Sources of springs supplying base flow to the Verde River headwaters, Yavapai County, Arizona

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U.S. DEPARTMENT OF THE INTERIOR
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Contents

Figures

Tables

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ABSTRACT

Multiple lines of evidence were used to identify source aquifers, quantify their respective contributions, and trace the ground-water flow paths that supply base flow to the uppermost reach of the Verde River in Yavapai County, Arizona. Ground-water discharge via springs provides base flow for a 24-mile long reach from the mouth of Granite Creek (river mile 2.0) to Perkinsville (river mile 26). The flowing reach is important to downstream water users, maintains critical habitat for the recovery of native fish species, and has been designated a Wild and Scenic River. Sources of base flow are deduced from (a) geologic information, (b) ground-water levels, (c) precipitation and streamflow records, (d) downstream changes in base-flow measurements, (e) hydrologic analysis of water-budget components, and (f) stable-isotope geochemistry of ground water, surface water, and springs. Combined, this information clearly indicates that interconnected aquifers in Big Chino Valley are the primary source of Big Chino Springs, presently supplying at least 80 percent of the upper Verde River's base flow.

INTRODUCTION

Steady, year-round flow in the upper Verde River is supplied by a network of river-channel springs. Virtually all the base-flow discharge upstream from Perkinsville (river mile 26) occurs between the mouth of Granite Creek (river mile 2.0) and river mile 4.0 (see Fig. 1) through small, discrete springs in the stream banks and also from diffuse discharge through sand and gravel in the main channel and from Granite Creek. From 1963 to present, the average base flow was 24.9 cubic feet per second (ft^3/s) with mean daily values ranging from 15 to 33 ft^3/s at the U.S. Geological Survey (USGS) gaging station near Paulden (09503700) near river mile 10. The sources of ground water supplying these springs are complex, as are the paths followed by ground water from major recharge areas to the river. This perennial reach provides a steady source of water for downstream water users and sustains important riparian habitat for abundant wildlife, including several native fish species. Recently, the U.S. Fish and Wildlife Service (1999) has proposed the designation 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 in the past two decades, although the loach minnow has been extirpated from the Verde watershed. Wildlife biologists consider the lower Granite Creek area in particular as an important expansion area for the recovery of spikedace. In addition, in 1984, Congress declared most of the Verde River downstream from the headwaters area—from Camp Verde to Sycamore Creek—a Wild and Scenic River.

The upper Verde River watershed is largely within Yavapai County-presently the fastest growing non-metropolitan county in Arizona, with a growth rate of 3.4 percent, which is four times the national average (Woods & Poole Economics, Incorporated; 1999). Population has risen from 37,000 in 1970 to 140,000 in 1996 and is expected to increase to 313,000 by the year 2020 (Woods & Poole Economics, Incorporated; 1999). Much of this growth is near or within the Little Chino Valley in which the city of Prescott obtains most of its water. 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 the source springs of the Verde River (Arizona Department of Water Resources; 1999 and 1998; Corkhill and Mason, 1995; Remick, 1983). Although the Little Chino and

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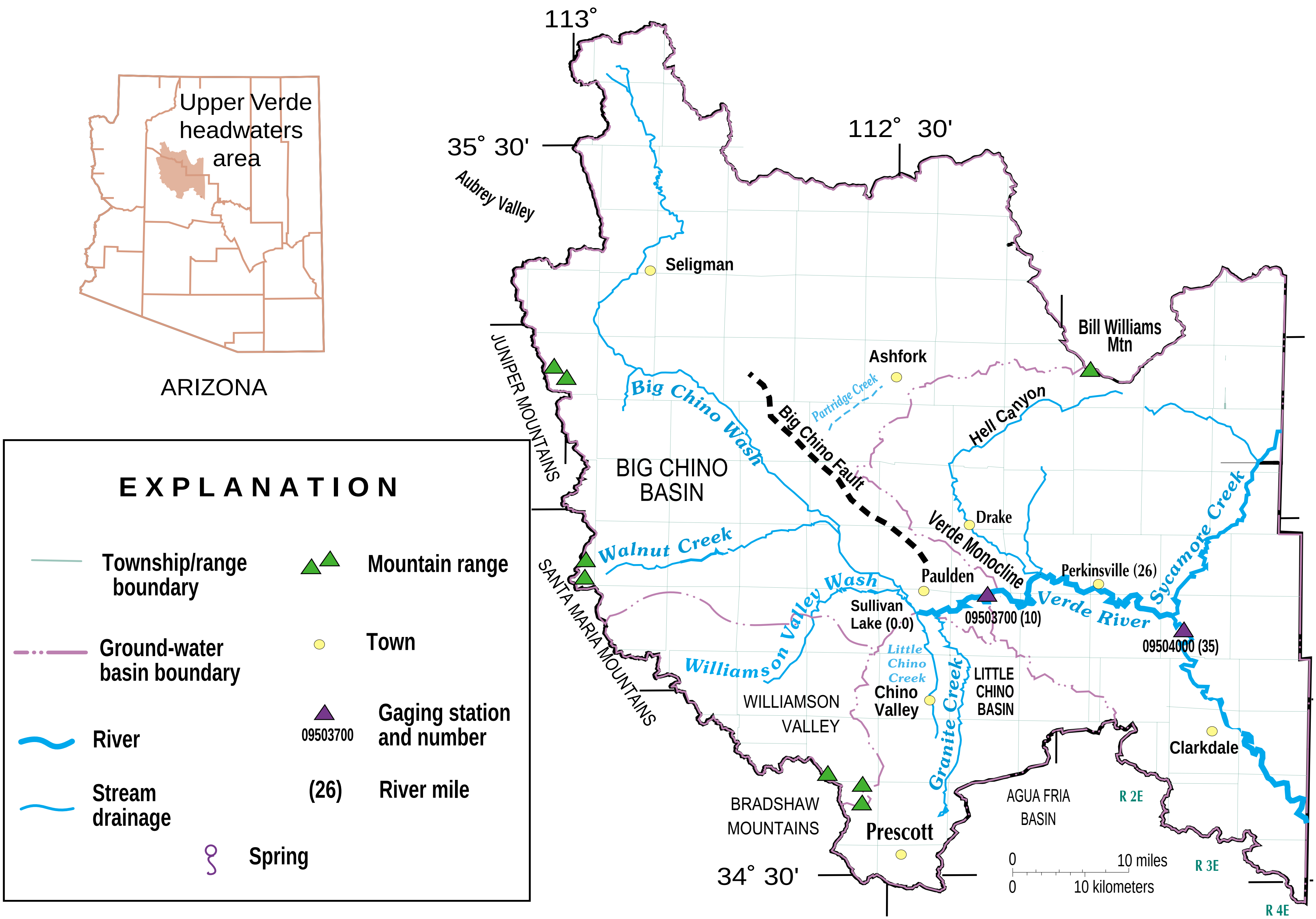

Figure 1. Major geographical features of the Verde River headwaters area.

Big Chino Valleys provide all surface-water drainage to the upper Verde River above Hell Canyon, there has been some dispute whether the major source of ground water supplying base flow is wholly derived from these two basins. Historical water-level data (Wallace and Laney, 1976; Schwab, 1995) indicate the ground-water flow direction in Big Chino Valley is toward the Verde River. However, Knauth and Greenbie (1997) have recently suggested that the major source of base flow could be from an aquifer underlying Big Black Mesa to the north, on the basis of stable-isotope data.

Moreover, ground-water discharge from Little Chino Valley to the Verde River has substantially declined. Perennial flow apparently was once but is no longer continuous from Del Rio Springs via what is now Sullivan Lake (the topographical confluence of Big and Little Chino Valleys) to the mouth of Granite Creek (Krieger, 1965, p 118). Del Rio Springs is fed by the Little Chino artesian aquifer, which has been depleted substantially since the 1940's. Surface discharge from Del Rio Springs has also been diverted for municipal and agricultural uses. There is no longer continuous perennial flow from Del Rio Springs to Sullivan Lake or in the first mile of the Verde River downstream from Sullivan Lake. Perennial flow presently begins where the Verde River crosses the intersection of several faults about one mile downstream from Sullivan Lake, at the upstream end of what is locally known as Stillman Lake. Granite Creek also has a permanent flow of water downstream from where the creek crosses a fault about 0.8 miles south of the Verde River (Krieger, 1965, p 118). Whether flow may be declining from these smaller springs is unknown.

Demand for water resources in the upper Verde River Valley is increasing because of rapid population growth near the city of Prescott. The Little Chino Valley falls entirely within the Prescott Active Management Area (PAMA), as defined by the Arizona Groundwater Management Act of 1980. The PAMA is a water-management area that is required to reach safe yield by the year 2025. Safe yield is defined by State statute as a balance between the amount of ground water withdrawn and the annual amount of natural and artificial recharge. Recent findings by the Arizona Department of Water Resources (ADWR) show the PAMA has exceeded safe yield since about 1990. From 1994 through 1998, water levels declined in over 73 percent of wells monitored annually within the PAMA (ADWR 1999; 1998). The Director of the Arizona Department of Water Resources determined on January 12, 1999, that the PAMA was no longer in safe yield. The Little Chino artesian aquifer —the major source of water supply in the PAMA—was determined out of safe yield, and ground-water depletion is projected to continue beyond 2025 in what is considered one of Arizona's three most severely depleted areas (State of Arizona Office of the Auditor General, 1999).

Because available water in Little Chino Valley will not meet increasing demands, the PAMA is considering importation of Big Chino ground water. To date, Big Chino Valley has not experienced large ground-water declines, although pumping for irrigated agriculture has at times had an effect on water levels in some parts of the sub-basin (Wallace and Laney, 1976; Schwab, 1995). Over the past several decades, residential development in this rural area has increased slightly, whereas ground-water use for agriculture has decreased (although recently stabilized), resulting in a small net decrease in water use (Anning and Duet, 1994). The few Big Chino Valley wells having more than 10 years of historical water-level measurements do not exhibit any substantial long-term changes (Wallace and Laney, 1976; Schwab, 1995; ADWR and USGS water-level databases), although fluctuations of a few feet have been observed between summer and non-irrigated winter months.

There is concern that over-use of Big and Little Chino Valley ground water has reduced base flow in the past, may reduce base flow in the future, and could eventually dry up base flow in the upper Verde River (series of articles in the Prescott Daily Courier, 1999; and in the Verde Bugle, 1999). Reductions in base flow will negatively impact downstream water users in the Verde watershed and diminish wildlife habitat. At present, base flow in the Verde River has actually increased slightly in recent decades in response to decreasing irrigation in Big Chino Valley. Improved understanding of ground-water sources, travel paths, and the relative contributions of each source are needed so that the limited water resources in Big and Little Chino Valleys can be managed effectively.

The purpose of this report is to briefly analyze and summarize multi-disciplinary evidence that identifies and describes the two principal ground-water sources that provide base flow in a 24-mi reach of the Verde River between the mouth of Granite Creek (river mile 2.0) and Perkinsville (river mile 26). Nearly all of the data used has been available in published reports and in water data files of the USGS and ADWR. These data indicate the relative contribution of each source, characteristics of the source aquifers (such as rock-type and relative ground-water age), the direction of ground-water travel paths, and the locations of major recharge areas. Data were derived from the following sources:

a) the geology and fault locations in the Big and Little Chino Valleys and along the upper Verde River from Krieger (1965 and 1967a-c); Ostenaa et al. (1993); and Menges and Pearthree (1983)

b) ground-water levels in the Verde River headwaters region using USGS and ADWR data that are published in Wallace and Laney (1976); Corkhill and Mason (1995); and Schwab (1995). Water-level data are digitally available upon request from the USGS and ADWR computer databases

c) Records of streamflow at the USGS gage on the Verde River near Paulden (09503700) and at gages in nearby basins, which are published in the USGS annual Water-Resource Data reports for Arizona. Stream discharge data are digitally available upon request from the USGS ADAPS computer database

d) estimates of ground-water pumping for irrigation in Big Chino Valley in Anning and Duet (1994) and Ewing et al. (1994)

e) regional precipitation records in Sellers and Hill (1974) and from the National Weather Service, and

f) stable-isotope analyses from 1991 to present, collected by the USGS (under the direction of the lead author) and by Arizona State University (Knauth and Greenbie, 1997).

APPROACH

This report primarily relies on three independent approaches: (1) evaluation of the existing geologic and hydrologic information, (2) a water-budget analysis of existing hydrologic data, and (3) the interpretation of stable-isotope data. This information is used to identify ground-water sources of Verde River base flow, to determine ground-water flow paths, and to estimate the amount of ground water entering the Verde River from each source under present (1991-99) conditions. Understanding of the geology and geologic history of the area helps to identify the major obstructions and conduits for ground-water flow. The hydrologic analysis is largely based on a simplified water-budget model of the major flow components in the Big Chino Valley. The hydrologic analysis defines distinct relations between annual water use for irrigation, winter ground-water levels, and base flow in the Verde River. The isotope interpretation considers physical features of the area such as the geology, the lithology of permeable and impervious units, the location of major faults, ground-water levels, and base-flow measurements to determine flow paths and estimate the relative contribution of Verde River base flow from the two aquifer sources.

In general, ratios of stable isotopes of hydrogen and oxygen in ground water can be considered “conservative” in that they do not change with residence time or distance traveled once water (runoff) infiltrates beneath the land surface. However, isotope interpretations are often lacking in certainty without detailed knowledge of all possible source areas and their ground-water flow paths. Therefore, it is necessary to also consider geologic and hydrologic factors when developing an interpretation of ground water and surface-water interactions based on isotope data. Together, the use of multiple lines of independent evidence significantly improves the confidence level of the final hydrologic interpretation.

A BRIEF GEOLOGIC HISTORY OF THE UPPER VERDE HEADWATERS

The geology of the Verde headwaters and its major source aquifers is complex, hence, an understanding of the conceptual geologic framework is essential to identifying the barriers to flow and the conduits that provide for the movement of ground water. For reference, we include a generalized geologic map of the major lithologies for the Upper Verde Watershed, shown in Fig. 2A, which was abridged from a 1:1,000,000 scale GIS digital compilation by Richard and Kneale (1998). The detailed geology of a small but critical part of the watershed (Fig. 2B), as mapped by Krieger (1965) at a 1:48,000 scale, depicts the geology surrounding Sullivan Lake, lower Granite Creek, Del Rio Springs and other important springs; as well as the outlet regions of Big and Little Chino Valleys. Basement rocks in this area are predominantly Paleozoic limestone. In Big Chino Valley, the Martin Limestone and Redwall Limestone are underlain by Precambrian granite (Krieger, 1965; Ostenaa et al., 1993). Basement rocks in Little Chino Valley (Mason and Corkhill, 1995) and Williamson Valley (Ostenaa et al., 1993) consist of Precambrian igneous and metamorphic rocks. These rocks are exposed in the Granite Dells and along the margins of the basins.

Limestone and granitic basement rocks are also exposed in the walls of the Verde River canyon. Both Big and Little Chino Valleys are structurally controlled and are filled with unconsolidated alluvium and volcanic rocks.

Big Chino Valley is part of a physiographic and tectonic transition zone between the Colorado Plateau province to the northeast and the Valley and Range province to the south. The basin consists of a half graben formed by Cenozoic displacement on normal faults, principally the Big Chino Fault. A down-dropped block of Paleozoic limestone underlies Big Chino basin fill and is tilted northeast, as shown by deep well logs (Ostenaa et al., 1993). The valley is surrounded by structurally higher blocks of Proterozoic rocks that are capped by a mostly carbonate sequence of Paleozoic rocks. Big Chino is typical of several basins within the Transition Zone that are filled with late Cenozoic sedimentary and volcanic deposits.

The Big Chino Fault is an important structural feature relevant to the hydrology of the Big Chino Valley (Fig. 2A). The Big Chino Fault is a large regional feature that has been delineated for at least 26 miles northwest of Paulden (Krieger, 1965, 1967a-c). On a regional scale, northwest-southeast-trending fractures throughout the Colorado Plateau area in northern Arizona tend to be more open to fluid flow (Thorstenson and Beard, 1998; L. S. Beard, oral commun., 1999). Outside of the major half graben of Big Chino Valley, 4.5 million year old basalt flows post-date most faulting. However, within the center of the half graben, the youngest faulting post-dates the basalt flows and is probably less than 100,000 years old.

Downward displacement has preserved a thick wedge of sediments near the center of the basin along the hanging wall, where displacement of the Big Chino Fault is the largest (Ostenaa et al., 1993).

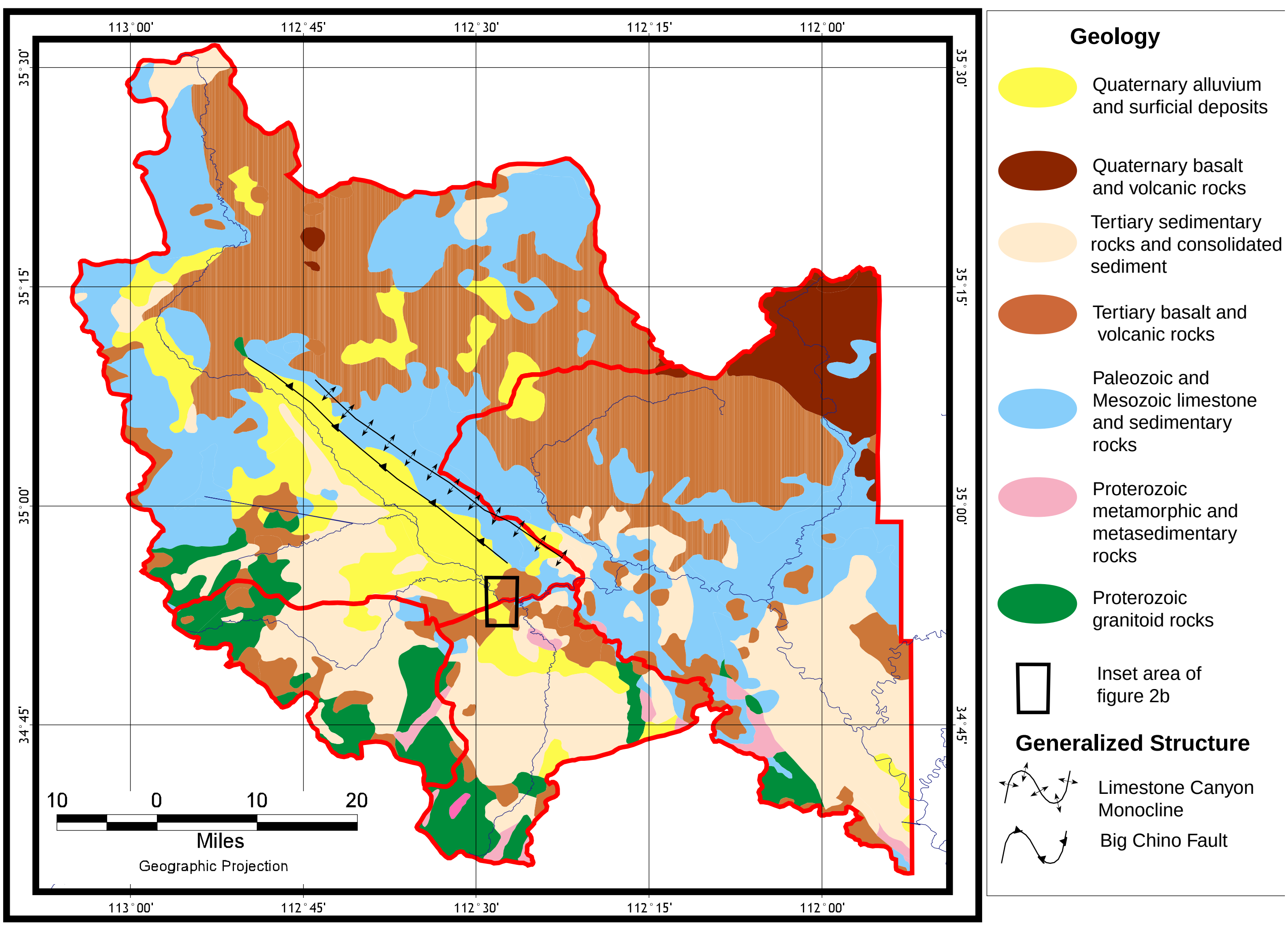

Figure 2a. Geology of the Verde River headwaters, abridged from S.J. Reynolds and S.M. Richard (AGS GIS map report, 1993)

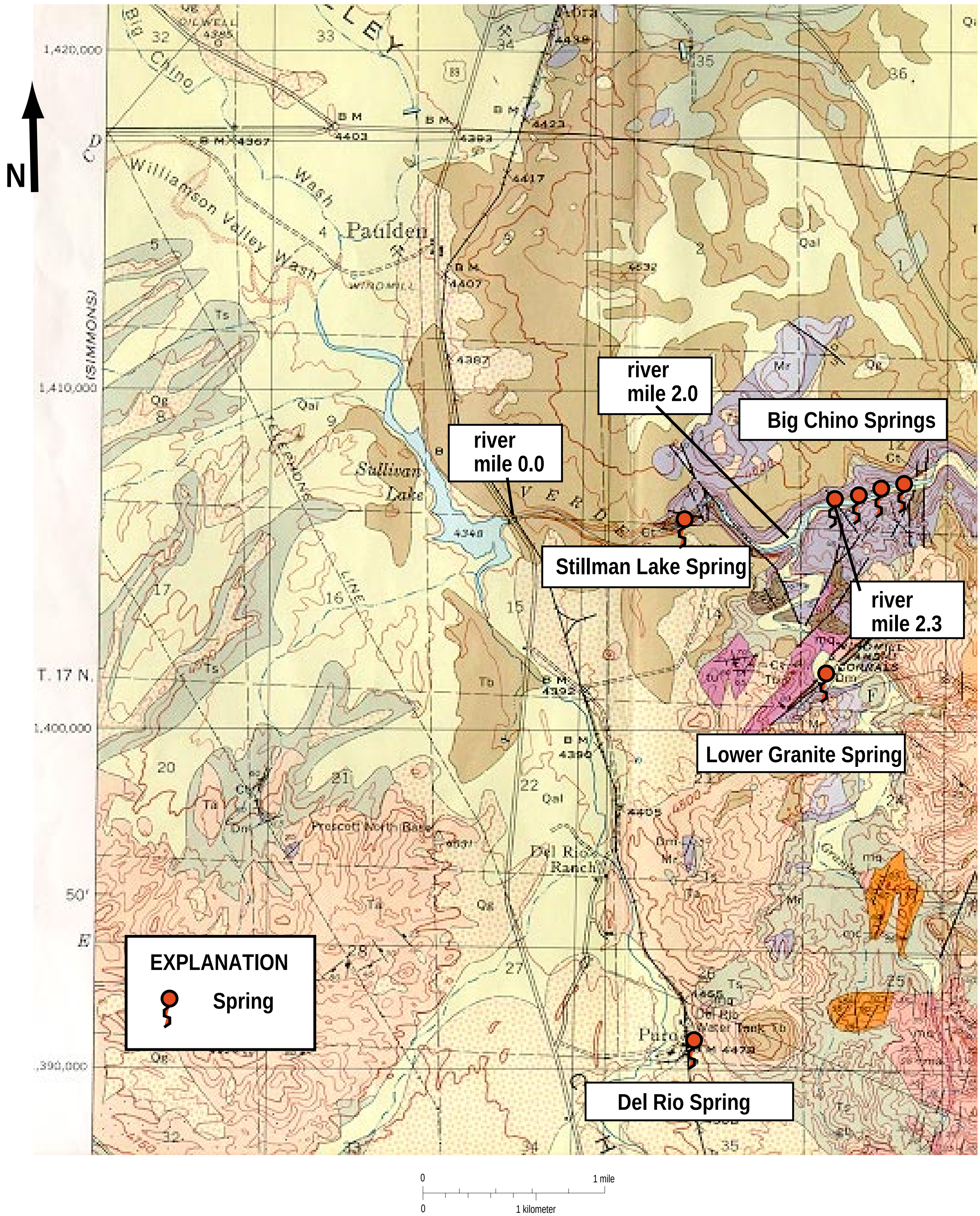

Figure 2b. Geology of the area surrounding Sullivan Lake (Krieger, 1965) and locations of important springs.

EXPLANATION

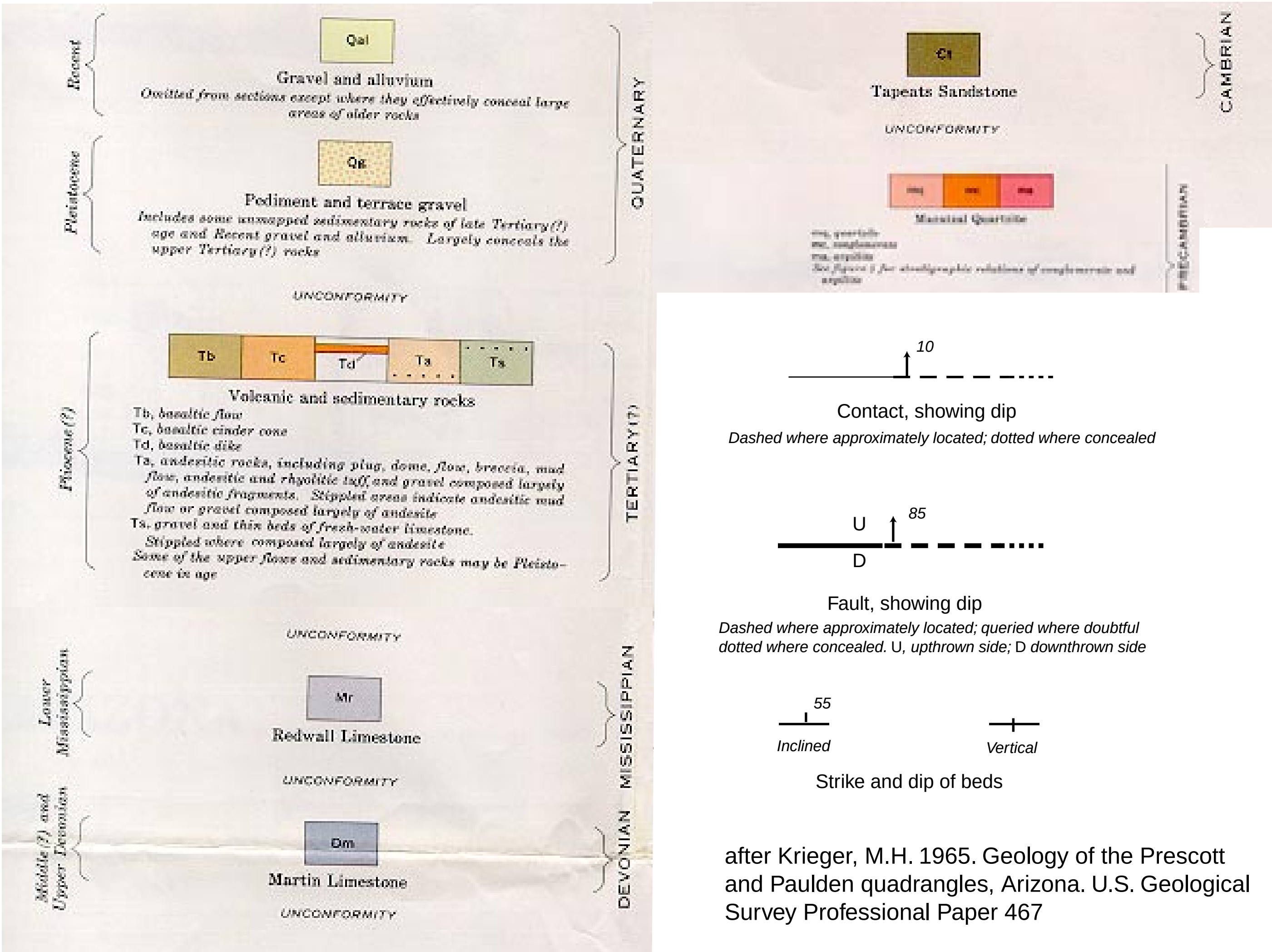

Figure 2b. (continued)

This alluvium was deposited by alluvial fans along Big Black Mesa. Throughout much of the history of Big Chino Valley, drainage from the basin was blocked, creating a large playa as evidenced by thick clay layers in the center of basin (Ostenaa et al., 1993, Ewing et al., 1994). The less-permeable clays are thought to impede ground-water movement from the upper end to the lower end of Big Chino Valley. Three deep boreholes drilled in the center of the basin penetrated between 500 to 1800 ft of silt and clay (Ostenaa et al., 1993, p. 17), indicating that the lake sediments were deposited continually over a long period. Valley subsidence was probably responsible for depositing the clays. On the down drop (southwest) side of the Big Chino Fault, clays interfinger with alluvial fan gravel near the center of the basin (Ostenaa et al., 1993, map cross-section G-G'). Preferential ground-water movement is likely through coarser-grained alluvium along the edges of clay unit, both along the fault and across the broad outlet of Williamson Valley Wash.

Alluvial fan sediments along the Big Chino Fault are composed of coarser-grained material including large blocks of limestone. Poor sorting and solution cavities in the limestone alluvium are thought to create a highly permeable aquifer along the fault (Ed DeWitt, oral commun., 1999). The decrease in the altitude of Big Black Mesa southeastward toward the Verde River appears to mimic displacement on the Big Chino Fault. Krieger has mapped the Big Chino Fault at its southeastern end as splaying outward in a complex zone of short, discontinuous faults having varied displacements. In the area near Paulden, the net offset along the entire zone of faults is negligible and the alluvial basin is considerably shallower (Ostenaa et al., 1993; map cross-section H-H').

Volcanic activity began less than 30 million years ago (Reynolds et al., 1986) when a major northward-dipping layer of latite extruded into the Big

Chino Valley and the area that is now the upper Verde River from dikes in the Little Chino-Lonesome Valley area (Krieger, 1965). In addition, lava extruded south and east along topographic depressions from Big Black Mesa and the Juniper Mountains, respectively (Ostenaa et al., 1993). The volcanic rock penetrated in water wells is reported as basalt, or "malpais," which is a Spanish term for lava and cinders, meaning "bad land." Some volcanic units are basalt, but the older units are now termed "latite" (Edward DeWitt, oral commun., 1999), which is referred to in older publications as andesite (Krieger, 1965).

Beginning about 5 million years ago, basalt erupted along the Colorado Plateau rim area and flowed into the Hell Canyon-Verde River lowland from the north (Krieger, 1965, pp. 67-85; Ostenaa et al., 1993). The basalt flowed around topographic obstacles and filled depressed areas. In Big Chino Valley, the limestone margins and valley alluvium were covered with layers of clastic volcanic rock and sediments. A large lobe of basalt extruded southward into the confluence of Big and Little Chino Valleys near present-day Sullivan Lake, which probably blocked the pre-existing drainage near the outlet of the basins. This event is preserved in the rock record east of Paulden, where basalt layers slope several hundred feet downhill towards the present-day channel of the Verde River (Krieger, 1965; Ostenaa et al., 1993).

Ostenaa et al. (1993) surmised that the basalt layers east of Paulden "apparently buried a highly irregular landscape of Tertiary gravel deposits, Paleozoic limestone hills several hundred feet high, and exposed Proterozoic rocks." In some areas of Little Chino Valley, the volcanic units contain lava tubes and comprise the major water-bearing units. As exposed in the canyon below Sullivan Lake, the basalt lies beneath the valley surface and, in this location, is non-porous and apparently serves as an obstacle to ground-water flow. As the alluvium becomes shallower and pinches out against the basalt towards the eastern end of Big Chino Valley (Ostenaa et al., 1993), ground water moving downgradient has no outlet except fractures and solution cavities in the underlying limestone. At the edge of the mesa northeast of Paulden, the base of the lower basalt contact is higher than the valley, and ground water can move beneath the basalt through limestone (Fig. 2B). Solution features and irregular subsurface terrain provide the likely hydrologic connection between Big Chino Valley and the upper Verde River.

In fact, several solution features and springs have been identified in close proximity to the largest base-flow gains in the first 26 miles of the Verde River. Several small ponds and springs have recently been identified at the base of the limestone cliffs on both sides of the river near river mile 2.3. One spring-fed pond had about 2-ft of artesian head, located just below a small side canyon and fault. This spring, which is part of a network of spring-like areas along the north bank of the Verde River between river miles 2.3 and 4.0, is visible in a 1949 aerial photograph (National Archives Air Survey Center, Bladensburg, Maryland, photo ID 188VT55RTM532311AD-16APR49-7P54). Alluvial deposits and riparian vegetation presently cover these springs; but at the time the photograph was taken a recent flood (possibly associated with the record January 1949 precipitation at Prescott) had scoured the left bank. Knauth and Greenbie (1997) identified an artesian pond at river mile 2.5 in a larger side canyon, and reported that the side canyon appears to have been formed by dissolution of the Martin Limestone and the collapse of overlying non-carbonate material. The surface altitude of the pond is 3.5 ft higher than the water level of the Verde River, as measured by Hjalmarson using a steel tape on April 16, 1999. Coinciding with the locations of the solution features and springs, base flow increases rapidly from less than 5 to more than 17 ft^3/s from river mile 2.3 to 2.7 (Boner and others, 1991; Table 1).

Ground-water discharge from Del Rio Springs and Lower Granite Spring may be interconnected. Lower Granite Spring, 0.8 mile upstream from the mouth of Granite Creek, coincides with-mapped fault locations (Fig. 2B). Large cottonwood trees and riparian vegetation mark the onset of flow about 1 mile upstream from the mouth of Granite Creek. The first occurrence of ground-water discharge, referred to here as the lower Granite Spring, coincides with a fault zone mapped by Krieger (1965) in which the Tapeats Sandstone is fault bounded between Mazatzal Quartzite and Martin Limestone.

In recent geologic times, the Verde River eroded through the basalt obstruction between the confluence of Big and Little Chino Valleys (Sullivan Lake) and the confluence with Granite Creek for a distance of at least 2 miles to form a narrow basalt canyon. The location of the present-day head cut is now the man-made cement dam at Sullivan Lake. Sullivan Lake is just upstream from where Big Chino alluvium pinches out against the southward sloping basalt obstruction.

To summarize what is known about geologic controls on the hydrology of the upper Verde River headwaters area, we conceptualize that ground-water movement from major recharge areas in Big Chino Valley is ultimately toward and along the Big Chino

Table 1
Base-Flow Measurements for the Upper Verde River (1977-97)
[All meaurements made with AA-type flow meter except as noted:
bold is estimated, *italics* is mean daily flow at gage,
and * indicates Parshall flume]

Station Name	Verde River Distance (river miles)	Latitude	Longitude	Collecting Agency	Date of Discharge Measurement (cubic feet per second) 5/2/77	7/2/91	5/22/96	7/4/97
Granite Creek, 0.3 mi abv confluence with Verde R.	NA	34 51' 33"	112 25' 58"	USGS	0.55	**<.5**		
" " " " " "	NA	34 51' 42"	112 25' 53"	ADWR			0.13*	
Verde R., 500 ft blw Granite Creek	2.1	34 51' 48"	112 25' 50"	USGS	0.49			
Verde R., 0.25 mi blw Granite Creek	2.3	34 51' 54"	112 25" 39"	ADWR			4.62	4.44
Verde R., 0.5 mi blw Granite Creek	2.5	NA	NA	ADWR				20.5
Verde R., 0.7 mi blw Granite Creek	2.7	34 52' 01"	112 25' 18"	USGS	14.6	17.3		
Verde R., at Stewart Ranch	3.8	34 52' 03"	112 24' 05"	USGS	20.3	19.3		
" " " "	3.8	34 52' 03"	112 24' 05"	ADWR			22.3	19.1
Verde R., gage nr Paulden (09503700)	10	34 53' 40"	112 20' 32"	USGS	*27*	20.3	*25*	*23*
Verde R., nr Duff Spring	13	34 52' 40"	112 17' 20"	USGS		23.7		
Verde R. nr U.S. Mines	19	34 54' 29'	112 15' 29"	USGS		17.1		
Verde R., nr bridge at Perkinsville	26	34 53' 52"	112 12' 04"	USGS	18.9	27		

Notes:
ADWR measurements were made in cooperation with ASU (Knauth and Greenbie 1997).
USGS measurements in 1977 are published in Owen-Joyce and Bell (1983).
USGS measurements in 1991 are published in Ewing and others (1994).

Fault. At the end of the fault zone near Paulden, flow is through fractures or solution features in the Martin Limestone, which underlie the basalt unit. The southward-dipping basalt unit apparently blocks underflow in the vicinity of Sullivan Lake, which would account for the lack of springs in the first river mile. The Martin Limestone discharges to Big Chino Springs in the Verde channel between river miles 2.3 and 4.0, as conceptualized in Fig. 3. On the basis of water-level contours and geology, the source of Lower Granite Spring is probably the Little Chino alluvial aquifer, however, the possibility that it receives some contribution from the Big Chino unconfined aquifer cannot be ruled out.

HISTORICAL CHANGES IN WATER LEVELS

Human activities and thus water-level changes in rural Big Chino Valley have been relatively small, and almost entirely related to agriculture, although future residential use is expected to increase. In contrast, the Little Chino artesian aquifer has been extensively developed for public water supply, industry, and agriculture. In this section we present the available data showing water-level changes in the two basins.

Changes in water levels in Big Chino Valley were evaluated by comparing data from Wallace and Laney (1976) with Schwab (1995). Water levels in lower Big Chino Valley downstream from Walnut Creek were similar in 1992 (Schwab, 1995) to what they were in 1975-76 (Wallace and Laney, 1976), although large declines have been observed near irrigated farmland in the upper Big Chino Valley (up gradient from the clay unit). Water levels in Williamson Valley were a few feet lower in a few wells in 1992 (Schwab, 1995) than when water levels were measured in those wells in 1975 and 1976 (Wallace and Laney, 1976).

Short-term or daily changes in water level appear to be related to the depth and degree of confinement, as illustrated by the following observation. From June 1974 to December 1975, the USGS monitored water levels in two existing wells in Big Chino Valley (Ewing and others, 1994; Appendix E). The first well (at T18N, R3W, 26acc) recorded a steady but gradual decline during the 18 months from approximately 15.7 feet to 16.7 feet below land surface. This well, with a depth of 400 feet, is assumed to represent conditions in the shallow alluvial aquifer. The second well (T18N, R3W, 31bcb) displayed a wildly fluctuating record for the same period. Depth to water ranged from 139.4 feet at the beginning of the period and 138.8 feet at the end of the period, however, daily fluctuations were recorded in excess of 0.6 feet. The depth of the second well is unknown. It also is not known whether this well or a nearby well were in operation during this period. Barometric pressure changes recorded at the Prescott Municipal Airport appeared to influence water levels in the second well. According to Ewing and others (1993), this indicates that the second well is probably completed in a deep aquifer under confined conditions. The occurrence, interconnection, and depth of confined aquifer units in lower Big Chino Valley is not well understood.

In the northern part of Little Chino Valley (T. 17 N., R. 2 W.), water from artesian wells flows at the land surface. Remick (1983) reported 7 flowing wells during the winter of 1981-82. Many of these wells have since been capped. Schwalen (1967) described the artesian area as extending from Del Rio Springs southward for a distance of 6.5 miles and has a known width of about 4 miles. The town of Chino Valley is located near the center of the artesian area. A perched aquifer in alluvium composed of clay, silt, sand, gravel, and conglomerate overlies the artesian area, probably because the confining layer of the artesian zone also forms the perching layer for the perched aquifer (Remick, 1983). Depth to water ranges from less than 10 to more than 150 ft below land surface (Remick, 1983). Outside the artesian area, water levels may be more than 250 ft below land surface in the southern part of the basin (for example in T. 15 N., R. 1., 2 W).

At the north end of Little Chino Valley, perennial Del Rio Springs was known as a reliable source of water to the earliest explorers and settlers. Camp Whipple was temporarily established at Del Rio Springs on December 23, 1863 to provide the governor's party a secure place to stay and to use as a base for further exploration in order to establish a territorial capital (Henson, 1965). In written accounts by these explorers (Henson, 1965), Del Rio Springs (referred to as Cienega Creek) is described as the headwater tributary of the Verde River.

The springs were developed in the early part of the century for water supply and irrigation. In 1901 (Krieger, 1965; p. 115), the City of Prescott built a 21-mile pipeline that pumped 500,000 gallons per day (560 acre-feet per year; Baker et al., 1973) from Del Rio Springs to Prescott from 1904 to 1927 (Matlock et al., 1973). Although the supply of water was adequate for Prescott’s needs, the cost of pumping was considered excessive and the pipeline was eventually disassembled (Krieger, 1965). Other less-expensive water-supply options favored at that time

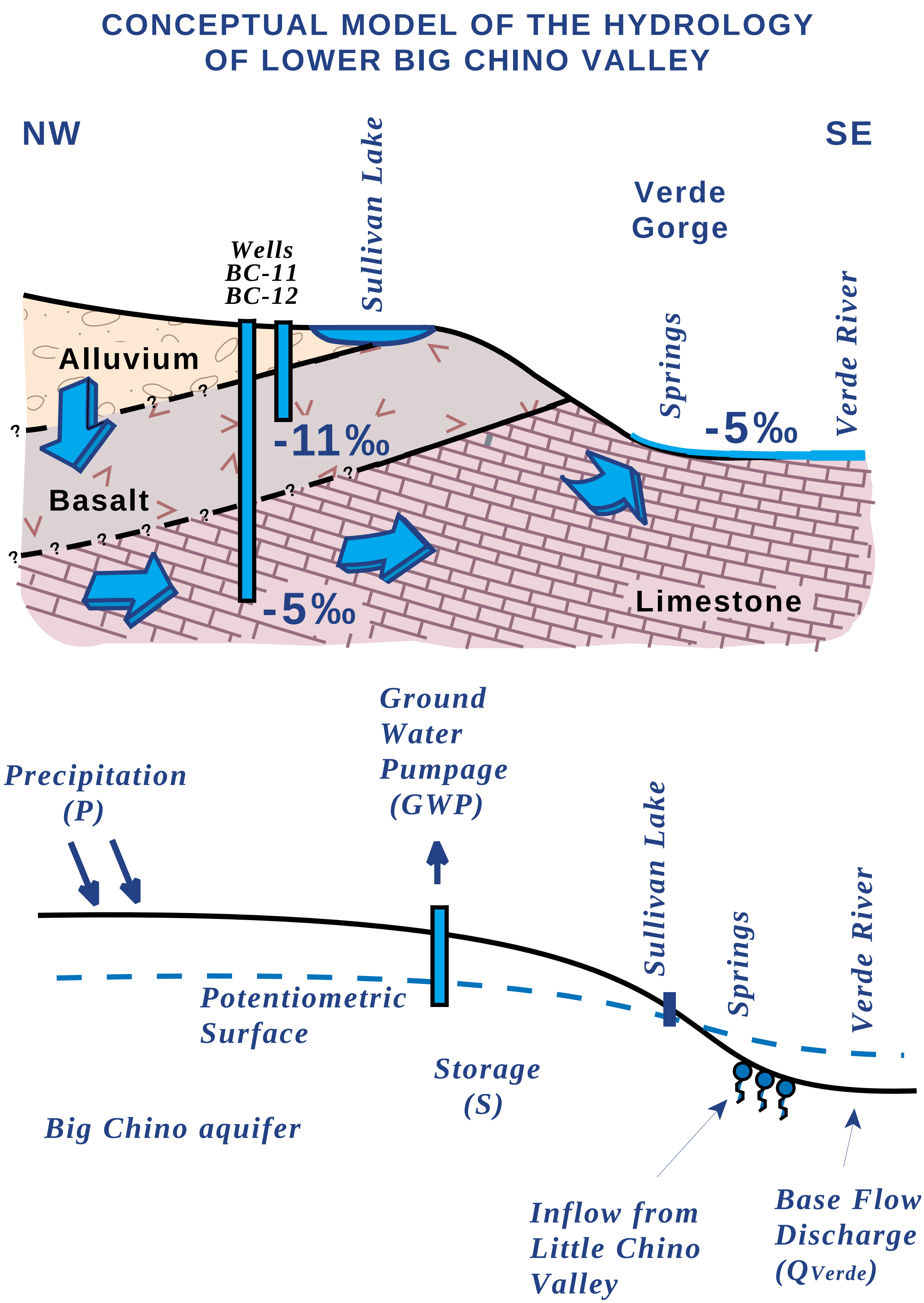

Figure 3. Conceptual model of hydrology of lower Big Chino Valley and the upper Verde River in longitudinal section showing flow components, flow paths, rock units, springs, selected wells, potentiometric surfaces, and carbon-13 isotope data (eg. -5 is per mil of carbon-13).

included the construction of several upstream dams and an infiltration gallery that was installed in the alluvial channel of Granite Creek near Prescott. Well drilling to tap the artesian aquifer near the town of Chino Valley first began around 1925, with many wells drilled in the 1930's and 1940's. The Santa Fe Railroad operated the Puro siding at Del Rio Springs to supply water tanks for trains. In the winter of 1925-26, the railroad drilled 2 wells, replacing a sump pump system (Matlock et al., 1973; p. 44). Deep wells in the artesian aquifer near the town of Chino Valley are the primary source of supply for the Chino Valley Irrigation District, which is supplemented by water from man-made Watson Lake (Krieger, 1965). An investigation by the U.S. Geological Survey in 1945 and 1946 was unsuccessful in finding an adequate water supply near Prescott, and so in 1947 the city drilled two wells approximately 5 miles south of Del Rio Springs (Krieger, 1965). Several municipal wells in this area remain in use today. To give the reader an idea of the amount of water presently withdrawn from Little Chino Valley, annual pumping in 1993 was 12,811 acre-feet, as estimated by Corkhill and Mason (1995; p 72).

Water levels in the Little Chino artesian aquifer have declined by as much as 75 ft in recent decades (ADWR, 1998, 1999; Corkhill and Mason, 1995; Remick, 1983). In 1999, water-level declines of 1 to 11 ft per year were observed in 20 wells that tap the alluvial and volcanic aquifers in the Chino Valley area (Frank Corkhill, written commun., March 27, 2000). In the northern part of the basin where the decline has been greatest, the discharge at Del Rio Springs has decreased substantially over the past several decades. Examination of the available discharge data for the springs (Table 2 and Fig. 4) indicates that base flow is quite variable from year to year. According to Corkhill and Mason (1995), the annual variation is related to variations in annual precipitation, natural recharge, ground-water pumping, and incidental recharge. For example, increases in discharge during the 1980's are attributed to local reductions in pumping from the artesian aquifer (Corkhill and Mason, 1995; p 81). The mean annual discharge at Del Rio Springs from 1997 to 1999 was 1,460$\pm$60 acre-feet ($\pm$ standard deviation), or about 50 percent of the mean annual discharge of 2,830$\pm$450 acre-feet that was measured from 1940 to 1945. Pumping of nearby water-supply wells for the Santa Fe Railroad may have caused discharge from Del Rio Springs to decrease during the 1940's, however, pumping records are incomplete for much of this time period. Schwalen (1967) notes that the effects of pumping were particularly noticeable in the War years of 1942 and 1943, in which the outflow from the spring was apparently decreased by 600 to 800 acre-feet. In 1943, the only year in which accurate pumping records are available, pumping was 855 acre-feet (Schwalen 1967). Thus, annual discharge of Del Rio Springs from 1940 to 1946 may have typically exceeded 3,000 acre-feet, and could have been higher before the advent of well drilling in the Little Chino artesian aquifer. Since 1930 more than 100 wells have been drilled into the artesian aquifer, not all of them successful, but some flowing at rates as high as 1,500 gallons per minute (Matlock et al., 1973).

In addition to surface discharge from Del Rio Springs, natural discharge from the artesian aquifer flows northward towards Sullivan Lake, presumably as underflow through the alluvium underlying Little Chino Creek (Matlock et al. 1973; Corkhill and Mason, 1995). Schwalen (1976) estimated a total predevelopment natural discharge from the Little Chino artesian aquifer system towards the Verde River headwaters region of about 5,000 acre-feet. Matlock et al. (1973; p. 9) estimated a slightly lower predevelopment value of 4,000 acre-feet, but neither Matlock et al. or Schwalen considered possible changes in ground-water flow resulting from the construction of Watson and Willow reservoirs circa 1915. Whether the impoundment of runoff may have affected the amount of ground-water underflow is unknown. Prior to 1940, little quantitative data are available to indicate whether natural discharge may have been higher, however a minimum predevelopment value of at least 4,000 to 5,000 acre-feet is probably valid "since there has been no major climatic change in the area" (Matlock et al., 1973; p.9).

SURFACE-WATER DRAINAGE AND GROUND-WATER CONDITIONS IN THE UPPER VERDE HEADWATERS AREA

Prior to the early 1970's, the first perennial flow in the Verde River system began at Del Rio Springs (Krieger, 1965; p 118). A large cienega fed by Del Rio Springs provided permanent base flow from lower Little Chino Creek to Sullivan Lake (Corkhill and Mason, 1995; p 27). Spillage over the cement dam at Sullivan Lake (constructed from 1935 to 1939; Sharlott Hall Museum archives) is thought to have supplied continuous flow through the basalt canyon of the Verde River between the dam and the mouth of Granite Creek (A.L. Medina, oral commun., 1999). Since the early 1970's the lower reach of Little Chino Creek has been ephemeral, along with Sullivan Lake and the first mile of the Verde River below Sullivan Lake, owing to declining and diverted

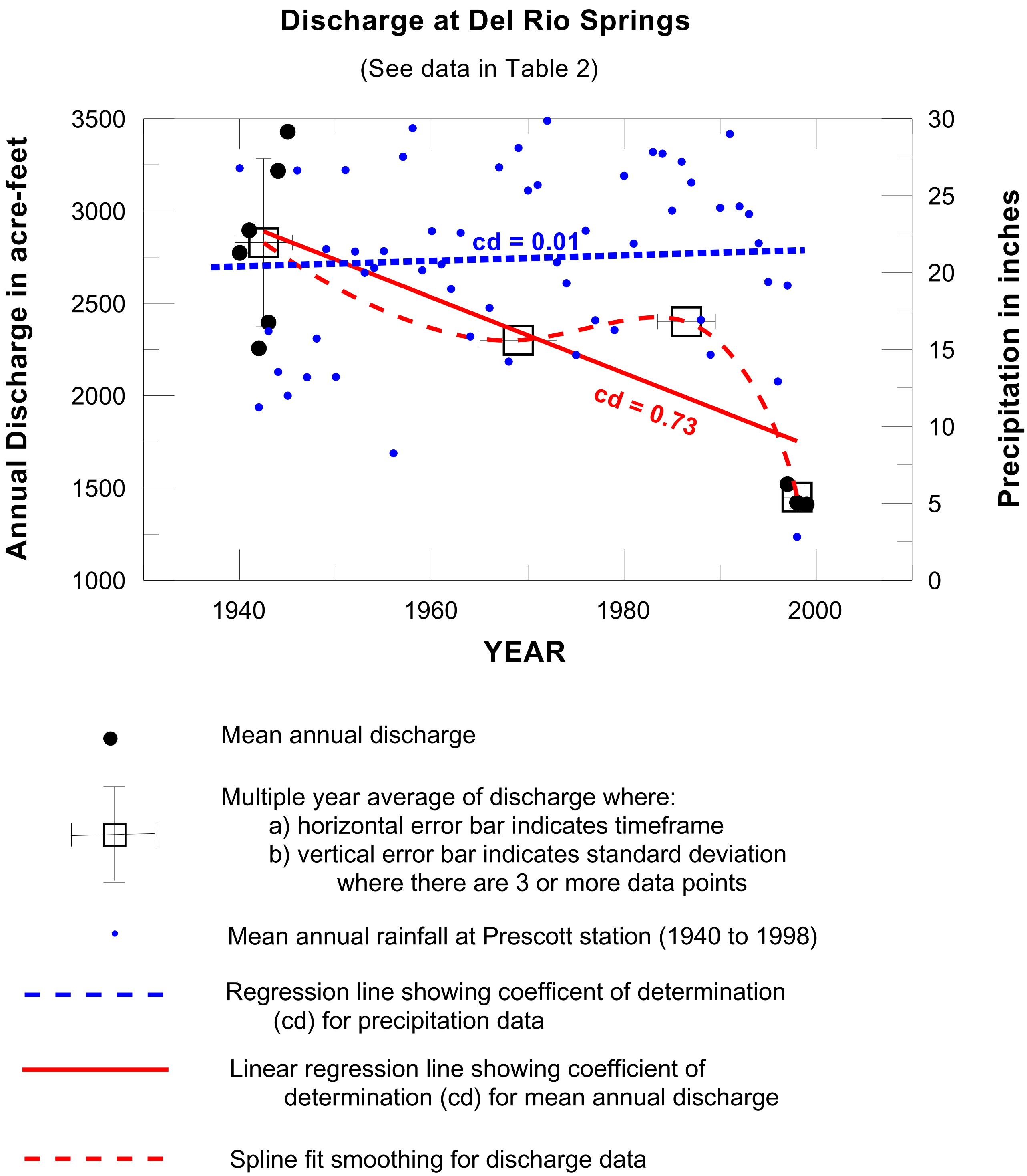

Figure 4. Mean annual discharge at Del Rio Springs in acre feet (1939 to present). A straight line and spline-fit curve represent interpolation of averaged data values. Small circles indicate mean annual precipitation at the Prescott municipal airport.

Table 2. Annual Discharge at Del Rio Springs in Acre-Feet (1939 to present)

[parentheses ( ) indicate mean value for multiple years;
± standard deviation provided where data allows]

Water Year(s)	Annual Discharge	Data Source	Comments
1940-45	(2,828 ± 455)	1	6-year average
1965-72	(2,300)	2	8-year average
1984-1989	(2,400)	3	6-year average
1997-99	(1,450 ± 61)	4	3-year average
1939	--	1	monthly records began August 1939 using a 36-inch rectangular weir
1940	2,773	1	
1941	2,895	1	
1942	2,256	1	
1943	2,396	1	discharge reduced by 855 acre-feet of pumpage from nearby Santa Fe wells
1944	3,217	1	
1945	3,429	1	
1946	--	1	incomplete record; weir installation permanently damaged by flood on Aug. 4
1996	--	4	monthly records began at new gage in August 1996; new gage is slightly downstream from old gage.
1997	1,520	4	
1998	1,420	4	
1999	1,410	4	

Data sources:
1 = University of Arizona Agricultural Experiment Station, in Schwalen (1967)
2 = University of Arizona Agricultural Experiment Station, in Matlock et al. (1973)
3 = Arizona Department of Water Resources, Basic Data Section, in Corkhill and Mason (1995)
4 = U. S. Geological Survey, in Annual Water-Resources Data reports (1997-1999)

flow from Del Rio Springs (Schwalen, 1967; Matlock et al., 1973, Corkhill and Mason, 1995). Most of Sullivan Lake was silted in within a few years following its construction (A.L. Medina, oral commun., 1999), however, a large shallow pond is sometimes present on a seasonal basis (Harley Shaw, oral commun.,2000), usually following infrequent runoff from Big Chino Wash, Williamson Valley Wash, or Little Chino Creek. The bottom of the lake now lies several feet below the top of the cement spillway, and is often dry during the agricultural pumping season (March through October). Schwab (1995) reported water levels in nearby wells of 95 to 113 ft below the top of the land surface, hence seasonal water in the lake is either impounded or fed by perched ground water, or is some mixture of these conditions.

Unlike the ground-water flow paths that typically develop in a homogeneous alluvial aquifer, ground water in both Big and Little Chino Valleys follows substantially different flow paths than the surface drainage, as will be further illustrated in the following sections. We begin by examining the differences between the surface-water and ground-water drainage patterns. This will provide the background necessary for a discussion of ground-water recharge and discharge, aquifer storage, and historical trends in the major source aquifers. Ultimately, this information will be used to develop a conceptual ground-water model for the Big Chino confined and unconfined aquifers, which includes our major premise that Big Chino Valley is the primary source of Verde River base flow.

Base-flow measurements in the upper Verde River. As defined by state statute, the origin of the Verde River begins at Sullivan Lake (river mile 0.0), near Paulden, Arizona. Little Chino Creek, Williamson Valley Wash, and Big Chino Wash converge at the confluence of Big and Little Chino Valleys to form a narrow basalt canyon. In the first mile below the Sullivan Lake dam, there have been no reports of spring flow or ground-water seepage, although puddles may persist following storm runoff. A small pool is often present at the base of the dam, which may be the result of a small amount of ground-water seepage around the dam or runoff remaining from flow over the spillway. The first mile of the canyon is ephemeral, but the second mile contains a large mile-long spring-fed pond, known locally as Stillman Lake, that is impounded by alluvial debris above the mouth of Granite Creek.

Uppermost perennial flow in the upper Verde River presently begins at the spring near river mile 1.0 at the upstream end of Stillman Lake. The uppermost perennial flow in lower Granite Creek begins Lower Granite Springs (0.8 mile south of the confluence). Lower Granite Springs is within the Little Chino watershed, and the Stillman Lake spring straddles the boundary of the Big Chino-Little Chino drainage divide. Both reaches are intermittent, as both the Verde River and Granite Creek are generally dry at the mouth of Granite Creek. The disappearance of perennial flow is attributed to underflow through the abundant sandy alluvium near the confluence. The canyon is wider near the confluence, but quickly narrows and measurable perennial flow resumes in the Verde River about 0.1 mile (500 ft) downstream from the confluence with Granite Creek. During wetter years, perennial flow has been observed to begin further upstream, at the confluence.

At the downstream end of Stillman Lake there is little if any measurable current. Although there is slow-moving current in a few narrow stretches of lower Granite Creek, large sections of the reach are wide and marshy, and discharge can be difficult to measure. As observed during low-flow conditions on several occasions from 1991 to present, flow in the Verde River channel disappears entirely at the confluence with Granite Creek and probably travels beneath the surface through channel alluvium to emerge in the Verde streambed several hundred feet downstream. Base flow in lower Granite Creek has been measured at 0.55 ft^3/s in 1977 (Owen-Joyce and Bell, 1983), estimated at <0.5 ft^3/s in 1991 (Boner and others, 1991; Ewing et al. 1994), and measured by Parshall flume at 0.13 ft^3/s in 1996 (Knauth and Greenbie, 1997). The data were probably collected at different locations, and there are too few data to support a trend. On the basis of decreases in discharge at Del Rio Springs, loss of surface flow from Little Chino Creek, and declining water levels in the Little Chino artesian aquifer (Schwalen 1967, p. 47; ADWR, 1998; ADWR and USGS water-level databases), we hypothesize that base flow from Little Chino Valley to the upper Verde River—as well as surface flow—may have declined over the past century.

Base flow downstream from the confluence with Granite Creek begins as a trickle (river mile 2.1) and gradually increases to about 4.6 ft^3/s near about mile 2.3, as measured by ADWR in May 1996. Krieger (1965) mapped a northwest-southeast-trending fracture crossing the Verde channel near this location, about 1500 ft downstream from the confluence of Granite Creek. The fault location coincides with the onset of the rapid increase in discharge from Big Chino Springs. Base flow near the old Stewart Ranch (river mile 4.0) was measured at 20.3 ft^3/s in 1977, 19.3 ft^3/s in 1991, and 22.3 ft^3/s in 1996 (Fig. 5 and Table 1). Base flow does not increase substantially between Stewart Ranch and the USGS gaging station near Paulden, Arizona (09503700) (river mile 10).

Thus, discharge measurements and field observations suggest at least three separate spring systems. The Verde River reach downstream from Granite Creek (river mile 2.1 to 2.3) and above the first inflow from Big Chino Springs is probably a mixture of underflow from the lower Granite Creek and from the Stillman Lake spring systems, which may or may not be interconnected. On the basis of the available discharge data, Big Chino Springs provides at least 80 percent or more of the total base flow measured at the Paulden gage.

The possibility of an unknown component of Big Chino or Little Chino ground water moving beneath or around the Paulden gage is largely addressed by geologic constraints. Precambrian crystalline rocks underlie the Devonian and Mississipian units in the Verde River canyon at a fairly shallow depth, normally less than 300 ft beneath the surface. In selected places along the river these crystalline rocks are exposed because of uplift along Laramide monoclines or exposure along Tertiary normal faults. Quartz diorite (Krieger, 1965, plate 2), assigned to the Government Canyon Granodiorite (DeWitt, unpub. data, 1999), is exposed between river miles 10 and 15 downstream from the Paulden gage

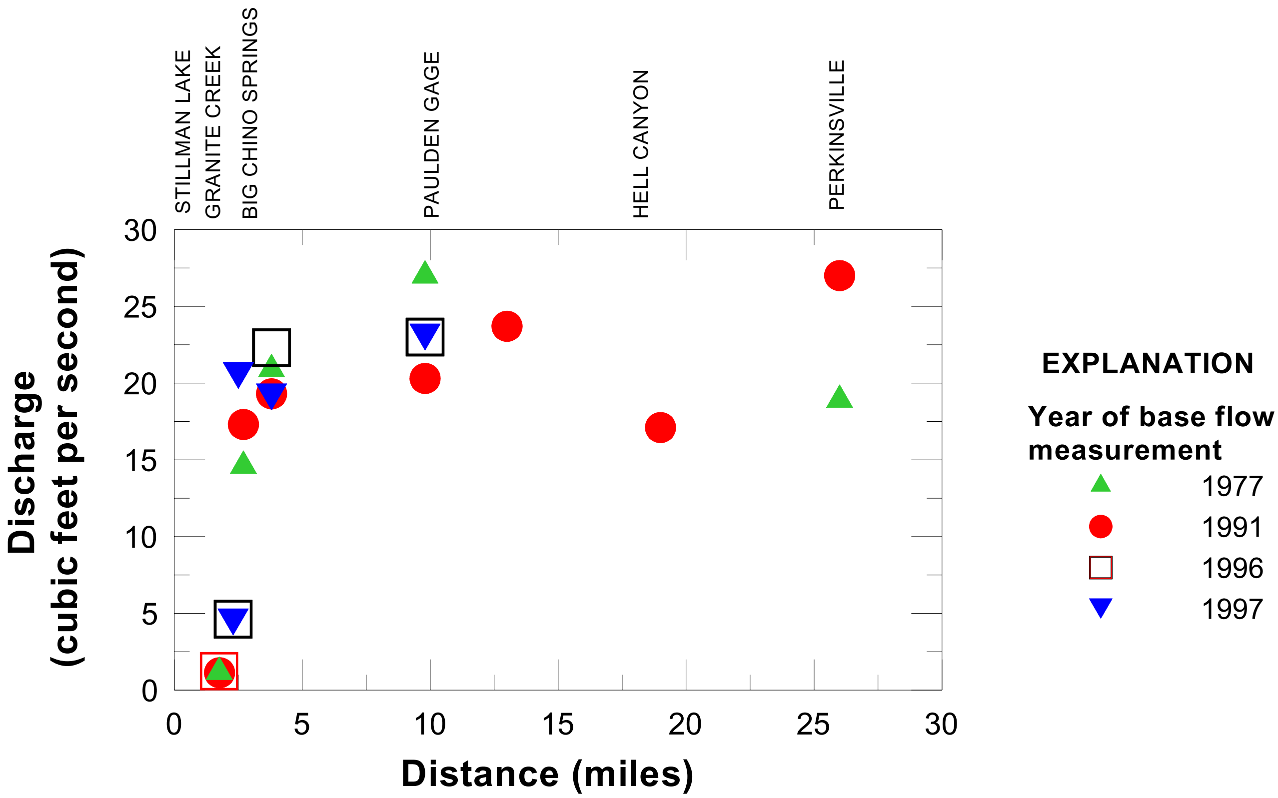

Figure 5. Base-flow discharge versus distance along the upper Verde River from Granite Creek (river mile 2.0) to Perkinsville (river mile 26). Location of major hydrological and geographical features are labeled along the top x-axis.

(09503700). Based on interpretation of aeromagnetic data, the uplifted granodiorite extends north and south from the river for several miles (DeWitt, oral commun.,1999). Widely spaced epidote-filled fractures are common in the otherwise undeformed granodiorite. Except for these fractures and the weathered part of the granodiorite immediately below the basal Cambrian strata, the granodiorite is presumed to be impermeable. In general, uplifted Precambrian basement serves as a barrier to ground water moving downward or eastward along the canyon, and probably facilitates ground-water discharge at Big Chino Springs. Thus, the possibility of underflow from the Big and Little Chino watersheds around or beneath the Paulden gage is considered unlikely. Discharge from Big Chino Springs between river mile 2.3 and 4.0 is the major source of perennial flow in the Verde River, accounting for at least 80 percent or more of total base flow. The remaining fraction of ground-water discharge is attributed to Lower Granite Spring and spring discharge beneath Stillman Lake on the basis of low-flow discharge measurements upstream from mile 2.3 (Table 2).

Base flow in the Verde River gradually increases from a dry streambed at the confluence with Granite Creek (river mile 2.0) to a 35-year mean (1963 to 1997) of 24.9 ft^3/s at the USGS gaging station near Paulden, Arizona (09503700), located at river mile 10 (Fig.1), on the basis of observations and historical discharge measurements (USGS and ADWR databases, presented in Table 1 and Fig. 5). Virtually all ground-water contributions to base flow, or river-channel springs, occur between miles 2.1 and 4.0. Additional gains, if any, between the Paulden gage and Perkinsville (river mile 26) are not considered significant. In 1977 stream flow appeared to decrease slightly between the Paulden gage and Perkinsville; in 1991 there was a small net gain (Fig. 5). These fluctuations in the 1991 measurements are attributed to several possible factors. A daily range in discharge of about 2 ft^3/s, as measured continuously at the Paulden gage, is caused by evapotranspiration during summer base-flow conditions. A small gain of about 1 to 3 ft^3/s or less is attributed to Duff Spring, a small spring in a south-side tributary near river mile

13. In the reach downstream from river mile 15, temporary stream-flow losses may occur to fractures and karst features in the exposed Redwall Limestone. In addition, there is a ranching diversion several thousand feet upstream from the road bridge at Perkinsville that seasonally diverts a small but unknown amount of stream flow, but probably on the order of a few ft^3/s.

Surface drainage and geologic controls on ground-water movement. Virtually all surface runoff upstream from the Paulden gage (09503700) is derived from Big Chino Wash in Big Chino Valley and from Granite Creek in Little Chino Valley. Water-level contours in the major Big and Little Chino aquifers have been compiled in Fig. 6 from Schwab (1995) for Williamson Valley and Big Chino Valley and from Corkhill and Mason (1995) in Little Chino Valley. The ground-water flow direction is downgradient or perpendicular to the contour lines. Ground-water flow directions should be considered approximate and may not accurately reflect conditions where multiple aquifer levels are present. In many instances, the down-valley flow path does not closely follow the surface drainage, as might be expected in a more homogeneous aquifer, because of variations in the alluvial material, basalt layers, solution features, and faulting along the valley margins.

The headwaters of Big Chino Wash are the small springs and streams draining the Bradshaw, Santa Maria, and Juniper Mountains to the southwest, and Big Black Mesa to the northwest. Williamson Valley Wash and Walnut Creek are the two largest tributaries to Big Chino Wash. Williamson Valley is a sub-basin that lies between Big and Little Chino Valleys. It receives drainage from the Bradshaw and Santa Maria Mountains, whereas Walnut Creek receives drainage from the Santa Maria and Juniper Mountains. Although perennial springs in the headwaters of these tributaries provide year-round recharge to Williamson Valley Wash, Walnut Creek, and ultimately to aquifers in Big Chino Valley, surface-water runoff to the Verde River from Big Chino Wash is ephemeral. Only seasonal runoff in occasional wet years connects these tributaries with the upper Verde River downstream from Sullivan Lake.

Ground-water movement in Big Chino Valley is obstructed, first by the vertically and horizontally extensive clay unit in the center of the basin and secondly by the non-porous basalt flow near Sullivan Lake (Fig. 6). If the Big Chino Valley were a closed basin, a lake would be formed and water-level contours would be concentric around the lake. This was probably the case during much of the basin's geologic past. At present, however, the potentiometric surface in the unconfined aquifer slopes toward the southeast outlet and the terminus of the Big Chino Fault (Fig. 6), which has no likely outlet other than the Martin Limestone and the Verde River (Fig. 2). Ground water flows around the clay unit through coarse-grained alluvial-fan sediments, either along Big Chino Fault or near the mouth of Walnut Creek and across the outlet of Williamson Valley Wash. Schwab (1995) indicates ground-water flow in central Big Chino Valley up gradient from the clay unit is from the west to east (Fig. 6). Ground-water flow in Williamson Valley is toward lower Big Chino Valley to the northeast.

In lower Big Chino Valley, Schwab (1995) reported seven water-level measurements less than 4,260 ft that form a narrow saddle in the potentiometric surface trending northeast from the mouth of Williamson Valley Wash towards the Big Chino Fault. This narrow divide in the potentiometric surface is immediately downgradient from the thick clay layer in the center of the basin and west of Paulden. Ground water probably exits Big Chino Valley through fractures or solution openings in the Martin Limestone northeast of Paulden. Ground water would then flow beneath the basalt overlying the limestone toward the Verde River. Eastward movement of ground water toward Hell Canyon is probably obstructed by shallow Precambrian granite beneath the NW trending Laramide monoclines (the largest being the Limestone Canyon Monocline), which intersect the Verde gorge near Duff Spring (river mile 13). Thus, ground-water movement does not precisely follow surface-water drainage patterns but must detour around poorly permeable obstacles that may be hidden in the subsurface, such as the clay unit, basalt layers, and shallow exposures of Precambrian granite—whereas large faults and solution features provide favorable conduits through bedrock.

Disparate water levels in the southeast end of Big Chino Valley indicate the presence of an unconfined aquifer overlying a deeper confined or semi-confined aquifer (Schwab, 1995; Wallace and Laney, 1976). Discontinuous layers of basalt or latite interbedded with alluvium form an aquifer unit with shallow water levels, but nearby wells that penetrate extensive volcanic layers may have water levels as much as 100 ft deeper. Artesian conditions have been observed in the Big Chino confined aquifer and in Williamson Valley. Hjalmarson observed in the 1960s that at least one Williamson Valley well flowed at the land surface. Lithology is difficult to correlate from one well log to the next, owing to the irregular patterns of the basalt flows and the varying degree of sorting and consolidation of the interbedded alluvium. The irregular deposition pattern of the volcanic material and alluvial fill is important because it explains why one well log may indicate volcanic layers, while a neighboring well log indicates none, and why water levels in adjacent wells can differ as much as 100 ft. Additional work is needed to better define extent of the unconfined aquifer in lower Big Chino Valley, its source of recharge, the precise location of its outlet, and also whether the confined and unconfined aquifers are interconnected, particularly in the vicinity of Sullivan Lake.

As in Big Chino Valley, ground-water movement in Little Chino Valley also deviates substantially from surface drainage patterns. Granite Creek is the surface-water outlet for most of Little Chino Valley. The headwaters of Granite Creek are south and west of the city of Prescott in the Bradshaw Mountains. With the exception of several intermittent reaches in the upper basin near Prescott and downstream from Lower Granite Spring, Granite Creek is ephemeral. Little Chino Valley is separated by the Granite Dells into a shallow headwaters area near Prescott, and a deeper sub-basin centered on the town of Chino Valley to the north. The upper Agua Fria ground-water sub-basin (as defined by Corkhill and Mason, 1995) lies on the eastern side of the Little Chino basin. The northern Little Chino sub-basin is filled with unconsolidated and consolidated sediments and volcanic rocks that are on the order of several hundred feet in thickness. The buried volcanic rocks in Little Chino Valley (probably latites) are thought to be more porous (Krieger, 1965; p 122) and contain lava tubes, as evidenced by driller's logs. Corkhill and Mason (1995) describe a lower volcanic unit and an upper alluvial unit. In their ground-water model, they depict the two aquifers as being interconnected at several locations in the watershed. In addition, the aquifers extend across the relatively flat topographic divide separating the Agua Fria and Granite Creek watersheds.

About 3 miles upstream from its mouth, Granite Creek changes from a low-gradient ephemeral wash draining a wide valley to a narrow incised bedrock canyon. The primary ground-water outlet for the Little Chino Valley does not follow the surface drainage through the bedrock canyon, but follows the more permeable alluvium to a second outlet to the northwest. Matlock et al. (1973) and Corkhill and Mason (1995) show the general direction of ground-water flow in the Little Chino alluvial aquifer is to the north beneath Little Chino Creek (Fig. 6). Because of the large gradient toward Sullivan Lake, ground water may presently flow or may once have flowed from the upper Little Chino alluvial aquifer into the Big Chino unconfined aquifer. The primary source of water in the Little Chino alluvial aquifer down gradient from Del Rio Springs is the underlying artesian aquifer. Older latite and younger basalt units near the outlet could provide either conduits or obstacles, respectively, to ground-water movement. Volcanic rocks and late Pleistocene sediments northeast of Del Rio Springs obscure the surface expression of possible faults or fractures in bedrock that may connect ground water in northern Little Chino Valley or near Sullivan Lake with the lower Granite Creek and Stillman Lake spring systems (Fig. 2B). Thus, the precise path or paths of ground water leaving Little Chino Valley is unknown.

To summarize this section, ground water in both Big and Little Chino Valleys follows substantially different flow paths than the surface drainage. Faults, solution features, lava tubes, and deposits of coarser grained alluvium provide conduits to flow. Clay units, changes in lithology, and, in some instances, basalt units may serve as obstructions to ground-water movement. On a regional scale, however, the ground-water and surface-water drainage in both basins is ultimately toward the upper Verde River.

Ground-water recharge, discharge, and storage. The concepts of ground-water recharge, discharge, and storage in Big and Little Chino Valleys are analogous to the characteristics of a bathtub. The water flowing into the tub is the recharge, water overflowing or exiting through the drainage outlet is the discharge, and the water contained inside the bathtub is the storage. An important characteristic of this analogous bathtub is the outlet or drain is on the side of the tub rather than the typical drain on the bottom. Thus, some of the stored water remains in the tub and does not drain under the influence of gravity alone. Ground-water recharge (also referred to as inflow) begins with infiltration of runoff along the alluvial slopes of mountains at the edges of the basins and beneath stream channels that drain the valleys.

Unlike a bathtub, the water table is not flat, but has a sloping surface that is higher near recharge areas along the margins and is lowest near the outlet. The tub is filled with non-homogeneous sediments and layers of basalt. Cracks in the bottom or fault-bounded sides of the "bathtub" may be present, but the Precambrian basement is several orders of magnitude less permeable than typical alluvium. Ground water would have to penetrate dense mountain ranges to exit the basin fill. Thus, leakage leaving the basin through the sides of the tub is thought to be minimal, except through the relatively shallow (less than 200 or 300 ft in depth) limestone units near the outlet (Ed deWitt, oral

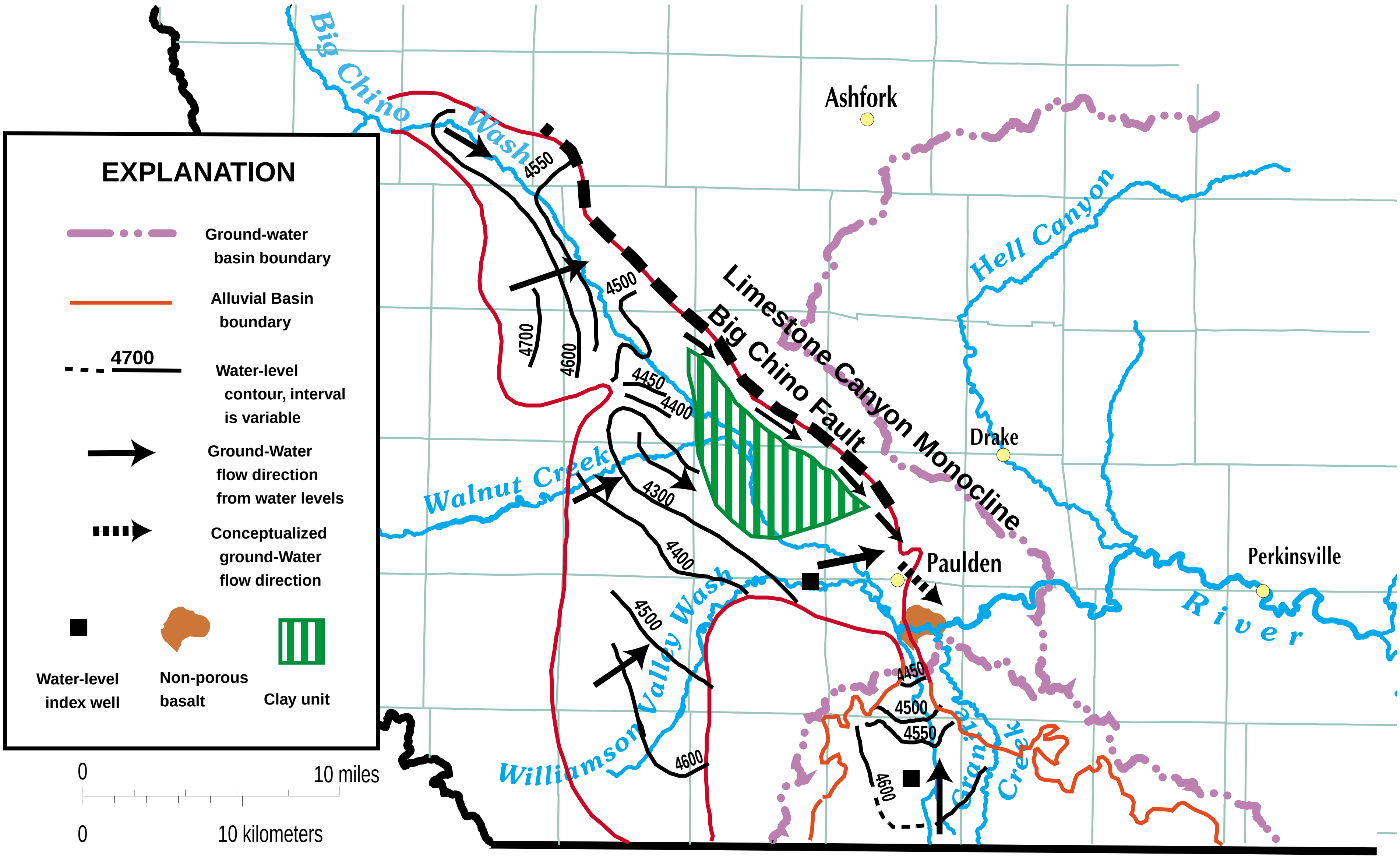

Figure 6. Compilation of water-level contours in the Verde River headwaters area (after Schwab 1995 and Corkhill and Mason 1995).

commun.,2000).

Recharge can also occur in the upland areas through bedrock fractures and solution cavities. The combined surface-water and ground-water drainage of Big Chino and Little Chino Valleys (which includes the Williamson Valley sub-basin) is measured at the USGS Paulden gage (09503700). After separating the contribution from surface-water runoff for the period from 1963-96, ground-water discharge, or outflow (Table 3), averaged about 18,000 acre-ft per year (acre-ft/yr). The geometry of the basins and the degree of porosity of the basin fill and surrounding bedrock determine the capacity of ground-water storage.

The Verde River upstream from the Paulden gage (09503700) drains an area of 2,507 mi^2. Included in this area are the Big and Little Chino Valleys. Also included is a 357-mi^2 closed basin in Aubrey Valley at the northern end of the drainage area. Surface drainage from this closed basin does not reach the Verde River, leaving an effective area drained by the Verde River of 2,150 mi^2. The drainage area of Big Chino Valley encompasses approximately 1,848 mi^2 including Big Chino Valley, Williamson Valley, and the areas between and to the north of the towns of Seligman and Ash Fork (Schwab, 1995). The area of Little Chino Valley drained by Granite and Little Chino Creeks is about 302 mi^2 (Corkhill and Mason, 1995). Most of the ground-water recharge is from high-altitude precipitation in the mountains that surround the alluvial basins. About 15 percent of Big Chino Valley (about 280 mi^2) exceeds an altitude of 6,000 ft, predominantly in the Bradshaw, Santa Maria, and Juniper Mountains. The altitude of almost all of Big Black Mesa is below 6,000 ft.

The potential amount of recharge to Big and Little Chino Valleys and Williamson Valley is large because the basins are large and deep and are therefore capable of storing large volumes of ground water. For example, the estimated thickness of Big Chino Valley fill exceeds 1,200 ft throughout an area of about 200 mi^2, and is 300 ft thick or greater in an area of about 430 mi^2. Hjalmarson (unpub. data, 1967) estimated the amount of ground water in storage to a depth of 1,000 ft in the valley fill in the Little Chino, Big Chino and Williamson Valley Valleys as 6 million, 11 million, and 3 million acre-ft, respectively. These estimates closely agree with estimates of 9.2 million, 12.8 million, and 3.83 million acre-ft, respectively, by the Bureau of Reclamation (1974). ADWR (1999) recently estimated the volume of ground water in storage in Little Chino Valley at 2.26 million acre-ft. Thus, it is reasonable to assume that at least 10 to 20 million acre-ft of water may be stored in the three basins. In addition, large amounts of water may be stored in the rocks of the surrounding mountains. The limestone and sandstone that underlie parts of the mountain ranges are known to transmit large quantities of water where fractures or solution cavities exist. Owen-Joyce and Bell (1983, p. 20) report that well yields in the Middle Verde Valley are generally improved by the presence of solution cavities along fractures in the Redwall Limestone and Martin Limestone. These limestone units are exposed along the margins of Big Chino Valley and in the canyon walls of the upper Verde River (Fig. 2).

Because of basin contours and the presence of geologic constraints near the surface-water outlets of Big and Little Chino Valleys, only relatively shallow ground water in the basins is capable of draining to the Verde River (recall the analogous bathtub with the side drain). Large volumes of ground water are located below the natural outlet. In a study of southwestern alluvial basins, Robertson (1991) found that the chemistry of these deep waters evolves under closed conditions without mixing from additional recharge after the initial filling of the basins. Thus, streams of the area may not have influenced much of the deeper ground water (perhaps below 500 ft). Obviously, withdrawal of this deep water by pumping will lower water levels in the basins. As with the bathtub analogy, there will be no outflow to the upper Verde River when ground-water levels fall below the natural outlet. The altitude of the ground-water outlet, as indicated by the elevation of Big Chino Springs, lies between about 4,240 and 4,220 ft. Infiltration along the margins of Big Chino Valley is highest where there are coarse-grained alluvial fans and sediments underlying stream channels. The same is true for the mountain front areas in Williamson Valley and upper Little Chino Valley. Sediment derived from the Proterozoic rocks surrounding the Williamson Valley tends to be much sandier than sediment derived from Paleozoic limestone or Tertiary volcanics exposed on Big Black Mesa (Ostenaa et al., 1993). The coarsest alluvial materials are deposited close to the basin margins.

The major recharge areas for Big Chino Valley are the northeastern drainages of the Bradshaw, Santa Maria, and Juniper Mountains. The altitude of these three mountain ranges is generally between 5,000 and 7,000 ft, and average annual rainfall exceeds 20 inches at the higher altitudes (Sellers and Hill, 1974). Several major tributaries, including Williamson Valley Wash, Walnut Creek, Pine Creek, and Turkey Canyon have perennial flow or springs in their upper reaches. The Bradshaw Mountains also serve as the major source of precipitation and recharge to Little Chino Valley.

Little Chino Valley near the town of Chino Valley (altitude of 4750 ft) has a relatively dry climate, receiving less than 12 inches of precipitation in an average year (Sellers and Hill, 1974). In the headwaters of the basin, Granite Creek has several intermittent perennial reaches near Prescott at the base of the Bradshaw Mountains, having an average annual precipitation of 18 inches derived predominantly from summer thunderstorms (Sellers and Hill, 1974, as measured at Prescott). Watson Lake and Willow Lake Reservoirs intercept some of the streamflow in Granite Creek that could potentially provide recharge to the northern end of Little Chino Valley and base flow to the Verde River.

Precipitation and recharge on Big Black Mesa are probably insufficient to fully account for more than a small fraction of the large volume of ground water in Big Chino Valley or base flow in the upper Verde River. The scarcity of well data probably attests to large depths to water and unpredictable yields in a region capped by volcanic deposits (Krieger, 1965; Fig. 2). Big Black Mesa is an asymmetric uplift or monocline (Krieger, 1965). The mesa is generally 1,000 to 2,000 ft lower than the three mountain ranges and has a mean annual precipitation of about 13 inches near Drake (Sellers and Hill 1974). The highest parts of the mesa, containing surface outcrops of Martin and Redwall limestone, have surface drainages to the southwest toward Big Chino Valley. This high part comprises about 30 percent of the uplift. Here, surface exposures of Martin and Redwall limestone do not support substantial runoff because they are permeable, and the karst topography retains most of the precipitation that falls. In contrast with the three other mountain ranges, there are very few springs on Big Black Mesa; a notable exception being the short perennial reach of Partridge Creek, the largest tributary draining toward Big Chino Valley. Some recharge from the highest parts of Big Black Mesa probably occurs along its base in the vicinity of the Big Chino Fault. Lower parts of the mesa, containing surface outcrops of the Supai Formation and Tertiary basalt, drain predominantly east and southeast toward Hell Canyon, which joins the Verde River near river mile 18. According to Ed deWitt of the USGS, surface runoff in this area is generally lost to permeable sandstone units in the Supai Formation and to fracture and rubble zones in the basalt. The underlying Redwall and Martin limestones are exposed by Hell Canyon, so surface runoff in the incised canyon would also be lost to these units. Because the regional dip of these units is gently to the southeast, ground water present in the formation most likely to drains southeast toward the Verde River (river miles 10 to 13) in the vicinity of exposures of Martin Limestone or Tapeats Sandstone (Ed deWitt, oral commun., 2000). Duff Spring is on the south bank of the Verde River near river mile 13. Hell Canyon, however, appears to contribute an insignificant amount of base flow to the Verde River above Perkinsville, as evidenced by low-flow discharge measurements in 1977 and 1991 (Owen-Joyce and Bell, 1983, Boner and others, 1991; Table 1). Although scant, the water-level data north of the Verde River also suggest a gradient toward the east, or possibly the southeast (Fig. 6; Owen-Joyce and Bell, 1983). Ground water moving due south or southwest from the lower parts of Big Black Mesa or from Bill Williams Mountain to reach the Verde River in the vicinity of Big Chino Springs, as suggested by Knauth and Greenbie (1997), is possible, but considered unlikely.

WATER-BUDGET RELATIONS FOR BIG CHINO VALLEY AND THE UPPER VERDE RIVER

A conceptual model and idealized water budget of the hydrology of the lower Big Chino Valley and upper Verde River for the flow components shown is in Fig. 3. The conceptual model is a synthesis of our understanding of the hydrologic system, as developed throughout this report. In simplest terms, water from precipitation recharges the Big Chino Valley aquifer network, which then discharges to springs in the upper Verde River. Under present conditions, some ground water is withdrawn by pumping for irrigation relatively high in the Big Chino Valley. This technique takes advantage of measured behavior averaged over time to examine relations between inflow, outflow, and ground-water storage in Big Chino Valley.

Recent declines in annual withdrawals for irrigation in Big Chino Valley provide the opportunity to assess related hydrologic flow components. Because some of the budget components were progressively changing while other budget components did not exhibit a trend, the behavior of related hydrologic components such as ground-water pumping and outflow to the Verde River could be examined. In this modified water-budget approach, some water-budget components are defined as functions of related parameters. Principally, the trends in annual amounts of ground-water pumping, precipitation, and ground-water levels in a joint USGS/ADWR index well in Big Chino Valley (located near the outflow of the basin, and base flow of the Verde River at the Paulden gage (09503700) are compared (Table 3). Water levels in USGS/ADWR index wells typically are collected prior to the beginning of the summer irrigation season.

The annualized water budget for the Big Chino aquifer is defined by the following standard equation:

I – O = ΔS, where:

I = Annual inflow including
(a) Big Chino mountain-front recharge,
(b) Big Chino recharge along stream channels, and
(c) Ground-water underflow from Little Chino Valley, Big Black Mesa, Williamson Valley, Walnut Creek, and other areas;

O = (a) Annual outflow is the discharge at the Paulden gage, where evapotranspiration of ground water is neglected, and
(b) Ground-water withdrawal (and consumed) mostly for irrigation of crops

ΔS = Annual storage change in the aquifer.

Available data for measured hydrologic components of the water budget were used, recognizing that these data have certain limitations. The budget cannot be quantified in its entirety because some components, such as accurate estimates of recharge, cannot be directly measured. Certain data were used as proxies for other components of the budget. Two simplifying assumptions in the model and budget were made. Only Big Chino Valley was included in the budget because it is the largest drainage above Sullivan Lake and because it presently appears to be the major source of base flow in the upper Verde River. Little Chino Valley was deliberately excluded because of added complexities that are beyond the scope of this report, resulting from large changes in recent water use and pumping.

Water-budget components. Water-budget components and indicators of unmeasured water-budget components used for the analysis are from published data (Table 3). Inflow from recharge and ground water from tributary underflow moves through the Big Chino Valley to the Verde River under the influence of gravity. Outflow from the basin occurs primarily by withdrawals for crop irrigation and by discharge to springs in the Verde River channel. Storage of water in the basin changes when inflow amounts are different than outflow amounts.

Inflow. Inflow to the aquifers in Big Chino Valley is from mountain-front recharge, recharge along stream channels and ground-water underflow from surrounding areas such as Williamson Valley, Walnut Creek, and possibly Little Chino Valley. A function (fP) of the precipitation (P) is used as an index of water that recharges the aquifer from direct percolation and along mountain fronts and from the surrounding areas except for Little Chino Valley. This is a reasonable assumption because ground-water withdrawals in Big Chino Chino Valley are relatively small. Conversely, precipitation cannot be used as an indicator of inflow from Little Chino Valley because of the substantial water-level declines from ground-water withdrawals. Generally speaking, only a small portion of precipitation that does not runoff as surface flow or is lost to ET recharges the aquifer.

Outflow. Ground water exits the Big Chino Valley aquifer(s) via pumping, mostly for irrigation in the upper valley (Wallace and Laney, 1976), and via discharge to springs in the Verde River channel. The measurable ground-water outflow components are the pumping (GWP) and the Verde River (Q_{verde}). Also, any evapotranspiration (ET) from the aquifer is relatively small and is assumed to not undergo any significant change over the study period. The potentiometric surface typically is deeper than 20 ft below the land surface and beyond the reach of evaporation and transpiration by plants, except beneath the perennial reach of the Verde River in the gorge. The ET component is considered negligible and thus is not shown in the conceptual model in Fig. 3.

Storage change. The difference between inflow to and outflow from the Big Chino Valley is the change of storage (ΔS) in the basin. For this study, storage change is considered to be a function of the water level (f ΔS) at an observation well measured annually by USGS and ADWR. This well was selected on the basis of its having more than 40 years of water-level data, sufficient depth to penetrate the lower aquifer, and its central location in the southeast end of Big Chino Valley. The index well is completed in alluvium on the Wineglass Ranch about 3 miles west of Paulden (Fig.6) at latitude 34°53'40", longitude 112° 31'20", (B-17-02) 06 bbb, with a land surface altitude of 4,390 ft and a well depth of 342 ft.

Increasing ground-water storage is assumed because the water level in the index well (Table 3) is increasing. The water level has increased about 0.1 ft/yr as ground-water withdrawals for crop irrigation have decreased. A rough estimate of the amount of ground-water that is accumulating in storage can be made by assuming that this change in storage is spread equally over the area of lower Big Chino Valley southeast of the clay plug area. Using a specific yield of 10 percent, a 0.1 ft/yr increase of water level over about 40 square miles of the Big Chino Valley would account for about 250 ac-ft/year. This is probably a maximum estimate, in that it is unlikely that storage is increasing equally in all areas of the lower basin. A more confident estimate of ΔS could be made by using water levels at additional wells and estimating the specific yield at each well. However, we are aware of few if any wells in lower Big Chino Valley with suitable historical water-level records and well-completion characteristics. Moreover, a representative estimate of specific yield at individual wells would require aquifer testing or analysis of lithologic character, both which are beyond the scope of this effort.

Period of response to changes in recharge. Another important characteristic of the water budget is that 1-year periods were used because annual data were readily available. Ideally, the time step of a water budget would be based on the system response to changes in budget components, such as recharge from snowmelt and carryover storage in major aquifers. Based on a cursory examination, base-flow discharge (Q_{Verde}) appears to change in response to seasonal and annual recharge on the order of months or years. Because of the system's response to recharge, which varies over space and time periods that may exceed one year, the general relations among the annualized budget parameters are not quantitative. Thus, judicial use of these relations are recommended. For additional insight on the selection of budget periods see Hjalmarson and Robertson (1991) and Bills and Hjalmarson (1990).

Statistical trends in recharge. Base flow in the Verde River has increased over the past four decades (Table 3). A possible explanation is that recharge has increased, but the precipitation data do not support this explanation. There was no trend (α=0.05) for annual precipitation over the full period of record in the upper Verde headwaters area at National Weather Service precipitation gages at Prescott or at Walnut Creek (Fig. 7A) using linear, quadratic and Kendall-Tau trend analysis. There is also no trend for annual precipitation during the period 1957-97 that is common to both datasets. A visual examination of the graphs (Fig. 7A) of annual precipitation shows considerable variability but a generally flat relation (no trend) for both gages. Use of precipitation as an alternative proxy for recharge excludes ET effects, although others have used it in a water budget successfully (see Karl and Riebsame, 1989). To test whether precipitation could serve as a proxy for recharge in the Big Chino Valley water budget, we considered stream flow discharge data from other nearby watersheds.

The annual tenth percentile of daily discharge at two nearby USGS stream-flow gages were examined as an alternative proxy for recharge. The tenth percentile of a set of measurements arranged in order of magnitude is that value that has at most 10 percent of the measurements below it and at most 90 percent above it (Ott, 1988; p. 44). Using this approach, the tenth percentile of daily discharge is considered to reflect the base-flow conditions of a perennial stream. For a discussion of this tenth percentile approach also see Lins and Slack (1998). The two gages used were the Oak Creek near Cornville gage (09504500) and the Verde River below Tangle Creek gage (09508500). The Oak Creek near Cornville gage has a drainage area of 355 mi^2 that is east of the upper Verde River Valley. The Verde River below Tangle Creek gage is downstream on the Verde River and has a drainage area of 5,858 mi^2. The annual tenth percentile of daily discharge for the USGS stream-flow gage on the Verde River near Paulden (09503700) was compared with that of the Cornville and Tangle Creek stations as shown in Fig. 7B. As a visual examination of the graphs or a statistical analysis of trend (Minitab, 1995) might suggest, there is no trend for either the Oak Creek or Tangle Creek gages, although there is an increasing trend at the Paulden gage (09503700).

Second, trends in mean annual discharge were examined for two drainage basins roughly comparable in size to the drainage area represented by the Paulden gage. The two gages selected were the Oak Creek near Cornville used in the previous example (again, with a drainage area of 355 mi^2) and the Santa Maria River near Bagdad (09424900), which drains a 1,129 mi^2 basin. The Santa Maria River was selected because it is one of the few gage records with a similar catchment size, howver the flow near the gage is intermittent rather than perennial. Most streams to the west are ephemeral. Like the Verde River, these streams are located along the transition zone between the Colorado Plateau and the Mogollon Rim. Once again, neither a visual examination of the graphs or a statistical analysis of trend (Minitab, 1995) indicates a trend (Fig. 7C), in contrast to the hydrograph for the Paulden gage (Fig 7C).

The graphs in Fig. 7 show considerable variation in the annual amounts of precipitation and stream-flow runoff, which is typical of the climate of Central Arizona. Other stream-flow gages in central Arizona (southeast of the upper Verde River Valley) exhibit an increasing trend over a longer period than was used for this analysis (Lins and Slack, 1998) but no such trend is apparent for the upper Verde River area. For example, the annual tenth percentile of daily discharge at Verde River below Tangle Creek has an increasing trend for the period of record (1946-1997) that was influenced by drought years before this study period. Although not statistically significant, there is a slight decreasing trend suggested by the precipitation at Prescott and Walnut Creek (Fig. 7A) and average annual discharge at the Oak Creek near Cornville gage (Fig. 7B).

Other factors that might mask small trends in annual precipitation—such as base flow and mean annual stream flow—include variations over time and space in stream flow, ET, and/or precipitation. Pitfalls in non-parametric trend analysis—such as the effect of multi-year sequences of wetter or drier than normal periods (Wahl, 1998)—are not apparent for the study period. In regard to ET effects, average annual temperature at Prescott (National Weather Service) was used as proxy data and found temperature may be increasing slightly (Tau was significant (α= 0.05%) but linear and quadratic regression was not). An increasing temperature suggests increasing potential ET. If ET in the upper Verde River basin were increasing then a decrease in base flow of the Verde River might be expected. Thus, the real increase in base flow might have been greater in this possible scenario. Again, a more detailed, comprehensive process-based hydrologic model of the upper Verde Valley might better account for the variable nature of stream flow, ET and precipitation over time and space than this simplified analysis. On the basis of this cursory examination of the available historical data, however, no evidence supporting the notion that climate, and therefore recharge, has changed over the period of concern was found. Therefore, anthropogenic effects were explored as a more plausible explanation for the observed increase in upper Verde River base flow.

Changes in Outflow from Big Chino Valley to the Verde River. The increase in Verde River base flow (Q_{Verde}) appears related to a historical decrease in pumping for crop irrigation in Big Chino Valley. Annual pumping was estimated by multiplying the irrigated acreage by an annual consumptive use of 5 acre feet (Anning and Duet, 1994). Annual pumping for irrigation (GWP) from the Big Chino aquifer has decreased by an average of 350 acre-ft/yr during the past three decades (Fig. 8A). The decrease in GWP in the northern part of the aquifer has resulted in rising water levels in the southern part of the aquifer (Fig. 8C). An increase in base flow of 110 acre-ft/yr in the Verde River (Fig. 8D) has accompanied the rise in water levels in the Big Chino aquifer. This hydrologic connection is predictable because the Verde River is down gradient along the potentiometric surface (Wallace and Laney, 1976), and is further supported by the following observation.

While collecting hydrologic data in the Little and Big Chino Valleys during the 1960s and early 1970s for the USGS, Hjalmarson witnessed the apparent effects of ground-water pumping in lower Big Chino Valley on the base flow of the Verde River. At that time there was a land sales operation in the east part of Big Chino Valley that eventually became known as "Holiday Lake Estates." The lakes were about three miles northwest of Paulden and about two miles south of the tail end of Big Chino Fault. During the late spring of 1964 at least three recreation lakes in the development were filled with water pumped from wells in Big Chino aquifer. The volume and pattern of ground water pumped is unknown but given the estimated size of the lakes, the total volume probably exceeded 100 acre-ft during a several week time period. According to the landowner (Beuford Yarbro, oral commun., August 30, 1999), the capacity of a 2-ft diameter well at Wineglass Lake, the largest of the lakes, was 6,500 gallons per minute. Reportedly there were a total of eleven different lakes, each with their own well, which were or could have been filled. During this period of heavy pumping the base flow of the Verde River (20 ft^3 /s) decreased by 5 ft^3/s (Fig. 9). For 11 days (May 13-23, 1964) the mean daily discharge in the Verde River at the Paulden gage (09503700) was 15 ft^3/s—the lowest daily discharge ever recorded since the gage began operation in mid 1963. When the lakes were filled and pumping decreased, base flow in the Verde River quickly recovered to between 22 and 23 ft^3/s, despite the dry summer conditions.

The relation between Verde River base flow and water level in the index well is shown in Fig. 8E. The log for the index well shows gravel, clay and sand, and cemented conglomerate to a depth of 342 ft. The index well is about two miles southwest of Wineglass Lake, three miles west of Paulden, and near Williamson Valley Wash. The lowest water lev-

Table 3. Annual Base-Flow, Water-Level, Ground-Water Pumping, and Precipitation Data (1952-1997) used for Water-Budget Analysis.

Precipitation data for the National Weather Service station at Prescott were obtained from the Western Regional Climatic Center of the Desert Research Institute at Reno, NV. Base flow is the dry-weather discharge of the USGS streamflow-gaging station near Paulden (0919503700). Discharge data are available in annual water-data reports of the USGS and from http://www.daztcn.wr.usgs.gov/index.html. Annual water levels are for a joint USGS/ADWR index well in Big Chino Basin located at latitude 34’ 53’ 40", longitude 112’ 31’ 20", and land surface elevation 4390 ft above sea level (ASL). Data for ground water pumpage is from the upper Big Chino Basin [Anning and Duet, 1994]. For days with snowmelt or storm runoff, the base flow (QVerde) was estimated by linear interpolation between adjacent days of base flow (see Lindsley et al. 1949, chapter 15). * indicates data were not available.

Year	Precipitation at Prescott [inches]	Verde River Base Flow [ft3/s]	Index well Water Level [feet ASL]	Ground-water Pumpage [1000 acre-ft]
1952	17.80	*	4260.32	*
1953	16.65	*	4259.51	*
1954	16.91	*	4258.73	*
1955	17.82	*	4257.45	*
1956	6.88	*	4257.75	*
1957	22.93	*	4257.91	*
1958	24.48	*	4257.92	*
1959	16.78	*	4258.68	*
1960	18.91	*	4258.90	*
1961	17.10	*	4252.96	*
1962	15.77	*	4255.77	*
1963	18.81	20.774	4251.22	*
1964	13.20	21.148	4256.11	*
1965	35.94	22.526	4257.10	*
1966	14.75	23.962	4258.69	*
1967	22.35	23.518	4259.05	9
1968	11.84	23.937	4259.00	9
1969	23.41	24.381	4259.05	9
1970	21.11	23.688	4252.80	9
1971	21.41	23.077	4258.30	9
1972	24.88	22.402	4254.70	8
1973	17.21	24.767	4259.80	8
1974	16.08	24.110	4260.30	11
1975	12.20	25.490	4259.90	12
1976	18.93	22.661	4258.20	10
1977	14.08	22.874	4257.70	9
1978	27.16	22.655	*	6
1979	13.55	25.148	*	5
1980	21.90	25.568	*	5
1981	18.23	26.644	4261.20	6
1982	27.03	25.121	4259.50	0.5
1983	23.19	26.049	4260.00	0.5
1984	23.10	25.273	4261.80	1
1985	20.02	27.800	4261.20	3
1986	22.66	27.323	4261.00	5
1987	21.54	27.403	4261.20	3
1988	14.10	27.290	4261.10	3
1989	12.21	25.636	4259.90	4
1990	20.17	25.630	4259.40	4
1991	24.17	23.885	4259.10	*
1992	20.25	24.825	4259.40	*
1993	19.83	28.227	4263.10	*
1994	18.25	28.252	*	*
1995	16.15	27.559	*	1.8
1996	10.76	26.051	*	*
1997	15.96	*	*	*

els in the index well (Fig. 8C) and lowest mean annual discharge values at the Paulden gage (Fig. 8D) were apparently affected by intermittent pumping of the recreation lakes at Holiday Lakes Estates during the mid-1960s and early 1970s. On the basis of the trend line shown in Fig. 8E, a 1-foot drop in water level at the index well produces a decrease of 1.3 ft^3/s in the Verde River. The Holiday Lakes Estates pumping occurred within a few miles of outlet of the basin where the effects on base flow in the Verde River would be expected to be the greatest. Pumping of similar wells in other parts of Big Chino Valley that are further to the northwest might not affect the base flow in the Verde River as quickly.

Coincidentally or not, if one were to visually project the slope in Fig. 8E beyond the range of measured water levels to a value of zero discharge, the y-axis intercept falls between the range in altitude of Big Chino Springs. The altitude of Big Chino Springs lies between about 4,220 and 4,240 ft and the measured water levels in the index well range between 4,251 and 4,262 (See Fig. 8E and Table 3). This translates to a difference in altitude of between about 10 and 40 ft. Extrapolating beyond the range of the measured water-level data to this extent is somewhat speculative, thus no attempt was made to quantify the amount of ground-water withdrawal required to dry up the springs. Common sense dictates, however, that given the demonstrated hydraulic connection, discharge to springs in the Verde River channel would decrease if ground-water levels decrease near the outlet.

Changes in Outflow from Little Chino Valley to the Verde River. Up to this point inflows from Little Chino Valley have not been considered in the modified water-budget approach. Decreasing ground-water inflow from Little Chino Valley, however, could possibly explain some of the difference between the observed annual decrease in pumping of 350 acre-ft (Fig. 8A) and the increase in base flow of 110 acre-ft in the Verde River. Only about 31 percent (110/350 x 100) of the change in pumping is reflected by the increase of base flow. The remaining 69 percent of the annual pumping decrease may be from several possible factors, the most likely being (1) increasing ground-water storage in the Big Chino aquifer and (2) decreasing inflow from the Little Chino aquifer.

As discussed earlier, ground-water storage is apparently increasing in some areas of lower Big Chino Valley. Storage could in fact account for most or all of the entire discrepancy. Thus, attributing the entire apparent shortfall (240 acre-ft/year) to decreasing outflow from the Little Chino Valley is unrealistic. Nonetheless, there is a likelihood that outflow from Little Chino Valley—although it contributes less than 20 percent of total base flow in the uppermost reach of the Verde River—has been decreasing due to ground water withdrawal from that basin. Decreasing discharge from the Little Chino artesian aquifer, as implicated by dropping water levels (Fig. 8F) and decreasing flow at Del Rio Springs (Fig. 4 and Table 2), may have been masked by the increase in ground-water discharge to the Verde River associated with the decreased pumping for irrigation from the Big Chino Valley in recent decades. The Little Chino index well (latitude 34°45'43," longitude 112° 26'22," (B-16-02) 14cda) with a well depth of 600 ft (Fig. 8F) is representative of aquifer conditions in the artesian area near the town of Chino Valley. At least 20 wells that tap the alluvial and volcanic aquifers in Chino Valley (Township 16N Range 2W) have experienced water-level declines of 1 to 11 ft per year (Frank Corkhill, written commun., March 27, 2000). Additional effort is needed to more precisely determine changes in storage in the Big Chino aquifer and possible changes (if any) in outflow from Little Chino Valley.

Summary of Water-Budget Analysis. The above hydrological observations and analyses strongly support that the Big Chino Valley is the major source of base flow in the Verde River. This conceptual model agrees with physical, hydrological, and geological characteristics of the Big Chino Valley as previously determined by Krieger (1965), Wallace and Laney (1976), Freethey and Anderson (1986), Ewing et al. (1994) and Ostenaa et al. (1993) as well as with the new stable-isotope data presented next in this report. Hydrological observations and analyses indicate that (1) ground-water pumping directly affects the water levels near the outlet of the Big Chino Valley, (2) base flow of the Verde River is directly proportional to the water levels near the basin outlet and (3) base flow in the Verde River is inversely proportional to ground water pumping in Big Chino Valley.

On the basis of past pumping in Big Chino Valley, a 1-ft decline in the index well correlates with a 1.3 ft^3/s decrease in the base flow of the Verde River. However, the precise effects caused by hypothetical ground-water withdrawals are difficult to predict. For example, lowering of water levels will result in increased (induced) recharge, removal of ground-water from storage and less water leaving the aquifer to the Verde River. The amount of additional recharge that might be induced is not known. Conversely, a decrease in pumping may result in increased storage. More quantitative ground-water modeling that considers the aquifer properties and geologic framework

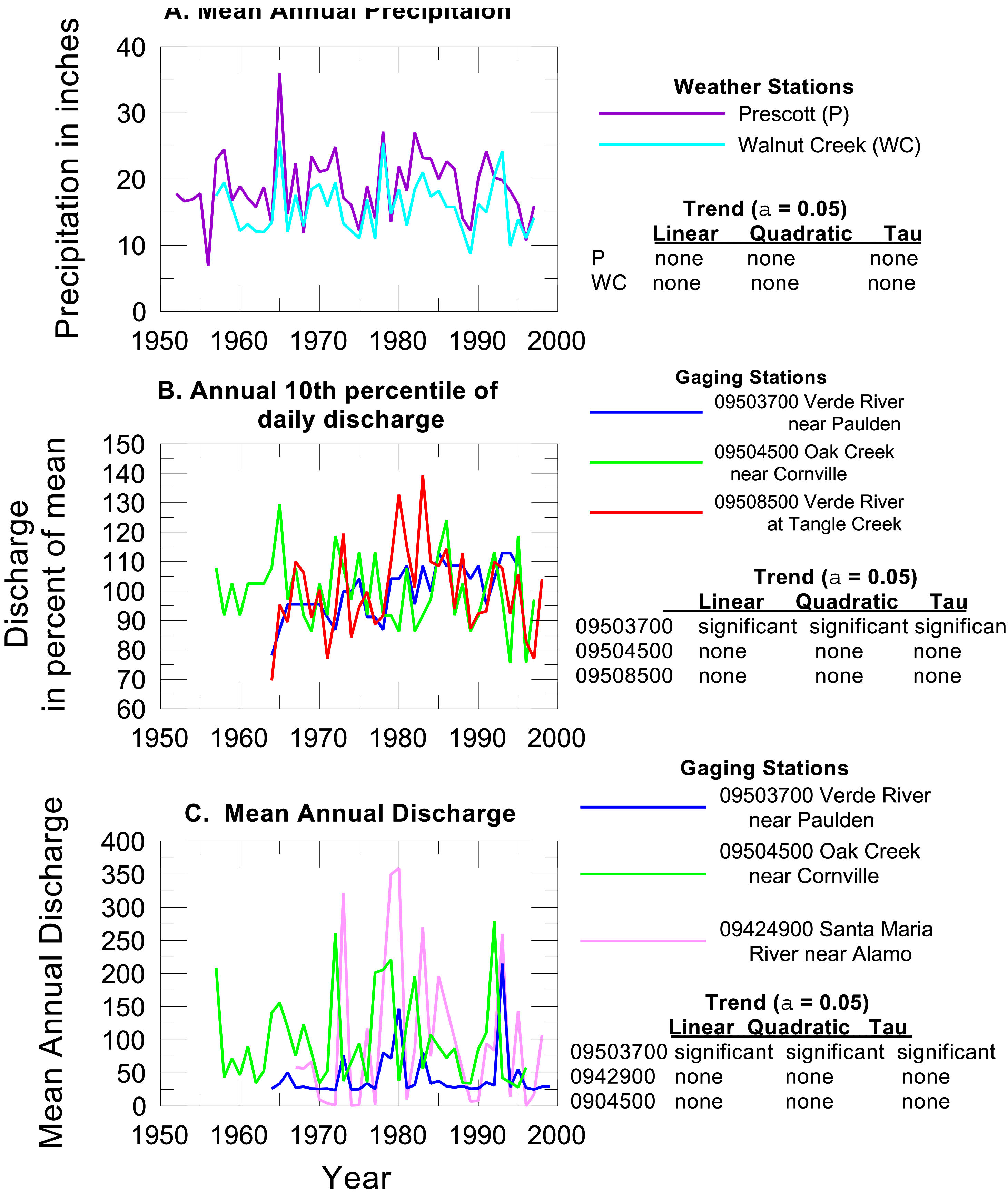

Figure 7. Precipitation and base-flow trends for available data in the Verde Watershed and nearby streams.

throughout both the Big and Little Chino alluvial basins is needed to more accurately predict the response to potential pumping scenarios resulting from an increasing demand for water supplies.

ISOTOPIC EVIDENCE FOR SOURCE OF SPRINGS IN THE UPPER VERDE RIVER

Additional evidence for the sources of base flow in the upper Verde River headwaters region is provided by isotope analyses of ground-water and spring samples. Stable-isotope analyses of hydrogen, oxygen, and carbon are reliable indicators of the origin and geochemical evolution of natural waters (for more information refer to chapter 17 of Drever, 1988; Clark and Fritz, 1997; and Coplen, 1996). Stable-isotope data are used as a naturally occurring means to distinguish among different sources of water in rivers and other water bodies fed by aquifers. Stable oxygen ($^{18}O/^{16}O$ values or $\delta^{18}O$) and hydrogen ($^{2}H/^{1}H$ values or $\delta^{2}H$) isotope data can yield information about the source areas of recharge to aquifer systems, whereas carbon isotope ratios ($^{13}C/^{12}C$ values, or $\delta^{13}C$) reflect the type of rock and soil substrate ground water has been in contact with. Stable isotopes of hydrogen and oxygen in water do not fractionate with time or distance once runoff has infiltrated beneath the land surface, assuming that they do not react with their aquifer materials or come into contact with thermal areas. Isotope interpretations, however, are often lacking in certainty because of the number of physical variables involved. For example, it is not possible to differentiate among multiple aquifer sources if those sources have the same stable-isotope signature. Isotope data can be misleading without some knowledge of the hydrogeology. Therefore, it is prudent to integrate geologic and hydrologic factors with stable-isotope data when developing an interpretation of ground-water and surface-water interactions.

The vapor pressure of water containing the lighter isotopes of oxygen and hydrogen (^{1}H and ^{16}O) is greater than that of water containing the heavier isotopes, deuterium and oxygen-18 (^{2}H and ^{18}O). Because of this, isotopically lighter water evaporates more readily; thus, rain and snow become progressively depleted in ^{2}H and ^{18}O as water evaporated from near the equator travels toward the poles, from the coast inland, and from lower to higher altitudes. In northern Arizona, Van Metre et al. (1997, p. 29-30) have observed significant variations in the ^{2}H and ^{18}O of precipitation and subsequent runoff (1) seasonally between winter storms and summer monsoons, (2) locally due to differences in altitude, and (3) as a consequence of the high rate of evapotranspiration that may occur prior to recharge. The ^{2}H and ^{18}O in a spring sample are a flow-weighted composite of prevailing conditions in the ground-water recharge area. As long as recharge and discharge conditions remain essentially static, the stable-isotope signature can be expected to remain constant through time, from point of recharge to point of discharge.

Isotope interpretations in this report are based on new and published data from the USGS (USGS QWDATA database; Ewing et al., 1994) and from researchers Knauth and Greenbie (1997) at Arizona State University (ASU). The objective of both USGS and ASU research efforts was to identify the aquifers that supply springs in the upper Verde River. In July 1991, the USGS collected 28 samples, including 16 samples from base flow in the Verde River between Sullivan Lake and Clarkdale and 12 ground-water samples in Big and Little Chino Valleys (Tables 4 and 5) in cooperation with the Bureau of Reclamation (BOR) and ADWR. Water samples were analyzed for stable isotopes of hydrogen, oxygen, selected dissolved constituents, and field parameters including pH, specific conductivity, and alkalinity. Selected samples were analyzed for carbon isotopes. The USGS National Water Inventory System (NWIS) database also contains 10 additional oxygen and hydrogen isotope samples that were collected by the USGS in 1988. These historical data provide additional stable-isotope coverage near Ash Fork, Big Black Mesa, southern Little Chino Valley, and along the upper and lateral margins of Big Chino Valley. To address important gaps in the data, two additional spring samples were collected on May 1, 1999.

Knauth and Greenbie (1997) conducted a stable-isotope investigation in the upper Verde headwaters in cooperation with ADWR from 1996 to 1997. The ASU study collected more than 25 ground-water samples from wells and springs in Big Chino, Little Chino, and Williamson Valley and Walnut Creek drainages, and one sample northeast of the Verde River. Base-flow samples were collected quarterly between Sullivan Lake and the Stewart Ranch from May 1996 to July 1997. Samples were analyzed for stable isotopes of oxygen and hydrogen (Tables 4 and 5). The ASU study focused on the area upstream from the Stewart Ranch (river mile 4.0), whereas the 1991 USGS study sampled surface water from Sullivan Lake (river mile 0.0) to the USGS streamflow-gaging station near Clarkdale (river mile 36).

The effect of recent precipitation on the base

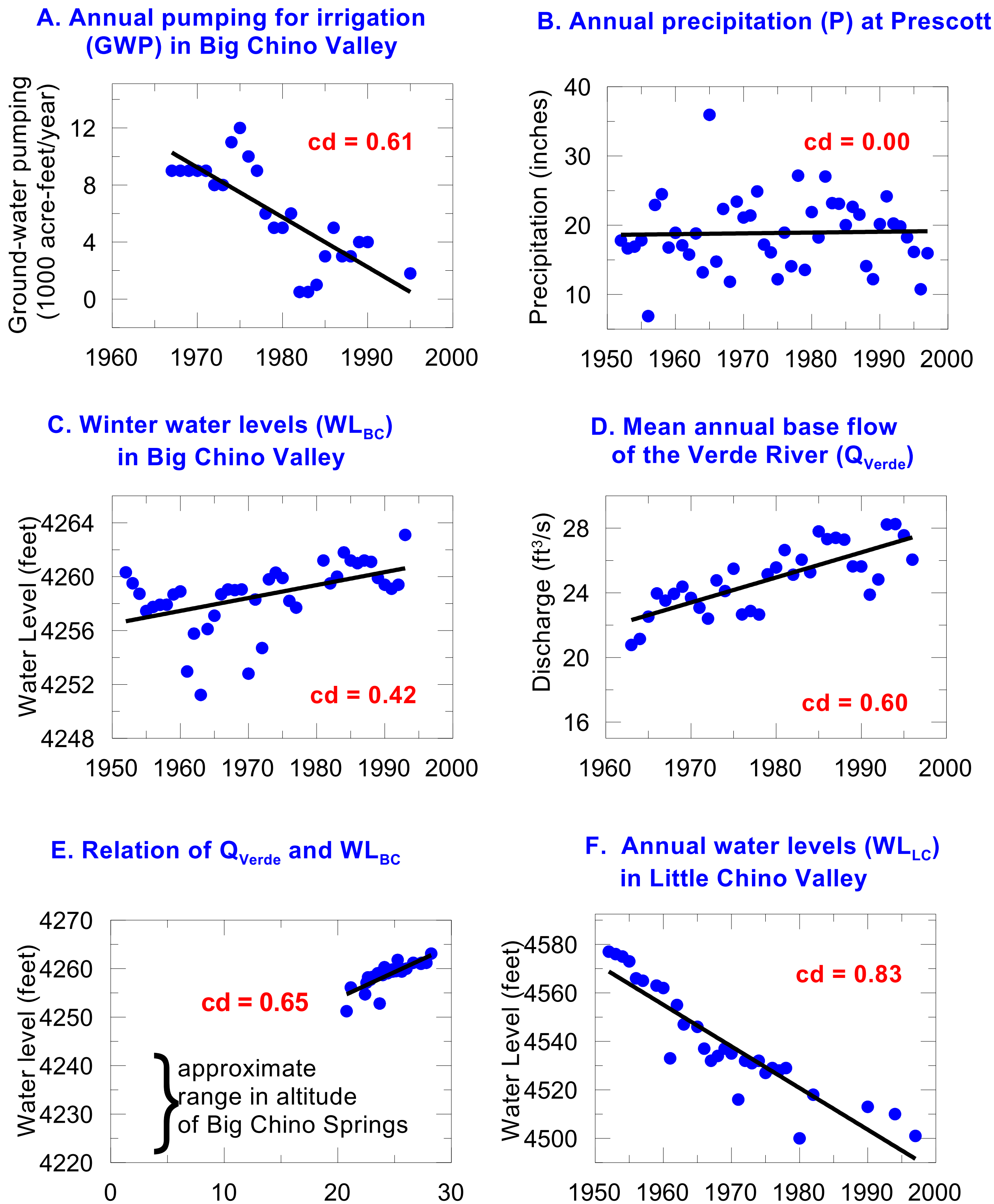

Figure 8. Hydrologic relations of water-budget analysis. The linear relations are from statistical regression analysis (Minitab 1995), and coefficients of determination (cd) are labeled.

flow data is thought to be minimal. The USGS study collected samples in early July of 1991, following the driest time of year (May-June), whereas the ASU study collected samples in the months of May, September, and December 1996 and March and July of 1997. Inspection of mean daily discharge values at the Paulden gage (09503700) indicates that there was little if any runoff when the ASU samples were collected. Mean daily discharge ranged from 23 to 27 ft^3/s during these five months (U.S. Geological Survey, 1995 and 1996 water years). This 5 ft^3/s difference in the mean daily discharge is related to seasonal variations in evapotranspiration, and not to surface-water runoff.

At various times, stable-isotope samples were collected at the same or similar locations as previous studies. Table 5 includes all discrete USGS and ASU ground-water samples collected, irrespective of time of year or runoff conditions. Notwithstanding differences in sampling times, personnel, objectives, sampling methods, laboratories, and analytical techniques, the reproducibility of stable oxygen and hydrogen isotope data is within $\pm$0.2 per mil for $\delta^{18}O$ and $\pm$2.5 per mil for δ^2H. For example, Del Rio Springs was sampled once by the USGS and three times by ASU with a $\delta^{18}O \pm$ standard deviation value of - 9.9$\pm$0.1 per mil and δ^2H of - 68$\pm$1 per mil (Table 5). This is the mean of the component variances technique. These limits of sampling uncertainty are comparable or below the reported analytical precision of most stable-isotope laboratories. It was presumed that the wells were too deep to be affected by local runoff conditions. Depths for the 40 wells in Table 5 range from 57 to 3010 ft, with a mean of 383 ft. Some of the depths were estimated on the basis of nearby well logs.

Sources of base flow as evidenced by stable isotopes of oxygen and hydrogen. During this study, extensive review of the existing stable-isotope data identified several problems with the available sample results. First, although lower Granite Creek had been sampled more than 10 times between 1991 and 1997, none of the samples could be identified as having been collected at the initial onset of base flow in Granite Creek. This leaves the possibility that base flow may have been slightly affected by a small contribution from bank storage, or that a small evaporative shift could have occurred as a consequence of the hot climate and long residence time in the marshy area downstream from the spring. Either scenario could affect the interpretation of the data.

A second problem was that there were no unmixed spring samples representing the major source of ground-water discharge (Big Chino Springs) in the gaining reach downstream from river mile 2.3. Armed with an improved understanding of water-budget relations and of the effects of local geologic controls on ground-water movement, the upper Verde River was revisited on May 1, 1999 with two objectives: first, to find the precise onset of perennial flow in lower Granite Creek, and secondly, to find a location where the major springs downstream from river mile 2.3 could be sampled directly before entering the Verde River streambed and mixing with the Granite Creek source of water. Both sampling locations were identified and sampled in a flowing reach as close as possible to where ground water was emerging from the sub-surface. The samples were collected following an extended dry period, during which almost no rainfall or runoff is known to have occurred for more than 6 months. For quality assurance, the samples were submitted to three independent laboratories at the University of Colorado in Boulder, Colorado; ASU in Tempe, Arizona; and the Laboratory of Isotope Geochemistry at the University of Arizona in Tucson, Arizona (Table 5). The isotopic values and standard deviations of the three replicates for lower Granite Spring were $\delta^{18}O \pm$ -9.7+0.2 and $\delta^2H \pm$ -68.4+0.4. The mean values for Big Chino Springs were $\delta^{18}O$ of -10.2$\pm$0.1 and δ^2H of -72.2$\pm$0.8.

During collection of the spring samples, several important observations were made. As mentioned earlier, the onset of first perennial flow in lower Granite Creek coincided with a fault zone identified by Krieger in Martin Limestone and Tapeats Sandstone (1965), about 1 mile upstream from the mouth (Fig. 2B). The sample was collected in the part of the reach where moving current was present, near a side drainage with large cottonwood trees on the west riverbank. The Big Chino Springs sample was collected on the north bank of the Verde River from a previously unknown spring flowing from the base of a cliff of Martin Limestone. The spring is just below a small side canyon near river mile 2.3, which also coincides with a small fault (Fig. 2B). A thicket of brushy vegetation in a grove of trees hides the spring from view. A narrow channel (approximately 2-3 ft wide and 50 ft in length) connects the spring to the main stream channel. Flow was estimated at greater than 0.1 ft^3/s near the cliff and about 5 ft^3/s in the river.

The following discussion of the stable-isotope results follows an upstream to downstream order, beginning with Sullivan Lake and Stillman Lake, fol-

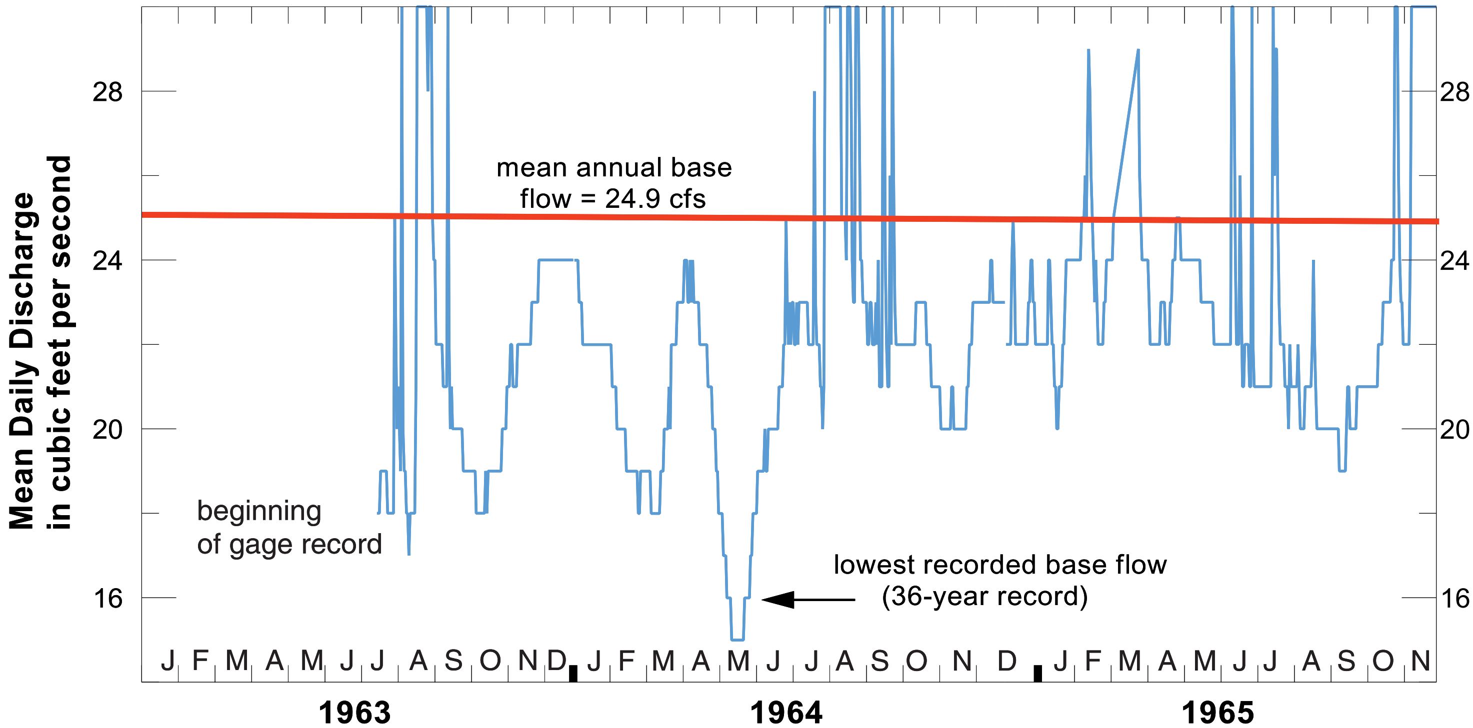

Figure 9. Mean daily discharge for the Paulden gage (09503700) for calendar years 1963-65 showing lowest recorded base flow of 15 ft³/s for 11 consecutive days in May, 1964. Gaging records began on July 17, 1963.

lowed by a discussion of the lower Granite and Big Chino aquifer sources and their corresponding stream reaches. Next, the stable-isotope characteristics of the two springs will be compared with the available ground-water data to present the evidence for ground-water flow paths between the major recharge areas and the upper Verde River.

Sullivan Lake and Stillman Lake. The stable-isotope values of ASU and USGS samples collected from Sullivan Lake (river mile 0.0) and Stillman Lake are isotopically heavier than Verde River base-flow samples from river miles 2.1 to 2.3 (Fig. 10A). Sullivan Lake and Stillman Lake samples vary greatly with the seasons and with respect to runoff conditions. Evaporation of water molecules, preferentially containing a higher percentage of lighter isotopes in the vapor phase, causes the water that remains behind to be isotopically heavier. Evaporated meteoric waters characteristically plot increasingly below and to the right of the Meteoric Water line (MWL) (Craig, 1961). In addition, summer thunderstorms in Arizona often produce rainfall that is isotopically heavier than precipitation at other times of the year (Van Metre et al. 1997, p. 29-30). Water in Sullivan Lake and Stillman Lake may contain ground-water discharge, but may also include impounded water leftover from the last major storm that may or may not show an evaporative influence. In general, summer samples tend to be more evaporated than winter samples. These impounded and evaporated waters do not appear to supply a significant source of base flow to the Verde River, but they do suggest the presence of ground water seeping to the surface at a slow rate.

The stable-isotope evidence shows at least two distinct sources of base flow; one that is above and one that is below river mile 2.3. Base flow in the Verde River upstream from mile 2.3 is isotopically similar to the lower Granite Creek and Lower Granite Spring (Fig. 10B; Table 4). The unevaporated isotopic composition of the spring discharging to upper Stillman Lake has not been sampled and thus its potential contribution is unknown. Although only three base-flow samples were collected from the Verde River upstream from river mile 2.3, their values generally fall within the range of values measured for 10 base-flow samples collected from Granite Creek above its confluence with the Verde River from 1991 to 1997 (^{18}O = -9.4$\pm$0.3; = -67.9$\pm$2.5). In addition, the three samples are similar to the stable isotope value of Lower Granite Spring of ^{18}O = -9.7$\pm$0.2 and = -68.7$\pm$0.4 that was collected on May 1, 1999. The one exception is the δ^2H value of –61 per mil that was measured in December 1996. A possible explanation is that this sample could represent evaporated water or unidentified inflow from the Stillman Lake spring network. Stable-isotope data for Verde River miles 2.1 to 2.3 indicate that evaporated contributions to base flow from Stillman Lake and Sullivan Lake are negligible, however, a contribution of unevaporated ground water flowing beneath Stillman Lake is a distinct possibility.

Verde River miles 2.3 to 10. Base-flow samples in the Verde River collected downstream from river mile 2.3 are isotopically similar to the sample from Big Chino Springs ($\delta^{18}O$ = -10.2$\pm$0.12 and δ^2H = -72.1$\pm$0.7). Ground-water discharge from Big Chino Springs is significantly depleted in ^{18}O and ^2H in comparison to Lower Granite Spring and Verde base flow upstream from river mile 2.3. The blending of base flow from lower Granite Creek and the Big Chino Springs gaining reach yields a mixture that is intermediate to the two springs.

Stable-isotope characteristics of major aquifers and their recharge areas. The $\delta^{18}O$ and δ^2H values of the source aquifers are assumed to be conservative, meaning that the stable-isotope values remain constant from the recharge source area to the point of discharge. Despite non-homogeneities in different water-bearing units and variations in recharge characteristics that are spread over a wide area, we also assume the aquifer is well mixed at the point of spring discharge. Candidate aquifer sources must have (1) a flow path that is geologically feasible, (2) a recharge area capable of receiving enough precipitation or runoff, and (3) stable-isotope values that are similar to Lower Granite Spring or Big Chino Springs.

Measured stable-isotope values for Lower Granite Spring and Big Chino Springs were compared with those of ground-water samples from wells in Little Chino Valley, near Sullivan Lake, Big Chino Valley, Williamson Valley and Walnut Creek, and Big Black Mesa (Fig. 11 and Table 5). In instances where more than one sample was collected at the same location on different days, those values were averaged so as not to weight the mean.

Little Chino Valley. Mean stable-isotope values from seven Little Chino wells and Del Rio Spring ($\delta^{18}O$ = -9.8$\pm$ 0.4 and δ^2H = -69.5$\pm$4.0 per mil; Fig. 12A and Table 5) compare closely with Lower Granite Spring ($\delta^{18}O$ = -9.7$\pm$ 0.2 and δ^2H = -68.7$\pm$0.4 per mil). Given the hydrologic and geologic considerations, ground water discharge to Lower Granite Spring must be derived from within the Little Chino Valley. The homogeneous stable-isotope signature of Del Rio Springs ($\delta^{18}O$ = - 9.9$\pm$0.1 per mil and δ^2H = - 68$\pm$1 per mil), which has been measured four times in the past decade, is undistinguishable from Lower Granite Spring, indicating a Little Chino Valley source for both spring networks. The Little Chino aquifer may contribute to Big Chino Springs, but only if mixing were to occur with an equal or greater amount of water from a second source having a substantially lighter (more negative) average isotopic value.

Wells near Sullivan Lake. Because it is still unknown whether wells near Sullivan Lake intercept flow from Little Chino Valley, Big Chino Valley, or a mixture of both, samples within 5 miles of the lake were grouped separately (see Fig. 12A and Table 5). The mean of the 10 wells ($\delta^{18}O$ = -9.8$\pm$ 0.3 and δ^2H = -70.3$\pm$2.5 per mil) falls within the range for both Little Chino and most Big Chino well (Fig. 12B) samples. Ground-water flow paths for the two basins converge in the vicinity of Sullivan Lake (Fig. 6), hence a mixture is quite possible.

Big Chino Valley. The scatter of stable-isotope values for most well samples in Big Chino Valley is indistinguishable from Little Chino Valley (Fig. 12B, Table 5). Like the Little Chino samples, Big Chino samples are similar to samples from wells near Sullivan Lake; lower Granite Creek base flow, and Lower Granite Spring. The mean values for 13 well samples are $\delta^{18}O$ = -9.9$\pm$ 0.3 and δ^2H = -71$\pm$2.4 per mil.

Samples from three wells along the northeast lateral margin of Big Chino Valley (Fig. 12B), however, are indistinguishable to Big Chino Springs in $\delta^{18}O$ and δ^2H. Two of the wells (BCM-11 and BCM-12) are north of Paulden near the Big Chino Fault. The well logs for these two wells indicate limestone at 285 and 504 ft, respectively. The third well (BCM-18) is in the northern end of Big Chino Valley and is 500 ft deep. The lithology and proximity to faulting of the third well is unknown, although contact with limestone is likely on the basis of depth. Sand, gravel, clay, conglomerate, boulders, and basalt or malpais are prevalent in most other Big Chino well logs, but only BCM-11 and BCM-12 are known to penetrate limestone. These differences are consistent with the conceptual model of an unconfined, predominantly alluvial aquifer overlying a confined, predominantly bedrock aquifer of Paleozoic limestone.

The more negative isotopic composition of wells BCM-11, BCM-12, and BCM-18 may represent ground water recharged from higher altitudes and transmitted to faults along the valley margins. Recharge to these three wells could be from the higher altitude mountain ranges on the southwest edge of the basin. A second possibility is that these wells are producing older, deeper ground water that was recharged during cooler, wetter climate conditions—such as the Pleistocene. As mentioned earlier, Robertson (1991) has shown that the chemistry of deep ground water in other southwestern alluvial basins evolves under closed conditions without mixing after the initial filling of the basins. Hence, deeper ground water would be expected to have chemical characteristics that are distinct from shallow ground water. Although the source and timing of the recharge are unknown, the differences in isotopic composition for these three wells versus other Big Chino Valley samples—and their similarity to Big Chino Springs—is attributed to their contact with Paleozoic limestone.

Ashfork and Big Black Mesa. The measured stable-isotope values of several alternate source areas, including Ash Fork and Big Black Mesa, are also shown in Fig. 12. A deep water-supply well was sampled at the town of Ash Fork in 1987 and again in 1991 by the USGS. Ash Fork is about 25 miles north of Paulden on a plateau surrounded by basalt exposures. Surface drainage is southeast to Big Chino Valley. The direction of ground-water flow in this area is largely unknown, owing to the scarcity of wells in the region. Although no well log was available, the well is believed to be in contact with limestone on the basis of its 1700-ft depth. The Ash Fork sample is not statistically unique from other samples from Big and Little Chino Valleys and Big Chino Springs, however it is most similar to samples from the Big Chino limestone wells.

Two wells were sampled north of the Verde River on the low altitude end of Big Black Mesa. Well BBM-04, or “Hell’s Well” near Drake was sampled by the USGS in 1987 and has a depth of 460 ft, and is completed in limestone. Well BBM-111, near Glidden, was sampled twice by ASU in May and September of 1996. No well log is available for BBM-111. Because of the disparity in the deuterium (–70 and –78 per mil for the two samples from the Glidden well), all three Big Black Mesa analyses were plotted individually, instead of averaged (Fig. 12B). The disparity might be explained by seasonal variations in the source of the ground water; however, because the $\delta^{18}O$ analyses match closely (-10.4 and -10.5), it is thought that an analytical problem with the deuterium of one or both samples is more likely. The Big Black Mesa samples cannot be differentiated from that of Big Chino Springs or any of the major aquifers. They are most similar to other samples from limestone wells in Big Chino Valley and Ash Fork. Despite the apparent similarities with other limestone wells, Big Black Mesa is probably not a major recharge source of ground water to Big Chino Springs (as asserted by Knauth and Greenbie, 1997) on the basis of the following geologic and hydrologic evidence.

The water level of the Glidden well, measured by ADWR on both April 12, 1994, and April 19, 1999, was about 4,218 ft above sea level(Frank Corkhill, oral commun., July 13, 1999). This value is slightly lower than the range in altitude of Big Chino Springs (4220 to 4240 ft); and is strong physical evidence that this part of Big Black Mesa is not contributing to the springs. It is conceivable that ground water may travel east as far as the Limestone Canyon Monocline near river mile 13 (Edward DeWitt, oral commun.,1999; Figs. 2 and 6) , which is underlain by uplifted granite; however, there is little evidence of ground-water discharge beyond the monocline toward Hell Canyon. A more likely possibility is that ground water travels from northeast to southwest from the limestone aquifer underlying Big Chino Valley toward the Verde River and Big Black Mesa. As noted earlier, ground water in the vicinity of Drake would be most likely to drain southeast toward the Verde River (river miles 10 to 13) through exposures of Martin Limestone or Tapeats Sandstone in the canyon (Ed deWitt, oral commun., 2000). A small gain in base flow may occur in this reach, but this cannot be verified because of limited data and the large (as high as $\pm$ 2 ft^3/s) diurnal variability in discharge. Big Black Mesa probably contributes an unknown amount of mountain-front recharge to the northwest margin of Big Chino Valley along the Big Chino Fault, however it is unlikely to contribute a significant amount of recharge to the upper Verde River in the vicinity of Big Chino Springs.

Williamson Valley and Walnut Creek. Isotope ratios of samples from Williamson Valley and Walnut Creek closely match those of the three limestone wells in Big Chino Valley; however, this could be coincidental, as these wells appear to tap alluvial sediments (Fig. 12). The wells are relatively shallow, ranging in depth from 150 to 300 ft, and probably do not encounter limestone. Two of the six wells (WV-109 and WV-110) are cased in alluvium at the northern end of Williamson Valley near its confluence with

Big Chino Wash. Well logs for the other wells are absent. Based on their geographic locations, stable-isotope values, and water levels, these wells appear to intercept ground water from the Williamson Valley and Walnut Creek drainages. The Bradshaw, Santa Maria, and Juniper Mountains range in altitude from 5,000 to more than 7,600 ft, and average annual precipitation commonly exceeds 20 inches and may exceed 30 inches during wet years (Sellers and Hill, 1974). On the basis of water-level contours (Fig. 6) ground water from Walnut Creek and Williamson Valley appears to travels eastward across Big Chino Valley toward the area north of Paulden.

One possibility explaining the similarity in isotopic composition is that ground water from Williamson Valley and Walnut Creek recharges the deeper limestone aquifer. Mixing from several source areas in the vicinity of Paulden would also produce water that is isotopically similar to Big Chino Springs. The δO^{18} and δD values for Big Chino Springs (-10.2 ± 0.1 and -72.2 ± 0.8 per mil) closely match the mean (-10.2 ± 0.4 and -72.9 ± 2.9 per mil) of all wells that were sampled in Big Chino Valley including the limestone wells (16 wells), Williamson Valley (5 wells), and Walnut Creek (1 well). Hence, Big Chino Springs may be a composite of ground water from several interconnected aquifers that receive recharge from different parts of Big Chino Valley. An unknown contribution of ground water from Little Chino Valley or upper Big Black Mesa to Big Chino Valley is also possible.

Bill Williams Mountain. Because of its high altitude and abundant snow in winter, Bill Williams Mountain has been mentioned as a possible source of recharge for the upper Verde River. The major southern drainage for Bill Williams Mountain is Sycamore Creek, which joins the Verde River nearly 35 miles downstream from Sullivan Lake. Despite the limestone terrain, it is probable that ground water moving southwest from Bill Williams Mountain is intercepted by Hell Canyon. Hell Canyon contributes no measurable base flow to the Verde River near its outlet. On the basis of samples collected in 1991, Sycamore Creek is significantly depleted in $\delta^{18}O$ and $\delta^{2}H$ compared to Big Chino Springs, with values of -11.7 and -80.5 per mil (Fig. 12C).

Water with the isotopic value of Sycamore Creek mixed with equal amounts of water from a source with an isotopic value for $\delta^{18}O$ of -8.7 would produce the $\delta^{18}O$ of Big Chino Springs. To evoke mixing between Sycamore Creek and a heavier $\delta^{18}O$ source, however, would require an unknown recharge source having either a lower altitude or higher rate of evaporation, such as from another alluvial basin recharged by ephemeral streams. All of the obvious sources, however, have been sampled. Virtually all of the $\delta^{18}O$ sample data are lighter than -9.0 with the exception of one well sample in Little Chino Valley having a $\delta^{18}O$ value of -8.9. Such a scenario might be possible but is highly unlikely, as there are no alluvial basins lower in altitude or more arid than Little Chino Valley adjacent to the Sycamore Creek subbasin. Given these considerations, Bill Williams Mountain is an unlikely source of ground-water recharge for the first 26 miles of the Verde River, although it is the most likely source supplying large limestone springs in the reach between Perkinsville and the mouth of Sycamore Creek (Wirt, 1992; Wirt, 1993).

Carbon isotopes as an indicator of aquifer lithology. Carbon-13 is useful for determining sources of carbon and is particularly valuable for distinguishing between carbon derived from organic matter (light) and carbon derived from carbonate minerals (heavy). The $\delta^{13}C$ of ground water is determined by the $\delta^{13}C$ of the inflow water and the supply of carbon to and removal of carbon from the water during its transit through the aquifer (Drever, 1988). Dissolution of limestone introduces relatively heavy carbon, as dissolved carbonate materials in the ocean have $\delta^{13}C$ equal to 0 per mil, whereas atmospheric CO_2 is about -7 per mil. The major process that introduces relatively light carbon (having a more negative value) into ground water is the dissolution of carbon dioxide from soil gas in the unsaturated zone.

Selected ground-water and base-flow samples collected by the USGS in 1991 were analyzed for carbon isotopes ($^{13}C/^{12}C$ values or $\delta^{13}C$). Stable carbon ratios were interpreted with respect to $\delta^{18}O$ and saturation indices for calcite (Fig. 13). As discussed earlier, the ^{18}O serves as a conservative ground-water tracer from the point of recharge to discharge, providing an indication of the altitude and climate of the recharge area. Saturation indices of calcite provide an indication of the equilibrium with respect to calcite ($CaCO_3$) and were calculated using PHREEQC, a computer program capable of performing speciation and saturation-index calculations (Parkhurst, 1995).

The PHREEQC calculations utilized major and trace element analyses of water samples collected by the USGS in 1991. No cation or anion analyses were available for Lower Granite Spring and Big Chino

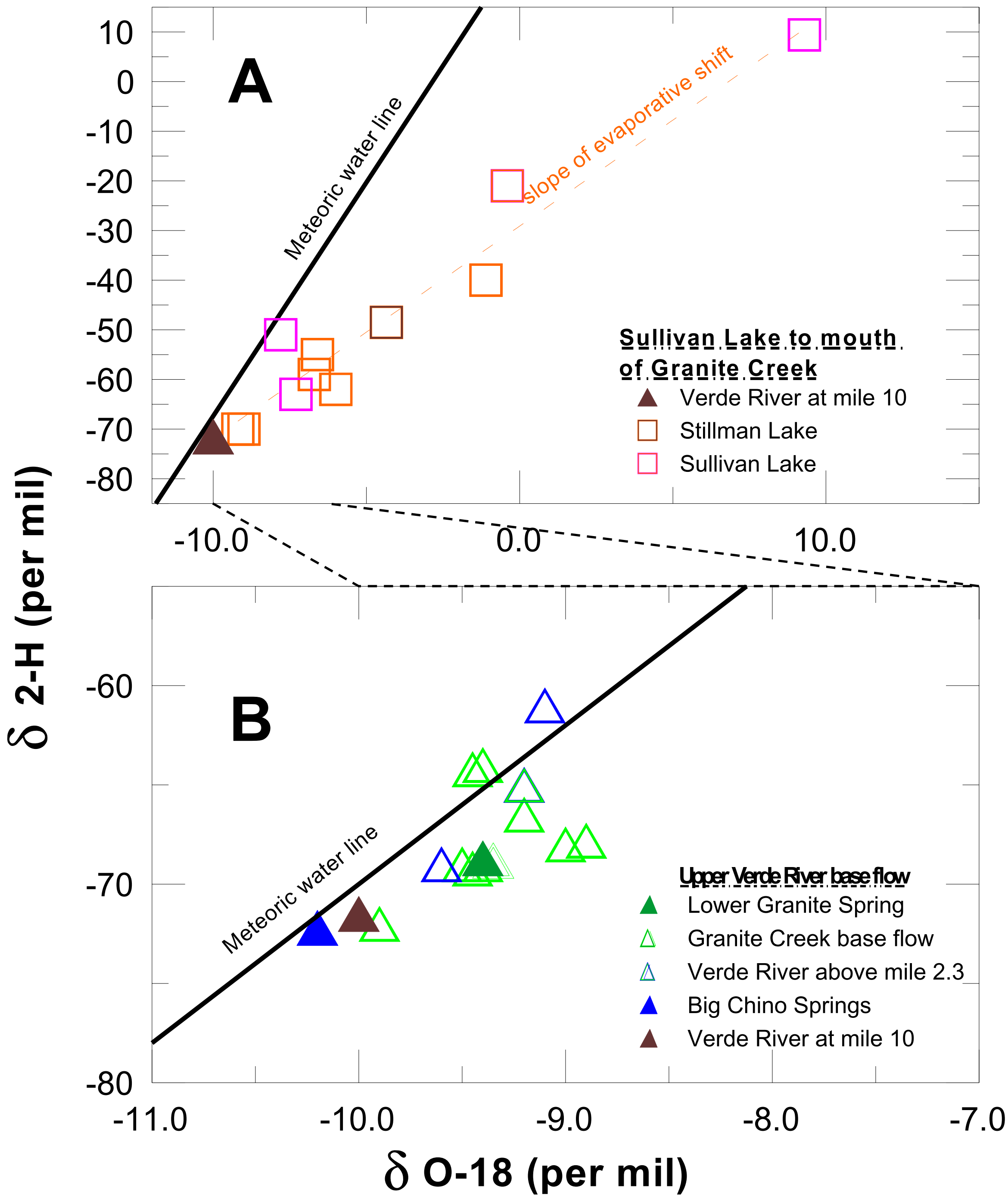

Figure 10. Oxygen-18 and deuterium plots for (A) impounded water in Sullivan Lake and Stillman Lake and (B) base flow from lower Granite Creek, Big Chino Springs, and the upper Verde River. In graph A, samples from Sullivan Lake and Stillman Lake show a substantial evaporative shift to the lower right of the meteoric water line, unlike unevaporated base flow in the Verde River near river mile 10. In graph B, which is an inset of graph A, a mix of flow from Verde base flow above mile 2.3 with discharge from Big Chino Springs yields water with an intermediate isotopic composition at river mile 10. Granite Creek base flow and the Verde River above river mile 2.3 are isotopically similar to Lower Granite Spring.

Table 4. Stable-Isotope and Hydrologic Data for Base Flow in the Upper Verde River
[NA = not applicable]

	Location	Verde River Mile	Sample_Id	Laboratory	Sample Date	Oxygen-18 per mil	Deuterium per mil	Carbon-13 per mil	Tritium (PCI/L)
1	Lower Granite Spring	NA	LG-1	ASU	5/1/99	-9.8	-69.0		
2	" " "	"	"	CU	"	-9.5	-68.8		
3	" " "	"	"	UA	"	-9.7	-67.5	-8.80	<5.1
	Mean±standard deviation (x=3)					**-9.7+0.2**	**-68.7+0.4**		
4	Granite Creek abv confluence with Verde River	NA	GC-215	ASU	Dec-96	-9.4	-69.0		
5	" " " " " " "	"	"	ASU	Mar-97	-9.4	-69.0		
6	" " " " " " "	"	GC-302	ASU	Dec-96	-9.4	-64.0		
7	" " " " " " "	"	"	ASU	Mar-97	-9.4	-64.0		
8	" " " " " " "	"	"	"	Jul-97	-9.9	-72.0		
9	" " " " " " "	"	GC-02	USGS	7/1/91	-9.2	-66.5	-11.0	5.0+0.6
10	" " " " " " "	"	GC-201	ASU	May-96	-9.0	-68.0		
11	" " " " " " "	"	"	"	Sep-96	-9.0	-68.0		
12	" " " " " " "	"	"	"	Dec-96	-9.5	-69.0		
13	" " " " " " "	"	"	"	Mar-97	-9.4	-69.0		
	Mean±standard deviation (x=10)					**-9.4+0.3**	**-67.9+2.5**		
14	Verde River <0.3 mile blw confluence with Granite Creek	2.3	V-204	ASU	May-96	-9.2	-65.0		
15	" " " " " " " " "	"	"	"	Dec-96	-9.1	-61.0		
16	" " " " " " " " "	"	"	"	Jul-97	-9.6	-69.0		
	Mean±standard deviation (x=3)					**-9.3+0.3**	**-65.0+4.0**		
17	Stillman Lake	1.0 to 1.9	VP-01	USGS	7/1/91	-4.4	-48.5	-5.3	10.4+0.7
18	" " " " " " "	"	VP-203R1	ASU	May-96	-1.1	-40.0		
19	" " " " " " "	"	"	"	Dec-96	-6.0	-62.0		
20	" " " " " " "	"	VP-203R2	ASU	Dec-96	-9.2	-70.0		
21	" " " " " " "	"	VP-203R3	ASU	Dec-96	-9.0	-70.0		
22	" " " " " " "	"	VP-202	ASU	May-96	-6.6	-55.0		
23	" " " " " " "	"	"	"	Dec-96	-6.7	-59.0		
24	Sullivan Lake	0.0	SL-207	ASU	May-96	9.3	9.4		
25	" "	"	"	"	Sep-96	-0.4	-21.0		
26	" "	"	"	"	Dec-97	-7.8	-51.0		
27	" "	"	"	"	Mar-97	-7.3	-63.0		
28	Big Chino Springs	2.3	BC-1	ASU	May-99	-10.3	-72.0		
29	" " "	"	"	CU	"	-10.1	-73.0		
30	" " "	"	"	UA	"	-10.3	-71.5	-3.0	<5.1
	Mean±standard deviation (x=3)					**-10.2+0.1**	**-72.2+0.8**		
31	Verde River nr Paulden gage (09503700)	10	V-05	USGS	7/3/91	-10.1	-71.5	-5.4	1.7+0.6
32	Verde River nr Perkinsville	26	V-09	USGS	7/2/91	-	-	-4.4	
33	Sycamore Creek	34	SC-14	USGS	7/2/91	-11.7	-80.5		
34	Verde River nr Clarkdale (09504000)	36	V-16	USGS	7/4/91	-10.9	-77.5	-5.9	2.9+0.6

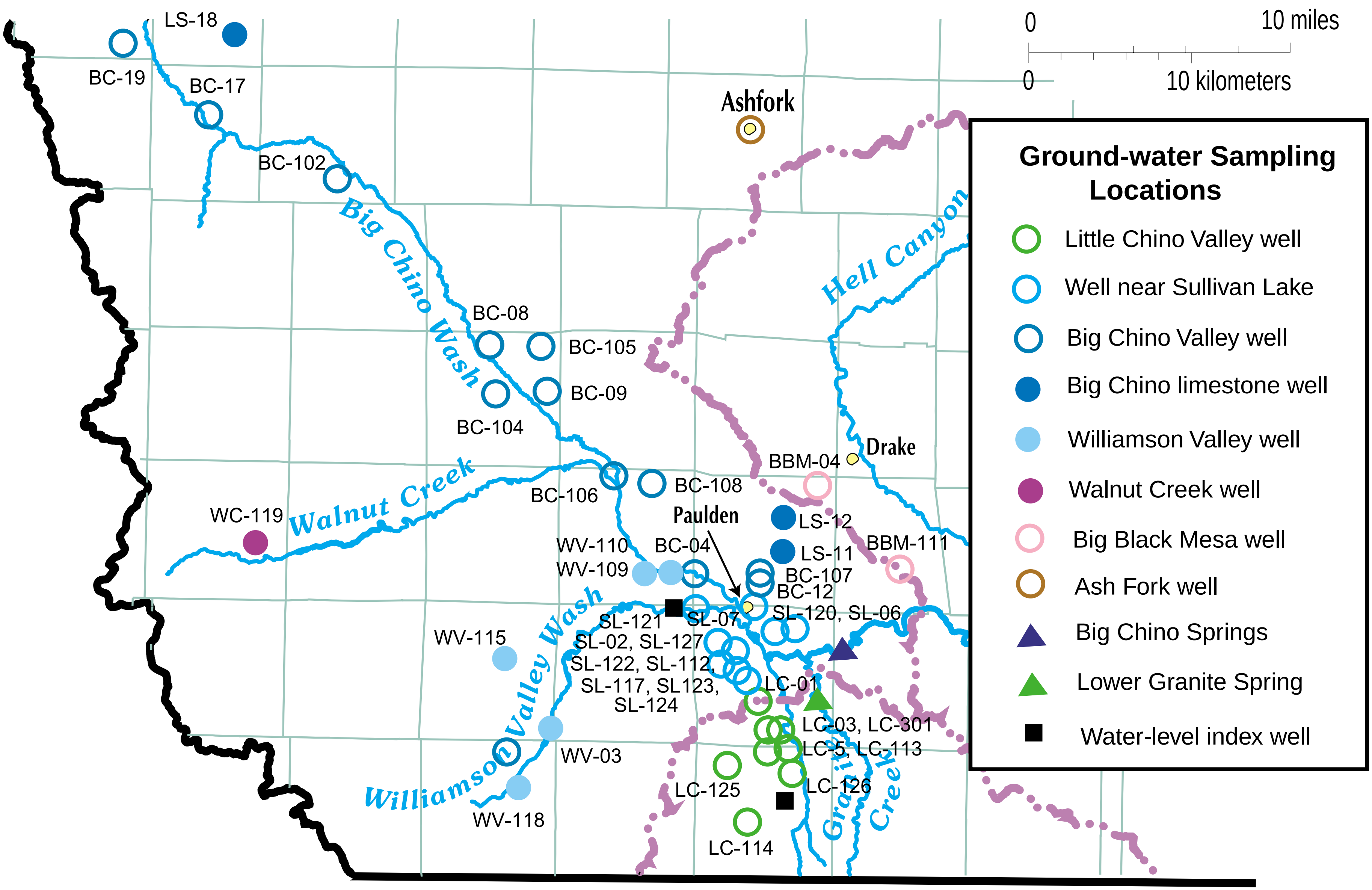

Figure 11. Ground-water sampling locations in the Verde River headwaters area.

Springs, which were sampled at a different time.

In Fig. 13A, Big Chino Springs (–3.0 per mil) is enriched in $\delta^{13}C$ relative to base flow for Lower Granite Spring (-8.8 per mil). The presence of heavy carbon suggests that the major source to Big Chino Springs is a carbonate aquifer and, conversely, that the source of Lower Granite Spring contains relatively less carbonate. For example, an alluvial aquifer might be expected to contain more isotopically light dissolved carbon from soil gas in the unsaturated zone than a bedrock aquifer. Except in its northern end, close to the Verde River where the Martin and Tapeats formations are exposed, Little Chino Valley is largely underlain by a variety of igneous and metamorphic rocks (Corkhill and Mason, 1995). The Big Chino unconfined aquifer is also non-carbonate and is largely composed of alluvium and basalt. Samples from wells in contact with limestone are on the right side of graph 13A, while ground water from wells and springs in contact with non-carbonate rock types plot toward the left side. Interestingly, the limestone wells were consistently lighter in $\delta^{18}O$, which may reflect the altitude or climate of the recharge environment. High altitude or mountain-front recharge would tend to produce isotopically lighter recharge than low altitude recharge, such as might occur beneath ephemeral streams on the valley floor. For example, mountain-front recharge might predominantly occur during periods of snowmelt (isotopically lighter), whereas ephemeral stream runoff might include a higher component from summer thunderstorms (isotopically heavier), as shown by Van Metre et al. (1997, p. 29-30).

In Fig. 13B, saturation indices for calcite are generally higher for wells enriched in ^{13}C, owing to contact with carbonate minerals. As might be expected, ground water in contact with marine limestone has more heavy carbon than ground water in contact with non-marine rocks. Non-carbonate ground water from Del Rio Spring, Little Chino well LC-01, and Lower Big Chino wells BC-02 and BC-04 are relatively depleted in $\delta^{13}C$. Upper Big Chino wells BC-06, BC-07, BC-08, BC-09, and Little Chino well LC-05 are moderately depleted in $\delta^{13}C$. Ground water in contact with limestone from wells BCF-11, BCF-12, and Ash Fork are nearly as enriched in $\delta^{13}C$ as Verde River surface water. Enrichment of ^{13}C in ground water is probably correlated to the amount of contact with limestone along the flow path, however, stream-flow samples $\delta^{13}C$ may become more enriched in $\delta^{13}C$ because lighter carbon tends to be lost when CO_2 degasses into the atmosphere or is taken up by growing plants. No relation between $\delta^{13}C$ and well depth was observed.

Carbon-13 enrichment in Big Chino Springs and Verde River base flow is a compelling indication that the ground water has traveled extensively through limestone before discharging to the river. This is consistent with the conceptual model of ground water flowing through the deeper confined aquifer in the Martin Limestone, and also through the shallower unconfined aquifer comprised of limestone-bearing alluvium along the Big Chino Fault zone, before discharging to Big Chino Springs. Unfortunately, no carbon-13 data were available for wells in Williamson Valley or Walnut Creek. As water transmits to the underlying limestone, it is enriched in $\delta^{13}C$ before emerging to the surface as flow in the Verde River, shown conceptually in Fig. 3. Carbon-13 enrichment may prove useful in distinguishing among the interconnected aquifers in Big and Little Chino Valleys.

Discussion of isotope evidence. The stable isotope data are consistent with the geologic and hydrologic evidence presented earlier in the surface-water, ground-water, and water-budget sections. Major ground-water recharge areas for Big Chino Valley include Williamson Valley, Walnut Creek, and other major tributaries of the Bradshaw, Santa Maria, and Juniper Mountains that receive higher amounts of precipitation. Snowmelt and surface runoff recharge the southwest edge of Big Chino Valley and Williamson Valley. These waters are relatively depleted in ^{18}O and ^{2}H because the primary source of recharge is precipitation at higher altitudes. The upper end of Big Chino Valley may also contribute a substantial fraction of the total recharge, and more data are needed to quantify the relative contributions. Stable-isotope values for wells in Ash Fork and Big Black Mesa are similar to those for other wells in Paleozoic limestone. Possible recharge areas that have not been sampled extensively include the upper end of Big Chino Valley (which may or may not include the area north of Seligman), Pine Creek and Turkey Creek in the Juniper Mountains, and runoff from Big Chino Wash and the major ephemeral drainages of Big Black Mesa, such as Partridge Creek. More isotopic data are also needed from wells in these areas to determine the extent of possible contributions.

Big Chino Fault apparently serves as a mixing zone as well as conduit for waters from various recharge areas. Ground water from Williamson Valley and Walnut Creek travels across Big Chino Valley

Table 5.
Stable-Isotope and Well Data for Ground Water in the Verde River Headwaters Region

[* indicates that well depth is estimated on the basis of nearby well log(s); ? indicates that well depth is unknown]

Note: Averaged value of wells that were sampled repeatedly was used to calculate standard deviation.

	Location	Sample_ID	Agency	Location	Sample Date	Well Depth (ft blw surface)	O-18 per mil	H-2 per mil	C-13 per mil	Saturation Indices ($CaCO_3$)
1	Little Chino Basin	LC-01	USGS	B(17-2)22bca4	09-09-91	57	-9.9	-71.0	-11.9	0.294
2	" " "	LC-03	USGS	B(17-2)26ccc	08-26-91	Del Rio Spring	-9.9	-71.0	-11.5	0.401
3	" " "	LC-301	ASU	"	Dec-96	"	-10.0	-69.0		
4	" " "	"	"	"	Mar-97	"	-9.9	-74.0		
5	" " "	"	"	"	Jul-97	"	-9.9	-72.0		
6	" " "	LC-113	ASU	B(17-2)34 aca	May-96	130*	-9.5	-65.0		
7	" " "	"	"	"	Dec-96	"	-10.1	-70.0		
8	" " "	LC-05	USGS	B(17-2)34bba	09-09-91	?	-10.1	-71.5	-10.3	0.196
9	" " "	LC-126	ASU	B(17-2)35 cda	Dec-96	110*	-9.4	-61.0		
10	" " "	LC-125	ASU	B(16-2)4 cbb	Dec-96	200*	-10.0	-74.0		
11	" " "	LC-114	ASU	B(16-2)15 ada	May-96	300	-8.9	-67.0		
12	" " "	"	"	"	Sep-96	"	-8.9	-66.0		
13	" " "	LC-101	ASU	B(15-2)23 cba	May-96	560	-10.1	-69.0		
14	" " "	"	"	"	Sep-96	"	-10.1	-67.0		
15	" " "	LC-10	USGS	B(15-2)23cbd	07-04-87	578*	-10.3	-73.0		
	Mean+standard deviation (x=9)						**-9.8+0.4**	**-69.5+4.0**		
16	nr Sullivan Lake	SL-06	USGS	B(17-2)2cac	08-30-91	480	-10.0	-71.5	-9.6	0.529
17	" " "	SL-120	ASU	B(17-2)S03cbb1	Dec-96	167	-10.0	-69.0		
18	" " "	SL-07	USGS	B(17-2)4aaa	09-09-91	298	-9.4	-71.5	-9.4	0.243
19	" " "	SL-127	ASU	"	Dec-96	"	-10.4	-69.0		
20	" " "	SL-121	ASU	B(17-2)6 aba	Dec-96	240*	-9.5	-65.0		
21	" " "	SL-112	ASU	B(17-2)9 bbc	May-96	207*	-10.0	-66.0		
22	" " "	"	"	"	Sep-96	"	-10.0	-69.0		
23	" " "	"	"	"	Dec-96	"	-10.3	-68.0		
24	" " "	"	"	"	Mar-97	"	-10.2	-71.0		
25	" " "	SL-117	ASU	B(17-2)9 ccb	Sep-96	130	-9.5	-73.0		
26	" " "	"	"	"	Dec-96	"	-9.7	-73.0		
27	" " "	"	"	"	Mar-97	"	-9.5	-76.0		
28	" " "	SL-123	ASU	B(17-2)9 ccd	Dec-96	260*	-9.6	-71.0		
29	" " "	SL-02	USGS	B(17-2)09ddd2	09-09-91	130	-9.5	-69.5	-11.8	0.433
30	" " "	SL-124	ASU	B(17-2)15 cdd	Dec-96	128	-9.8	-72.0		
31	" " "	SL-122	ASU	B(17-2)17 aad	Dec-96	320*	-10.2	-72.0		
	Mean+standard deviation (x=10)						**-9.8+0.3**	**-70.3+2.5**		
32	Big Chino Basin	BC-107	ASU	B(18-2)27 dda	May-96	2003	-10.0	-72.0		
33	" " "	"	"	"	Sep-96	"	-10.3	-69.0		
34	" " "	BC-108	ASU	B(18-3)3 aaa	May-96	230	-9.6	-65.0		

35	" " "	BC-106	ASU	B(18-3)4 ccc	May-96	80	-10.0	-70.0		
36	" " "	"	"	"	Sep-96	"	-10.2	-74.0		
37	" " "	BC-04	USGS	B(18-3)25cda	09-10-91	334	-9.7	-72.0	-11.3	0.156
38	" " "	BC-105	ASU	B(19-4)1 bad	May-96	300	-10.0	-69.0		
39	" " "	"	"	"	Sep-96	"	-10.2	-75.0		
40	" " "	BC-09	USGS	B(19-3)18ccc	09-10-91	200	-10.0	-72.5	-8.0	0.207
41	" " "	BC-08	USGS	B(19-4)4cac	08-27-91	?	-	-	-9.1	0.257
42	" " "	BC-104	ASU	B(19-4)15 aac	May-96	350*	-9.4	-70.0		
43	" " "	"	"	"	Sep-96	"	-9.4	-69.0		
44	" " "	BC-102	ASU	B(21-5)35 aba	May-96	110	-10.0	-71.0		
45	" " "	BC-17	USGS	B(21-6)14ccd	07-06-87	140	-9.9	-74.5		
46	" " "	BC-19	USGS	B(23-7)1ccc	07-05-87	500*	-9.6	-69.0		
47	" " "	BC-10	USGS	B(23-7)26dda	07-04-87	474	-9.9	-72.5		
48	" " "	BC-12	USGS	B(17-2)N34acc	07-04-87	420*	-10.2	-72.0		
	Mean+standard deviation (x=13)						**-9.9+0.3**	**-70.8+2.4**		
49	Limestone wells	LS-11	USGS	B(18-2)27cba	09-10-91	285	-10.3	-75.5	-6.6	0.410
50	" " " "	LS-12	USGS	B(18-2)27cda	08-31-87	3010	-10.5	-74.0		
51	" " " "	"	"	"	08-30-91	"	-10.5	-76.0	-6.4	0.627
52	" " " "	LS-18	USGS	B(22-7)25adb	07-04-87	500*	-10.4	-74.5		
	Mean+standard deviation (x=3)						**-10.4+0.1**	**-75.3+0.8**		
53	Walnut Creek	WC-119	ASU	B(18-6)24 ddd	Dec-96	150	-10.4	-73.0		
54	Williamson Valley	WV-03	USGS	B(17-4)36bcb	08-30-87	200	-11.1	-77.0		
55	" "	WV-109	ASU	B(18-3)25 ada	May-96	300*	-10.4	-78.0		
56	" "	"	"	"	Sep-96	"	-10.6	-78.0		
57	" "	WV-110	ASU	B(18-3)26 baa	May-96	285	-10.2	-75.0		
58	" "	"	"	"	Sep-96	"	-10.3	-77.0		
59	" "	WV-115	ASU	B(17-4)14 cbd	May-96	150	-10.8	-77.0		
60	" "	"	"	"	Dec-96	"	-10.6	-70.0		
61	" "	WV-118	ASU	B(16-4)14 dcd	Dec-96	250	-10.6	-75.0		
	Mean+standard deviation (x=6)						**-10.6+0.3**	**-75.4+2.0**		
	Mean+standard deviation (x=21)		**All wells in Big Chino Basin and tributaries**				**-10.2+0.4**	**-72.9+2.9**		
62	Ash Fork	AF-06	USGS	B(21-02)14bcc	08-31-87	1700	-10.1	-75.5		
63	" "		"	"	08-27-91	"	-10.1	-76.0	-7.1	0.651
	Mean+standard deviation (x=2)						**-10.1+0.04**	**-75.8+0.4**		
64	Big Black Mesa nr Drake	BBM-04	USGS	B(18-1)06 abb	07-04-87	460	-10.1	-73.5		
65	Big Black Mesa nr Glidden	BBM-111	ASU	B(18-1)27 aac	May-96	?	-10.4	-70.0		
66	" " "	"	ASU	"	Sep-96	?	-10.5	-78.0		
	Mean+standard deviation (x=3)						**-10.3+0.2**	**-73.8+4.0**		

down gradient from the clay unit, as shown both by stable-isotope data and water-level contours (Figures 12 and 6; Schwab, 1995). These ground waters join the Big Chino Fault near Paulden, where ground water moves downgradient from Big Chino alluvium into the Martin Limestone as the basin becomes shallower near its outlet. Fractures and solution cavities in the underlying limestone along the extension of the Big Chino Fault provide the likely conduit for water to reach Big Chino Springs. Ground water is significantly enriched in $\delta^{13}C$ at the point of discharge to the Verde River, indicating extensive contact with carbonate rocks. Thus, a composite of ground water from interconnected aquifers in Big Chino Valley supplies Big Chino Springs, the primary source of base flow in the upper Verde River.

Because ground water from wells in most of Big Chino Valley are heavier in ^{18}O and ^{2}H than ground water from the wells that are known to intercept limestone (Fig. 12B), one can infer that recharge to the upper (unconfined) non-carbonate aquifer is derived from a different source. Recharge to the unconfined alluvial aquifer may be from precipitation that has been substantially evaporated, has fallen principally at lower altitudes, or has a larger component from summer storms that recharge along mountain fronts. Direct infiltration may occur within the center of the basin along stream channels during periods of extended runoff. This would appear to be the main source of recharge for most wells tapping the unconfined alluvial aquifer in the lower end of Big Chino Valley. The stable-isotope values of the unconfined Big Chino aquifer are largely indistinguishable from that of the Little Chino alluvial aquifer, suggesting that recharge areas in both basins are similar in altitude, climate, and mechanism. Based on the range of values for $\delta^{18}O$ in wells in lower Big Chino Valley (Fig. 12; Table 5), the zone of mixing between the two basins could extend as far north as the town of Paulden. The present data do not preclude the possibility that ground water from Little Chino Valley may have entered Big Chino Valley in the vicinity of Sullivan Lake.

The source of Lower Granite Spring is probably a non-carbonate aquifer, as evidenced by $\delta^{13}C$ of –8.8 per mil. Determining the recharge area for ground water discharging at Lower Granite Spring, however, is problematic. Both the Little Chino and the unconfined Big Chino aquifers are candidates, but well samples from the two aquifers are largely indistinguishable from one another on the basis of stable isotopes of oxygen and hydrogen. The mean $\delta^{18}O$ and $\delta^{2}H$ for the two basins are within error bars of one another. Both aquifers are relatively depleted in $\delta^{13}C$ with values ranging between –11.9 and –8.0 per mil. Because the values are so similar, the source of Lower Granite Spring could be from the unconfined Big Chino aquifer, the Little Chino aquifer, or a mixture of the two. Compounding the problem, faults in lower Granite Creek are covered to the west by volcanic and sedimentary deposits. Ground water from northern Little Chino Valley and the Sullivan Buttes area may have mixed with Big Chino ground water in the vicinity of Sullivan Lake. Additional sampling is needed to determine a more accurate age of the spring waters. Ground-water age dating techniques such as carbon-14 or chlorine-36 applications could be useful in determining ground-water flow paths, time of travel, and degree of mixing between Big and Little Chino aquifers, if any.

SUMMARY

The following major conclusions are each supported by multiple lines of evidence:

1. *Two spring networks in the upper Verde River contribute virtually all base flow in the upper 24-mi reach. Big Chino Springs is fed by ground water from a carbonate aquifer, and Lower Granite Spring is fed by ground water from a non-carbonate aquifer.* Evidence for two aquifer sources supplying base flow is based on mapped fault and spring locations, low-flow discharge measurements spanning three decades, and significant variations in two independent types of isotopic data. Differences in $\delta^{18}O$ and $\delta^{2}H$ values indicate at least two different ground-water recharge areas. Differences in carbon-13 enrichment suggest different degrees of ground-water exposure to carbonate rock.

2. *There is a strong hydrologic connection between water levels in Big Chino Valley and Big Chino Springs, which presently (1991-99) supplies at least 80 percent of total base flow in the upper Verde River.* Water-level contours clearly indicate that the Big Chino Fault serves as a conduit for ground water from various recharge areas in Big Chino Valley and possibly Little Chino Valley. Geologic evidence indicates that ground water likely exits Big Chino Valley north of Paulden through fractures and solution features in the Martin Limestone that have been observed at river level in the major gaining reach. Increases in base flow correspond to fault locations

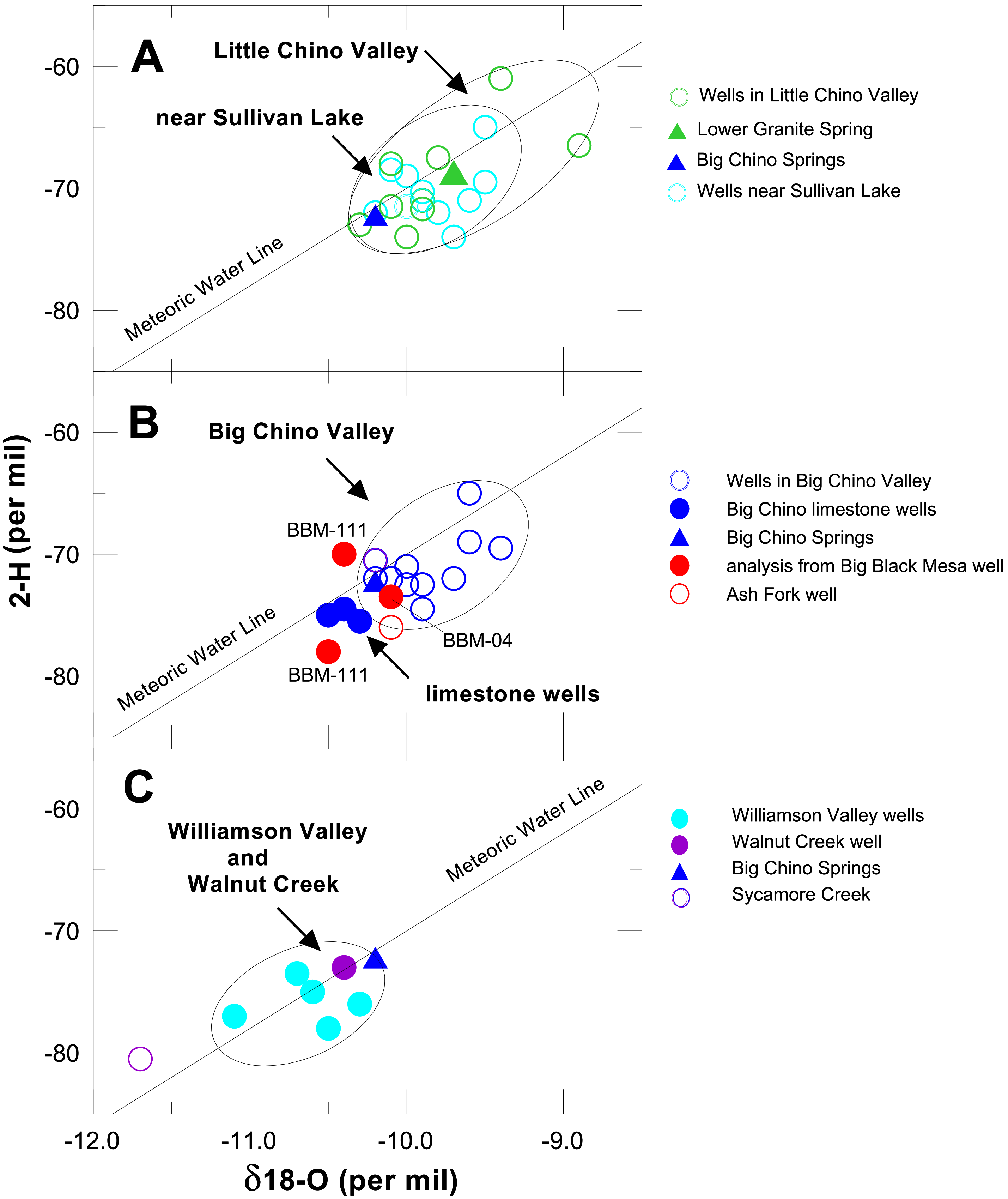

Figure 12. Oxygen-18 versus deuterium plots for samples (A) near Sullivan Lake and from Little Chino Valley, (B) from Big Chino Valley, Ashfork and Big Black Mesa, and (C) in major tributaries to Big Chino Valley and Sycamore Creek (analogous to Bill Williams Mountain runoff).

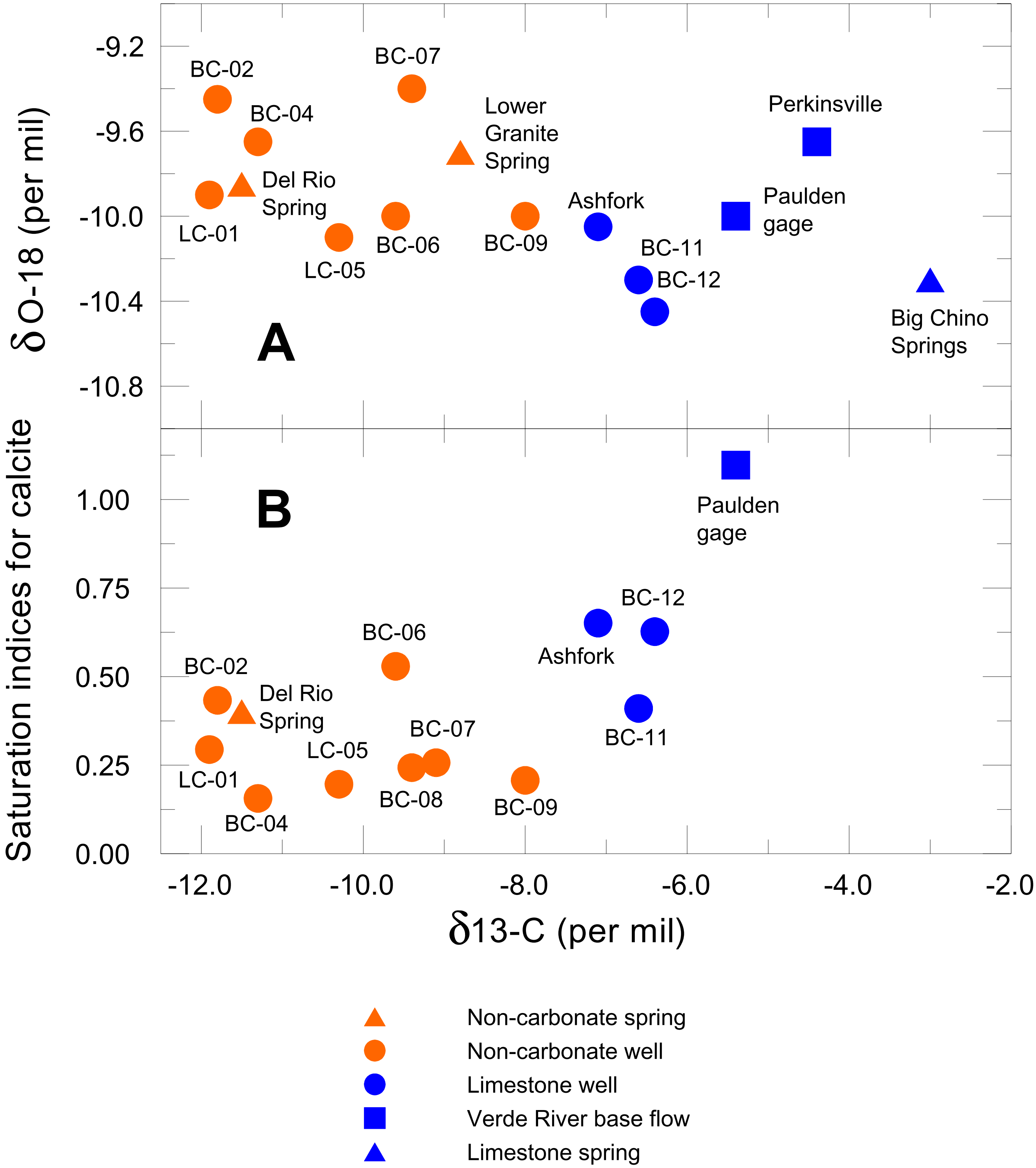

Figure 13. Plots of carbon-13 ratios versus (A) oxygen-18, and (B) saturation indices for calcite in base flow and ground water.

and to changes in pH, specific conductivity, and stable-isotope chemistry. Water-budget relations show strong correlation between measured water levels in Big Chino Valley, base flow in the Verde River, and historical pumping for irrigation in Big Chino Valley. On the basis of historical measurements in Big Chino Basin, a 1-ft decline in water level at the index well correlates with a 1.3-ft^3/s decrease in the base flow. Water-budget interpretations are consistent with the work of Wallace and Laney (1976), Freethey and Anderson (1986), Krieger (1965), and Ewing et al. (1994), and are based on historical data in the USGS and ADWR databases. In addition, stable-isotope values for Big Chino Springs closely match analyses for Big Chino Valley limestone wells and analyses for Williamson Valley and Walnut Creek wells, as well as the statistical mean for all of the available stable-isotope analyses in Big Chino Valley.

3. *Tributaries that drain higher-altitude drainages such as Williamson Valley Wash and Walnut Creek, and/or Pleistocene recharge are likely sources of recharge to the Big Chino Valley limestone aquifer.* The highest altitudes and consequently the greatest rates of precipitation in the Verde headwaters region are in the Bradshaw, Santa Maria, and Juniper Mountains. Williamson Valley and Walnut Creek are the major drainages on the northeast slope of these ranges. In addition, the amount of recharge may have been greater (and isotopically similar to that from present-day higher altitude areas) during the cooler, wetter Pleistocene era. Stable-isotope values for Williamson Valley and Walnut Creek samples closely match analyses of well samples penetrating limestone along the margins of the basin. Water-level contours indicate that ground water from these two tributaries travels across Big Chino Valley to join the Big Chino Fault zone in limestone bedrock north of Paulden. Additional recharge to the shallow aquifers may also occur in the center of the basins beneath ephemeral tributaries such as Big Chino Wash and Granite Creek.

4. *The most likely source(s) of Lower Granite Spring is the Little Chino Valley aquifer, the Big Chino unconfined aquifer, or a mixture from both aquifers.* Mean oxygen-18 and deuterium values for Little Chino Valley of -9.8 ± 0.4 and -69.5 ± 4 per mil, respectively (where x = 9 well samples), are within standard deviation of the means of 10 wells near Sullivan Lake, 13 wells from Big Chino Valley, and 10 spring samples from lower Granite Creek; as well as for Lower Granite Spring. Because of the north-sloping gradient from Del Rio Springs toward Sullivan Lake, there may be flow from Little Chino Valley into Big Chino Valley. Some Little Chino ground water may also reach the Verde River via the lower reach of Granite Creek.

5. *Ground-water discharge from the Little Chino Valley to the Verde River (and/or to the Big Chino Valley) may have decreased in recent decades.* In the northern part of Little Chino Valley, discharge at Del Rio Springs is presently 50 percent lower than it was from 1939 to 1945, and ground-water levels in the Chino Valley artesian aquifer have decreased in some areas by more than 75 ft. The surface drainage from Del Rio Springs along Little Chino Creek to the Verde River above Stillman Lake was once considered perennial and is now ephemeral. Moreover, water-budget relations show a less-than-predicted recovery of Verde River base flow associated with decreasing pumping in Big Chino Valley for the past several years, which may or may not be fully accounted for by recent changes in aquifer storage.

6. *The regions surrounding Ash Fork, Big Black Mesa, and Bill Williams Mountain contribute little if any direct base flow to the uppermost Verde River above Perkinsville.* Although ground water underlying Big Black Mesa is isotopically indistinguishable from Big Chino Springs, it is not a likely source on the basis of hydrologic and geologic evidence. Precipitation is considerably less for Big Black Mesa, which is a few thousand feet lower in altitude than the Bradshaw, Santa Maria, and Juniper Mountain ranges. Recharge is also likely to be substantially lower. Hell Canyon, the major tributary, contributes little if any base flow to the reach of the Verde River near its outlet. More likely sources with the same isotopic signature as Big Chino Springs include Williamson Valley, Walnut Creek, and the limestone aquifer in Big Chino Valley.

Interpretations in this study are based on three independent approaches: (1) evaluation of the existing geologic and hydrologic information, (2) modified water-budget analysis of historical field measurements and (3) evaluation of stable-isotope data. The use of multiple lines of evidence significantly improves the confidence level of these interpretations. All geologic, hydrologic, and stable-isotope data during recent conditions (1991-99) strongly indicate that the Big Chino Valley is the major source of base flow in the Verde River. Moreover, the available hydrologic data are sufficient to qualitatively assess the effect of pumping on the water levels in lower Big Chino Valley and Verde River base flow.

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