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Synthesis of Geologic, Geophysical, Hydrological, and Geochemical Data

By Laurie Wirt

Chapter G

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

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Prepared in cooperation with the Arizona Water Protection Fund Commission

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Synthesis of Geologic, Geophysical, Hydrological, and Geochemical Data

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Introduction

The upper Verde River is a true desert river. Its surface flow begins—not high in the mountains—but instead from a network of diffuse springs at the bottom of a narrow bedrock canyon. In marked contrast to the headwaters of large rivers in more temperate climates where two or more mountain streams typically come together to form a river, base flow in the upper Verde River discharges from springs downgradient from large aquifers in Big and Little Chino Valleys. Near their topographic outlets, the Big and Little Chino basin-fill aquifers discharge to Paleozoic sedimentary rocks, which, in turn, are drained by an incised canyon. In addition, a carbonate aquifer underlies most of Big Chino Valley and the area north of the upper Verde River near Paulden.

Water resources of the Big and Little Chino basin-fill aquifers are under increasing pressure from population growth and residential development. The rural towns of Chino Valley and Paulden in Big Chino Valley are shifting from an economy of irrigated agriculture and ranching to one of suburban land use. In 2004, the city of Prescott purchased a ranch in upper Big Chino Valley with the intent to build a pipeline to import 8,717 acre-ft/yr of water into the Prescott Active Management Area, or PAMA (Southwest Ground-Water Consultants, 2004). The proposed water pipeline and accelerated rural development add to increasing concern about water-resource issues and the effects of pumping on base flow of the upper Verde River. Better understanding of relations between the three major aquifers and the river is needed to manage limited water resources. The stated goal of this report has been to describe the geologic framework of aquifer units and ground-water flowpaths in the Verde River headwaters region.

Together, the chapters in this report offer a synoptic summary, or snapshot in time, of the geologic, geophysical, and geochemical information presently available for the Verde River headwaters region. This framework of information is needed for future scientific investigations such as ground-water modeling, as well as for water-resource policy decisions. In this final chapter, the findings of six previous chapters are summarized and integrated according to the following topics: (a) hydrologic setting, (b) geologic framework, (c) major aquifers and ground-water flowpaths, and (d) water chemistry. Lastly, proportions of base flow from each of the three major source aquifers to the upper Verde River are reevaluated based on a synthesis of new and preexisting data. Collectively, a synthesis of multidisciplinary evidence from varied and independent sources improves confidence in our knowledge of the hydrogeologic system and allows us to better define contributions from distinct source areas. This chapter serves as an executive summary of the findings in this report.

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Hydrological Setting

The Verde River is a major tributary of the Gila River watershed which is part of the Colorado River drainage. The Verde River headwaters region encompasses Big and Little Chino Valleys, which are part of the Transition Zone geologic province. The two valleys are bounded by the Bradshaw, Santa Maria, and Juniper Mountains to the south and west; and to the north by Big Black Mesa, which is the southernmost margin of the Colorado Plateau (figs. A1–A2, Chapter A, this volume; fig. D1, Chapter D, this volume). The 35-mi reach of the Verde River upstream from Verde Valley begins at the Sullivan Lake dam and ends at the mouth of Sycamore Creek. The reach referred to as the “upper Verde River” is considered here to be the uppermost 10-mi reach above the U.S. Geological Survey streamflow gauging station near Paulden (09503700), or “Paulden gauge.” The climate of the study area is arid to semiarid.

Predevelopment Conditions

Present surface- and ground-water conditions no longer reflect predevelopment conditions in Big or Little Chino Valleys. Continuous perennial flow in the Verde River historically began at the confluence of Big Chino Wash and Williamson Valley Wash in Big Chino Valley and at Del Rio Springs in Little Chino Valley, but now begins 2–5 mi farther downstream. Ground-water pumping began in 1930 with the drilling of the first deep artesian well in Little Chino Valley. Predevelopment conditions are thought to have persisted in Little Chino Valley through 1937, when storage capacity in reservoirs increased, and pumping became more widespread (Schwalen, 1967). At present, year-round flow between Del Rio Springs and Sullivan Lake via Little Chino Creek has all but disappeared, and uppermost perennial flow now emerges downstream at three distinct spring networks within a 1-mi radius of the Granite Creek/Verde River confluence (fig. F1, Chapter F, this volume).

Little hydrologic information is available for Big Chino Valley before 1946, but segments of Big Chino Wash probably were intermittent or perennial before about 1950. Historical USGS topographic maps (1947) and aerial photographs indicate perennial segments (fig. A10A, ChapterA, this volume) and native fish were documented in upper Big Chino Wash in 1897 (Gilbert and Scofield, 1898) and again in 1950 (Winn and Miller, 1954). On the basis of these historical observations and modern water-level data, it is estimated that the water table in the vicinity of Sullivan Lake has declined by more than 80 ft since 1947 (fig. A10B, Chapter A, this volume). Streamflow records at the Paulden gauge began in 1963, long after diversions for irrigation and ground-water pumping had started, and thus true predevelopment base-flow conditions will never be accurately known.

Water Use

Pre-existing water-use data for Big and Little Chino basins are confusing and sometimes inaccurate because of differences in the way the data are collected. Water-use data have been collected for different areas by different agencies using different approaches over different timeframes. In addition, estimates of agricultural water use vary widely depending on whether a consumptive use or water-duty reporting method is taken. Indirect measurements of consumptive use often have a large error component and are unreliable compared with direct approaches, such as gauging or metering (Chapter A, this volume).

In general, agricultural use is diminishing as residential use is expanding. In 1997, water use in Little Chino Valley was about one-half municipal (including residential, commercial, and industrial demand) and one-half agricultural (Arizona Department of Water Resources, 2000). Because most of the water used in the PAMA is either metered or gauged, estimates of water use in Little Chino Valley are fairly accurate. Since 1997, the PAMA overdraft in excess of recharge has been reported variously between 6,610 and 9,830 acre-ft/year (Arizona Department of Water Resources, 1998, 1999a, 1999b, and 2000).

Water use in Big Chino Valley is more than 90 percent agricultural and has varied greatly since the 1950s. Irrigated agriculture probably peaked between 9,000 and 15,000 acre-ft/yr in the 1950s through the 1970s and steadily declined through the 1990s. Seventy percent of ground-water pumping prior to 1967 was in northern or “upper” Big Chino Valley (Bob Wallace, oral commun., 1989). Since about 1998 water use reportedly has increased (Arizona Department of Water Resources, 2000, p. 3–31), but current estimates of water use are largely based on indirect consumptive use estimates which are unreliable. Large discrepancies between various indirect estimates are attributed to differences in consumptive use factors, soil types, farming practices, delivery methods, and system efficiencies, as well as to differences in estimating the amount of land under cultivation (Chapter A, this volume). More accurate and direct methods such as metering are sorely needed.

Geologic Framework

The basins beneath Big and Little Chino Valleys developed in late Tertiary time between 10 Ma to the present by crustal extension in central Arizona (Chapter B, this volume). They are the northernmost basins of the Transition Zone. Not as extensive or as deep as Basin-and-Range basins to the south and west, the Big and Little Chino basins are distinguished by fault-bounded margins, incorporation of volcanic material within the basin-fill deposits, and facies variations within the sediment fill.

Big Chino Valley, which is the larger of the two basins, is an elongate, northwest-trending, 45-km-long graben that is at least 700 m deep in the center and shallower around the northwestern, southeastern, and southwestern margins. Basalt flows entered the valley from the north, west, and southeast from 6.0 to 4.5 Ma. The basin contains Quaternary and late Tertiary sediment and is bordered by the Quaternary Big Chino Fault on the northeastern side of the valley. Fine-grained carbonate sediment indicates that the central part of the basin was a playa. Alluvial fans and major tributaries, predominantly Williamson Valley and Walnut Creek, contributed sediment to the margin of the playa from the south and west.

The basin underlying Little Chino Valley is smaller than the Big Chino basin and contains a thinner sequence of Quaternary and late Tertiary sediment. The deepest part of the basin trends northwest and is 18 km long. Maximum sediment thickness is about 200 m. Alluvial fans contributed sediment from the west, south, and southeast. The valley lacks proven playa deposits and young (4–6 Ma) basalt flows. Beneath the Quaternary and late Tertiary sediments are extensive basalt flows of the 10–15-Ma Hickey Formation, as well as the abundant flows, domes, and intrusive centers of 24-Ma lati-andesite (figs. B5 and B7, Chapter B, this volume). These volcanic rocks formed an irregular topographic surface on which the

Quaternary and late Tertiary sediment was deposited. Consequently, sediment thickness in Little Chino basin varies and mirrors the underlying relief of Tertiary volcanic rocks. Shallowly buried (<200–300 m) lati-andesite plugs in northern Little Chino Valley, detected as semicircular magnetic lows, probably act as barriers to ground-water flow. The complexity of volcanic facies beneath Little Chino Valley is the major cause of artesian conditions.

Gravity data indicate an asymmetric basin beneath Big Chino Valley at least 1–2 km deep and 3–4 km wide (fig. C13, Chapter C, this volume). The areal extent of the Big Chino gravity low coincides with a thick playa deposit that is corroborated by well data. The lack of a distinct gravity low in Little Chino Valley suggests that the sedimentary and volcanic fill is much thinner (< 1 km) than that of Big Chino Valley. As shown by gravity values in both basins, the basin-fill deposits thin and become narrower toward their topographical outlets in the direction of Sullivan Lake. The reduction of the basin-fill deposits toward their outlets coincides with the emergence of predevelopment discharge in lower Big Chino Wash and Little Chino Creek north of Del Rio Springs.

The Big Chino Fault is the largest structural feature in the study area, a northwest-trending fault with at least 1,100 m of displacement that forms the northern boundary of the basin graben. Where displacement is large, basin-fill deposits abut Proterozoic basement rocks beneath Big Black Mesa, which serve as a barrier to flow across the fault. The fault decreases in displacement to the southeast and dies in a series of horsetail splays north of Paulden, where there is connection between the basin-fill aquifer and the underlying and adjoining carbonate aquifer north of the upper Verde River (Chapter D, this volume).

Unlike Big Chino Valley, Little Chino Valley does not have large displacement faults. The pervasive magnetic grain within Little Chino Valley is northeast and northwest striking, but apparently none of the structures responsible for this grain have a large vertical offset like the Big Chino fault. Geophysical and borehole data suggest the presence of a northwest-striking, low-displacement fault in Little Chino Valley north of Del Rio Springs.

Major Aquifers and Ground-Water Flowpaths

Three major aquifers in the headwaters study slope toward the upper Verde River. They are the Big and Little Chino basin-fill aquifers and the carbonate aquifer north of Big Black Mesa and the upper Verde River within the Transition Zone (fig. D2, Chapter D, this volume). Although smaller, the basin-fill aquifers have the large storage capacity of typical Basin-and-Range basin-fill aquifers and deliver steady, reliable discharge to perennial streams near their outlets. The part of the carbonate aquifer contributing to the Verde River headwaters is the eroded and exposed margin of an extensive regional aquifer that lies more than 3,000 ft beneath much of the southwestern Colorado Plateau (fig. D1, Chapter D, this volume).

Igneous and metamorphic Proterozoic basement rocks generally have very low permeability and define the bottom and edges of the basin-fill aquifers. Where basement rocks are absent or fractured, ground water can move into or out of the basins. The most permeable water-bearing units producing the largest well yields include medium- to coarse-grained Quaternary and Tertiary alluvium, some (but not all) Tertiary basalt flows, and Paleozoic carbonate rocks.

Recharge to the aquifers varies seasonally, temporally, and spatially throughout the headwaters area as a function of climate, stream gradient, and rock type. The greatest amounts of recharge generally are attributed to losing reaches of mountain-front areas having the most precipitation. Williamson Valley Wash, Walnut Creek, and Granite Creek are the largest tributaries draining mountain fronts to the south and west. Substantial amounts of recharge, however, also appear to occur along the valley floors. In lowland areas, direct recharge to the basin-fill aquifers along low-gradient stream reaches may be substantial, particularly near the basin outlets. The amount of recharge resulting from infrequent flooding of Williamson Valley Wash, lower Big Chino Wash, and Granite Creek may be underestimated, as indicated by decreasing apparent ground-water ages toward the valley outlets (figs. E7 and E8, Chapter E, this volume).

The degree of recharge also is influenced by the types of rocks exposed at the ground surface. Relatively impermeable igneous and metamorphic rocks in the Bradshaw and Santa Maria Mountains probably produce little high-altitude recharge, but supply the largest amounts of runoff to the basins where there is substantial low-gradient recharge beneath ephemeral streams overlying alluvium. In contrast, in high-altitude carbonate regions such as Big Black Mesa or the Juniper Mountains, the rate of infiltration is probably relatively higher owing to greater permeability of carbonate rocks and fractured basalts. The highest rates of infiltration are likely to occur where there is karst, and the water table is near land surface; for example, along Hell Canyon near King Spring.

In general, ground-water movement within the basin-fill aquifers is from the valley margins and tributaries toward the valley center and then down the longitudinal axis of the valley toward the basin outlet. Ground-water flowpaths within the basin-fill aquifers may deviate from surface-water drainage patterns (a) where confining conditions exist, (b) where fine-grained playa sediment or thick latite plugs create less-permeable obstructions to flow, and (c) near the outlets of the basins where ground water is transmitted through pre-Cenozoic rock units. Within the carbonate aquifer, preferential ground-water movement is caused by abrupt changes in the secondary porosity of the lithology caused by karst or extensive fracturing, which on a regional scale may be broadly associated with large structural features (such as faults or monoclines).

Regional Carbonate Aquifer

The region north of the Big Chino Fault and the upper Verde River (in the Transition Zone and extending southward from the Colorado Plateau) is a continuous expanse of Paleozoic sedimentary rocks that is partly overlain by Tertiary basalt flows. Eroded remnants of these same rocks also are exposed in the Juniper Mountains, Sullivan Buttes, and Black Hills. Paleozoic rocks also are concealed beneath Big Chino Valley and part of northern Little Chino Valley. Although largely disconnected from the carbonate aquifer beneath the Colorado Plateau, these remnants are considered part of the regional carbonate aquifer. Within the Transition Zone, the carbonate aquifer consists of many discrete zones which may be faulted or eroded and may or may not be interconnected. The carbonate aquifer typically discharges to lakes or springs at the bottom of incised canyons such as Stillman Lake, King Spring, and the springs in the Verde River/Granite Creek confluence area (fig. D8, Chapter D, this volume).

The crest of Big Black Mesa and the Mogollon Rim south of Bill Williams Mountain form a ground-water divide for the regional carbonate aquifer between the Colorado Plateau and the Transition Zone. North of Big Black Mesa, the Limestone Canyon Monocline, and the Mogollon Rim, Paleozoic rocks gently dip to the north or northeast (fig. D3, Chapter D, this volume). Although high-altitude surface-water runoff is produced on the Colorado Plateau overlying the carbonate aquifer, it typically reaches Big Chino Valley only a few times in any given decade. Consequently, little if any groundwater recharge to Big Chino Valley or the upper Verde River is contributed from the area north of Big Black Mesa and the Mogollon Rim (Chapter D, this volume).

In the study area, the primary water-bearing unit within the regional carbonate aquifer is the Martin Formation, followed to a lesser degree by the Redwall Limestone. The lower Martin contains abundant northwest-striking high-angle joints, dissolution cavities, and other small karst features that enhance its overall permeability. The underlying Tapeats Sandstone, due to its low overall porosity, forms a resistive layer to vertical ground-water movement from above. For this reason, springs such as those in the Verde River/Granite Creek confluence area preferentially emerge near the base of the Martin. The occurrence of elevated concentrations of lithium, boron, and arsenic are spatially associated with the presence of the Chino Valley Formation (Cambrian?) (Chapter E, this volume). This discontinuous sedimentary facies is found along the contact between the Martin and the Tapeats within the Devonian-Cambrian zone, or “D-C zone” in the Verde River/Granite Creek confluence area (Chapter E, this volume).

Basalt flows in the carbonate aquifer have high-overall permeability and provide important flowpaths, due in large part to extensive intersecting columnar joints or rubble zones. For example, a basalt-filled paleochannel in the Martin limestone (which intercepts the D-C zone) offers a preferential flowpath, as indicated by a two-fold increase in dissolved silica between the Big Chino basin-fill aquifer near Paulden and upper Verde River springs (table F2, Chapter E; this volume). The ground-water flow direction at Paulden is east or southeast, consistent with regional gradients and the Big Chino aquifer as the major source of discharge to the Verde River (figs. D7–D8, Chapter D, this volume).

In the Paulden area, the carbonate aquifer acts as a conduit between Big Chino Valley and the Verde River, as indicated by water levels and water chemistry. The basin-fill aquifer and the D-C zone of the carbonate aquifer are strongly connected at the Big Chino outlet and function together as a single aquifer source (Chapter D, this volume). A small amount of mixing between the Big Chino aquifer units and the Mississippian-Devonian or M-D sequence of the carbonate aquifer may occur along this conduit (Chapter F, this volume). The M-D sequence contributes less than 6 percent of the base flow to the upper Verde River at the Paulden gauge, based on the results of the tracer study and inverse geochemical modeling.

Little Chino Basin-Fill Aquifer

In Little Chino Valley, a complex sequence of alluvial and volcanic deposits forms a highly productive aquifer. The Little Chino basin-fill aquifer is connected on its southeastern boundary with the Agua Fria basin-fill aquifer and at its northern outlet near Stillman Lake and lower Granite Creek with the carbonate aquifer (fig D1, Chapter D, this volume). Artesian flow near the town of Chino Valley is attributed to multiple complex facies environments that include (a) trachyandesite overlying small pockets of irregularly distributed sediment, (b) volcanic-clastic sequences within the lati-andesite, (c) lati-andesite over sedimentary rock or alluvium, (d) permeable basalt beneath strongly cemented alluvium, and (e) unconsolidated alluvium beneath strongly cemented alluvium. The narrow basin outlet and low permeability of latite plugs restrict northern movement of ground water, which partly accounts for discharge at Del Rio Springs. From Del Rio Springs, northward flow is constricted by shallow basement south of Sullivan Lake. The most reasonable outlet flowpath is northeast through faulted Paleozoic rock and lati-andesite toward spring-fed Stillman Lake and Lower Granite Spring.

Big Chino Basin-Fill Aquifer

The Big Chino basin contains (a) buried basalt flows in the northwest and southeast parts of the basin, (b) thick fine-grained playa deposits in the basin center, and (c) other basin-fill deposits. Ground-water flowpaths are locally influenced by the heterogeneous distribution of alluvial deposits (ranging from coarse-grained alluvial fans to the fine-grained playa sediment) and by the buried basalt flows. Williamson Valley is by far the largest source of tributary recharge, followed by Walnut Creek.

Much attention has been given to the role of the playa deposit as a potential obstruction to ground-water movement between the northern and southern ends of Big Chino Valley (Ewing and others, 1994; Ostenaa and others, 1993; Southwest Ground-water Consultants, 2004). Owing to a shortage of deep well logs, the full extent of the playa deposit cannot be mapped but can be approximately inferred by the inflection of water-level contours around the center of the valley where the playa is known to be present (fig. D7, Chapter D, this volume). Preferred ground-water movement occurs down the axis of the valley along the western edge of the playa through coarser-grained sediment. Some ground water may flow beneath the playa through pre-Cenozoic rocks or above the playa deposit through alluvial fans that interfinger with and partly overlie the playa deposit along the Big Chino Fault. The full areal extent of the playa is poorly constrained, particularly where elongated along the Big Chino Fault, where it could extend as far northwest as Partridge Creek. Consequently, the productive part of the aquifer northwest of the playa could be substantially smaller than the area proposed in a recent ground-water model by Southwest Ground-water Consultants (2004). More work is needed to better define the vertical and lateral extent of the playa deposit in the center of Big Chino Valley.

The Big Chino basin-fill aquifer boundary is fairly impermeable where defined by contact with Proterozoic basement rocks (such as where the two are juxtaposed because of large vertical displacement along the Big Chino Fault) or with extensive occurrences of Sullivan Buttes lati-andesite. The mouth of Partridge Creek is such an area where substantial ground-water movement across the basin boundary is highly unlikely. On the other hand, the basin-fill aquifer is thought to be interconnected with carbonate units in several locations where basement rocks are absent. For example, the basin-fill aquifer abuts extensive erosional remnants of the carbonate aquifer along the base of the Juniper Mountains and in the graben block underlying the basin. The most obvious interconnected area is north of Paulden, where displacement along the Big Chino fault terminates. Here, the basin alluvium is shallowly underlain by the regional carbonate aquifer near its ground-water outlet. Buried basalt flows straddle both sides of the basin margin east of Paulden, creating another potential conduit between the two aquifers, and major joint sets in the Martin Formation parallel the trend of the Big Chino Fault. This combination of structures directs ground water out of the Big Chino basin-fill aquifer, through the D-C zone of the carbonate aquifer, and toward the incised canyon of the upper Verde River.

Water Chemistry

Geochemical and isotopic methods were used to characterize the water chemistry of major aquifers and springs in the Verde River headwaters, to identify changes along the basin outlet flowpath in southeastern Big Chino Valley, and to determine sources of water contributing to the upper Verde River (Chapters E and F). Water-chemistry groups that were characterized include (a) high-altitude areas west and south of Big Chino Valley, (b) the carbonate aquifer north of Big Chino Valley and the upper Verde River (M-D sequence), (c) the Little Chino basin-fill aquifer, (d) the Big Chino basin-fill aquifer, (e) the carbonate aquifer underlying the Big Chino basin-fill aquifer (D-C zone), and (f) low-altitude springs discharging to the upper Verde River, including lower Granite Creek, Stillman Lake, and upper Verde River springs (fig. E1, Chapter E, this volume). Characterization of water-chemistry groups helped to identify the sources of low-altitude springs and delineate major flowpaths near the basin outlets. This helped in selection of representative water compositions used in the inverse geochemical modeling, which is discussed in more detail at the end of this section.

Tritium and Carbon-14

In general, water from high-altitude springs and major tributaries in the Verde River headwaters has the highest tritium activities and youngest apparent ages (fig. E7, Chapter E, this volume). None of the tritium values exceed 10 TU, a level that would have indicated that some portion of precipitation was recharged during atmospheric nuclear testing of the 1950s and 1960s or after radioactive fallout during the 1970s. Deep wells in northwestern Big Chino Valley and in the carbonate aquifer north of the Verde River have no detectable tritium, indicating that ground water in these areas was recharged before 1953. The presence of low-level tritium in springs and wells along low-altitude drainages indicates that modern recharge from storm runoff is occurring. Major springs near the outlets of Big and Little Chino Valleys often have tritium activities slightly above the analytical detection limit, which is interpreted as evidence for direct recharge along these low-gradient stream segments.

Likewise, ^{14}C data also indicate that direct recharge to the basin-fill aquifers is occurring beneath major drainages. Some of the highest ^{14}C activities occur along Walnut Creek and Williamson Valley Wash, which receive runoff from high-altitude areas having some of the highest rates of precipitation (fig. E8, Chapter E, this volume). Ground water in the northernmost part of the Little Chino basin-fill aquifer becomes progressively younger toward the Verde River. This trend indicates direct recharge from runoff along perennial tributaries and ephemeral stream channels near the valley outlets, consistent with the results from the tritium data.

Trace Elements

Water/rock interaction with shales of marine or lacustrine origin or playa sediment is the most likely source for the unusual occurrence of elevated As, Li, and B in the Verde River/Granite Creek confluence area. Ground water sampled from the Martin/Chino Valley/Tapeats (D-C zone) of the carbonate aquifer beneath the basin-fill aquifer near Paulden has a distinctive water chemistry that is moderately mineralized, with the highest concentrations of As, Li, and B (fig. E3B, Chapter E, this volume). At upper Verde River springs, moderate concentrations of As, Li, and B are interpreted as evidence that water has had contact with Paleozoic rocks in the D-C zone. Disproportionate increases in B relative to Li along the Big Chino basin outlet from near Paulden to upper Verde River springs also suggests water-rock interaction as the predominant process, as opposed to mixing. In contrast, ground waters from the carbonate aquifer (M-D sequence) north of the Verde River have low concentrations of these trace elements (fig. E2B, Chapter E, this volume).

Strontium concentrations are a useful indicator of Little Chino ground-water sources in the Verde River/Granite Creek confluence area. The amount of Sr represents the degree of contact ground water has had with Sr-rich igneous rocks, particularly lati-andesites. Water samples from Del Rio Springs, Lower Granite Springs and Stillman Lake are elevated substantially in strontium, owing to contact with Sr-rich lati-andesite in northern Little Chino Valley and the Sullivan Buttes. In central Big Chino Valley, the playa deposit (although largely unsampled) is thought to provide another potential source of elevated strontium concentrations. Water samples from upper Verde River springs contain moderate concentrations of Sr, between 350 to 420 micrograms per liter (µg/L) Sr, compared with 460 to 620 µg/l for the Little Chino basin-fill aquifer (fig. E3C, Appendix A). In contrast, water samples from the carbonate aquifer north of the Verde River (M-D sequence) are comparatively lacking in Sr (70 to 120 µg/L).

Stable Isotopes of Hydrogen and Oxygen

Past stable-isotope interpretations have been a basis for conflicting conclusions about the source of upper Verde River springs. In Chapter E, stable isotopes of hydrogen and oxygen were used to show that many of the samples collected from spring-fed lakes (for example, Stillman Lake and King Spring) and some earlier well samples collected from stock tanks (for example, Hell well) had undergone substantial evaporation. Samples that had undergone evaporation could not be used to evaluate the degree of mixing with the carbonate aquifer.

Similarly, stable-isotope results for the basin-fill aquifers indicate considerable vertical and horizontal heterogeneity. Ground water from the basin-fill aquifers had a broad range of $\delta^{18}O$ versus δD with substantial overlap between basins (figs. E5B and E6, Chapter E, this volume), as might be expected for samples collected on different dates, from different screened depths, and from different areas of the basins. Consequently, the mean stable-isotope values calculated for the basin-fill aquifers were not useful endpoints for mass-balance mixing calculations (fig. E6 and table E2, Chapter E, this volume). For this reason, samples collected near the outlets of the Big and Little Chino basin-fill aquifers were selected as volumetric composites of water leaving the aquifer. In Little Chino Valley, Del Rio Springs was used to represent the Little Chino basin-fill aquifer. In Big Chino Valley, a $\delta^{18}O$ value of approximately $-10.3\pm0.2‰$ was used to trace the main flowpath backwards or upgradient from upper Verde River springs through the D-C zone of the carbonate aquifer to the outlet of the Big Chino basin-fill aquifer near Paulden (fig. E10, Chapter E, this volume). A well along the main basin outlet flowpath near Paulden was chosen to represent a volumetric composite of the Big Chino basin-fill aquifer.

No mixing of the Big Chino aquifer with another source is required to account for the stable-isotope composition at upper Verde River springs, although a small amount of mixing within the range of analytical uncertainty for $\delta^{18}O$ could not be rejected. Using a mass-balance approach, the maximum hypothetical contribution from the M-D sequence of the carbonate aquifer north of the Verde River that could occur without affecting the $\delta^{18}O$ content of upper Verde River springs is about 15 percent. Consequently, mixing with the carbonate aquifer less than about15 percent could not be determined with any confidence (Chapter E, this volume). Because of this large degree of uncertainty, the mixing hypothesis was tested further by inverse modeling (Chapter F, this volume), which relied on multiple lines of geochemical evidence rather than stable-isotope data alone.

Synoptic Sampling and Tracer-Dilution Studies

Tracer-injection and water-chemistry synoptic studies were conducted during low-flow conditions to identify locations of diffuse springs and to quantify the relative contribution from each major aquifer source to base flow in the upper Verde River. Base flow begins downstream from Big and Little Chino Valleys in three different locations: Stillman Lake, lower Granite Creek, and 600 ft downstream from the Granite Creek/Verde River confluence. The relative contribution of flow from each source is difficult to measure directly because most of the inflows occur diffusely through the streambed.

By using the results of the tracer study and synoptic sampling, base flow was calculated at 19.5 ± 1.0 ft^3/s at Stewart Ranch, compared with 21.2 ± 1.0 ft^3/s measured at the Paulden gauge during the same time interval. By subtraction, approximately 7 percent of base flow at the Paulden gauge was contributed between Stewart Ranch and the Paulden gauge. Most of the undetected inflow presumably occurs in the vicinity of the Muldoon Canyon confluence where inflow has been observed from both banks. The Little Chino basin-fill aquifer contributed 2.7 ± 0.08 ft^3/s, or 13.8 ± 0.7 percent, of total base flow at Stewart Ranch. Approximately four fifths of the Little Chino inflow was derived from the flowpath beneath Stillman Lake, as opposed to base flow from the Granite Creek area. By subtraction, discharge from upper Verde River springs contributed the remaining 86.2 ± 0.7 percent. Inverse modeling was used to determine the proportions of water types that contribute ground water to upper Verde River Springs.

Inverse Modeling of Geochemical Data

Inverse modeling was used to constrain hypotheses regarding the nature of water-rock interactions and possible mixing along the flowpath between the Big Chino aquifer near Paulden and upper Verde River springs. The computer program PHREEQC (Version 2; Parkhurst and Appelo, 1999) was used (a) to calculate saturation indices and the distribution of aqueous species, (b) to identify net geochemical mass-balance reactions between initial and final waters along the outlet flowpath, and (c) to calculate proportions of water types contributing to the final mixture. PHREEQC allows the user to specify the analytical uncertainty range for each element or isotope entered in the model. In addition, PHREEQC identified only the mass-transfer models that minimized the number of phases involved, referred to as “minimal models.”

Four initial water compositions were used in the model to represent (a) well H representing the D-C zone of the regional carbonate aquifer underlying basin-fill alluvium near the outlet, (b) well E, representing basin alluvium and basalt facies of the Big Chino basin-fill aquifer near its outlet, (c) well F representing the carbonate aquifer between Big Chino Valley and upper Verde River springs, and (d) well M representing the M-D sequence of the carbonate aquifer north of the Verde River near Drake. The final water composition was represented by the largest discrete spring contributing to upper Verde River springs. An uncertainty of ±5 percent was assigned to concentrations of all the major and trace elements except boron and lithium because of their nonconservative behavior in this setting. Stable isotopes of oxygen, hydrogen, and carbon were assigned an uncertainty equal to the reported analytical precision. Although many plausible models were possible, the “minimal” option was used to identify only those models with the fewest phases that were a best fit for the input data.

Important reactions identified by the inverse modeling include the dissolution of silicate minerals and degassing of carbon dioxide, interpretations that are largely supported by field observations as well as analytical data. The most likely cause of a two-fold increase in dissolved silica is water-rock interaction with basalt along the outlet flowpath. Degassing of CO_2 is inferred by variations in pH along gaining reaches of the Verde River and Granite Creek (fig. F11, Chapter F, this volume). Notably, calcite and dolomite minerals remain near or at saturation along the flow paths, indicating that dissolution of carbonate rocks is *not* a major process affecting concentrations of Ca, Mg, and HCO_3^-. Dissolution of silicate minerals and mixing of initial water types are the predominant processes affecting compositional variations in the major elements along the Big Chino basin outlet flowpath.

Six out of thirteen minimal models support a small amount of mixing between Big Chino ground water and the M-D sequence of the carbonate aquifer at upper Verde River springs. The sum of three initial waters from Big Chino Valley accounts for between 93 and 100 percent of total discharge at upper Verde River springs, with the M-D sequence outside of Big Chino Valley accounting for a maximum of 7 percent of total spring inflow(1,200 acre-ft/yr), if any. At the outlet of the Big Chino basin-fill aquifer near Paulden, the D-C zone of the underlying carbonate aquifer contributes on the order of 10 to 15 percent of the ground water discharging from Big Chino Valley.

Contributions from each aquifer source, readjusted for the Paulden gauge, are as follows: (a) the combined Big Chino basin-fill aquifer and D-C zone of the underlying carbonate aquifer, greater than 80 to 86 percent, (b) the D-C zone of the carbonate aquifer alone, 10 to 15 percent, (c) Little Chino basin-fill aquifer, 14 percent, (d) M-D sequence north of the Verde River, less than 6 percent. Contributions of flow to the Verde River from each aquifer is presumed to vary seasonally and annually in response to climatic or anthropogenic variables, such as long-term drought or changes in the amount of pumping. The calculations presented here are based on synoptic measurements of June 2000, representing a snapshot in time during low-flow conditions.

Sources of Base Flow

Previous estimates of the sources of base flow to the upper Verde River were reconciled with the hydrogeologic framework and geochemistry. Pie charts in fig. G1 compare the relative contributions to Verde River base flow based on previous studies using a water-budget approach (table A4 and fig. A16, Chapter A, this volume) with the results from the tracer study and inverse modeling (Chapter F, this volume). In accordance with the conceptual model developed in this study, the relative contributions are linked to three major aquifers (right pie chart) as opposed to less specific geographical areas for Big and Little Chino Valleys and Big Black Mesa (left and center pie charts). In addition, contributions from different parts of the regional carbonate aquifer are subdivided with respect to the D-C zone and M-D sequence.

Contemporary estimates presented in the 1990 and 2000 pie charts assume mean annual base flow at the Paulden gauge of 17,000 acre-ft/yr (Freethey and Anderson, 1986; Wirt and Hjalmarson, 2000; Table A4, Chapter A, this volume), a level that is corroborated by mean annual flow during a drought year with no runoff of 16,370 acre-ft (MacCormack and others, 2002). Results of the tracer study (Chapter F, this volume) indicate that 13.8±0.7 percent of the base flow, or 2,350 acre-ft/year, was derived from the Little Chino basin-fill aquifer. Other recent studies (Arizona Department of Water Resources, 2000; Nelson, 2002) estimate that the amount of underflow from Little Chino Valley to the Verde River was about 2,100 acre-ft/yr during the mid-1990s. The tracer-study measurement is within 250 acre-ft/year of that by Nelson (2002), which is considered excellent agreement for independent results using different approaches. An important distinction in our conceptual understanding here is that not all outflow from the Little Chino basin-fill aquifer becomes inflow to the Big Chino basin-fill aquifer near Sullivan Lake.

Little Chino outflow travels north and east from Del Rio Springs and does not provide inflow to the Big Chino basin-fill aquifer. An indeterminate fraction of Little Chino outflow probably enters the Big Chino aquifer near Sullivan Lake. The proportion of Little Chino outflow discharging directly to Stillman Lake without first entering Big Chino Valley is also unknown, but appears to be substantial and probably represents the majority of contemporary outflow from the Little Chino basin-fill aquifer. Given that the Little Chino aquifer is out of safe yield (Arizona Department of Water Resources, 1998, 1999a, 1999b, and 2000) and in light of the historical loss of perennial base flow between Del

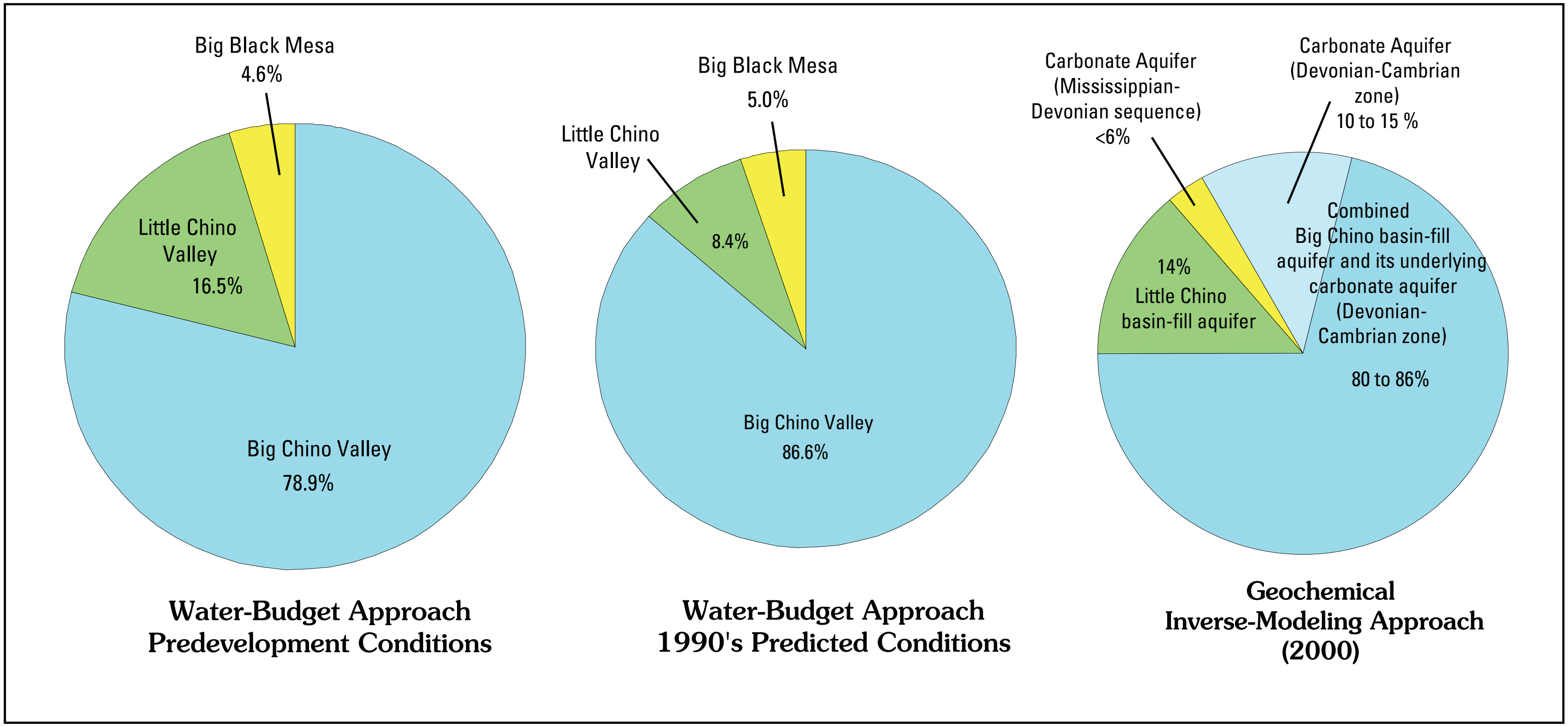

Figure G1. Pie charts showing sources of base flow to the upper Verde River, comparing water-budget estimates with those based on inverse modeling using geochemistry and tracer-study data. Data from previous studies is provided in table A4 and figure A16 (Chapter A, this volume). Note that the predevelopment pie diagram on the left is proportionately larger than those on the center and right.

Rio Springs and Sullivan Lake along the Little Chino Creek (Chapter A, this volume, fig. 10b), Little Chino outflow probably has declined more rapidly along the Sullivan Lake flowpath than along the Stillman Lake and lower Granite Creek flowpaths. This finding has significant implications for whether all of the Little Chino outflow ought to be counted as Big Chino inflow in a water-budget calculation, particularly if the budget is intended to represent modern conditions.

On the basis of the geologic framework and the tracer and inverse geochemical modeling results (Chapter F, this volume), the combined basin-fill aquifer and carbonate aquifer underlying Big Chino Valley are here estimated to contribute 80 to 86 percent, or between 13,600 and 14,650 acre-ft/yr of the mean base flow at the Paulden gauge. This compares favorably with data compiled from previous studies using a water-budget approach (Table A4, Chapter A, this volume), which were used to calculate that the Big Chino Valley area contributed about 78.9 percent of mean annual discharge at the Paulden gauge during predevelopment conditions and about 86.6 percent of mean annual discharge during 1990s conditions. Thus, estimates based on the tracer study and geochemical modeling approach independently corroborate the findings of earlier studies, although contributions from the Big and Little Chino basin-fill aquifers are presumed to be declining in response to increasing water usage. Unexpectedly, the tracer study directly measured a larger contribution from Little Chino Valley in 2000 (13.8 percent versus 8.4 percent) than that predicted with 1990s data using a water-budget approach. One possible explanation for this discrepancy is a delayed response to the effects of pumping, in which the predicted rate of decline in Little Chino base flow is lower than the observed rate. Whether discharge from the Big Chino aquifer has also decreased from predevelopment conditions cannot be quantified from the available data, though the results of the 2000 tracer study can be used to provide a baseline for making a point-in-time comparison in the future.

Based on the geochemical modeling, the geographical region south of the crest of Big Black Mesa and lower Hell Canyon near Drake is estimated to contribute less than 6 percent, or a maximum of about 1,200 acre-ft/year, of base flow to the Verde River—about the same as that estimated for Big Black Mesa by Ford (2002). Ford (2002) estimated Big Black Mesa recharge at 1,250 acre-ft/yr, by calculating the land area of the mesa exceeding 5,000 ft above sea level and applying a recharge rate based the rate of precipitation. Ford's (2002) estimate cannot be directly compared to the contribution from the regional carbonate aquifer north of the upper Verde River (M-D sequence) because the geographical extent of the two contributions is not the same. In addition, a substantial part of the recharge from the Big Black Mesa area probably enters the Big Chino basin-fill aquifer directly through alluvial fans along the Big Chino fault, or through the underlying carbonate aquifer near Paulden, and, thus, cannot be discriminated from the rest of the Big Chino basin-fill aquifer using a geochemical approach. Consequently, it is difficult to differentiate a Big Black Mesa contribution as distinct from the Big Chino basin-fill aquifer and its underlying carbonate aquifer.

As a closing observation, previous studies of recharge (Ford, 2002; Ewing and others, 1994; Freethey and Anderson, 1986) have not rigorously addressed the issue that infiltration rates are spatially variable as a function of geology as well as of climate. Rates presumably are higher for Paleozoic carbonate rocks and Tertiary basalts in the Transition Zone region than for igneous and metamorphic rocks in the Bradshaw and Santa Maria Mountains, owing to their greater permeability and the short distance to water tables beneath deeply incised canyons such as Limestone Canyon and Hell Canyon (Chapter D, this volume). The amount of direct runoff infiltrating beneath low-gradient streams, during large but infrequent floods and seasonal runoff, is probably more substantial than thought earlier as indicated by elevated carbon-14 and tritium values along low-altitude stream segments near the basin outlets (figs. E7 and E8, Chapter E, this volume). Improved understanding and delineation of recharge areas could be used to protect important recharge areas or possibly to enhance recharge in certain areas. Additional stream monitoring and directed geologic studies of recharge are needed to address these and other data gaps listed below.

Recommendations for Future Studies

1. Fill data gaps in streamflow records by maintaining the long-term gauging stations recently reestablished at Williamson Valley Wash, Walnut Creek, and Del Rio Springs. Add high-flow capability to gauging stations on Pine Creek, Partridge Creek, upper Big Chino Wash, and lower Granite Creek.

2. Provide more accurate water-use records in Big Chino Valley by direct measurements such as metering and gauging instead of indirect methods such as estimating consumptive use.

3. Improve definition of the vertical and lateral extent of the playa deposit and buried basalt flows in north central Big Chino Valley by using ground-based geophysical surveys and drilling of additional deep boreholes. Recommended geophysical approaches include audio-magneto telluric (AMT) and "mise-a-la-messe" direct-current (DC) methods that are able to identify water-bearing properties of geologic units and preferential flowpaths as a function of depth. The mise-a-la-messe approach has been used to determine discrete flowpaths through basalt rubble zones and karst.

4. Determine infiltration rates for selected geologic units and evaluate the effects of prominent structural features such as faults, monoclines, and prominent joint sets to improve estimates of recharge in different parts of the headwaters region.

5. Complete geochemical modeling to calculate ground-water ages of representative composite waters at the basin outlets, using the ^{14}C activities measured in this study, to determine rates of ground-water movement.

Summary of Conclusions

Multiple lines of evidence indicate that the major source of ground water to the upper Verde River is the Big Chino aquifer at its ground-water outlet near Paulden (80 to 86 percent) with the Little Chino aquifer providing about 14 percent of 17,000 acre-ft/yr. Flowpaths from the Big Chino basin-fill aquifer and its underlying carbonate aquifer converge north and east of Paulden. The Big Chino basin-fill aquifer and D-C zone of the carbonate aquifer are strongly connected between Paulden and upper Verde River springs. Here, the D-C zone of the carbonate aquifer acts as a conduit for outflow from Big Chino Valley and provides as much as 15 percent of ground water attributed to the Big Chino basin-fill aquifer. Distinctive water-chemistry changes along the Big Chino outlet flowpath are largely caused by dissolution of silicate minerals, leaching of trace elements, and mixing with ground water from the D-C zone of the carbonate aquifer. Inverse modeling constrains the potential contribution from the M-D sequence of the regional carbonate aquifer north of the upper Verde River to less than 6 percent of base flow at the Paulden gauge.

Numerous stratigraphic and structural features influence ground-water flowpaths and the location of springs supplying base flow to the upper Verde River. Prominent features that provide preferential flow in the regional carbonate aquifer include karst openings, faults and fractures (including the horsetail splays at the terminus of the Big Chino Fault), joint sets parallel to monoclines (such as the Limestone Canyon Monocline), and a basalt-fill paleochannel that straddles the basin-fill aquifer boundary near Paulden. Basalt flows have high-overall permeability and sometimes provide important flowpaths, owing to extensive columnar fractures and rubble zones. Igneous and metamorphic basement rocks usually have very low permeability and define the bottom and edges of the basin-fill aquifers.

Ground-water movement within the basin-fill aquifers is from the valley margins and tributaries toward the valley center and then down the longitudinal axis of the valley toward the basin outlet. Elongate basin-fill deposits tend to narrow and thin toward their topographic outlets, resulting in low-altitude springs that correspond spatially with the distal end of the aquifer. Major buried obstacles to ground-water movement include resistive lati-andesite plugs and shallow basement rocks in northern Little Chino Valley and a playa deposit in central Big Chino Valley. In lower Big Chino Valley, a basalt-filled paleochannel straddles the basin boundary between the basin-fill aquifer and the carbonate aquifer, offering an intermediate conduit between alluvium and carbonate aquifer units. Synthesis of independent data from a variety of geological, geophysical, hydrological, and geochemical sources provides a more detailed conceptual understanding of the geologic framework, the aquifer units, and major ground-water flowpaths in the Verde River headwaters.

References Cited

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

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

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

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

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

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

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

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

MacCormack, H.F., Fisk, G.G., Duet, N.R., Evans, D.W., and Castillo, N.K., 2002, Water Resources Data, Arizona, Water Year 2001: U.S. Geological Survey Water-Data Report AZ-01–1, p. 257.

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

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

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

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

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

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

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

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