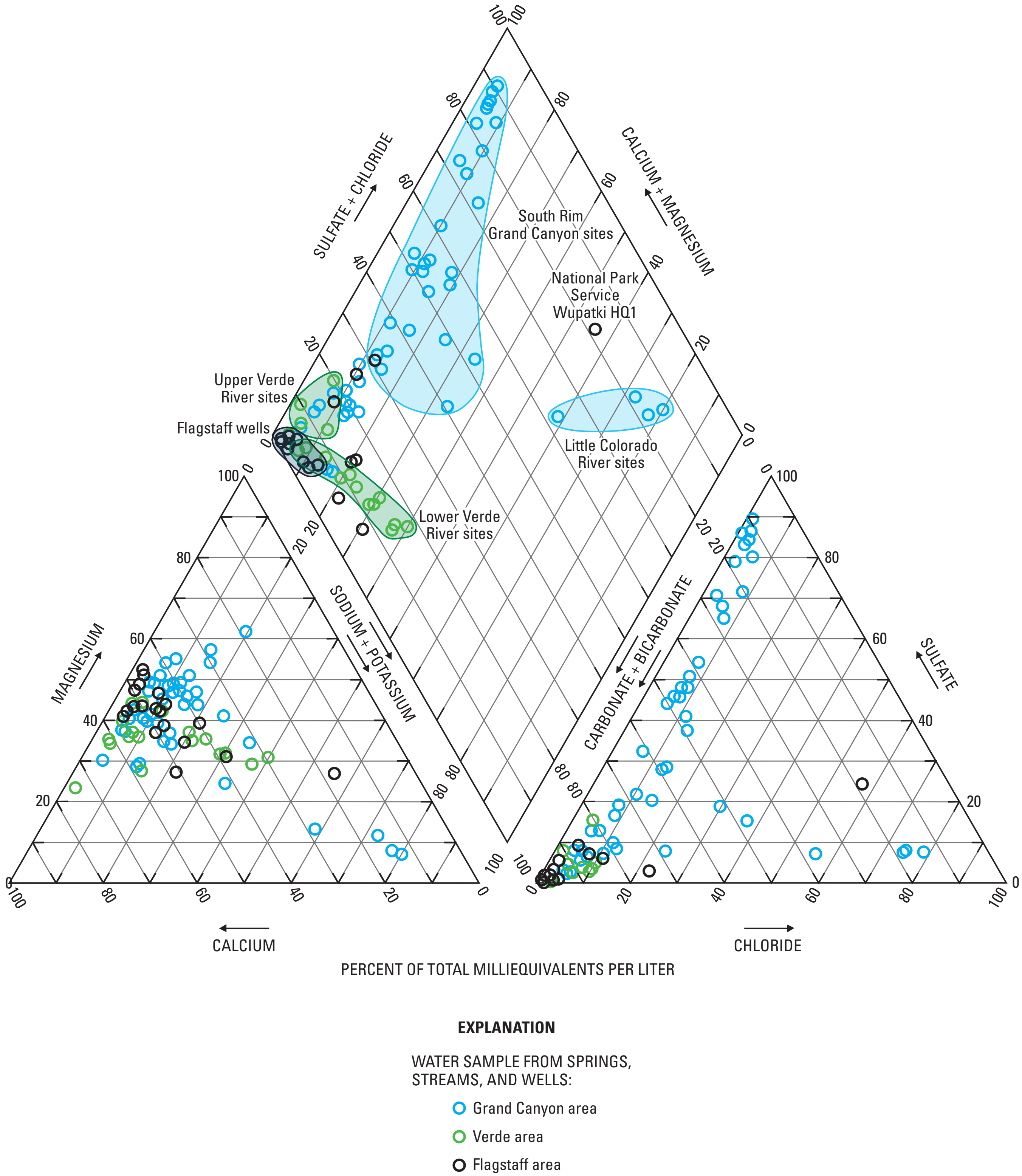

Figure 11. Relative ion composition of water from springs, streams, and wells that are points for discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1975–2003.

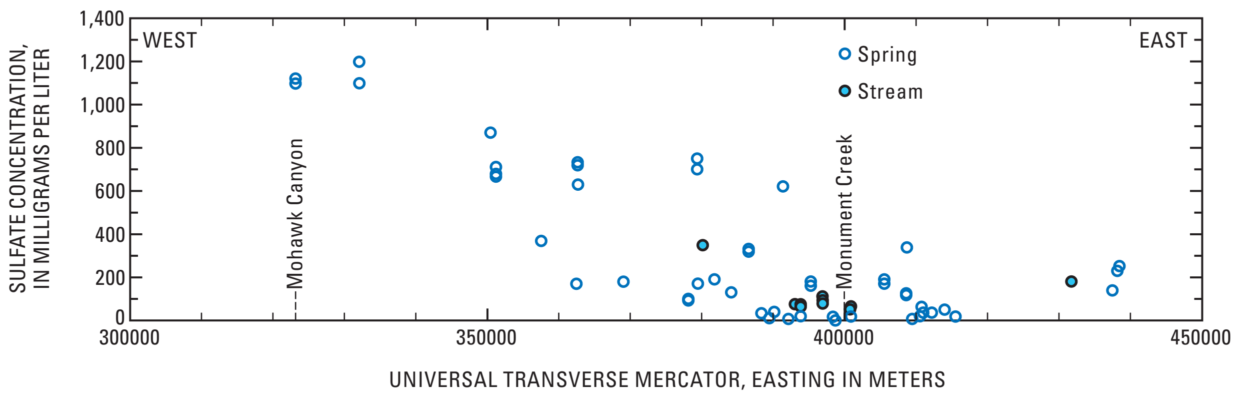

Figure 12. Concentrations of sulfate in relation to spring or stream locations near the south rim of Grand Canyon from the mouth of the Little Colorado River to Mohawk Canyon, Arizona, 1991–2002.

Major-ion data from sites near the southern boundary of the Coconino Plateau study area form two subgroups. Water from Verde River sites upstream from Mormon Pocket (fig. 11; upper Verde River sites) discharges from valley fill in Big Chino Valley and the upper Verde Valley and (or) the Redwall-Muav aquifer, and data from these sites form a subgroup characterized by higher proportions of bicarbonate, sodium, calcium, and magnesium than data from sites downstream from Mormon Pocket. Mormon Pocket Springs, Parsons Spring, and Summers Spring (lower Verde River sites) all discharge from the Redwall Limestone and have higher proportions of sodium and potassium (fig. 11 and pl. 4). Water from wells developed in the C aquifer near Flagstaff had low proportions of most major ions and was similar in composition to water from springs near the Verde River (fig. 11; Flagstaff wells). NPS Wupatki HQ1 well, northeast of Flagstaff, yields water from the C aquifer. Water from the well had relatively high concentrations of sodium, potassium, sulfate, and chloride compared to Flagstaff wells and was most similar in composition to spring samples from the Little Colorado River Canyon (fig. 11).

The proportion of major ions of the four Little Colorado River sites are distinct from other south rim Grand Canyon sites, Flagstaff wells, and upper and lower Verde River sites (fig. 11 and pl. 4). Blue Spring discharges from the west side of the Little Colorado River Canyon and had lower concentrations of sodium, chloride, and sulfate, and higher concentrations of calcium and bicarbonate than GC-1 Spring and Curtain Spring, which discharge from the east side of the canyon less than half a mile upstream from Blue Spring (table 3 and pl. 4). The sample collected from the Little Colorado River at river mile 3.1, about 10 mi downstream from Blue Spring and downstream from all major spring flows into the river canyon, was similar in composition to water from GC-1 Spring and Curtain Spring.

Water from most wells developed in the Redwall-Muav aquifer on the Coconino Plateau study area was similar in composition to water from springs near the south rim of Grand Canyon (pl. 4). The distinct difference in major-ion composition between water from the Bar Four Well, which is near the village of Supai, and water from nearby Havasu Spring suggests that these waters have different source areas and (or) interact with different rock units along their respective flow paths (pl. 4).

The influence of local geology is evident in the relation between selected major-ion concentrations and dissolved-solids concentration (fig. 13). Calcium and magnesium are present in almost equal proportions, and their predominance is consistent with the presence of limestones and dolomites in most ground-water flow paths. Higher concentrations of silica are evident in parts of the C aquifer near Flagstaff that have received recharge from infiltration of precipitation through volcanic rocks (Bills and others, 2000). A similar trend is noted for Flagstaff wells and springs and Verde River sites in this report (fig. 13D and Supplemental Data). Sulfates are predominant in water from most springs, streams, and wells in the western part of the plateau. The source of the sulfates may be evaporites or breccia pipes along the flow paths (Wenrich and others, 1994).

Principal components analysis (PCA) of major-ion data from springs, seeps, and wells on the plateau determined that about 93 percent of the variability in the data set was contained in the first four principal components (table 6). The first component accounts for 45 percent of the total variance in the major-ion data suggesting patterns of similarity among samples where calcium, magnesium, and sulfate are the dominant ions. The greater load values for calcium, magnesium, and sulfate reflect differences in major-ion chemistry between water discharging from springs in central and western Grand Canyon and water discharging from wells, springs, and streams near Flagstaff and the Verde River. The second component accounted for 26 percent of the variance contained in the data set and reflects variability introduced by the greater concentrations of sodium, chloride, and bicarbonate in water from sites along the Little Colorado River (table 6).

The third and fourth components account for 22 percent of the total variance, and the loading factors for these components reflect a similarity in major-ion chemistry of water from springs and streams in the central part of Grand

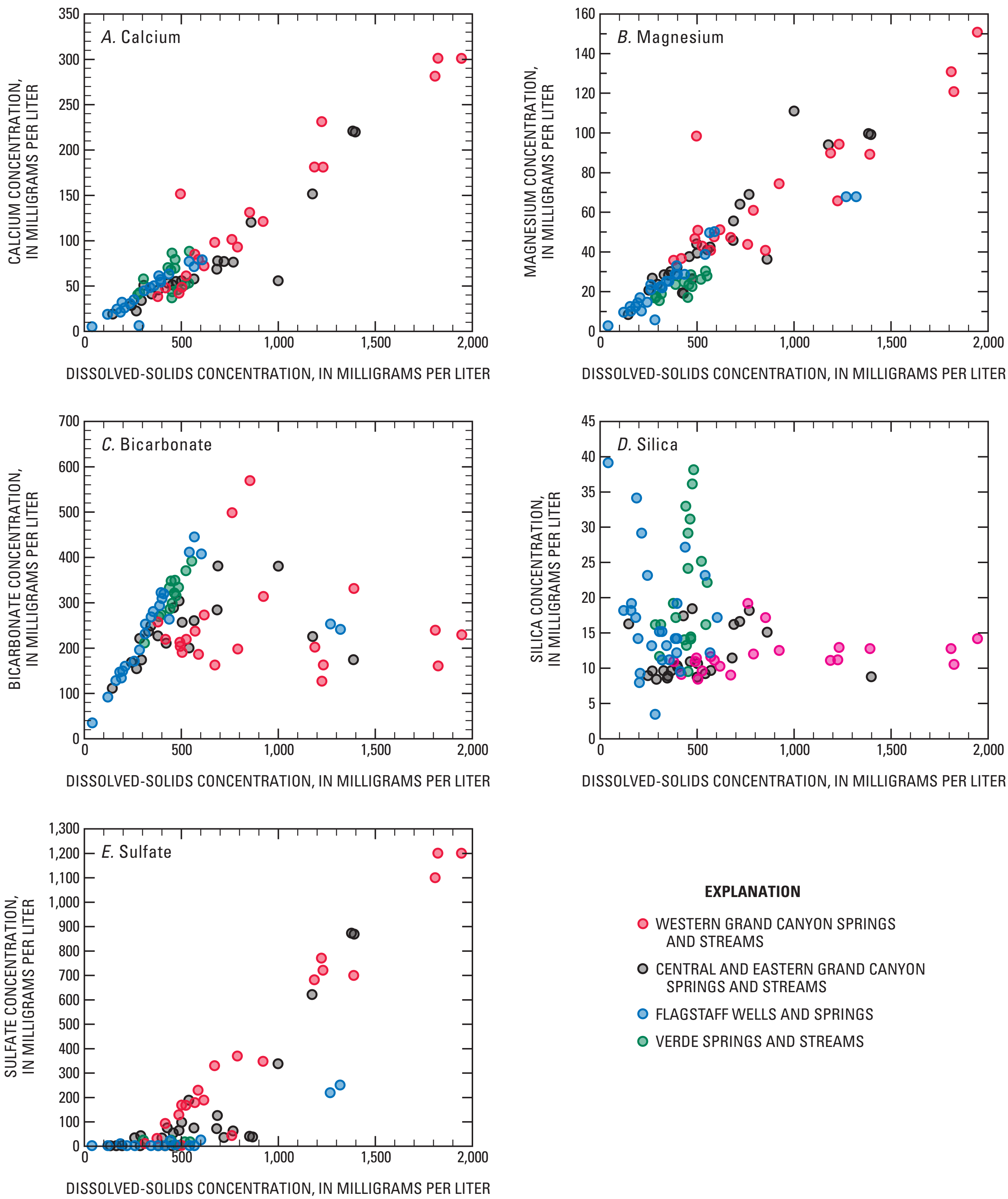

Figure 13. Relation between concentrations of dissolved solids and major ions in water from springs, streams, and wells in the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1921–2003: *A*, Calcium; *B*, Magnesium; *C*, Bicarbonate; *D*, Silica; and *E*, Sulfate.

Table 6. Results of principal components analysis of major-ion data for water from selected springs, streams, and wells, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2003.

[The number of variables is 8 and the number of observations is 99; ---, indicate no data]

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7	Component 8
Standard deviation	1.897	1.452	1.049	0.799	0.683	0.282	0.080	0.042
Proportion of variance	0.45	0.26	0.14	0.08	0.06	0.01	0.00	0.00
Cumulative proportion	0.45	0.71	0.85	0.93	0.99	0.999	1.00	1.00
Loadings								
Sodium (Na)	0.301	0.533	---	0.327	---	---	–0.437	0.561
Potassium (K)	0.377	–0.184	0.295	–0.264	0.758	0.298	---	---
Calcium (Ca)	0.477	–0.141	–0.168	---	0.427	0.519	0.427	0.298
Magnesium (Mg)	0.470	–0.257	---	–0.143	---	–0.788	0.181	0.188
Chloride (Cl)	0.298	0.531	---	0.336	---	---	0.427	–0.556
Bicarbonate (HCO_3)	0.229	0.422	–0.173	–0.773	0.215	---	–0.237	–0.192
Carbonate (CO_3)	---	---	0.916	–0.104	0.388	---	---	---
Sulfate (SO_4)	0.421	–0.373	---	0.281	0.171	---	–0.593	–0.463

Canyon National Park, on the Havasupai Indian Reservation, and wells on the Coconino Plateau that are distinctly different from springs near the Verde River, and springs and wells near Flagstaff.

Hierarchical cluster analysis (HCA) produced similar results to PCA. HCA assigned the sites to three clusters on the basis of PCA of the major-ion data (fig. 14). Sites included in cluster one correspond to sites described by the first component of the PCA where calcium, magnesium, and sulfate were the dominant ions. These sites included the springs near the Verde River, wells and springs in the Flagstaff area, and springs along the eastern portion of the south rim of Grand Canyon. The sites included in cluster three correspond to the Little Colorado River spring and stream sites described in the second principal component of the PCA where sodium, chloride, and bicarbonate were the dominant species. Cluster two represents the trend of increasing sulfate and bicarbonate values from spring and well sites westward along the south rim. Cluster two also included four sites described by the third principal component. These sites were Boucher Spring, Turquoise Creek, and 140 Mile Plus Spring.

The water discharging from the C aquifer and the Redwall-Muav aquifer on the Coconino Plateau study area is generally of good quality for most intended uses. Barium was the only trace element that equaled or exceeded U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) for drinking water in wells near Flagstaff; the highest barium concentration was in the Pine Grove Well (2.0 mg/L; Bills and others, 2000).

Water from GC-1 Spring, Curtain Spring, and Blue Spring, and from the Little Colorado River at mile 3.1 in the Little Colorado River Canyon, generally had higher concentrations of most trace elements than other springs and streams on the Coconino Plateau study area. The difference in water chemistry between GC-1, Curtain, and Blue Springs and the geologic setting of their points of discharge suggests that either the water that discharges from these systems has had a higher residence time in the flow system resulting in greater dissolution of minerals or, the water has traveled along different flow paths. Mohawk Canyon Spring, National Canyon Spring, and Bar Four Well also generally had higher concentrations of many trace elements than those from wells on the Coconino Plateau study area or springs in Havasu Canyon (Ronald Antweiler, hydrologist, U.S. Geological Survey, written commun., 2005). This difference suggests that water that discharges at Mohawk Canyon Spring, National Canyon Spring, and Bar Four Well have different recharge areas and travel along different flow paths than other ground water that reaches discharge areas along the western part of Grand Canyon (pl. 4).

The concentrations of arsenic and lead exceeded the MCLs at some sites. Concentrations of arsenic exceeded the MCL (10 µg/L) at Red Canyon Spring (average 16.7 µg/L), JT Spring (10.7 µg/ L), Miners Spring (18.0 µg/L), Havasu Spring (17 µg/L), Havasupai Well No. 1 (12.0 µg/L), Dogtown Well No. 1 (20.4 µg/L), Rodeo Grounds Well (17.4 µg/L), Parson Springs (13.0 µg/L), and Summers Spring (13 µg/L; Bills and Flynn, 2002; Ronald Antweiler, hydrologist, U.S. Geological Survey, written commun., 2005). The concentrations of lead at Havasu Spring and Fern Spring (20 µg/L) exceeded the MCL of 15 µg/L. Arsenic and lead are common accessory metals in uranium ore deposits.

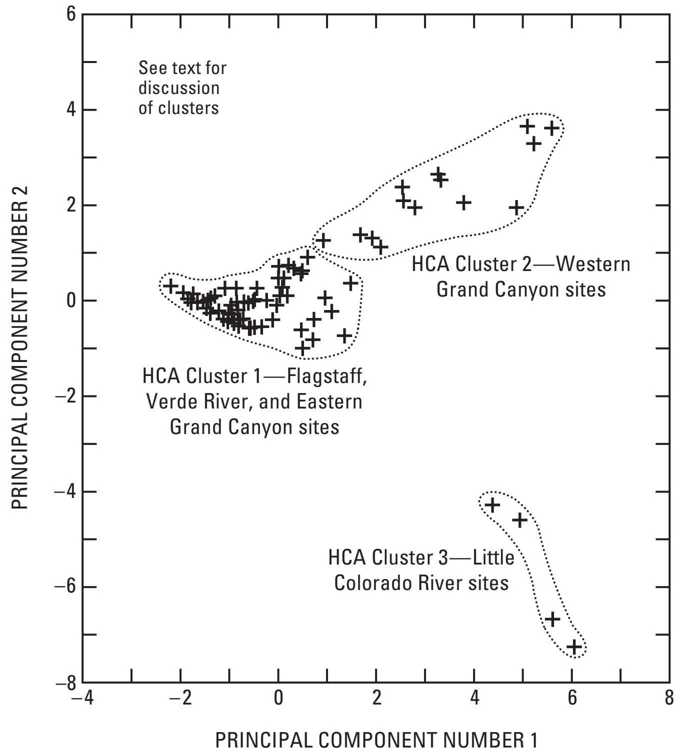

Figure 14. Grouping of sites based on principal components analysis and hierarchical cluster analysis (HCA) of major-ion data for water from selected springs, streams, and wells, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2003.

Radioactive constituents were near or above MCLs at a few sites (see "Supplemental Data"). The concentration of uranium in samples from Salt Creek Spring (average 30.6 µg/L) exceeded the proposed USEPA MCL of 30 µg/L. One sample from Horn Creek had a concentration of 29.2 µg/L. The gross alpha-particle activity in a sample from Salt Creek Spring (22 pCi/L) exceeded the USEPA MCL of 15 pCi/L (Ronald Antweiler, hydrologist, U.S. Geological Survey, written commun., 2005). An abandoned uranium and copper mine (Orphan Lode mine) in the vicinity of Salt Creek and Horn Creek (pl. 2) likely indicates that these constituents are naturally abundant in this area. Samples from Turquoise Creek, Forster Canyon Spring No. 2, Mohawk Canyon Spring, and the Bar Four Well near Supai all had gross alpha-particle activities greater than 14 pCi/L. These sites are downstream from or near breccia pipes that are known to concentrate uranium ores on this part of the Coconino Plateau (Wenrich and others 1994; Wenrich and others, 1997; Billingsley and others, 2000).

Isotope Hydrology

Local meteoric water lines were constructed by using ^{18}O and ^{2}H data from precipitation samples collected between 1989 and 2003 from a site near the south rim of Grand Canyon (Pendall, 1997; Harvey, 2000; National Atmospheric Deposition Program, 2003), samples collected between 1962 and 1965 in Flagstaff (International Atomic Energy Agency in cooperation with the World Meteorological Organization, 2001), and samples collected near Flagstaff during 2003–04 by the USGS. The $\delta^{18}O$ and $\delta^{2}H$ data from all three sample sets have a strong seasonal pattern; winter precipitation samples generally were isotopically lighter than summer precipitation samples (fig. 15A). The $\delta^{18}O$ values for precipitation collected near the south rim of Grand Canyon range from about –23 to +3 ‰, and $\delta^{2}H$ values range from about –175 to –5 ‰. Precipitation samples collected in Flagstaff between 1962 and 1965 had $\delta^{18}O$ values that ranged from –20.4 to +3.3 ‰ and $\delta^{2}H$ values that ranged from –158 to +2 ‰. Precipitation samples collected near Flagstaff in 2003 and 2004 had $\delta^{18}O$ values that ranged from –11.8 to –0.8 ‰ and $\delta^{2}H$ values that ranged from –84 to –3 ‰ (table 7).

Isotopic data from the springs and streams near the south rim of Grand Canyon commonly plot below the local meteoric water lines for the south rim (1989–2003) and Flagstaff (2003–04) as well as the global meteoric water line (fig. 15B). These data could indicate the contribution to south rim springs and streams of water older, and thus heavier, than water from a local meteoric source or, fractionation during secondary evaporation prior to recharge (Mazor, 2004).

The 1962–65 Flagstaff local meteoric water line has a significantly different slope from the global meteoric water line, the south rim local meteroric water line, and the 2003–04 Flagstaff local meteroric water line (fig. 15B). Data from Flagstaff springs and wells plot in a relatively tight cluster close to or below the 1962–65 line. Bills and others (2000) suggest that this pattern indicates a common recharge source for ground water in the Flagstaff area. Well data that plot below the 1962–65 line indicate that ground water at these wells had received recharge from surface water that had undergone evaporation.

Isotopic compositions of water samples from springs, streams, and wells on the Coconino Plateau study area do not show a clear seasonal pattern and are most similar to the composition of winter precipitation (figs. 15A and 15B). Multiple water samples for $\delta^{18}O$ and $\delta^{2}H$ analysis were collected at most sites during multiple seasons, and data for individual sites generally are consistent (see "Supplemental Data"). Springs and seeps in Grand Canyon show a trend of increasing isotopic enrichment from east to west (Monroe and others, 2005). Water from Flagstaff springs and wells generally is enriched in ^{18}O and ^{2}H compared to water from springs and wells in Grand Canyon (fig. 15B).

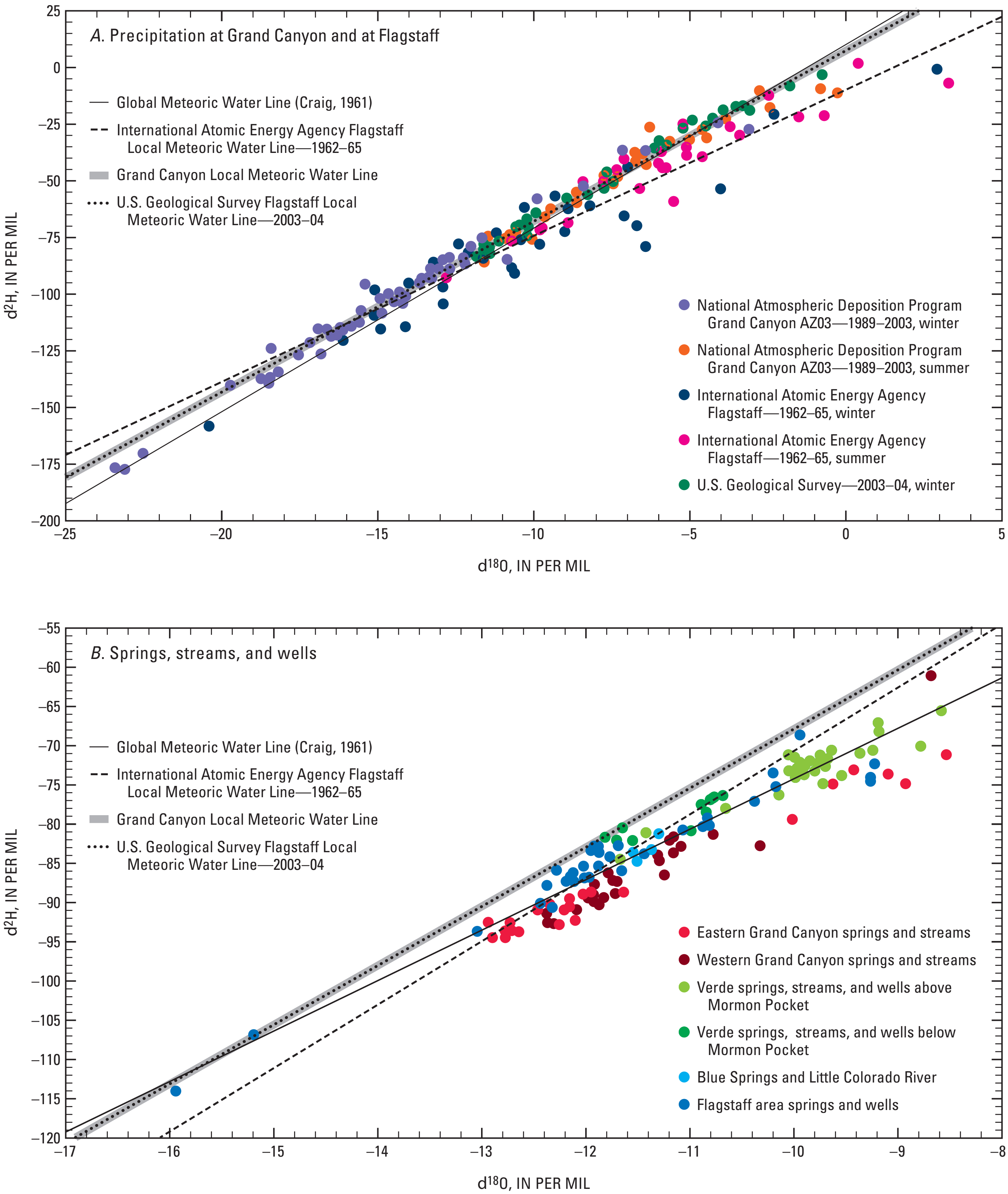

Figure 15. Oxygen and hydrogen data for precipitation and for springs, streams, and wells that are discharge points from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona: *A*, Precipitation at Grand Canyon 1989–2003, and at Flagstaff 1962–2004; *B*, Springs, streams, and wells, 1991–2004.

Table 7. Summary of hydrogen and oxygen isotope data, from precipitation and from water discharging from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1962–2004.

[δ, delta notation, in parts per mil; ^{18}O, oxygen-18; ^{2}H, deuterium; r^2, goodness of fit]

Sample group	Data collection period	Number of samples	Mean		Variance		Correlation r^2	Slope
			$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$		
Grand Canyon precipitation—All	1989–2003	109	–11.4	–79	22.0	1,335	0.99	$\delta^2H=7.6\delta^{18}O+8$
Grand Canyon precipitation—Winter	1989–2003	67	–14.1	–98	14.6	944	0.98	$\delta^2H=8.0\delta^{18}O+13$
Grand Canyon precipitation—Summer	1989–2003	42	–7.4	–48	8.6	426	0.95	$\delta^2H=6.9\delta^{18}O+2$
Grand Canyon springs, streams, and wells	1993–2003	104	–11.8	–88	0.8	36	0.92	$\delta^2H=6.4\delta^{18}O+12$
Flagstaff precipitation—All	1962–1967	53	–8.3	–63	23.7	1,095	0.90	$\delta^2H=6.5\delta^{18}O+9$
Flagstaff precipitation—Winter	1962–1967	30	–10.5	–79	20.6	914	0.87	$\delta^2H=6.2\delta^{18}O+14$
Flagstaff precipitation—Summer	1962–1967	23	–5.5	–42	14.2	554	0.87	$\delta^2H=5.8\delta^{18}O+10$
Flagstaff springs and wells	1996–1997	40	–10.8	–77	10.1	801	0.82	$\delta^2H=4.5\delta^{18}O+32$
Flagstaff precipitation—All	2003–2004	33	–7.8	–51	11.3	661	0.99	$\delta^2H = 7.59\delta^{18}O+8$
Verde springs and streams	1991–2002	43	–10.7	–78	0.8	26	0.93	$\delta^2H=5.6\delta^{18}O+18$

^{18}O and ^{2}H data from the Verde River and associated springs plot as two subgroups. The upper Verde River sites (above Mormon Pocket) are more enriched in ^{18}O and ^{2}H than the lower Verde River sites (below Mormon Pocket). This difference indicates that the upper Verde River sites receive recharge from a lower altitude source than do the lower Verde River sites. The lighter isotopic compositions of water at the lower Verde River sites, similar to that of water at Flagstaff wells and springs, indicate that the lower Verde River sites receive recharge from higher altitudes along the Mogollon Rim and near Flagstaff. Isotopic values for sites along the lower Little Colorado River are similar to values for sites along the lower Verde River, near Flagstaff, and in the western part of Grand Canyon (fig. 15B). Sites in other parts of the study area have an evaporative isotopic signature (see "Supplemental Data"). In Grand Canyon, they include Grapevine East Spring, JT Spring, and Sam Magee Spring. Other sites with evaporative signatures include Ash Fork Well No. 1, Lake Mary Well No. 4, and King Spring. Water from Bar Four Well has distinctly lighter ^{18}O and ^{2}H compositions than water from other sites (see "Supplemental Data").

Strontium-isotope concentrations can provide information about water-rock interactions in ground-water systems. $^{87}Sr/^{86}Sr$ values for water samples from springs, streams, and wells on the Coconino Plateau study area ranged from 0.70363 at Horn Creek to 0.71514 at Grapevine East Spring (table 8). Rock samples collected near the Bright Angel Fault in Grand Canyon and in the Verde River area, and well cuttings from Dogtown Well No. 1 and Rodeo Grounds Well had $^{87}Sr/^{86}Sr$ values that ranged from 0.70504 (basalt) to 0.76912 (granite; table 8), respectively. Water from wells near Flagstaff had low $^{87}Sr/^{86}Sr$ values that are indicative of interactions of water infiltrating through volcanic rocks or water and rocks of the Kaibab Formation (Bills and others, 2000). Water from springs and streams near the south rim of Grand Canyon had higher $^{87}Sr/^{86}Sr$ values than water from wells in the Flagstaff area (see "Supplemental Data"). $^{87}Sr/^{86}Sr$ values for sites east of the Hermit Fault generally were higher than values for sites west of the fault (fig. 16B). Values for sites east of Hermit Fault, including Ash Fork Well No. 1 and Rodeo Grounds Well, were greater than values for any other wells or springs that discharge water from the Paleozoic rocks (fig. 16B; table 8). These high values indicate that ground water at these sites mixes with deeper ground waters (Frost and Toner, 2004; Laura Crossey, professor, University of New Mexico, written commun., 2004) or interacts with rocks not analyzed for this study. Rock samples from the Supai Group, the Redwall Limestone, and the Muav Limestone had $^{87}Sr/^{86}Sr$ values that generally were most similar to $^{87}Sr/^{86}Sr$ values for water from Boucher Spring, Forster Spring No. 2, Turquoise Spring, Blue Springs, Canyon Mine Well, Little Colorado River Mile 3.1, and Hermit Spring.

Within the study area, $^{87}Sr/^{86}Sr$ values for some well or spring sites are more radiogenic than values for rocks or well cuttings. The higher ratios could be due to interactions between ground water and the siliceous Coconino Sandstone, the Hermit Formation, or the Upper Supai Formation, which are more radiogenic than the other rock units; between ground water and secondary carbonates encountered in fractures or solution cavities along the flow path; or between ground water and rocks that were not analyzed during this study.

Table 8. Strontium and carbon-13 isotope data and X-ray diffraction mineralogy for selected water and rock samples representing the major stratigraphic units on the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

[m, meter; δ, delta notation; per mil, per thousand; na, not available; ---, indicate no data; k-feldspar, potassium feldspar; %, percent; shaded rows indicate water samples]

Sample site	Altitude of land surface, meters	$^{87}Sr/^{86}Sr$	$\delta^{13}C$, per mil	Rock name	Bulk mineralogy (Rod Parnell, professor, and Travis Loseke, graduate student, Northern Arizona University, written commun., 2002)[1]
Horn Creek	1,273	0.70363	–10.8	---	
King Spring Basalt	na	0.70463	na	Basalt	na
Dogtown Well No. 1	1,992-1,989	0.70504	na	Basalt	Plagioclase (58%), pyroxene (28%), olivine (14%)
Meath Spring Basalt	na	0.70530	na	Basalt	na
Henden	2,369	0.70632	–9.7	---	
Rodeo Grounds Well	2,019-2,016	0.70535	–2.0	Basalt	Plagioclase (42%), olivine (43%), quartz (14%)
Rodeo Grounds Well	959-956	0.70586	–2.6	Tapeats Sandstone	Clear to red to purple coarse quartz veins
WM-1	2,343	0.70588	–10.8	---	
Sterling Springs	1,890	0.70648	–10.9	---	
WM-9	2,326	0.70655	–11.0	---	
Hidden Hollow	2,320	0.70663	–10.7	---	
Dogtown Well No. 1	2,308	0.70679	–8.8	---	
BBDP-MVR-1	2,103	0.70693	–8.6	---	
FH-5	2,221	0.70702	–10.8	---	
Clark Spring	2,298	0.70706	–12.6	---	
King Spring	1,380	0.70716	na	---	
Mountainaire	2,226	0.70723	–10.5	---	
BBDP-Marijka	2,157	0.70731	–6.9	---	
King Spring Travertine	na	0.70741	na	Travertine	na
Babbitt Spring	2,262	0.70748	–10.8	---	
Mtn Dell-1	2,267	0.70751	–10.4	---	
Rodeo Grounds Well	1,934-1,931	0.70756	–2.0	Kaibab Formation, Fossil Mountain Member	Quartz (58%), dolomite (33%), calcite (5%), clays-kaolinite (4%)
Rodeo Grounds Well	1,718-1,715	0.70760	na	Coconino Sandstone	Quartz (85%), k-feldspar (5%), dolomite (5%), calcite (2%), clays-kaolinite (3%)
Rodeo Grounds Well	2,050-2,047	0.70764	na	Volcanics	Quartz (25%), plagioclase (28%), clays-illite, kaolinite (47%)
Summers Spring	1,188	0.70770	–8.1	---	
Rodeo Grounds Well	1,894-1,891	0.70773	na	Kaibab Formation, Fossil Mountain Member	Quartz (54%), dolomite (36%), calcite (8%), clays-kaolinite (2%)
Royal Arch Spring	997	0.70777	–9.4	---	
Foxglenn-1	2,223	0.70785	–9.2	---	
Rodeo Grounds Well	1,971-1,968	0.70789	–1.0	Kaibab Formation, Harrisburg Member	Calcite (65%), dolomite (23%), quartz (9%), clay-illite (3%)
Bar Four Well	1,844	0.70795	–3.4	---	
Dogtown Well No. 1	1,870-1,867	0.70800	–0.4	Kaibab Formation, Harrisburg Member	Calcite (56%), quartz (22%), dolomite (11%), k-feldspar (3%), clays-kaolinite, illite, smectite (8%)
Dogtown Well No. 1	1,178-1,175	0.70804	–1.3	---	Calcite (89%), quartz (11%)
Dogtown Well No. 1	1,474-1,471	0.70810	–0.3	Hermit Formation	Dolomite (45%), quartz (38%), k-feldspar (4%), clays-illite (13%)
Dogtown Well No. 1	1,780-1,797	0.70813	–0.2	Kaibab Formation, Fossil Mountain Member	Quartz (69%), calcite (11%), k-feldspar (15%), clays-kaolinite (5%)
LM-4	2,234	0.70814	–9.6	---	
Purl	2,228	0.70816	–8.3	---	
Matkatamiba Spring	840	0.70819	–5.0	---	
Grand Canyon—Bright Angel Trail	1,475	0.70820	–0.3	Redwall Limestone	Calcite (98%), quartz (2%)

See footnote at end of table.

Table 8. Strontium and carbon-13 isotope data and X-ray diffraction mineralogy for selected water and rock samples representing the major stratigraphic units on the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona—Continued.

Sample site	Altitude of land surface, meters	$^{87}Sr/^{86}Sr$	$\delta^{13}C$, per mil	Rock name	Bulk mineralogy (Rod Parnell, professor, and Travis Loseke, graduate student, Northern Arizona University, written commun., 2002)[1]
Mohawk Canyon Spring	719	0.70824	–5.1	---	
Dogtown Well No. 1	1,748-1,745	0.70826	–1.9	Kaibab Formation, Fossil Mountain Member	Quartz (69%), calcite (11%), k-feldspar (15%), clays-kaolinite (5%)
Grand Canyon—Bright Angel Trail	1,954	0.70829	–1.8	Toroweap Formation	Dolomite (55%), calcite (32%), quartz (11%), clays-kaolinite (2%)
Rodeo Grounds Well	1,834-1,830	0.70832	–1.0	Toroweap Formation	Quartz (43%), k-feldspar (13%), calcite (23%), dolomite (6%), clays-kaolinite (12%)
Rodeo Grounds Well	1,181-1,178	0.70833	–4.7	Supai Group, Lower Supai Formation	na
Rodeo Grounds Well	1,169-1,166	0.70842	–4.7	Redwall Limestone	na
Dogtown Well No. 1	1,138-1,135	0.70850	–1.2	Redwall Limestone	Dolomite (91%), quartz (9%)
Dogtown Well No. 1	1,210-1,207	0.70851	–5.0	Redwall Limestone	Calcite (91%), quartz (7%), clays-kaolinite (2%)
Rodeo Grounds Well	1,446-1,443	0.70860	–0.6	Supai Group, Upper Supai Formation	na
Grand Canyon—Bright Angel Trail	1,615	0.70871	–3.9	Supai Group	Calcite (68%), quartz (24%), k-feldspar (3%) clays-illite (5%)
Dogtown Well No. 1	1,080-1,077	0.70872	–0.8	Redwall Limestone	Dolomite (89%), calcite (8%), quartz (3%)
Grand Canyon—Bright Angel Trail	1,550	0.70877	–0.8	Supai Group, Watahamogi Member	Calcite (72%), quartz (19%), k-feldspar (5%), clays-illite (4%)
Rodeo Grounds Well	1,257-1,254	0.70877	–3.9	Supai Group, Lower Supai Formation	na
Grand Canyon—Bright Angel Trail	855	0.70879	–1.3	Temple Butte Formation	Dolomite (100%)
Dogtown Well No. 1	1,108-1,105	0.70880	–2.1	Redwall Limestone	Dolomite (81%), calcite (12%), quartz (7%)
LM-9	2,256	0.70882	–9.0	---	
Rodeo Grounds Well	1,553-1,550	0.70887	na	Schnebly Hill Formation	Fine to very fine red sandstone
Boucher Spring	1,165	0.70892	–6.6	---	
Big Chino Springs Limestone	na	0.70892	na	na	na
Forster Spring No. 2	850	0.70901	–4.6	---	
Grand Canyon—Bright Angel Trail	1,431	0.70902	0.0	Redwall Limestone, Mooney Falls Member	Dolomite (97%), calcite (3%)
Rodeo Grounds Well	1,004-1,001	0.70902	–1.4	Redwall Limestone	na
Rodeo Grounds Well	971-968	0.70902	–2.6	Tapeats Sandstone	na
Dogtown Well No. 1	1,687-1,684	0.70902	na	Coconino Sandstone	na
Dogtown Well No. 1	1,260-1,257	0.70905	–3.5	Supai Group, Lower Supai Formation	Quartz (79%), calcite (10%), k-feldspar (8%), clays-lllite (3%)
Spring Seep carbonate	na	0.70907	na	---	
Dogtown Well No. 1	1,382-1,279	0.70908	–2.8	Supai Group, Esplanade Sandstone	Quartz (43%), dolomite (33%), calcite (11%), k-feldspar (6%), clays-illite (7%)
Rodeo Grounds Well	1,370-1,367	0.70909	–3.0	Supai Group, Upper Supai Formation	na
Turquoise Creek	1,048	0.70914	–10.7	---	
Grand Canyon—Bright Angel Trail	2,031	0.70918	–0.5	Kaibab Formation, middle member	Quartz (62%), calcite (19%), dolomite (10%), k-feldspar (7%), clays-kaolinite (1%)
Drake Well	na	0.70920	na	---	
Dogtown Well No. 1	1,321-1,318	0.70930	–2.1	Supai Group, Middle Supai Formation	Calcite (40%), quartz (39%), dolomite (13%), k-feldspar (6%), clays-illite (2%)
Blue Spring	984	0.70932	–2.4	---	
Dogtown Well No. 1	1,526-1,522	0.70932	–1.2	Schnebly Hill Formation	na

See footnote at end of table.

Table 8. Strontium and carbon-13 isotope data and X-ray diffraction mineralogy for selected water and rock samples representing the major stratigraphic units on the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona—Continued.

Sample site	Altitude of land surface, meters	$^{87}Sr/^{86}Sr$	$\delta^{13}C$, per mil	Rock name	Bulk mineralogy (Rod Parnell, professor, and Travis Loseke, graduate student, Northern Arizona University, written commun., 2002)[1]
Grand Canyon—Bright Angel Trail	1,339	0.70954	–0.3	Redwall Limestone, Whitmore Wash Member	Dolomite (77%), calcite (23%)
Grand Canyon—Bright Angel Trail	825	0.71018	–1.1	Bright Angel Shale	Dolomite (52%), quartz (19%), k-feldspar (11%), clays-illite (18%)
Ash Fork Well No. 1	1,677	0.71027	–6.8	---	
Grand Canyon—Bright Angel Trail	1,750	0.71035	–1.7	Supai Group, Esplanade Sandstone	Quartz (66%), dolomite (19%), clays-kaolinite (15%)
Rodeo Grounds Well	2,210	0.71049	–3.2	---	
Monument Spring	1,417	0.71070	–8.2	---	
Grand Canyon—Bright Angel Trail	1,724	0.71083	–3.8	Supai Group, Wescogame Member	Quartz (82%), clays-kaolinite (18%)
Boucher East Spring	1,020	0.71104	–6.7	---	
Grand Canyon—Bright Angel Trail	1,860	0.71122	na	Coconino Sandstone, lower	Quartz (63%), k-feldspar (31%), clays-kaolinite (6%)
Grapevine Main Spring	1,542	0.71140	–8.1	---	
Hawaii Spring	1,089	0.71152	–7.6	---	
Red Canyon Spring	1,437	0.71164	–8.6	---	
Grand Canyon—Bright Angel Trail	1,934	0.71173	na	Coconino Sandstone, upper	Quartz (97%), clays-kaolinite (3%)
Pumphouse Spring	1,286	0.71190	–9.3	---	
Miners Spring	1,424	0.71196	–7.7	---	
Grand Canyon—Bright Angel Trail	1,800	0.71216	–2.3	Hermit Formation	Quartz (43%), dolomite (22%), clays-illite (35%)
Salt Creek Spring	1,299	0.71248	–6.3	---	
JT Spring	1,430	0.71250	–8.1	---	
Cottonwood Creek No. 2	1,375	0.71264	–10.0	---	
Lonetree Spring	1,404	0.71327	–10.8	---	
Cottonwood Creek No. 1	1,276	0.71374	–13.1	---	
Serpentine Spring	1,112	0.71385	–6.9	---	
Burro Spring	1,217	0.71435	–9.8	---	
Pipe Creek	1,245	0.71440	–10.3	---	
Grapevine East Spring	1,198	0.71514	–11.1	---	
Surprise Spring granite	na	0.71618	na	---	na
Cabin Spring schist	na	0.72092	na	---	na
Aspen Creek granite	na	0.76912	na	---	na

[1]Rock samples were leached for 24 hours in 0.1N Hydrochloric Acid.

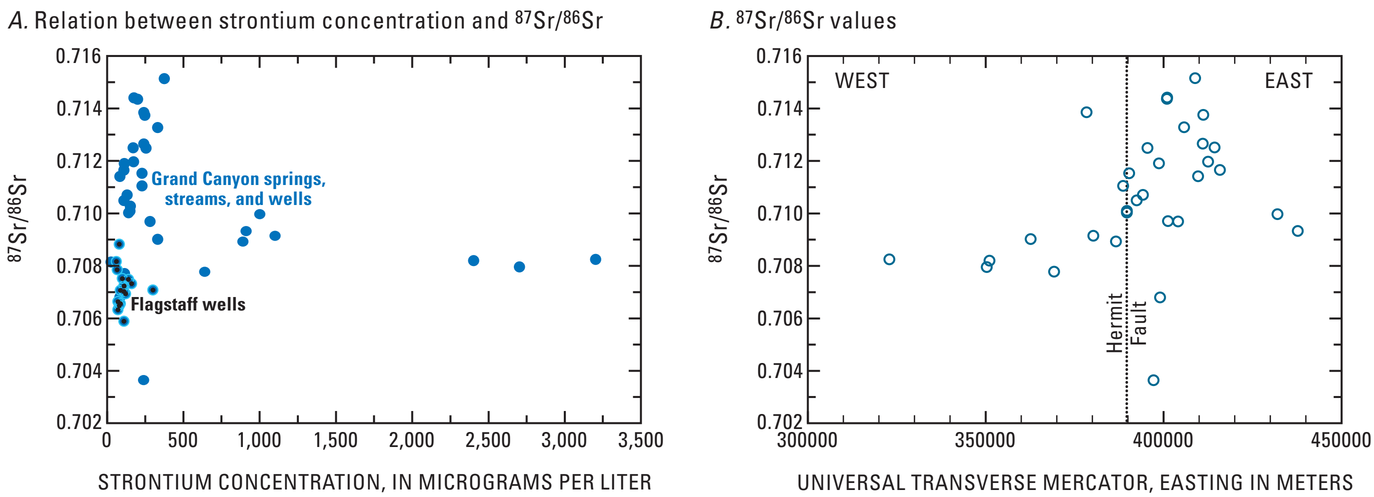

Figure 16. Strontium isotope values for water, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona 2000–2003: *A*, Relation between strontium concentrations and $^{87}Sr/^{86}Sr$ in water from wells near Flagstaff and springs, streams, and wells near Grand Canyon; *B*, $^{87}Sr/^{86}Sr$ values in relation to spring or stream locations near the south rim of Grand Canyon.

Water in Horn Creek on the south rim of Grand Canyon had a value of 0.70363; however, none of the rocks sampled from the nearby Bright Angel Fault had a similar value. Values for well cuttings of basalt from the Rodeo Grounds Well near Williams were similar to those for Horn Creek and could indicate interactions between ground water and basalt.

^{14}C activities for water samples ranged from 1.4 percent modern carbon (pmc) at Rodeo Grounds Well in Williams to 103.4 pmc at Grapevine East Spring near the south rim of Grand Canyon. Values generally were between about 40 and 75 pmc for sites on the Coconino Plateau study area (see “Supplemental Data”). Wells and larger springs, such as Blue Spring and Havasu Spring, which discharge from the Redwall-Muav aquifer, generally had lower ^{14}C activity (3.2 to 20.2 pmc; average 9 pmc) than did smaller springs (13.3 to 103.4 pmc; average 55 pmc; see “Supplemental Data”) that discharge from the same aquifer. Wells and springs that discharge from the C aquifer near Flagstaff generally have higher ^{14}C activities (18.7 to 113.1 pmc; average 54 pmc; Bills and others, 2000) than wells discharging from the Redwall-Muav aquifer (1.4 to 103.4 pmc; average 35 pmc; see “Supplemental Data”.

Ground-water residence times for water discharging from the Redwall-Muav aquifer range from modern to 22,600 yr (fig. 17; pl. 4; see “Supplemental Data”). Organic carbon sources that are not accounted for in ground-water flow paths can result in a ^{14}C value that is biased toward a shorter residence time. Water-rock interaction in carbonate rock can cause a change of about 60 percent in pmc from the original recharged water (Mazor, 2004). Carbon isotope analysis (^{13}C) of water and rock samples (table 8) were used to correct ^{14}C results for ground-water residence times for these biases by a combination of Stuiver and Polach (1977) conventional radiocarbon-age method and Pearson and Hanshaw’s (1970) dilution equation. ^{14}C activities close to or higher than 100 pmc indicate the presence of predominantly post-bomb radiogenic carbon in ground water (Clark and Fritz, 1997). Estimated ground-water residence times for C aquifer wells in the Flagstaff area ranged from modern to 7,000 yr (Bills and others, 2000). Estimates for wells developed in the Redwall-Muav aquifer range from 7,500 to 22,600 yr. These residence times were significantly longer than those for spring water that discharges from the Redwall-Muav aquifer (modern to 11,300 yr).

Water samples were collected for tritium analysis during more than one site visit at most sites. Tritium values less than about 0.5 TU indicate that ground water at the site did not contain post-bomb (after 1952) water at the time samples were collected. Tritium values for water samples from springs and stream sites that are discharge points for the Redwall-Muav aquifer in the study area ranged from less than 0.3 TU (detection limit) to about 2.7 TU, and averaged 0.9 TU (fig. 17; see “Supplemental Data”). Wells developed into the Redwall-Muav aquifer had values that ranged from less than 0.3 TU to 0.6 TU. Tritium values for ground-water discharge sites near the south rim of Grand Canyon and near the Verde River generally were similar. Wells and springs that discharge ground water from perched aquifers and wells and springs that yield water from the C aquifer near Flagstaff had tritium values that ranged from 0.31 to 10.3 TU (Bills and others, 2000). Values for the perched aquifer wells and springs ranged from less than 0.3 TU to 10.3 TU and averaged 6.3 TU. The average value for the C aquifer wells and springs near Flagstaff was 2.8 TU.

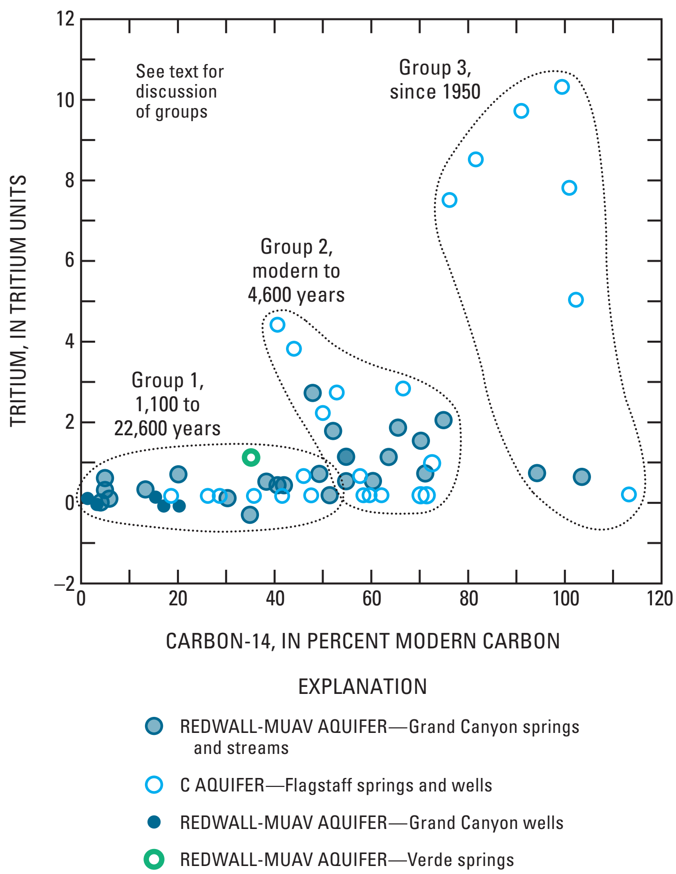

Figure 17. Relation between tritium and carbon-14 in water from springs, streams, and wells that are discharge points for the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2003.

Three age groups were identified on the basis of tritium and ^{14}C data (fig. 17). Sites in group 1 had tritium values less than 0.5 TU, ^{14}C activities less than about 50 pmc, and estimated ground-water residence times that ranged from 1,100 to 22,600 yr. Sites in this group include wells developed in the Redwall-Muav aquifer and Blue Spring, Little Colorado River Mile 3.1, Pumphouse Spring, Salt Creek Spring, Monument Spring, Hermit Spring, Hawaii Spring, Matkatamiba Spring, Havasu Springs, Fern Spring, and Mohawk Canyon Spring (pl. 4 and fig. 17). These springs are in the lower Little Colorado River Canyon or are west of the Bright Angel Fault in Grand Canyon, and are associated with major structural features (pls. 1 and 4). The absence of tritium in these waters suggest that little, if any, recent recharge has reached this part of the regional ground-water flow system. However, some mixing of younger and older water is still likely to have occurred resulting in actual residence times longer than calculated from the ^{14}C data.

A second group had tritium values that ranged from 0.5 TU to about 4 TU and ^{14}C values that ranged from 40 pmc to 80 pmc. Estimated ground-water residence times for sites in this group range from modern to 4,600 yr. Sites in this group include wells developed in the C aquifer in the Flagstaff area and Havasupai well No. 1, JT Spring, Red Canyon Spring, Miners Spring, Cottonwood Creek No. 2, Grapevine Main Spring, Lonetree Spring, Burro Spring, Pipe Creek, Horn Creek, Salt Creek Spring, Boucher Spring, Turquoise Creek, Serpentine Spring, and Royal Arch Spring (pls. 2 and 4; see “Supplemental Data”). The presence of tritium in these waters indicates that a component of recent recharge (post 1952) is present. For mixtures of young and old water such as this, the actual residence time is longer than the calculated residence time (Mazor, 2004).

The third age group (fig. 17) is composed of sites where water has tritium values generally greater than 4.0 TU or ^{14}C activities generally greater than 80 pmc. This group includes wells and springs that discharge from the C aquifer in the Flagstaff area, wells and springs that discharge from perched aquifers, and Cottonwood Creek No. 1 and Grapevine East Spring in Grand Canyon (pl. 4; see “Supplemental Data”). These data are indicative of ground water that has received recharge since 1952.

Conceptual Model of the Ground-Water Flow Systems

Available hydrogeologic data, information, and interpretations were used to develop an integrated conceptual model for the ground-water flow systems in the study area. Discussion of the flow-systems components includes a description of the boundaries of the regional and local systems, and the source, occurrence, and movement of ground water in the flow systems.

Regional and Local Flow-System Boundaries

Ground-water flow systems can have physical and hydraulic boundaries. Physical boundaries are those resulting from changes in lithology or configuration of rock units. Hydraulic boundaries are those resulting from the configuration of the potentiometric surface. Typically, hydraulic boundaries are defined by specified-flow or hydraulic-head conditions. The upper boundary of a flow system typically is a hydraulic boundary represented by the potentiometric surface or the water table. The lower boundary typically is a physical boundary represented by a lower confining layer. The horizontal limits of a ground-water flow system can be physical, hydraulic, or both. Flow conditions exist where water-level gradients permit horizontal or vertical flow through fractures, faults, or more permeable rock. No-flow conditions or boundaries exist where the physical properties of the rocks or sediments prevent flow or cause a divergence of the ground-water flow path. This can happen where a water-bearing zone terminates at the erosional or depositional limits of a rock unit or where faults offset virtually impermeable rock against permeable rock. Ground-water divides are also boundaries where a high in the potentiometric surface or water table causes ground water to diverge in opposite directions.

The regional boundaries for the Coconino Plateau study area ground-water flow systems are a combination of physical and hydraulic boundaries derived from the geology, stratigraphy, and regional characteristics of the C aquifer and the Redwall-Muav aquifer. Most of the regional boundaries are the result of either large erosion escarpments or regional faults that interrupt the flow of ground water in the aquifers. The principal physical boundaries include (1) the Colorado River in the northern part of the study area where an erosion escarpment of more than 6,000 ft has truncated all the sedimentary rock units of the aquifers, (2) the Aubrey Cliffs in the western part of the study area where sedimentary rocks of the aquifers have been uplifted to the east by more than 500 ft and tilted eastward, and (3) the Mogollon Rim in the southern part of the study area where erosion and faulting has resulted in an escarpment of more than 2,000 ft that truncates most of the sedimentary rocks of the C aquifer and has uplifted the remaining rocks above the regional potentiometric surface (pl. 1). The eastern boundary of the conceptual model of study area ground-water flow systems is a constant-head flow boundary coincident with the monoclines that define the western edge of Black Mesa Basin where sedimentary rocks of the C aquifer and the Redwall-Muav aquifer dip steeply to the east. The southeastern boundary of the conceptual model is a combination of specified-flow conditions defined by the deeply incised West Clear Creek drainage and divergent ground-water flow paths of the Little Colorado River Basin (pls. 1 and 3). The southwestern boundary of the study area ground-water flow systems is a constant-head boundary coincident with the eastern edge of Big Chino Wash (pl. 2). Here, ground water in the Redwall-Muav aquifer probably migrates laterally from Coconino Plateau and Big Black Mesa into unconsolidated sediments of Big Chino Wash and the upper Verde Valley. The lower boundary of the Coconino Plateau study area ground-water flow systems is a physical boundary defined by the erosion surface of basement Proterozoic rocks underlying the study area (pl. 1). These basement rocks are virtually impermeable granitic and metamorphic rocks that transmit water only where they are faulted and fractured.

Several local boundaries within the Coconino Plateau study area ground-water flow systems are defined by both physical and hydraulic properties of the C aquifer and the Redwall-Muav aquifer. The C aquifer is unconfined in the study area and its water table defines the upper boundary of the study area ground-water flow system in the eastern half of the study area (pl. 3). The Redwall-Muav aquifer is predominantly a confined aquifer that occurs throughout the study area and has a potentiometric surface that generally is below the water table of the C aquifer in the eastern part of the study area. Because the C aquifer is unsaturated in the western and northern parts of the study area, the potentiometric surface of the Redwall-Muav aquifer defines the upper boundary of the Coconino Plateau study area ground-water flow system in these areas (pl. 3). The C aquifer and the Redwall-Muav aquifer are separated by the relatively impermeable Lower Supai Formation, which occurs throughout the study area and varies in thickness from 100 ft to several hundred feet (pl. 1). Ground water is not easily transmitted through this confining layer except where the unit is faulted or fractured.

The Mesa Butte Fault System in the central part of the study area is a physical boundary that influences ground-water flow on the Coconino Plateau study area. The Mesa Butte Fault and intersecting monoclines have raised the sedimentary rocks on the interior part of the Coconino Plateau from several hundred to more than 1,000 ft above corresponding rocks in adjacent parts of the plateau, providing both a barrier to ground-water flow in the east-west direction and a conduit to ground-water flow in the northeast-southwest direction (pl. 1).

Source, Occurrence, and Movement of Ground Water in the Flow Systems

The Coconino Plateau study area ground-water flow systems can be divided into three subbasins on the basis of the source, occurrence, and movement of ground water: (1) the Havasu/Cataract Creek subbasin, (2) the Little Colorado River subbasin, and (3) the Verde subbasin (pl. 3). These subbasins contain ground-water flow systems that have defined flow paths interconnected by hydraulic and physical conditions of the regional flow system.

The Havasu/Cataract subbasin has regional physical boundaries on its northern and western margins, and shares hydraulic and physical boundaries and characteristics with the Verde subbasin and the Little Colorado River subbasin. The physical boundaries discussed earlier are the erosion escarpment of the south rim of Grand Canyon, the Aubrey Cliffs, and the Mesa Butte Fault (pl. 1). The shared hydraulic boundaries are ground-water divides that affect the occurrence and flow of water in the subbasins (pl. 3). The source of water for the Havasu/Cataract subbasin is precipitation that falls on exposed sedimentary rocks of the Coconino Plateau and in higher altitudes of the San Francisco and Mount Floyd Volcanic Fields, the south rim of Grand Canyon, and the Mogollon Rim.

The Little Colorado River subbasin has a regional hydraulic boundary on its eastern margin and shares hydraulic and physical boundaries with the Havasu/Cataract subbasin and the Verde subbasin. The regional hydraulic boundary is a constant-flow boundary defined by steeply dipping monoclines on the eastern edge of the study area. The Mesa Butte Fault prevents east-west migration of water between most of the Little Colorado River and Havasu/Cataract subbasins and concentrates flow along its northeastern and southwestern sides. A ground-water divide coincident with the Mogollon Rim represents the shared hydraulic boundary among the three subbasins (pl. 3).

The Verde subbasin shares hydraulic boundaries with the Havasu/Cataract and Little Colorado River subbasins. Some of the precipitation that falls on outcrops of the sedimentary rocks of the Coconino Plateau and at higher altitudes of the San Francisco and Mount Floyd Volcanic Fields and the Mogollon Rim reaches the ground-water system and flows southward into the upper and middle Verde Valley (pl. 3). The Mesa Butte Fault could be a barrier to east-west flow and a conduit for northeast-southwest flow in the Verde subbasin. The Verde Fault at the west end of Verde Valley, outside of the study area, is a physical barrier to ground-water flow westward, and the western edge of the Verde subbasin is defined by the constant-head boundary of the Verde River (pl. 1).

Horizontal and Vertical Flow Paths

Ground water in the Havasu/Cataract subbasin is derived from precipitation and runoff concentrated in unconsolidated alluvial channels and closed basins where water can most easily infiltrate into the subsurface and from precipitation at higher altitudes of the south rim of Grand Canyon, the Mogollon Rim, and the San Francisco and Mount Floyd Volcanic Fields (pl. 1). Water migrates vertically through pore spaces, fractures, and faults to the Lower Supai Formation where, in parts of the formation that do not contain fractures, it will reside temporarily as perched ground water. Water in these deep, perched zones migrates laterally along the regional slope to fractures that permit continued downward migration or to discharge zones on the south rim of Grand Canyon. Water that migrates downward through fractures can reach saturated conditions in the Redwall-Muav aquifer.

In the Redwall-Muav aquifer, ground water migrates vertically and laterally to discharge areas along the south rim of Grand Canyon from a local ground-water mound coincident with the rim (pl. 3). Several factors account for this mound centered on Tusayan. Land-surface altitudes in this area are highest between Grand Canyon’s south rim, Tusayan, and the rest of the Havasu/Cataract Creek basin causing more precipitation to fall locally. The extreme and rapid downcutting of the Colorado River have created a steep hydraulic gradient northward toward discharge areas on the south rim of Grand Canyon. The Vishnu Fault directly underlies the Tusayan area and enables rapid infiltration of water, which likely enhances the mound. In addition, at least two wastewater-treatment plants discharge water to drainages that are in direct contact with the Vishnu and Bright Angel Faults. For the remainder of the Havasu/Cataract Creek subbasin, ground water migrates laterally toward the interior of the subbasin from recharge areas along the south rim of Grand Canyon and from recharge areas associated with the San Francisco and Mount Floyd Volcanic Fields.

Some ground water in the Redwall-Muav aquifer also migrates into the adjacent Verde and Little Colorado River subbasins. From ground-water divides near Williams and Ash Fork, water migrates southward and southwestward into basin-fill deposits of Big Chino Valley and to discharge areas along the upper Verde River (pl. 3). A ground-water divide parallel to the Mogollon Rim could be present in the Redwall-Muav aquifer in the Little Colorado River subbasin, but additional data are needed for confirmation. Ground-water discharge areas north and south of Flagstaff, the Mesa Butte Fault, and data from a test well drilled into the Redwall-Muav aquifer near Flagstaff are indicative of a divide in this area (pl. 3). Little information is available on ground-water flow in the Redwall-Muav aquifer in this part of the study area.

Ground water in the Little Colorado River subbasin is derived from precipitation at high altitude areas of the Mogollon Rim, on the San Francisco Volcanic Field, and as underflow from the Little Colorado River Basin (pl. 3 and fig. 3). Water migrates vertically through permeable rocks in recharge areas and through a series of shallow perched zones in volcanic rocks and alluvial material until it reaches the C aquifer. In the C aquifer, ground water migrates laterally and vertically to discharge areas along the Little Colorado River and to discharge areas along channels that drain into the Verde Valley (pl. 3). As ground water migrates laterally toward the Little Colorado River, it encounters fractures and faults that allow it to migrate deeper into the subsurface. Northwest of Cameron, rock units of the C aquifer are unsaturated owing to folds and faults that have uplifted these units above the water table, and fractures that allow the ground water to migrate into the underlying limestone rocks of the Redwall-Muav aquifer (pl. 3). Ground water migrates laterally and vertically through the Redwall-Muav aquifer to reach the regional discharge area along the Little Colorado River near and below Blue Spring. Here, ground water derived from recharge areas in the Little Colorado River subbasin mixes with ground water migrating westward across the eastern boundary between the Coconino Plateau study area and the Little Colorado River Basin. The total amount of water discharged to the lower Little Colorado River from the Coconino Plateau study area is largely unknown owing to uncertainties in the flow rates of springs and differences in water chemistry of springs (Cooley and others, 1969; McGavock and others, 1986; Loughlin, 1983; Hart and others, 2002).

Ground water in the Verde subbasin of the Coconino Plateau study area is derived from precipitation at high altitude areas of the Mogollon Rim and on the San Francisco and Mount Floyd Volcanic Fields (pl. 3 and fig. 3). In the southwestern part of the subbasin, most of the overlying sedimentary rocks that constitute the C aquifer have been removed by erosion, and thus volcanic rocks of the San Francisco and Mount Floyd Volcanic Fields and unconsolidated sediments are in direct contact with limestones of the Redwall-Muav aquifer. Ground water migrates vertically through these permeable rocks into the underlying Redwall-Muav aquifer where it migrates vertically and laterally to discharge areas in Big Chino Valley and the upper reaches of the Verde River. In the southeastern part of the Verde subbasin, ground water migrates vertically from recharge areas of the San Francisco Volcanic Field and the Mogollon Rim into the C aquifer. In the C aquifer, ground-water migrates laterally and vertically to springs in drainages incised into the Mogollon Rim at Sycamore Canyon, Oak Creek, Beaver Creek (pl. 2), and West Clear Creek (outside the study area). The occurrence and orientation of these drainages are controlled in part by fractures and faults, which enable migration of ground water from the C aquifer into the Redwall-Muav aquifer. Ground water in the Redwall-Muav aquifer in the southeastern part of the Verde subbasin migrates laterally into Verde Valley where it either discharges at large regional springs, such as Page Springs, or flows laterally into the permeable Verde Formation.

Effluent Recharge

Treated effluent from wastewater-treatment plants has been a potential source of recharge to ground-water flow systems on the Coconino Plateau study area since about the mid-1980s. The main areas where treated effluent can infiltrate into ground-water flow systems are Flagstaff, Tusayan, Cameron, Leupp, Winslow, Williams, Ash Fork, Seligman, the village of Supai, and Moenkopi Wash (pl. 2).

The city of Flagstaff has monitored its effluent discharge since construction of the Wildcat Treatment plant in the early 1980s. The city currently has two wastewater-treatment plants, Wildcat and Rio de Flag, with a combined annual effluent flow of 6,701 acre-ft (Flagstaff Utility Department, 2004). In 2003, the city of Flagstaff reused 2,655 acre-ft of this effluent as irrigation at schools, parks, golf courses, and Northern Arizona University (Flagstaff Utility Department, 2004). The remaining 3,966 acre-ft was discharged to the Rio de Flag where fractures and faults provide ideal pathways for infiltration to the C aquifer. The quantity of water that reaches the aquifer is unknown; however, recent water-chemistry data collected by the USGS and the city of Flagstaff indicate that the recharge is occurring (Margot Truini, hydrologist, U.S. Geological Survey, written commun., 2003).

The communities of Grand Canyon Village and Tusayan (fig. 1) received their water supply entirely from the north rim of Grand Canyon outside the study area until the early 1990s when deep wells were drilled in the Tusayan area to supplement the supply. Because of the scarcity of water and the difficulty in developing ground-water supplies at the south rim, Grand Canyon Village and Tusayan have developed state-of-the-art recycling and reuse programs for their effluent. Despite these aggressive reuse programs, some of the effluent is discharged to the environment and is available as a source of ground-water recharge locally along the south rim of Grand Canyon.

Currently, Grand Canyon Village has two wastewater-treatment plants with an annual effluent flow of 393 acre-ft. In 2003, the village reused 126 acre-ft of this effluent for irrigation in Grand Canyon National Park (Steve Homan, Grand Canyon National Park, written commun., 2004). The remaining 267 acre-ft was discharged to Bright Angel Wash where fractures and faults provide pathways for infiltration to water-bearing zones that discharge along the south rim. Although it is not known how much of this effluent recharges the water-bearing zones, water-chemistry data for the south rim springs suggest the influence of effluent contributions (Monroe and others, 2005).

The community of Tusayan, just south of Grand Canyon Village, has one wastewater-treatment plant with an annual effluent flow of 68 acre-ft. In 2003, Tusayan reused 30 to 50 percent of this effluent for irrigation in the community and for secondary gray-water systems (Bob Petzoldt, Tusayan Wastewater-Treatment Plant, oral commun., 2004). The remaining effluent was discharged to Coconino Wash (pl. 2) where fractures and faults provide pathways for infiltration to water-bearing zones that discharge to the Havasu/Cataract subbasin. It is not known how much of this effluent recharges the water-bearing zones that discharge at springs west of Tusayan along the south rim or at Havasu Spring.

Cameron and Leupp are the two largest communities on the Navajo Indian Reservation near the eastern boundary of the study area. These communities are upstream from ground-water flow paths that converge on the lower Little Colorado River in the Blue Spring area and have wastewater-treatment systems that consist of partial water treatment and the use of evaporation or spreading ponds for the effluent. Although most of the effluent is lost through evaporation, an unknown but likely small amount infiltrates beneath the ponds or flows through the outlets when the ponds are filled beyond capacity.

The wastewater-treatment plant for the city of Winslow, which is about 25 mi southeast of Leupp outside the study area, produces about 1,300 acre-ft of effluent annually. Some of the effluent is used to irrigate farms in the Winslow area, and the remainder is discharged to the Little Colorado River (Alan Rosenbaum, city of Winslow Utilities, oral commun., 2004). The amount of effluent lost to evapotranspiration and infiltration at the Little Colorado River is unknown.

The city of Williams discharges all its treated effluent to evaporation ponds south of the city along Cataract Creek. Williams produced about 140 acre-ft of effluent in 2003 (Ron Stillwell, city of Williams, oral commun., 2004). Most of the effluent produced each year is used for irrigating a golf course during the summer. During the rest of the year, effluent beyond the capacity of the evaporation ponds is discharged to Cataract Creek. Of this portion, the amount lost to evapotranspiration and infiltration is unknown.

Ash Fork, Seligman, and the village of Supai in the west-central and northwestern parts of the study area also produce significant amounts of treated effluent. These communities discharge their treated effluent to evaporation ponds and little is discharged directly to the environment. The amount of effluent that seeps into sediments below the ponds is unknown but likely is small.

Perennial flow in Moenkopi Wash, which enters the study area north of Cameron (pl. 2), is supported by effluent discharge from the Navajo and Hopi communities of Tuba City, Moencopi, and Moenkopi northeast of Cameron outside the study area. One plant treats wastewater from the three communities; about 13,500 acre-ft of treated effluent is discharged to Moenkopi Wash each year (Chester Whiterock, Tuba City, oral commun., 2004). The wash is dry where it joins the Little Colorado River. The amount of effluent lost to evapotranspiration and infiltration is unknown.

Relation of Hydrologic Flow Components

Ground-water flow systems on the Coconino Plateau study area are connected hydraulically to some stream reaches along the south rim of Grand Canyon, to the lower Little Colorado River, to Havasu Creek, and to some streams that flow southward into Verde Valley and to the upper part of the Verde River (pl. 2). The interaction of ground water and surface water at these stream reaches is controlled by the physical properties of the rock units and sediments that make up the stream channels and (or) the aquifer properties.

Short reaches of several streams on the south rim of Grand Canyon have perennial flow because of ground-water discharge where the stream channels intersect rock units of the Redwall-Muav aquifer (pl. 2 and table 2). Most of the flow in these channels is discharge from small springs and seeps in the lower rock units of the Redwall-Muav aquifer. A few of these streams—Olo, Matkatamiba, Royal Arch, Monument, Hermit, and Pipe Creeks (pl. 2)—have sufficient volumes of water to sustain perennial flow to their respective mouths at the Colorado River (table 2).

The lower reach of the Little Colorado River and Havasu Creek below Havasu Spring are the main regional discharge areas for ground-water flow systems in the northern part of the Coconino Plateau study area (pl. 2). The lower Little Colorado River is perennial because large-volume springs, controlled by normal faults, discharge from the Redwall-Muav aquifer in this reach (pl. 2 and table 3). Cooley (1976) suggests that most of the water that discharges at springs in the lower Little Colorado River originates in the Black Mesa area, east of the study area for this report, whereas Loughlin (1983) suggests that as much as 75 percent of the water originates at the volcanic field of San Francisco Mountain. Hart and others (2002) suggest that most of the water is derived from downward movement of ground water from the C aquifer into the "Redwall-Muav Limestone" aquifer in the greater Little Colorado River Basin. Although available data are not sufficient for quantifying contributions from individual sources, the movement of water from the C aquifer into the Redwall-Muav aquifer upstream from the lower part of the Little Colorado River as a result of geologic structure has been postulated by several investigators (Metzger, 1961; Cooley, 1976; Appel and Bills, 1981; Loughlin, 1983; McGavock and others, 1986; and Hart and others, 2002).

Havasu Creek also is perennial because of spring flow from the Redwall and Muav Limestones. Spring flow in the creek is controlled by normal faults and deep incision of the creek channel. A fault and parallel fractures in the Lower Supai Formation are visible in the canyon walls adjacent to the channel where Havasu Spring is located. Ground water in the Redwall-Muav aquifer rises under hydraulic pressure through faults and fractures in the Lower Supai Formation and through the stream-channel alluvium to discharge at Havasu Spring. Additional spring discharge along the channel and upwelling in the channel from the Redwall-Muav aquifer contribute to flow in Havasu Creek downstream from Havasu Spring (U.S. Geological Survey, unpublished data, 1995).

Sycamore Creek, Oak Creek, and Beaver Creek are the largest drainages in the study area that flow southward from the Mogollon Rim into Verde Valley and are incised deeply enough to intersect ground-water flow in the C aquifer (Twenter and Metzger, 1963; Levings, 1980; and Owen-Joyce and Bell, 1983). The location and orientation of these drainages also are at least partially controlled by faults (pl. 1), which together with associated fractures, provide pathways for the downward movement of ground water from the C aquifer to the Redwall-Muav aquifer where it then flows laterally into the ground-water flow systems of Verde Valley. Along the upper reaches of the Verde River, upstream from Sycamore Creek, ground water discharges directly from the Redwall-Muav aquifer through fractures that have been widened by solution. The base flow of the Verde River increases by more than 300 percent from Perkinsville to Sycamore Creek in this area (Woodhouse and others, 2000).

Water Budgets

Steady-state and transient water budgets were developed for the study area to estimate the amounts of water entering and leaving the area. Separate budgets were developed for the watershed and the ground-water system (tables 9 and 10; fig. 18). The steady-state budgets represent conditions assumed to be present before large-scale ground-water development began in 1975. The transient budgets were based on hydrologic conditions in 2002; however, these budgets are not considered representative of long-term or average conditions in the study area because precipitation during the 2002 water year was 50 percent or less of the average annual precipitation at most weather stations and ground-water withdrawals were significant (table 5 and fig. 10).

The basic form of any water-budget equation is

$$\Sigma i - \Sigma o \pm \Delta S = 0, \qquad (1)$$

where Σi is a summation of all the inflow components, Σo is a summation of all the outflow components, and ΔS is the change in storage—the net gain or loss from a flow system that results from changes in inflows and outflows. For steady-state conditions, inflows and outflows are assumed to be balanced and changes in storage are assumed to be zero. In the transient state, changes occur in inflow and (or) outflow that result in storage changes.

Table 9. Estimated steady-state water budget (pre-1975) for Coconino Plateau flow systems, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

	Annual flow, acre-feet	Potential error, percent	Potential error, acre-feet per year	Minimum, acre-feet per year	Maximum, acre-feet per year	Remarks
			Watershed budget			
Inflows to watershed						
Precipitation (*P*)	8,700,000	3.3	290,000	8,400,000	9,000,000	Estimate based on area weighted-average annual precipitation by using PRISM and DEM data, and station error as defined by the National Weather Service
Outflows (water leaving watershed)						
Natural recharge (*R*)	302,000	64.0	193,000	109,000	495,000	Estimated as a residual from the ground-water budget (below)
Runoff (R_o)	200,000	15.0	30,000	170,000	230,000	Gaged and ungaged estimates from area-runoff equations (Roeske, 1978; Hill and others, 1988)
Evapotranspiration from the watershed (ET_{ws})	8,198,000	65.0	5,330,000	2,870,000	13,530,000	Estimated as residual of the Watershed budget; error is component weighted
			Ground-water flow systems budget			
Inflows						
Natural recharge (*R*)	302,000	64.0	193,000	109,000	495,000	Estimated as a residual of the ground-water budget; error is component weighted
Underflow from the east (GW_u)	6,000	50.0	3,000	6,000	9,000	Flownet analysis at eastern boundary of study area
Total inflows	308,000	81.0	249,000	58,000	557,000	Error is component weighted
Outflows						
Ground-water discharge (GW_o)	300,000	8.0	24,000	276,000	324,000	Estimated based on ground-water discharge assuming steady state, from table 3
Evaporation from ground-water flow systems (ET_{GW})	8,000	40.0	3,200	4,800	11,200	Calculated from base-flow reduction and ET rates of significant plant species for riparian areas and springs. The practical maximum ET, based on average annual evaporation rates and riparian area is 15,500 acre-feet per year
Ground-water withdrawals (GW_w)	0					Assumed, based on table 4
Total outflows	308,000	50.0	154,000	154,000	462,000	Error is component weighted

Table 10. Estimated transient-state water budget (2002) for Coconino Plateau flow systems, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona.

	Annual flow, acre-feet	Potential error, percent	Potential error, acre-feet per year	Minimum, acre-feet per year	Maximum, acre-feet per year	Remarks
			Watershed budget			
Inflows to watershed						
Precipitation (*P*)	4,350,000	23.0	1,000,000	3,350,000	5,350,000	Estimate based on area-weighted 1/2 of average annual precipitation (precipitation in 2002 was 1/2 of the annual average owing to the drought)
Outflows (water leaving watershed)						
Natural recharge (*R*)	0					Assumed to be zero based on precipitation records and evapotranspiration
Runoff (R_o)	0					Gaged and ungaged estimates from area-runoff equations (Roeske, 1978; Hill and others, 1988)
Evapotranspiration from the watershed (ET_{ws})	4,350,000	23.0	1,000,000	3,350,000	5,350,000	1/2 of the residual from steady-state condition owing to drought conditions
			Ground-water flow systems budget			
Inflows						
Natural recharge (*R*)	0					Assumed to be zero based on precipitation records and evapotranspiration
Underflow from the east (GW_u)	6,000	50.0	3,000	3,000	9,000	Flownet analysis at eastern boundary of study area
Incidental recharge (*IR*)	9,000	5.0	450	8,550	9,450	Effluent from communities (Flagstaff, Williams, Tusayan, Cameron, Sedona, Ash Fork, and Seligman)
Storage loss (ΔS)	313,000	25.0	78,000	233,000	410,000	Residual of ground-water budget
Total inflows	328,000	56.0	184,000	144,000	512,000	
Outflows						
Ground-water discharge (GW_o)	300,000	8.0	24,000	276,000	324,000	Estimated based on ground-water discharge assuming steady state, from table 3
Evapotranspiration from ground-water flow systems (ET_{gw})	8,000	40.0	3,200	4,800	11,200	From table 9
Ground-water withdrawals (GW_w)	20,000	10.0	2,000	18,000	22,000	From table 5
Total outflows	328,000	42.0	138,000	190,000	466,000	Error is component weighted

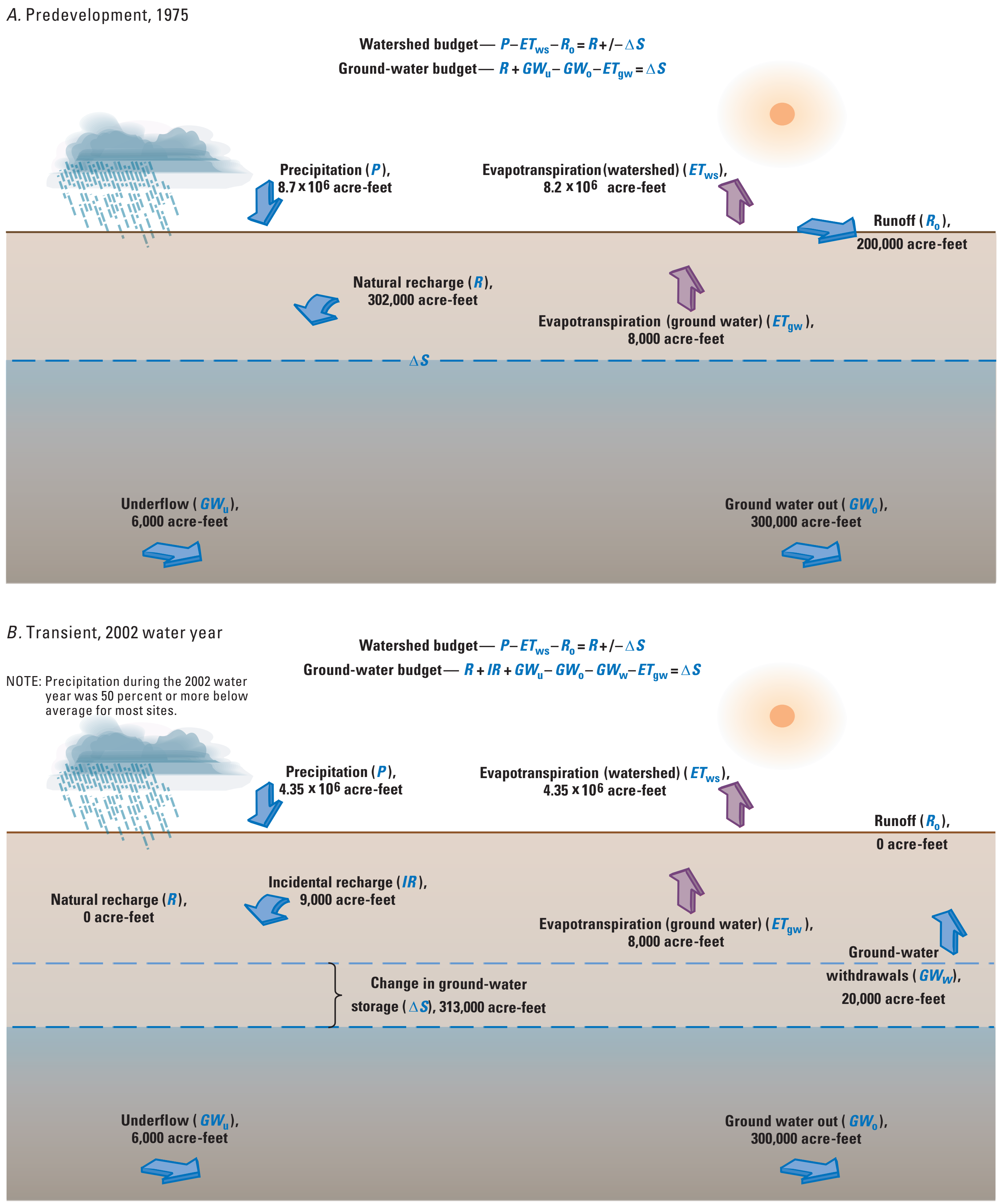

Figure 18. Schematic representation of water-budget components for the Coconino Plateau study area, Coconino and Yavapai Counties, Arizona: *A*, Predevelopment, pre-1975; *B*, transient, 2002 water year.

Changes to the inflow, outflow, and storage components can be either natural or anthropogenic. Natural changes in a flow system occur in response to climate variability or other environmental factors such as catastrophic floods or fire that can change the physical characteristics of the flow system. Anthropogenic changes to flow systems can occur as the result of engineered diversions from the flow system, alteration of vegetation and land cover, or other man-caused physical changes to the drainages.

For the steady-state and transient watershed budgets, the inflow component is precipitation and the outflow components are runoff, natural ground-water recharge, and evapotranspiration (ET). The equation for the watershed budgets is

$$P - ET_{ws} - R_o = R \pm \Delta S, \qquad (2)$$

where

P = precipitation in the study area,
ET_{ws} = evapotranspiration from the watershed,
R_o = runoff,
R = natural recharge to the ground-water systems, and
ΔS = change in storage.

Precipitation, P, was obtained by summing the area-weighted PRISM data (Spatial Climate Analysis Service, 2001). Runoff, R_o, was derived from streamflow-gaging station data and estimates from area-runoff equations for ungaged channels (Roeske, 1978; Hill and others, 1988). Natural ground-water recharge, R, was assumed to be the sum of spring discharge and base flow to streams (table 3). Evapotranspiration, ET_{ws}, was calculated as a residual value from the budget calculation.

Component values for the steady-state watershed budget were primarily based on pre-1975 data; however, more recent data were used for areas in which earlier data were nonexistent and steady-state conditions were assumed to prevail (table 9; fig. 18A). The estimated precipitation value for the steady-state period is 8,700,000 acre-ft/yr. This value was calculated on the basis of area-weighted PRISM data as previously described. The runoff value of 200,000 acre-ft/yr was calculated by hydrographic separation of gaging-station data. Calculated runoff for periods after 1975 was used for some stations (Havasu Creek, Little Colorado River near the mouth, and Oak Creek) where pre-1975 data were not available and runoff conditions were assumed to be unchanged since 1975. Estimated natural recharge to ground-water systems was 302,000 acre-ft/yr. This value also required the use of post-1975 data where earlier data were not available and steady-state conditions were assumed to prevail. As a residual in the budget calculation, estimated ET was 8,200,000 acre-ft/yr. These results are consistent with earlier reports that indicated high ET rates for selected parts of the study area and runoff components that are among the smallest in the State (Blee, 1988; Hill and others, 1988; and Roeske, 1978).

Component values for the transient watershed budget were based on 2002 data (table 10; fig. 18B). The estimated precipitation value for the 2002 water year was 4,350,000 acre-ft/yr. Gaging-station data indicate that no runoff occurred during the water year. Estimated natural recharge also was assumed to be zero because (1) precipitation was less than half of the average annual, (2) on the basis of temperature data and other climate indicators, ET was the same or greater than the long-term average, and (3) most of the precipitation occurred during the summer when potential ET rates exceeded precipitation rates by a factor of two or more. As a residual in the budget calculation, estimated ET was 4,350,000 acre-ft/yr.

For the steady-state ground-water budget, inflow components are natural recharge and underflow, and outflow components are natural ground-water discharge and evapotranspiration. The equation for the steady-state ground-water budget is

$$R + GW_u - GW_o - ET_{gw} = \Delta S, \qquad (3)$$

where

R = natural recharge,
GW_u = underflow,
GW_o = natural ground-water discharge,
ET_{gw} = evapotranspiration from ground water, and
ΔS = change in storage.

Natural ground-water recharge, R, was calculated as the residual of the ground-water budget (table 9). Ground-water underflow, GW_u, is the amount of ground water that enters the study area along the eastern boundary. Natural ground-water discharge, GW_o, is the amount of water discharged at springs and to channels. Evapotranspiration, ET_{gw}, was estimated using three methods; (1) a maximum ET rate for ground water was estimated using average annual evaporation rates for the study area (fig. 3) and a calculation of riparian and free-water surface area, (2) by base-flow reduction for principal streams in the study area, and (3) by applying ET rates for prominent plant types in riparian and spring areas weighted by percent cover.

Component values for the steady-state ground-water budget were primarily based on pre-1975 data; however, more recent data were used for areas in which earlier data were nonexistent and steady-state conditions were assumed to prevail (table 9; fig. 18A). Estimated natural recharge of 302,000 acre-ft/yr was calculated as a residual of the steady-state ground-water budget. Underflow was estimated by using flownet analysis applied to a 32-mi length of the C aquifer along the eastern boundary of the study area—this is the only location where underflow occurs. Estimated underflow was about 6,000 acre-ft/yr on the basis of a cross-sectional area of 3.6 mi^2, a hydraulic conductivity of 2.36 ft/d (Bills and Flynn, 2002), and a hydraulic gradient of 0.003 ft/ft (pl. 3). Estimated ground-water discharge of 300,000 acre-ft/yr was based in part on post-1975 data where earlier data were not available and steady-state conditions were assumed to prevail. Of this amount, about 223,000 acre-ft discharges at the northern boundary of the study area and about 77,000 acre-ft discharges at the southern boundary (table 3 and pl. 2). The calculated ET_{gw} for each of the three methods used were 15,500 acre-ft/yr, 6,560 acre-ft/yr, and 8,860 acre-ft/yr respectively. The first value, based on average annual evaporation and riparian area, represents a practical maximum value for the study area. The second two methods, base-flow reduction and ET rates from plants and estimated percent cover, are probably closer to the actual ET value for the study area and were averaged for a conservative estimate of about 8,000 acre-ft/yr.

The hydrologic system in the study area currently is in a transient condition owing to ground-water withdrawals from the C aquifer, the Redwall-Muav aquifer, and drought. Component values for the transient ground-water budget were based on 2002 data (table 10; fig. 18B). For the transient ground-water budget, inflow components are natural recharge, incidental recharge, and underflow, and outflow components are natural ground-water discharge, ground-water withdrawals, and evapotranspiration. The equation for the transient ground-water budget is

$$R + IR + GW_u - GW_o - GW_w - ET_{gw} = \Delta S, \qquad (4)$$

where

R = natural recharge,
IR = incidental recharge,
GW_u = underflow,
GW_o = natural ground-water discharge,
GW_w = ground-water withdrawals,
ET_{gw} = evapotranspiration from ground water, and
ΔS = change in storage.

Natural ground-water recharge, R, was assumed to be zero because (1) precipitation was less than half of the average annual for 2002, (2) on the basis of temperature data and other climate indicators, ET in 2002 was the same or greater than the long-term average, and (3) most of the precipitation in 2002 occurred during the summer when potential ET rates exceeded precipitation rates by a factor of two or more. The assumption of zero recharge is supported by the stable or declining water levels throughout the study area during 2002 (pl. 2). Incidental recharge, IR, is the amount of effluent from wastewater-treatment plants that recharges the ground-water system. In 2002, incidental recharge was 9,000 acre-ft. Estimated underflow, GW_u, was 6,000 acre-ft on the basis of a flow-net analysis. Natural ground-water discharge, GW_o, was 300,000 acre-ft in 2002. Natural ground-water discharge was based in part on post-1975 data where earlier data were not available and steady-state conditions were assumed to prevail. Ground-water withdrawals, GW_w, totaled 20,000 acre-ft in 2002 (table 5). Evapotranspiration, ET_{gw}, in 2002 was 8,000 acre-ft (table 9). Results of the transient water budget for the 2002 water year indicate a net loss in storage of about 313,000 acre-ft or a change in ground-water levels of –0.05 ft averaged over the entire study area (table 10 and fig. 18B). The net loss in storage does not occur evenly over the entire study area but is concentrated in areas of maximum water use or areas where aquifer characteristics allow ground-water flow systems to respond more rapidly to changes (pl. 2). Ground-water declines are greatest where the municipal demand for water is greatest in areas like Flagstaff. In other parts of the study area, changes in water levels either show no trend or declines of a few tens of feet or less. Declines in stream base flow are consistent with the continuing drought (fig. 6 and pl. 2). Smaller drainage basins respond more quickly to short-term changes in precipitation. Cottonwood Spring, at the south rim of Grand Canyon, had perennial flow in the late 1990s but is now intermittent as a result of the ongoing drought (pl. 2).

Considerations for Additional Data Collection and Monitoring

Ground-water development on the Coconino Plateau study area is increasing as the demand for water increases; however, gaps remain in hydrologic data sets that are used to quantify aquifer characteristics and water-budget components, and describe the occurrence and movement of ground water. These gaps make it difficult to predict with any degree of certainty the sustainability of the water supply for meeting natural or anthropogenic water demands. Ground-water data for the Redwall-Muav aquifer are sparse, and the local and regional aquifer characteristics remain largely unknown. Useful information that can be obtained during the drilling and development of new wells in the aquifer include (1) geologic data for stratigraphic correlations, (2) borehole logs for determining localized structural characteristics and the location of principal water-bearing zones, and (3) well and aquifer test data for determining aquifer characteristics. These data not only improve our overall understanding of the Redwall-Muav aquifer, they improve the success rate for developing additional wells.

The geologic structure in several parts of the Coconino Plateau study area has not been mapped in sufficient detail to improve the overall understanding of the geologic framework that partly controls the occurrence and movement of ground water. The geology of the Cameron 1:100,000-scale topographic map is currently being studied by the USGS as part of a cooperative program with the NPS (George Billingsley, geologist, U.S. Geological Survey, oral commun., 2004). Only the geology of the Williams 1:100,000-scale topographic map is needed to complete a detailed geologic framework for the Coconino Plateau study area. Interaction of the C aquifer and the Redwall-Muav aquifer is still poorly understood in much of the study area. Geophysical investigations in selected transition areas and areas heavily fractured by faulting should provide additional insight into where and how ground water is migrating vertically from the C aquifer to the Redwall-Muav aquifer. The continued collection of well and spring data and water-chemistry data will provide greater understanding of ground-water flow paths from recharge areas to discharge areas.

Many of the springs in the study area have been measured only once or twice since the 1950s, and some springs still have not been inventoried. Most of the large springs have been identified, and there are at least periodic flow measurements available for them, but these data do not provide enough information to determine flow trends. The sustainability of spring resources that support riparian habitat, which in some cases includes rare and endangered species, is a key concern as the result of continued growth and development in the study area. Continuous, or at least seasonal, monitoring of indicator springs would show when and how natural or anthropogenic stresses are affecting spring flows.

The potentiometric surface contours of the C aquifer and the Redwall-Muav aquifer on plate 3 are based on a combination of historical and recent data that do not represent current conditions. A comprehensive inventory of water levels in the C aquifer and Redwall-Muav aquifer completed within a short time span could be used to construct a map that is representative of the conditions during a single time period. Data from additional wells could be used to better characterize changes in ground-water storage in the aquifers and would be important in the development of interpretive or predictive ground-water models.

Summary and Conclusions

Recent growth and development on the Coconino Plateau study area and the attendant increases in demand for water have raised concerns about the effects of increased water use on the availability and sustainability of regional water supplies for riparian resources and human needs. Regional stakeholders agree that an improved understanding of the regional hydrogeologic system is needed to address these concerns. In order to develop a conceptual hydrogeologic framework for the study area, a comprehensive effort was needed to collect additional data, evaluate the data, and identify remaining data gaps.

The hydrogeologic framework of the Coconino Plateau study area consists of two regional ground-water-flow systems, the C aquifer and the Redwall-Muav aquifer. The C aquifer is contained in rock units of the Kaibab Formation, the Coconino Sandstone, the Schnebly Hill Formation, and the Upper and Middle Formations of the Supai Group. These rock units are hydraulically connected and function as a water-table aquifer in the eastern and central parts of the study area where they are fully to partly saturated. The Lower Supai Formation is a leaky confining layer between the C aquifer and the underlying Redwall-Muav aquifer. On a northeast-southwest trend through the middle of the study area, the C aquifer becomes dewatered as ground water migrates vertically through faults and fractures into the underlying Redwall-Muav aquifer near Cameron. Rock units of the C aquifer are largely dry in the western part of the study area except where water is perched 1,000 feet or more above the Redwall-Muav aquifer. Principal discharge areas of the C aquifer are in drainages that flow southward from the Mogollon Rim.

The Redwall-Muav aquifer is contained in rock units of the Redwall Limestone, the Temple Butte and (or) Martin Formation, the Muav Limestone, and the Tapeats Sandstone. These rock units are hydraulically connected and under confined conditions except at the northern and southern boundaries of the study area. The aquifer occurs throughout the study area and is best defined by the exposed stratigraphy in deeply incised canyons and borehole lithology in the northern and west-central parts of the study area. Little is known about the occurrence and movement of ground water in the aquifer in the central and eastern parts of the study area because few wells penetrate the aquifer in these areas. In the northern part of the study area, ground water discharges from the aquifer in the lower Little Colorado River drainage and in tributaries along the south rim of Grand Canyon. In the southern part of the study area, ground water discharges from the aquifer to the Verde River between Paulden and Clarkdale and as underflow into the Verde Formation in Verde Valley.

About 600 wells and 18 springs that yield water from the C aquifer, and 47 wells and 35 springs that yield water from the Redwall-Muav aquifer were evaluated as part of this study. Yields from the C aquifer range from a few gallons per minute to more than 1,000 gal/min. Higher well yields are strongly correlative with subsurface fractures. Yields from wells developed in the Redwall-Muav aquifer range from a few tens of gallons per minute to several hundred gallons per minute. As with the C aquifer, higher yielding wells in the Redwall-Muav aquifer are correlative with fractures in the subsurface. Yields from springs that discharge from the Redwall-Muav aquifer range from a few gallons per minute to more than 40,000 gal/min. The higher yielding springs in the Redwall-Muav aquifer flow from solution channel systems and fractures near the northern and southern boundaries of the study area.

Hydraulic conductivity values range from 84 to 181,400 gpd/ft^2 for the C aquifer and from 20 to 16,000 gpd/ft^2 for the Redwall-Muav aquifer. Specific yield for the C aquifer ranges from 0.0002 to 0.14 and averages 0.077. Storativity for the Redwall-Muav aquifer has not been determined. Since the C aquifer and the Redwall-Muav aquifer are heavily influenced by fracture flow, no attempt was made to estimate the total storage for either aquifer.

Ground-water withdrawals from the aquifers have been steadily increasing since 1975. Total withdrawals from the two aquifers in 2004 was about 19,600 acre-ft. About two-thirds of the withdrawals are from the C aquifer and about one-third is from the Redwall-Muav aquifer. Water-level declines in response to withdrawals from the C aquifer have been about 200 ft or more near large municipal pumping centers such as the city of Flagstaff well field south of Lake Mary. Smaller declines from a few feet to a few tens of feet occur in observation wells throughout the study area and probably are the result of regional ground-water withdrawals and effects of the current drought. There are no indications of water-level declines in the Redwall-Muav aquifer. The number of wells and quantity of ground-water withdrawn from this aquifer are still small in relation to the potentially large volume of water in storage. Declines in spring flows from the Redwall-Muav aquifer have been observed at some of the smaller springs along the south rim of Grand Canyon. These springs are more sensitive to climate change than larger springs, and likely have been effected by the current drought.

Water discharging from the C aquifer and the Redwall-Muav aquifer in the study area is a calcium magnesium bicarbonate type with low concentrations of the major dissolved constituents and generally is of good quality for most intended uses. Water discharging from springs in the Little Colorado River Canyon is a sodium chloride type, with greater concentrations of most major dissolved constituents and trace elements relative to water from other springs, wells, and streams in the study area. Concentrations of sulfate and chloride increase toward the west in springs near the south rim of Grand Canyon. Samples from the Verde River above Mormon Pocket had higher concentrations of most dissolved constituents than samples from springs at Mormon Pocket and in Sycamore Canyon, suggesting different source areas for these waters. Multivariate statistical analyses of the major-ion data confirmed these groupings. Concentrations of barium, arsenic, uranium, and lead, and gross alpha radioactivity were greater than USEPA MCLs for drinking water at some sites in the study area.

Isotopic compositions of water samples from springs, streams, and wells on the Coconino Plateau and in adjacent areas do not show a clear seasonal pattern but are most similar in composition to winter precipitation. This correlation likely indicates that most recharge occurs during the winter months. The $\delta^{18}O$ and $\delta^{2}H$ data from springs, streams, and wells cluster in three groups: Grand Canyon south rim springs, Flagstaff wells and springs, and the Verde River watershed. Recharge to the upper Verde River likely is from a low altitude source owing to the ^{18}O and ^{2}H enrichment in water from the upper Verde River compared to water from the lower Verde River. The lighter isotopic compositions of water from lower Verde River sites are similar to compositions of water from Flagstaff wells and springs, indicating recharge to the lower Verde River from higher altitude areas along the Mogollon Rim and near Flagstaff. The presence of an evaporative signature for some sites suggests isotope fractionation owing to predischarge or postdischarge evaporation.

Strontium isotope data provide information about water-rock interactions and ground-water flow paths. The strontium values for rock samples collected throughout the study area were in agreement with values from rock samples collected from around the world. Water samples collected at wells near Flagstaff had strontium values similar to those for younger Permian rock units of the C aquifer, whereas water from springs near the south rim of Grand Canyon had values that were more radiogenic and most similar to values for older, mid-Paleozoic age rocks of the Redwall-Muav aquifer. Water discharging from springs east of the Bright Angel Fault in Grand Canyon had strontium values that were more radiogenic than values for samples from sites west of the fault. Water from some springs and wells in the study area had values that were greater than values for Paleozoic rocks in the study area. This could be due to mixing with deep ground water or to interaction with rocks that were not sampled and analyzed.

Ground-water residence times were estimated by using radiocarbon dating techniques. Ground-water residence times for C aquifer wells in the Flagstaff area ranged from modern to 7,000 yr. Most of these wells had tritium values greater than the detection limit, indicating mixing of younger and older ground waters. Estimated residence times of 7,500 to 22,600 yr and small tritium values for water discharging from wells developed in the Redwall-Muav aquifer indicate that this water is older than water discharging from the C aquifer. Tritium and ^{14}C data indicate that ground-water discharging at most springs and streams is a mixture of young and old ground waters, indicating that ground water likely follows multiple flow paths from multiple recharge areas to discharge zones.

A conceptual model of the Coconino Plateau study area ground-water systems was developed to organize interpretations of this analysis into uniform flow-system components. The regional boundaries for the ground-water systems are a combination of physical and hydraulic boundaries derived from the descriptions of the geology, stratigraphy, and regional characteristics of the C aquifer and Redwall-Muav aquifers. Most of the boundaries are the result of either large erosion escarpments or regional faults that interrupt ground-water flow in the two aquifers. Several local boundaries are defined by both physical and hydraulic properties of the aquifers. On the basis of the source, occurrence, and movement of water in the aquifers, three ground-water subbasins were identified in the study area: (1) the Havasu/Cataract Creek subbasin, (2) the Little Colorado River subbasin, and (3) the Verde River subbasin. These subbasins contain ground-water systems that have defined flow paths that are interconnected by boundaries of the regional flow system.

Steady-state and transient water budgets were developed for the study area to estimate the amounts of water entering and leaving the area. Budgets were developed for the watershed and for the ground-water systems. Components for the steady-state budgets are assumed to be representative of hydrologic conditions before large-scale ground-water development began in 1975. Components for the transient budgets were determined on the basis of measured and estimated data for 2002.

The steady-state budget calculations were based primarily on pre-1975 data; however, more recent data were used for areas in which earlier data were not available and steady-state conditions were assumed to prevail. Estimated precipitation in the steady-state watershed budget is 8,700,000 acre-ft/yr. A value of 200,000 acre-ft/yr was used for the runoff component. Estimated natural recharge to the ground-water systems was 302,000 acre-ft/yr. About 223,000 acre-ft of ground water discharges at the northern boundary of the study area from the Redwall-Muav aquifer and about 77,000 acre-ft discharges at the southern boundary of the study area from both the C aquifer and the Redwall-Muav aquifer. Calculated as a residual in the budget equation, estimated ET for the watershed was 8,198,000 acre-ft/yr. These component values are based on average data values and estimates of prevailing conditions. Short-term and long-term changes in basin characteristics can have significant effects on the availability of water in the study area.

To illustrate these potential effects, a transient water budget was calculated on the basis of 2002 water-year data. A value of 4,350,000 acre-ft was used for the precipitation component in the transient watershed budget for the 2002 water year. Because no runoff was recorded at gaging stations in the study area during the water year, a value of zero was used for the runoff component in the budget. Recharge to the ground-water systems also was estimated to be zero because precipitation was much less than average and most occurred during the summer when ET is greatest. Estimated ET from the watershed was 4,350,000 acre-ft as a residual in the water-budget equation.

The steady-state ground-water budget included underflow of ground water into the study area as an additional inflow component. Component values for the budget were primarily based on pre-1975 data; however, more recent data were used for areas in which earlier data were not available and steady-state conditions were assumed to prevail. Natural recharge was calculated as a residual of the ground-water budget in the amount of 302,000 acre-ft/yr. Estimated underflow, which occurs only along the eastern boundary of the study area, was 6,000 acre-ft/yr. Of the 300,000 acre-ft of water that discharges each year, about 223,000 acre-ft discharges at the northern boundary of the study area and 77,000 acre-ft discharges at the southern boundary. Evapotranspiration from ground water was estimated to be 8,000 acre-ft/yr.

The hydrologic system in the study area currently is in a transient condition owing to ground-water withdrawals from the major aquifers. In the transient ground-water budget for the 2002 water year, natural recharge was assumed to be zero because precipitation was much less than average and most occurred during the summer when ET is greatest. In addition to underflow, the transient ground-water budget also included incidental recharge, which is the amount of effluent from wastewater-treatment plants that recharges the ground-water systems. Estimated incidental recharge for the 2002 water year was 9,000 acre-ft. Estimated underflow was 6,000 acre-ft/yr, and natural ground-water discharge was 300,000 acre-ft. Ground-water withdrawals during water year 2002 totaled 20,000 acre-ft. Estimated ET from ground water was 8,000 acre-ft/yr.

Results of the transient water-budget calculation indicate a net loss from storage of about 313,000 acre-ft/yr or an average change in ground-water levels of -0.05 ft over the entire study area. The net loss in storage and declines in water level do not occur evenly over the entire study area, but are concentrated in areas of greatest water withdrawals or areas where aquifer characteristics allow ground-water systems to respond more rapidly to changes. No water level change was detected in the Redwall-Muav aquifer. Changes in the base flow of springs or streams seem to be in consistent decline in response to the continuing drought. Those drainages with smaller catchment basins and storage seem to respond more rapidly to short-term change in the environment.

The next phase in continuing the study of ground-water-flow systems on the Coconino Plateau study area is to convert the conceptual model developed thus far into a numeric model of regional ground-water flow. The numerical model will enable examination of continuing drought conditions and possible development scenarios, and identify potential effects on spring and surface-water resources in discharge areas of the flow systems.

The continued monitoring of water-budget components is important to the overall understanding of the hydrogeologic systems and will provide valuable data for development of the numerical model. The more rigorously each component of the water budget is developed, the more confidence can be placed on the overall budget and numerical model. Existing gaps in hydrologic data make it difficult to predict with any degree of certainty the sustainability of the water supply for either natural or anthropogenic water demands.

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Supplemental Data

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004.

[δ, delta; per mil, per thousand; TU, tritium units; pCi/L, picocuries per liter; μg/L, micrograms per liter; PE, two-sigma precision estimate; MDC, minimum detectable concentration; ^{2}H, Deuterium; ^{18}O, Oxygen-18; ^{14}C, Carbon-14; U, Uranium; ^{137}Cs, Cesium-137; ^{230}Th, Thorium-230; Sr/^{90}Y, Strontium/Yttrium-90; ^{226}Ra, Radium-226; ^{228}Ra, Radium-228; ^{222}Rn, Radon-222; ^{234}U, Uranium-234; ^{235}U, Uranium-235; ^{238}U, Uranium-238; nc, not collected; <, less than; UNSURV, unsurveyed; MODERN, less than 250 years]

Site identification number	Spring, stream, well, or owner name	Site identifier	Date of sample	$\delta^{2}H$, per mil	$\delta^{18}O$, per mil	^{14}C count error, percent modern carbon	^{14}C, percent modern carbon
345644112193701	King Spring	A-18-01 18WBBD	06/15/2000	-70.0	-8.8	nc	nc
			02/08/2002	-76.3	-10.2	nc	nc
350535112263601	Meath Spring	B-20-02 35BAA	04/17/2001	-16.5	3.1	nc	nc
350107112305601	Storm Seep	B-19-02 19BDD	04/19/2001	-81.0	-11.4	nc	nc
			06/20/2002	-77.1	-10.8	nc	nc
			04/19/2004	-78.0	-10.7	nc	nc
350022112324001	Pool Seep	B-19-03 26ADB	04/19/2001	-80.8	-11.0	nc	nc
350641112043701	Hitt Springs	nc	04/18/2004	-71.2	-10.1	0.71	108.6
350802112014001	Willow Spring	A-20-03 12BAA	04/18/2004	-65.4	-8.6	nc	nc
09503700	Verde River near Paulden	Verde River near Paulden	07/03/1991	-71.5	-10.0	nc	nc
			06/13/2000	-73.2	-10.1	nc	nc
345251112191300	Verde River at Bull Basin Canyon	Verde River at Bull Basin Canyon	06/13/2000	-73.5	-9.9	nc	nc
345239112173400	Verde River above Duff Spring	Verde River above Duff Spring	06/13/2000	-72.1	-10.0	nc	nc
			12/18/2002	-74.0	-10.0	nc	nc
345235112172501	Duff Spring	Duff Spring	07/04/1991	-67.0	-9.2	nc	nc
			06/13/2000	-68.1	-9.2	nc	nc
			12/18/2002	-70.5	-9.3	nc	nc
345240112172001	Verde River below Duff Spring No. 1	Verde River below Duff Spring 1	07/04/1991	-72.0	-9.9	nc	nc
345239112171600	Verde River below Duff Spring No. 2	Verde River below Duff Spring 2	06/13/2000	-72.1	-9.9	nc	nc
			12/18/2002	-72.8	-10.0	nc	nc
345501112164200	Verde River above Hell Canyon	Verde River above Hell Canyon	06/13/2000	-71.2	-9.8	nc	nc
			12/18/2002	-73.0	-9.8	nc	nc
345503112163100	Verde River below Hell Canyon	Verde River below Hell Canyon	06/13/2000	-71.8	-9.7	nc	nc
			12/18/2002	-71.9	-9.9	nc	nc
345429112152901	Verde River at US Mine No. 1	Verde River at US Mine 1	07/03/1991	-70.5	-9.7	nc	nc
345425112152300	Verde River at US Mine No. 2	Verde River at US Mine 2	06/14/2000	-73.8	-9.6	nc	nc
			12/18/2002	-72.2	-9.8	nc	nc
345338112124500	Verde River above Perkinsville Diversion	Verde River above Perkinsville Diversion	06/14/2000	-70.9	-9.4	nc	nc
			12/18/2002	-71.6	-9.7	nc	nc
345352112120400	Verde River near Perkinsville	Verde River near Perkinsville	06/14/2000	-72.6	-9.7	nc	nc
345356112120501	Spring near Perkinsville	Spring near Perkinsville	01/17/2002	-77.2	-10.7	nc	nc
345352112120401	Verde River below Spring below Perkinsville Bridge	Verde River below Spring below Perkinsville Bridge	07/02/1991	nc	nc	nc	nc
345344112103901	Verde River below Railroad Bridge	Verde River below Railroad Bridge	07/02/1991	-72.5	-9.9	nc	nc
345334112102100	Verde River below Orchard Fault	Verde River below Orchard Fault	06/14/2000	-73.7	-9.9	nc	nc
345245112092601	Verde River above Mormon Pocket	Verde River above Mormon Pocket	07/04/1991	nc	nc	nc	nc
			06/14/2000	-74.8	-9.7	nc	nc
345325112081701	Mormon Pocket Small Spring	A-17-02 03ABB2	12/18/2001	-83.5	-11.7	nc	nc
			06/17/2002	-84.6	-11.7	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Site identification number	Spring, stream, well, or owner name	Site identifier	Date of sample	δ²H, per mil	δ¹⁸O, per mil	¹⁴C count error, percent modern carbon	¹⁴C, percent modern carbon
345327112081501	Mormon Pocket Big Spring	A-17-02 03ABB UNSURV	07/04/1991	nc	nc	nc	nc
			12/18/2001	-83.0	-11.7	nc	nc
			06/17/2002	-84.8	-11.7	nc	nc
345152112045700	Verde River 0.25 mile above Sycamore Creek	Verde River 0.25 mile above Sycamore Creek	06/14/2000	-76.3	-10.7	nc	nc
345255112035900	Sycamore Creek upstream from Summers Spring	Sycamore Creek upstream from Summers Spring	06/17/2002	-82.8	-11.4	nc	nc
345255112035801	Summers Spring	A-17-03 05D UNSURV	12/20/2001	-84.4	-11.7	nc	nc
			06/17/2002	-84.7	-11.7	nc	nc
			02/11/2003	-82.6	-12	0.3	35.1
345301112041901	Sycamore Creek Spring #2 (opposite Summers)	A-17-03 05C2 UNSURV	12/17/2002	-81.7	-11.6	nc	nc
345147112043501	Sycamore Creek	Sycamore Cr	07/02/1991	-80.5	-11.7	nc	nc
			06/14/2000	-82.1	-11.6	nc	nc
345135112043001	Verde River below Sycamore Creek	Verde River below Sycamore Creek	07/02/1991	-77.0	-10.8	nc	nc
345128112042100	Verde River 0.5 mile below Sycamore Creek	Verde River 0.5 mi below Sycamore Creek	06/14/2000	-76.6	-10.8	nc	nc
345129112041701	Spring below Sycamore Creek	A-17-03 17BBD	06/14/2000	-81.7	-11.8	nc	nc
345129112041701			02/07/2002	-82.0	-11.4	nc	nc
09504000	Verde River near Clarkdale	Verde River near Clarkdale	07/03/1991	-77.5	-10.9	nc	nc
			10/29/2003	-78.5	-10.9	nc	nc
09504420	Oak Creek near Sedona	Oak Creek near Sedona	10/27/2003	-82.8	-11.7	nc	nc
350625111350501	LM-4	(A-20-08)19aba	07/01/1996	-72.3	-9.2	nc	76.2
			02/20/1997	-74.5	-9.3	nc	nc
			08/20/1997	-74.0	-9.3	nc	nc
350547111343001	LM-8	(A-20-08)20cca	07/01/1996	-87.5	-12.2	nc	113.1
350451111352501	LM-9	(A-20-08)30cda	07/01/1996	-85.6	-11.8	nc	71.4
350924111440101	WM-1	(A-21-06)35cba	07/01/1996	-86.0	-12.3	nc	44.0
350847111440401	WM-6	(A-20-06)02bdb	07/01/1996	-83.5	-12.0	nc	46.0
350745111435601	WM-9	(A-20-06)11bdc	07/01/1996	-85.6	-12.0	nc	41.6
			02/25/1997	-85.4	-12.0	nc	nc
			08/26/1997	-86.8	-12.1	nc	nc
351223111342802	Continental-2	(A-21-08)17bca2	04/17/1997	-90.7	-12.3	nc	52.9
351127111360001	Foxglenn-1	(A-21-07)24aad	06/01/1997	-90.2	-12.4	nc	59.5
350124111273501	Pine Grove	(A-19-09)17dcd	06/10/1996	-84.4	-11.7	nc	47.6
351025111303701	NPS Walnut Canyon	(A-21-08)26dab	06/11/1996	-83.8	-11.9	nc	58.6
350511111400001	Mountainaire	(A-20-07)28bcc	06/12/1996	-82.8	-11.9	nc	50.0
351130111411601	Hidden Hollow	(A-21-07)19aca	06/14/1996	-87.9	-12.4	nc	58.4
351025111425201	Flag Ranch	(A-21-06)25bcd	06/13/1996	-85.7	-11.9	nc	35.8
351043111363701	Purl	(A-21-07)25bbd	06/18/1996	-85.8	-11.7	nc	70.2
351136111430901	Henden	(A-21-06)23aad	06/18/1996	-85.5	-11.9	nc	26.2
353110111221001	NPS Wupatki HQ1	(A-25-10)30bdb	06/26/1996	-73.5	-10.2	nc	18.7
			07/09/1996	-75.2	-10.2	nc	nc
352027111390001	IB-9	(A-23-07)33aab2	07/02/1996	-93.8	-13.1	nc	99.4
			07/02/1996	-125.2	-17.6	nc	nc
			01/15/1997	-106.9	-15.2	nc	nc
			01/29/1997	-114.1	-15.9	nc	nc
350401111321601	Babbitt Spring	(A-20-08)34cdb	06/14/1996	-86.3	-12.1	nc	81.6
350402111344401	Clark Spring	(A-20-08)32cca	06/13/1996	-68.6	-10.0	nc	100.9

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Site identification number	Spring, stream, well, or owner name	Site identifier	Date of sample	δ^2H, per mil	$\delta^{18}O$, per mil	^{14}C count error, percent modern carbon	^{14}C, percent modern carbon
351120111380001	Rio de Flag MW-1	(A-21-07)23cac	06/13/1996	-77.1	-10.4	nc	nc
350625111420301	FH-5	(A-20-06)24abb	06/25/1996	-86.9	-12.0	nc	62.1
351153111393801	Old Town Spring	(A-21-07)16cdb	07/08/1996	-79.3	-10.8	nc	102.3
351052111363301	Rio de Flag MW-3	(A-21-07)25bba2	06/12/1996	-86.1	-11.7	nc	nc
350130111442201	Sterling Spring	(A-19-06)15ddd1	06/18/1996	-82.9	-11.9	nc	57.7
351313111495801	NAD-1	(A-21-05)11abc	06/21/1996	-83.8	-11.4	nc	91.0
351416111285601	BBDP-MVR-1	(A-21-09)06baa	06/11/1996	-80.8	-11.1	nc	40.8
			04/08/1997	-80.4	-10.9	nc	nc
			08/26/1997	-80.2	-10.8	nc	nc
351656111305201	BBDP-Marijka	(A-22-08)23abb	06/11/1996	-82.8	-11.7	nc	28.8
350946111405301	Mtn Dell-1	(A-21-07)32bbc1	06/19/1996	-87.2	-12.1	nc	72.5
			03/11/1997	-86.7	-12.2	nc	nc
			08/28/1997	-87.4	-12.1	nc	nc
350948111405201	Mtn Dell-2	(A-21-07)32bbc2	06/19/1996	-86.8	-12.0	nc	66.5
360629111411201	GC-1	03 079-10.42X09.78	02/16/2002	-81.3	-11.3	nc	nc
360656111405801	Curtain Spring	A-32-07 31 UNSURV	02/16/2002	-83.2	-11.4	nc	nc
360700111413701	Blue Spring	03 079-10.81X09.20	06/29/2001	-84.9	-11.5	0.09	4.2
			02/16/2002	-83.6	-11.6	nc	nc
361203111452501	LCR Mile 3.1	RM 3.1, Little Colorado River	11/18/2002	-84.0	-11.4	0.11	5.9
360020111560401	Red Canyon Spring	A-30-04 11 UNSURV	09/26/2001	-94.2	-12.7	0.47	49.2
			06/03/2002	-93.9	-12.7	nc	nc
360025111571501	JT Spring	A-30-04 10 UNSURV	04/08/2001	-73.1	-9.4	nc	nc
			05/11/2001	-91.4	-12.2	0.4	55.1
360100111582001	Miners Spring	A-30-04 04 UNSURV	05/24/2000	-93.1	-12.3	0.46	71.1
			11/28/2000	-90.7	-12.2	nc	nc
			04/07/2001	-92.3	-12.1	nc	nc
			06/06/2002	-92.5	-12.1	nc	nc
360128111591200	Cottonwood Creek No. 1	A-31-04 32 UNSURV	05/25/2000	-91.6	-12.3	0.66	94.2
			10/07/2002	-90.0	-12.2	nc	nc
360108111592600	Cottonwood Creek No. 2	A-31-04 32 UNSURV	11/29/2000	-93.9	-12.7	0.44	60.3
			03/07/2002	-93.8	-12.8	nc	nc
			06/05/2002	-92.7	-12.7	nc	nc
			10/08/2002	-94.6	-12.8	nc	nc
360232112004801	Grapevine East Spring	A-31-03 25 UNSURV	05/25/2000	-73.6	-9.1	0.58	103.4
			12/12/2000	-74.9	-8.9	0.57	89.7
			04/09/2001	-71.0	-8.5	nc	nc
			11/14/2001	-74.9	-9.6	nc	nc
360040112000901	Grapevine Main Spring	A-30-04 01 UNSURV	04/10/2001	-94.6	-12.9	nc	nc
			04/30/2001	-92.7	-12.9	0.39	54.3
			11/15/2001	-92.7	-12.9	nc	nc
360400112025001	Lonetree Spring	A-31-03 14 UNSURV	04/11/2001	-89.1	-11.9	nc	nc
			05/01/2001	-89.9	-12.0	0.49	70.2
360439112034501	Sam Magee Spring	A-31-03 15 UNSURV	04/20/2001	-79.4	-10.0	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Site identification number	Spring, stream, well, or owner name	Site identifier	Date of sample	δ²H, per mil	δ¹⁸O, per mil	¹⁴C count error, percent modern carbon	¹⁴C, percent modern carbon
360436112060401	Burro Spring	A-31-03 17 UNSURV	05/22/2000	-91.0	-12.4	0.44	63.6
			12/07/2000	-92.9	-12.3	nc	nc
			04/08/2001	-91.1	-12.5	nc	nc
360410112055700	Pipe Creek	A-31-03 18 UNSURV	05/22/2000	-91.9	-12.3	0.42	54.6
			12/07/2000	-91.5	-12.4	nc	nc
			04/08/2001	-90.9	-12.4	nc	nc
09403013	Pumphouse Gage	Pump House Wash Spring nr Grand Canyon, AZ	12/09/2000	-93.0	-12.3	nc	nc
360441112073201	Pumphouse Spring	A-31-02 13 UNSURV	05/22/2000	-92.6	-12.3	0.38	51.4
			12/07/2000	-93.1	-12.3	nc	nc
			04/07/2001	-92.8	-12.3	nc	nc
			11/19/2001	-90.3	-12.4	nc	nc
			06/12/2002	-91.3	-12.3	nc	nc
			11/23/2002	-91.7	-12.3	nc	nc
360443112083300	Horn Creek	A-31-02 11 UNSURV	05/22/2000	-88.8	-11.9	0.51	74.9
			12/06/2000	-89.3	-11.7	nc	nc
			04/07/2001	-88.9	-11.8	nc	nc
			11/22/2002	-90.0	-12.0	nc	nc
360439112094101	Salt Creek Spring	A-31-02 15 UNSURV	05/23/2000	-87.3	-11.8	0.31	40.5
			12/06/2000	-90.2	-12.1	nc	nc
			04/10/2001	-87.1	-11.7	nc	nc
			11/22/2002	-90.8	-12.1	nc	nc
09403033	Monument Creek No. 3	Monument Creek	05/02/2002	-88.8	-11.7	nc	nc
			05/16/2002	-87.4	-11.7	nc	nc
			11/21/2002	-88.5	-11.7	nc	nc
360356112103201	Monument Spring	A-31-02 16 UNSURV	12/05/2000	-91.1	-12.2	0.34	42.0
			04/09/2001	-91.2	-12.2	nc	nc
			11/19/2001	-90.2	-12.2	nc	nc
			05/02/2002	-90.7	-12.2	nc	nc
			05/16/2002	-89.7	-12.2	nc	nc
			11/21/2002	-90.6	-12.2	nc	nc
360417112130701	Hawaii Spring	A-31-02 18 1 UNSURV	05/25/2000	-88.3	-11.9	0.28	38.3
			12/04/2000	-89.1	-11.9	nc	nc
			04/11/2001	-88.9	-11.9	nc	nc
360347112133001	Hermit Spring	A-31-02 18 2 UNSURV	12/04/2000	-89.7	-12.0	nc	nc
			04/11/2001	-88.2	-11.8	nc	nc
			11/19/2001	-88.8	-12.0	0.35	34.9
			11/21/2002	-89.1	-12.0	nc	nc
360411112141701	Boucher East Spring	A-31-01 01 UNSURV	05/26/2000	-84.1	-11.4	0.46	72.2
			04/12/2001	-86.6	-11.3	nc	nc
360511112155501	Boucher Spring	A-31-01 10 UNSURV	04/25/2002	-84.2	-11.5	0.34	47.9
			10/21/2002	-84.7	-11.3	nc	nc
360658112170701	Slate Spring	A-32-01 33 UNSURV	04/24/2002	-82.8	-10.3	nc	nc
360711112184601	Sapphire Spring	A-32-01 32 UNSURV	04/23/2002	-89.0	-11.9	nc	nc
			10/23/2002	-87.7	-11.8	nc	nc
360814112195100	Turquoise Creek	A-32-01 19 UNSURV	04/22/2002	-87.5	-11.8	0.49	65.5
360735112201601	Turquoise Spring	A-32-01 25 UNSURV	10/23/2002	-90.0	-12.0	nc	nc
360952112203501	Ruby Spring	A-32-01 13 UNSURV	04/21/2002	-81.4	-10.8	nc	nc
			10/24/2002	-81.8	-11.2	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Site identification number	Spring, stream, well, or owner name	Site identifier	Date of sample	δ^2H, per mil	$\delta^{18}O$, per mil	^{14}C count error, percent modern carbon	^{14}C, percent modern carbon
361141112211101	Serpentine Spring	A-32-01 02 UNSURV	04/21/2002	-91.1	-12.1	0.41	54.8
			10/24/2002	-89.1	-11.9	nc	nc
361119112271501	Royal Arch Spring	A-32-02 01 UNSURV	03/23/2002	-83.0	-11.3	0.41	52.1
361403112314201	Forster Canyon Spring 2	B-33-02 29 UNSURV	01/20/2002	-93.0	-12.3	0.16	10.6
			05/03/2002	-92.7	-12.4	nc	nc
			11/02/2002	-92.8	-12.3	nc	nc
361648112315101	Fossil Spring	A-33-02 5 UNSURV	05/18/2002	-80.8	-11.0	nc	nc
			11/02/2002	-80.5	-10.9	nc	nc
362338112351601	140 Mile Plus Spring	A-35-03 35 UNSURV	11/04/2002	-83.0	-11.2	nc	nc
361928112393201	Matkatamiba Spring	B-34-03 30 UNSURV	01/21/2002	-87.8	-11.7	nc	nc
			04/29/2002	-87.5	-11.7	nc	nc
			05/05/2002	-87.8	-11.7	0.22	20.2
			11/04/2002	-89.0	-11.7	nc	nc
361303112411200	Havasu Spring	B-33-04 26 UNSURV	08/24/1994	-86.3	-11.8	0.3	5.0
			08/24/1994	nc	nc	nc	nc
361524112420400	Fern Spring	B-33-04 11 UNSURV	08/24/1994	-85.4	-11.7	0.2	13.3
			08/24/1994	nc	nc	nc	nc
361346112521501	National Canyon Spring	A-33-05 30 UNSURV	05/06/2002	-89.5	-11.8	nc	nc
			11/06/2002	-90.4	-11.9	nc	nc
361518112523900	National Canyon Creek	NATIONAL CANYON ABV MOUTH AT RM 166.5 IN HUALAPAI	10/08/1993	-61.8	-8.7	nc	nc
361252112580901	Mohawk Canyon Spring	B-33-06 30 2 UNSURV	09/18/2001	-83.7	-11.2	0.25	30.4
361252112580901			05/19/2002	-83.7	-11.2	nc	nc
361310112580400	Mohawk Canyon Creek	B-33-06 30 1 UNSURV	10/09/1993	-82.9	-11.1	nc	nc
			01/06/1995	-84.0	-11.3	nc	nc
351300112063601	Dogtown Well #1	A-21-03 07ADB	03/30/2001	-84.1	-11.7	0.24	17.2
351534112105701	Rodeo Grounds Well	A-22-02 28ACD	12/12/2002	-82.4	-11.5	0.06	1.4
360823112394802	Bar Four Well	B-32-04 24CDA2	05/01/2002	-112.2	-14.6	0.09	3.2
351207112283701	Ash Fork Well No. 1	B-21-02 14BCC	07/09/1991	nc	nc	nc	nc
			08/27/1991	-76.0	-10.1	nc	nc
			02/13/2003	-75.6	-10.0	0.22	20.2
355308112054101	Canyon Mine Well	A-29-03 20BDB	05/20/2003	-89.5	-12.2	0.21	15.5
353930112075001	Patch Karr Well	A-26-02 01CDD	04/13/2004	-86.7	-11.6	0.13	7.5
361352112413201	Havasupai Well No. 1	B-33-04 22 UNSURV	08/23/1994	-85.0	-11.6	0.3	5.0
			08/23/1994	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Average corrected residence time, years rounded	Tritium, 2-sigma, pCi/L	Tritium, pCi/L	Tritium, TU	Alpha radio-activity, 2-sigma water, filtered, U natural, pCi/L	Gross alpha radio-activity, water, filtered, U natural, pCi/L	Alpha radio-activity, 2-sigma, water, filtered, ^{230}Th, pCi/L	Alpha PE ^{230}Th, pCi/L	Alpha radio-activity, water, filtered, ^{230}Th, pCi/L	Gross alpha radio-activity, 72 hour count, ^{230}Th curve, pCi/L
King Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	7.0	1.9	2.2	nc	nc	nc	nc	nc	nc
Meath Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Storm Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pool Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hitt Springs	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Willow Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Paulden	nc	0.6	1.7	0.5	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at Bull Basin Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Duff Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Duff Spring	nc	0.6	<0.31	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Perkinsville Diversion	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Spring below Perkinsville Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Railroad Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Orchard Fault	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Mormon Pocket	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Small Spring	nc	0.7	2.0	0.6	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Big Spring	nc	1.9	3.0	0.9	nc	nc	nc	nc	nc	nc
	nc	1.3	1.0	< 0.31	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.25 mile above Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Average corrected residence time, years rounded	Tritium, 2-sigma, pCi/L	Tritium, pCi/L	Tritium, TU	Alpha radio-activity, 2-sigma water, filtered, U natural, pCi/L	Gross alpha radio-activity, water, filtered, U natural, pCi/L	Alpha radio-activity, 2-sigma, water, filtered, ^{230}Th, pCi/L	Alpha PE ^{230}Th, pCi/L	Alpha radio-activity, water, filtered, ^{230}Th, pCi/L	Gross alpha radio-activity, 72 hour count, ^{230}Th curve, pCi/L
Sycamore Creek upstream from Summers Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Summers Spring	nc	1.3	4.0	1.3	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	4,600	1.0	3.5	1.1	nc	nc	4.28	2.72	1.3	nc
Sycamore Creek Spring #2 (opposite Summers)	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.5 mile below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.3	2	0.6	nc	nc	nc	nc	nc	nc
Verde River near Clarkdale	nc	0.6	2.9	0.9	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Oak Creek near Sedona	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-4	MODERN	nc	24	7.5	nc	nc	nc	nc	nc	nc
	nc	1.9	26	8.2	nc	nc	nc	nc	nc	nc
	nc	1.9	24	7.5	nc	nc	nc	nc	nc	nc
LM-8	MODERN	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
LM-9	MODERN	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
WM-1	2,100	1.0	12	3.8	nc	nc	nc	nc	nc	nc
WM-6	2,300	1.0	2	0.6	nc	nc	nc	nc	nc	nc
WM-9	2,900	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
	nc	1.0	1.3	<0.41	nc	nc	nc	nc	nc	nc
	nc	0.6	1	<0.31	nc	nc	nc	nc	nc	nc
Continental-2	MODERN	1.0	8.6	2.7	nc	nc	nc	nc	nc	nc
Foxglenn-1	MODERN	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Pine Grove	2,600	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
NPS Walnut Canyon	200	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Mountainaire	800	1.0	7	2.2	nc	nc	nc	nc	nc	nc
Hidden Hollow	300	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Flag Ranch	4,000	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Purl	MODERN	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Henden	5,900	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
NPS Wupatki HQ1	5,000	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
IB-9	MODERN	3.0	33	10.3	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Babbitt Spring	MODERN	2.0	27	8.5	nc	nc	nc	nc	nc	nc
Clark Spring	MODERN	2.0	25	7.8	nc	nc	nc	nc	nc	nc
Rio de Flag MW-1	nc	2.0	19	6.0	nc	nc	nc	nc	nc	nc
FH-5	MODERN	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Old Town Spring	MODERN	1.0	16	5.0	nc	nc	nc	nc	nc	nc
Rio de Flag MW-3	nc	2.0	29	9.1	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Average corrected residence time, years rounded	Tritium, 2-sigma, pCi/L	Tritium, pCi/L	Tritium, TU	Alpha radio-activity, 2-sigma water, filtered, U natural, pCi/L	Gross alpha radio-activity, water, filtered, U natural, pCi/L	Alpha radio-activity, 2-sigma, water, filtered, ^{230}Th, pCi/L	Alpha PE ^{230}Th, pCi/L	Alpha radio-activity, water, filtered, ^{230}Th, pCi/L	Gross alpha radio-activity, 72 hour count, ^{230}Th curve, pCi/L
Sterling Spring	MODERN	1.0	2	0.6	nc	nc	nc	nc	nc	nc
NAD-1	MODERN	2.0	31	9.7	nc	nc	nc	nc	nc	nc
BBDP-MVR-1	1,800	1.0	14	4.4	nc	nc	nc	nc	nc	nc
	nc	1.3	15	4.7	nc	nc	nc	nc	nc	nc
	nc	1.3	16	5.0	nc	nc	nc	nc	nc	nc
BBDP-Marijka	3,400	1.0	<1.0	<0.31	nc	nc	nc	nc	nc	nc
Mtn Dell-1	MODERN	1.0	3	0.9	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	4.2	1.3	nc	nc	nc	nc	nc	nc
Mtn Dell-2	MODERN	1.0	9	2.8	nc	nc	nc	nc	nc	nc
GC-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Curtain Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Blue Springs	11,300	1.0	<1.0	<0.31	nc	nc	12.02	5.97	1.6	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LCR Mile 3.1	nc	1.0	<1.0	<0.31	nc	nc	23.59	14.75	nc	nc
Red Canyon Spring	2,400	1.0	2.2	0.7	nc	nc	3.1	2.03	3.14	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
JT Spring	nc	1.0	13.1	4.1	nc	nc	nc	nc	nc	nc
	1,500	1.0	3.5	1.1	nc	nc	2.12	1.79	3.56	nc
Miners Spring	500	1.0	2.2	0.7	nc	nc	nc	3	3.87	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	2.6	0.8	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 1	MODERN	1.0	2.2	0.7	nc	nc	nc	2	<3.00	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 2	1,300	1.0	1.6	0.5	nc	nc	nc	1.1	<3.00	nc
	nc	1.0	1.9	0.6	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Grapevine East Spring	MODERN	1.0	1.9	0.6	nc	nc	nc	1.6	<3.00	nc
	MODERN	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	2.2	0.7	nc	nc	nc	nc	nc	nc
	nc	1.0	1.0	<0.31	nc	nc	nc	nc	nc	nc
Grapevine Main Spring	nc	1.0	1.6	0.5	nc	nc	nc	nc	nc	nc
	1,700	1.0	3.5	1.1	nc	nc	1.87	1.5	2.64	1.5
	nc	1.0	1.6	0.5	nc	nc	nc	nc	nc	nc
Lonetree Spring	nc	1.0	5.1	1.6	nc	nc	nc	nc	nc	nc
	1,300	1.0	4.8	1.5	nc	nc	1.93	1.93	5.3	nc
Sam Magee Spring	nc	1.0	1.0	0.31	nc	nc	nc	nc	nc	nc
Burro Spring	nc	1.0	1.0	<0.31	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	3.2	1.0	nc	nc	nc	nc	nc	nc
Pipe Creek	2,300	1.0	3.5	1.1	nc	nc	nc	2.4	<3.00	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	2.9	0.9	nc	nc	nc	nc	nc	nc
Pumphouse Gage	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Average corrected residence time, years rounded	Tritium, 2-sigma, pCi/L	Tritium, pCi/L	Tritium, TU	Alpha radio-activity, 2-sigma water, filtered, U natural, pCi/L	Gross alpha radio-activity, water, filtered, U natural, pCi/L	Alpha radio-activity, 2-sigma, water, filtered, ^{230}Th, pCi/L	Alpha PE ^{230}Th, pCi/L	Alpha radio-activity, water, filtered, ^{230}Th, pCi/L	Gross alpha radio-activity, 72 hour count, ^{230}Th curve, pCi/L
Pumphouse Spring	1,900	1.0	<1.0	<0.31	nc	nc	nc	3.0	3.89	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	0.6	0.2	nc	nc	nc	nc	nc	nc
	nc	1.0	2.6	0.8	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Horn Creek	800	1.0	6.4	2.0	nc	nc	nc	3.3	5.93	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	7.0	2.2	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	5.9	4.61	9.4	nc
Salt Creek Spring	2,000	1.0	1.3	0.4	nc	nc	nc	5.5	22	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	3.2	1.0	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	5.87	5.31	14	nc
Monument Creek No. 3	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Monument Spring	3,400	1.0	1.3	0.4	nc	nc	nc	1.3	3.06	nc
	nc	1.0	2.2	0.7	nc	nc	nc	nc	nc	nc
	nc	1.0	1.9	0.6	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hawaii Spring	3,400	1.0	1.6	0.5	nc	nc	nc	2.6	<3.00	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	1.0	<0.31	nc	nc	nc	nc	nc	nc
Hermit Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	4,500	1.0	-1.0	<0.31	nc	nc	5.77	4.01	4.21	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Boucher East Spring	MODERN	1.0	< 1.0	<0.31	nc	nc	nc	2.7	<3.00	nc
	nc	1.0	1.6	0.5	nc	nc	nc	nc	nc	nc
Boucher Spring	MODERN	1.0	8.6	2.7	nc	nc	nc	6.16	5.7	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Slate Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sapphire Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Turquoise Creek	1,200	1.0	5.8	1.8	nc	nc	nc	8.77	14.06	nc
Turquoise Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Ruby Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Serpentine Spring	1,000	1.0	1.6	0.5	nc	nc	nc	6.2	5.24	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Royal Arch Spring	2,000	0.6	5.6	1.8	nc	nc	nc	3.24	4.17	nc
Forster Canyon Spring 2	9,300	1.0	1.2	0.4	nc	nc	11.22	8.17	14.15	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Average corrected residence time, years rounded	Tritium, 2-sigma, pCi/L	Tritium, pCi/L	Tritium, TU	Alpha radio-activity, 2-sigma water, filtered, U natural, pCi/L	Gross alpha radio-activity, water, filtered, U natural, pCi/L	Alpha radio-activity, 2-sigma, water, filtered, ^{230}Th, pCi/L	Alpha PE ^{230}Th, pCi/L	Alpha radio-activity, water, filtered, ^{230}Th, pCi/L	Gross alpha radio-activity, 72 hour count, ^{230}Th curve, pCi/L
Fossil Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
140 Mile Plus Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Matkatamiba Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	1.0	2.2	0.7	nc	nc	nc	10.65	15.1	nc
	5,100	nc	nc	nc	nc	nc	nc	nc	nc	nc
Havasu Spring	12,400	1.0	1.0	<0.31	2.3	6	1.6	nc	4	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Fern Spring	2,200	1.0	1.0	<0.31	2.3	6.3	1.6	nc	4	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Creek	nc	1.0	14.0	4.4	1.8	7.4	1.3	nc	5	nc
Mohawk Canyon Spring	1,700	1.0	<1.0	<0.31	nc	nc	24.63	14.1	14.76	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mohawk Canyon Creek	nc	1.0	1.0	<0.31	3.4	22	2.5	nc	16	nc
	nc	1.0	1.0	<0.31	nc	nc	nc	nc	nc	nc
Dogtown Well #1	11,100	1.0	–0.3	<0.31	nc	nc	1.04	0.96	2.24	nc
Rodeo Grounds Well	22,600	1.0	0.3	<0.31	nc	nc	3.86	3.32	6.23	nc
Bar Four Well	16,500	1.0	0.0	<0.31	nc	nc	nc	10.59	14.33	nc
Ash Fork Well No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	7,500	1.0	–0.3	<0.31	nc	nc	4.46	3.24	3.56	nc
Canyon Mine Well	10,600	1.0	0.4	<0.31	nc	nc	nc	nc	nc	8.46
Patch Karr Well	13,700	0.6	0.0	<0.31	nc	nc	nc	nc	nc	8.48
Havasupai Well No. 1	15,600	2.0	2.0	0.6	2.3	5.9	1.7	nc	4	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Gross alpha radio-activity, 30 day count, ^{230}Th curve, pCi/L	Beta radio-activity, 2-sigma, water, filtered, ^{137}Cs, pCi/L	Beta PE ^{137}Cs, pCi/L	Gross beta radio-activity, water, filtered, ^{137}Cs, pCi/L	Gross beta radio-activity, 72 hour count, ^{137}Cs, pCi/L	Gross beta radio-activity, 30 day count, ^{137}Cs, pCi/L	Beta radio-activity, 2-sigma, water, filtered, Sr/ ^{90}Y, pCi/L	Gross beta radio-activity, filtered, Sr/ ^{90}Y, pCi/L	^{226}Ra, pCi/L	^{228}Ra, pCi/L
King Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Meath Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Storm Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pool Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hitt Springs	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Willow Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Paulden	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at Bull Basin Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Duff Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Duff Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Perkinsville Diversion	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Spring below Perkinsville Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Railroad Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Orchard Fault	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Mormon Pocket	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Small Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Big Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.25 mile above Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sycamore Creek upstream from Summers Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Summers Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.32	1.89	0.3	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Gross alpha radio-activity, 30 day count, ^{230}Th curve, pCi/L	Beta radio-activity, 2-sigma, water, filtered, ^{137}Cs, pCi/L	Beta PE ^{137}Cs, pCi/L	Gross beta radio-activity, water, filtered, ^{137}Cs, pCi/L	Gross beta radio-activity, 72 hour count, ^{137}Cs, pCi/L	Gross beta radio-activity, 30 day count, ^{137}Cs, pCi/L	Beta radio-activity, 2-sigma, water, filtered, Sr/ ^{90}Y, pCi/L	Gross beta radio-activity, filtered, Sr/ ^{90}Y, pCi/L	^{226}Ra, pCi/L	^{228}Ra, pCi/L
Sycamore Creek Spring #2 (opposite Summers)	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.5 mile below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Clarkdale	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Oak Creek near Sedona	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-4	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-8	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-6	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Continental-2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Foxglenn-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pine Grove	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NPS Walnut Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mountainaire	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hidden Hollow	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Flag Ranch	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Purl	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Henden	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NPS Wupatki HQ1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
IB-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Babbitt Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Clark Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Rio de Flag MW-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
FH-5	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Old Town Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Rio de Flag MW-3	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sterling Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NAD-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
BBDP-MVR-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
BBDP-Marijka	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Gross alpha radio-activity, 30 day count, ^{230}Th curve, pCi/L	Beta radio-activity, 2-sigma, water, filtered, ^{137}Cs, pCi/L	Beta PE ^{137}Cs, pCi/L	Gross beta radio-activity, water, filtered, ^{137}Cs, pCi/L	Gross beta radio-activity, 72 hour count, ^{137}Cs, pCi/L	Gross beta radio-activity, 30 day count, ^{137}Cs, pCi/L	Beta radio-activity, 2-sigma, water, filtered, Sr/ ^{90}Y, pCi/L	Gross beta radio-activity, filtered, Sr/ ^{90}Y, pCi/L	^{226}Ra, pCi/L	^{228}Ra, pCi/L
Mtn Dell-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mtn Dell-2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
GC-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Curtain Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Blue Springs	nc	10.61	7.04	8.92	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LCR Mile 3.1	nc	19.63	12.1	11.6	nc	nc	nc	nc	nc	nc
Red Canyon Spring	nc	1.9	1.39	3.67	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
JT Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.65	2.25	5.37	nc	nc	nc	nc	nc	nc
Miners Spring	nc	nc	4.2	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 1	nc	nc	4.9	4.48	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 2	nc	nc	2.3	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Grapevine East Spring	nc	nc	5	5.61	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Grapevine Main Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	2.72	1.6	2.59	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Lonetree Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.18	1.6	2.45	nc	nc	nc	nc	nc	nc
Sam Magee Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Burro Spring	nc	nc	4.6	4.38	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pipe Creek	nc	nc	4.5	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pumphouse Gage	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pumphouse Spring	nc	nc	4.4	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Gross alpha radio-activity, 30 day count, ^{230}Th curve, pCi/L	Beta radio-activity, 2-sigma, water, filtered, ^{137}Cs, pCi/L	Beta PE ^{137}Cs, pCi/L	Gross beta radio-activity, water, filtered, ^{137}Cs, pCi/L	Gross beta radio-activity, 72 hour count, ^{137}Cs, pCi/L	Gross beta radio-activity, 30 day count, ^{137}Cs, pCi/L	Beta radio-activity, 2-sigma, water, filtered, Sr/ ^{90}Y, pCi/L	Gross beta radio-activity, filtered, Sr/ ^{90}Y, pCi/L	^{226}Ra, pCi/L	^{228}Ra, pCi/L
Horn Creek	nc	nc	4.6	5.34	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.58	2.72	13	nc	nc	nc	nc	nc	nc
Salt Creek Spring	nc	nc	5	12.1	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.51	2.87	18	nc	nc	nc	nc	nc	nc
Monument Creek No. 3	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Monument Spring	nc	nc	2.6	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hawaii Spring	nc	nc	4.4	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hermit Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	2.35	1.73	2.67	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Boucher East Spring	nc	nc	4.2	<4.00	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Boucher Spring	nc	nc	3.13	12.34	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Slate Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sapphire Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Turquoise Creek	nc	nc	4.04	15.07	nc	nc	nc	nc	nc	nc
Turquoise Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Ruby Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Serpentine Spring	nc	nc	3.02	6.13	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Royal Arch Spring	nc	nc	4.7	7.4	nc	nc	nc	nc	nc	nc
Forster Canyon Spring 2	nc	8.38	5.26	12.66	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Fossil Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
140 Mile Plus Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Matkatamiba Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	4.57	11.41	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	Gross alpha radio-activity, 30 day count, ^{230}Th curve, pCi/L	Beta radio-activity, 2-sigma, water, filtered, ^{137}Cs, pCi/L	Beta PE ^{137}Cs, pCi/L	Gross beta radio-activity, water, filtered, ^{137}Cs, pCi/L	Gross beta radio-activity, 72 hour count, ^{137}Cs, pCi/L	Gross beta radio-activity, 30 day count, ^{137}Cs, pCi/L	Beta radio-activity, 2-sigma, water, filtered, Sr/ ^{90}Y, pCi/L	Gross beta radio-activity, filtered, Sr/ ^{90}Y, pCi/L	^{226}Ra, pCi/L	^{228}Ra, pCi/L
Havasu Spring	nc	2.5	nc	8	nc	nc	1.9	6.3	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Fern Spring	nc	2.2	nc	8	nc	nc	1.7	5.9	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Creek	nc	3.7	nc	16	nc	nc	2.7	12	nc	nc
Mohawk Canyon Spring	nc	12.32	8.62	17.24	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mohawk Canyon Creek	nc	5.3	nc	20	nc	nc	4	15	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Dogtown Well #1	nc	1.59	1.1	2.54	nc	nc	nc	nc	nc	nc
Rodeo Grounds Well	nc	3.08	2.74	20.83	nc	nc	nc	nc	nc	nc
Bar Four Well	nc	nc	5.38	14.05	nc	nc	nc	nc	nc	nc
Ash Fork Well No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	3.45	2.13	3.62	nc	nc	nc	nc	nc	nc
Canyon Mine Well	3.31	nc	nc	nc	3.86	8.20	nc	nc	0.162	0.448
Patch Karr Well	8.58	nc	nc	nc	2.14	6.68	nc	nc	0.216	0.063
Havasupai Well No. 1	nc	2.2	nc	7	nc	nc	1.7	5.4	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	^{222}Rn, 2-sigma, water, unfiltered, pCi/L	^{222}Rn, water, unfiltered, pCi/L	U natural, 2-sigma, water, filtered, µg/L	U natural, water, filtered, µg/L	^{234}U, 2-sigma, water, filtered, pCi/L	^{234}U, water, filtered, pCi/L	^{235}U, 2-sigma, water, filtered, pCi/L	^{235}U, water, filtered, pCi/L	^{238}U, 2-sigma, water, filtered, pCi/L	^{238}U, water, filtered, pCi/L
King Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Meath Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Storm Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pool Seep	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hitt Springs	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Willow Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Paulden	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at Bull Basin Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Duff Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Duff Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Duff Spring No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Hell Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River at US Mine No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Perkinsville Diversion	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring near Perkinsville	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Spring below Perkinsville Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Railroad Bridge	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Orchard Fault	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River above Mormon Pocket	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Small Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mormon Pocket Big Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.25 mile above Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sycamore Creek upstream from Summers Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Summers Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	^{222}Rn, 2-sigma, water, unfiltered, pCi/L	^{222}Rn, water, unfiltered, pCi/L	U natural, 2-sigma, water, filtered, µg/L	U natural, water, filtered, µg/L	^{234}U, 2-sigma, water, filtered, pCi/L	^{234}U, water, filtered, pCi/L	^{235}U, 2-sigma, water, filtered, pCi/L	^{235}U, water, filtered, pCi/L	^{238}U, 2-sigma, water, filtered, pCi/L	^{238}U, water, filtered, pCi/L
Sycamore Creek Spring #2 (opposite Summers)	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River 0.5 mile below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Spring below Sycamore Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Verde River near Clarkdale	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Oak Creek near Sedona	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-4	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-8	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LM-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-6	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
WM-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Continental-2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Foxglenn-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pine Grove	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NPS Walnut Canyon	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mountainaire	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hidden Hollow	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Flag Ranch	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Purl	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Henden	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NPS Wupatki HQ1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
IB-9	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Babbitt Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Clark Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Rio de Flag MW-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
FH-5	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Old Town Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Rio de Flag MW-3	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sterling Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
NAD-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
BBDP-MVR-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
BBDP-Marijka	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	^{222}Rn, 2-sigma, water, unfiltered, pCi/L	^{222}Rn, water, unfiltered, pCi/L	U natural, 2-sigma, water, filtered, µg/L	U natural, water, filtered, µg/L	^{234}U, 2-sigma, water, filtered, pCi/L	^{234}U, water, filtered, pCi/L	^{235}U, 2-sigma, water, filtered, pCi/L	^{235}U, water, filtered, pCi/L	^{238}U, 2-sigma, water, filtered, pCi/L	^{238}U, water, filtered, pCi/L
Mtn Dell-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mtn Dell-2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
GC-1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Curtain Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Blue Springs	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
LCR Mile 3.1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Red Canyon Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
JT Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Miners Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Cottonwood Creek No. 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Grapevine East Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Grapevine Main Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Lonetree Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sam Magee Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Burro Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pipe Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pumphouse Gage	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Pumphouse Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	^{222}Rn, 2-sigma, water, unfiltered, pCi/L	^{222}Rn, water, unfiltered, pCi/L	U natural, 2-sigma, water, filtered, µg/L	U natural, water, filtered, µg/L	^{234}U, 2-sigma, water, filtered, pCi/L	^{234}U, water, filtered, pCi/L	^{235}U, 2-sigma, water, filtered, pCi/L	^{235}U, water, filtered, pCi/L	^{238}U, 2-sigma, water, filtered, pCi/L	^{238}U, water, filtered, pCi/L
Horn Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Salt Creek Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Monument Creek No. 3	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Monument Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hawaii Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Hermit Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Boucher East Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Boucher Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Slate Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Sapphire Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Turquoise Creek	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Turquoise Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Ruby Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Serpentine Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Royal Arch Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Forster Canyon Spring 2	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Fossil Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
140 Mile Plus Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Matkatamiba Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

Isotope data for water from springs, streams, and wells that discharge from the C aquifer and the Redwall-Muav aquifer, Coconino Plateau study area, Coconino and Yavapai Counties, Arizona, 1991–2004—Continued.

Spring, stream, well, or owner name	^{222}Rn, 2-sigma, water, unfiltered, pCi/L	^{222}Rn, water, unfiltered, pCi/L	U natural, 2-sigma, water, filtered, µg/L	U natural, water, filtered, µg/L	^{234}U, 2-sigma, water, filtered, pCi/L	^{234}U, water, filtered, pCi/L	^{235}U, 2-sigma, water, filtered, pCi/L	^{235}U, water, filtered, pCi/L	^{238}U, 2-sigma, water, filtered, pCi/L	^{238}U, water, filtered, pCi/L
Havasu Spring	nc	nc	1.4	4	0.35	2.9	0.02	< 0.1	0.16	1.1
	26	100	nc	nc	nc	nc	nc	nc	nc	nc
Fern Spring	nc	nc	1.2	4	0.44	3.6	0.03	< 0.1	0.17	1.2
	26	380	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
National Canyon Creek	nc	nc	nc	4	0.49	4	0.04	< .1	0.27	1.9
Mohawk Canyon Spring	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Mohawk Canyon Creek	92	160	nc	12	1.1	10	0.06	0.2	0.59	5.2
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Dogtown Well #1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Rodeo Grounds Well	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Bar Four Well	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Ash Fork Well No. 1	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
Canyon Mine Well	nc	nc	nc	nc	nc	9.151	nc	0.2145	nc	4.509
Patch Karr Well	nc	nc	nc	nc	nc	8.369	nc	0.2485	nc	5.012
Havasupai Well No. 1	nc	nc	1.1	3	0.44	3.7	0.02	< 0.1	0.18	1.4
	30	440	nc	nc	nc	nc	nc	nc	nc	nc

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