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The Verde River Headwaters, Yavapai County, Arizona

By Laurie Wirt

Chapter A

Geologic Framework of Aquifer Units and Ground-Water Flowpaths, Verde River Headwaters, North-Central Arizona

Edited by Laurie Wirt, Ed DeWitt, and V.E. Langenheim

Prepared in cooperation with the Arizona Water Protection Fund Commission

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This report has not been reviewed for stratigraphic nomenclature.

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The Verde River Headwaters, Yavapai County, Arizona

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Abstract

This study combines the results of geophysical, geologic, and geochemical investigations to provide a hydrogeologic framework of major aquifer units, identify ground-water flowpaths, and determine source(s) of base flow to the upper Verde River. This introductory chapter provides an overview of previous studies, predevelopment conditions, present surface-water and ground-water conditions, and a conceptual water budget of the hydrologic system. In subsequent chapters, this conceptual model will be evaluated and refined with respect to the results of each successive investigation. First, a compilation of mapping and field verification of the surficial geology, reinterpretation of driller's logs, and contour mapping of alluvial thicknesses and buried volcanic rocks provide new three-dimensional geologic information. Second, a suite of geophysical techniques—including aeromagnetic and gravity surveys and inverse modeling approaches—was used to interpret the deeper subsurface geology. Third, geologic, geophysical, and hydrological data were integrated to define basin boundaries, describe aquifer units in the basin-fill aquifers of Big and Little Chino valleys and the regional carbonate aquifer north of the upper Verde River, and develop a hydrogeologic framework. Water-level gradients were used to infer outlet flowpaths from the basin-fill aquifers through the carbonate aquifer toward the upper Verde River. Fourth, geochemical investigations employing analyses of dissolved major and trace elements and isotopes of δD, $\delta^{18}O$, ^{3}H, ^{13}C, and ^{14}C were used to characterize major aquifers, identify recharge areas, and determine evolution of water chemistry along ground-water flowpaths. Fifth, results of a tracer-dilution study and synoptic sampling identify locations of major spring inflows discharging to the upper Verde River, measure base-flow contributions, which were used to calculate the relative contributions from each aquifer to upper Verde River springs using inverse geochemical modeling. In the final chapter, synthesis of multiple lines of evidence improve understanding of the relationships between the three aquifers, regional ground-water flowpaths, and the proportion of flow from each aquifer to the upper Verde River. Collectively, data from many varied and independent sources improves confidence in the conceptual model of the hydrogeologic system.

Introduction

The Verde River begins in a canyon below the confluence of two tributary basin-fill aquifers in Big and Little Chino valleys (fig. A1). The two basin-fill aquifers and an adjoining carbonate aquifer supply a network of springs that discharge about 25 cubic feet per second (ft^3/s) of base flow to a 24-mi reach of river canyon between Granite Creek and Perkinsville (fig. A2, table A1). Most of the ground-water gains occur within the first few miles. Semiarid Big and Little Chino valleys are experiencing rapid population growth, which is entirely dependent on ground water. A detailed understanding of ground-water movement in the three aquifers is critical toward maintaining base flow in the upper Verde River.

Homeowners, municipalities, ranchers, environmental organizations, water utilities, and agencies responsible for resource management at the County, State, and Federal levels have a need to understand the geologic framework of major aquifers that are used for human water supply and that sustain the natural environment. Stakeholders recognize that an improved understanding of the hydrogeologic system is needed to manage water resources and to address the concerns of limited water supplies and environmental degradation. There is a need to understand not only the source of base flow to the Verde River but also the underlying geologic framework including the geometry, the geologic conduits and barriers that affect ground-water flowpaths, and the structure of the individual aquifer units where the greatest quantities of water are stored.

Purpose and Scope

The area of investigation for the upper Verde River (figs. A1 and A2) was selected at the basin scale of the three principal aquifers (fig. A3) to include the Big and Little Chino valleys, the regional carbonate aquifer north of the Verde River, and surrounding upland areas. The upper Verde River is located in north-central Arizona, in Yavapai County, and begins about 20 mi north of Prescott. The river flows from west, near the town of Paulden; to east, near the town of Clarkdale. The study area is roughly bounded to the north by the

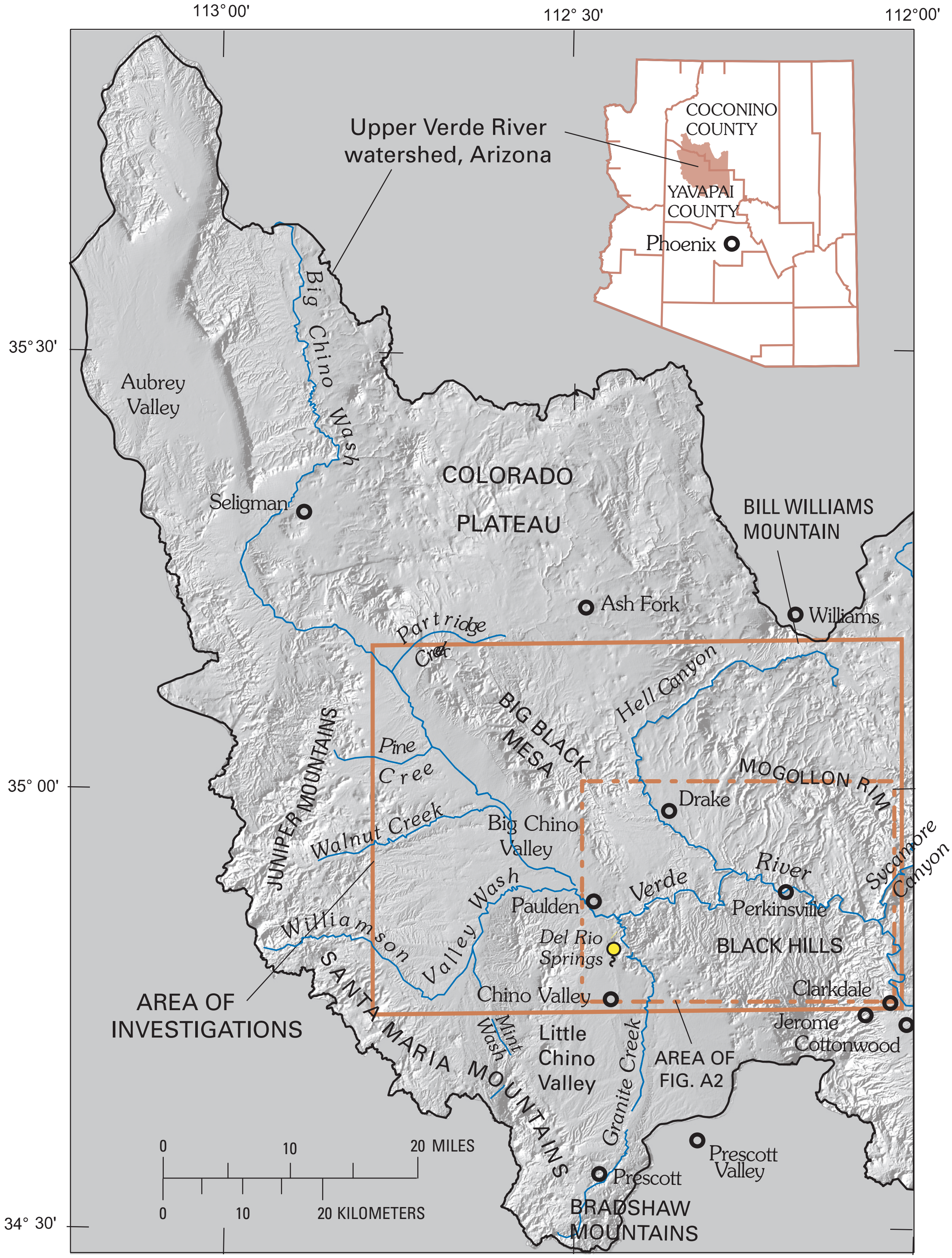

Figure A1. Shaded relief map showing upper Verde River watershed, locations of major physiographic features, and principal area for study investigations in this report. Base is from U.S. Geological Survey digital data 1:100,000; sun angle elevation is 45 degrees from southeast; azimuth is 120 degrees.

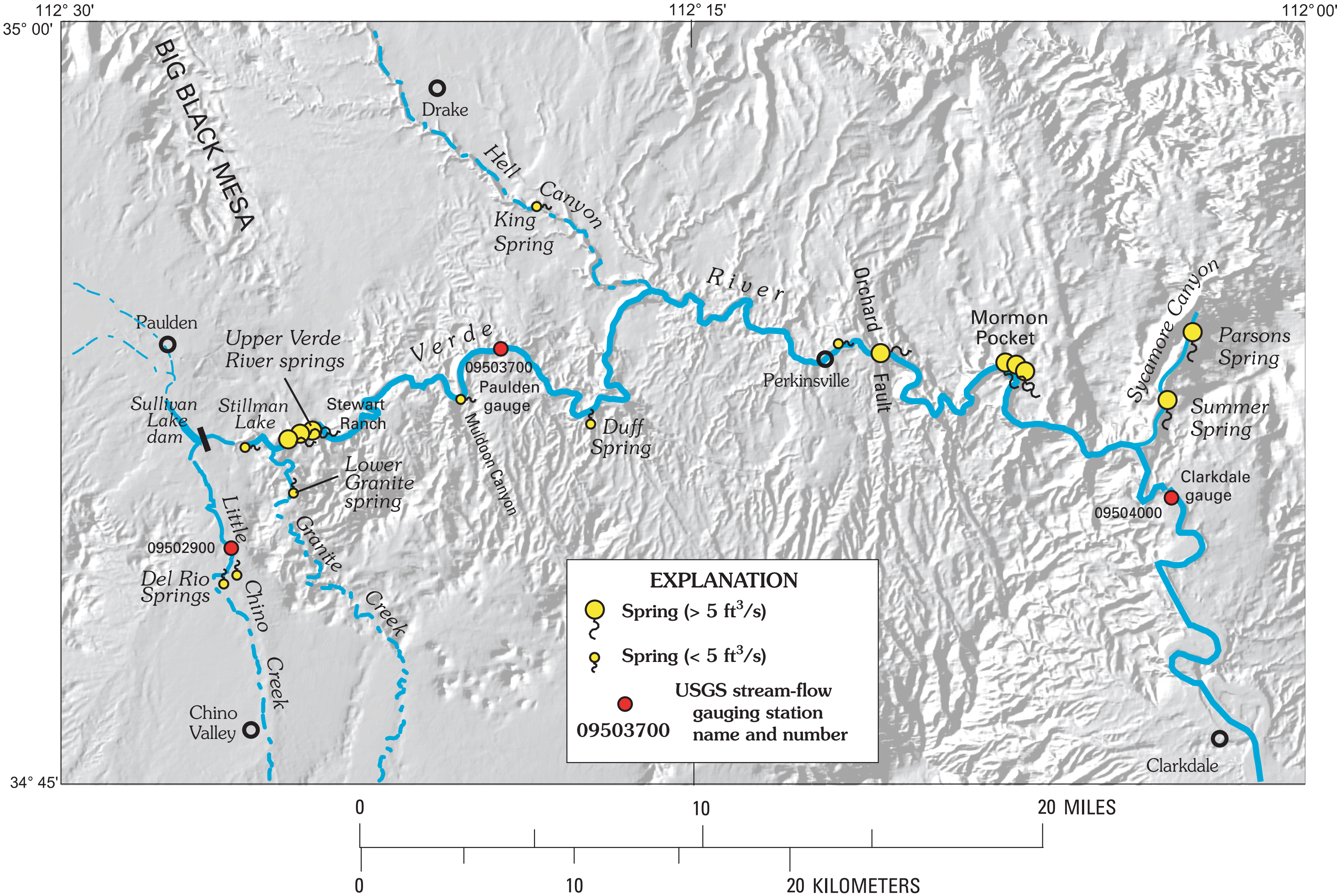

Figure A2. Locations of known springs along the upper Verde River from Sullivan Lake to Sycamore Creek. Base is from U.S. Geological Survey digital data 1:100,000; sun angle elevation is 45 degrees from southeast; azimuth is 120 degrees.

Table A1. Distance from Sullivan Lake dam to major springs, tributaries, and other geographic locations along the upper Verde River, Arizona.

[Distances are approximate and have not been surveyed]

Major tributaries or physiographic features	Miles	Kilometers
Del Rio Springs via Little Chino Creek	–3.0*	–4.8*
Lower Granite Spring*	1.0**	1.6**
Sullivan Lake Dam	0.0	0.0
Stillman Lake (upstream end)	1.0	1.6
Stillman Lake (downstream end)	1.9	3.1
Granite Creek confluence	2.0	3.2
Continuous flow begins	2.1	3.4
Upper Verde River springs (upstream end)	2.2	3.6
Stewart Ranch (west access)	3.2	5.1
Muldoon Canyon	8.0	12.9
Paulden gauge (09503700)	9.8	15.8
Verde Valley Ranch	10.3	16.6
Bull Basin Canyon	11.5	18.5
Duff Spring	13.9	22.4
Hell Canyon	18.0	29.0
U.S. Mine	19.4	31.2
Perkinsville diversion ditch	23.7	38.1
Perkinsville	24.0	38.6
Verde River near Orchard Fault	26.0	41.8
RR Crossing downstream of Perkinsville	26.6	42.8
Mormon Pocket springs	31.0	49.9
Sycamore Canyon	34.9	56.2
Clarkdale gauge (09504000)	36.6	58.9

*Distance upstream from Sullivan Lake dam
**Distance upstream from Granite Creek and Verde River confluence

Mogollon Rim and northwest by Big Black Mesa (fig. A4), and to the east by Sycamore Canyon. To the southeast, the boundaries are the Black Hills and Agua Fria watershed, and to the south and southwest, the study area includes the Bradshaw, Santa Maria, and Juniper Mountains. The westernmost boundary of the study area is the confluence of Big Chino Wash with Partridge Creek. For this report, the reach referred to as the "upper Verde River" is the 10-mi reach upstream from the U.S. Geological Survey streamflow gauging station near Paulden (station number 09503700 on fig. A2; river mi 10; referred to in this report as the "Paulden gauge").

The common goal of the multi-disciplinary studies in this report is to provide a more detailed understanding of the hydrogeologic framework of the Verde River headwaters, especially the relation between major aquifers and the upper Verde River. Major aquifers contributing to the upper Verde River include (*A*) the two Big and Little Chino basin-fill aquifers and adjoining carbonate aquifer underlying Big Chino Valley and Big Black Mesa, and (*B*) the part of the carbonate aquifer directly north of the upper Verde River between Big Black Mesa and Hell Canyon. As part of the geochemical investigations, some additional sampling was conducted downstream from the main study area to better characterize water chemistry of springs discharging from the carbonate aquifer between Perkinsville and Sycamore Creek.

The chapters in this report present geologic, geophysical, hydrogeologic, and geochemical interpretations for the Verde River headwaters study area. Surficial geologic maps are based on compilation of earlier studies and reconnaissance mapping. Sub-surface geologic interpretations are based on modeling of gravity measurements and high-resolution airborne geophysical data, and by interpreting available well

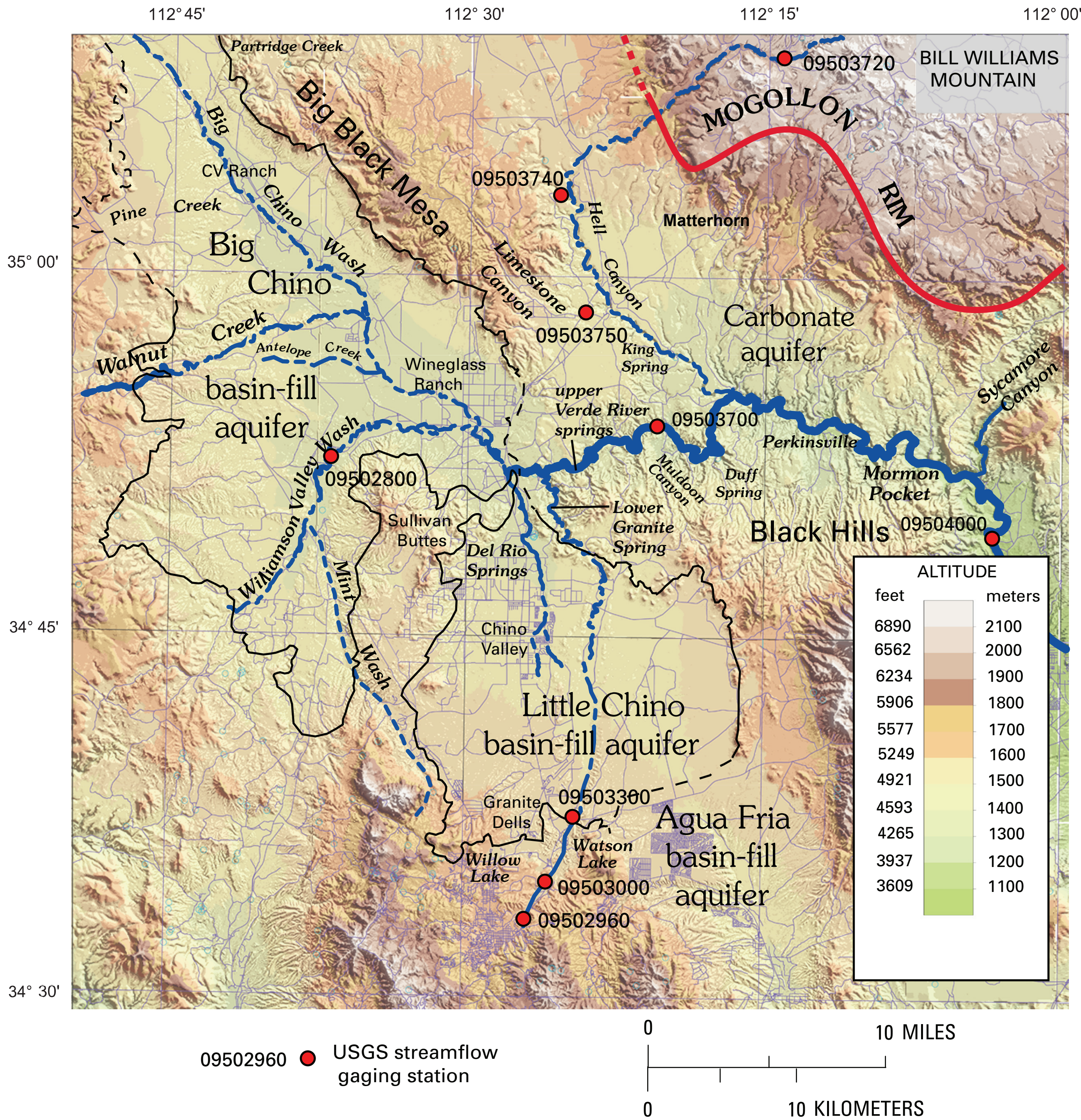

Figure A3. Shaded elevation map showing basin-fill aquifer boundaries. Basin-fill aquifer boundaries are dashed where likely interconnected with adjacent carbonate aquifer (Wirt and DeWitt, this volume; Chapter D). Base is from 1:100,000 U.S. Geological Survey digital data.

Figure A4. Photograph of Paleozoic rocks exposed on Big Black Mesa. Big Black Mesa forms the northern boundary of the Transition Zone with the Colorado Plateau. View is northwest. Rocks in foreground are Devonian Martin Formation capped by cliff-forming Mississippian Redwall Limestone. Prominent peak in distance is Picacho Butte.

logs and borehole data. An understanding of the hydrogeology was developed from the geology and from water-level data, surface-water data, and other hydrologic information. Interpretations of ground-water source areas and flowpaths were determined from geochemical and stable-isotope data from selected wells and springs and the relative age of ground water and the location of recharge areas is inferred from naturally occurring radioactive isotopes of tritium and carbon-14 (^{14}C). Sources of ground-water inflow to the upper Verde River were characterized and quantified based on the results of a tracer study and synoptic sampling during low-flow conditions. Finally, multiple lines of geochemical evidence were integrated by inverse modeling using PHREEQC, a computer program for simulating chemical reactions and mixing (Parkhurst and Appelo, 1999).

The studies in this report were designed to address data gaps in earlier studies and in available geologic, geophysical, driller's log, water-level, water-chemistry, and stable-isotope data. Ongoing geologic mapping efforts by the U.S. Geological Survey (USGS) in the Prescott National Forest was supplemented by field mapping and reinterpretation of drillers logs from the ADWR database (Arizona Department of Water Resources, 2002). Ground-based gravity data and an airborne survey of magnetic and radiometric data were subcontracted in 1999 by World Geoscience (now Fugro) and in 2000 by Goldak Airborne Surveys. Geochemical studies include (a) geochemical analysis of wells and springs that were sampled for this study from 1999 to 2004, and (b) a June 2000 tracer-dilution study in the major gaining reach of the uppermost Verde River during low-flow conditions. Results of each study are presented sequentially and integrated with other studies to create a multidisciplinary conceptual model of the hydrogeology of the Verde River headwaters study area.

Collectively, the studies in this report yield information on geologic structures and basin geometry, ground-water flowpaths, relative rates of travel, and relative contributions from different aquifer sources that presently are needed by ground-water modelers and water-resource managers in State and Federal agencies, the Prescott Active Management Area, the Yavapai County Water Advisory Committee, and other stakeholders throughout the Verde River watershed.

Overview of Report

Each chapter in this report presents the results of a different discipline or approach, with the final chapter serving as a synthesis and summary of all the results. As much as possible, chapters in this report are arranged in a logical sequence so that earlier chapters help provide a basis for subsequent interpretations made in following chapters. Geologic interpretations provide a framework for interpreting the geophysical investigations, as well as describing aquifer units. In much the same way, results of the geophysical surveys were used to interpret the basin geometry and subsurface geology. Both the geology and geophysics chapters provide background for the hydrogeology chapter. The hydrogeologic framework, in turn, helps constrain geochemical interpretations in water-chemistry chapters regarding ground-water flow directions and source areas of major springs discharging to the upper Verde River.

Chapter A—The Verde River Headwaters: This chapter provides an overview of study objectives as well as a compilation of background information about physical features, climate, and the hydrologic system as it is presently understood. Available data on predevelopment conditions, surface and ground-water conditions, water use, and a conceptual water budget based on recharge estimates from earlier studies also are presented.

Chapter B—Geologic framework: The regional geologic history and the physical nature of rock units and sediments are described. Geologic reinterpretation of driller's logs and contour mapping of buried volcanic rocks and overlying alluvium provides a three-dimensional understanding of the shallow geology, with emphasis near the outlets of the Big and Little Chino basins.

Chapter C—Geophysical framework: Geophysical modeling is used to estimate basement geometry in deeper parts of the alluvial basins and beneath adjoining upland areas, especially where deep well logs are unavailable. Aeromagnetic data are used to identify contrasts between rock and alluvium that promote or obstruct ground-water movement such as large faults and buried volcanic rocks. Gravity measurements are interpreted to estimate basin geometry, basin thickness, and structural features.

Chapter D—Hydrogeologic framework: The permeability and water-bearing characteristics of rock and sediment units within the major aquifers, basin geometry, aquifer boundaries, and nature of faults and buried volcanic rocks are described. Water-level gradients are integrated with geologic information to define ground-water flowpaths near the outlets of the basin-fill aquifers.

Chapter E—Geochemistry of major aquifers and springs: Trends in the concentrations of dissolved major and trace elements are used to characterize each major aquifer. Stable isotopes of hydrogen and oxygen are used to infer the altitude of recharge source areas. Naturally occurring radioactive isotopes of tritium and carbon-14 help to identify areas where modern recharge is occurring and indicate apparent ages of ground water. Changes in water chemistry are delineated along selected ground-water flowpaths.

Chapter F—Sources of base flow in the upper Verde River: A tracer-injection study and synoptic water-chemistry sampling were conducted during low-flow conditions to determine locations of diffuse springs and to quantify the relative contributions from each major aquifer source to base flow. Sources of inflows are identified on the basis of multiple lines of geochemical evidence, including field parameters, major and trace elements, and stable isotopes of hydrogen and oxygen. Multi-parameter inverse-geochemical modeling is used to determine the relative contribution from each major source, including the carbonate aquifer north of the Verde River.

Chapter G, Synthesis of Geologic, Geophysical, Hydrogeological, and Geochemical Evidence: The final chapter summarizes and integrates results of the earlier chapters to provide understanding of interconnections between the aquifers and the Verde River, directions of ground-water flowpaths, and relative contributions from each of the major source areas.

Acknowledgments

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Environmental Setting

In a multidisciplinary study of this scope, it is necessary to examine the framework elements at a broad range of scales in order to evaluate major geologic features, topographic relief, and major aquifer units at the proper perspective. Framework components considered at the regional scale are physiographic features such as topography, climate, ecology, and geology. Components considered at the basin or aquifer scale include all of the regional factors plus well and spring data, surface-water runoff data, underlying basement geometry, and local structural features. Interrelations among these factors provide the context for movement of ground water from the principal recharge areas, through the major aquifers, to major springs.

Geology generally is a major topic in a discussion of environmental setting; however, because it is the major focus of the next three chapters, the regional geologic setting is not presented here. The following discussions of historical water use, threatened and endangered species, physical features, and climate provide background for hydrological information summarized in the remainder of this chapter.

History of Water Use

The Verde River headwaters area has played an important role in Arizona history. Archeological artifacts indicate ancestral native Americans lived here thousands of years ago, as evidenced by ruins throughout the upper Verde River canyon and its major tributaries (fig. A5). Gold mining and ranching brought settlers to the Prescott area in the 1850s and 1860s. Owing to its excellent water supply and tall grass for grazing, the provisional territorial capital of Arizona initially was established at Del Rio Springs in 1864 (fig. A6; Henson, 1965). After several months, the fort was moved to Prescott to be closer to gold mining and timber resources in the Bradshaw Mountains (fig. A1). Military forces were sent to protect miners and early settlers of the Arizona Territory from raids by Apache Indians. In the late 1800s, early white settlers successfully cultivated the area surrounding Del Rio springs, growing hay and vegetables for the miners and eventually shipping to more distant markets (Munderloh, 2000 and 2001; Allen, Stephenson & Associates, 2001). A ranching and farming settlement was established in Big Chino Valley by 1879 (Granger, 1985).

From 1901 through the 1930s, ranches and farms near Del Rio Springs supplied food and water for the railroad and tourism industry in Grand Canyon (Metzger, 1961), as well as the northern Arizona railroad towns of Ash Fork, Seligman, Williams, and Winslow. Ash Fork would be totally dependent on Del Rio water until 1956 (Allen, Stephenson & Associates, 2001). Trains stopped at Del Rio Springs to fill tank cars and transport farm produce. Also, the city of Prescott built a 21-mi pipeline from Del Rio Springs to Prescott in 1901 (Krieger, 1965; p. 115). The pipeline supplied 500,000 gallons per day (560 acre-ft/year; Baker and others, 1973) between 1904 and 1927 (Schwalen, 1967). Although the water supply was adequate for Prescott's needs, the cost of pumping was considered excessive, and the pipeline eventually was disassembled (Krieger, 1965). In the winter of 1925–26, the railroad drilled two wells at Del Rio Springs to replace the sump-pump system there (Matlock and others, 1973; p. 44). Beginning in the late 1930s, many deep wells were drilled for agricultural irrigation to tap the artesian aquifer underlying the town of Chino Valley. In 1947, the city of Prescott drilled two wells approximately 5 mi south of Del Rio Springs (Krieger, 1965), offering a much shorter pipeline. This event was the beginning of the main well field in Chino Valley that continues to supply most of the municipal water for the city of Prescott and the town of Chino Valley.

In the mid-1930s, Sullivan Lake was constructed as a public works project to offer recreation and fishing below the confluences of Williamson Valley Wash, Big Chino Wash, and Little Chino Creek. Perennial flow in Little Chino Creek and probably lower Big Chino Wash extended upstream from the dam at the time of its construction. Historical photos show a small sluice to divert base flow around the dam during construction (fig. A7). The lake filled with sediment by the early 1940s, and today its maximum depth is less than several feet. The small dam is a local landmark and generally is recognized as the beginning of the Verde River.

The upper Verde River is an important part of the water supply for downstream water users in Verde Valley communities and the city of Phoenix, and is particularly valued for its water quality. The Verde River generally is lower in total dissolved solids than other Phoenix water-supply sources, including the Salt River, Central Arizona Project water, and ground water from southeastern and western Salt River Valley (Greg Elliot, Salt River Project, written commun., 2004). Moreover, the Verde River is a precious supply of reliable water during prolonged droughts.

Accelerated development has led to increasing concern about water resource issues and the effects of pumping on base flow of the upper Verde River. Water use in the Tri-Cities area of Prescott, Prescott Valley, and Chino Valley is growing rapidly as the area becomes a suburban and retirement destination. The rural towns of Chino Valley and Paulden in Big Chino Valley are shifting away from an economy of irrigated agriculture and ranching to one of suburban land use, such as housing. The primary crops used to be cattle, corn, and alfalfa, but important agricultural products now include turf, hothouse flowers, and fresh produce. From 1980 to 1997, Yavapai County's population increased 108 percent from 68,145 to 142,075; or an average of 6.4 percent annually over the 17-year period (Arizona Department of Water Resources, 2000; Arizona Department of Economic Security, 1990; Arizona Department of Commerce, 1993–1997). In the year 1997, Yavapai County was one of three counties in the State that experienced an increase in population greater than 24.6 percent. In the Little Chino subbasin, the populations of Prescott and Chino Valley increased by 170 and 244 percent from 1980 to 1997, respectively (Arizona Department of Water Resources, 2000; table 2–2).

Water resources in both the Big and Little Chino basin-fill aquifers are under increasing pressure from population growth and residential development. The Little Chino basin-fill aquifer lies within the state-designated Prescott Active Management Area (PRAMA), which regulates ground-water withdrawals (Arizona Department of Water Resources, 1998). In 1999, the Arizona Department of Water Resources (ADWR) determined that the PRAMA was no longer at safe yield. Safe yield is an Arizona State water management goal that attempts to maintain a long-term balance between the amount of water withdrawn and the amount of water naturally and artificially recharged to the system. Since 1997, the PRAMA overdraft in excess of recharge has been estimated on the order of 6,610 to 9,830 acre-ft/year (Arizona Department of Water Resources, 1998, 1999a, 1999b, and 2000). To counterbalance the growing overdraft, the PRAMA plans to augment its water supplies from outside its watershed (Arizona Department of Water Resources, 1999b; Arizona State Legislature, 1991). Recently, the City of Prescott purchased a ranch in upper Big Chino Valley with the intent of building a pipeline to import 8,717 acre-ft/yr into the PRAMA (Southwest Groundwater Consultants, 2004). Concerns that future pumping of the Big Chino aquifer will decrease the flow of the Verde River are compounded by less restrictive development occurring outside the PRAMA in Big Chino Valley.

Figure A5. Photograph of ancient fort ruin on bluff overlooking the upper Verde River. Photograph by M. Collier.

Figure A6. Aerial photograph of heavily vegetated area surrounding Del Rio Springs (foreground), Tertiary volcanic rocks of the Sullivan Buttes volcanic field (middle ground), and Paleozoic sedimentary rocks of the Colorado Plateau (background). View is to the northeast. Photograph by M. Collier.

Figure A7. Photographs showing construction of Sullivan Lake Dam, circa 1936. View is west. Sluice box in upper photo was used to divert perennial flow around the dam. Exposed rocks in gorge near the dam are 4.5 Ma basalt flows. Sullivan Buttes shown at skyline in upper photo. Note sediment filling channel upstream of the dam.

Since 1940, ground-water levels in Little Chino Valley have declined more than 75 ft in the north end of the basin—only a few miles from Del Rio Springs and the source springs of the Verde River (Arizona Department of Water Resources, 1999a and 2000; Corkhill and Mason, 1995; Remick, 1983). Decreasing ground-water storage trends have been observed in most parts of the PRAMA (Arizona Department of Water Resources, 1999). In 2003, the annual discharge of Del Rio Springs was about 1,000 acre-ft/year (Fisk and others, 2004)—less than one-half the 2,400–3,400 acre-ft/year of annual discharge when the spring was first gauged between 1940 and 1945 (Schwalen, 1967). Perennial flow in the Verde River historically began near Del Rio Springs (Henson, 1965; Krieger, 1965; p. 118), but year-round flow to Sullivan Lake via Little Chino Creek had disappeared by the early 1970s (A.L.Medina; U.S. Forest Service, oral commun., 1999), owing to agricultural diversions and ground-water pumping.

Threatened and Endangered Species

The upper Verde River sustains important riparian habitat for fish and wildlife, including several threatened and endangered species. The U.S. Fish and Wildlife Service (2000) has designated the reach of the Verde River below Sullivan Dam as critical habitat for two threatened species, the spikedace minnow (*Meda fulgida*) and the extirpated loach minnow (*Tiaroga cobitis*). Native populations of spikedace minnow have been identified within this reach and elsewhere in the Verde River. Wildlife biologists consider lower Granite Creek, a perennial tributary to the upper Verde River, a particularly important expansion area for the recovery of spikedace (U.S. Fish and Wildlife Service, 2000).

Native fish populations in the upper Verde River are recognized as among the most diverse in Arizona (Arizona Game and Fish, 2004). Because of its outstanding native fish diversity and abundance as indicators of biotic integrity, Arizona Game and Fish acquired 796 acres along the upper Verde River and lower Granite Creek, now designated as the upper Verde River Wildlife area (Arizona Game and Fish, 2004). Arizona Game and Fish's primary management objective for this area is to monitor, manage, and maintain the extant native fish populations, which also include roundtail chub (*Gila robusta*), razorback sucker (*Xyrauchen texanus*), desert sucker (*Catostomus clarki*), Sonora sucker (*Catostomus insignis*), Longfin dace (*Agosia chrysogaster*), and speckled dace (*Rhinichthys osculus*).

Other wildlife of special concern that may occupy the upper Verde River and vicinity include Northern leopard frog (*Rana pipiens*), Mexican garter snake (*Thamnophis eques*), Arizona toad (*Bufo microscaphus*), belted kingfisher (*Ceryle alcyon*), Bald eagle (*Haliaeetus leucocephalus*), common black hawk (*Buteogallus anthracinus*), peregrine falcon (*Falco peregrinus*), southwestern willow flycatcher (*Empidonax traillii extimus*), red bat (*Lasiurus borealis*), spotted bat (*Euderma maculatum*), and southwestern river otter (*Lontra canadensis sonora*) (Arizona Game and Fish, 2004).

Physical Features

The Verde River is part the Colorado River drainage basin which empties into the Gulf of California. The world famous Grand Canyon is the next major drainage to the north, and Phoenix's West Salt River basin is the next large valley to the south. The Verde River headwaters region covers 2,500 mi^2 of rugged mountains, steeply incised canyons, and rolling valleys, including Big and Little Chino valleys and Williamson Valley. Mountain ranges are predominantly oriented northwest to southeast with maximum elevations between 6,000 and 9,000 ft above mean sea level. The "headwaters" area is the source and upper part of a stream, especially of a large stream or river, including the upper drainage basin (Bates and Jackson, 1980). For the purposes of this report, the "Verde River headwaters" is defined as the part of the watershed upstream from the Paulden gauge (fig. A2). The largest spring inflows occur immediately downstream from the confluence of the Verde River and Granite Creek, which also is the confluence of the Big and Little Chino Valley topographical watersheds. At least 80 percent of the base flow at the Paulden gauge is supplied by upper Verde River springs (Wirt and Hjalmarson, 2000), also referred to as Big Chino Springs or Headwater Springs. The remaining inflow is derived from Stillman Lake, lower Granite Creek, and a small gain occurs near Muldoon Canyon (fig. A2). Duff Spring is the only known spring in the reach between the Paulden gauge and Perkinsville.

Major tributaries to Sullivan Lake and the upper Verde River (the reach upstream from the Paulden gauge) include Big Chino Wash, Williamson Valley Wash, Little Chino Creek, and Granite Creek. The reach of the Verde River upstream from Verde Valley begins at the Sullivan Lake dam and ends at the mouth of Sycamore Canyon (fig. A2, table A1). This 35-mi reach receives ephemeral tributary runoff in the narrow bedrock canyon between Granite Creek and the mouth of Sycamore Creek. On the north side of the Verde River, the largest tributary is Hell Canyon. South of the Verde River, this reach drains many low-lying canyons (altitudes are mostly between 4,000 and 5,000 ft).

The effective surface drainage of Big Chino Valley encompasses 1,850 mi^2 including Big Chino Valley, Williamson Valley, and at least 600 mi of watershed north of Interstate 40 between the towns of Seligman and Ashfork (fig. A1)—but does not include 357 mi^2 in Aubrey Valley, a closed basin (Schwab, 1995). Bill Williams Mountain is the highest peak at 9,256 ft, compared with 4,117 ft at the Paulden gauge. About 15 percent of the Big Chino watershed (about 280 mi^2) exceeds an altitude of 6,000 ft, predominantly in the Bradshaw, Santa Maria, and Juniper Mountains (Wirt and Hjalmarson, 2000). Several peaks in these three mountain ranges exceed an altitude of 7,000 ft. The largest tributary is Williamson Valley Wash, with a drainage area of 255 mi^2. Flow in lower Williamson Valley Wash is perennial for about 4.2 miles, from near its confluence with Mint Wash to the Williamson Valley Wash USGS streamflow gauging station near Paulden (09502800). Walnut Creek has perennial segments

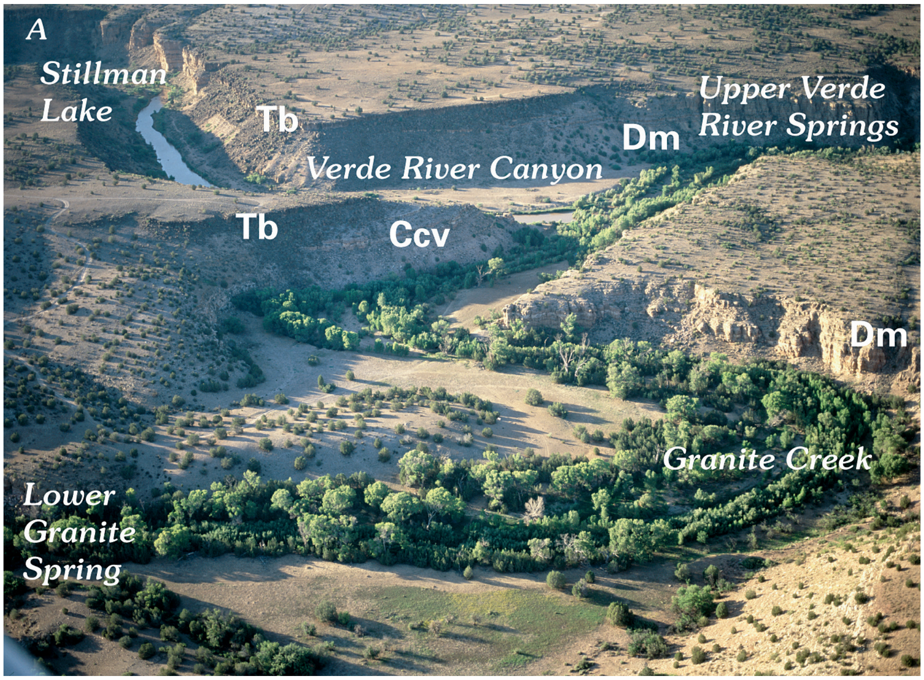
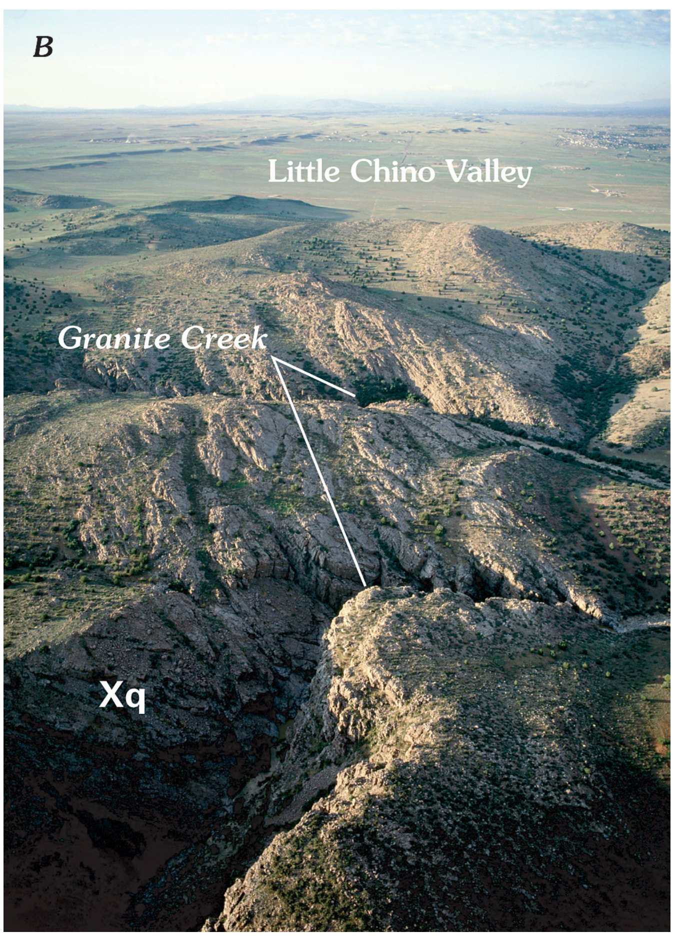


Figure A8. Aerial photographs of lower Granite Creek. A, Lower Granite Creek and its confluence with the upper Verde River. View is north. Last mile of both Granite Creek and the Verde River above confluence are perennial. Canyon walls of Devonian Martin Formation and Chino Valley Formation (Cambrian?) capped by Tertiary basalt; B, Rugged bedrock canyon in lower Granite Creek. View is south toward Little Chino ground-water basin. Dipping strata are Proterozoic Mazatzal Quartzite. Photographs by M. Collier.



and perennial tributaries west of the study area boundary, including North and South Forks and Apache Creek.

Little Chino Valley differs from Big Chino Valley in that it has not one but two surface-water outlets—Granite Creek and Little Chino Creek. The combined watershed area of Granite Creek and Little Chino Creek is about 300 mi^2 (Corkhill and Mason, 1995). Granite Creek has upper, middle, and lower reaches that are quite different in character. Granite Creek is perennial near Prescott where it is close to the Bradshaw Mountains. Middle Granite Creek is a wide, sandy, ephemeral wash north of the Granite Dells that accounts for the southern and eastern two-thirds of the Little Chino ground-water basin. In its lowermost reach above its confluence with the Verde River, Granite Creek changes character again and is a rugged bedrock channel with restricted ground-water underflow in the last 6 mi (fig. A8). Little Chino Creek drains a 40-mi^2 area surrounding the town of Chino Valley. The 220-mi^2 drainage area that corresponds with the ephemeral reach of Granite Creek and with Little Chino Creek approximately overlies the Little Chino basin-fill aquifer.

Climate

The climate of the study area is arid to semiarid, with precipitation varying greatly from place to place and also by large differences from one year to the next. Two periods of warm and cold precipitation are related to seasonal atmospheric flow patterns and pressure systems (Western Regional Climate Center, 2004). From November through March, storm systems from the Pacific Ocean cross the state. These winter storms occur more frequently at higher altitudes and sometimes bring snow. Summer rainfall usually begins early in July and lasts until mid-September. Moisture-bearing winds sweep into Arizona from the south or southeast, with their source in the Gulf of California or Gulf of Mexico. Summer rains occur in the form of thunderstorms which largely result from excessive heating of the ground and the lifting of moisture-laden air along main mountain ranges. Water from these brief, but often violent downpours can cause flash flooding. Winter storms tend to be less frequent but longer in duration.

Precipitation is governed to a great extent by elevation (fig. A9) and the season of the year (table A2). North of the Mogollon Rim, rain and snowfall on the southern edge of the Colorado Plateau is highly variable. At the northern edge of the study area, Bill Williams Mountain (9,256 ft) receives as much as 30 inches of precipitation, compared with less than 13 inches at nearby Ash Fork (5,130 ft). The greatest amounts of precipitation over the greatest areal extent occur at altitudes greater than 6,000 ft in the Bradshaw, Santa Maria, and Juniper Mountains. These mountain regions receive greater than 20 inches of precipitation annually, with some precipitation falling as snow. In contrast, the relatively dry valleys near the towns of Chino Valley (4,600 ft) and Paulden (4,400 ft) receive about 10–12 inches annually, predominantly during the summer monsoon season. Slightly separated from the rest of the Colorado Plateau and mostly lower than 6,000 ft in altitude, Big Black Mesa receives less rainfall than the other mountain ranges, between 12 and 18 inches per year.

Like rainfall, temperature varies greatly from season to season (table A2). Large spatial differences in temperature mainly result from differences in altitude. High temperatures are common throughout the summer months at the lower elevations. Cold air masses from Canada sometimes penetrate into the state, bringing temperatures well below zero in the high plateau and mountainous regions. In the summer, valley temperatures commonly exceed 95 degrees Fahrenheit (°F), and may reach 104°F (Ewing and others, 1994). Great extremes occur between day and night temperatures. During winter months, daytime temperatures may average 70 °F, with night temperatures often falling to freezing in the lower valleys. The minimum temperature of record is minus 12 °F at Seligman, on the Colorado Plateau northwest of Big Chino Valley (Ewing and others, 1994).

The length of the growing season (period between freezes) typically lasts 4 to 5 months within the study area, ranging from less than 119 days in the higher parts of the Juniper and Santa Maria Mountains to an average of approximately 155 days in Big Chino Valley (Ewing and others, 1994). Annual free-water surface evaporation ranges between 50 and 60 inches per year (Ewing and others, 1994). Evaporation losses from small lakes such as Watson Lake and Willow Creek reservoirs (fig. A3) average 850 acre-ft/yr (Ewing and others, 1994; Appendix A, p. 2).

Flood conditions occur infrequently, although heavy thunderstorms during July and August at times cause floods that do considerable local damage. Heaviest runoff usually occurs when moist tropical air from hurricanes dissipates over land. The heavy rains associated with these systems usually come during August or September but are likely to occur on the average of once every 10 years (Western Regional Climate Center, 2004).

Overview of the Hydrology

The goal for the remainder of this chapter is to summarize all of the available hydrological information from previous studies in order to develop a working model of the hydrologic system. This will provide the necessary background for the data and interpretations presented in later chapters.

Previous Hydrological Investigations

The earliest investigations in the headwaters of the Verde River were geologic maps by the U.S. Geological Survey (USGS) completed in the 1950s and 1960s. These investigations initially focused on mineral exploration, but gradually the emphasis shifted to include water resources. The Clarkdale quadrangle was mapped by Lehner (1958). Krieger (1965) mapped the geology of the Prescott and Paulden quadrangles and described the water resources of the Prescott area. Twenter and Metzger (1963) summarized the geologic framework in the Mogollon Rim region surrounding Verde Valley with respect to the ground-water hydrology.

From 1933 to 1967, detailed water-level surveys in Little Chino Valley were conducted by the University of Arizona (UA), including an accounting of discharge at Del Rio Springs and pumping withdrawals from the Little Chino basin-fill aquifer (Schwalen, 1967). These early UA studies were continued through the early 1970s (Matlock and others, 1973). Water-level monitoring of the Little Chino basin-fill aquifer was continued by ADWR and evolved from water-level contour maps (Remick, 1983) to ground-water models (Corkhill and Mason, 1995; Nelson, 2002). In the 1990s, the water-level monitoring program was expanded to include more wells, including a few in Big Chino Valley and the Paleozoic carbonate aquifer north of the upper Verde River. In 1996, the USGS resumed monitoring of gauges at Del Rio Springs and lower Williamson Valley Wash. Presently, water-level data from ADWR index wells and streamflow data from USGS gauges are continually updated and made available to the public through ADWR and USGS databases, annual data reports, and the internet.

In Big Chino Valley, the first water-level contour map was produced by Wallace and Laney (1976); this map was last updated by Schwab (1995). Predevelopment hydrologic conditions in the alluvial basins of Arizona, including those in the Verde River headwaters region, were compiled by Freethey and Anderson (1986). Other maps of hydrologic conditions by Levings and Mann (1980), and Owen-Joyce

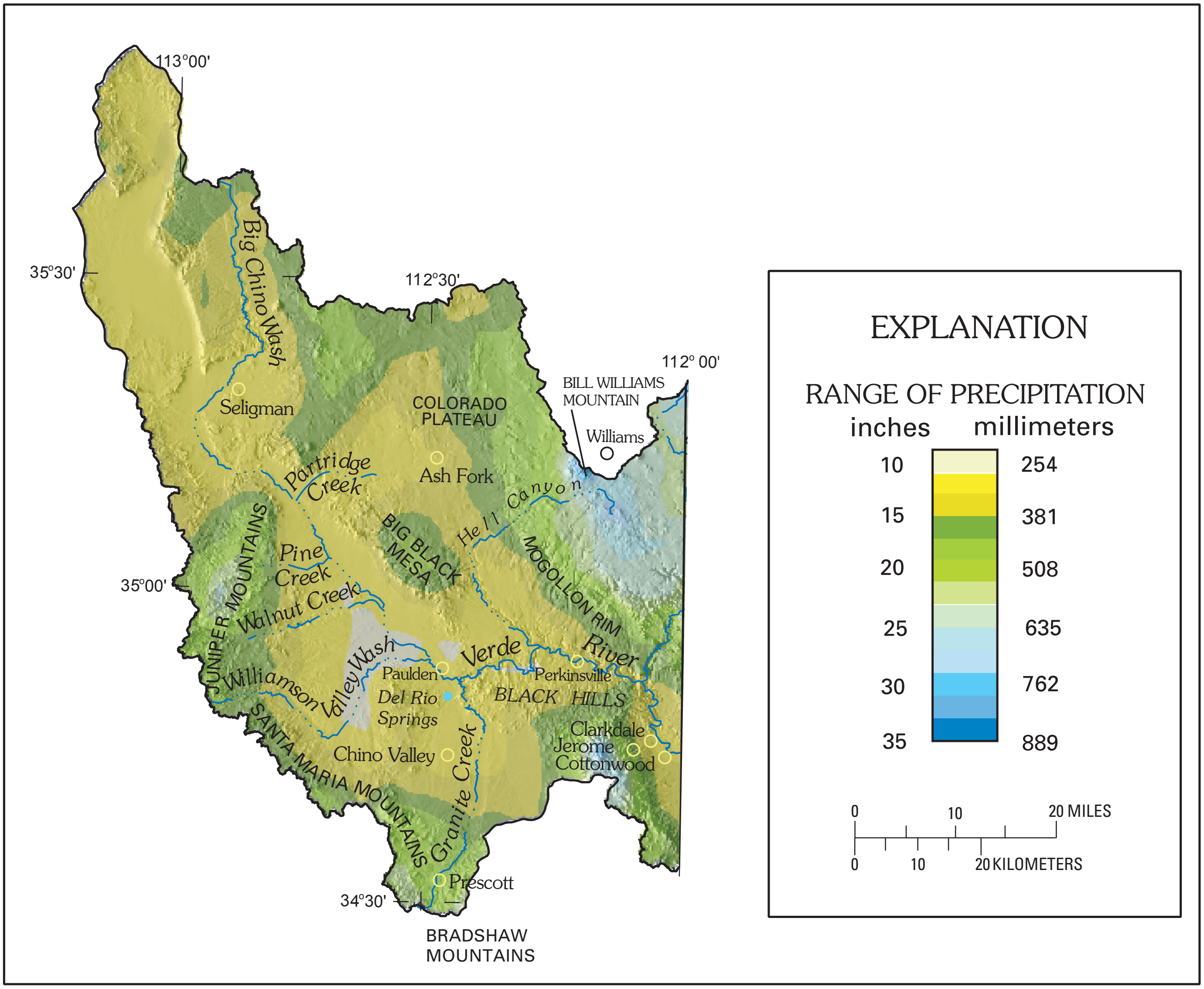


Figure A9. Map of upper Verde River watershed showing annual precipitation (Data source: U.S. Geological Survey website, http://az.water.usgs.gov/rwi-ii/; courtesy of Marilyn Flynn, based on PRISM dataset (1971-2000).

and Bell (1983) of the Verde Valley include some data for the region north of the Verde River between Paulden and Sycamore Canyon. Water Resource Associates (1990) conducted a hydrogeologic inventory of Big Chino Valley; the inventory consisted of a summary of hydrologic and geologic data, available well logs, and aquifer tests of candidate supply wells for the city of Prescott.

In the early 1990s, the Bureau of Reclamation carried out an extensive geologic and hydrologic investigation of the Big Chino Valley as a potential source of water supply for Prescott. The main objective was to examine the relation between ground water in Big Chino Valley and the upper Verde River. As part of the geological investigation, ground-based geophysical surveys were conducted and three deep boreholes were drilled in the center of Big Chino basin (Ostenaa and others, 1993). Two ground-water models of the basin indicated that the ground water in the basin was connected to the river (Ewing and others, 1994; p. 7). Wirt and Hjalmarson (2000) compiled available hydrologic and geochemical data, including stable-isotope data, to consider the sources of ground water supplying base flow to upper Verde River springs and to examine historical water-budget relations between Big Chino Valley and the river. Arizona Department of Water Resources (2000) has compiled an overview of available data on water resources in the middle and upper Verde River watershed.

Table A2. Summary of monthly climate records for stations in the Verde River headwaters study area.

[Data source: Western Regional Climate Center, 2004]

CHINO VALLEY, ARIZONA (021654) Period of Record : 1971 to 2000 Elevation 4,748 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	53.5	57.7	62.5	69.7	78.0	88.2	91.8	89.4	84.5	74.9	61.0	54.2	72.3
Average min. temperature (F)	22.9	25.5	29.5	35.2	42.9	51.0	58.8	57.9	50.5	39.1	27.2	22.3	38.7
Average total precipitation (in.)	1.2	1.3	1.2	0.6	0.5	0.4	1.7	2.2	1.6	1.1	0.9	0.9	13.4

PRESCOTT, ARIZONA (026796) Period of Record : 5/1/1898 to 12/31/2003 Elevation 5,205 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	50.7	54.0	59.0	66.8	75.3	85.7	89.0	86.0	81.7	72.1	60.5	51.7	69.4
Average min. temperature (F)	21.2	24.0	28.2	34.0	40.6	48.9	57.4	56.0	48.5	37.1	27.3	21.9	37.1
Average total precipitation (in.)	1.7	1.9	1.8	0.9	0.5	0.4	2.9	3.3	1.7	1.1	1.3	1.6	19.1
Average total snowfall (in.)	6.2	5.0	5.2	1.3	0.2	0.0	0.0	0.0	0.0	0.2	2.2	4.8	25.0

WALNUT CREEK, ARIZONA (029158) Period of Record : 12/1/1915 to 12/31/2003 Elevation 5,090 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	51.6	56.4	61.4	69.4	77.5	86.9	90.1	87.5	83.2	73.4	60.6	51.8	70.8
Average min. temperature (F)	21.0	23.2	26.0	30.3	36.9	44.0	53.7	53.1	44.9	34.1	25.3	20.0	34.4
Average total precipitation (in.)	1.5	1.6	1.4	0.7	0.5	0.4	2.3	2.8	1.5	1.0	0.9	1.4	16.2
Average total snowfall (in.)	3.7	2.8	1.7	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.4	2.4	11.8

SELIGMAN, ARIZONA (027716) Period of Record : 12/1/1904 to 12/31/2003 Elevation 5,205 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	51.1	55.1	61.2	69.1	77.8	87.5	91.2	88.4	83.8	73.8	61.9	52.5	71.1
Average min. temperature (F)	21.2	24.0	26.9	32.0	38.8	46.3	55.1	54.1	46.8	36.5	26.9	21.6	35.8
Average total precipitation (in.)	0.9	1.0	1.0	0.5	0.4	0.3	1.8	2.1	1.1	0.7	0.7	0.9	11.4
Average total snowfall (in.)	3.3	2.8	1.8	0.4	0.2	0.0	0.0	0.0	0.0	0.1	1.2	2.8	12.6

ASH FORK 6 N, ARIZONA (020482) Period of Record : 4/ 2/1902 to 9/30/1987 Elevation 5,130 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	51.5	55.2	61.0	68.9	77.9	87.8	91.7	88.9	84.5	74.3	63.0	53.8	71.5
Average min. temperature (F)	20.8	23.7	26.9	33.1	39.8	48.1	56.3	55.4	48.2	37.8	27.4	22.4	36.6
Average total precipitation (in.)	0.98	1.01	1.01	0.8	0.4	0.5	1.8	2.3	1.3	0.9	0.6	1.2	12.7
Average total snowfall (in.)	4.5	3.4	2.7	0.4	0.2	0.0	0.0	0.0	0.0	1.0	0.8	3.7	16.5

WILLIAMS, ARIZONA (029359) Period of Record : 3/26/1897 to 12/31/2003 Elevation 6,750 ft	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max. temperature (F)	45.1	47.5	52.3	61.0	69.9	80.4	83.6	80.9	75.9	66.4	55.0	47.1	63.8
Average min. temperature (F)	19.4	21.7	25.4	31.3	38.4	46.2	53.0	52.0	46.0	35.5	26.0	20.6	34.6
Average total precipitation (in.)	2.0	2.2	2.1	1.3	0.7	0.5	2.8	3.2	1.8	1.4	1.4	2.0	21.5
Average total snowfall (in.)	16.2	13.6	13.6	5.9	1.3	0.0	0.0	0.0	0.0	0.9	5.4	12.7	69.6

Predevelopment Conditions

Early settlement of Little Chino Valley was described in the environmental setting of this chapter, and predevelopment conditions have been described by Schwalen (1967) and modelled by Corkhill and Mason (1995). Schwalen states that recharge to the artesian basin was in equilibrium with natural discharge before the construction of Watson Lake and Willow Creek dams in 1915 and 1937 (fig. A3). Ground-water pumping in Little Chino Valley began with the drilling of the first deep artesian well in 1930 (Schwalen, 1967). Schwalen (1967) notes that there was no appreciable pumping in the Little Chino basin or evidence that outflow was affected by reservoir storage until after 1937. Widespread water-level measurements in Little Chino Valley were first made in 1937 and have been used to simulate predevelopment conditions modeled by Corkhill and Mason (1995). The assumption that equilibrium conditions existed in the neighboring Agua Fria basin-fill aquifer prior to the 1940s also is reasonable (Corkhill and Mason, 1995).

Under predevelopment conditions, the ground-water system is assumed to be in long-term equilibrium in response to annual or longer-term climatic variations (Alley and others, 1999). Unfortunately, most ground- and surface-water data collection efforts in Williamson and Big Chino Valleys were initiated long after irrigated agricultural activities in the region began and, therefore, do not represent true predevelopment conditions. Although there are many historical accounts regarding the settlement of Del Rio Springs, Prescott, and Chino Valley dating back to the 1850s, little hydrologic information is available for Big Chino Valley prior to 1946. Big Chino Wash presently is ephemeral throughout its entire length, but there is evidence that some reaches may have been intermittent or perennial prior to agricultural development.

Among the earliest written descriptions of the landscape are the journals of the United States Army explorations. The Whipple expedition explored the length of Partridge Creek and upper Big Chino Valley for 23 days in 1854, describing the water, vegetation, and soils (Shaw, 1998). On January 19, the wagon party traveled down the valley to a point 8 mi and 20 degrees west of south from the confluence of Partridge Creek and Big Chino Wash. Lieutenant John Tidball wrote, *"…Good grass, no water. A messenger arrived from the advanced party stating that to the southwest of us were two running creeks besides a small lagoon and other water.*" The location described probably is the confluence of Pine Creek with Cienaga Creek, which had a large spring, later diverted for agricultural purposes (Shaw, 1998). Similar accounts of this site are repeated in journals by other expedition members. The expedition apparently crossed the main valley and explored the Pine Creek and Walnut Creek tributaries, eventually crossing over a pass at the head of Walnut Creek into the Bill Williams watershed. Thus, the expedition did not follow Big Chino Wash very far below the mouth of Partridge Creek. The journals of the Whipple expedition recommended Big Chino Valley for its good grass and promising agricultural potential. Before long "*settlement in the rich valley was steady, and by 1879 there was a need for a post office*" (Granger, 1985). The Big Chino post office closure in 1891 approximately coincides with a pattern of cattle overstocking and drought that wiped out many of the ranchers in the Prescott and Chino Valley areas in the 1890s (Henson, 1965).

Topographical maps published in 1947 (USGS 1:62,500 series), based on 1946 aerial photographs, show Big Chino Wash represented by a solid or double blue line between Partridge Creek and Antelope Wash (west of Wineglass Ranch), indicating either perennial or intermittent conditions (fig. A10). These maps are inconclusive because the aerial photography and field checking may have occurred during a wetter timeframe. In addition, flow may have varied greatly from season to season. Evidence that there were pools capable of withstanding droughts, however, is provided by biologists who collected fish in the vicinity of CV Ranch. Several native fish species were taken from upper Big Chino Wash in 1897 (Gilbert and Scofield, 1898) and again in 1950 (Winn and Miller, 1954). Species identified in 1897 included Roundtail Chub *(Gila Robusta intermedia),* Spikedace *(Meda fulgida),* Speckled dace, *(Rhinichthys osculus*) and loach minnow *(Tiaroga cobitis).* Roundtail chub and Sonora sucker *(Catostomus insignis)* were identified in 1950. Weedman and others (1996) describe the collection site as 2 mi southeast of K4 Farm, which is near the meandering confluence of Big Chino Wash with Pine Creek. An oblique aerial photograph taken in 1940 of this area shows a large dark area interpreted as a large marsh or cienaga between Pine Creek and Big Chino Wash (fig. A10A). The photograph shows water in both Pine Creek and Big Chino Wash, a diversion dam on lower Pine Creek with impounded water, roads and irrigation ditches, and irrigated fields. Pine Creek and Big Chino Wash are now ephemeral.

Comparisons of water-level contour maps by Wallace and Laney (1976) and Schwab (1995) indicate that historical pumping for irrigated agriculture has, at times, had a measurable effect on water levels in parts of Big Chino Valley. Although water levels in lower Big Chino Valley downstream from Walnut Creek were similar in February 1992 (Schwab, 1995) to what they were in March 1975 (Wallace and Laney, 1976); large declines have been observed near irrigated farmland in the upper Big Chino Valley. The water table along Big Chino Wash between its confluences with Partridge Creek and Pine Creek apparently was near or at land surface prior to 1950 (fig. A10A). In 1975, water levels along this reach were approximately 30 to 100 ft below land surface (Wallace and Laney, 1976). Agricultural activity decreased after 1975, and in 1992 water levels along this reach were approximately 20 to 80 ft below land surface. The largest rises in water level were clustered along a narrow strip of irrigated farmland. The rise for some individual wells was as much as 40 ft from 1975 to 1992 (Schwab, 1995). Wirt and Hjalmarson (2000, p. 32) identify an inverse correlation between decreased pumping (mostly in northern or "upper" Big Chino Valley) and an increase in Verde River base flow between the 1960s and the 1990s.

Although little predevelopment hydrological information is available for Williamson Valley Wash, roundtail chub and an unidentified sucker species were found by Arizona Game and Fish in authorized surveys of Williamson Valley Wash in 1990, 1992, and 2001 (Weedman and others, 1996; Girmendonk and others, 1997; Clark, 2002). Roundtail chub are abundant in the reach between the Williamson Valley Road and the Williamson Valley Wash streamflow gauging station (Clark, 2002). This 4.2-mi stream segment presently is about the same length as indicated as perennial on the 1947 USGS Simmons quadrangle, which lends additional credibility to the segments of Big Chino Wash mapped as perennial. In addition, speckled dace are common in Walnut Creek and several of its tributaries (Kevin Morgan, Arizona Game and Fish, written commun., November 2000).

The Sullivan Lake dam was built below the confluence of Little Chino Creek and Big Chino Wash in the late 1930s (fig. A6). In Little Chino Valley, a 6-mi perennial reach in Little Chino Creek originated 2 mi south of the Puro railroad siding at Del Rio Springs (fig. A10B). Base flow in Little Chino Creek was the primary source of water to Sullivan Lake (and the Verde River between Sullivan Lake and Stillman Lake) until the early 1970s (A.L. Medina; U.S. Forest Service, oral commun., 1999). Presently, the creek is perennial for about 0.5 mi north and 0.5 mi south of the Puro railroad siding at Del Rio Springs. Part of the original cienaga is still present in this reach.

As mentioned earlier, ground-water discharge from Del Rio Springs to Little Chino Creek is declining, and at present is less than one half of what it was 60 years ago. Average annual discharge was 2,828±455 acre-ft per year (acre-ft/yr) between 1939 and 1945, when first measured by Schwalen (1967). Between 1997 and 2002, average annual discharge was 1,360±150 acre-ft/yr (McCormack and others, 2003). All base flow in Little Chino Creek currently is diverted or infiltrates to irrigated pasture and several ponds that are part of the cattle ranch (Allen, Stephenson & Associates, 2001). About 150 acre-ft/yr of the discharge from Del Rio Springs bypasses the USGS gauge (Allen, Stephenson & Associates, 2001) as does runoff from Big Draw, an ephemeral tributary. Big Draw joins Little Chino Creek about one mi north of Del Rio Springs.

The historical decrease in ground-water discharge near Del Rio Springs is largely attributed to ground-water pumping in Little Chino Valley and to surface-water diversions from Del Rio Springs and Little Chino Creek (Wirt and Hjalmarson, 2000). Drought conditions (Betancourt, 2003) are thought to account for the decline from about 1,500 to 1,000 acre-ft/yr during the 1997 through 2003 water years. The 2003 water year had the lowest mean daily discharge of any year on record (0.85–1.0 ft^3/s during 14 consecutive days in July; Fisk and others, 2004). Because there is no longer perennial flow from either Big Chino Wash or Little Chino Creek, the size of Sullivan Lake (fig. A11) is usually considerably smaller than depicted in 1947 (fig. A10B), and usually looks more like a large meadow than a lake. Impounded runoff generally is retained for extended periods of several months or longer following large storms, but the author has observed a dry lake on several occasions.

In an early account of lower Big Chino Valley, the Bureau of Reclamation (1946) described the relation of streams in the Verde River headwaters as follows: "the head of the Verde, formed by the junction of Chino Creek (*Big Chino Wash?*) and Williamson Valley Wash, is fed by permanent ground water." The confluence of Big Chino Wash and Williamson Valley Wash at that time was located about 1 mi upstream from Sullivan Lake. This segment of Big Chino Wash is now ephemeral, and aggraded with sediment above Sullivan Lake dam (fig. A11). The 1947 USGS map shows this segment of lower Big Chino Wash as perennial or intermittent (fig. A10B); however, for reasons described earlier this assignment is considered questionable. Because of the inflow from the Little Chino basin, the water table would have been at lake level between Sullivan Lake and the confluence of Williamson Valley Wash with Big Chino Wash (elevation 4,350 ft) in 1947. In 1990, the water level of a nearby production well was reported as 4,255 ft in 1990 (Dugan well at (B-17-02) 04 CDA; Water Resource Associates, 1990). In addition, Schwab (1995) reports the water-level elevation of several nearby wells as ranging between 4,246 and 4,270 ft. Thus, the water table in the vicinity of Sullivan Lake apparently had declined by more than 80 ft since 1947, and was about 20 ft higher than upper Verde River springs during the early 1990s (the upper range of elevation used for upper Verde River springs in this study is 4,235±1 ft; Wirt and DeWitt, this volume; Chapter D).

To summarize ground-water conditions prior to about 1950, upper Big Chino Wash probably was intermittent or perennial in a few segments between Partridge Creek and Antelope Wash. During droughts, there must have been at least enough water for fish to survive in isolated pools. The water table would have been at land surface or near land surface over much of this reach. The water table is still fairly shallow, between about 20 and 70 ft below land surface (Schwab, 1995). In lower Big Chino Valley, the water table was near or at the land surface between the confluence of Big Chino Wash and Williamson Valley Wash and present-day Sullivan Lake dam. Water levels near Sullivan Lake appear to have declined more than 80 ft since 1947 and are presently about 20 ft higher than the maximum elevation for upper Verde River springs. Since 1950, about 6 mi of perennial stream segments surrounding Sullivan Lake became ephemeral—at least 4 mi in Little Chino Creek, 1 mi in lower Big Chino Wash, and 1 mi of the Verde River between Sullivan and Stillman Lakes. These changes are broadly attributed to a combination of surface-water diversions, ground-water pumping, and climatic factors such as prolonged and reoccurring droughts.

Surface-Water Conditions

Streamflow has two components—storm runoff and base flow. Storm runoff occurs in direct response to rainfall and snowmelt, typically over brief periods of time or having a relatively short seasonal duration. Base flow is the amount of

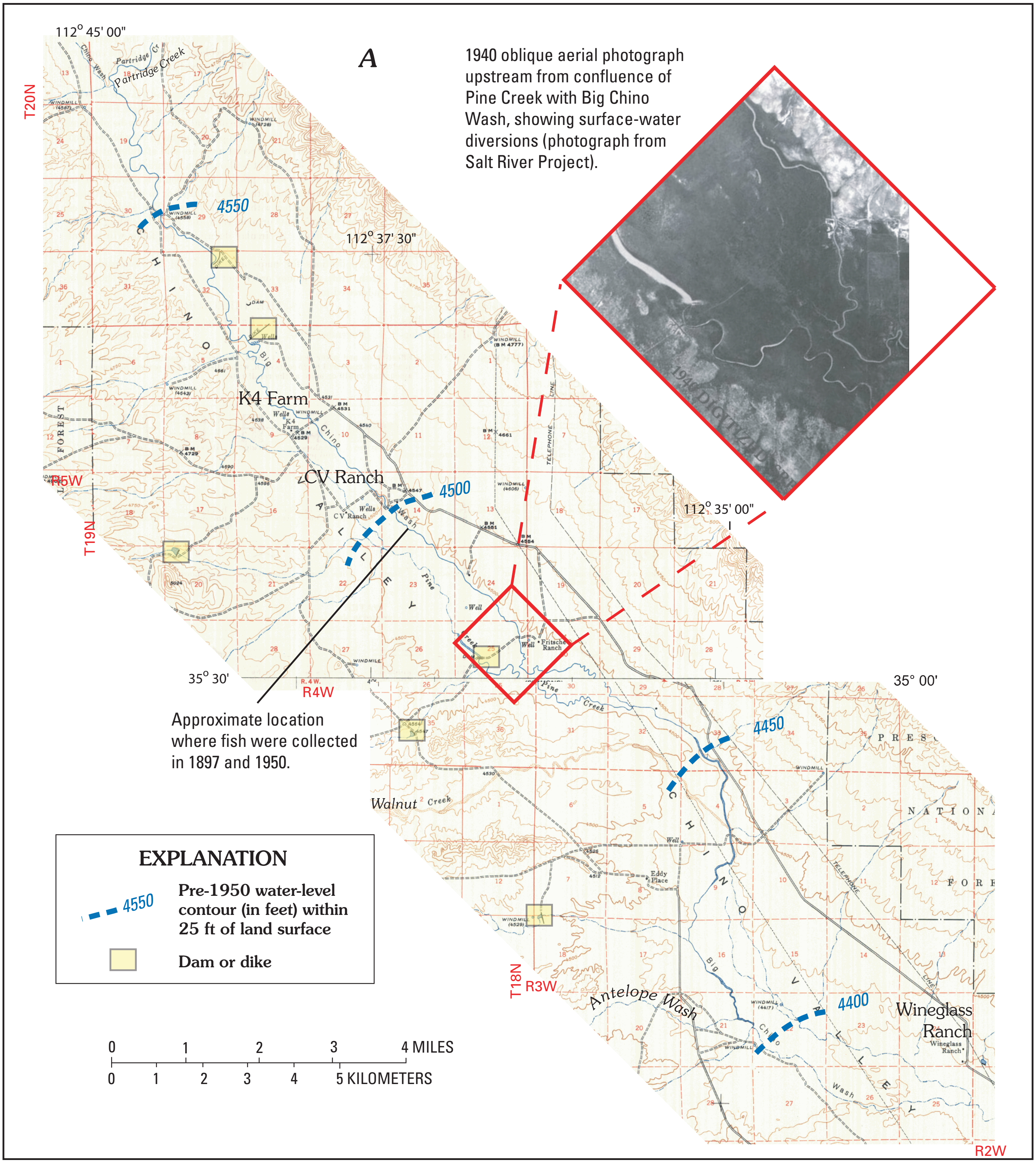


Figure A10. Pre-1950 ground-water conditions inferred from 1947 U.S. Geological Survey topographic maps, indicating shallow water table in parts of Big and Little Chino Valleys. A, intermittent reach of upper Big Chino Wash between Partridge Creek and Wineglass Ranch (1947 Pichacho Buttes and Simmons quadrangles; 1:62,500 scale). Inset shows 1940 aerial photograph of Pine Creek and Big Chino Wash with cienaga; B, (facing page).

B

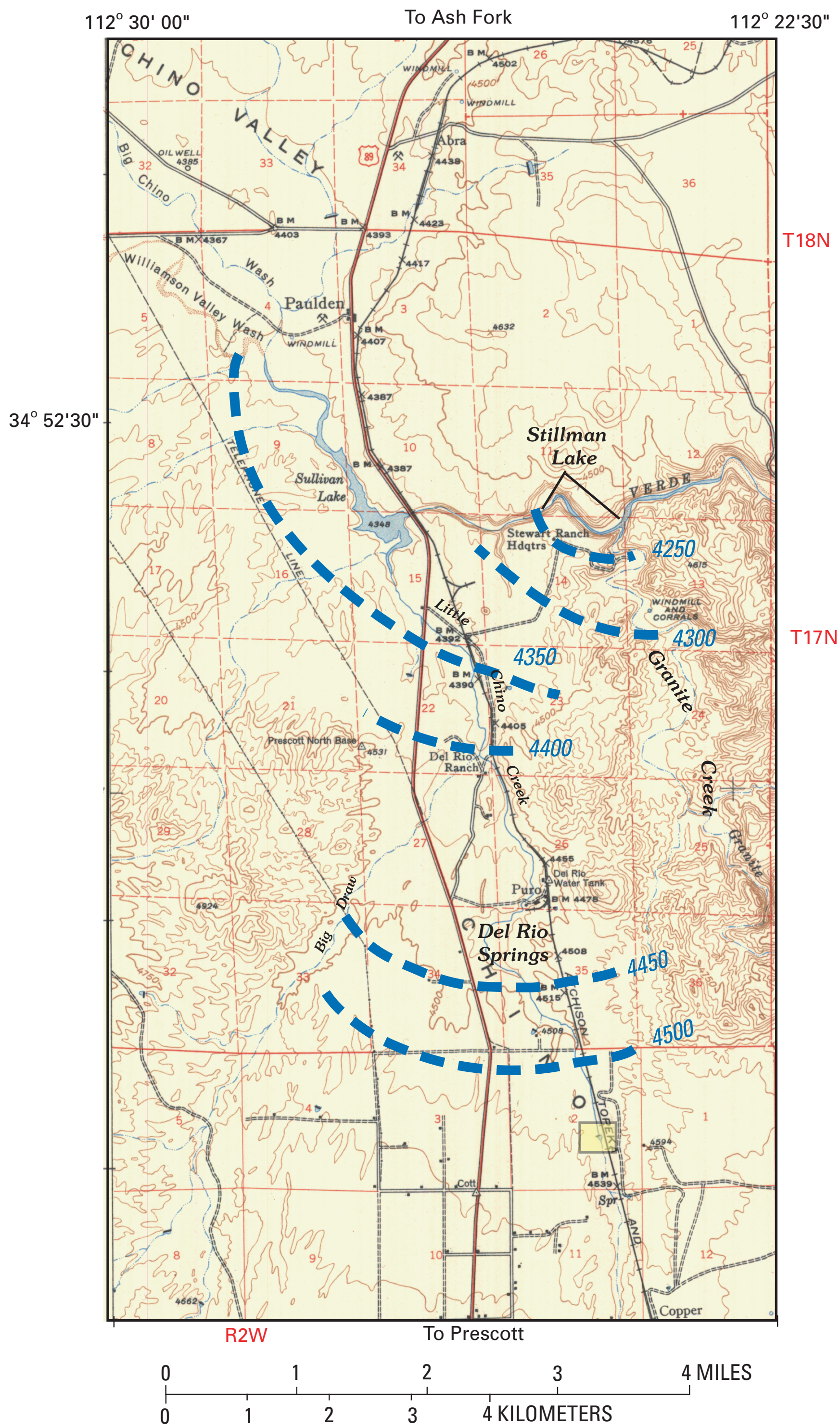


Figure A10. (Continued) B, ground-water conditions inferred from intermittent reaches in lower Big Chino Wash and Little Chino Creek (1947 USGS Paulden quadrangle, 1:62,500). Big Chino Wash is shown as a perennial segment from its confluence with Williamson Valley Wash to Sullivan Lake. Little Chino Creek is mapped as perennial from Del Rio Springs to Sullivan Lake, as is the upper Verde River downstream from Sullivan Lake to Stillman Lake.

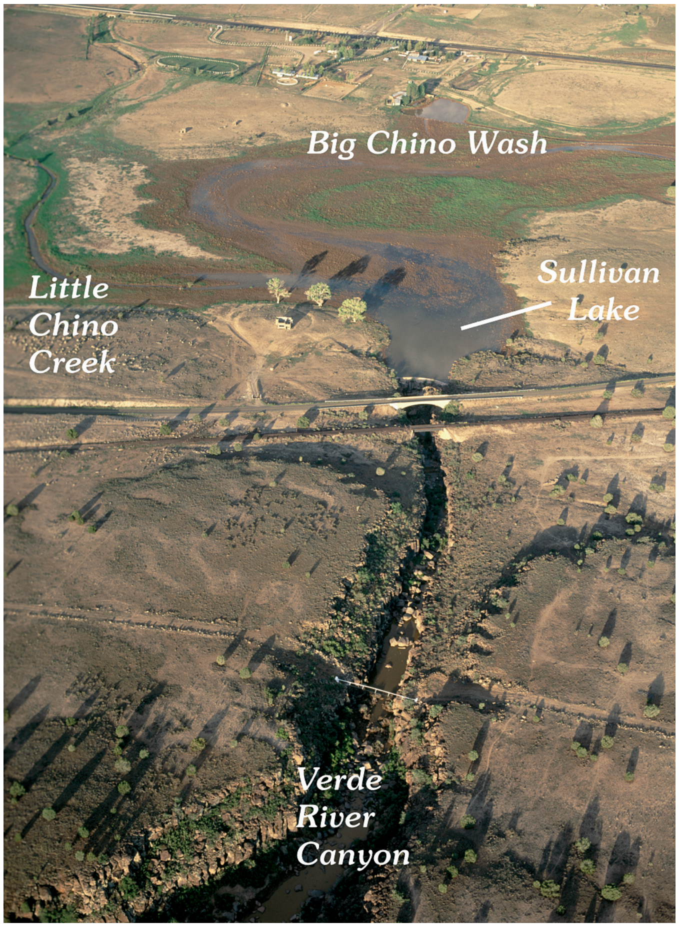


Figure A11. Aerial photograph of Sullivan Lake showing confluence of Little Chino Creek and Big Chino Wash. View is to the west. Rocks in foreground are 4.5-Ma basalt, and the background is valley-fill sediments overlying the basalt. Runoff in response to a regional storm, September 2003. Photograph by M. Collier.

streamflow sustained by discharge of ground water. Long-term changes in base flow indicate changes in the volume of water stored in the aquifer and how discharge from the aquifer is distributed among pumpage, streamflow, and evapotranspiration losses, which depend on rainfall and land use (Alley and others, 1999).

Base flow and storm-runoff characteristics are highly variable in time and space for different parts of the Verde River headwaters study area. Direct comparisons between streamflow gauges are difficult because of differences in the period of the gauge record, elevation, precipitation, recharge, water use, and the uneven distribution of rock types. Stream gauges are operated for different objectives and timeframes, resulting in widely different periods of record (table A3). Many large streams or intermittent tributaries, such as Big Chino Wash or lower Granite Creek, have no continuous streamflow records at all.

In general, the larger the drainage area the larger the base flow, as well as the peak runoff. For example, the Verde River near Paulden gauge (drainage area = 2,507 mi^2) has a 50th percentile daily mean flow duration of 25 ft^3/s, compared to that of 82 ft^3/s for the Verde River near Clarkdale (drainage area = 3,503 mi^2) (Fisk and others, 2004). Flow duration of daily mean discharge, expressed in a percentage of time, are specified daily flows that are equaled or exceeded for a given percentage of time, expressed in percentiles (Pope and others, 1998). The "50th percentile" represents a flow value that is equaled or exceeded 50 percent of the time throughout the period of annual record. A 10th percentile daily mean flow at the Paulden gauge of 29 ft^3/s is likely to be exceeded less than 10 percent of the time; whereas the 90th percentile daily mean flow of 22 ft^3/s is likely to be exceeded 90 percent of the time (Fisk and others, 2004). In contrast, the maximum recorded discharge (or daily peak discharge) values, which represent almost entirely storm water runoff, is 23,200 ft^3/s for the Paulden gauge and 53,200 ft^3/s for the Clarkdale gauge. The exceedance probability for flows of this magnitude is within a reccurrence interval of 25 to 50 years (Pope and others, 1998), indicating that most surface-water runoff occurs during large but infrequent floods. These statistics are cited here to illustrate that ground-water discharge (or base flow) accounts for nearly all of the water in the upper Verde River, nearly all of the time.

Big Chino Valley

Walnut Creek (fig. A12) and Williamson Valley Wash are the two largest tributaries to Big Chino Valley with perennial reaches (fig. A1). Ewing and others (1994) operated a U.S. Forest Service gauge on Walnut Creek from August 1991 to July 1992 and reported a mean discharge of 1,500 acre-ft/yr, reported as 2.07ft^3/s for those 10 months (table A4). They also estimated average runoff from Williamson Valley Wash gauge at 11,583 acre-ft/yr (mean annual discharge of 15.7 ft^3/s for the 1965–1985 water years). This compares with a mean annual discharge of 14.5 ft^3/s over the period from 1965 to 2003, with a daily mean flow of 1.7 ft^3/s and no flow measured on some days (table A3; Fisk and others, 2004).

Few, if any, streamflow data are available for Pine Creek, Partridge Creek, or Big Chino Wash, which (along with smaller ephemeral tributaries and areal recharge in upland areas) were assumed by Ewing and others (1994) to contribute the remaining fraction of base flow to the upper Verde River. In their ground-water model, Ewing and others (1994) assumed that surface-water runoff and, therefore, direct recharge from Partridge Creek was insignificant. Areal recharge in upland areas was estimated between 0.43 and 0.83 inches per year (Ostenaa and others, 1993).

Because there is no gauge for Big Chino Wash, its peak discharge of record can only be indirectly inferred, but probably exceeds 15,000 ft^3/s. The peak of the largest recorded flood at the Paulden gauge was 23,200 ft^3/s on February 20, 1993, which also included an unknown amount of inflow from

Table A3. Summary of available surface-water data and characteristics of drainage basins for streamflow-gauging stations, Verde River headwaters, Arizona.

[Data from annual USGS water data reports, 1997 to 2003; Pope and others, 1998; ft, feet; mi2, miles squared; ft3/s, cubic feet per second; --, no data]

Station name	Station no.	Mean basin elevation (ft)	Drainage area (mi^2)	Mean annual basin precipitation (in.)	Stream length (mi^2)	Maximum discharge (ft^3/s)	Minimum discharge (ft^3/s)	Daily mean flow[1] (ft^3/s)	Mean annual discharge (ft^3/s)	Period of record
Williamson Valley Wash near Paulden	09502800	5,120	255	17.3	19.2	14,800	no flow	1.7	14.5	March 1965 to 2003
Granite Creek at Prescott	09502960	5,285	30			6,600[2]	no flow	no flow	4.2	1994 to 2003
Granite Creek near Prescott	09503000	5,900	36.3	22.1	7.3	3,200	no flow	no flow	5.8	July 1932 to Sept 1943; Oct 1994 to Sept 2003
Granite Creek below Watson Lake	09503300	5,020	--	--	--	247	no flow	no flow	0.57	1999 to 2003
Del Rio Springs	09502900	4,430	40.9	--	--	652	0.85	1.82	1.83	1996 to 2003
Verde River near Paulden	09503700	5,410	2,507[3]	16.3	78.4	23,200	15	25	42.0	1963 to 2003
Hell Canyon near Williams	09503720	7,110	14.9	24.1	5.3	1,080	no flow	no flow	--	1966 to 1979
Hell Canyon tributary near Ash Fork	09503740	5,180	0.75	17.2	1.7	84	no flow	no flow	--	1969 to 1980
Limestone Canyon near Paulden	09503750	5,310	14.5	15.5	8.4	1,100	no flow	no flow	--	1969 to 1980
Verde River near Clarkdale	09504000	5,490	3,503[3]	19.1	115	53,200	55	82	177	1915 to 2003

[1]Discharge which was equaled or exceeded 50% of the time.
[2]Flood occurred outside of period of record.
[3]364 mi^2 generally is considered noncontributing, including 357 mi^2 in Aubrey Valley playa, a closed basin. Actual noncontributing area is thought here to be much higher (Wirt and DeWitt, Chapter D).

Granite Creek and Little Chino Creek (fig. A13). The maximum discharge that has been measured for Williamson Valley Wash was 14,800 ft^3/s on September 23, 1983. The magnitude of a flood having a 5-year recurrence interval is 4,080 ft^3/s at the Williamson Valley Wash gauge and 4,550 ft^3/s at the Paulden gauge (Pope and others, 1998). The amount of direct runoff infiltrating beneath Big Chino Wash and Williamson Valley Wash during large but infrequent floods is unknown, but could be substantial.

Little Chino Valley

There is a large gap in the period of record for the gauge at Del Rio Springs on Little Chino Creek. The initial gauge was washed out by a peak flood of 65 ft^3/s on August 4, 1946 (Schwalen, 1967). Fifty years later the USGS installed a new gauge at a nearby location in August, 1996. Mean annual discharge for this gauge was 1.83 ft^3/s between 1996 and 2003 (table A3). There is no gauge for lower Granite Creek near its confluence with the Verde River, but there are three long-term gauges in the upper Granite Creek watershed near Prescott.

Prior to the construction of dams for Watson Lake and Willow Creek reservoirs in 1915 and 1937 (fig. A3), upper Granite Creek contributed about 6 ft^3/s of mean annual discharge to Little Chino Valley through a narrow canyon in the Granite Dells (Schwalen, 1967; table A4). The discharge to the two reservoirs between 1933 to 1947, which is considered here to be representative of predevelopment inflow from the upper Granite Creek watershed to Little Chino Valley, averaged 6,250 acre-ft/yr from 1933 to 1947 (Schwalen, 1967; p. 20) with a median value of 3,200 acre-ft/yr (Corkhill and Mason, 1995).

The maximum recorded discharge for Granite Creek near Prescott was 6,600 ft^3/s on August 19, 1963 (Fisk and others, 2004; table A3). The total predevelopment recharge for the Little Chino ground-water basin, assuming flow-through runoff and evaporative losses, is estimated at about 4,500 acre-ft/yr (table A4; Schwalen, 1967; Matlock and others, 1973).

Upper Verde River Canyon

Base flow in the upper Verde River is steady—changing little in response to precipitation or lack thereof—from year to year, and within a year. Base flow for the Verde River near Paulden has been nearly constant over its historical period of record (July 1963 to present), and generally ranges between 22 and 26 ft^3/s (Owen-Joyce and Bell, 1983; Pope and others, 1998). Using a hydrograph separation approach, Wirt and Hjalmarson (2000) determined a mean base flow for the Paulden gauge of 25 ft^3/s or 18,000 acre-ft/yr. This compares reasonably well with a mean base flow of 16,000 acre-ft/yr calculated by Freethey and Anderson (1986), using a different period of record (table A4). In this report, the base flow value that will be used for the Verde River near Paulden is the mean for the two hydrograph separation estimates, or 17,000

Table A4. Summary of predevelopment base-flow discharge and calculated recharge for major areas in the Verde River headwaters, Arizona.

[mi2, miles squared; acr-ft/yr, acre feet per year; bold indicates mean where n is total number of estimates]

Basin	Subbasin	Drainage area (mi^2)	Base flow discharge[2] (acre-ft/yr)	Predevelopment calculated recharge (acre-ft/yr)	Recharge as percent of total calculated recharge[6]	Data source
Big Chino Valley		1,850		21,600[5]		Ewing and others (1994); Ford (2002)
				21,500		Freethey and Anderson (1986)[4]
				21,550	78.9	**Average of above (n = 2)**
	Williamson Valley Wash	255	11,583			Ewing and others (1994)
	Walnut Creek		1,500			Ewing and others (1994)
Little Chino Valley	Granite Creek and Little Chino Creek watersheds	300		5,000		Schwalen (1967)
				4,000		Matlock and others (1973)
				4,500		Freethey and Anderson (1986)[4]
				4,500	16.5	**Average of above (n = 3)**
	Del Rio Springs	41	2,849			Schwalen (1967)
	Willow Creek		1,420			Schwalen (1967)
	Granite Creek near Prescott (above Watson Lake)	36	4,830			Schwalen (1967)
Big Black Mesa		100		1,250	4.6	Ford (2002)
Verde River gage near Paulden		2,507[1]	18,000[3]	**27,300**[6]	100.0	Wirt and Hjalmarson (2000)
			16,000[3]			Freethey and Anderson (1986)[4]
			17,000			**Average of above (n = 2)**

[1]Includes 357 mi^2 of noncontributing area in Aubrey Valley.
[2]Base-flow discharge is same as mean annual discharge, except as noted.
[3]Base-flow discharge determined by hydrograph separation for period of record at time of study.
[4]Data from Freethey and Anderson (1986) are the raw values used to construct the pie charts in their report.
[5]Value of 23,700 acre-ft/yr of recharge for upper Verde River watershed (Ewing and others, 1994) minus 2,100 acre-ft/year of inflow in 1990 from Little Chino Valley (ADWR, 2000) equals 21,600 acre-ft/year (Ford, 2002).
[6]Sum of average calculated recharge for Big and Little Chino Valleys and Big Black Mesa.

acre-ft/yr (table A4). This mean value compares favorably with the annual mean discharge of 16,370 acre-ft per year during the 2000 water year at the Paulden gauge (MacCormack and others, 2002), a year without any storm runoff and which currently is the lowest annual discharge of record.

Surface-water runoff in the upper Verde River and its bedrock canyon tributaries may exceed daily base flow by three to four orders of magnitude. The maximum flow of record at the Paulden gauge was 23,200 ft^3/s in 1993 (fig. A13). The lowest mean daily flow of record was 15 ft^3/s during May 13–23, 1964, which coincided with pumping to fill artificial lakes constructed for real estate promotion near Wineglass Ranch in Big Chino Valley (Wirt and Hjalmarson, 2000). This response to pumping suggests a hydraulic connection between the Big Chino basin-fill aquifer, Verde River base flow, and the part of the regional carbonate aquifer that lies in between. When pumping ceased, the base flow quickly recovered to 23 ft^3/s in June 1964—a period with little, if any, rainfall runoff. In comparison, the lowest mean daily flow measured since May 1964 was 19 ft^3/s for several weeks in June and July of 2003, following several years of extended drought conditions.

The USGS conducted synoptic surveys of base flow in 1979, 1991, 1999, and 2000 to define base-flow conditions and sources of inflow to the upper reach (Owen-Joyce and Bell, 1983; Ewing and others, 1994; and U.S. Geological Survey, 2000 and 2001; fig. A14). Perennial base flow in the Verde River canyon presently begins downstream from the Sullivan Lake dam as an impounded section of river channel that is informally known as Stillman Lake (between river mi 1.0 and 2.0), where the river canyon intersects the water table (fig. A15). This reach is dammed by a natural levee of sand deposited by Granite Creek, currently vegetated with cattails. Although the lower reach of Granite Creek also is perennial, the reach immediately downstream from Stillman Lake and Granite Creek was ephemeral from 1999 to 2001. In June 2000, the dry reach extended more than 500 ft downstream from Stillman Lake, although this area has since been impounded by beaver dams. Base flow from Stillman Lake and lower Granite Creek travels beneath the surface through shallow alluvium in this reach (Wirt, Chapter F, this volume).

Perennial discharge in the upper Verde River reemerges near mi 2.1 and increases to about 19 ft^3/s by Stewart Ranch

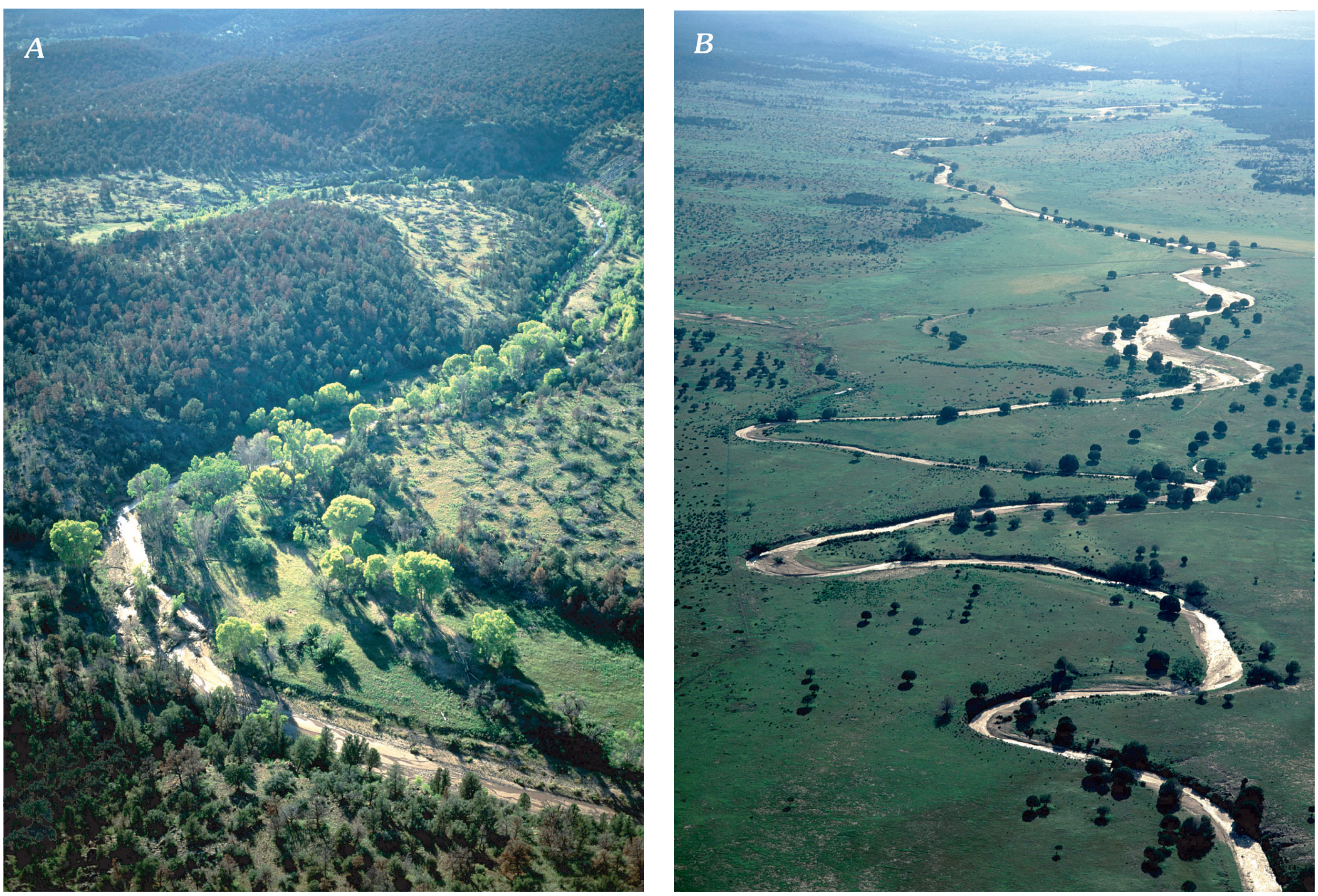


Figure A12. Photographs of Walnut Creek (A) in perennial segment, and (B) near confluence with Big Chino Wash following regional storm of September 2003. Views to west and southwest. Photographs by M. Collier.

Figure A13. Photographs showing A, flood of February 20, 1993, at Sullivan Lake dam. View to southwest. Sullivan Buttes in background. Dam is behind hydraulic drop. B, Verde River gorge below the dam. View downstream to east. Canyon is carved from Tertiary basalt. Peak discharge of 23,200 ft^3/s and daily mean discharge of 13,700 ft^3/s are the sum of Big Chino Wash, Williamson Valley Wash, Little Chino Creek, and Granite Creek at Paulden gauge. Photographs by E. Carr.

(river mi 3.2; fig. A14, located on fig. A2). Most of the gain occurs from a large, diffuse spring network discharging from the Martin Formation near river mi 2.2, formerly referred to as “Big Chino Springs” (Wirt and Hjalmarson, 2000) and here referred to throughout this report as “upper Verde River springs.” Since 2000, beavers have intermittently dammed the Verde River near upper Verde River springs, creating a series of ponds and flooding the major spring outlet.

Below river mi 3.0, the upper Verde River typically is a narrow, free-flowing stream about 10- to 20-ft wide and less than 3-ft deep; with deeper and wider pools present in a few locations. At least 2 ft^3/s of inflow occurs from small seeps on both banks of the Verde River near the mouth of Muldoon Canyon (river mi 8; fig. A14; located on fig. A2). An additional 2.5 ft^3/s of gain below the Paulden gauge is derived from Duff Spring (river mi 14; fig. A14; located on fig. A2). Beavers have been active in some localities.

Although Hell Canyon receives as much as 25 inches of annual rainfall in its headwaters near Bill Williams Mountain, the Verde River experiences no change in base flow in the vicinity of Hell Canyon (fig. A14). This suggests that ground water does not travel beneath Hell Canyon to reach the Verde River. Three streamflow gauges on the Colorado Plateau—in upper Hell Canyon, a small tributary of Hell Canyon, and in Limestone Canyon—have small drainage areas less than 15 mi^2, with mean annual basin precipitation ranging from 15.5 to 24.1 inches (table A3). These stream segments are ephemeral and usually dry, although individual flash floods have exceeded 1,000 ft^3/s.

Base flow in June 2000 decreased more than 30 percent in the 10-mi reach between Duff Spring and Perkinsville (fig. A14). The loss is attributed to a variety of potential factors including evaporation from water surfaces, plant transpiration, losses to the underlying limestone, and seasonal diversions to an irrigation ditch upstream from the Perkinsville bridge.

The Verde River gains about 10 ft^3/s between the State Route 72 bridge at Perkinsville (river mi 24) and the railroad bridge (river mi 27). This gain is attributed in part to groundwater inflows from small springs and in part to possible seepage inflows from local irrigation returns. The largest of these inflows is an unnamed spring at the intersection of the Verde River and the Orchard Fault (fig. A2). Here, fault breccia and rubble zones have been observed in Redwall Limestone north of the Verde River. Farther downstream, base flow increases to 57 ft^3/s downstream from a large spring at Mormon Pocket. A large tributary inflow (Sycamore Creek) occurs at Sycamore Canyon, with an annual low flow for the USGS streamflow gauging station near Clarkdale (09504000, hereto referred to as the Clarkdale gauge) of 71 ft^3/s. Based on a discontinuous record (1916, 1918–20; 1966–1996), the mean monthly minimum values for the Clarkdale gauge range from 61.6 to 73.8 ft^3/s (Fisk and others, 2004).

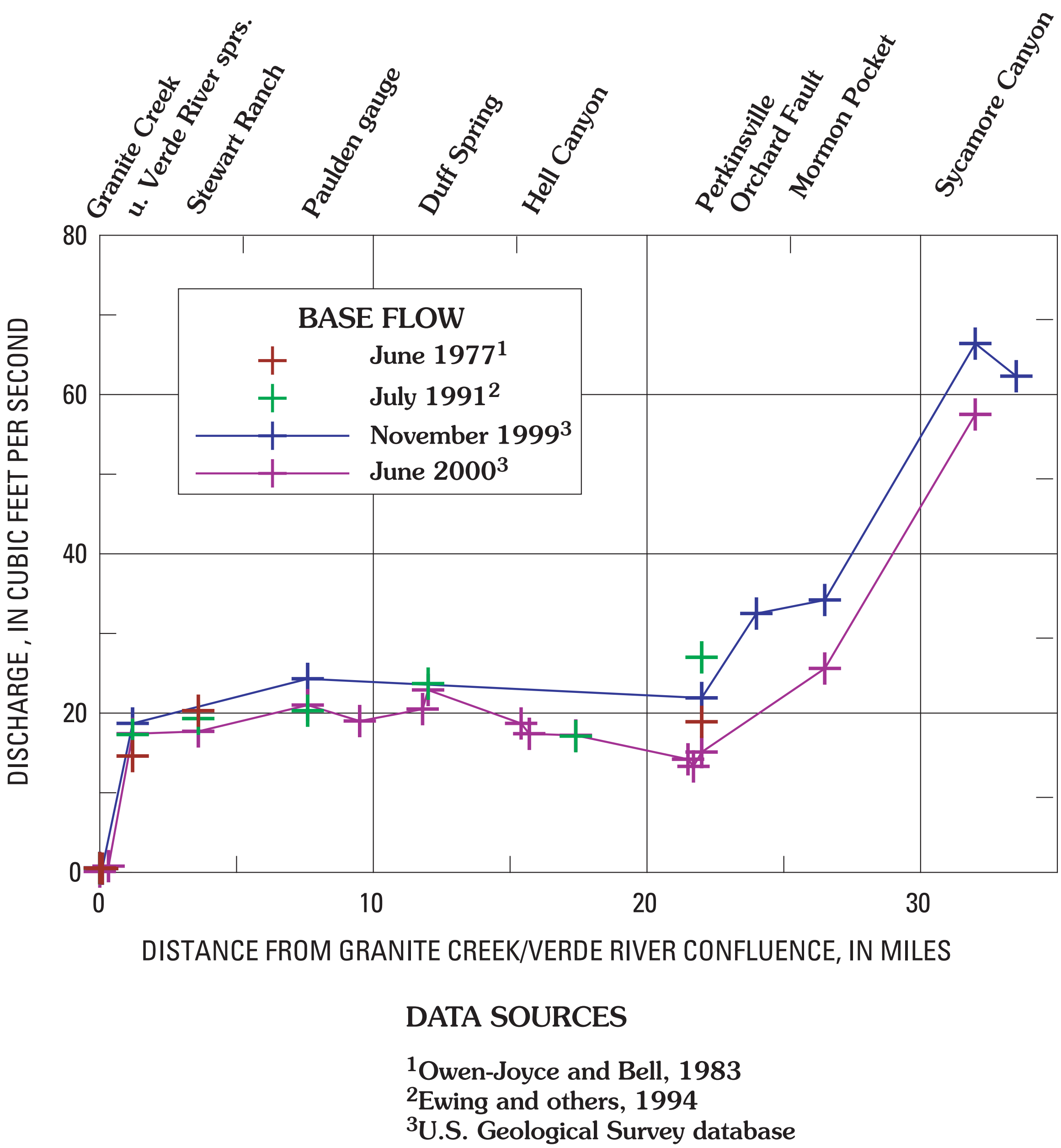


Figure A14. Graph showing changes in base flow with distance along the upper Verde River.

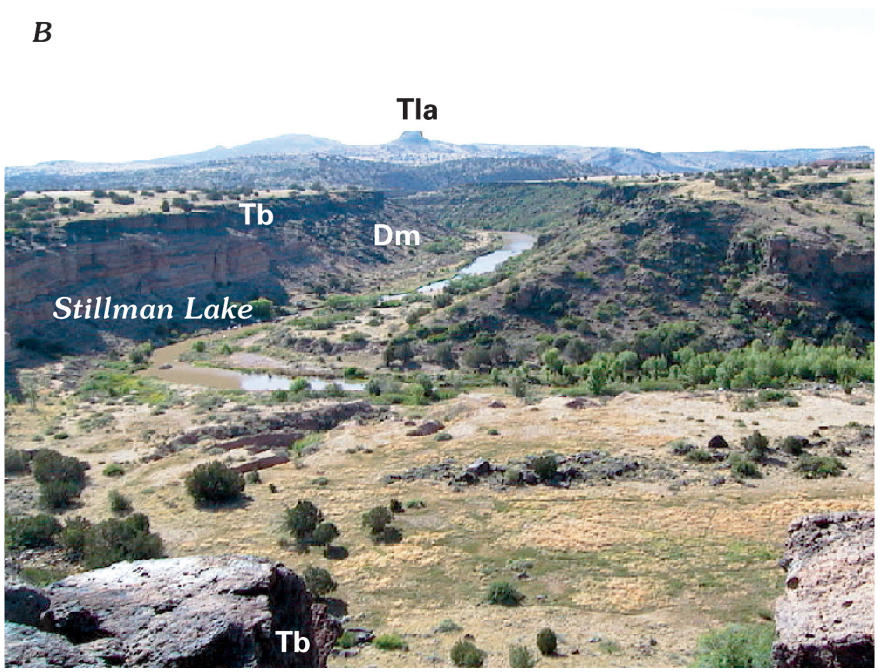


Figure A15. Photographs of Stillman Lake facing downstream (A) overlooking the confluence of Verde River canyon with Granite Creek , and (B) southeast from north canyon rim towards Little Thumb Butte; by R. Pope and L. Wirt, respectively. Stillman Lake is dammed by a natural levee of sediment from Granite Creek, which enters center right of upper photograph. Verde River canyon walls are predominantly Devonian Martin Formation (Dm), capped by the 4.5 Ma basalt flow (Tb). Rocks in background of lower photograph are Tertiary volcanic rocks in the Sullivan Buttes volcanic field (Tla).

Ground-Water Conditions

Basin-fill aquifers in Big and Little Chino valleys serve as a ground-water reservoir and distribution system. Recharge and discharge are the inflow and outflow terms of the storage system. Recharge is the percentage of precipitation that becomes ground water. The amount of recharge that occurs is dependent on many factors including climate, runoff characteristics of the soil and rock, and the amount and type of vegetation. Recharge usually travels through an unsaturated zone to reach the water table, but also can occur directly beneath wetlands, lakes, or losing stream reaches. Recharge and discharge can occur at the same locality under different runoff conditions.

The term “discharge” refers to the flow in a stream as well as to the outflow from an aquifer. Discharge in a stream is naturally derived from ground-water discharge, precipitation runoff, or a combination of both. As discussed previously, the discharge in a stream during low-flow conditions is entirely from ground-water discharge and is referred to as “base flow.” In the study area, ground-water movement through the aquifer is driven by gravity to points of discharge—to springs (for example, Del Rio Springs), natural lakes and ponds (for example, Stillman Lake and King Spring), or gaining streams (for example, the upper Verde River from Granite Creek to Stewart Ranch).

Variations in predevelopment base flow are attributed solely to seasonal or long-term changes in climate. Variations in historical base-flow measurements also result from surface-water diversions or impoundments, ground-water withdrawals (pumping), and land use, as well as climatic variability. Human activities such as surface-water diversions and large-scale pumping of ground water have a direct impact on the base flow downstream. The delay of impact from pumping may be years or even decades, particularly with increasing distance from the stream. Other nonpoint-source changes in land use such as suburban development, agricultural practices, and altering the type of vegetation can result in a gradual impact on base flow that is difficult to distinguish from natural climate variability.

In Big Chino Valley, present ground-water conditions no longer reflect true predevelopment conditions. This is evident by comparing modern water-level contour maps (Schwab, 1995) with fig. A10, in which predevelopment ground-water conditions have been inferred from 1947 USGS maps and historical aerial photographs. The vertical accuracy of predevelopment water-level contours is estimated at one-half the 50-ft contour interval or to within 25 ft of land surface. For predevelopment conditions in Little Chino Valley, the reader is referred to water-level contour maps in Schwalen (1967) and modeled predevelopment conditions in Corkhill and Mason (1995). Modern water levels in Big and Little Chino valleys are discussed in greater detail in Chapter D (Wirt and DeWitt, this volume), in regard to the major aquifer boundaries and hydrogeologic framework.

Water Use

As of 1997, water use in the Verde River headwaters was about 81 percent agricultural and 11 percent residential, with the remaining fraction of use by commerce and industries located primarily in the Prescott and Chino Valley areas (Arizona Department of Water Resources, 2000). A great deal of current municipal, residential, agricultural, industrial, and commercial water use information is available for upper Verde River watershed in general, and the Little Chino basin in particular, which has recently been summarized for 1997 conditions by Arizona Department of Water Resources (2000). Unfortunately, the water-use data are often confusing in that they are sometimes reported for the Verde watershed as a whole, or for the Middle and Upper Verde River basins combined, or for the Prescott Active Management Area (PRAMA) only (which may or may not include the upper Agua Fria watershed). Water-use data are not always easily broken out for individual subbasins. In addition, past water use has been reported by different agencies using different approaches over different timeframes. Estimates of agricultural water use vary widely in part depending on whether a consumptive use or water-duty reporting method is taken. Consumptive use generally means the amount of water consumed by the crop itself, whereas a water-duty approach is the total amount of water supplied. The water-duty factor could include water lost due to field inefficiencies such as conveyance losses, evaporation, crop leaching requirements, and so forth; in addition to the amount of water consumed by the crop. Water-use information generally is thought to be fairly accurate for Little Chino Valley, but considerably less accurate for Big Chino Valley. The greater accuracy of water-use data for the Little Chino Valley is attributed to early hydrological studies by Schwalen (1967) and Matlock and others (1973), and lately because of detailed reporting requirements for the PRAMA by ADWR (Arizona Department of Water Resources, 1998, 1999a, 1999b, 2000; Corkhill and Mason, 1995; Nelson, 2002).

Little Chino Valley

As discussed earlier, water demand in the Prescott Active Management Area is increasing as a consequence of rapid population growth (Arizona Department of Water Resources, 2000). Water use in excess of safe yield for the combined Little Chino Valley and upper Granite Creek watersheds was estimated at about 13,000 acre-ft/yr in 1990 by Corkhill and Mason (1995). This estimate is now reported differently for the entire PRAMA instead of for just the Little Chino basin-fill aquifer and has been revised to include recharge beneath Granite Creek (Nelson, 2002). Since 1997, the PRAMA overdraft in excess of recharge has been reported variously between 6,610 and 9,830 acre-ft/year (Arizona Department of Water Resources; 1998, 1999a, 1999b, and 2000). Predictive ground-water model simulations by Nelson (2002) presume that surface-water discharge from Del Rio Springs will be gone by 2025. The Arizona Department of Water Resources (2000) estimated Little Chino inflow to the upper Verde River in 1990 at about 2,100 acre-ft/year, compared with 4,500 acre-ft/yr during predevelopment (table A4).

Water use in Little Chino Valley in 1997 was about one-half municipal (including residential, commercial, and industrial demand) and one-half agricultural (Arizona Department of Water Resources, 2000). In general, agricultural use is diminishing as residential use is expanding. Because municipal water use generally is metered for billing purposes, the amount delivered can be determined quite accurately. Major water providers in Prescott and Little Chino Valley supplied about 6,750 acre-ft/yr in 1997 (Arizona Department of Water Resources, 2000). The largest agricultural user is the Chino Valley Irrigation District (CVID). In 1998, the city of Prescott entered into an agreement with the CVID and acquired their surface-water rights. The diversion volume to satisfy these rights averaged 3,250 acre-ft/yr from 1991–1997 (Arizona Department of Water Resources, 2000). In 1997, agricultural demand within Little Chino Valley was 6,610 of acre-ft/yr for 2,170 irrigated acres (Arizona Department of Water Resources, 2000).

In order to compare different methods, ADWR tried a consumptive use approach with a weighted water duty of 6.6 acre-ft for the same 2,170 acres where the amount of water use was known accurately. Based on their consumptive use method, ADWR estimated total agricultural water use for Little Chino Valley at 14,310 acre-ft/yr (Arizona Department of Water Resources, 2000; p. 3–34 and p. 6–5)—or more than twice the 6,610 acre-ft/yr reported by more direct approaches, such as gauging of irrigation ditches or metering of wells. The large degree of error in the consumptive use estimate reflects large uncertainties in many of the assumptions the analysis is based on (Frank Corkhill, written communication, 2005). In the following section on Big Chino Valley, it is important to note that the less accurate consumptive-use approach is the only method used, which does not take into consideration the practice of deficit irrigation. Pasture is the predominant crop grown in the upper Verde River watershed and is typically deficit irrigated (Arizona Department of Water Resources, 2000, p. 3–20). Deficit irrigation applies whatever limited amount of water that is available to keep the crops alive, resulting in reduced crop yield. A deficit application rate generally is substantially lower than the recommended application rate for a given crop type.

Big Chino Valley

Any discussion of past water use in Big Chino Valley should consider the discussion of predevelopment hydrology presented earlier in this chapter, as well as information in studies by the Arizona Crop and Livestock Reporting Service (1974), annual reports on ground-water conditions by the USGS such as Anning and Duet (1994), Wallace and Laney (1976), Schwab (1995), Ewing and others (1994), and the Arizona Department of Water Resources (2000).

To evaluate historical changes in water use, one must look at changes in land-use patterns in Williamson Valley, upper Big Chino Valley, and Walnut Creek, as well as the study or method used to produce the estimate. Ranching and irrigated agriculture in Big Chino Valley, Walnut Creek, and Williamson Valley started with settlement in the 1860s and probably peaked in the 1950s and 1960s. Accounts prior to 1967 vary considerably, and few direct measurements are available. From the mid 1970s through the mid 1990s, ground-water pumping for irrigated agriculture decreased to less than a tenth of that reported for 1975 (Anning and Duet, 1994). Since 1998, land actively cultivated in upper Big Chino Valley has reportedly increased by 1,350 acres (Arizona Department of Water Resources, 2000; p. 3–31).

Water use throughout Big Chino Valley is more than 90 percent agricultural. Although the amount of water used by private wells in lower Big Chino Valley is growing rapidly, the amount of residential use after subtracting for septic tank recharge was estimated at about 348 acre-ft/yr in 1997 (Arizona Department of Water Resources, 2000). Arizona Department of Water Resources reports that Abra Water Company, the largest municipal supplier, delivered 56 acre-ft/yr to its customers in 1997. Water demand for town of Ash Fork in the northern part of the watershed, although thought to be part of the Colorado Plateau aquifer system, was 81 acre-ft/yr. The sum of this municipal and residential water use is still far less than 10 percent of total water use for the basin.

Williamson Valley was settled in 1865, and irrigated acreage and cropping patterns have not changed substantially since reporting began in the 1960s. About 1,300 acres are actively irrigated, with more than 90 percent in pasture (Arizona Department of Water Resources, 2000). Water-duty estimates of the amount of water pumpage, however, vary widely depending on the report. Active irrigation was reported as 2,000 acre-ft/yr between 1950 and 1974 (Wallace and Laney, 1976). Although land-use patterns did not change substantially, Ewing and others (1994) recalculated water use as about 3,000 acre-ft/yr in 1990. Using a weighted duty factor, Arizona Department of Water Resources (2000) estimated 1997 agricultural water use in Williamson Valley at 5,204 acre-ft/yr. During this timeframe, water levels in Williamson Valley appear to have dropped slightly. Water levels in a few wells were a few feet lower in 1992 (Schwab, 1995) than when water levels were measured in those wells in 1975 (Wallace and Laney, 1976). The amount of residential water use is unknown, but the number of new homes has increased substantially since the 1980s.

Seventy percent of ground-water pumping prior to 1967 was in northern or "upper" Big Chino Valley, according to Bob Wallace (USGS hydrologist, oral commun. in 1989; in Water Resource Associates, 1990, p. 6). Reports of water use in upper Big Chino Valley generally are combined with water use in Walnut Creek. Water diversions for ranching operations started in Walnut Creek around 1869 and peaked in the late 1950s and early 1960s (Arizona Department of Water Resources, 2000). Estimates of ground-water pumping for Big Chino Valley of

20,000 acre-ft/yr prior to 1967 (Wallace and Laney, 1976; Schwab, 1995) are unsubstantiated and are considered here as inaccurate. The USGS, in cooperation with A. Allen, County Agricultural Agent, field checked the land under active irrigation in 1967. As a result of these inspections, ground-water pumpage for upper Big Chino Valley was downwardly revised from 20,000 to 9,000 acre-ft/yr, beginning in 1967 (H.W. Hjalmarson, written commun., 2004; based on his USGS field notes dated June 8, 1967). There is little indication that water use for Big Chino Valley ever exceeded 15,000 acre-ft/yr prior to 1967 (H.W. Hjalmarson, written commun., 2004). Estimates of early ground-water pumping in Big Chino Valley vary considerably in other studies, which may reflect different consumptive use factors or that the amount of land actively under cultivation kept changing. A study by the Bureau of Reclamation (Ewing and others, 1994) states that water use was 5,200 acre-ft/yr in 1960. An earlier appraisal report by the Bureau of Reclamation (1974) lists the amount of agricultural water use in Big Chino Valley at the time of that study at 994 acre-ft. Anning and Duet (1994) report 11,000 acre-ft for 1974. The large differences among these estimates suggests either that reporting practices or the amount of irrigated land may have changed greatly from year to year.

Annual pumping estimates reported by the USGS from 1967 to 1990 (Anning and Duet, 1994) were estimated by multiplying the irrigated acreage by an annual water duty of 5 acre ft. Ground-water pumping in upper Big Chino Valley decreased from about 12,000 acre-ft/yr in 1975 to 2,000 acre-ft/yr in 1982-83 (Wallace and Laney, 1978; Anning and Duet, 1994). Water use remained low through the 1980s and early 1990s. Recently, active irrigation in upper Big Chino Valley and Walnut Creek has reportedly more than doubled—from about 1,130 acres in the mid 1990s to a total of 2,480 acres in 1998 (Arizona Department of Water Resources, 2000; p. 3–31). Using their weighted-water duty approach, Arizona Department of Water Resources estimated agricultural water use for both Big Chino Valley and Walnut Creek in 1998 at 9,924 acre-ft/yr. This estimate is about 5 times greater than the 1990 estimate of 2,000 acre-ft/yr by Ewing and others (1994), and is 2.5 times greater than the 4,000 acre-ft/year reported by Anning and Duet (1994). Again, the large differences among the Big Chino agricultural estimates for the 1990s brings into question the accuracy of the various water-use data.

In summary, the amount of agricultural water use in Big Chino Valley has varied greatly. The amount of agricultural demand steadily decreased from its peak in 1975 through the early 1990s (Anning and Duet, 1994). Since about 1998 demand has probably increased, but by an unknown factor. ADWR's water-duty estimates based largely on historical aerial photography have been more than twice as high as those obtained by more direct accounting methods in Little Chino Valley. Large discrepancies among various studies are attributed to differences in consumptive use factors, soil types, farming practices, delivery methods, and system efficiencies, as well as differences in estimating the amount of land under cultivation. More accurate and direct methods such as metering to calculate agricultural water use in this basin are sorely needed.

Upper Verde River

The total amount of water use in the carbonate aquifer north of the upper Verde River is unknown, but is minor relative to water use in Big and Little Chino valleys. Between Paulden and Clarkdale, several wells in the carbonate aquifer north and south of the Verde River are used for ranching and domestic use. Return flows from irrigated pasture at Perkinsville may account for part of the observed inflows to the Verde River in this reach. Total water use probably is less than a few hundred acre-ft/yr.

Conceptual Water Budget

Developing a conceptual water budget for the upper Verde River watershed involves balancing ground-water inflows and outflows. Inflows include recharge from infiltrating precipitation and runoff, ground-water underflow from adjacent basins (if any), and stream inflow into the basin that is lost to the aquifer (not applicable in this case study). Outflows include evapotranspiration, stream base flow out of the basin, and ground-water underflow out of the basin (if any). Of these inflows and outflows, only base flow can be measured directly and accurately. Ground-water recharge generally is calculated as the sum of inflows and outflows to the aquifer system, which includes base flow from streams entering and exiting the aquifer, evapotranspiration, and ground-water underflow out of the basin of interest. Calculating the relative ground-water contribution from each subbasin involves a substantial amount of uncertainty.

Several studies have used various approaches and statistical methods to develop estimates of recharge for the Verde River headwaters and its major subbasins. The hydrologic data compiled in table A4 are publically available and come from reputable sources recognized for their scientific expertise, including the USGS, Bureau of Reclamation, and University of Arizona. For the Verde River headwaters, Freethey and Anderson (1986) presumed that underflow past the Paulden gauge was relatively insignificant, accounting for less than 3 percent (500 acre-ft/yr) of outflow from Big Chino Valley. Evapotranspiration was estimated at 7,000 acre-ft/year for Big Chino Valley, and 2,000 acre-ft/yr for Little Chino Valley (Freethey and Anderson, 1986). Because few predevelopment data are available for Big Chino Valley, the recharge estimates by Freethey and Anderson (1986) and Ewing and others (1994) are largely based on historical base flow at the Paulden gauge, which began operation in 1963. Base flow at the Paulden gauge is estimated at about 17,000 acre-ft/yr (table A4). Water-budget components such as base flow that are reliably known were considered fixed in order to estimate the remaining components (Freethey and Anderson, 1986). Differences among estimates from different studies are largely attributed to slightly different statistical approaches (for example, using the mean versus the median), or to different periods of record. For a more detailed understanding of these approaches, the reader is referred to the original data sources. These estimates are compiled here to develop a conceptual understanding of the primary inflow and outflow components in the hydrologic system rather than a detailed budget analysis.

Base flow in the upper Verde River is supplied by Big and Little Chino valleys and the carbonate aquifer in the vicinity of Big Black Mesa. During predevelopment conditions, ground-water inflow to the upper Verde River from Little Chino Valley was about 4,500 acre-ft/yr (table A4), but was about 2,100 acre-ft/yr during the 1990s (Arizona Department of Water Resources, 2000). Ford (2002) estimated Big Black Mesa recharge at 1,250 acre-ft/yr based the land area of the mesa exceeding 5,000 ft above sea level and a rate of precipitation between 16 and 18 inches. Because some recharge on the north side of the Big Black Mesa may be tributary to the Colorado Plateau, this estimate is considered a maximum value. Most recharge for Big Black Mesa area probably discharges directly to ground water in Big Chino Valley, or to the carbonate aquifer north of the Verde River, and is estimated to provide about 5 percent of base flow at the Paulden gauge (Ford, 2002). Mean annual discharge from Williamson Valley Wash and Walnut Creek can account for two-thirds to three-fourths of base flow at the Paulden gauge. The remainder is attributed to discharge from Little Chino Valley, Big Black Mesa, and other Big Chino Valley nonperennial tributaries such as Pine Creek and Partridge Creek, as well as recharge in upland areas or recharge from storm runoff beneath ephemeral streams (Ewing and others, 1994).

By assuming that predevelopment recharge is proportionate to modern base flow, Big Chino Valley contributes 78.9 percent, or about 13,400 of the 17,000 acre-ft/yr of mean annual discharge at the Paulden gauge (fig. A16). If we include Big Black Mesa as part of Big Chino Valley, these combined areas contribute about 14,200 acre-ft/yr of base flow. Using the predevelopment value of 4,500 acre-ft/yr, Little Chino Valley originally contributed about 16.5 percent of recharge to the upper Verde River but presently is thought to deliver about half its predevelopment value, or 8.4 percent,

SOURCES OF RECHARGE TO THE UPPER VERDE RIVER

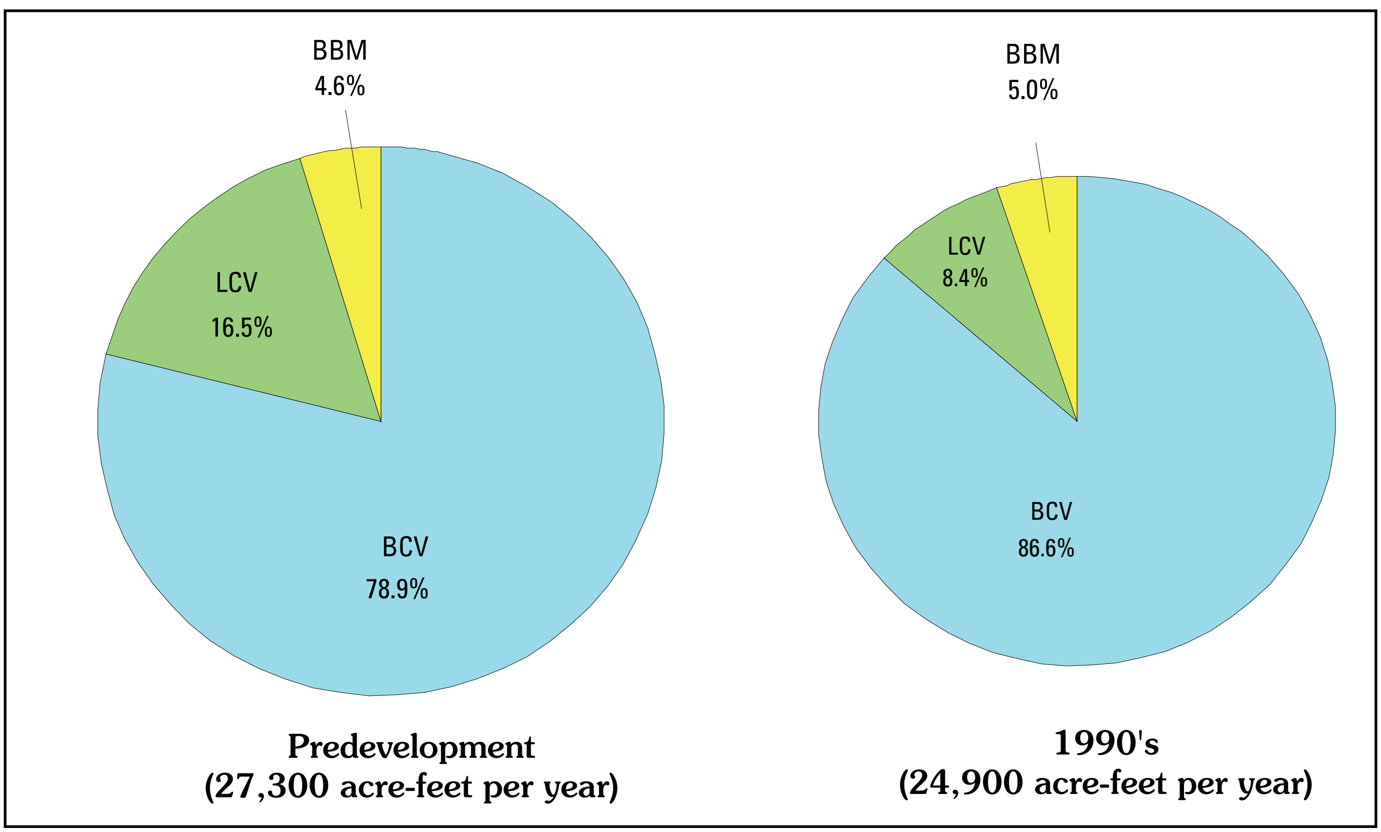


Figure A16. Conceptual water budget for upper Verde River based on previously published estimates of recharge, as given in table A4. (LCV = Little Chino Valley, BCV = Big Chino Valley, BBM = Big Black Mesa). Note that pie diagram on the right is proportionately smaller (91 percent) than the one on the left.

with Big Chino Valley and Big Black Mesa combined contributing the remaining 92 percent of base flow at the Paulden gauge. This overly simplistic water budget is compiled from several studies using various approaches—therefore, no precision or accuracy can be assigned to these percentages. Moreover, current water consumption in Big Chino Valley is unknown and therefore neglected. Nevertheless, this water-budget exercise provides a rough conceptual framework that summarizes much of the earlier work that has been done and provides a basis for comparison with new information presented in the following chapters in this report.

References Cited

Allen, Stephenson & Associates, 2001, Hydrogeology study of The Ranch at Del Rio Springs: prepared for The Bond Ranch at Del Rio Springs, LLC; available from Allen, Stephenson & Associates, Phoenix, Arizona, 88 p. plus appendices.

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Anning, D.W., and Duet, N. R,. 1994, Summary of ground-water conditions in Arizona 1987–90: U.S. Geological Survey Open-File Report 94–476, 1 map.

Arizona Crop and Livestock Reporting Service, 1974, Cropland atlas of Arizona: Phoenix, Arizona Crop and Livestock Reporting Service report, 68 p.

Arizona Department of Commerce, 1993–1997, County profiles: Coconino, Gila, and Yavapai Counties, Arizona.

Arizona Department of Economic Security, 1990, Housing unit data for Arizona, counties, places, and Indian reservations: April 1, 1990, Census.

Arizona Department of Water Resources, 1998, Preliminary report on the Safe-Yield Status of the Prescott Active Management Area: 44 p. plus appendices.

Arizona Department of Water Resources, 1999a, Report on the final decision and order that the Prescott Active Management area is no longer at safe-yield: January 12, 1999, 31 p.

Arizona Department of Water Resources, 1999b, Third management plan for Prescott Active Management Area 2000-2010: *http://www.water.az.gov/adwr/Content /Publications /files/ThirdMgmtPlan/tmp_final/prescott/pre-toc.pdf*

Arizona Department of Water Resources, 2000, Verde River Watershed Study: Arizona Department of Water Resources report, 208 p. plus appendices.

Arizona Department of Water Resources, 2002, Arizona Registry of Wells 55 CD-ROM, updated March 2002.

Arizona Game and Fish, accessed on May 19, 2004, *http://www.gf.state.az.us/outdoor_recreation/wildlife_area_upper.shtml*

Arizona State Legislature, 1991, Groundwater Transportation Act: Article 8.1, Withdrawals of groundwater for transportation to Active Management area; Section 45-555;Transportation of groundwater withdrawn in Big Chino subbasin of the Verde River groundwater basin to initial active management area; exception; definitions.

Baker, T.L., Rae, S.R., Minor, J.E., and Connor, S.V., 1973, Water for the Southwest-historical survey and guide to historic sites: American Society of Civil Engineers, Historical Publication no. 3, 205 p.

Bates, R.L., and Jackson, J.A., ed., 1980, Glossary of Geology: American Geological Institute, Falls Church, Virginia, p. 286.

Betancourt, J.L, 2003, The current drought (1999-2003) in historical perspective: 2003 Southwest Drought Summit report, May 12-13, 2003, Northern Arizona University, Flagstaff, Arizona, http://www.mpcer.nau.edu/megadrought/drought_summit_report/

Bureau of Reclamation, 1946, Chino Valley project, Arizona: U.S. Department of Interior, Project Planning Report No. 3-8b.9-0, April 1946, Appendix C.

Bureau of Reclamation, 1974, Chino Valley Unit Appraisal Report, U.S. Department of Interior, April 1974, table 9, p. 79.

Clark, R.J., 2002, Comments prepared in support of the proposed rule listing the Gila Chub as endangered with critical habitat: Department of the Interior, Fish and Wildlife Service, 50 CFR Part 17, Proposed Rules, Federal Register, v. 67, no. 154, August 9, 2002.

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

Ewing, D.B., Osterberg, J.C., Talbot, R.W., 1994, Groundwater Study of the Big Chino Valley—Hydrology and hydrogeology: Bureau of Reclamation Technical Report, Denver, Colorado, Sections I through III, including 6 appendices.

Fisk, G.G., Duet, N.R., Evans, D.W., Angeroth, C.E., Castillo, N.K., and Longsworth, S.A., 2004, Arizona Water Resources Data—Water Year 2003: U.S. Geological Survey Water-Data Report AZ-03-1, 328 p.

Ford, J.R. 2002, Big Chino Valley ground water as the source of the Verde River *in* Ground Water/Surface Water Interactions, July 1–3, 2002, American Water Resources Association summer specialty conference, 6 p.

Freethey, G.W., and Anderson, T.W., 1986, Predevelopment hydrologic conditions in the alluvial basins of Arizona and adjacent parts of California and New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA–664.

Gilbert, C.H., and Scofield, N.B., 1898, Notes on a collection of fishes from the Colorado Basin in Arizona. Proceedings U.S. National Museum, v. 20, p. 287–499 (plates XXXVI-XXXIX).

Girmendonk, A.L., and Young, K.L., 1997, Status review of Roundtail Chub, *Gila robusta*, in the Verde River Basin: Arizona Game and Fish Department, Technical Report 114, 68 p.

Granger, B.H., 1985, Arizona Place Names: University of Arizona Press, Tucson, p. 338.

Henson, Pauline, 1965, Founding a wilderness capital, Northland Press, Flagstaff, 261 p.

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

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

Levings, G.W., and Mann, L.J., 1980, Maps showing ground-water conditions in the upper Verde River area, Yavapai and Coconino Counties, Arizona-1978: U.S. Geological Survey Water-Resources Investigations, Open-File Report 80–726, maps.

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

McCormack, H.F., Fisk, G.G., Duet, N.R., Evans, D.W., Roberts, W.P., and Castillo, N.K., 2003, Arizona Water Resources Data—Water Year 2002: U.S. Geological Survey Water-Data Report AZ–02–1, 337 p.

Metzger, D.G., 1961, Geology in relation to availability of water along the South Rim, Grand Canyon National Park, Arizona: *in* Hydrology of the Public Domain, U.S. Geological Survey Water-Supply Paper 1475–C, p. 105–135, with plates.

Munderloh, Terry, 2000, Del Rio's quick brush with the seat of government: The Daily Courier, Days Past, October 19, 2000, Prescott, Arizona.

Munderloh, Terry, 2001, Del Rio Springs after Fort Whipple moved on: The Daily Courier, Days Past, February 20, 2000, Prescott, Arizona.

Nelson, Keith, 2002, Application of the Prescott Active Management Area—Ground-water flow model planning scenario 1999–2025: Arizona Department of Water Resources Modeling Report No. 12, 49 p.

Ostenaa, D.A., Schimschal, U.S., King, C.E., Wright, J.W., Furgerson, R.B., Harrel, H.C., and Throner, R.H., 1993, Big Chino Valley Groundwater Study—Geologic Framework Investigations Seismotectonic Report 93–2, Bureau of Reclamation, Denver Office, 31 p.

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

Parkhurst, D.L., and Appelo, C.A.J., 1999, User's guide to PHREEQC (Version 2)—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey Water-Resource Investigations Report 99–4259, 312 p.

Pope, G.L., Rigas, P.D., and Smith, C.F., 1998, Statistical summaries of streamflow data and characteristics of drainage basins for selected streamflow-gauging stations in Arizona through Water Year 1996: U.S. Geological Survey, Water-Resources Investigations Report 98–4225, 907 p.

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

Schwab, K.J., 1995, Maps showing ground-water conditions in the Big Chino sub-valley of the Verde River Valley, Coconino and Yavapai Counties, Arizona—1992: Department of Water Resources, Hydrologic Map Series Report Number 28, Phoenix, Arizona, 1 sheet.

Shaw, H.G., 1998, Wood Plenty, Grass Good, Water None: The Juniper Institute, unpublished draft manuscript, 150 p.

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

Southwest Ground-Water Consultants, 2004, C.V./C.F. Ranch Acquisition hydrology report: prepared for the City of Prescott, June, 2004, 6 chapters plus Appendix.

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

U.S. Fish and Wildlife Service, 2000, Endangered and threatened wildlife and plants; final designation of critical habitat for the Spikedace and Loach Minnow: Federal Register 65(80): p. 24328–24372.

U.S. Geological Survey, 1997 to 2004, Arizona Water Resources Data: U.S. Geological Survey Water-Data Reports AZ–97–1 through AZ–03–1.

Wallace, B. L. and Laney, R. L., 1976, Maps showing ground-water conditions in the lower Big Chino Valley and

Williamson Valley areas, Yavapai and Coconino Counties, Arizona—1975–76: U.S. Geological Survey Open-File Report Water Resources Investigations 76–78, 2 maps.

Weedman, D.A., Girmendonk, A.L., and Young, K.L., 1996, Status review of Gila Chub, *Gila intermedia*, in the United States and Mexico: Arizona Game and Fish Department, Technical Report 91, 100 p.

Western Regional Climate Center, *http://www.wrcc.dri.edu/narratives/ARIZONA.htm*, accessed on 6/18/2004.

Winn, H.E., and Miller, R.R., 1954, Native post-larval fishes of the lower Colorado River Basin, with a key to their identification: California Fish and Game, v. 40, p. 273–285.

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