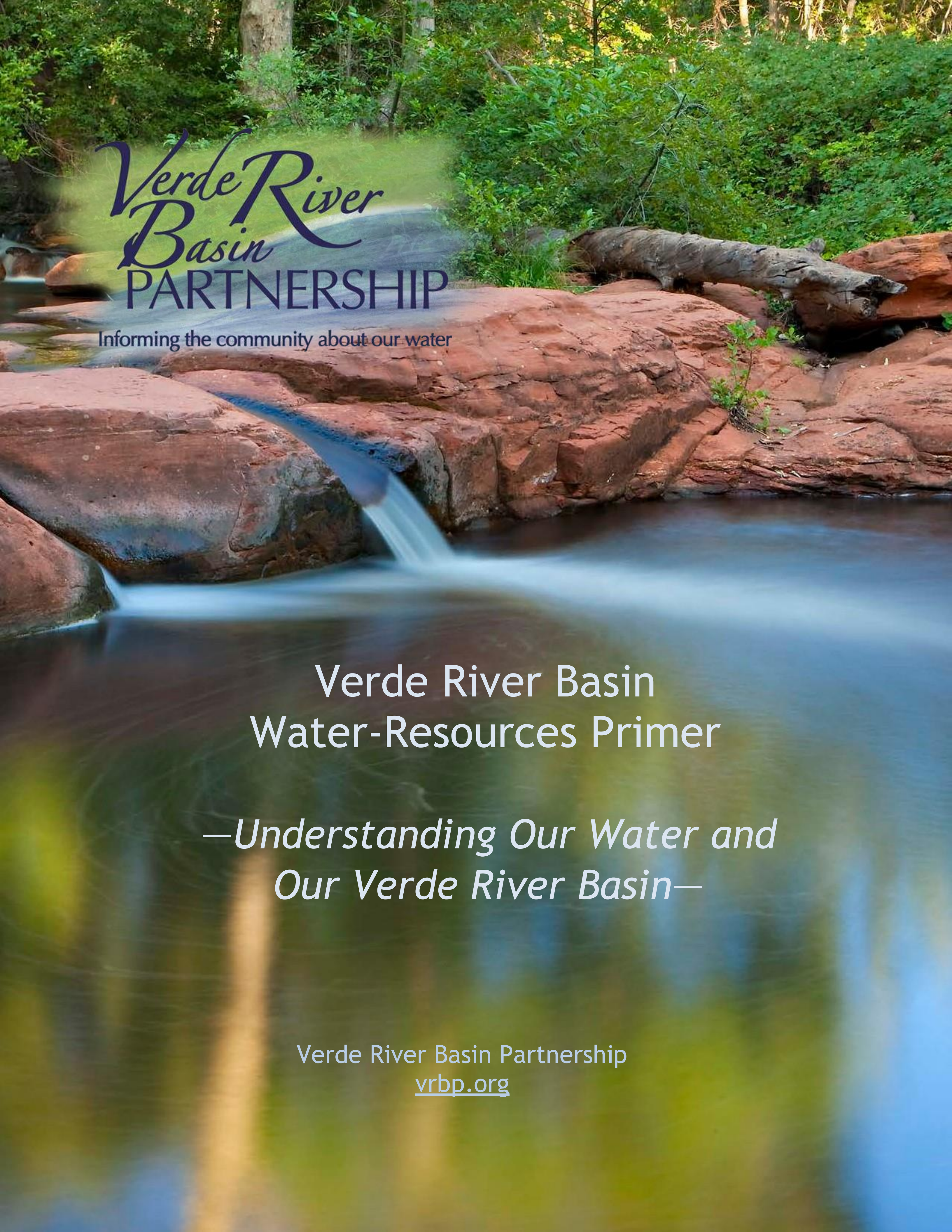

Verde River Basin PARTNERSHIP
Informing the community about our water

Verde River Basin Water-Resources Primer

—*Understanding Our Water and Our Verde River Basin*—

Verde River Basin Partnership
vrbp.org

Cover photograph: Water flowing over red sandstone in Wet Beaver Creek, Coconino National Forest.

Courtesy of:
Derek von Briesen.

Verde River Basin Water-Resources Primer
Understanding Our Water and Our Verde River Basin

2015 (revised 2018)

Verde River Basin Partnership
www.vrbp.org

Intent and Acknowledgements

The idea for this Water-Resources Primer stemmed initially from a series of PowerPoint presentations given by retired U.S. Geological Survey geologist Ed Wolfe to Watershed Steward classes at The University of Arizona Cooperative Extension of Yavapai County. The Primer's intended purpose is to provide well-explained, documented source material for interested citizens, public decision makers, teachers, and presenters of water-resource information that is germane, in particular, to the Verde River Basin.

Chapters 1 through 7 and Chapter 9 were written by Ed Wolfe. Jeanmarie Haney, biohydrologist with The Nature Conservancy, wrote Chapter 8. Chapters were reviewed variously by members of the Verde River Basin Partnership Educational Outreach Committee, the Partnership's Board of Directors, and hydrogeologist colleagues elsewhere in Arizona.

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Water-Resources Primer

Chapter 1: Introduction

Chapter 1: Introduction

A river flowing year-round in an arid environment is a marvel. The Verde River is such a river—one of the few remaining in Arizona! It flows nearly uninterrupted all year long from its source near Paulden (Figure 1.1) for about 137 river miles before reaching Horseshoe Reservoir. En route, it first flows 37 miles through rugged canyon country (Figure 1.2), then 46 miles through the broad Verde Valley with its river towns of Clarkdale, Cottonwood, and Camp Verde, and then through a second, 54-mile-long rugged canyon reach. Horseshoe and Bartlett dams impede the river's flow as it makes its way an additional 53 miles to join the Salt River 190 river miles from its source.

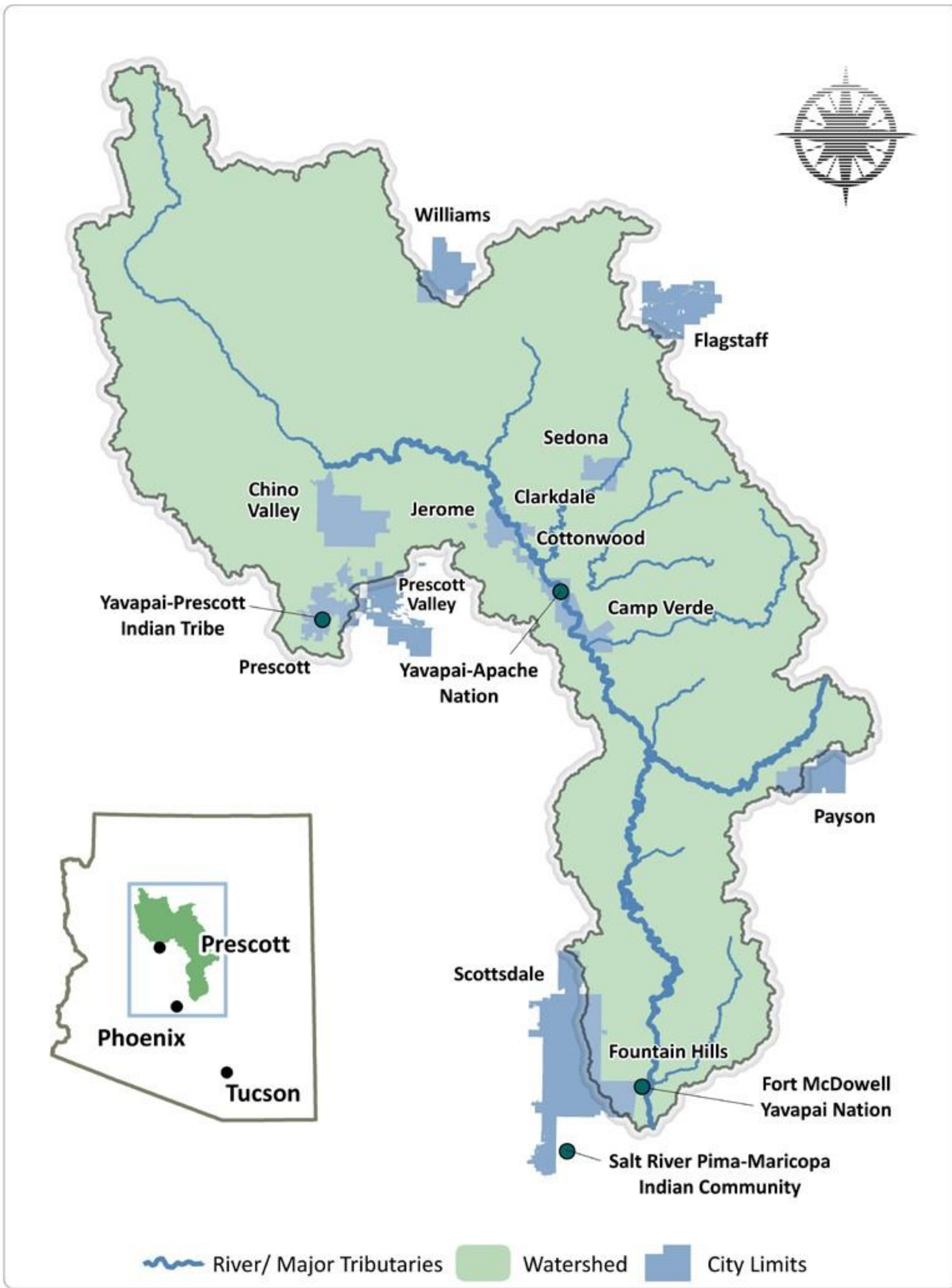

Figure. 1.1. Map of the Verde River Basin.

Figure 1.2. The Verde River and its lush riparian zone in the upper canyon reach (courtesy of Gary Beverly).
Figure 1.3. The Verde Valley's cottonwood-willow riparian forest (courtesy of Keith Anderson).

The Richness of the Verde River

The Verde River is an irreplaceable treasure. It supports a rich riparian habitat marked by cottonwoods, willows, and other species of trees whose roots must be well watered (Figure 1.3). The river and its green riparian corridor sustain a tremendous diversity of wildlife: 270 species of birds, 94 species of mammals, and 76 species of amphibians and reptiles, and a variety of rare animals including river otter, bald eagle, and native fish.

The river has been a vital resource for native peoples for millennia. In addition, the Verde River and its connected groundwater sub-basins are critical to the communities and present-day citizens of its entire drainage basin (Figure 1.1), providing fresh water, recreational opportunities (Figure 1.4), a local identity, and an agricultural lifestyle. Groundwater from within the Verde River basin not only keeps the river flowing year-round, but also provides virtually all of the domestic water for communities and rural households from the Prescott area through the Verde Valley. The surface water of the Verde River and its perennial tributaries provide most of the agricultural irrigation in the Verde Valley. Further, nearly 40 percent of the surface water delivered by the Salt River Project to consumers in the Phoenix area comes from the Verde River. A recent study by The Nature Conservancy (azconservation.org/dl/TNCAZ_Policy_Options_for_Water_Management_Verde_Valley_AZ.pdf) estimates that river-connected recreation and tourism in the Verde Valley account for an estimated $87.5 million and 737 jobs. The river is clearly the lifeblood of both agriculture and rural/suburban lifestyles along the Verde and its perennial tributaries in and around the Verde Valley.

Figure 1.4. Paddling on the Verde River (courtesy of Doug Von Gausig).

Sources of Verde River Streamflow

The water that flows in the Verde River is supplied primarily from two sources: (1) surface runoff from rain and snowmelt; and (2) release of groundwater from springs to the river and its perennial tributaries. Groundwater supplies about half of the Verde River's annual streamflow and is vital because it alone maintains year-round flow of the river. Without it the river, like so many formerly perennial river reaches in Arizona (Figure 1.5) would be dry much of the year, flowing only following periods of rain or snowmelt.

Figure 1.5. A formerly perennial reach of the Santa Cruz River north of Nogales, Arizona (courtesy of Dan Campbell, The Nature Conservancy).

Is Year-Round Flow of the Verde River at Risk?

Hydrologists have understood for more than 70 years that groundwater and surface water, such as streamflow, are intimately interconnected. Prior to human intervention—especially the extraction of water from wells—the quantity of water seeping below the ground surface and the root zone was in long-term balance with the quantity of groundwater exiting to springs and streams. Water wells provide unnatural, human-made diversions of the flowing groundwater that disrupt the long-term natural balance. A well either intercepts groundwater that was en route to springs and streams or accelerates the transfer of streamflow to the groundwater. Because the movement of groundwater through the subsurface to or from springs and streams is slow, the effect on streamflow of pumping from wells doesn't show up immediately. The inevitable consequence, however, is that eventually the component of groundwater that contributes to streamflow is reduced by an amount approximately equal to the consumption of water pumped from wells.

Hydrologic studies by the U.S. Geological Survey show that the groundwater that supports year-round flow of the Verde River comes from all parts of the Verde River basin. The groundwater is supplied by the very small percentage of rainfall and runoff that is able to seep below the ground surface and the root zones of plants. From there it moves downward to the water table and then begins its subsurface flow towards springs and the river.

Substantial groundwater pumping, primarily for irrigation, began in the late 1930s in the Verde River basin. Now, groundwater pumped from thousands of wells in the basin provides essentially all of the water for human uses—drinking, cooking, washing, toilet-flushing, landscaping, industrial and municipal uses, and, in part, agricultural irrigation. A significant exception is that nearly all agricultural irrigation in the Verde Valley is supplied by water diverted directly from the Verde River and its perennial tributaries.

The evidence of the impact of groundwater pumping on rivers in Arizona is stunning (Figure 1.5). Numerous rivers or parts of Arizona rivers—for example, substantial sections of the Salt, the Gila, the Little Colorado, the Santa Cruz, and the San Pedro—that once flowed year-round have become dry washes that now flow only following storms or snowmelt. Within our own

Verde River basin, the impact of groundwater pumping has apparently reduced the perennially free-flowing length of the Verde River by about 5.7 miles—from its predevelopment source at Del Rio Springs in the Town of Chino Valley to the river's current source springs about 0.1 mile below the mouth of Granite Creek. The current rate of groundwater discharge from Del Rio Springs has steadily decreased to about a tenth of its rate in the early 1940s, and the Arizona Department of Water Resources estimates that the discharge of groundwater from Del Rio Springs will cease by about 2025.

The inescapable implication is that if we continue to support an ever-expanding population as we have done so far—by simply consuming more groundwater—the Verde, or at least substantial parts of it will become another Arizona dry wash flowing only briefly in response to storms or snowmelt.

Can We Sustain Our Treasured Verde River?

Yes! But only if we understand and act on the issues. The purpose of this primer is to provide a readily available source of Verde-basin water-resource information to assist citizens, including their elected officials and public resource managers, in understanding these important water issues.

Verde River Basin PARTNERSHIP

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Chapter 2: The Global Water Cycle

Chapter 2: The Global Water Cycle

Earth's water is always in motion, and it is always changing states—from liquid to vapor to ice and back again. The water cycle (Figure 2.1) has been working for billions of years and the lives of countless living things depend upon it.

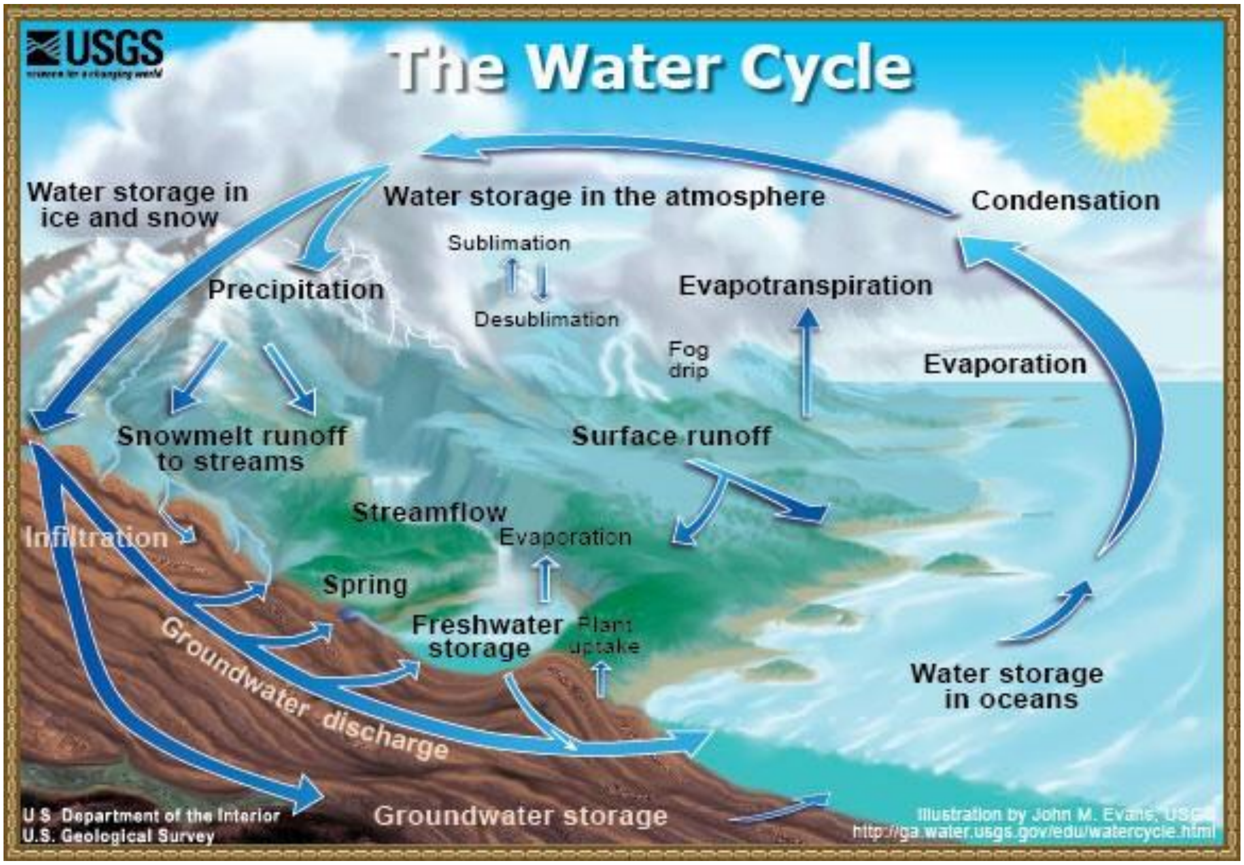


Figure 2.1. The Global Water Cycle. www.water.usgs.gov/edu/watercyclesummary.html

Motion of the Earth's water is a constant process—through the atmosphere, the oceans, streams, lakes, glaciers, and in the groundwater. The motion is driven by the heat of the sun and gravity.

The Earth's water supply is essentially a closed system; little water is either added to the system or removed from it. Thus, the same water has cycled for billions of years around the globe, being used over and over again to support life. A component of the Earth's water is even recycled from the oceans into the Earth's mantle miles below the Earth's surface and redelivered to the surface by volcanic eruptions.

Evaporation, which is driven by the heat of the sun, converts water at the surface of the oceans, streams, and lakes to the invisible gas that we call water vapor. Ice and snow can be converted directly to water vapor by the process of sublimation. Evapotranspiration, commonly denoted as ET, refers to the combination of water evaporated from the soil plus water transpired by plants.

Sublimation: A change directly from the solid to the gaseous state without becoming liquid; for example, a change directly from ice to water vapor without production of liquid water.

Evapotranspiration (ET): Evaporation of water from the soil plus transpiration—the release of water vapor from plants to the atmosphere.

Much of the precipitation, of course, falls directly back into the oceans. In some areas—though not in the Verde River watershed—precipitation falling as snow accumulates as ice caps and glaciers, which can store water for thousands of years. In Arizona, snow accumulates at higher elevations during the winter. Some of it sublimates, sending water vapor directly to the atmosphere, some infiltrates into the ground during temporary winter thaw periods, and the rest thaws in the spring. The snowmelt flows overland, downhill under the influence of gravity, as part of the annual runoff.

Runoff: Water from rain or snowmelt that flows over the land surface and is neither evaporated nor absorbed into the ground, instead flowing into streams, lakes, or the ocean.

During warmer weather in Arizona—largely during the summer monsoon months—the precipitation occurs mostly as rain. Like snowmelt, the rain-produced runoff also flows overland. In Arizona's dry, warm climate, part of the runoff evaporates, forming water vapor, which rises directly into the atmosphere.

Runoff, whether from snowmelt or rain finds its way into gullies, streams, and rivers. In the Verde watershed, the runoff may get trapped in reservoirs such as Watson and Willow Lakes in Prescott or Horseshoe and Bartlett Reservoirs on the lower Verde River north of Phoenix. During wet years, runoff that reaches the Verde River may exceed the capacity of the reservoirs and be permitted to flow downstream to the Salt River to then join the Gila River. The Gila River joins the Colorado River near Yuma, and, in exceptionally wet years, runoff in these rivers may flow all the way to the ocean entering the Gulf of California.

Infiltration: The downward movement of water from the land surface into soil or porous rock.

Some of the runoff soaks into the ground as infiltration. Gravity carries it downward, and whatever part of the infiltrating water gets past the root zone of plants moves on downward, in response to gravity, to become part of the groundwater. Large amounts of groundwater may have infiltrated during much wetter climatic regimes.

Groundwater: Water below the ground surface that completely fills (saturates) all of the void spaces in porous sedimentary deposits or rock, and is capable of supplying springs and wells.

Groundwater is stored in voids between grains of gravel, sand, silt, and clay in unconsolidated sedimentary deposits and in pore spaces or fractures in consolidated rock. Groundwater flows continuously, although usually slowly, under the influence of gravity from the areas of infiltration to the areas where the groundwater exits to wetlands, springs, streams, lakes, or the ocean. Thus, the groundwater is one component of the Earth's never-ending water cycle.

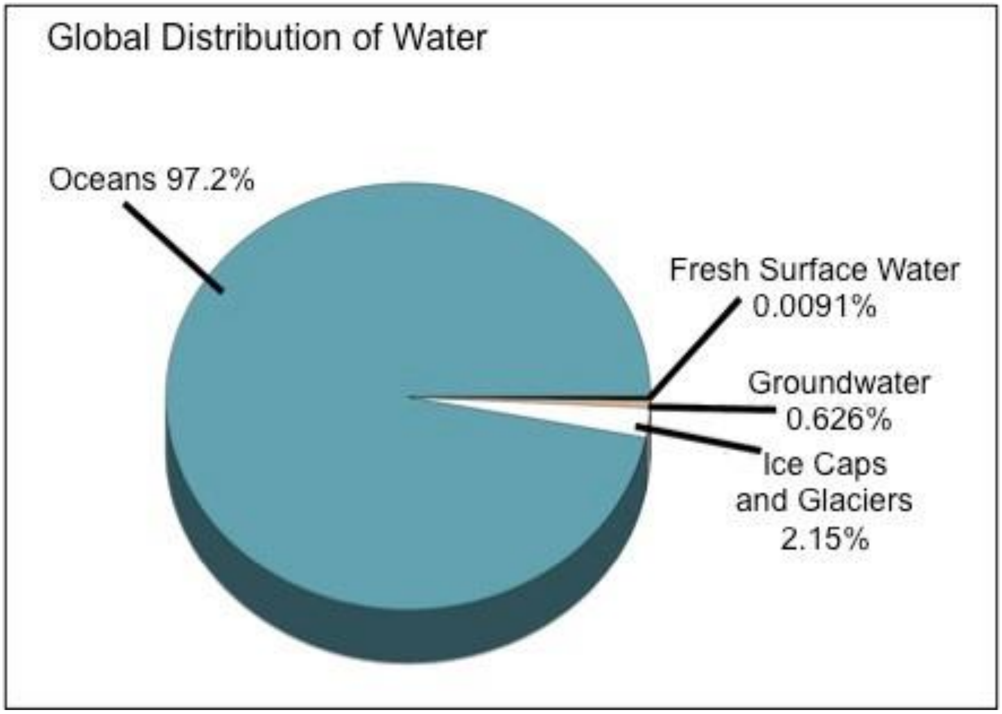


Figure 2.2. Distribution of the Earth's Water. Modified from McReynolds and others (2006).

Various estimates of the distribution of the Earth's water differ only slightly. The estimate illustrated in the pie chart above (Figure 2.2) shows the oceans containing about 97.2 percent of the Earth's water—about 329 million cubic miles of water—and covering about 70 percent of the Earth's surface. About 2.15 percent—or approximately 7 million cubic miles—of the Earth's water is currently stored in ice caps or glaciers. Water in the atmosphere, wetlands, soil moisture, and in living organisms (not shown in Figure 2.2) comprises about .015 percent or about 50,000 cubic miles of the Earth's water.

Our supply of fresh surface water, denoted as "Fresh Surface Water" in Figure 2.2, occurs as rain catchment and in groundwater, rivers, streams, and lakes. Groundwater represents approximately .626 percent—about 2 million cubic miles—and streams, rivers, and lakes approximately .0091 percent—about 31,000 cubic miles—of the Earth's water. This supply, while less than one percent of Earth's total water supply, is vital to the sustenance of virtually all land-based life on Earth.

Chapter 3: Groundwater

Chapter 3: Groundwater

Nearly all of the water used for municipal, domestic, and industrial consumption in the upper and middle Verde River watersheds, plus a substantial part of the water used for agricultural irrigation, comes from local groundwater. Groundwater enters the aquifer system as recharge, moves through it continuously under the influence of gravity, and exits the aquifer system as discharge to the Verde River and its tributaries as well as to plants whose roots tap into groundwater.

Groundwater Recharge

The natural source of groundwater is precipitation in the form of both rain and snow. When precipitation hits the ground, it generally either infiltrates into soils or evaporates. If the intensity of rainfall exceeds these two processes, the surplus water begins to flow overland into streams and rivers as runoff.

Water that does infiltrate into the ground can be used by plants and is also subject to evaporation by the sun to depths of about 3 feet. If the infiltration rate exceeds these two processes, the remaining water continues downward under the pull of gravity and becomes groundwater recharge.

Runoff from rain and snowmelt can occur anywhere within the Verde River watershed but is generally greatest in areas of high elevation—such as Mogollon Rim, Juniper Mountains, Santa Maria Mountains, Bradshaw Mountains, and Black Hills (Figure 3.1). This runoff continues via gullies and washes to areas of low elevation where it either infiltrates or, in some cases, flows all the way to the Verde River.

Runoff that infiltrates below the root zone and past the zone where evaporation occurs becomes groundwater recharge. Infiltration is particularly high once streams enter onto valley floors, with the rate of infiltration often capable of consuming all of an intermittent stream's water before it reaches a river. Infiltration of runoff—a form of natural recharge—is a major source of groundwater recharge in the Verde watershed.

Groundwater recharge: Infiltration of water from the ground surface to the groundwater.

Natural recharge: Natural replenishment of an aquifer generally from snowmelt and runoff, through seepage from the surface.

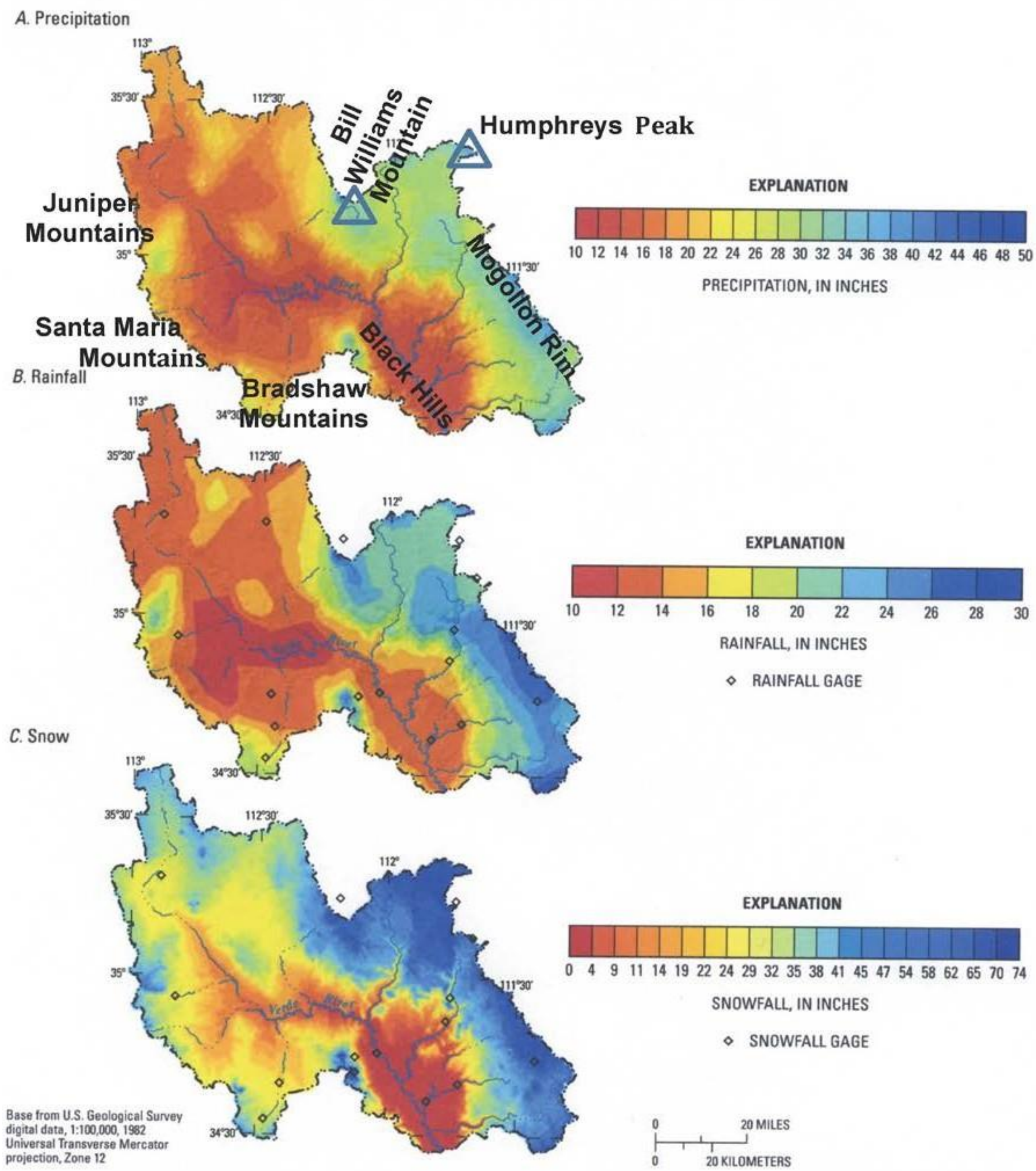


Figure 3.1. Maps showing distribution of average values for (A) total precipitation (rain: 1971 to 2000; snowfall: 1981 to 2003), (B) rain (1971 to 2000), and (C) snow (1981 to 2003) in the upper and middle Verde River watersheds. Modified from Blasch and others (2006).

Human-induced recharge occurs from a variety of processes. Engineered return of treated wastewater to the groundwater is a form of artificial recharge practiced explicitly to offset depletion of the groundwater supply. Several municipalities in the Verde River Basin return part of their treated wastewater to spreading basins from which the introduced treated effluent percolates downward to the groundwater. Injection wells represent another engineered method of deliberately returning treated wastewater to the groundwater supply.

Another form of human-induced recharge, known as incidental recharge, is the non-engineered infiltration of irrigation water or water from septic-system leach fields to the groundwater or the infiltration of treated wastewater discharged directly into dry stream channels. So far, the greatest volume of incidental recharge within the upper and middle Verde River watersheds results from the irrigation of crops.

Artificial recharge: Engineered return of treated wastewater to the groundwater via injection wells or prepared spreading basins.

Incidental recharge: Non-engineered return of water from the surface to the groundwater from human activities that include irrigation, septic-tank use, and discharge of treated wastewater into dry stream channels.

Figure 3.2. Water table and groundwater in a hole at a sandy beach. (ga.water.usgs.gov/edu/earthgwaquifer.html)

Water table: The upper surface of the saturated zone, in which all pore spaces in rock or sediment are completely filled with water.

Aquifer: A formation, group of formations, or part of a formation that contains sufficient saturated, permeable rock, sand, and/or gravel to yield significant quantities of water to wells and springs. (water.usgs.gov/ogw/aquiferbasics/)

Aquifers and the Water Table

If you have ever dug a hole in a sandy lakeshore and struck water in the hole, as shown in Figure 3.2, you have, in effect, created a well that penetrated the water table, the uppermost part of an aquifer. The water that fills the bottom of your hole is groundwater. The surface of the groundwater in your hole defines the water table. If you were to take some of that standing water out with a bucket, more water would flow into your well to replace what you removed.

Indeed, long before the advent of well drilling, water wells were dug by hand, often to depths of many tens of feet, and groundwater was hauled to the surface in buckets at the end of a rope.

Figure 3.3 is a schematic cross section from the ground surface downward, past the water table and into an aquifer. It gives a broader view to support discussion of recharge, aquifers, and the water table.

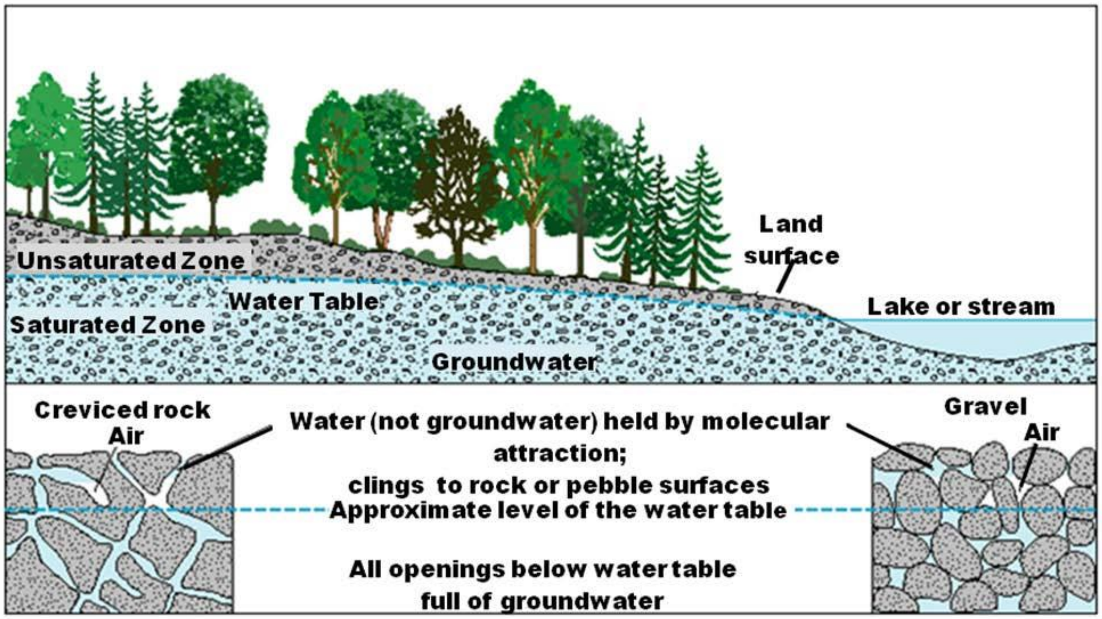


Figure 3.3. Schematic cross section illustrating the water table and the saturated and unsaturated zones. (Modified from http://ga.water.usgs.gov/edu/earthgwaquifer.html)

Runoff or rainfall that seeps into the ground continues to move downward under the influence of gravity until it reaches the water table as groundwater recharge. En route to the water table, the recharge descends through the unsaturated zone (Figure 3.3), a layer of soil, sediment, or rock in which the pore spaces contain air or air and water. In some places, such as where the water table is at the ground surface, the unsaturated zone is absent as is common where there are wetlands, lakes, and some sections of streams. In arid regions, the unsaturated zone may be hundreds of feet thick.

Unsaturated zone: The portion of the subsurface above the water table. Its pores contain air or air and water.

Saturated zone: Porous rock or sediment, beneath the water table, in which all open spaces are completely filled with water.

The descending recharge water eventually reaches the water table, which marks the upper surface of the saturated zone (Figure 3.3), where the pore spaces in rock or sediment are completely filled with water. Water wells are able to pump groundwater only from the saturated zone.

The kind of aquifer described above is an unconfined aquifer (sometimes referred to as a water-table aquifer). Its upper surface—the water table—is directly connected to the atmosphere via the interconnected air-filled pores in the unsaturated zone. Thus, the upper surface of the aquifer is at atmospheric pressure, so it can rise in direct response to rainfall or infiltrating runoff or fall in direct response to drought or pumping of a well. In a complex vertically-stacked system of aquifers (typical of the upper and middle Verde groundwater basins), the uppermost aquifer is normally an unconfined aquifer (Figure 3.4).

Unconfined aquifer: An aquifer whose upper water surface (water table) is at atmospheric pressure, and thus is able to rise and fall.

Confined aquifer: An aquifer that lies between less permeable layers (confining layers) of rock or sedimentary deposits in which groundwater flows less easily.

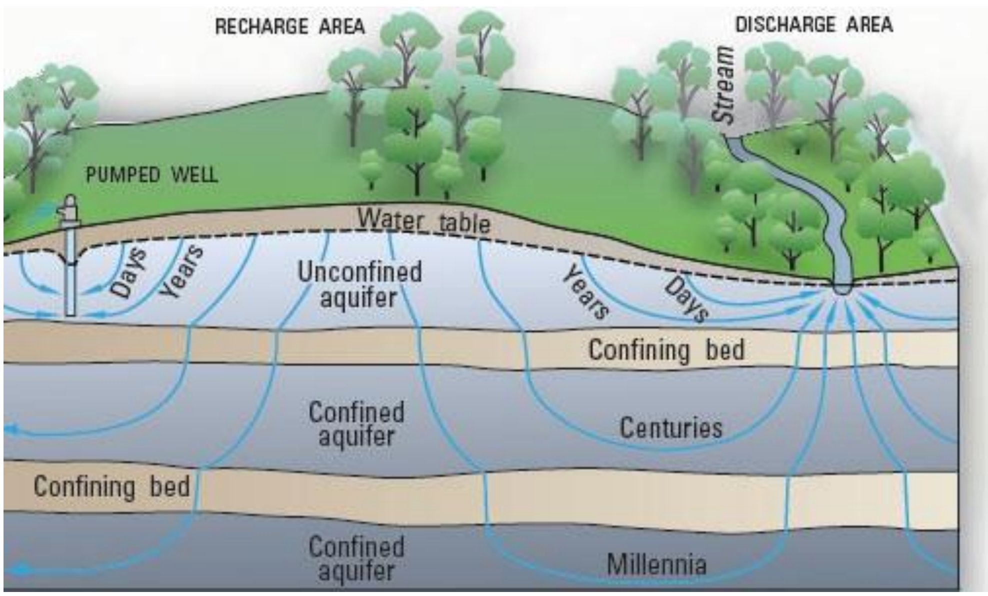


Figure 3.4. Schematic cross section showing groundwater flow paths through unconfined and confined aquifers and confining beds (Winter and others, 1998).

Understanding groundwater systems would be much simpler if they all consisted of a single unconfined aquifer. However, nature is usually more complex than that. Groundwater systems, including those in the Verde River watershed, commonly contain a number of different aquifer units through which groundwater flows at differing rates. Deposits within a groundwater system that transmit groundwater less readily than the aquifers above or below them are called confining units, confining beds, or confining layers, and they bound confined aquifers (Figure 3.4). Although water moves through them, the confining units impede vertical and horizontal movement of groundwater within the groundwater system.

Groundwater Movement

Groundwater is never static. Driven by gravity, the groundwater always flows, moving along curving paths that range from vertical to horizontal. The movement is from areas of groundwater recharge to areas of groundwater discharge.

Groundwater discharge: The movement or exit of groundwater to springs, streams, lakes, and the oceans; to plants and the atmosphere by evapotranspiration from wetlands and riparian zones, and by the human-caused consumption of water from wells.

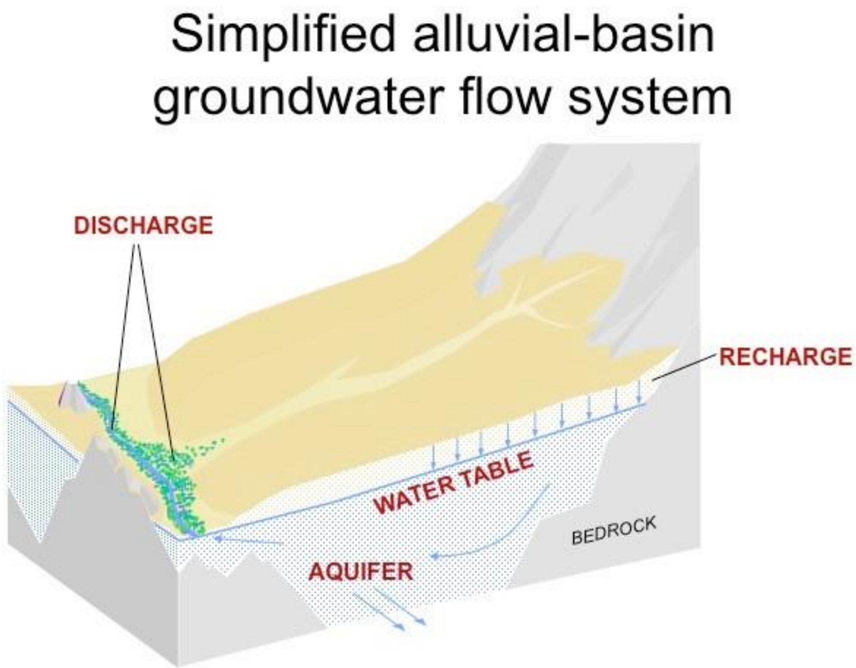


Figure 3.5. Block diagram illustrating a simplified southwestern groundwater system in an alluvial basin (courtesy of Stanley A. Leake, USGS, modified).

Alluvial basin: A deep down-warped or down-faulted basin filled with stream deposits (gravel, sand, silt, clay); may also include marsh, lake, or volcanic deposits.

The block diagram above (Figure 3.5) is a representation of a simplified southwestern groundwater flow system in an alluvial basin. The Verde River within the Verde Valley, Big Chino and Williamson Valley Washes, and Granite Creek and Little Chino Wash in the Prescott-Chino Valley area all exist on the surfaces of geologically and hydrologically complex alluvial basins.

The simplified basin portrayed in Figure 3.5 contains a single aquifer that is unconfined and bounded below and at its edges by bedrock that transmits little if any groundwater. Recharge is supplied from two sources. The first is infiltration of runoff in stream channels crossing the surface of the alluvial-basin deposits. The second is infiltration on the broad alluvial-basin surface of any water supplied directly by rain or snowmelt that escapes evapotranspiration and runoff.

Within the area of the diagram, groundwater discharge is to the stream, which flows toward the viewer, and to evapotranspiration by riparian vegetation that is rooted at or below the water table. The stream flows between runoff events because its bed, at least in places, intersects the water table. The groundwater flow, also toward the viewer, is from higher elevation near the mountain front to lower elevation at the flowing stream. If we could see the water table within the block diagram, we would see it slopes both from right to left—from the mountain front to the stream and toward the viewer—just as the stream flows toward the viewer.

In general, groundwater flows downhill or in the direction of decreasing hydraulic head. Hydraulic head is simply the altitude of the water level above some common reference level—usually sea level—at any given point in the aquifer or groundwater system.

Hydraulic head: The altitude of the water level at a given point in a groundwater system. The elevation of the water table in an unconfined aquifer represents the hydraulic head at that point in the unconfined aquifer.

Let's illustrate with something very familiar—your bathtub. With the drain in the bottom of the tub closed, you fill the tub with one foot of water (Figure 3.6). If the bottom of the tub is the elevation frame of reference, then the elevation of the water surface with respect to the frame of reference is one foot. You may not have thought about the pressure exerted on the bottom of the tub by one foot of water, but if you try to lift a bath tub with one foot of water in it you will realize that water one-foot deep exerts substantial force on the floor of the tub—actually 62.4 pounds per square foot. In case you're interested, the inside of a standard-size bathtub is 55 inches by 24 inches. Water within it one foot deep would have a volume of about 9. 7 cubic feet or 68.7 gallons and would weigh about 572 pounds. The downward pressure on the floor of the tub is 62.4 pounds per square foot or about 0.43 pounds per square inch.

Within your filled bathtub, the hydraulic head is one foot, the water in the tub is static, and there is no flow. When the drain is opened (when the cork in the diagram is removed), the water in the tub begins to exit via the drain. Prior to opening of the drain, there is no difference in hydraulic head within the tub; the hydraulic head is one foot throughout and there is no flow within the tub. Opening the drain causes a slight, almost imperceptible lowering of the water surface—a small decrease in hydraulic head—immediately above the drain. The water surface now slopes imperceptibly toward the drain, and the water flows to the area of lower head (above the drain). It continues to flow in that direction until the water is gone, and the hydraulic head is zero.

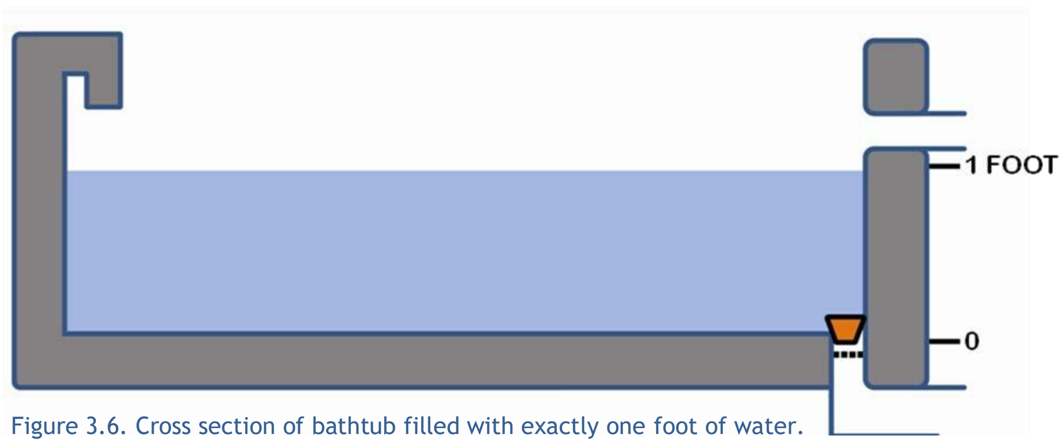


Figure 3.6. Cross section of bathtub filled with exactly one foot of water.

Let's take advantage of the tub to illustrate some other important ideas. For example, if you fill the tub to a level above the base of the overflow drain (Figure 3.7) water flows out of the overflow drain. If it flows out at exactly the rate at which it enters the tub from the spigot, the water level in the tub will remain constant at every location in the tub. Think of the water entering from the spigot as recharge and the water exiting from the overflow drain as discharge. They are exactly in balance. Increase the rate of recharge, and the water level in the tub will rise until the rate of discharge increases by the same amount. Decrease the rate of recharge and water levels will fall until the rate of discharge decreases by an amount equal to the new lower recharge.

If you dip a bucket of water out of the tub, with the tub water exiting at the same rate as it is entering from the spigot, you cause the outflow (the discharge) to decrease until the inflow from the spigot (the recharge) has supplied a volume of new water equal to the volume you dipped out with the bucket. In effect, by introducing a new component of discharge, you temporarily eliminated (captured) some of the discharge via the overflow drain. It's obvious of course but, as we'll see, similar principles apply in groundwater systems.

Figure 3.7. Cross section of water-filled bathtub illustrating steady-state recharge and discharge.

Next, let’s use the tub to illustrate the effect of hydraulic head during draining of the tub. At the moment we open the drain in the bottom of the tub—by removing the stopper—water begins to flow out of the drain under the force exerted by a hydraulic head of one foot (Figure 3.8).

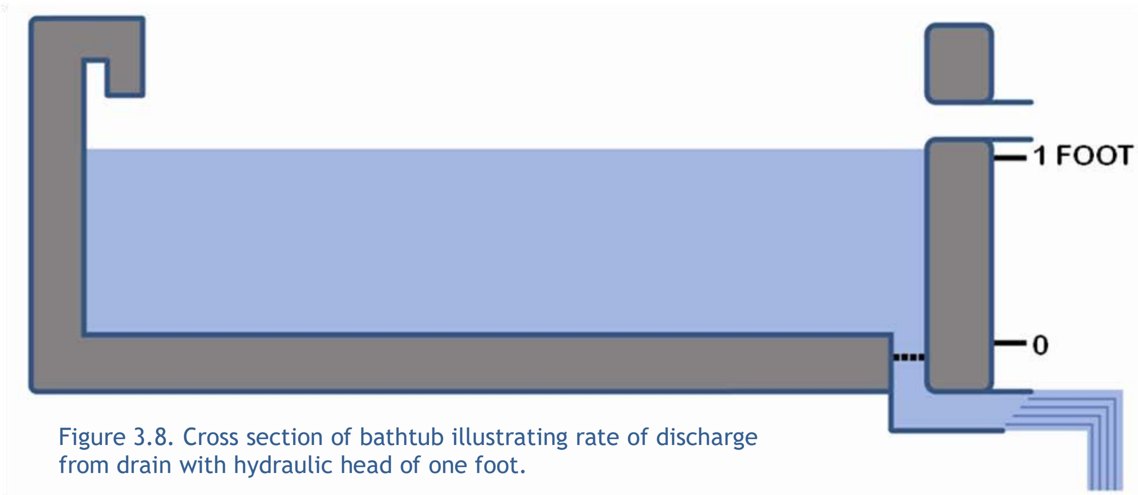


Figure 3.8. Cross section of bathtub illustrating rate of discharge from drain with hydraulic head of one foot.

As the water level falls, the hydraulic head and the downward water pressure related to it decrease (Figure 3.9). Consequently, the rate of flow of the water exiting the drain decreases, as portrayed schematically, by shortening of the water jet that extends beyond the end of the drainpipe. It reaches zero when there is no water left in the tub. Note that the water surface in the bathtub slopes imperceptibly toward the drain as the tub empties. Without the minute decrease in head from the left end of the tub toward the area of the drain, there would be no flow.

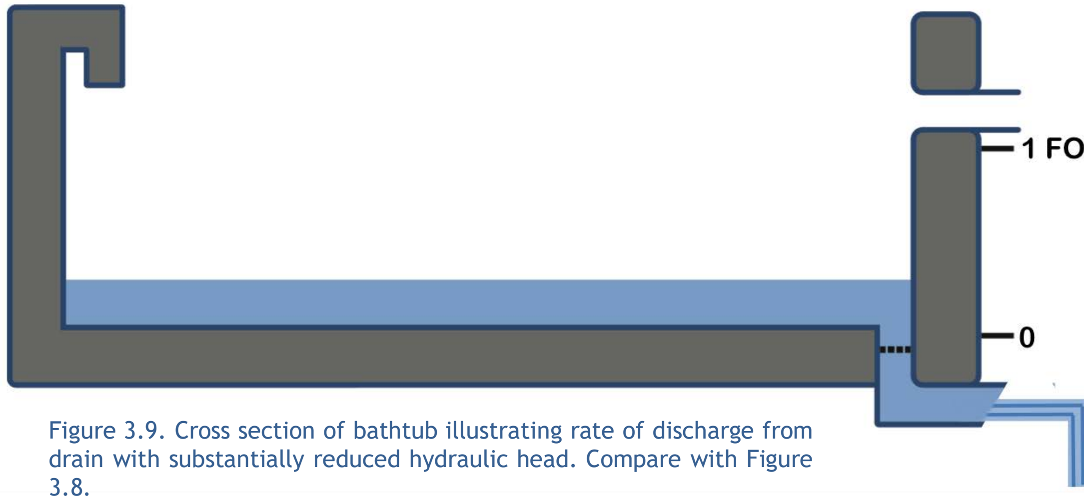


Figure 3.9. Cross section of bathtub illustrating rate of discharge from drain with substantially reduced hydraulic head. Compare with Figure 3.8.

Now let's explore a bit about aquifers by filling the tub with a one-foot thick deposit of gravel composed, for simplicity, solely of rounded pebbles (Figure 3.10). Let's add water to bring the water level within the gravel right to the top of the gravel at a height of one foot above the bottom of the tub. In clean gravel such as we show here—that is, without a component of finer-grained sediment such as sand, silt, or clay occupying the open spaces between the pebbles—the pore spaces, which contain the water, comprise about 20 percent of the volume of the gravel. Thus, the volume of water in the bathtub's mixture of gravel plus water is about 13.7 gallons, 20 percent or a fifth of what it was when the tub was filled only by water. This is simply a bathtub holding a one-foot thick mixture of gravel and water with a uniform hydraulic head of one foot.

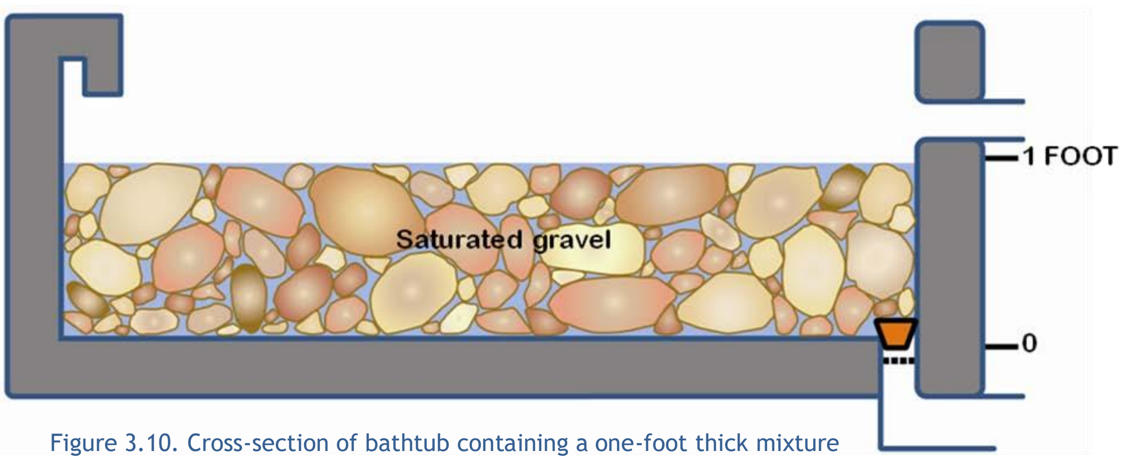


Figure 3.10. Cross-section of bathtub containing a one-foot thick mixture of gravel and water. It is not a simulated groundwater system; it is simply a bathtub holding a one-foot thick mixture of gravel and water with a uniform hydraulic head of one foot.

Next, let's open the drain to initiate a bathtub simulation of groundwater flow (Figure 3.11). Water draining from the pore spaces in the gravel begins to flow toward the drain, the only available exit. If we let the water all drain out, the gravel will be dewatered. It won't be quite dry because thin films of water will remain, adhering to some of the pebble surfaces.

However, we won't let the water all drain out. As the water discharges from the drain, we'll adjust the recharge from the spigot just enough to maintain the one-foot level of the water within the gravel immediately below the spigot and two inches of water directly above the drain. Eventually, the surface of the water that completely fills the pore spaces in the gravel declines to two inches above the bottom of the tub at the drain, which is where discharge is occurring. The hydraulic head at the right end of the tub (where the drain is located) is now two inches (Figure 3.11). With careful adjustment of the inflow (recharge) from the spigot, we maintain a hydraulic head of one foot at the left end of the tub and a hydraulic head of two inches directly above the drain. The difference between the hydraulic head in the area of recharge and the area of discharge is ten inches.

We now have a cartoon, a simple illustrative representation, of a groundwater system. The water-saturated gravel is the aquifer. The boundary between the water-saturated aquifer and the unsaturated zone represents the water table, which slopes from the area of recharge beneath the spigot to the area of discharge at the drain, the only exit for the groundwater. The system is in balance; the rate of discharge equals the rate of recharge. Most important, the water within the aquifer is flowing from the zone of recharge to the zone of discharge.

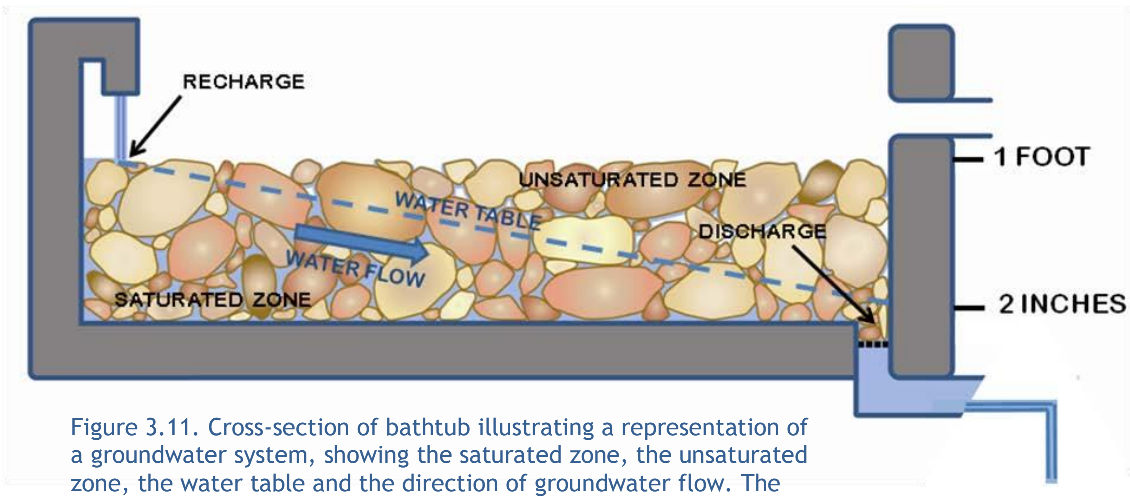


Figure 3.11. Cross-section of bathtub illustrating a representation of a groundwater system, showing the saturated zone, the unsaturated zone, the water table and the direction of groundwater flow. The system is in balance; recharge and discharge are equal.

As long as the recharge from the spigot is exactly sufficient to maintain the hydraulic head of one foot at the left end of the tub and two inches above the drain, the system maintains the same geometry. <u>Especially important is that the rate at which the "groundwater" is discharged via the drain equals the rate at which water from the spigot enters the aquifer as recharge</u>. A water table is maintained that slopes from the area of recharge to the area of discharge. Above the water table is the unsaturated zone, and below the water table is the saturated zone in which all the pores in the gravel are completely filled with water. The "groundwater" within the gravel—all beneath the water table and totaling about 8 gallons in this 55-inch by 24-inch tub—responds to the ten-inch difference in hydraulic head from the recharge area at the left end of the tub to the discharge area at the right end of the tub by flowing from the area below the spigot to the drain.

What factors control the velocity of flow of groundwater through an aquifer? There are two governing factors: (1) the <u>hydraulic conductivity</u> of the aquifer and (2) the <u>hydraulic gradient</u>. In fact, the velocity of groundwater flow in an unconfined aquifer, like the one represented in our bathtub, is proportional to both the hydraulic conductivity of the aquifer and the hydraulic gradient.

Hydraulic conductivity: The ability of aquifer material to transmit water or the rate (such as feet per day) at which water moves through an aquifer.

Hydraulic gradient: The change in head per unit distance.

Alley and others (1999) give a helpful explanation of groundwater flow: *"The movement of groundwater normally occurs as slow seepage through the pore spaces between the particles of unconsolidated earth materials or through networks of fractures and solution openings in consolidated rocks. A velocity of 1 foot per day or greater is a high rate of movement for groundwater, and groundwater velocities can be as low as 1 foot per year or 1 foot per decade. In contrast, velocities of stream flow generally are measured in feet per second. A velocity of 1 foot per second equals about 16 miles per day…The ability of earth materials to transmit groundwater (quantified as hydraulic conductivity) varies by orders of magnitude and is determined by the size, shape, interconnectedness, and volume of spaces between solids in the different types of materials. For example, the pore spaces in sand and gravel are larger than those in finer grained sediments, and the hydraulic conductivity of sand and gravel is larger than the hydraulic conductivity of the finer grained materials."*

The coarse, clean gravel portrayed in our bathtub aquifer was selected for its simple ability to illustrate the occurrence of groundwater in the pore spaces between the pebbles. Such gravel deposits, free of smaller fragments between the pebbles, are exceedingly rare in southwestern alluvial-basin aquifers. In fact, our alluvial-basin aquifers contain a complex mix of clay, silt, sand, and gravel, as well as limestone and volcanic deposits, all having far lower hydraulic conductivities than our hypothetical gravel bathtub aquifer.

In addition, the hydraulic gradient in the bathtub, ten inches in 55 inches or 0 .182, is far higher than hydraulic gradients normally expected in alluvial-basin aquifers. Suffice it to say, that all other factors being equal, the rate of groundwater flow through such a coarse, clean gravel deposit would be far greater than the rate of flow through the materials that comprise our basin-fill aquifers.

Let's shift gears now to a representation that more closely approximates a natural unconfined aquifer. In a natural predevelopment groundwater system such as once existed in the Verde watershed (prior to human alteration by the introduction of wells, dams, or stream diversions for irrigation), there were two major mechanisms for the discharge of groundwater: (1) discharge directly to surface water at springs or by seepage into streams and (2) evapotranspiration where the water table is close enough to the ground surface to support wetlands and riparian vegetation rooted in shallow groundwater.

In a predevelopment system, recharge and discharge of groundwater are in balance over the long term. In other words, on average over the long term, the rates of both recharge and discharge throughout the system are equal. However, they are not necessarily constant. For example, a drought might reduce recharge for some years, or a wet period might increase recharge for some years. In either case, the rate of discharge gradually diminishes or increases, respectively, so on average over the long term, the system is in balance.

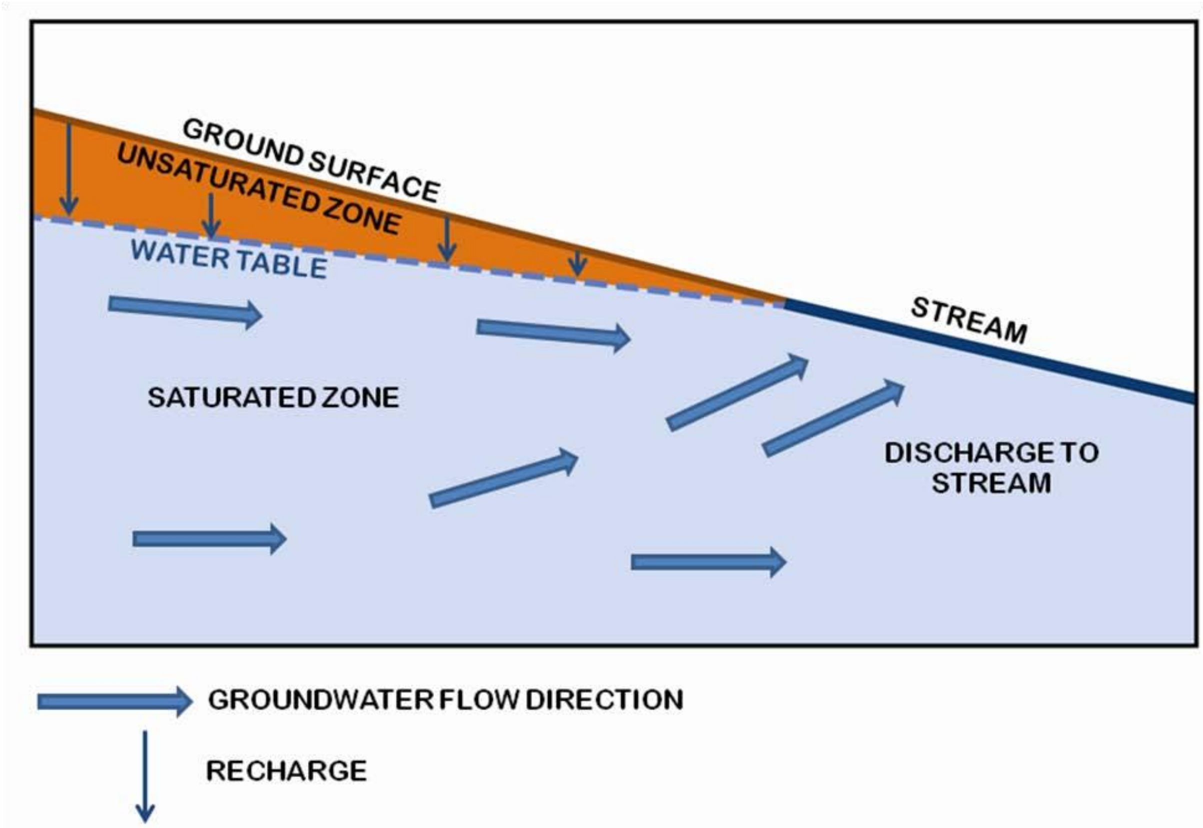


Figure 3.12. Cross section of a simple unconfined pre-development aquifer system with part of the groundwater discharging to a stream.

Figure 3.12 portrays a segment of a simple unconfined aquifer. Recharge is from infiltration through the unsaturated zone; the only discharge in the illustrated segment is to a stream. We can think of this as a cartoon of a segment of a natural predevelopment groundwater system where recharge and discharge are, on average over the long term, equal. Bathtub Figure 3.11 also mimics a predevelopment groundwater system.

Groundwater storage: Refers to the groundwater filling the pore spaces within an aquifer.

Cone of depression: A depression of the water table around a pumped well in an unconfined aquifer; a reduction of the pressure head around a pumped well in a confined aquifer.

The introduction of the extraction of groundwater from a manmade pumped well creates a new, additional component of groundwater discharge—specifically, discharge to the well. Pumping from a well in an unconfined aquifer (Figure 3.13) initially removes groundwater from storage in the immediate vicinity of the well. This dewatered area is referred to as a cone of depression surrounding the well. Lowering the water table around the well represents a reduction in hydraulic head at the well, which causes diversion of groundwater to the well from all directions. Such diversion redirects groundwater that had been supplying discharge toward maintaining the stream in the right-hand part of Figures 3.12 and 3.13. Eventually, in adjustment to the lowered hydraulic head at the well, the cone of depression, represented by a lowered water table, spreads laterally in all directions. Where it intersects the springs or seeps that sustained a groundwater-supported stream, it reduces or eliminates the discharge to the stream. In effect, the pumped well captures a part of the stream flow. This creates an opportunity, however, for a partly mitigating effect: there is an induced potential for infiltration of runoff—i.e., recharge—in the section of stream that no longer flows continuously and in which the water table is now below the stream bed and separated from it by the unsaturated zone.

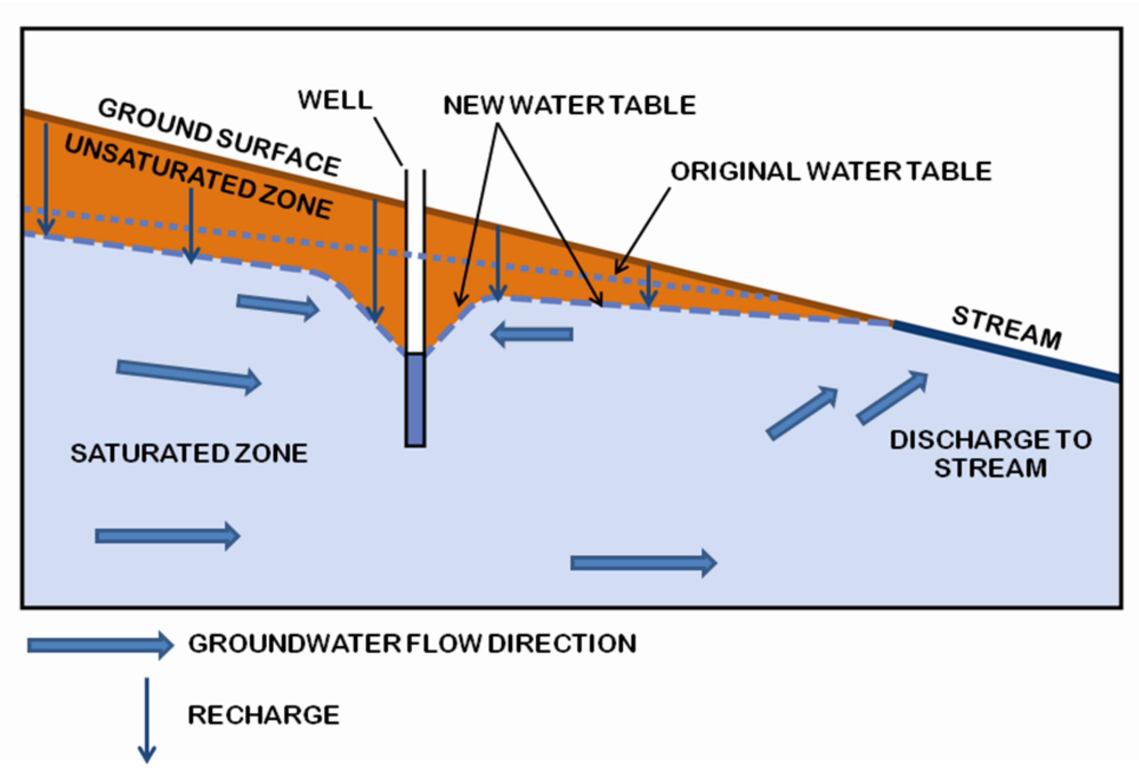


Figure 3.13. Cross section of a simple unconfined aquifer showing the effects of a pumped well on the water table and on a stream supplied by groundwater. Compare with Figure 3.12.

In a large groundwater system like that of the Verde watershed, pumping of a small number of domestic wells has such a small impact on the groundwater that supports the year-round flow of our perennial streams that the effect usually goes unnoticed. However, when pumping expands to thousands of wells—domestic wells, stock wells, municipal wells, etc.—capture of the surface water supplied by discharge of groundwater severely threatens our perennial streams.

Chapter 4: A Hydrology Tool Box

Chapter 4: A Hydrology Tool Box

Hydrology is the study of the movement, distribution, and quality of the Earth's water. As we learned in Chapter 2, the Earth's water is distributed throughout the global water cycle: the atmosphere, the oceans, streams, lakes, glaciers, and the groundwater. In this chapter, we discuss the variety of tools and techniques that hydrologists apply to explore and characterize groundwater. Water-bearing rocks underlying a given area, such as those under the Big Chino Valley or the Verde Valley, comprise a groundwater body, and the movement of water into, through, and out of the body constitutes a groundwater system. Management of our limited water resources will require the guidance that comes from a thorough understanding of our groundwater systems and their relations to our surface waters.

A major goal for hydrologists in developing a thorough understanding is to identify as clearly as possible the location and geometry of our groundwater systems, the hydrologic properties of the groundwater systems, sources and flow paths of the groundwater, and locations and rates of exchange from groundwater to springs and streams, and from streams to groundwater. This chapter addresses some of the important tools used by hydrologists to evaluate groundwater systems and how those systems interact with surface water.

Hydrology: The study of the movement, distribution, and quality of the Earth's water.

Water-Table Maps

In Chapter 3, we considered the occurrence and shape of the water table only in two-dimensional cross sections. However, the water table is a three-dimensional surface that is commonly portrayed in map form. A map of the water table is a critical hydrologic tool for evaluating and portraying the hydraulic head (i.e. elevation of the water table) at any spot over the mapped area.

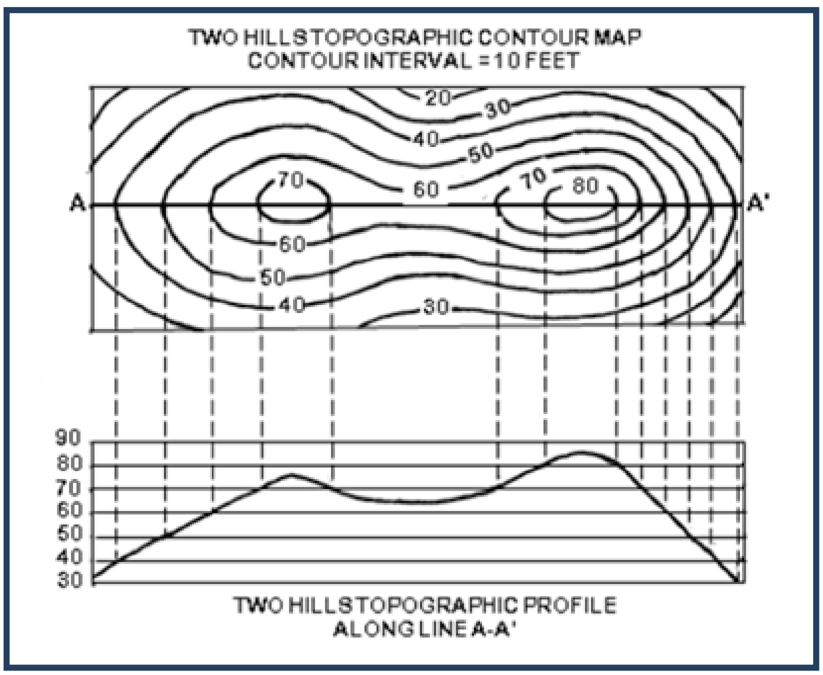
Figure 4.1A portrays a map showing the locations of wells drilled into an unconfined aquifer and gives the elevation of the water table, in feet above sea level, at each well. Just as shown in the example of the hand-dug hole at the beach (Figure 3.2), the level at which water stands in a well drilled into an unconfined aquifer is the elevation of the water table, if the well is constructed in order to be open to the groundwater at the top of unconfined aquifer. Hydrologists measure the depth to water in wells and subtract the measured depth from the elevation of the ground surface at the well site to determine the water level—hydraulic head—at each well. Recall that groundwater flows from sites of greater hydraulic head toward sites of lesser hydraulic head. Thus, as we'll see below, water-table maps give critical information about both the depth below the ground surface of groundwater and the groundwater flow direction.

Springs that occur where the water table intersects the ground surface also represent data points of elevation of the water table. It is important, though, for a hydrologist to distinguish water-table springs from springs that record drainage of a perched aquifer (Figure 4.2). Perched aquifers are generally local and are located above and isolated from the water table. They can occur where the unsaturated zone includes a layer that impedes the downward percolation of water.

Perched aquifer: An unconfined aquifer which occurs within the unsaturated zone and is thus above the regional water table.

Water-table contours are then drawn to portray the 3-dimensional shape of the water table (Figure 4.1B). The contour lines in this example represent the traces of the intersections of imaginary horizontal planes within the aquifer with the upper surface of the aquifer, the water table. These imaginary horizontal planes are spaced at 4,200, 4,300, 4,400, and 4,500 feet above sea level. The contour interval is 100 feet, and figure 4.1B portrays a water table that slopes smoothly downward from slightly more than 4,500 feet above sea level at the upper right to slightly less than 4,200 feet above sea level at the lower left.

Water-table contours: Imaginary lines of equal hydraulic head at the water table—or equal elevation of the water table—above sea level. In previous chapters we have portrayed the water table only in cross section. However, the three-dimensional shape of the water table can be portrayed throughout an area by lines (contour lines) that connect points of equal hydraulic head. The hydraulic gradient is steeper where the contours are closely spaced and less steep where the contours are more widely spaced.



Contour lines: Lines on a map that portray topography by connecting points of equal elevation. We use a topographic map (upper diagram to left) of the ground surface (lower diagram to left; ground surface portrayed as topographic profile in cross-section view) to explain contour lines. You could think of the contour lines as the intersections with the ground surface of the traces of imaginary horizontal planes within a hill. Contour lines can never cross each other. They represent a steeper slope where closely spaced and a more gentle slope where widely spaced.

Contour interval: The contour interval is the vertical separation between adjacent contours. In the diagram at left the contour interval is 10 feet. Thus the imaginary plane identified as "50" is 10 feet higher in elevation than the imaginary plane labeled "40".

Finally, flow lines showing the direction of flow at the water table (Figure 4.1C) are added. The flow paths follow the steepest trajectory, which is perpendicular to the water-table contours. Thus, the flow lines portray groundwater flow at the water table from upper right to lower left, from areas of greater hydraulic head to areas of lesser hydraulic head.

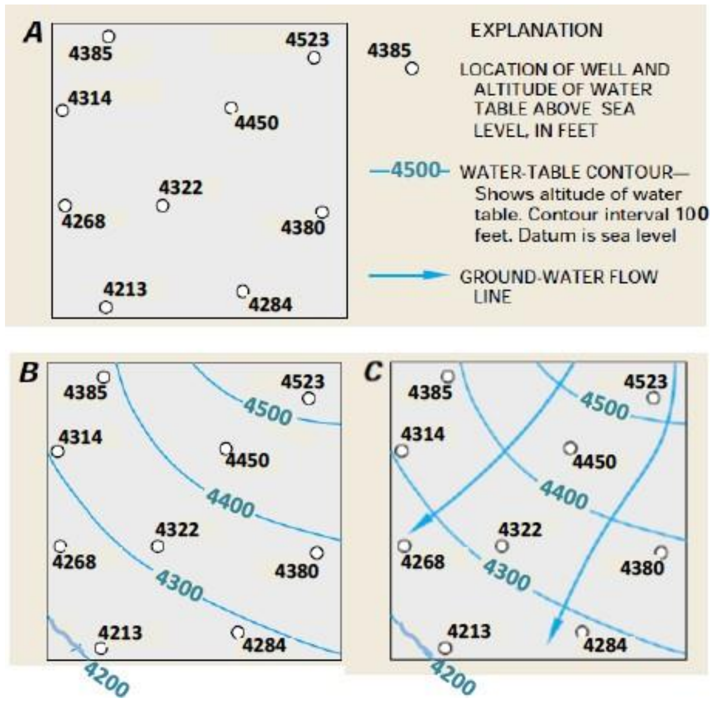


Figure 4.1. Developing a water table map: (A) Identify known elevations of the water table at individual wells (B) Draw water-table contour lines to portray the 3-dimensional shape of the water table (C) and determine directions of groundwater flow along the water table; flow is perpendicular to the contours. Contour interval is 100 feet. Modified from Winter and others (1988).

Flow paths below the water table are somewhat more complex. Recall that in Figure 3.5, which portrays a simplified groundwater system in an alluvial basin, the groundwater flow lines are directed downward in the area of higher terrain near the zone of recharge, and bend upward in the lower terrain near the zone of discharge. Although it may seem counterintuitive, this pattern is governed by the requirement that flow is always from higher head to lower head.

A water-table map such as shown in Figure 4.1B is a snapshot in time. Even in a pristine area where there has been no human intervention such as the introduction of wells, the geometry of the water table can change in response to weather or climate. For example, droughts commonly reduce the rate of natural recharge, which causes a lowering of the water table. Conversely, periods of greater than normal precipitation increase the rate of natural recharge, raising the water table. Similarly, different rates of evapotranspiration in summer and winter could lower the water table in the summer months when the rate of evapotranspiration is elevated and could raise the water table in the winter months when evapotranspiration is minimal.

Human effects, such as the introduction of groundwater pumping, which is a human-caused form of discharge, or human-caused forms of recharge such as artificial recharge of wastewater or infiltration of irrigation water (incidental recharge) also cause changes in the configuration of the water table. One such change is the development of a cone of depression around a pumped well (Figure 3.13). Identifying changes in the water table through time and seeking to understand how such changes relate to climate or human-imposed effects are important parts of the work of hydrologists.

Characterizing Confined Aquifers, Potentiometric Surfaces, and Artesian Wells

Hydraulic head in confined aquifers is manifested differently from hydraulic head in unconfined aquifers. Recall that the upper surface of an unconfined aquifer, the water table, is at atmospheric pressure. Gravity forces groundwater within the unconfined aquifer to flow from areas of greater hydraulic head to areas of lower hydraulic head. In confined aquifers, gravity also causes flow, but a confining unit, like that shown in Figure 4.2, reduces exchange with the overlying aquifer. Accordingly, groundwater in a confined aquifer is usually under additional pressure generated by the hydraulic head in the aquifer's recharge area (Figure 4.2).

A well screened only within the confined aquifer permits groundwater from that aquifer to rise to the level at which it is at equilibrium with atmospheric pressure (Figure 4.2). The hypothetical surface defined by the water level in such wells is called a potentiometric surface; it defines the hydraulic head within the confined aquifer. Such a well, in which water rises above the top of the confined aquifer, is called an artesian well. In some cases the pressure in the confined aquifer is sufficient to force the water above the ground surface and the top of the well creating a flowing artesian well (Figure 4.2).

Extraction of water, by a well in an unconfined aquifer, drains groundwater from the water-filled pore spaces below the water table. This lowers the water table around the well forming a cone of depression. In contrast, extraction of water by a well from a confined aquifer reduces pressure within the aquifer and may lower the potentiometric surface, but pore spaces remain water-filled.

Well screen: A perforated section of a well casing that permits access of groundwater to the well.

Potentiometric surface: A hypothetical surface representing the level to which groundwater would rise if not trapped beneath a confining unit.

Artesian well: A well in a confined aquifer in which water stands in the well at an elevation greater than the top of the confined aquifer.

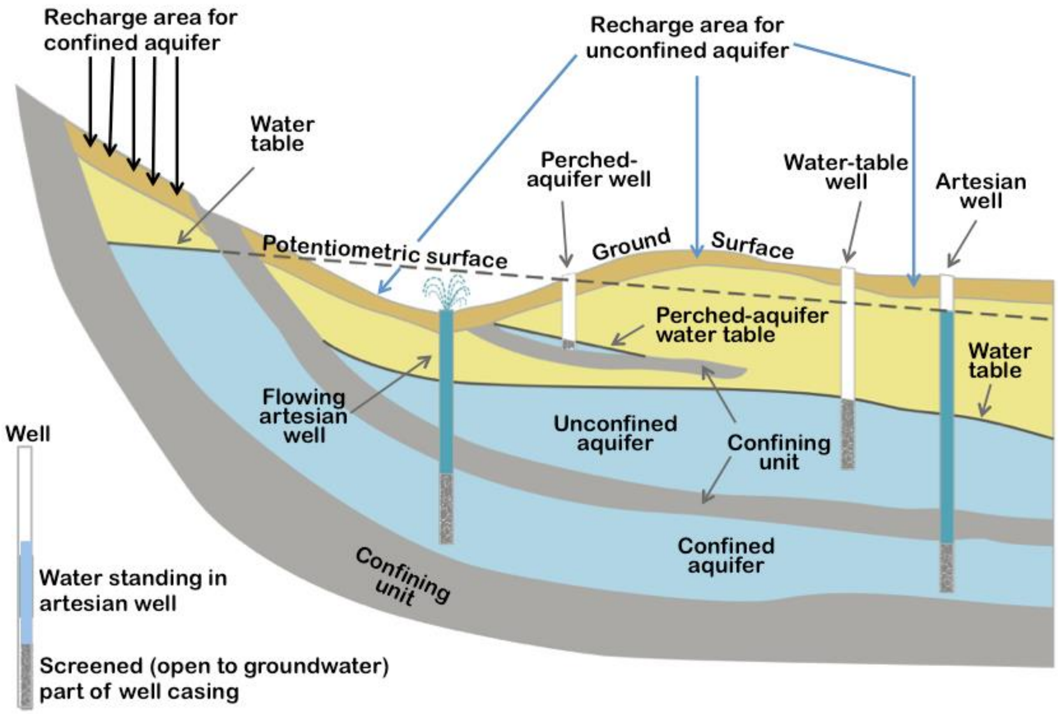


Figure 4.2. Schematic cross section showing wells and hydraulic heads in confined, unconfined, and perched aquifers in a groundwater body. Modified, with permission, from Topper and others, 2003.

An important part of the work of hydrologists is: (1) identifying aquifers within a groundwater system; (2) clarifying as fully as possible the interactions of aquifers with each other in a groundwater system; and (3) clarifying the inter-relations between a groundwater system and streamflow; and (4) evaluating how climatic or human-imposed effects on recharge, stream flow, and groundwater systems are inter-related.

Applications of Wells for Monitoring and Evaluating Groundwater Resources

Except for some occurrences, such as where springs or some reaches of rivers are coincident with the water table, groundwater and aquifers are entirely underground. Thus wells are a critical source of information for hydrologic investigations in addition to mapping water tables and potentiometric surfaces. They can provide important information about geologic properties of the rocks or sedimentary deposits that comprise aquifers, historic records of water-level change, hydrologic properties, and groundwater chemistry.

Geologic Properties of Aquifer Rocks and Sedimentary Deposits

Direct observation of the geologic character, distribution, and structure of the rocks and sedimentary deposits visible at the surface within and beyond a groundwater basin can provide critical information about the geometry and hydrologic characteristics of the basin’s aquifers. Important information about the geologic framework in which groundwater occurs is portrayed in geologic maps. Indeed, a recent geologic map by DeWitt and others (2008) is critical to our understanding of the setting for the groundwater of our upper and middle Verde River watersheds.

Supplementing direct observation on the ground, wells provide an additional major source of our information about the geologic materials that host our aquifers, particularly within the alluvial basins that provide most of our municipal and domestic water supplies. Most of the wells are drilled for water, and drilling commonly stops once a usable water supply is reached—this depth is necessarily below the water table but often not much deeper. Water wells are generally drilled by commercial well drillers, whose primary objectives are obtaining water, rather than describing the geology. Nevertheless, drillers are required to keep and report drilling logs, which commonly provide some useful geologic information.

A few exploratory wells are drilled specifically to obtain scientific information. In some cases, cores of the rock and sediment that the well penetrated are collected. In other cases, a geologist experienced in examining cuttings that are flushed out of the well as it is being drilled can make a very useful record of the geologic properties of the drilled materials. In a few cases geophysical measurements of the walls of an exploratory well provide important information about some of the properties of the penetrated rock or sediment.

Measurement of Hydraulic Heads within Aquifers

Hydraulic head varies with depth in both confined and unconfined aquifers. Measurement of hydraulic head can be made with a piezometer, which is an observation well located and screened to admit groundwater only at a predetermined depth. The level to which water rises within the observation well corresponds to the hydraulic head at the location of the screen.

Useful information about the direction of movement of groundwater within an aquifer, between adjacent aquifers, or across confining units can be obtained from nests of piezometers. In this case, several piezometers of varying depth are installed within a small area. This technique is used to gain information about the components of hydraulic gradients—upward, downward, or lateral—in the locality of the nest of piezometers. It is this kind of information that documents the occurrence of 3-dimensional groundwater flow paths like those in Figures 3.4 and 3.5.

Piezometer:
A well used to measure the hydraulic head of groundwater in aquifers.

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

Historic Records of Water-Level Change

Repeated measurements of water levels or automated recording of water levels in a well over an extended time period in a well provide important measurements that are critical in hydrologists' attempts to reconstruct former groundwater conditions and to interpret the effects of pumpage or changing climate on groundwater resources. Such a record provides a type of hydrograph (Figure 4.3) and is extremely useful to hydrologists exploring the relation over many years between water levels in wells and the effects of processes such as pumping or changing climate.

Figure 4.3 is a hydrograph that shows annually measured water levels from 1958 through 1967 and from 1976 through 2004 immediately north of the Verde River and about a mile and half south of the intersection of the Cornville road and Arizona State Route 89A. Water levels measured annually in the well varied little from 1958 through 1967, remaining between about 16 and 19 feet below the ground surface. Following a hiatus in measurements from 1969 to 1977, water levels measured annually declined during the period from 1977 to 2004 from about 24 feet to about 50 feet below the ground surface.

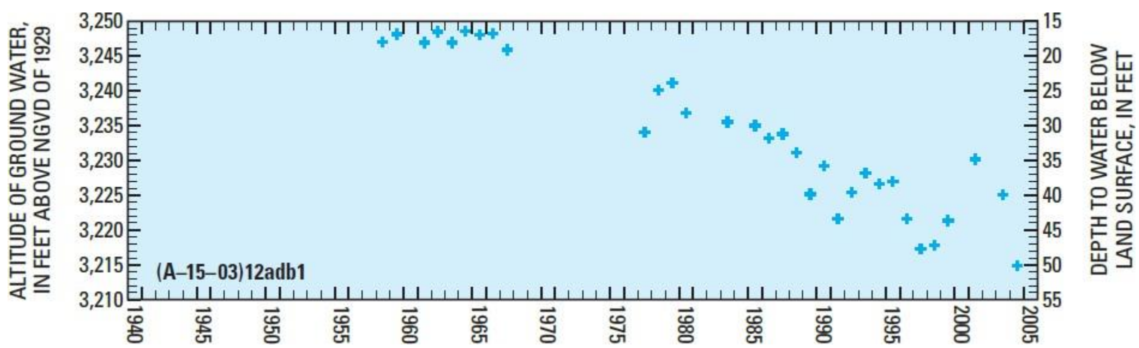


Figure 4.3. Hydrograph showing water levels measured between 1958 and 2004 in a well located on the northeast side of the Verde River about a mile and a half south of the intersection of the Cornville Road and Arizona 89A. NGVD, National Geodetic Vertical Datum. (Blasch and others, 2006).

Aquifer Tests

Information about important hydrologic properties in a local area within an aquifer can be derived from aquifer tests. Such tests are conducted by pumping water at a monitored rate from one well for at least a day, while simultaneously tracking the change in water levels in one or more nearby monitoring wells. When water is pumped from the pumping well the pressure in the aquifer that feeds that well declines. This decline in pressure will show up as decreased hydraulic head in the monitoring wells. The reduction of hydraulic head in the monitoring wells decreases with radial distance from the pumping well and increases with the length of time that the pumping continues.

Groundwater Chemistry

The chemical composition of groundwater, sampled from either wells or springs, can often provide important insight on the path that water takes as it flows through a groundwater system. As the groundwater slowly works its way through an aquifer, it may dissolve some of the minerals that comprise the rock or sediment of the aquifer. The groundwater then carries with it those dissolved components, usually in very small concentrations. The occurrence of distinctive individual dissolved components or of combinations of dissolved components may permit identification of a distinctive rock unit within a groundwater system or may enable estimation of the contribution of individual aquifer units to a groundwater system. A local example of this kind of sleuthing is given by Wirt's (2005b) estimation of the relative contributions of groundwater from the Big Chino and Little Chino sub-basins to the groundwater-fed springs at the head of the Verde River.

An interesting variation on the application of groundwater chemistry comes from study of the stable isotopes, ^{18}O and ^{2}H, of oxygen and hydrogen, respectively. The form of oxygen that is by far dominant in the atmosphere and in the Earth's waters is ^{16}O, which has 8 protons and 8 neutrons in its nucleus and a cloud of 8 electrons surrounding its nucleus. Similarly, the dominant form of hydrogen in the Earth's atmosphere and waters is ^{1}H, which has a single proton and a single electron. ^{18}O has 2 additional particles, neutrons, in its nucleus, and ^{2}H (also known as deuterium) has one additional particle, also a neutron, in its nucleus. ^{18}O and ^{2}H generally behave chemically like their more abundant counterparts, ^{16}O and ^{1}H. However, the extra mass exerted by their additional neutron(s) renders ^{18}O and ^{2}H slightly heavier than their more abundant counterpart atoms.

Stable isotopes: Isotopes are variants of atoms of a particular element that have differing numbers of neutrons. Stable isotopes are non-radioactive.

It turns out that the heavier (^{18}O and ^{2}H) atoms condense to form water from water vapor more readily with either decreasing temperature or increasing altitude than their lighter counterparts. Consequently, rainwater (or snow) at higher altitude becomes relatively enriched in the lighter, more abundant isotopes of oxygen and hydrogen (i.e., the ratios of ^{16}O to ^{18}O and ^{1}H to ^{2}H are greater). Blasch and others (2006) applied this tool to identifying winter precipitation in higher-elevation areas as the dominant source of water for groundwater recharge in the upper and middle Verde River watersheds.

Streamflow Measurements

Streamflow in natural systems is supported by two components: (1) the runoff generated from precipitation and snowmelt events and (2) base flow, which is the contribution of groundwater to streams (illustrated in Figure 3.12). In semi-arid climates like ours, perennial (year-round) streamflow is dependent on the persistent addition of groundwater to streamflow where the elevation of the water table near the stream is greater than the elevation of the stream surface. Without that base-flow component, the Verde River and its perennial tributaries such as Oak Creek, Wet Beaver Creek, and West Clear Creek, would flow only in response to runoff from rain and snowmelt. Clearly streamflow measurements and determinations of base flow are critical tools for hydrologists working to evaluate the current and future implications for streamflow of climatic and human stresses imposed on groundwater resources.

Base flow: The component of stream flow that comes from groundwater as seepage or spring water.

Stream gage Measurements

Fortunately, systematic measurements of streamflow are made and recorded by the USGS on rivers throughout the country including the Verde River and some its tributaries. The data, which include measurements every 15 minutes, as well as daily mean stream flow values, are available online from the USGS. Links to the data from the Verde River gages in the upper and middle Verde River watersheds are given in chapter 5.

Seepage Runs

A seepage run is a snapshot of river discharge over a section of a river. Several teams of hydrologists manually measure stream flow at as many points as possible over the designated length of stream. Such a survey might, for example, consist of one to several measurements of discharge per mile over some predetermined length of river. A seepage run is commonly made when the runoff component of stream flow is minimal so that the run records as nearly as possible the variations in base flow along the studied river section. Speed is critical to minimize any temporal variations in streamflow, and all efforts are made to take the measurements in as short a period of time as possible. In other words, speed is essential in order to assure that measured variations are truly variations in base flow, not the products of weather events or changing evapotranspiration rates.

A successful seepage run identifies reaches along the run in which groundwater seeping into the river is adding base flow—gaining reaches—as well as reaches in which the base flow is diminishing—losing reaches—as the river loses water to the groundwater.

River discharge: The volume of water passing through a cross section of a river or stream per unit time.

Gaining reach: A section of a steam or river in which groundwater adds base flow.

Losing reach: A section of stream or river in which streamflow is lost to groundwater.

This information may be of critical importance to hydrologists in order for them to evaluate the connection between rivers and groundwater in a groundwater system and the contribution that each makes to the other.

Discharge of groundwater to a stream in a gaining reach occurs when the water table near the stream is at greater elevation than is the stream surface (Figure 4.4A). The process is the familiar flow of groundwater from an area of greater hydraulic head to an area of lesser hydraulic head.

Conversely, loss of water from the stream to the groundwater (i.e., recharge of groundwater from a stream) in a losing reach occurs when the stream surface is at greater elevation than the water table near the stream (Figure 4.4B). Again, the process is the familiar flow of groundwater from an area of greater hydraulic head to an area of lesser hydraulic head.

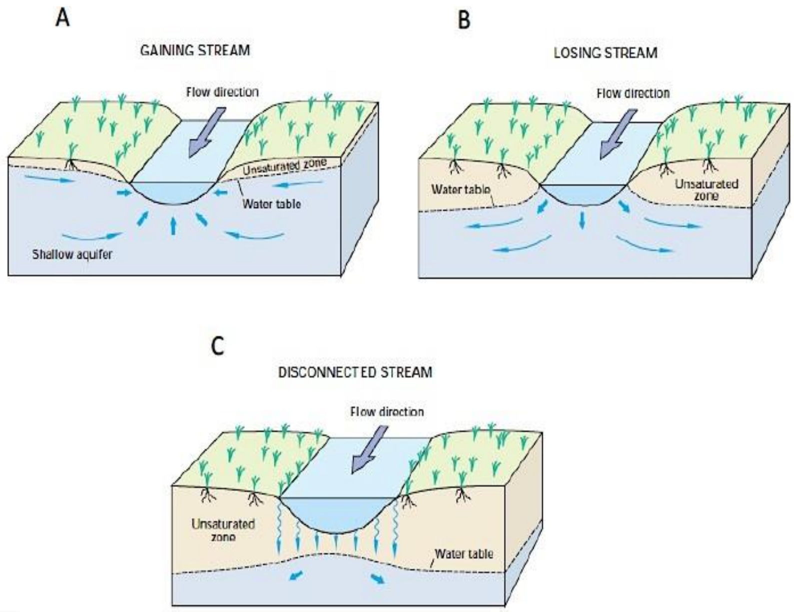


Figure 4.4. Gaining and losing streams and their relation to the water table. After Winter and others (1998).

> Geophysics: The study of the physics of the Earth.

A variation on recharge of water to the stream is portrayed in Figure 4.4C, in which the streambed is distinctly above the water table; in other words, this reach of the stream is completely within the unsaturated zone, and gravity is delivering recharge from the stream downward to the water table. If you could map the shape of the water table beneath the stream, you would most likely discover that the recharge from the steam locally raises the water table beneath the stream—i.e., creates a zone of elevated hydraulic head in the recharge zone beneath the stream.

Geophysical Tools

Geophysics offers a variety of tools that can give information about conditions below the Earth's surface. When combined with geologic information from drill holes—even if the drill holes are few—geophysical techniques can be a powerful aid for hydrologists trying to understand the shapes, dimensions, and boundaries of aquifers.

Seismology

Seismology is the study of earthquakes and of the structure of the Earth, by either natural (usually earthquake-generated) or artificially generated seismic waves.

> Seismology: The study of earthquakes and of the structure of the earth from the analysis of waves generated naturally (for example, by earthquakes) or artificially (for example, by explosions).

Earthquakes generate several types of waves that travel through the Earth much as sound waves travel through the atmosphere, but at substantially greater velocities. Sound waves that humans hear commonly travel through the atmosphere at about 1,100 feet per second, or about 1/5 mile per second. You can estimate how far away in feet a lightning bolt is by timing the interval between your observation of the lightning and the arrival of the thunderclap and multiplying the number of seconds between the two observations by 1,100. A time of 1-second means the lightning occurred about 1,100 feet away from you, 2 seconds equals approximately 2,200 feet distant, etc.

Nearly everyone is familiar with the return of an echo from a canyon wall or a distant cliff. The echo is the manifestation of a reflected sound wave. If it's foggy and you can't see the cliff, the existence of the echo tells you that there is a cliff, and you know roughly its direction from you. The time in seconds from your shout until you hear the echo is the round-trip travel time from you to the cliff and back to you. If you multiply that time in seconds by 1,100 feet per second and divide by two, you have an estimate of your distance from the cliff.

Geophone: A device that converts ground movement (displacement) into voltage, which may be recorded at a recording station.

The use of seismology to learn about the structure of rocks or aquifers below the ground surface is analogous to your interpretation from an echo that there is a reflecting surface such as a cliff facing you at an approximately known distance. The dominant waves generated by earthquakes most commonly travel through the earth at speeds of about two to four miles per second and are used to explore some kinds of earth structures. However, exploration of the structure of aquifers (or petroleum-bearing rocks) is much more effective with controlled, artificially generated seismic waves. The source of the artificially generated seismic waves is usually either controlled explosions or controlled impacts to the ground surface from trucks specially designed to drop a heavy weight to the ground or to impose a series of vibrations locally on the Earth's surface. The advantage of artificially generated seismic waves is that the exact time, location, and magnitude of wave propagation is known, and investigators don't have to wait for some distant earthquake to occur.

The velocity of the seismic waves traveling through the rocks and unconsolidated sediments depends on the physical properties of the rocks or sediments—properties such as their density and their rigidity. When a wave reaches a boundary between layers with different physical properties—for example, a layer of water-saturated sand or gravel overlying consolidated bedrock or a boundary between an alluvial-basin aquifer and the bedrock walls that contain the alluvial aquifer (see Figure 3.5)—part of the wave continues past the boundary at a different velocity and part is reflected back (echoes) from the boundary to the surface. There it is recorded by an array of geophones, each of which records the magnitude and timing of ground movement at its location.

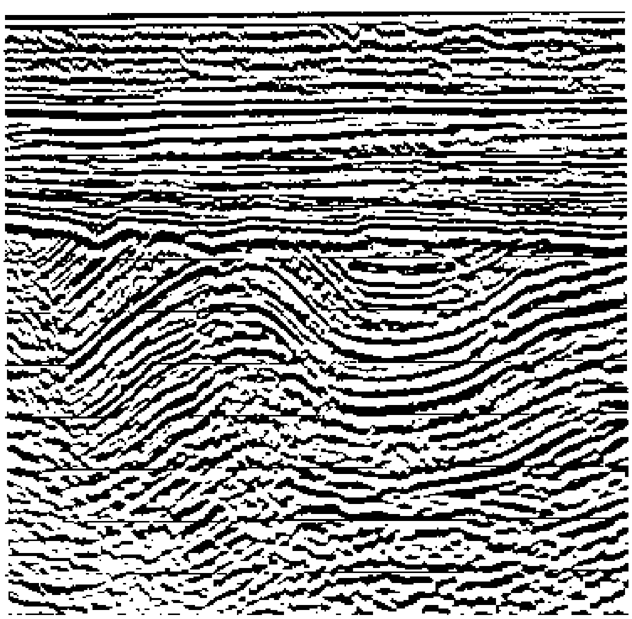


Figure 4.5. A seismic cross section showing folded rocks underlying nearly horizontal rock layers. Stanford University School of Earth Sciences: http://pangea.stanford.edu/~sklemp/bering_chukchi/images/seismic.section.gif

Density: The ratio of an object's mass to its volume. Density is commonly expressed as grams per cubic centimeter. The density of water (at sea level and at 20° C) is 1 gram per cubic centimeter (it is also 62.4 lbs. per cubic foot). Objects with a bulk density of less than 1 gram per cubic centimeter float in water; objects with a bulk density of more than 1 gram per cubic centimeter sink in water.

Regional Gravity and Magnetic Surveys

Ground-based gravity surveys and aerial magnetic surveys can reflect the surface and subsurface distribution of density and magnetization, respectively. Langenheim and others (2005) give an excellent example of the application of these techniques in the upper and middle Verde River watersheds.

Langenheim and others (2005) used gravity measurements from more than 3,000 gravity stations distributed throughout the upper and middle Verde River watersheds, in combination with well data to model the three-dimensional shape of the basin-filling sedimentary and volcanic deposits that comprise the alluvial and volcanic aquifer systems of the Big Chino, Little Chino, and Verde Valley sub-basins (see Figures 5.2 and 5.3 in Chapter 5). Their application of the gravity data to interpret basin depth and shape took advantage of the fact that the unconsolidated basin-filling deposits are generally lower in density—roughly by about 10 percent—than the older solid rocks that form the floors and walls of the alluvial basins.

The value of gravity at a spot on the Earth's surface reflects the density of the rocks or sedimentary deposits between the gravity meter and the center of the Earth and is most strongly influenced by the density of rocks or deposits closest to the surface. Thus, a measurement where there are thick, near-surface deposits of relatively low-density material such as unconsolidated gravel, sand, silt, or clay gives a substantially smaller gravity value than a measurement where denser consolidated rocks are at or near the ground surface. Descriptions of rocks or deposits penetrated by wells and the distribution or rock types and deposits at the surface as mapped by geologists provide important anchors for interpretation of the gravity data.

Aerial surveys of the magnetic properties of rocks and sedimentary deposits may give a regional overview of the geologic structure as interpreted from aeromagnetic maps. Thus an aeromagnetic survey is another tool that can give vital information about geologic structures that may influence the shapes of aquifers and the flow of groundwater. The aeromagnetic data are sensitive to the distribution of magnetic rocks, particularly those that contain the iron-oxide mineral magnetite. This technique was used by Langenheim and others (2005) in the upper and middle Verde River watersheds. There, the strongly magnetic rocks are mainly young volcanic rocks less than 30 million years old and some of the oldest rocks, which are between approximately 1.8 billion and 1.6 billion years old. In general, they contrast markedly with the much less magnetic young alluvial basin-filling deposits and the limestones and sandstones of intermediate age—generally between about 540 and 270 million years old. Boundaries between zones of contrasting magnetization can imply the presence of geologic boundaries between magnetically contrasting rock types. Sharp linear magnetic boundaries may be attributed, for example, to faults, which can serve as either conduits for or barriers to groundwater flow. Langenheim and others found that local strong circular aeromagnetic patterns and wormlike aeromagnetic patterns were found to be indicative of young volcanic rocks both at the ground surface and in the subsurface.

Aeromagnetic maps: Aeromagnetic maps portray the processed results of aerial magnetic surveys made by an aircraft to which a magnetometer is attached.

Langenheim and others used the gravity and aeromagnetic data together to infer as much insight as possible about the subsurface geometry of aquifers, faults, and geophysically distinctive bodies of rock or sediment. Measurements of rock densities and magnetic properties of samples as well as drill-hole data and well-established knowledge of the geology as seen at the surface were critical in interpreting the subsurface geology.

Precise Gravity Measurements for Storage-Change Analysis

Groundwater within an aquifer has mass, and the removal or addition of some of the groundwater in an aquifer causes a change in mass. Relatively small changes in mass can be detected by precise gravity measurements. Precise measurements of gravity at the same point on the ground surface repeated over months or years can detect small changes in mass that reflect the addition or loss of groundwater below the measurement station. A small change in ground elevation, either from subsidence or uplift of the ground surface may also cause a gravity change. Thus, it is important to combine each gravity measurement with a precise measurement of the elevation of the measurement station.

Specific yield: The proportion of water that will drain from the pore spaces in the aquifer under the influence of gravity.

Ideally the precise gravity measurement would be made at the same locality as a well in which the water level can also be measured at the time of each gravity measurement. The simultaneous changes in precise gravity and in water level from successive occupations of a site can be used to deduce specific yield at that locality in the aquifer. Such monitoring by the USGS was supported by the Yavapai County Water Advisory Committee at selected sites in the upper and middle Verde River watersheds.

Numerical Groundwater Models

A numerical groundwater model is a computer model of a groundwater system that is used to simulate recharge to, the movement of groundwater within, and the discharge of water from the system under both natural and human-caused conditions, such as pumping. The latter ability makes the model a predictive tool that allows evaluation of the probable consequences of human actions.

A numerical groundwater model is often the critical end product of hydrologic investigations. Each of the various hydrology tools described in the preceding sections has a potentially important role to play in the development of a robust groundwater model.

The purpose of constructing a model is usually to allow us to predict the hydrologic consequences of a particular human-induced stress or set of human-induced stresses on the groundwater system being modeled. The consequences of most interest are generally model predictions about water-level changes and changes in the amount and location of groundwater discharge. A numerical groundwater model integrates all the useful data produced by the set of hydrology tools described above. Thus, we can think of such a model as the ultimate tool for science-based guidance for important groundwater and surface-water management decisions.

> Numerical groundwater model:
> A computer model of a groundwater system that is used to simulate recharge to, the movement of groundwater within, and the discharge of water from the system under both natural and human-caused conditions, such as pumping.

The predictive capability of a numerical groundwater model depends upon the degree to which the model accurately simulates the groundwater system being modeled, i.e., the processes of recharge and discharge, and the rock properties that control the rates of movement and storage change of water within the groundwater system. Most numerical groundwater models are first constructed to simulate natural conditions prior, insofar as possible, to the earliest groundwater pumping. This process is referred to as steady-state model calibration. Following the steady-state calibration, the model is then adjusted in a process referred to as transient-model calibration to reproduce in a series of time steps (for example, decade-long intervals) known stresses (for example, groundwater pumping and artificial recharge) and their known hydrologic effects (for example, changes in hydraulic heads and measured base flow).

In fact, some information necessary to fully calibrate a model is nearly always lacking, and this lack requires educated estimates to be made during model construction. For instance, the distribution of rain gages is generally insufficient to accurately portray the distribution and rate of rainfall on a daily basis in a given modeled area. The same is true for evaporation. Therefore groundwater recharge from precipitation can at best be only estimated. Even less information may be available about the distribution of certain geologic factors that influence the movement and storage of water within the groundwater system. In general, the larger the area simulated by a model the more likely the need for making educated estimates that are incorporated into the model. The transient-model calibration process tests these estimates and provides a critical basis for adjusting them so that the model simulates as accurately as possible the measured hydrologic effects of known stresses throughout the transient-calibration period.

Despite such shortcomings, when the model’s conceptual design appropriately simulates the groundwater system being modeled, the calibration process can be used to establish reasonable limits on the model’s predictive capability. When these constraints are considered, a numerical groundwater model is, without question, the most effective tool available to evaluate the consequences of human-induced changes on the movement and storage of water in a groundwater system and the changes in the rates and location of groundwater discharge from it.

Chapter 5: Regional Hydrogeologic Framework in the Upper and Middle Verde River Watersheds

Chapter 5: Regional Hydrogeologic Framework in the Upper and Middle Verde River Watersheds

Geologic Setting

A useful first step in understanding the occurrence of groundwater in the upper and middle Verde River watersheds is to have a general picture of the regional hydrogeologic framework in which our groundwater occurs. The regional setting is summarized in the hydrogeologic cross section (Figure 5.1) of our groundwater systems and their relations to our surface waters.

The sequence of Paleozoic strata (see Table 5.1), about 4,000 feet thick, that is so well-exposed in the walls of the Grand Canyon extends with minor variation beneath the surface of the Coconino Plateau to the Mogollon Rim above Sedona. Southward, from the Mogollon Rim to Prescott, erosion has removed progressively more and more of the sequence. Thus the Paleozoic strata have been completely removed by erosion in Prescott, where exposures of Proterozoic rock, mostly granitic rock, abound. Along Arizona Highway 89A from Prescott Valley to Jerome, the oldest exposed rocks, found on the lowest part of the southwest flank of the Black Hills and on the northeast flank of the Black Hills above Jerome, are Proterozoic metamorphic rocks. These are overlain on both flanks of the Black Hills by much younger Paleozoic rocks - Tapeats Sandstone, the Martin Formation, and Redwall Limestone - that represent the older part of the Paleozoic Grand Canyon sequence. The Black Hills along Highway 89A are capped by a thick sequence of Tertiary basalt flows and basaltic fragmental deposits that rests directly on the Redwall Limestone.

Hydrogeologic: refers to the branch of geology that deals with the distribution and movement of groundwater in the rocks and sediments of the Earth's crust.

Granitic rock: Igneous rock formed by gradual cooling and crystallization of molten rock miles deep within the Earth's crust. This rock is coarsely crystalline, a consequence of gradual cooling at substantial depth.

Proceeding north across the Verde River on Highway 89A, one has to go almost to Sedona to see younger Paleozoic rocks up close. There they occur as the spectacular red sandstone and siltstone outcrops of the Supai Group, Hermit Shale, and Schnebly Hill Formation (Figure 5.1) in and around Sedona. Still farther north on Highway 89A, the tan, cross-bedded Coconino Sandstone is well exposed in the upper part of Oak Creek Canyon. The Permian Kaibab Limestone caps much of the Coconino Plateau; it is well exposed and visible along I-17 south of Flagstaff.

The red sandstone of the Triassic Moenkopi Formation is well exposed and visible along East Santa Fe Avenue (I-40 Business route), between the western and eastern parts of Flagstaff. It has been protected locally from erosion by a 6-million-year-old basalt flow that caps Switzer Mesa. In spite of the way the Moenkopi Formation is portrayed in the generalized cross section, geologic mapping (Ulrich and others, 1984) shows erosion has stripped it from much

Metamorphic rock: Rock with texture and mineralogy changed in response to heat, pressure, mechanical stress, and/or fluids at great depth within the Earth's crust.

Basalt: Dark, fine-grained igneous rock formed by rapid cooling and solidification of iron- and magnesium-rich lava at the Earth's surface.

of the area between San Francisco Mountain and the Mogollon Rim, although remnants are exposed locally between basalt flows and the underlying Kaibab Limestone.

Late Cenozoic basalt flows are prominent in the road cuts in the uppermost part of the switchbacks along Highway 89A above Oak Creek Canyon. Young basalt flows and related volcanic rocks of the San Francisco volcanic field continue from there north through Flagstaff and far beyond.

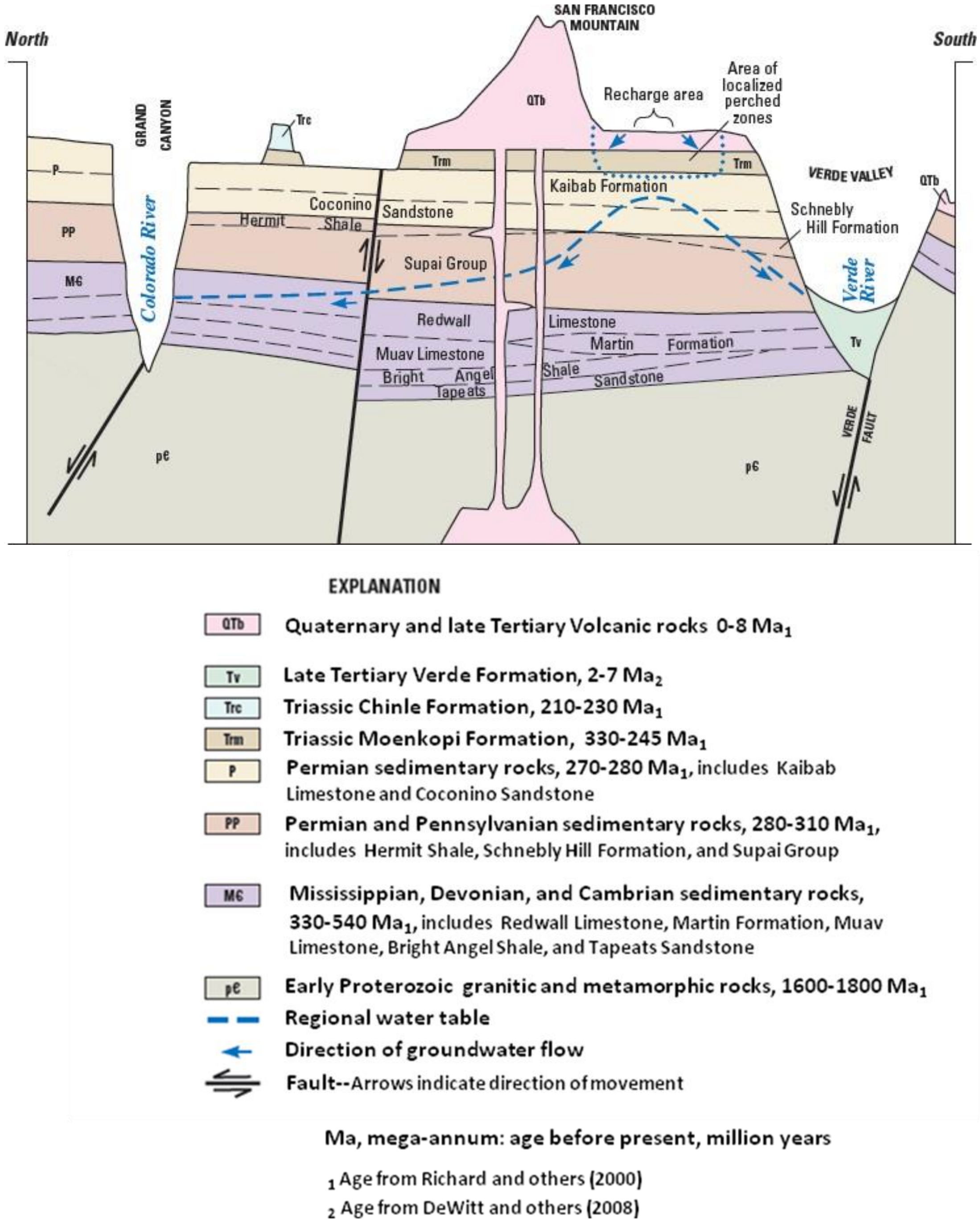


Figure 5.1. Generalized hydrogeologic cross section from the Verde River to the Colorado River, showing the groundwater divide between San Francisco Mountain and the Mogollon Rim. Blasch and others (2006). Table 5.1 summarizes the geologic time scale.

Regional Hydrologic Setting

The hydrogeologic cross section (Figure 5.1) notes the occurrence of localized perched zones (perched aquifers) between San Francisco Mountain and the Mogollon Rim. This is an area where scattered springs and some ephemeral ponds occur well above the regional water table. Their occurrence may reflect the presence of local mudstone layers within the Moenkopi Formation that impede infiltration.

The blue dashed line in the hydrogeologic cross section is a generalized representation of the regional water table in the area between the Verde Valley and the Grand Canyon. The area around Flagstaff and extending south to the Mogollon Rim receives some of the State's greatest annual precipitation. In general, there is little through-going drainage developed on the extensive area of basalt lava flows that dominate the San Francisco volcanic field. The general lack of through-going drainage suggests that infiltration is enhanced and runoff is minimized on these extensive young basalt flows. The combination of enhanced infiltration and relatively abundant precipitation accounts for the apparently great natural recharge and elevated water table between San Francisco Mountain and the Mogollon Rim.

Eon	Era	Period	Age, Ma	
			End	Beginning
Phanerozoic	Cenozoic	Quaternary	0	1.8
		Tertiary	1.8	65.5
	Mesozoic	Cretaceous	65.5	145.5
		Jurassic	145.5	201.6
		Triassic	201.6	251
	Paleozoic	Permian	251	299
		Pennsylvanian	299	318
		Mississippian	318	359
		Devonian	359	416
		Silurian*	416	444
		Ordovician*	444	488
		Cambrian	488	542
Proterozoic			542	2,500
	*Not known to be present in Arizona Ma (mega-annum): age, million years before present Geological Society of America geological time scale (2009)			

Table 5.1. Geologic time scale. Geological Society of America, 2009, http://www.geosociety.org/science/timescale/.

As shown in the cross section (Figure 5.1), the water table intersects the ground surface both in the south wall of the Grand Canyon and to the south on the long southwest-facing slope between the Mogollon Rim and the Verde River. Be aware that this cross section is schematic, meaning that it gives a general representation and is not specific as to exact location. Some of the major perennial streams between the Mogollon Rim and the Verde River, such as Oak Creek and Wet Beaver Creek, intersect the water table many miles upstream from the Verde River; at these localities, groundwater discharges to the streams. In other places, springs record the local intersection of the regional water table with the ground surface. Groundwater that does not discharge either to springs or streams between the Mogollon Rim and the Verde River and is not withdrawn by wells, continues south to lower elevations of the Verde Valley, where it discharges as groundwater to the Verde Formation (Pool and others, 2011).

The movement of groundwater from the area of high recharge between San Francisco Mountain and the Mogollon Rim reflects the large elevation change of the water table—and thus the large hydraulic head differences—between the area of high recharge and the areas of groundwater discharge in the Grand Canyon and the Verde Valley. The high point in any water table is a groundwater divide. The crest of this groundwater divide is oriented approximately east-west in this area and is about three miles south of Flagstaff's Pulliam Airport. On the north side of the divide all groundwater flows northward to the Colorado River; on the south side all groundwater flows southward toward the Verde River.

The positions of groundwater divides are not permanently fixed. Pumping on one side of a groundwater divide causes the divide to shift laterally away from the basin in which pumping occurs. Further, pumping on either side of a divide causes the development of cones of depression (Figure 3.13), reflecting lowered hydraulic head at each well. These reductions in head spread laterally in all directions from the wells, including the direction toward a groundwater divide. Eventually, lowering of the water table from the lateral propagation of cones of depression reduces the hydraulic head at the groundwater divide, causing a reduction of hydraulic head, lowering of the water table, and reduced discharge of groundwater in the adjacent basin. The rate at which such effects occur, of course, depends on the distance and the hydrologic properties of the aquifer between each well and the divide. Noticeable change in the adjacent basin might take decades or even centuries, but it is inevitable.

Groundwater divide: The boundary between two adjacent groundwater basins, which is represented by a ridge in the water table.

Alluvial Basins

Beginning about 10 million years ago, profound geologic changes in our area superimposed deep alluvial basins (Figure 5.2) on the regional geologic framework described above. The existence of these basins and the sedimentary deposits that fill them are vital to both the location and the perennial flow of the Verde River. The groundwater of the alluvial basins supplies nearly all of the water for domestic and municipal use in the upper Verde River watershed as well for the municipalities - Clarkdale, Cottonwood, and Camp Verde - and unincorporated developments near the Verde River in the middle Verde River watershed.

The alluvial basins formed as a result of tectonic extension (stretching) of the Earth's crust in a northeast-southwest direction between about 10 million and 2 million years ago. Particularly striking are the deep, linear, fault-bounded troughs that underlie the Big Chino and Verde Valleys, where vertical displacement was on the order of a half-mile or more.

As these troughs began to form, they carried whatever rocks or deposits were at the surface downward with them, including: Proterozoic granitic and related rocks in the Prescott area; approximately 300-million to 400-million-year-old Paleozoic limestone and dolomite of the Redwall Limestone and Martin Formation in the Verde and Big Chino Valleys; and mid- to late-Cenozoic alluvial sands and gravels as well as volcanic rocks that had formed locally between about 35 and 10 million years ago.

Beneath what is now the Verde Valley, the Little Chino sub-basin, Williamson Valley, and Big Chino Valley, the troughs subsided and they formed topographically low areas, or basins, which disrupted pre-existing drainage and captured the drainage that flowed into them from the adjacent uplands. Thus, they developed into loci of accumulation of water-transported sediment eroded from the adjacent uplands. The accumulation of transported sediment became ever thicker - up to 2,000 feet or more of sand, silt, gravel, clay, limestone, and even salt and gypsum - as the subsidence continued.

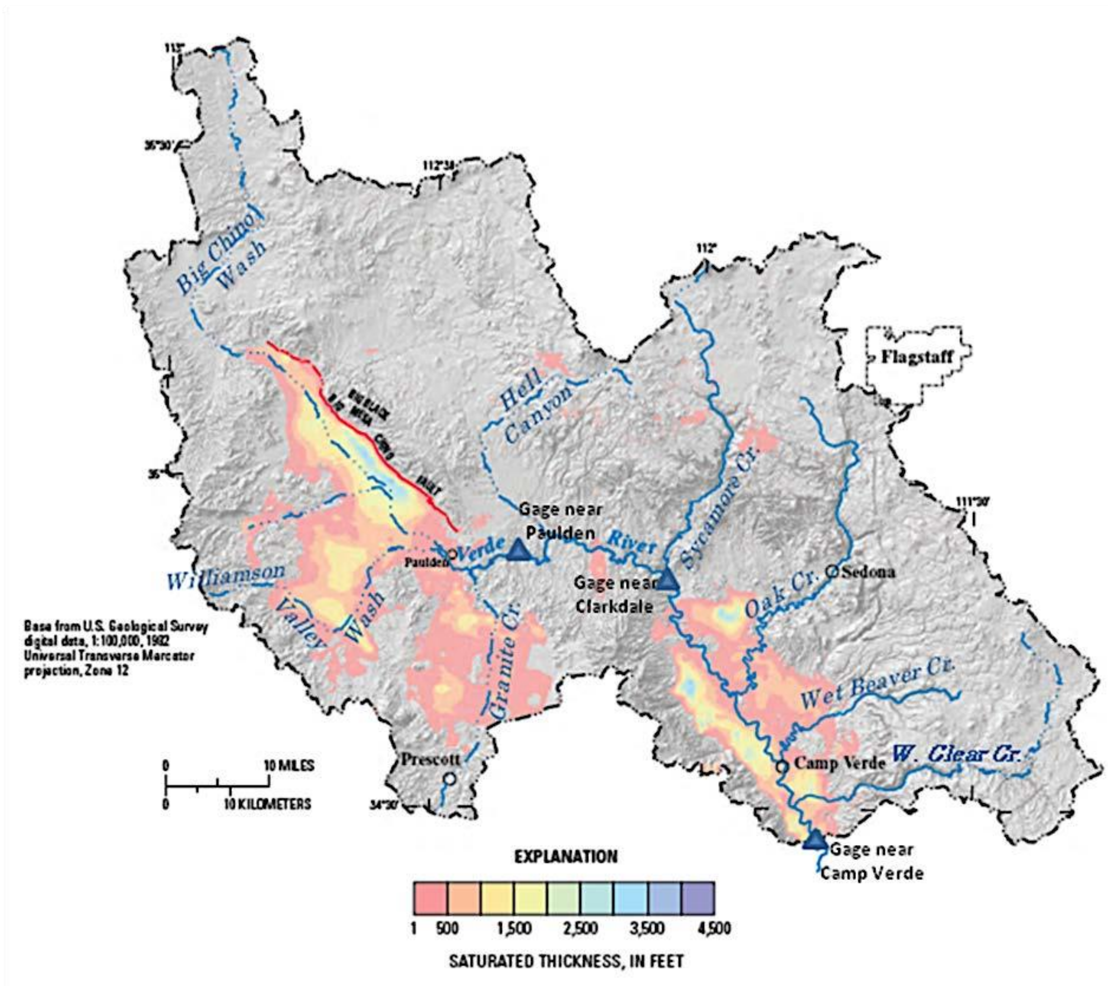


Figure 5.2. Map showing the thickness of water-saturated sediments (i.e., below the water table) and volcanic rocks that are interlayered with them in the upper and middle Verde River watersheds. Modified from Blasch and others (2006). Thickness data determined from gravity measurements and well records (Langenheim and others, 2005).

At least some of the time, the Big Chino and Verde Valley basins apparently subsided more rapidly than the incoming sediment could fill them. In such instances, little if any drainage left the basins, and deposits of silt and clay and, in the Verde Valley basin, limestone, mudstone, salt, and gypsum, accumulated where stream gradients were very low or runoff actually ponded. This is the apparent origin of a thick deposit of silt or clay in the central part of the Big Chino basin and of deposits of limestone, mudstone, and, locally, salt and gypsum in the Verde Valley basin. The extensive white hills of the Verde Valley represent the upper part of the Verde Formation and are predominantly limestone deposited in ephemeral lakes or marshes.

Any flowing basalt lava that crossed a margin of one of these basins during that time simply flowed downhill into the basin and is now preserved as a tongue of basalt within the basin-filling sediments. These solidified basalt flows are important because the ages of their eruptions can be measured, and thus they provide important age limits on the emplacement of the basin-fill deposits.

Subsidence of these basins waned about 2 million years ago, and a through-going drainage—now the Verde River—developed, establishing the canyon reaches between Paulden and Clarkdale and between the south end of the Verde Valley and the Salt River east of Phoenix.

The four block diagrams below (Figure 5.3) portray the areas of the alluvial basins, with (diagrams A and C) and without (diagrams B and D) the present cover of the mid- and late-Cenozoic sedimentary deposits and volcanic rocks (approximately 0 to 35 million years in age) that cover much of the ground surface. Based on analysis of gravity measurements and well records (Langenheim and others, 2005), a vivid picture is produced showing the shapes of the basins as bounded by the Paleozoic and Proterozoic rocks that form their walls and floors.

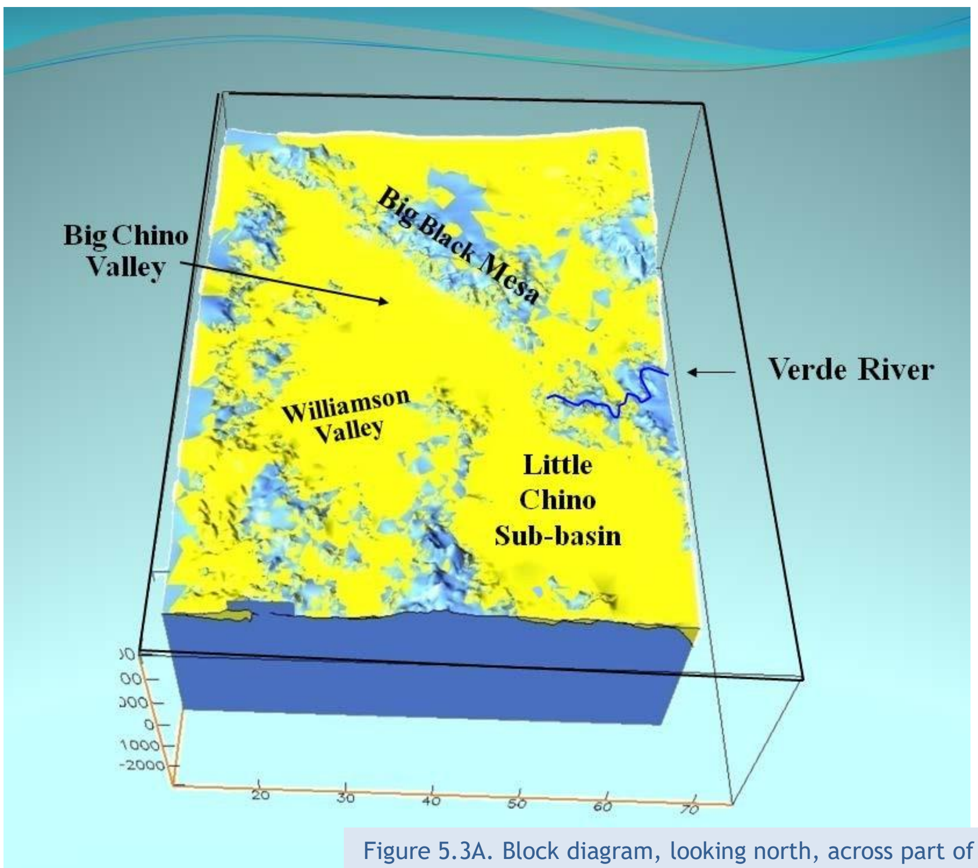


Figure 5.3A. Block diagram, looking north, across part of the upper Verde watershed, showing surface topography. The surface distribution of mid- to late-Cenozoic sedimentary deposits and volcanic rocks is shown in yellow and the exposed Precambrian and Paleozoic rocks are shown in blue.
Courtesy of V.E. Langenheim, USGS.

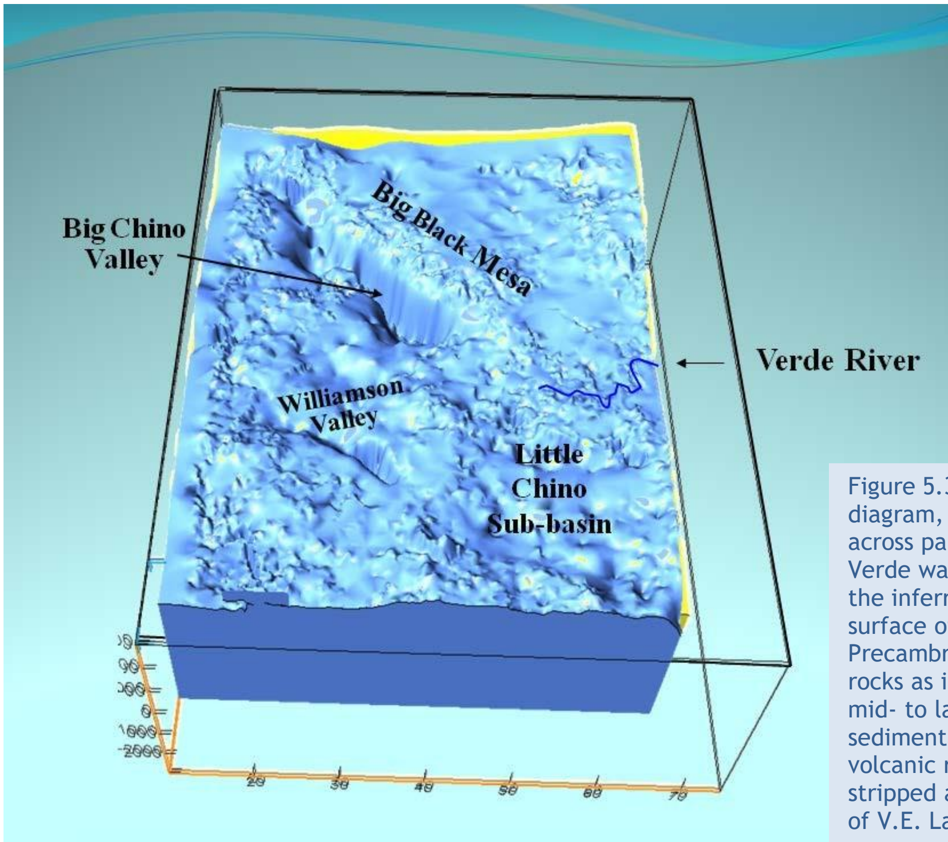


Figure 5.3B. Block diagram, looking north, across part of the upper Verde watershed, showing the inferred topographic surface of the Precambrian and Paleozoic rocks as if the overlying mid- to late-Cenozoic sedimentary deposits and volcanic rocks had been stripped away. Courtesy of V.E. Langenheim, USGS.

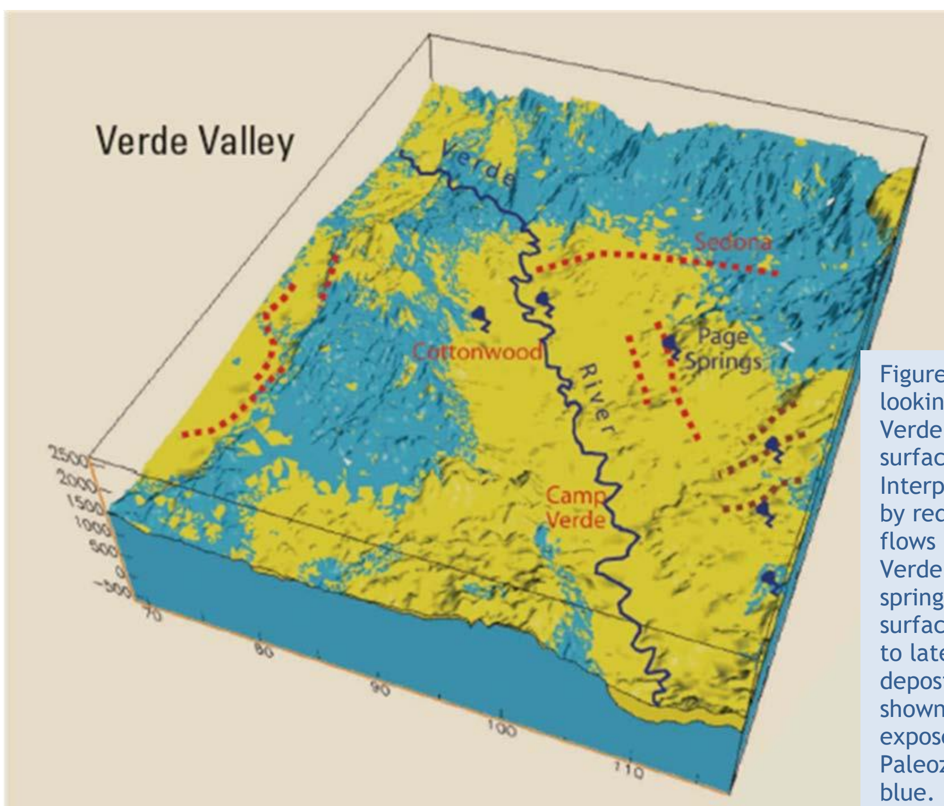


Figure 5.3C. Block diagram, looking north, across the Verde Valley, showing surface topography. Interpreted faults are shown by red dashes, buried basalt flows by brown dashes, the Verde River and major springs in dark blue. The surface distribution of mid- to late-Cenozoic sedimentary deposits and volcanic rocks is shown in yellow and the exposed Precambrian and Paleozoic rocks are shown in blue. From Langenheim and others (2005).

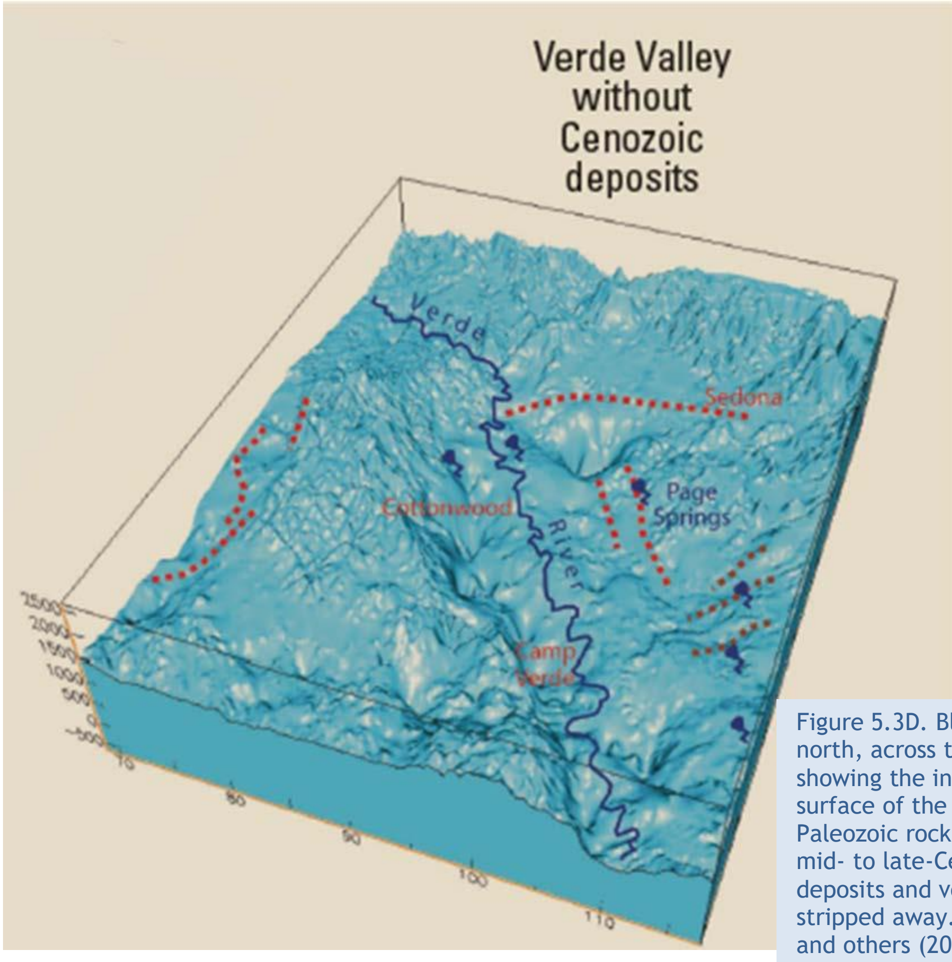


Figure 5.3D. Block diagram, looking north, across the Verde Valley, showing the inferred topographic surface of the Precambrian and Paleozoic rocks as if the overlying mid- to late-Cenozoic sedimentary deposits and volcanic rocks had been stripped away. From Langenheim and others (2005).

General Relation: Geology and Groundwater in the Upper and Middle Verde River Watersheds

Understanding the geologic framework, both regionally and locally, provides an essential foundation for understanding where groundwater is likely to be found, how it will move, and how it relates to springs and streams. For example, the oldest rocks, which are the Proterozoic granitic and metamorphic rocks, generally have low hydraulic conductivity. Thus they store or transmit little groundwater except where they are fractured. Consequently, they form a relatively non-transmissive "basement" beneath or, along faults, adjacent to the much more transmissive Paleozoic limestone and sandstone and the Cenozoic sedimentary deposits and volcanic rocks that form the thick alluvial-basin deposits of the Verde Valley, the Big Chino and Williamson Valleys, and the Prescott Active Management Area (PrAMA).

The much more transmissive Paleozoic limestone and sandstone layers serve as important conduits for the movement of groundwater from the relatively high-altitude and better-watered terrain of the Mogollon Rim and Juniper Mountains to the adjacent alluvial basins of the Verde and Big Chino Valleys. The Paleozoic aquifers are a vital source of well water for much of the area between the Verde River and the Mogollon Rim, and groundwater discharge from them maintain year-around streamflow in the Verde River above Clarkdale and in the river's perennial tributaries, Oak Creek, Wet Beaver Creek, and West Clear Creek in the Verde Valley.

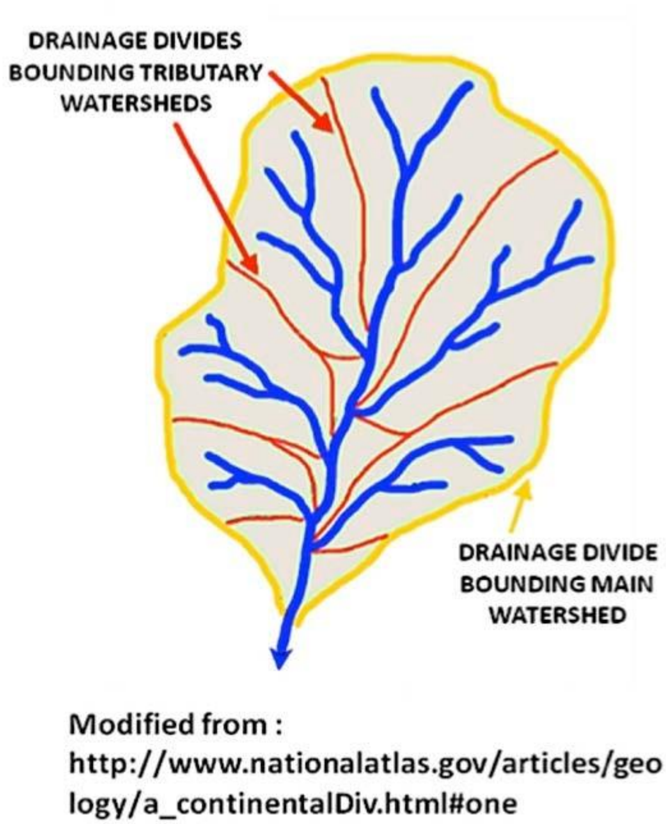
The sedimentary deposits and volcanic rocks of the thick Cenozoic alluvial basin-fill deposits are the major sources of water for wells in the Big Chino, Williamson, and Verde Valleys and the PrAMA. Water-bearing Paleozoic rocks underlie the alluvial-basin aquifers in the Big Chino and Verde Valleys. Thus, they are part of the aquifer system in those Valleys. Paleozoic rocks are rare or absent beneath the alluvial-basin aquifer of the PrAMA. There, the basin-filling alluvial deposits and volcanic rocks generally rest directly on the Proterozoic basement rocks.

Chapter 6: Occurrence and Flow of Groundwater and Surface Water in the Upper and Middle Verde River Watersheds

Chapter 6: Occurrence and Flow of Groundwater and Surface Water in the Upper and Middle Verde River Watersheds

What is a watershed?

A watershed is a drainage basin—a land area bounded by drainage divides and occupied by drainage systems. It is a land area that gathers surface water originating from runoff or springs and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water. In the diagram below (Figure 6.1), the major or trunk stream is supplied by numerous tributary watersheds. For example, the Verde River would be the major or trunk stream receiving water from the watersheds of each of its tributaries, such as Big Chino Wash, Williamson Valley Wash, Granite Creek, Sycamore Creek, Oak Creek, Wet Beaver Creek, West Clear Creek, Fossil Creek, and East Verde River. The Verde River and all of its tributary watersheds together comprise the Verde River watershed or Verde River basin (Figure 6.2).



Watershed: a land area bounded by drainage divides and occupied by drainage systems; specifically, a tract of country that gathers surface water originating from runoff or springs and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

Drainage divide: the topographic boundary that physically separates the drainage of one drainage basin from that of another; occurs as a ridge crest in hilly country; in flatter country it also occurs as a topographic high, but may not be very obvious. Precipitation on one side of a divide will drain into one basin, whereas precipitation on the other side will drain into another basin.

Figure 6.1. Diagram illustrating a watershed and drainage divides.

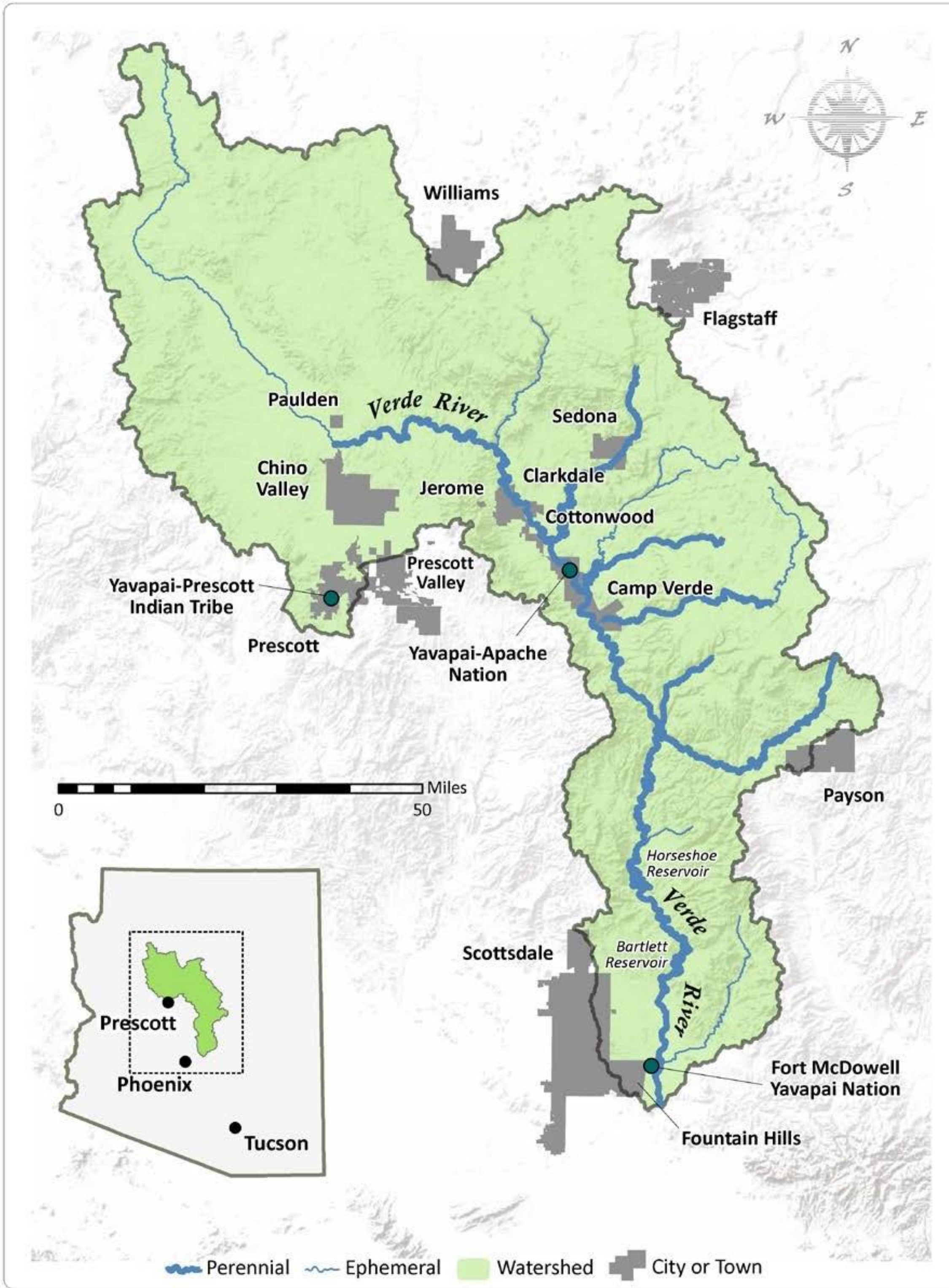


Figure 6.2. Map of the Verde River Basin (Verde River watershed).

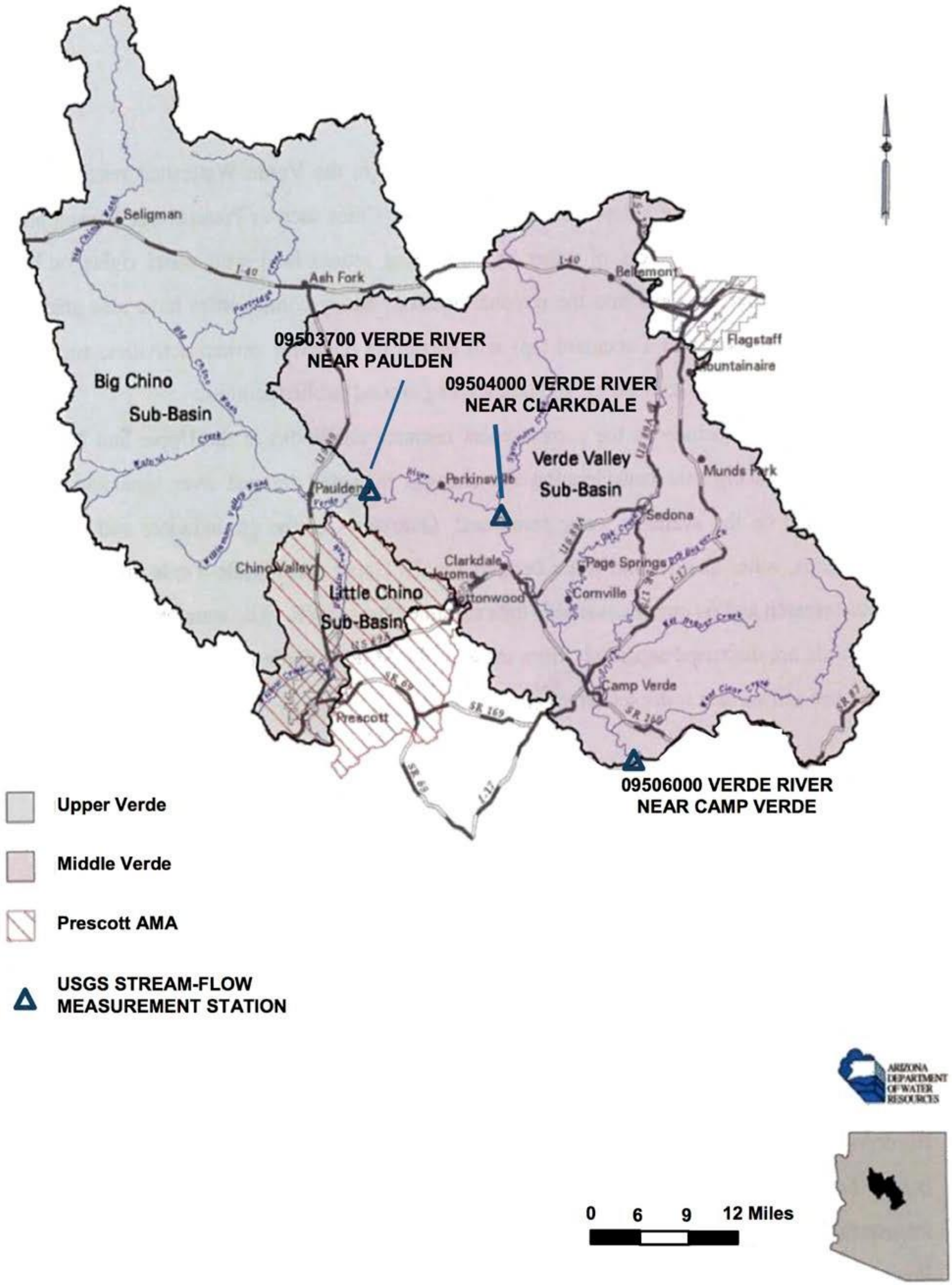


Figure 6.3. Map showing the locations of the Big Chino, Little Chino, and Verde Valley administrative groundwater sub-basins, the Prescott Active Management Area, and the active USGS stream-flow measurement stations located on the Verde River. Modified from ADWR (2000, Figure 4.1).

The Upper and Middle Verde River Watersheds and Their Administrative Groundwater Sub-basins

The Arizona Department of Water Resources has identified two administrative groundwater sub-basins, the Little Chino and Big Chino sub-basins, which together comprise the upper Verde River watershed, and a single administrative groundwater sub-basin, the Verde Valley sub-basin, which comprises the middle Verde River watershed. The downstream boundaries of the Big Chino sub-basin and the Verde Valley sub-basin were placed so as to coincide, respectively, with the locations of USGS stream gages near Paulden and Camp Verde (Figure 6.3).

The upper and middle Verde River watersheds host nearly all of the population, towns and cities, and agriculture within the Verde River basin. Thus they represent the major areas of concern about the sufficiency of water resources within the Verde River basin to sustain both an expanding population and a perennially-flowing Verde River.

Figure 6.4. USGS Paulden Gage. Photograph of stream gage USGS 09503700 Verde River near Paulden. Courtesy of Gary Beverly.

Stream gage: contains instrumentation that measures the amount of water flowing in a river or stream. The volume of flow per unit time is called the stream's discharge; it is usually expressed as cubic feet per second (cfs). Generally, discharge measurements occur automatically every 15 minutes, or more frequently in times of flooding. The measurement data are automatically transmitted by telemetry to the appropriate USGS office and posted on the web.

The USGS stream gage on the Verde River near Paulden is shown above (Figure 6.4). The records of river flow measured at USGS stream gages on the Verde River are available online. See:

Gage Verde River near Paulden: http://waterdata.usgs.gov/az/nwis/uv?09503700
Gage Verde River near Clarkdale:
http://nwis.waterdata.usgs.gov/az/nwis/uv/?site_no=09504000&agency_cd=USGS
Gage Verde River near Camp Verde:
http://nwis.waterdata.usgs.gov/az/nwis/uv/?site_no=09506000&agency_cd=USGS

Prescott Active Management Area

The Prescott Active Management Area (PrAMA; Figure 6.3) was created by Arizona's 1980 Groundwater Management Act and operates under the direction of the Arizona Department of Water Resources. The PrAMA is one of five Active Management Areas within Arizona that were instituted to reduce localized groundwater overdraft; three, the PrAMA and the Phoenix and Tucson Active Management Areas are charged to attempt achievement of safe-yield by 2025. Safe-yield means that the amount of groundwater pumped from the aquifer on an average annual basis must not exceed the amount of water that is naturally or artificially recharged. The area of the PrAMA coincides with two Department of Water Resources administrative groundwater sub-basins—the above-mentioned Little Chino sub-basin, which drains to the Verde River, and the Upper Agua-Fria sub-basin, which drains to the Agua Fria River.

Verde River Groundwater and Surface-Water Systems

Stream flow in the Verde River and its perennial tributaries is dependent on two sources of water: (1) base flow, which is the component of groundwater discharge to the river and its perennial tributaries, and (2) runoff from storms and snowmelt. This section deals with the groundwater and its critical role of providing Verde River base flow, which sustains flow in the river during periods of no precipitation.

Groundwater Flow

An important step in developing the Northern Arizona regional numerical groundwater model (Pool and others, 2011) was to determine the predevelopment (taken in this case as representing the groundwater system in 1910) groundwater conditions as rigorously as possible. Figure 6.5 portrays the simulated predevelopment water-table contours and groundwater flow directions for the part of the model area in which the flowing groundwater, except for that intercepted by springs and riparian vegetation, is en route to the Verde River. Pool and others note that: "*The groundwater flow system in 1910 was dominated by natural conditions across most of the study area except in the Little Chino and Verde valley sub-basins where the natural groundwater system was altered by surface-water diversions for agricultural use. Natural predevelopment conditions prior to surface-water diversions were not simulated because data to define that system are sparse*."

Why "simulated"? Neither predevelopment groundwater conditions nor predictions of future groundwater conditions can be directly measured. Thus, they are simulated, and the process can be described briefly as follows: The predictive capability of a numerical groundwater model depends upon the degree to which the model accurately simulates the groundwater system being modeled, i.e., the processes of recharge and discharge, and the rock properties that control the rates of movement and storage change of water within the groundwater system. Most numerical groundwater models are first constructed to simulate natural conditions prior, insofar as possible, to the earliest groundwater pumping. This process is referred to as steady-state model calibration. Following the steady-state calibration, the model is then adjusted in a process referred to as transient-model calibration to reproduce in a series of time steps (for example, decade-long intervals) known stresses (for example, groundwater pumping and artificial recharge) and their hydrologic effects (for example, changes in hydraulic heads and measured base flow). This process is referred to as transient-model calibration. The degree to which a model simulates the hydrologic effects of the known stresses throughout the transient-model calibration provides the modeler with an indication of the predictive capability of the model.

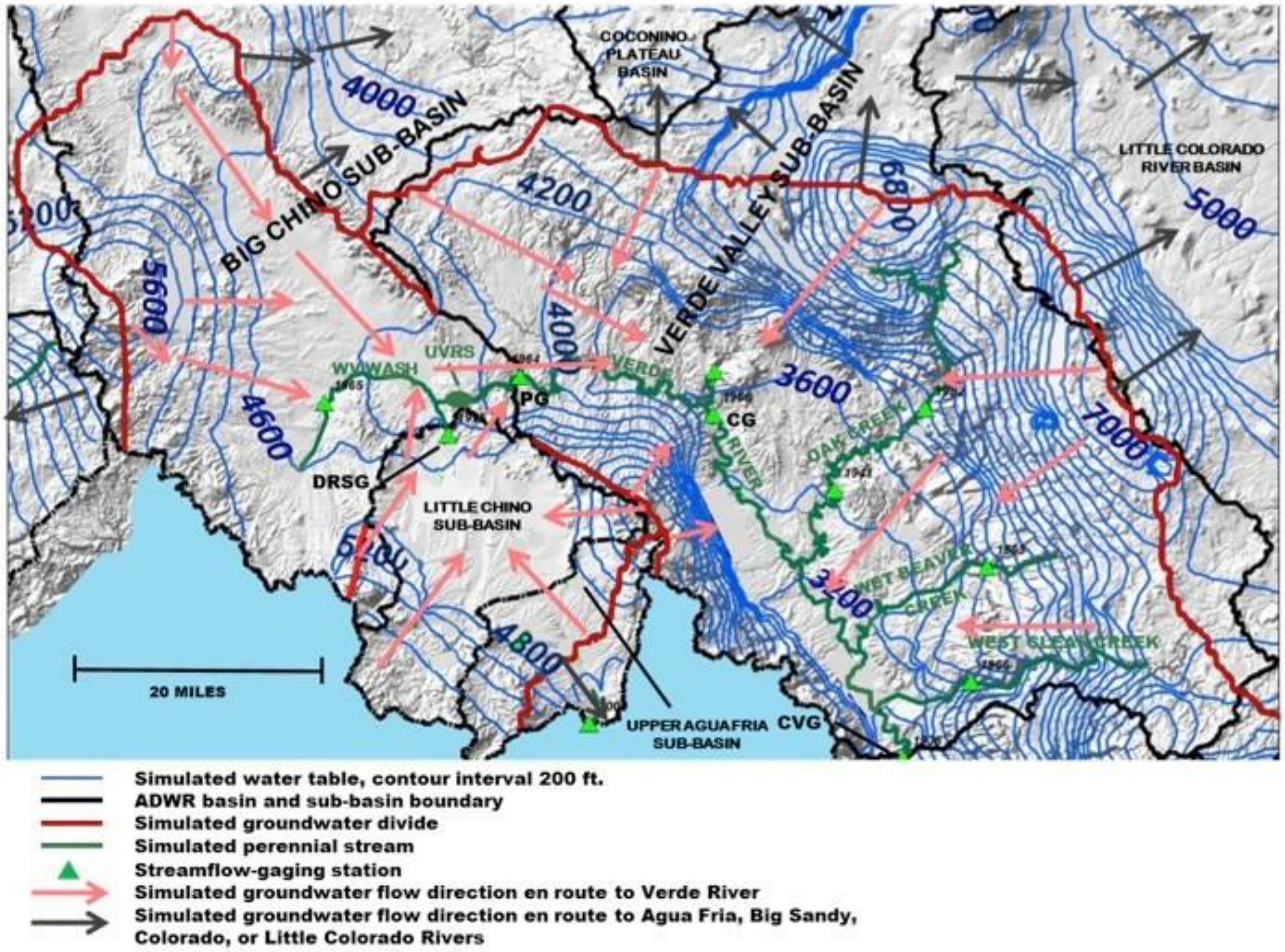


Figure 6.5. Map showing simulated predevelopment water-table contours and groundwater flow directions in the upper and middle Verde River watersheds and parts of the immediately adjacent watersheds. After Pool and others (2011). WV Wash, Williamson Valley Wash; UVRS, upper Verde River springs. Specifically identified USGS stream gages: DRSG, Del Rio Springs near Chino Valley (09502900); PG, Verde River near Paulden (09503700); CG, Verde River near Clarkdale (09504000); CVG, Verde River near Camp Verde (09505000).

Figure 6.5 shows the boundaries of the Arizona Department of Water Resources administrative groundwater basins and sub-basins (thick black lines) within and near the upper and middle Verde River watersheds. It also shows the simulated groundwater divides (thick red lines) within the upper and middle Verde River watersheds. The simulated predevelopment Big Chino and Verde Valley groundwater basins, as bounded by the simulated groundwater divides are substantially smaller than the Big Chino and Verde Valley administrative groundwater sub-basins designated by the Arizona Department of Water Resources (Figure 6.3). Those administrative groundwater sub-basins, as defined by the Department of Water Resources, are to a large extent watersheds—i.e., surface-water drainage basins.

Figure 6.5 also shows the simulated predevelopment water table, represented by contours with 200-foot spacing. The arrows show the directions of groundwater flow based on the water-table contours (groundwater flow direction is always perpendicular to the contours and directed from areas of greater hydraulic head to areas of lower hydraulic head).

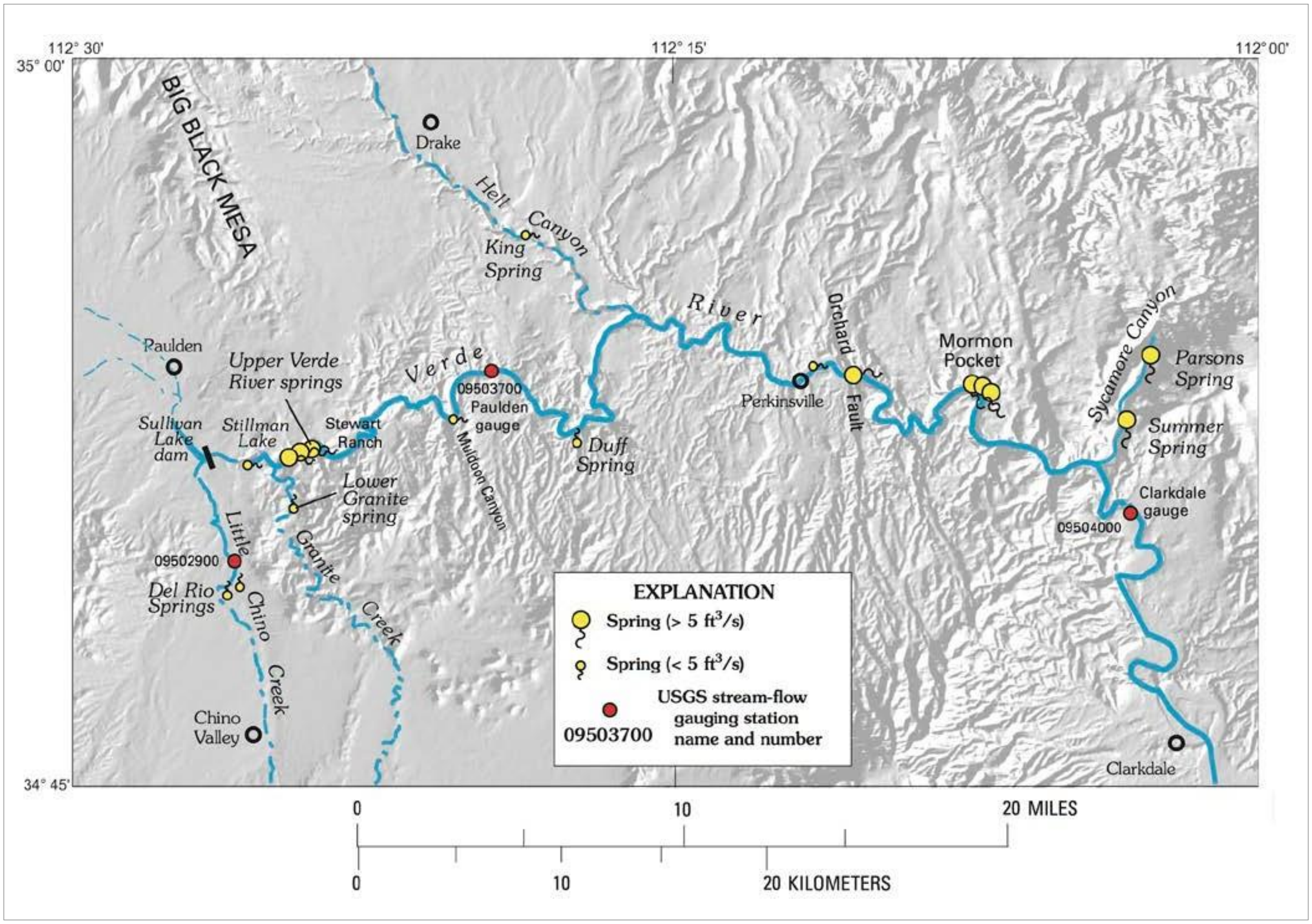


Figure 6.6. Map showing the Verde River from Paulden to Clarkdale, including location of the upper Verde River springs, Perkinsville, and locations of the Paulden, Clarkdale and Del Rio Springs stream gages. (Wirt, 2005a).

A critical observation that can be made from Figure 6.5 is that most of the groundwater within the areas of the simulated Big Chino and Little Chino groundwater basins is en route to discharge at the upper Verde River springs. All of the groundwater discharging from the springs is recorded as base flow at the Paulden gage (see Figure 6.6 for locations). However, some groundwater flows eastward across the boundary between the Big Chino and Verde Valley administrative groundwater sub-basins; some part of that eastward-flowing groundwater may bypass the Paulden gage. The water-table contours and the flow directions derived from them suggest that base flow measured at the Paulden gage is derived solely from the Big Chino and Little Chino groundwater basins and that no groundwater from elsewhere reaches the Paulden gage.

Vigorous perennial flow of the Verde River begins about 300 feet downstream from the mouth of Granite Creek at the upper Verde River springs (Figure 6.6). The springs, which extend about 2.4 miles downstream supply more than 90 percent of the base flow measured at the Paulden gage (Wirt, 2005b). The upper Verde River springs, as well as the other springs shown in Figure 6.6, mark locations in which the upper part of the Verde River, as well as in the lower part of Sycamore Creek, intersects the water table.

In a detailed analysis of geochemical measurements, Wirt (2005b) concluded that groundwater from the Big Chino and Little Chino sub-basins supplies between 94 and 100 percent (between approximately 80 and 86 percent from the Big Chino and approximately 14 percent from the Little Chino) of the discharge to the upper Verde River springs. She suggested that the same relationship exists about 5½ miles farther downstream for base flow at the Paulden gage. The uncertainty of 6 percent reflects her conclusion based on geochemistry that between 0 and 6 percent of that base flow could have originated from a Paleozoic-age limestone aquifer to the north. However, the groundwater flow directions implied by the water-table contours of Figure 6.5 suggest that all of the base flow passing the Paulden gage originates from the Big and Little Chino sub-basins.

Base Flow along the Verde River

Average annual base flow in the upper part of the Verde River generally decreases (Figure 6.7) downstream from the Paulden gage for the next 14 miles to Perkinsville—owing to (1) infiltration of stream flow to the underlying aquifer and (2) in part to evapotranspiration.

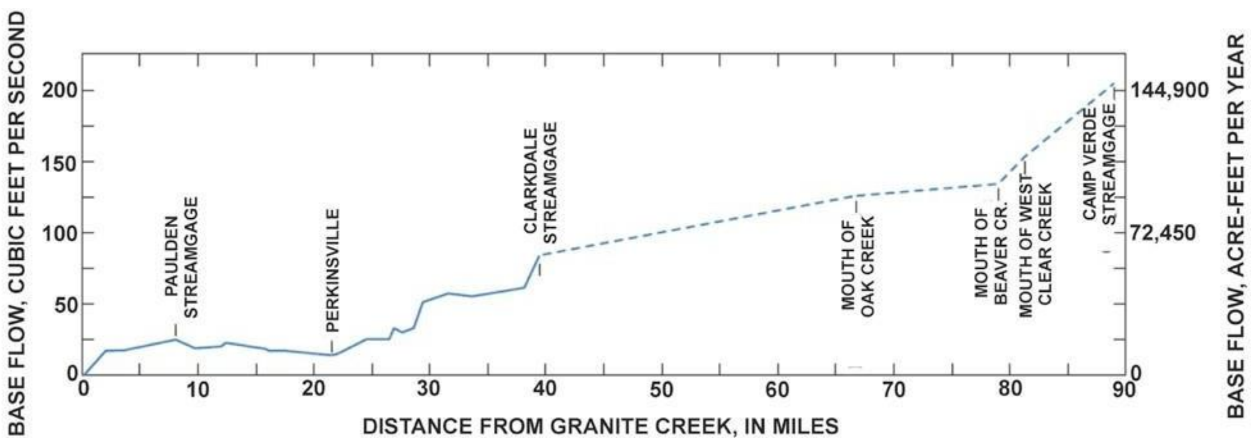


Figure 6.7. Base flow in the Verde River from the mouth of Granite Creek to the gaging station near Camp Verde (09506000). Modified from Blasch and others (2006).

Springs downstream from Perkinsville along the upper Verde as well as in Sycamore Canyon add substantial base flow to the Verde River, which enters the Verde Valley immediately below the Clarkdale gage.

Base flow continues to increase downstream through the Verde Valley to the stream gage near Camp Verde (Figure 6.7). In this Verde Valley reach of the river, the generally increased base flow reflects both base-flow contributions from the river's perennial tributaries—Oak Creek, Beaver Creek, and West Clear Creek—and direct contributions of groundwater in reaches in which the Verde River intersects the water table. In fact, along its entire length from the headwater springs to the stream gage near Camp Verde the river gains base flow from groundwater where the river intersects the water table and provides recharge to the groundwater in reaches in which the river bed is above the water table. **Thus the river and its flowing tributaries are all part of a single intimately connected and mutually interdependent surface-water and groundwater system.**

Annual Streamflow, Base Flow, and Runoff along the Verde River

Annual streamflow in the Verde River and its perennial tributaries reflects the contributions of both groundwater and runoff. Runoff occurs primarily in response to local summer monsoon storms and more regional winter storms that provide rain or, eventually, runoff of snowmelt.

Blasch and others (2006) provided average annual values for total streamflow and the base-flow and runoff components of annual streamflow for the periods of record (through March 2004) at the three USGS stream gages on the Verde River within the upper and middle Verde River watersheds (Table 6.1). These values provide a useful documented standard against which to judge subsequent and future changes in river flow.

USGS stream gage	Period of record	Average annual total streamflow	Base-flow component of total streamflow	Runoff component of total streamflow
Verde River near Paulden	July 1963 to March 2004	30,700 ac-ft/yr (42.4 cfs)	17,700 ac-ft/yr (24.4 cfs) [58 pct.]	13,000 ac-ft/yr (17.9 cfs) [42 pct.]
Verde River near Clarkdale	April 1965 to March 2004	122,100 ac-ft/yr (168.5 cfs)	57,200 ac-ft/yr (79.0 cfs) [47 pct.]	64,900 ac-ft/yr (89.6 cfs) [53 pct.]
Verde River near Camp Verde*	April 1934 to September 1945; October 1988 to March 2004	295,400 ac-ft/yr (407.7 cfs)	138,800 ac-ft/yr (191.6 cfs) [47 pct.]	156,600 ac-ft/yr (216.1 cfs) [53 pct.]
*Large-scale diversions for irrigation occur upstream from the stream gage; thus a fraction of the runoff and base-flow components is not accounted for in this table.				

Table 6.1. Average annual stream flow, base flow, and runoff for the periods of record at the USGS Paulden, Clarkdale, and Camp Verde stream gages (after Blasch and others, 2006).

Acre-feet per year (ac-ft/yr): One acre-foot is the volume of water that would cover one acre (43,560 square feet) with water one foot deep. An acre-foot of water contains approximately 325,851 gallons of water. A flow rate (discharge) in a stream of one acre-foot per year means passage over a year's time of 325,851 gallons of water in the stream. One acre-foot per year = approximately 0.00138 cubic feet per second.

Cubic feet per second (cfs): One cubic foot is the volume of water that would fill a container that is one foot deep and one foot square. A cubic foot of water contains 7.48 gallons of water. A flow rate (discharge) in a stream of one cubic foot per second means passage each second of 7.48 gallons of water in the stream. One cubic foot per second = approximately 724.5 acre-foot per year.

Seasonality of Base Flow along the Verde River

Blasch and others (2006) also provided estimates of average winter base flow and average summer base flow through 2003 at the USGS stream gages on the Verde River (Table 6.2). Note that average winter base flow exceeds average summer base flow at the Paulden stream gage by about 1.8 cfs or about 1,300 ac-ft/yr. Similarly, average winter base flow exceeds average summer base flow at the Clarkdale stream gage by about 6.9 cfs or about 5,000 acre-feet per year. The differences between summer and winter base-flow estimates largely reflect the enhanced warm-weather rates of evaporation from open water and of riparian evapotranspiration during the growing season.

USGS stream gage	Period of record	Average winter base flow	Average summer base flow
Verde River near Paulden	1964- 2003	18,200 ac-ft/yr (25.1 cfs)	16,900 ac-ft/yr (23.3 cfs)
Verde River near Clarkdale	1966-2003	60,500 ac-ft/yr (83.5 cfs)	55,500 ac-ft/yr (76.6 cfs)
Verde River near Camp Verde	1934-1945 1989-2003	155,000 ac-ft/yr (213.9 cfs) 144,000 ac-ft/yr (198.8 cfs)	NC

Table 6.2. Average winter and summer base flow for the periods of record at the USGS Paulden, Clarkdale, and Camp Verde stream gages (after Blasch and others, 2006). NC, not calculated.

The relative contributions of base flow and runoff as well as the seasonal variation in base flow are nicely illustrated in a graph (Figure 6.8) of average daily streamflow during calendar year 2010 at the USGS stream gage near Clarkdale, at the upstream end of the Verde Valley. The graph shows the effect of enhanced runoff from winter storms or snow melt from mid-January through April and again in late December, and some monsoon storm-related peaks from late July through early October.

Low relatively flat parts of the curve with average daily discharge barely above 60 cfs from late May through most of July and again in late September 2010 record periods of minimal or zero contribution from runoff—in other words, periods in which the river flow was largely if not entirely sustained by summer base flow. In November and early December, as well as in early January, the river flow is again low, but about 10 cfs higher than the low summer flow. This low winter discharge also reflects periods of minimal or zero contribution to the river from runoff—i.e., periods when the river was largely if not entirely sustained by base flow. The difference of about 10 cfs between winter and summer base-flow values primarily reflects the seasonal difference above the gage during 2010 in evaporation from open water and riparian evapotranspiration.

Irrespective of the season, without the steady contribution of groundwater (base flow) above the Clarkdale gage the river would have been dry at the gage during the long periods between the storm-related peaks in discharge. Importantly, the Verde River's established riparian habitat, along with the wildlife and human activities that the Verde River supports, requires the maintenance of perennial streamflow.

Blasch and others (2006) reported no estimate for average summer base flow at the Camp Verde stream gage (Table 6.2) because large-scale diversions of streamflow for irrigation within the Verde Valley during the growing season greatly reduce the summer streamflow measured there.

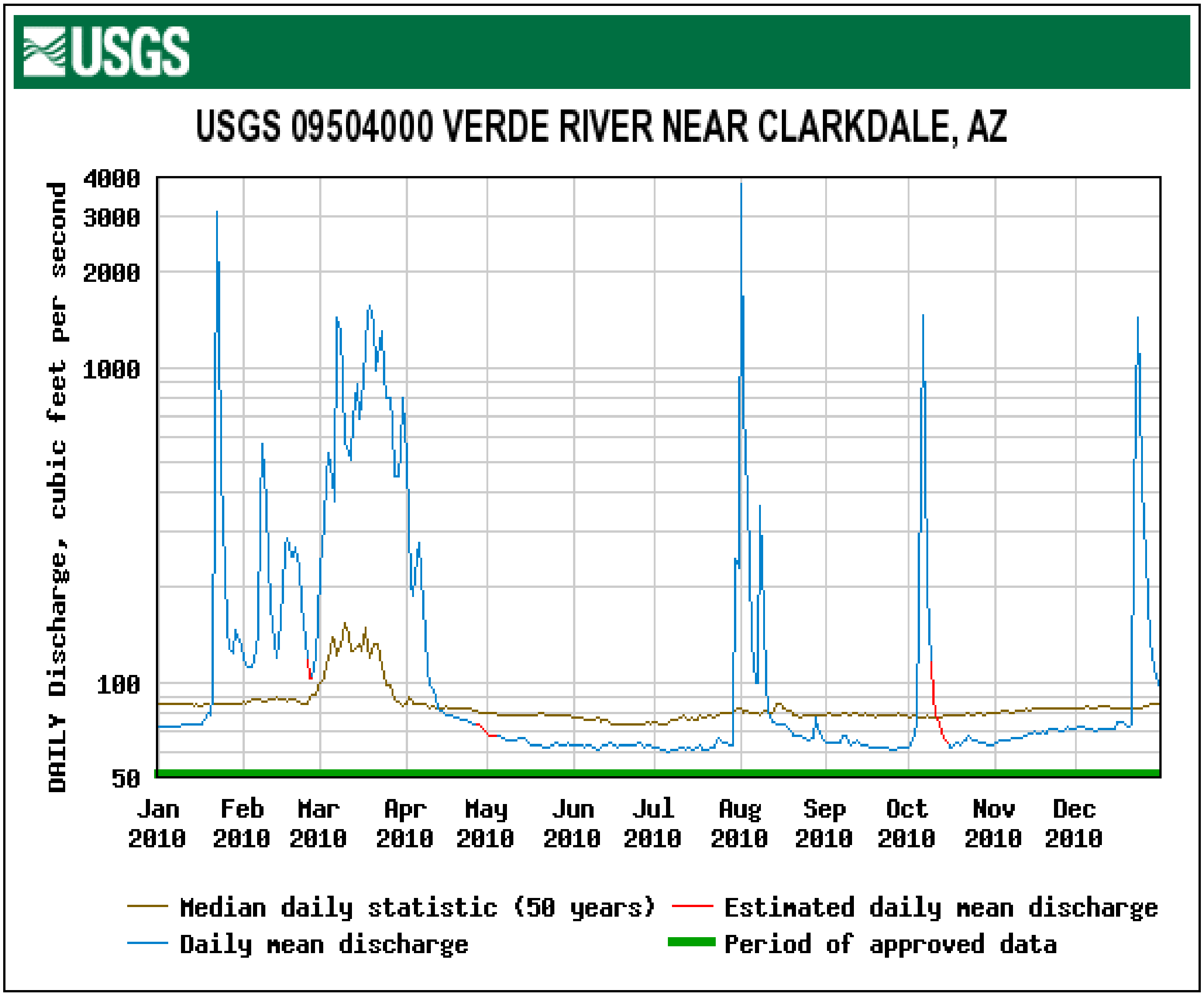


Figure 6.8. Blue curve: daily streamflow record from January 1, 2010, through December 31, 2010, from the USGS Clarkdale stream gage. Brown curve: average daily streamflow based on 50 years of measurement at the USGS Clarkdale stream gage.

Irrigation Diversions

An important component of Verde Valley water use and river dynamics is represented by river diversions for irrigation along the Verde River and its perennial Verde Valley tributaries, Oak Creek, Wet Beaver Creek, and West Clear Creek. Irrigation for farming in the Verde Valley is supplied primarily by surface water delivered by ditches. There are more than 67 surface-water diversions from the Verde River and its perennial tributaries (Garner and Bills, 2012).

There are seven major diversions and related irrigation systems along the Verde River itself (Figure 6.9).

The first irrigation ditch of modern times in the Verde Valley was constructed in the 1860s, and by the early 1900s, more than 50 ditches had been established. A surface-water right is attached to a specific piece of land. In recent years there has been a continuing conversion of farmland to residential development; thus, there is a continuing redirection of surface-water irrigation from agriculture to residential plots in the Verde Valley.

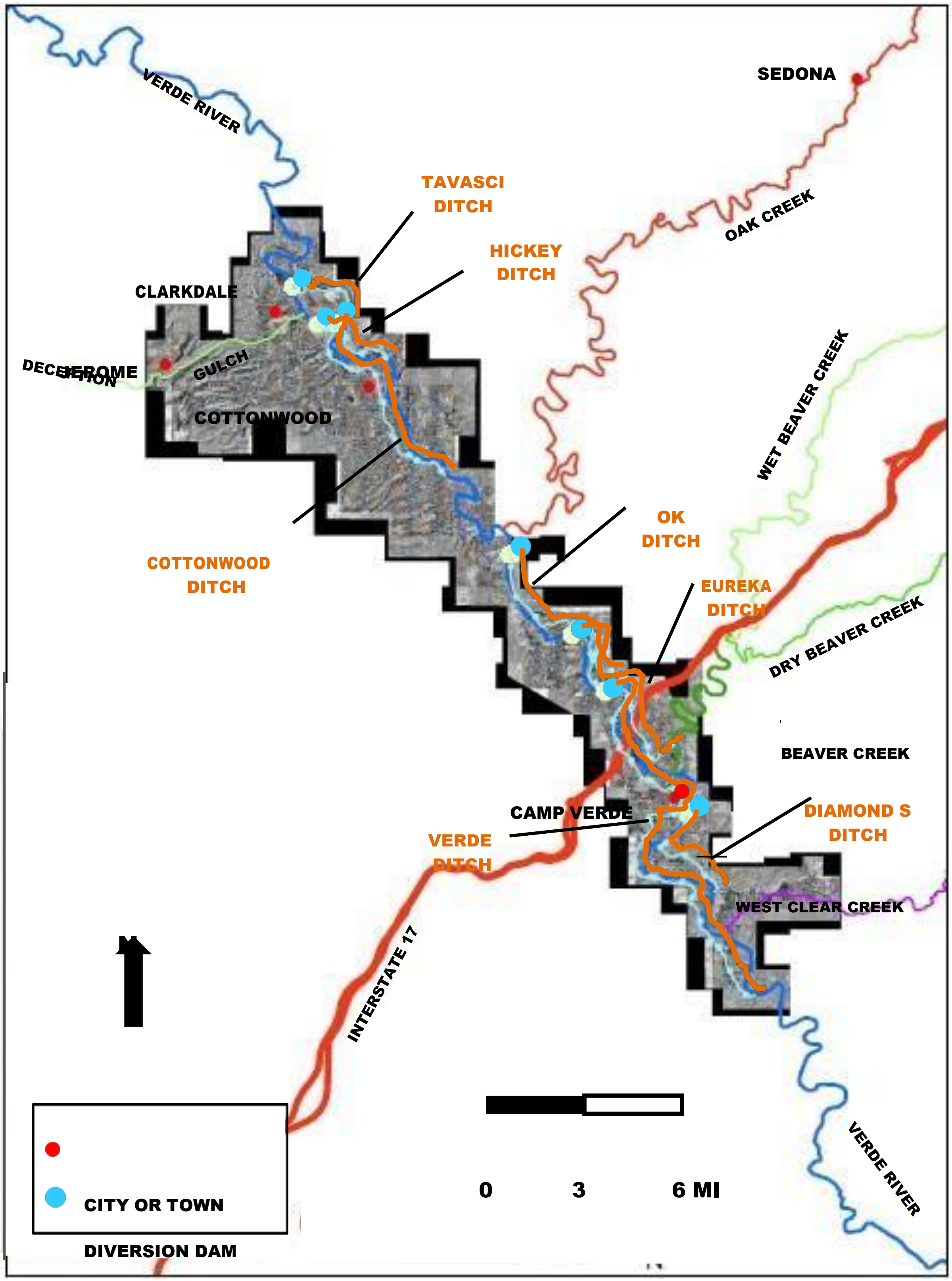


Figure 6.9. Irrigation ditches along the Verde River in the Verde Valley. Courtesy of R.P. Ross, U.S. Geological Survey (modified).

The right to divert surface water in Arizona is governed under state law by the doctrine of prior appropriation—"first in time, first in right". Thus, the earliest-established (senior) users of river or stream water have first priority, and the rights of later-arriving (junior) users are subordinate to those of senior users. When there is a shortage of water, a junior user's claim is satisfied only after all senior claims have been satisfied. Importantly, virtually all surface water in Verde Valley streams, including the Verde River, is fully appropriated.

Diversion of streamflow along the Verde River is generally achieved via construction of a dam of gravel (Figure 6.10) that directs the flow through a head gate into an irrigation ditch (Figures 6.11 and 6.12). Such diversion dams are easily built or repaired by a bulldozer that scrapes gravel and boulders from the stream bed or banks. Some of the diversions completely block streamflow immediately below the dam during the irrigation season, forming a barrier to migration of aquatic organisms during the irrigation season. Spring runoff commonly breaches the dams.

Figure 6.10. Cottonwood ditch diversion dam on the Verde River, breached, presumably by a winter flood event. Photo taken March 15, 2007. Courtesy of Jeanmarie Haney, The Nature Conservancy.

Delivery of the diverted streamflow depends on gravity. Thus, the water supplied for irrigation along each ditch system must flow downhill from the diversion dam. Accordingly, irrigation supplied by diversions is generally limited to low alluvial terraces that are not far above the elevation of the nearby river or tributary. The thickness of such alluvial terraces close to the Verde River or its tributaries is generally no more than a few tens of feet.

Alluvial terrace: A relatively long, narrow, gently-sloping surface composed of unconsolidated alluvium (gravel, sand, silt, clay) that was deposited in a formerly active floodplain of a stream and now stands above the stream owing to erosional downcutting of the stream channel.

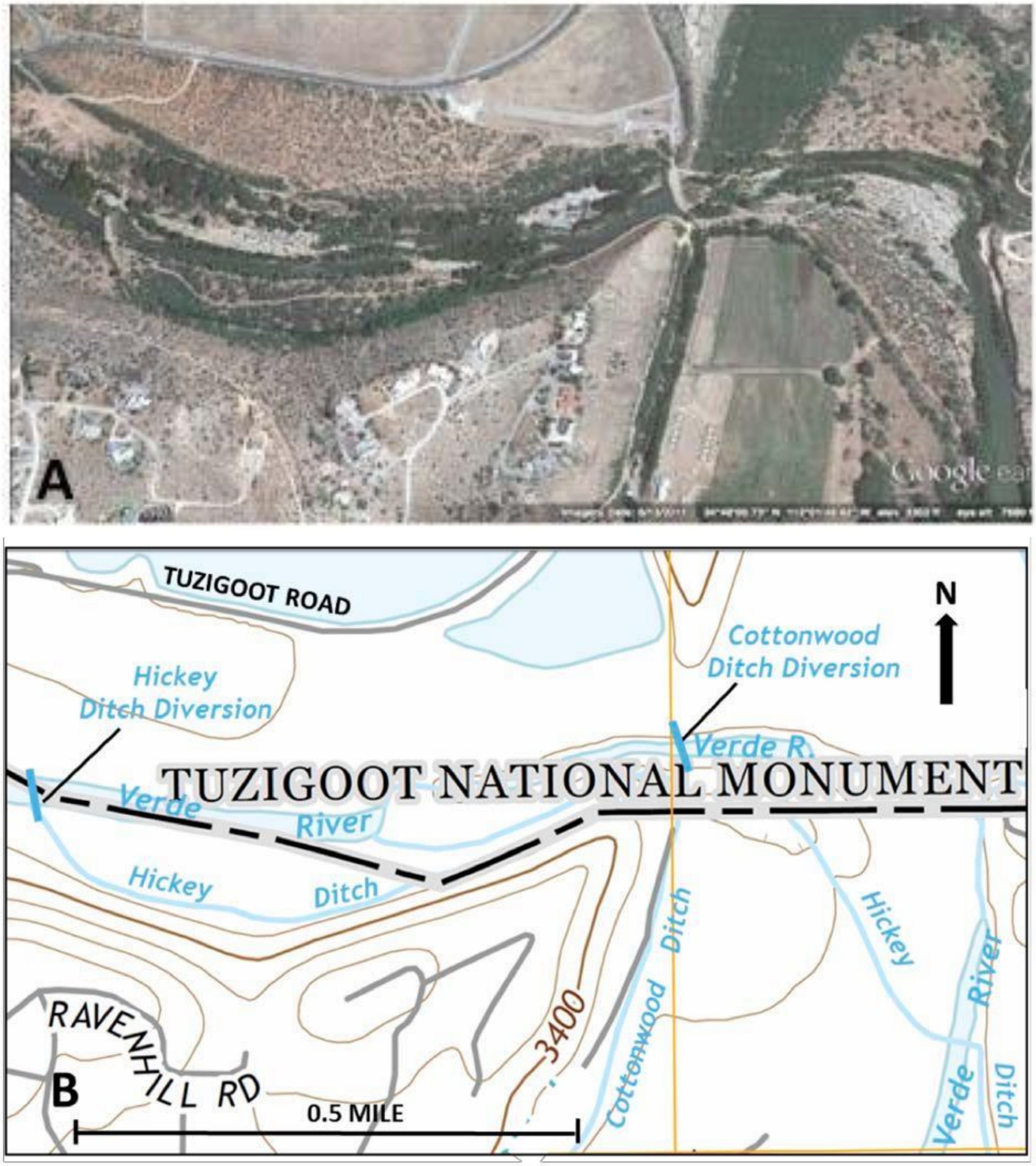


Figure 6.11. Aerial image and map showing parts of the Hickey and Cottonwood ditches and the diversion dams for the two ditches. Verde River flows from west to east in the upper part of the image and map areas, then swings south in the southeastern part of the image and map areas.

A. Google Earth image, date 6/13/2011. Note that the paths of the irrigation ditches are marked by narrow bands of relatively dense vegetation.

B. Topographic map of the approximate area of A. The Hickey ditch crosses over the Cottonwood ditch via a flume near the south end of the Cottonwood ditch diversion dam and crosses the Verde River via a flume in the southeast corner of the map area. Modified from U.S. Geological Survey Clarkdale, AZ, 7.5-minute quadrangle, 1:24,000 scale, 2014.

Figure 6.12. Aerial view of the Hickey ditch diversion dam. See fig. 6.11 for location. North is at top. Verde River flows around north end of the diversion dam and returns immediately to its natural channel. The diverted portion of the Verde River is visible flowing southeast in the bottom-center part of the image. Google Earth Imagery date 6/13/2011.

The amount of diverted streamflow actually used for irrigation in the Verde Valley has never been directly measured. An Arizona Department of Water Resources analysis (ADWR, 2000) provided an estimate that approximately 17,000 acre-feet of irrigation water would have been required annually to irrigate crops in 1996 and 1997 over an area of about 5,380 acres in the Verde Valley. Including another 860 acres that were not in production at the time, the estimated annual requirement would have been about 19,660 acre-feet for the amount of delivered irrigation water. A field-based survey of crop consumptive use throughout the Verde Valley estimated 10,000 acre-feet of evapotranspiration from irrigated fields during the 2010 growing season (Garner and Bills, 2012).

A recent USGS study (Garner and Bills, 2012; see Wolfe, 2012 for a synopsis) reported the results of two synoptic base-flow surveys—also called seepage runs—along the 51-mile reach of the Verde River between the Clarkdale and Camp Verde stream gages. One was conducted during the summer— June 20-21, 2007, and the second during the winter— February 1-3, 2011. Each survey consisted of tens of rigorous streamflow measurements collected in the shortest possible time frame: 2 days in the summer survey; 3 days in the winter survey. The seepage runs also included measurement of streamflow in Oak Creek, Beaver Creek, and West Clear Creek as close as possible to their confluences with the Verde River. These tributary measurements were important to evaluate the contributions of these perennial tributaries to Verde River streamflow at the time of the seepage runs. The streamflow-measurement results from the two surveys are portrayed graphically in Figure 6.13.

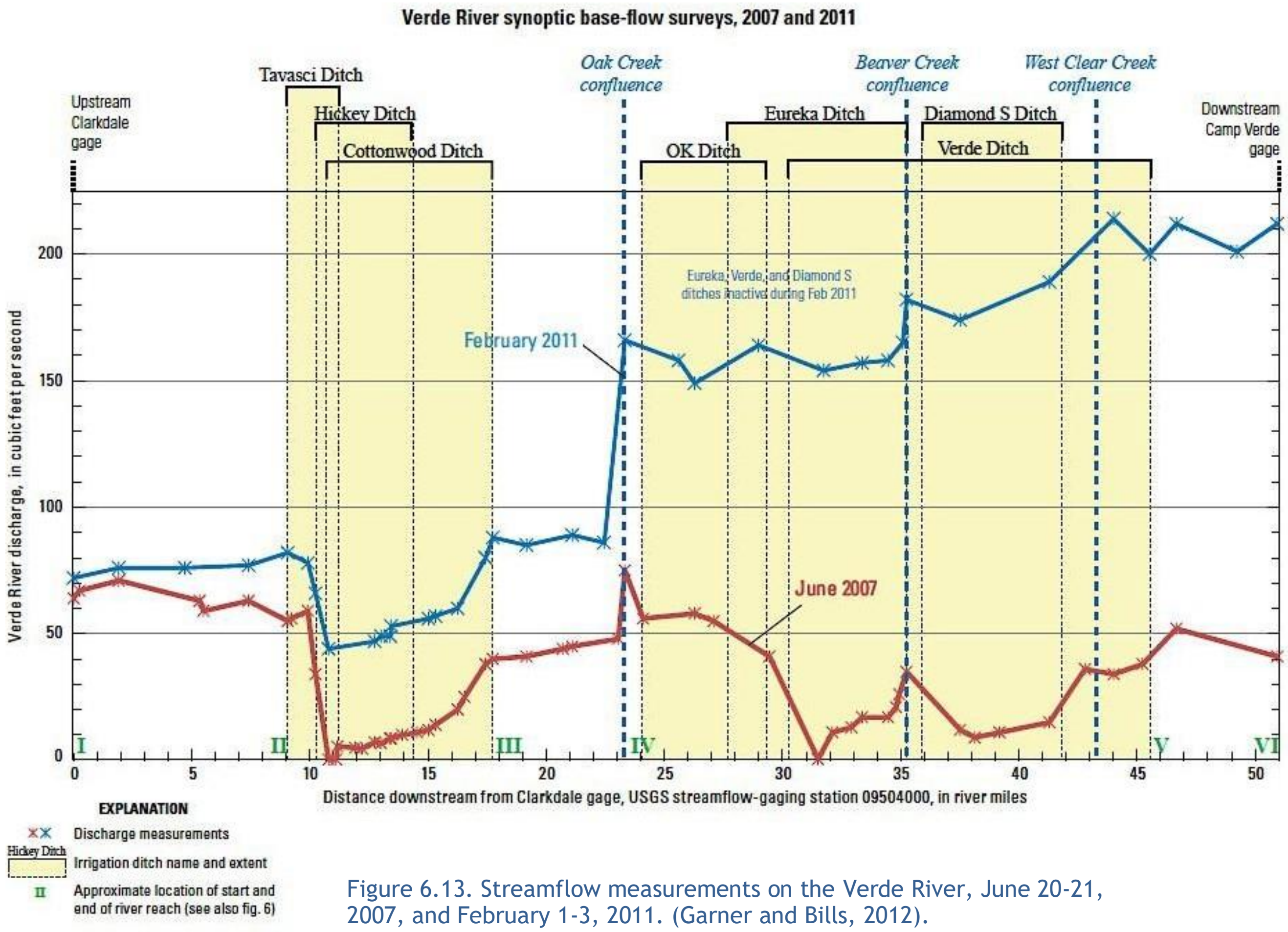


Figure 6.13. Streamflow measurements on the Verde River, June 20-21, 2007, and February 1-3, 2011. (Garner and Bills, 2012).

Both the winter and summer streamflow measurements were made essentially under base-flow conditions. That means that the surveys were made at times when there was neither precipitation nor evidence of storm-related runoff or substantial snowmelt-related runoff.

The selection of June and February for the two seepage runs permitted evaluation of streamflow under strongly contrasting seasonal conditions. In June, prior to the onset of summer monsoon rains, both evapotranspiration and diversion of river water for irrigation were in full operation. In February, both evapotranspiration and diversions were minimal.

Streamflow in the winter survey differed dramatically from streamflow in the summer survey (Figure 6.13; Table 6.3). The difference in streamflow between summer and winter is explained in part by evapotranspiration throughout the entire watershed above the Camp Verde stream gage and to a substantial degree by the effects of diversions during the growing season along the Verde River and its perennial tributaries.

	Streamflow Clarkdale Stream gage, cfs	Streamflow Camp Verde Stream gage, cfs	Difference between Stream gages, Camp Verde – Clarkdale, cfs
Feb 1-3, 2011 (Winter)	72	212	140
June 20-21, 2007 (Summer)	64	41	−23
Difference at stream gage, winter – summer, cfs	8	171	

Table 6.3. Streamflow measured at Clarkdale and Camp Verde stream gages, February 1-3, 2011, and June 20-21, 2007.

- In the winter, survey streamflow increased from 72 cfs at the Clarkdale stream gage to 212 cfs at the Camp Verde stream gage, for a gain of 140 cfs.
- In the summer, survey streamflow decreased from 64 cfs at the Clarkdale stream gage to 41 cfs at the Camp Verde stream gage, for a loss of 23 cfs.
- Streamflow at the Camp Verde stream gage in the winter survey was 171 cfs greater than streamflow there in the summer survey.

Some of the diverted streamflow irrigates agricultural fields, gardens, and lawns. Some infiltrates through both the purposely irrigated surfaces of farm fields, gardens, and lawns, and also through the walls and floors of the ditch systems that deliver the water. In either case, the diverted water supports vegetation—commercial crops, gardens, and lawns as well as accidental vegetation that has invaded along the ditches—that would not otherwise exist. The infiltrated diversion water supports a shallow aquifer system that would not otherwise be present and that may be either locally or extensively perched.

Groundwater stored in this human-generated aquifer system either percolates downward into the underlying basin-fill aquifer or seeps back to the river. Any diverted water that escapes infiltration, evaporation, consumption by crops, lawns, or gardens, or by volunteer vegetation that has invaded along the ditches returns as surface water directly from the ditch system to the river.

The water budget of the diverted streamflow is not well understood. It is certain that the volume of water diverted annually from the river is substantially greater than the volume required for irrigation of crops gardens and lawns. Initial effort to increase the efficiency of diversion, delivery, and application of diverted water for irrigation is under way for some of the ditch systems. An important goal for water-resource management in the Verde Valley would be to quantify the interrelations in both time and space of the diverted streamflow: the quantity diverted, the quantities required and actually used for irrigation, the quantity that supports accidental vegetation along the ditches, the storage and movement of groundwater within the artificially supported alluvial-terrace aquifers, and the flow paths and quantities and rates of transport of that groundwater either back to the streams or to the underlying regional aquifer.

Chapter 7: Pumping and Its Effect on Groundwater and Streamflow in the Upper and Middle Verde River Watersheds

Chapter 7: Pumping and Its Effect on Groundwater and Streamflow in the Upper and Middle Verde River Watersheds

Streamflow Depletion: A Consequence of Groundwater Pumping

In a predevelopment groundwater/streamflow system—one in which no human-driven modification such as pumping or irrigation has yet occurred—groundwater recharge and groundwater discharge to springs, streams, and for consumption by riparian vegetation are in long-term balance. Of course, the balance may change seasonally or in response to variations in rainfall or snowfall from one year to the next or even over several years, but over the long term, in a predevelopment system, and barring long-term climate change, average groundwater discharge is assumed to equal average groundwater recharge.

Introduction of pumping from a well adds a new component of groundwater discharge from the aquifer, modifying the previous long-term balance between recharge and discharge. Hydrologists have long understood that all water withdrawn by a well is balanced by a loss of water from somewhere (Theis, 1940). As summarized by Alley and others (1999) *"The source of water for pumpage is supplied by (1) more water entering the groundwater system (increased recharge), (2) less water leaving the system (decreased discharge), (3) removal of water that was stored in the system, or some combination of these three."*

The Verde River and its perennial tributaries are connected to the basin's groundwater. Thus river flow and riparian vegetation connected to the groundwater system are eventually affected by pumping from wells. The effects of pumpage from a well near a perennial stream in a system like that of the Verde River basin are elegantly and very readably described by Leake and Pool (2010). A part of that description is quoted below:

"When water is initially pumped from a well, all of the water comes from storage around the well. A cone of depression develops around the well and the gradient of the groundwater head is the driving force for movement of water into the well. If the aquifer is unconfined, nearly all of the storage change is from draining of pore spaces at the water table. This resulting cone of depression can be thought of as a lowering of the water table around the well, with the greatest decline in the water table at the location of the well (Figure 7.1A)*. If the aquifer is confined, the change in storage is the combined effect of reduction of the sizes of pore spaces and expansion of water that results from decreasing the fluid pressure in the aquifer. This resulting cone of depression is an area of decreased fluid pressure around the well, with the greatest decrease in fluid pressure at the well."*

"As pumping continues, the cone of depression expands to increasing distances from the well. When the cone of depression expands into areas with streams, (Figure 7.1B) *wetlands, rivers, and lakes that are in hydraulic connection with the aquifer and areas of vegetation that use groundwater* [collectively, connected surface-water features], *the natural gradients that drive the exchange of groundwater between the aquifer and these features are altered. For surface-water features that under natural conditions lose water to the aquifer, the cone of depression from a well can increase the gradients from those features; and for surface-water features that gain water from the aquifer, the cone of depression can decrease the gradients to those features. Whether the case is a reduction of groundwater flow to a surface-water feature or an increase in surface-water flow to the aquifer system, there is a net loss in water in the feature. In areas where plants use groundwater* (Figure 7.1)*, the cone of depression can lower the water table and reduce the uptake of water by these plants. The change in availability of water to these plants and the surface-water features caused by a pumping well is generally referred to as…"streamflow depletion"…"where dominant changes are decreased outflow to or increased inflow from streams and rivers…"*

Streamflow depletion: Pumping-caused reduction of streamflow and connected riparian vegetation owing either to reduction of groundwater discharge to the stream or to increased infiltration of streamflow to the aquifer.

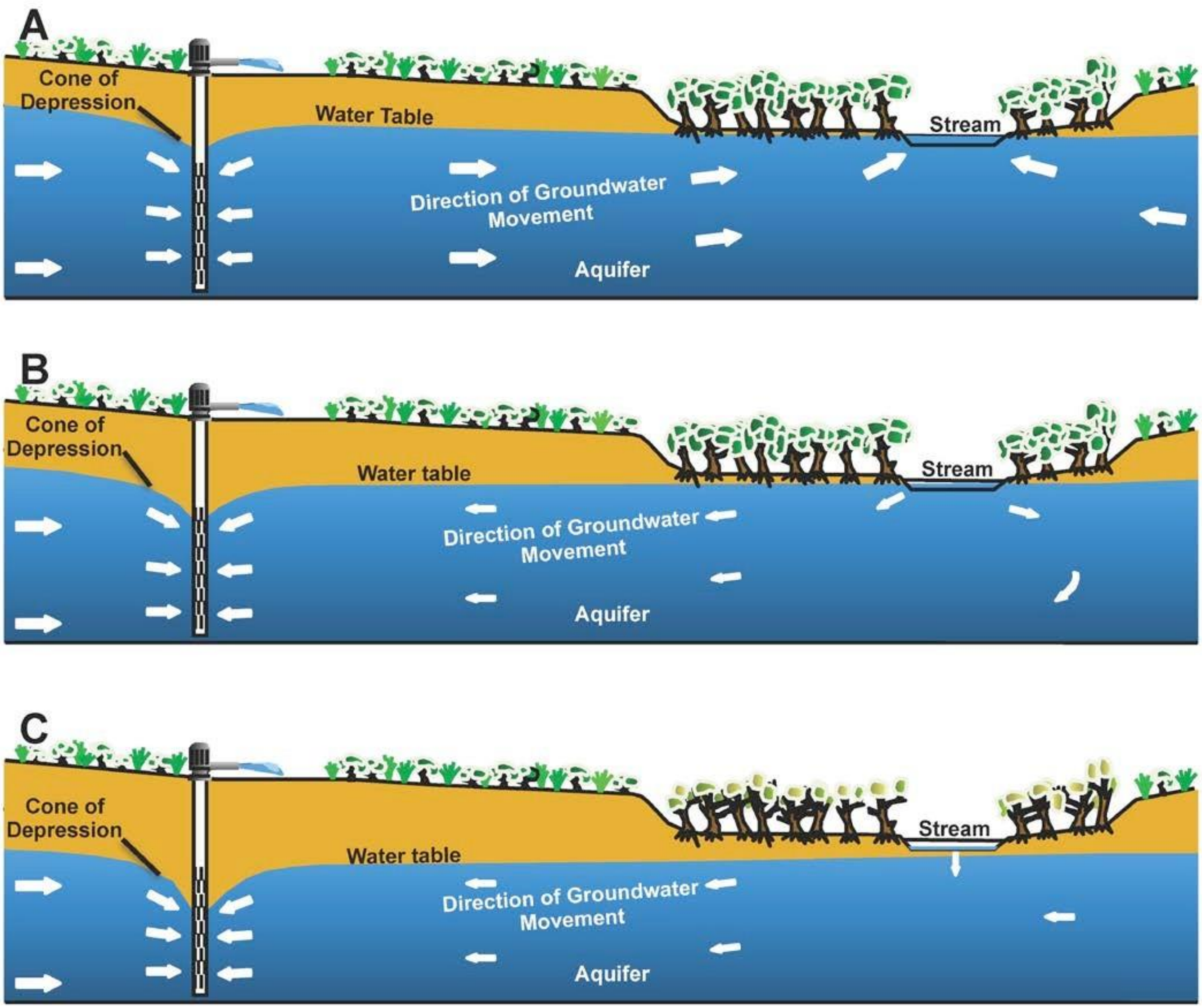


Figure 7.1. Schematic cross section illustrating the effects of a pumping well on a nearby stream. A. A cone of depression has developed around the well, but groundwater still discharges to the stream. B. After some time, the cone of depression has deepened and spread to the nearby stream, resulting in elimination of groundwater discharge to the stream and loss of water (infiltration) from the steam to the aquifer. C. When the stream cannot supply the quantity of water pumped, the stream may lose all its water to the aquifer and become ephemeral, and nearby riparian vegetation may be affected. (After Leake and Pool, 2010).

"The decreased outflow to and increased inflow from connected features is a source of water to the pumped well that tends to stabilize the cone of depression over time. If a well pumps for long enough at a constant rate and sufficient water can be captured from the connected features to supply the rate of water being pumped, the storage change in the aquifer from the pumping will diminish to zero and all of the water pumped by a well can be accounted for as changes in flow to or from connected features."

"The time over which all or nearly all of the groundwater pumping is supplied by connected features is dependent on (1) the proximity of the pumping wells to connected features that can supply water and (2) the hydraulic properties of the aquifer. In general, wells that are close to connected features will receive water from these features much faster than more distant wells. In cases where wells are many tens of miles from connected surface water, the time at which depletion is the dominant source of water to the well can be decades or even centuries after pumping begins. A graphical example of this process is shown in (Figure 7.2). *At time zero, when pumping begins, all of the water pumped is coming from storage in the aquifer. Over a period of 100 years in this example, the fraction of pumped water that comes from storage diminishes to 1 percent. The fraction of the pumping that is depletion (decrease in surface-water flow plus decrease in evapotranspiration) is the complement of the change in storage for any given time. For this example, depletion increases from zero initially to 99 percent at 100 years."*

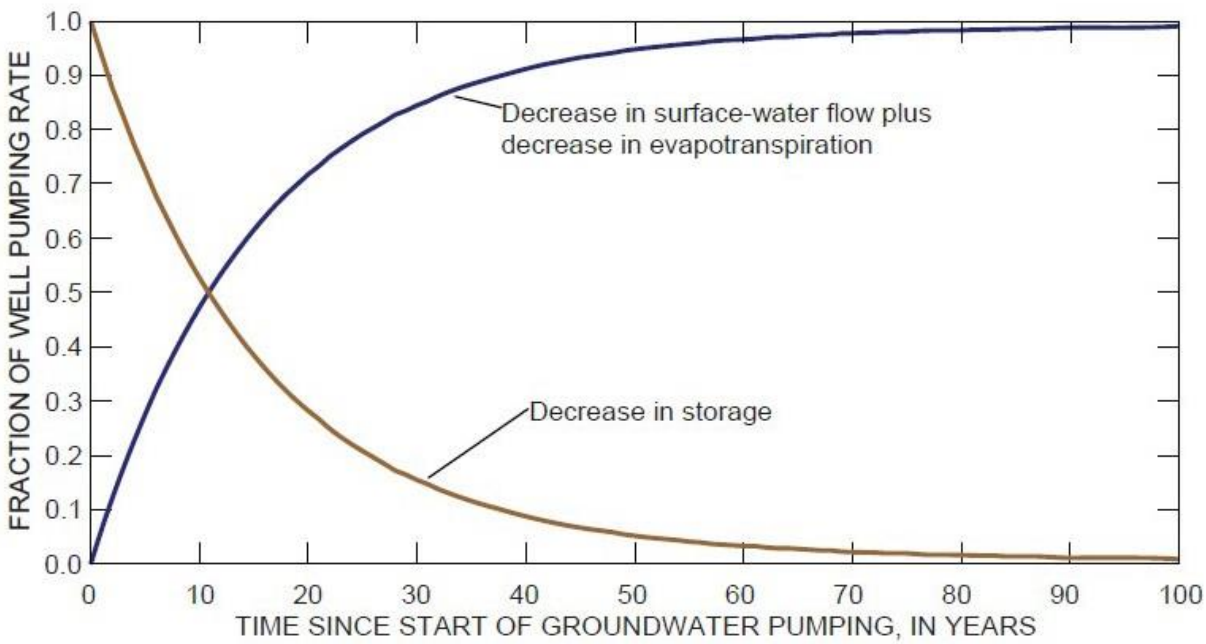


Figure 7.2. Sources of water to a pumped well through time (Leake and Pool, 2010). Note: The time scale of 100 years is arbitrary; the rate at which sources of water to a well change depends on the distance from the well connected features and the hydraulic properties of the aquifer.

Illustrations such as Figure 7.1, which portrays the effects of pumping on a nearby stream, may give the impression that capture requires that the water table near the well be lowered to an elevation lower than the stream bed. However, as illustrated in Figure 3.13, that is not the case. Reduction in hydraulic head at the well causes diversion of groundwater to the well from all directions. In response to the lowered hydraulic head at the well, the cone of depression spreads laterally in all directions, affecting connected surface-water features irrespective of whether they are up-gradient or down-gradient from the well.

Critically, if the rate of withdrawal of water from the aquifer exceeds the rate of discharge of groundwater to connected surface water features, those features eventually lose their perennial supply of groundwater. Consequently, affected streams become ephemeral, flowing only at times of increased runoff, and riparian vegetation may be deprived of its life-sustaining groundwater source (Figure 7.1C). The consequence is devastation of a formerly perennial river and the riparian habitat that it had supported—all too common effects of groundwater pumping in Arizona (Figure 7.3).

The question often asked is: How much groundwater is stored in the aquifer system? But from the standpoint of maintaining our perennial rivers, that question is irrelevant. In Arizona, if we pump and consume groundwater at a rate that exceeds the contribution of groundwater (base flow) to a connected river system, we eventually destroy the river's perennial flow and, along with it, the plant and animal populations and human lifestyles that the perennial river supports.

Figure 7.3. Former riparian zone along the Santa Cruz River north of Nogales, Arizona. Photo courtesy of Dan Campbell, The Nature Conservancy.

Streamflow Depletion in Action: Del Rio Springs, Little Chino Wash, Sullivan Lake, and the Uppermost Verde River

Depletion of discharge to springs and depletion of streamflow by pumpage of groundwater is instructively demonstrated by changes to Del Rio Springs (Figures 7.4 and 7.5), Little Chino Wash, Sullivan Lake, and the uppermost Verde River since the mid-20th century.

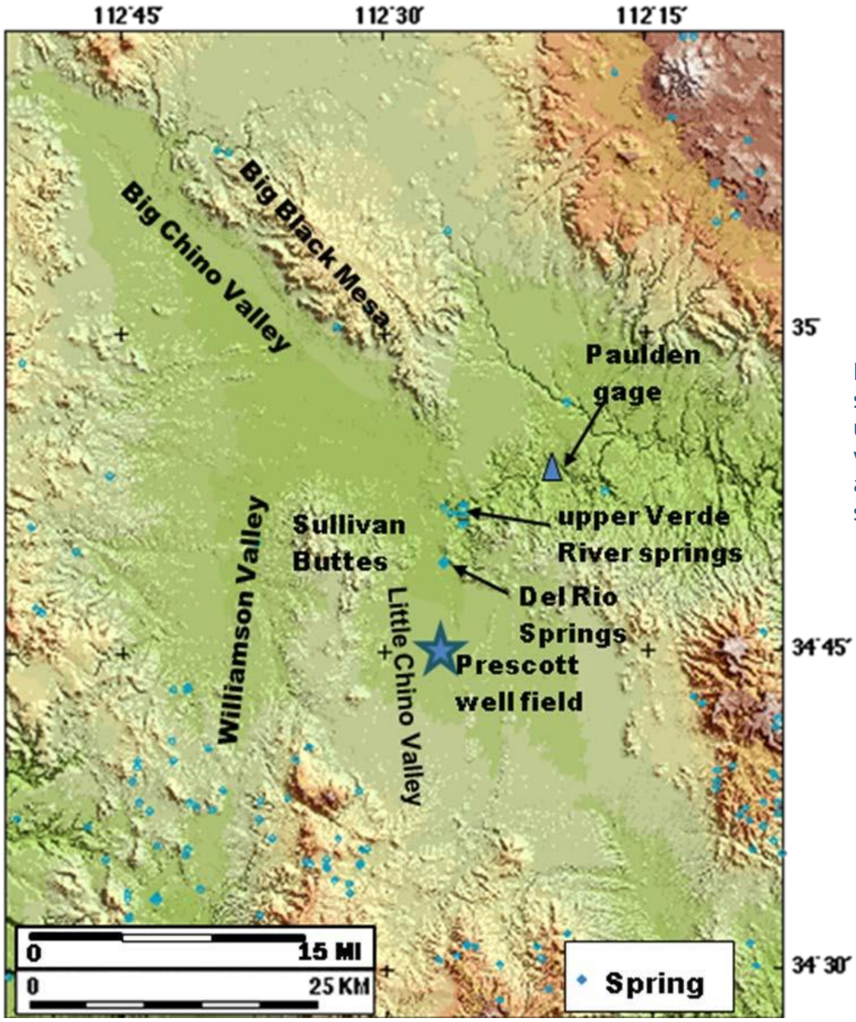


Figure 7.4. Shaded relief map showing locations of Del Rio Springs, upper Verde River springs, Prescott well field in the Town of Chino Valley, and their regional topographic settings.

Little Chino Wash (formerly called Del Rio Creek) was once a perennial stream originating at Del Rio Springs. It fed the formerly perennial Sullivan Lake (Figure 7.5), which emptied continuously to the Verde River. Medora Krieger (1965), who mapped the geology of the Prescott and Paulden area during 1947 through 1955, wrote: *"Perennial flow in streams is limited to the Verde River and two of its tributaries. Granite Creek has a permanent flow of water below a spring…about 0.8 mile south of the Verde River. Del Rio Creek issues from springs* [Del Rio Springs] *that tap the Chino artesian basin, and flows north to the headwaters of the Verde River".* Thus, in effect Del Rio Springs was the headwaters of the Verde River through the mid-20th century.

Sullivan Lake was created in the mid-1930s by construction of a small dam (Figure 7.6) just below the confluence of Big Chino Wash and Little Chino Wash at the upper end of the narrow steep- walled Verde River canyon, which is cut into basalt. The dam, which is considered to mark river-mile zero on the Verde River, was constructed to forestall headward cutting by the river into the lower part of Big Chino Wash (Corkhill and Mason, 1995). The lake, initially perennial but now ephemeral, was originally envisioned as a recreational feature. However, it was soon largely filled with sediment, and the lake's maximum depth now, when water is present, is no more than a few feet.

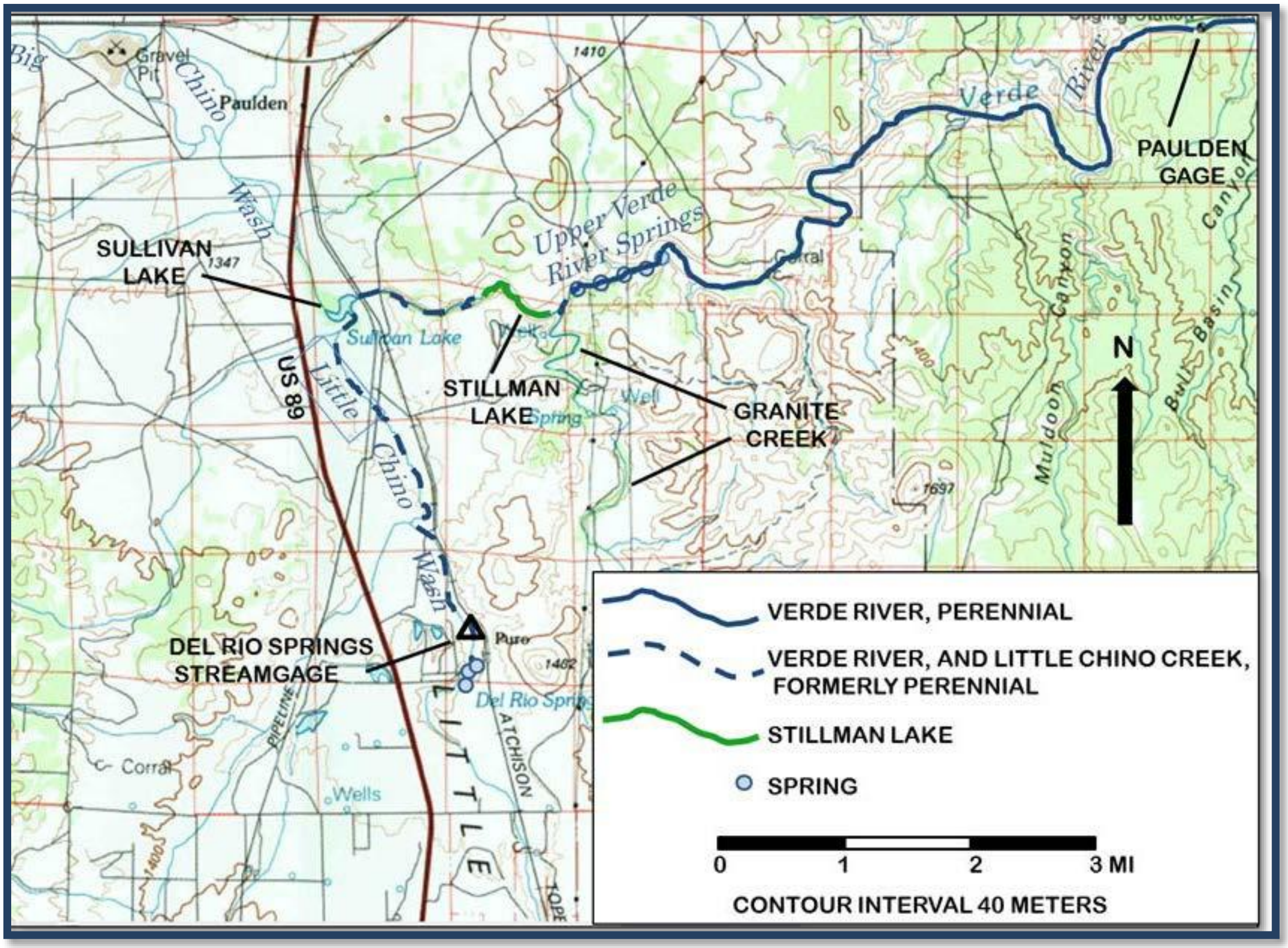


Figure 7.5. Map showing Del Rio Springs, the now-ephemeral Little Chino Wash and Sullivan Lake, Stillman Lake, and the upper Verde River springs, from which continuous free flow of the river now begins. Map base from U.S. Geological Survey Prescott 1:100,000-scale topographic map.

Figure 7.6. Low concrete dam that forms now-ephemeral Sullivan Lake. Dam, about 115 feet wide, is set into the head of a narrow steep-walled canyon cut into basalt. The dam marks river-mile zero on the Verde River, although the uppermost perennial reach now begins about a mile below the dam. View is westward. Photo by E.W.Wolfe,

Wirt (2005a) concluded that "*Perennial flow in the Verde River historically began near Del Rio Springs…, but year-round flow to Sullivan Lake via Little Chino Creek had disappeared by the early 1970s…, owing to agricultural diversions and ground-water pumping*". Indeed, Little Chino Creek, once perennial from Del Rio Springs, is now virtually a dry wash because of the effects of groundwater pumping. With the exception of Stillman Lake, continuous vigorous perennial flow has apparently been lost over nearly 6 river miles—3.7 miles from Del Rio Springs to the Verde River canyon and another 2 miles from there to the upper Verde River springs (Figure 7.5) about 0.1 mile below the confluence of Granite Creek and the Verde River canyon.

Stillman Lake (Figure 7.7) refers to a spring-fed, shallow perennial ribbon of water—about 100 feet across at its widest—that until recently submerged its bed in a reach of uppermost Verde River canyon about ⅔ mile in length. The upper end of Stillman Lake is approximately a mile below Sullivan Dam. Stillman Lake is impounded at its downstream (east) end (Figure 7.7A) by a local sand and gravel bar (alluvial fan) deposited by past floods in Granite Creek. The bar extends across the Verde River canyon floor from the mouth of Granite Creek. The gravel bar was breached sufficiently to partly drain Stillman Lake (Figure 7.7C) most likely in early 2010, perhaps by a brief flood event that peaked at 2,450 cfs on January 22

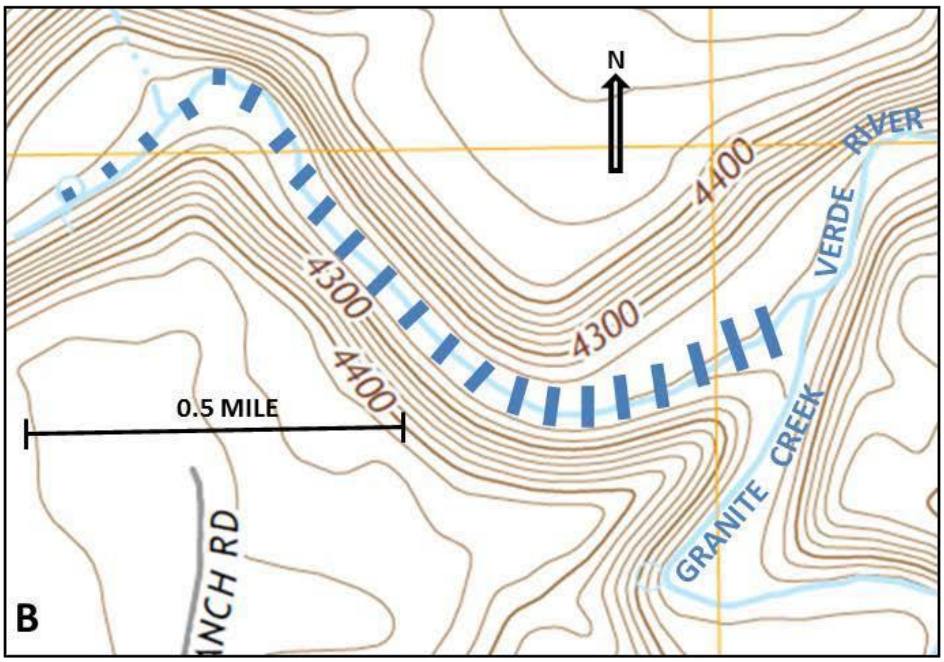
Because of its abundant surface water, the Del Rio Springs area was selected as the initial site for the first capitol of the Arizona Territory in 1864. After a few months the capitol was moved to the area of Prescott for better proximity to timber and mining. Through the first half of the 20th century, the Atchison, Topeka, and Santa Fe Railroad stopped at Del Rio Springs to fill tank cars with water and load local farm produce for delivery to northern Arizona railroad towns and the network of Fred Harvey hotels. In 1901 a pipeline was constructed to deliver water from Del Rio Springs to Prescott, about 19 miles to the south. However, owing to the excessive cost of pumping water 19 miles with an elevation gain of about 1,000 feet, the pipeline was eventually abandoned and dismantled (Krieger, 1965).

Intensive groundwater pumping for irrigation began in the vicinity of the village of Chino Valley in the 1930s. In 1947, the City of Prescott drilled two wells within the village of Chino Valley about 5 miles south of Del Rio Springs. Since 1948 the well field (Figure 7.4), within the (now) Town of Chino Valley, has been Prescott's primary source of municipal and industrial water as well as a source of water for part of the Town of Chino Valley. In addition, the majority of present-day Chino Valley residents are dependent on domestic wells drawing water from the Little Chino Valley sub-basin, the same sub-basin that supplies Prescott's water. Reports by the Arizona Department of Water Resources (Timmons and Springer, 2006; Nelson and Yunker, 2014) show that hydraulic heads in both the water-table aquifer and in the lower confined aquifer have each declined 50 or more feet across the broad central region of the Prescott Active Management Area since 1939-40.

Operators of the railroad built a weir in 1939 for measuring the discharge from the Del Rio Springs. From 1940 through 1945 discharge from the springs ranged from about 2,300 to 3,400 acre-feet per year (Corkhill and Mason, 1995). The low values apparently reflect diminished spring discharge correlative with pumping by the railroad at a rate of as much as 855 acre-feet per year. A projected water budget calculated by ADWR (Nelson, 2002) predicted steady decline of Del Rio Springs discharge, reaching zero by year 2025 (Figure 7.8).

Figure 7.7 Stillman Lake, within uppermost Verde River canyon in September 2009 and May 2014.

A. Stillman Lake in September 2009, prior to breaching of gravel dam at lake's downstream (east) end. Google Earth imagery date: 9/24/2009. Image©DigitalGlobe.



B. Canyons of Verde River and Granite Creek east of Paulden, AZ. Pattern of blue bars approximates the location of Stillman Lake. Modified from U.S. Geological Survey Chino Valley North 7.5-minute quadrangle, 1:24:000-scale, 2014.

C. Uppermost Verde River canyon and remnant of Stillman Lake in May 2014, after breaching of the gravel dam. Google Earth imagery date; 5/18/2014.

In 1996 the U.S. Geological Survey installed a stream gage in Little Chino Creek a short distance downstream from Del Rio Springs to record the rate of discharge from the springs. The record of that gage (Figure 7.9) clearly demonstrates that groundwater discharge from the springs is steadily decreasing toward extinction—a victim of capture by groundwater pumping. Winter low flow (average for seven consecutive days of lowest winter discharge) has decreased from about 2 cfs (about 1,450 ac-ft/yr) in the winter of 1996-67 to 0.67 cfs (485 ac-ft/yr) in the winter of 2014-15. Summer low flow (average for seven consecutive days of lowest summer discharge) has decreased from about 1.7 cfs (about 1,230 ac-ft/yr) in the summer of 1997 to 0.36 cfs (about 260 ac-ft/yr) in the summer of 2014. The repetitive difference between sustained winter and summer flows (Figure 7.9) apparently reflects the differences each year between winter and summer evapotranspiration. (Narrow spikes of increased discharge presumably reflect enhanced runoff from storm events. Brief zero-flow events in 2013 and 2014 may represent brief diversions of streamflow).

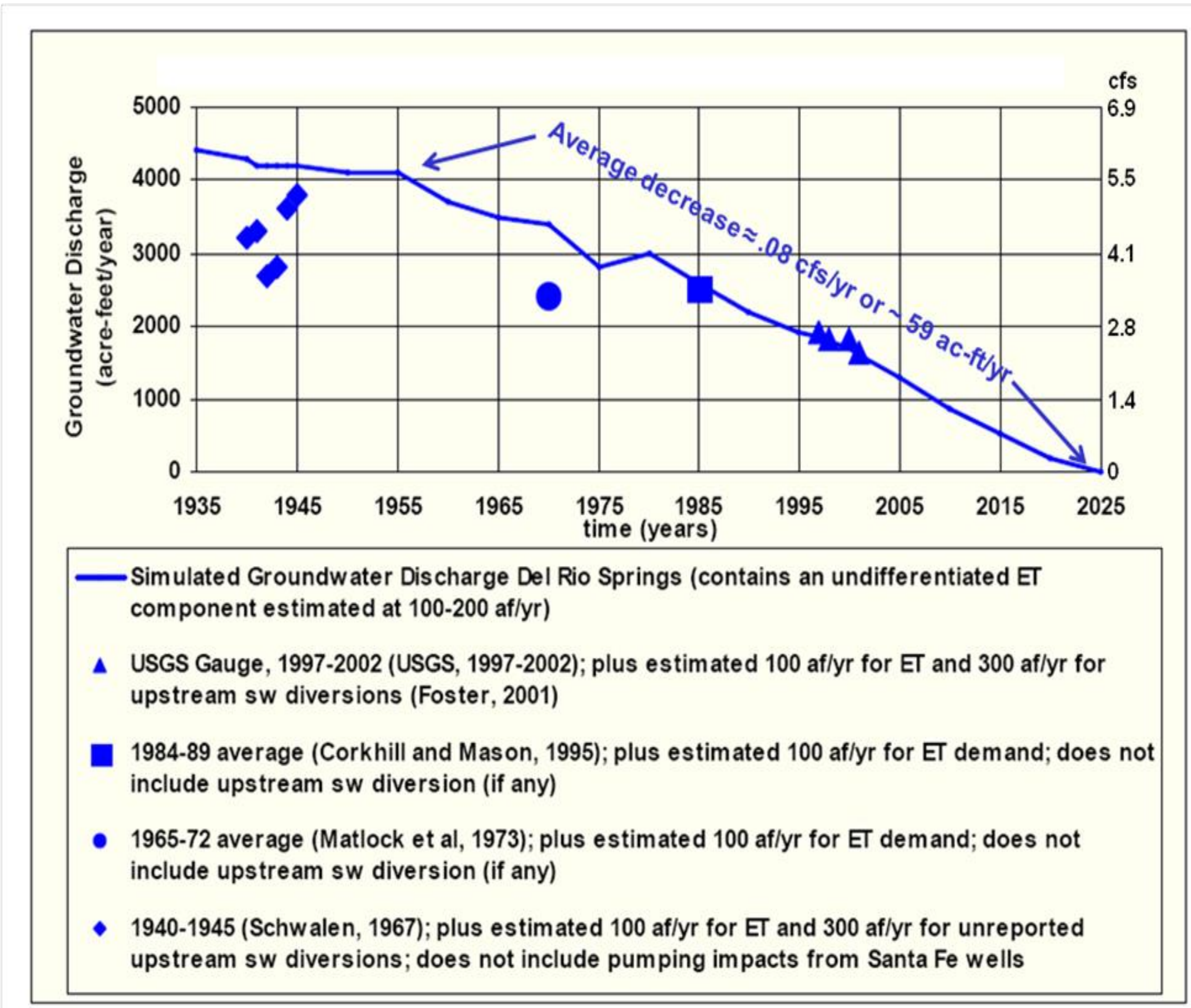


Figure 7.8. Hydrograph showing simulated groundwater discharge at Del Rio Springs from 1935 to 2025 (Nelson, 2002).

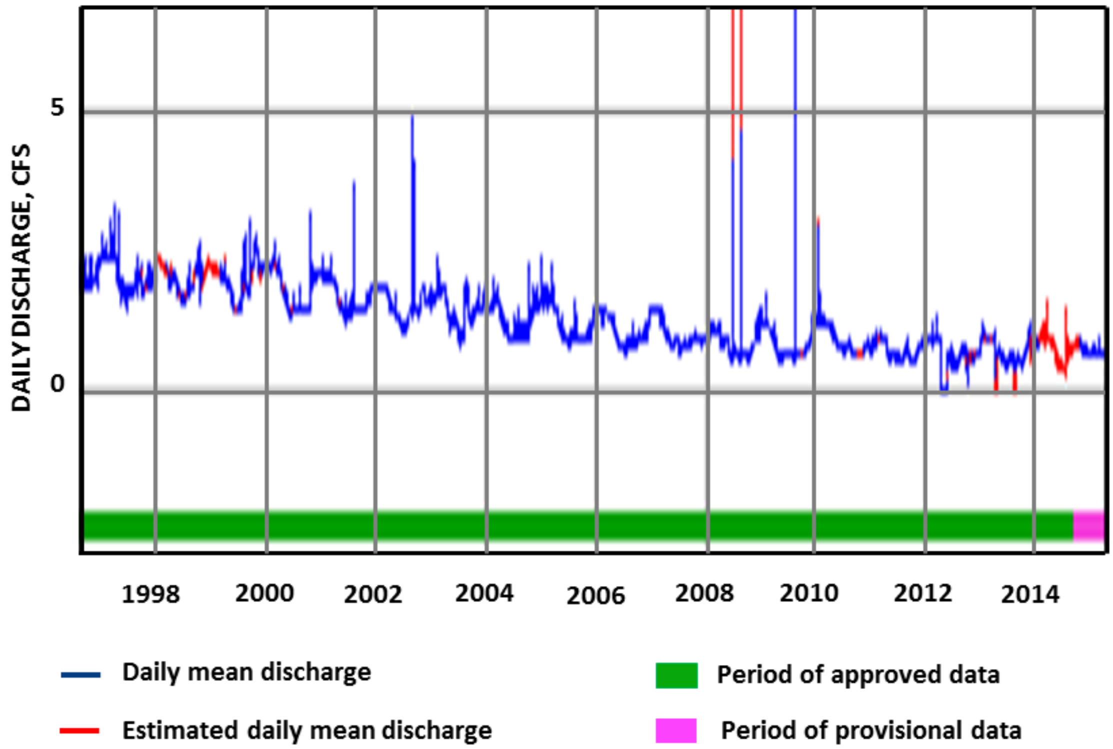


Figure 7.9. Hydrograph displaying daily mean discharge at the USGS 09502900 Del Rio Springs stream gage from August 8, 1999 through December 31, 2014. Vertical scale expanded.

Streamflow Depletion: Looking Ahead in the Verde Valley

The U.S. Geological Survey (USGS) Northern Arizona Regional Groundwater Flow Model (NARGFM, Pool and others, 2011) is a computerized simulation of the groundwater flow system throughout northern Arizona. It synthesizes much of the important hydrologic and hydrogeologic information of northern Arizona into a powerful tool that can be used to evaluate water-resource issues in both the present and the future. Although NARGFM simulates an area much larger than the Verde Valley (Figure 7.10), it was constructed as the best-available representation of the flow of water into, through, and out of the aquifer systems of the upper and middle Verde River watersheds. That representation includes not only the amount of water that enters and exits the aquifers but also how the flow of water in the aquifers and the streams connected to them responds to stresses to the system such as withdrawals by wells.

Potential Effects of Groundwater Pumping or Artificial Recharge on Streamflow and Groundwater-Dependent Vegetation in the Verde Valley

Two reports (Leake and Pool, 2010; Leake and Haney, 2010) represent the first published application of the NARGFM. The reports, prepared by the USGS in cooperation with The Nature Conservancy, document with maps the simulated effects of groundwater pumping as well as the simulated effects of artificial recharge on surface water and groundwater-dependent vegetation. They provide important insight into the relation between groundwater and surface water in the Verde Valley by their portrayal of the simulated future effects in space and time of groundwater pumping or artificial recharge for periods of ten and fifty years. A third USGS report (Garner and others, 2013) extends the analysis to 100 years.

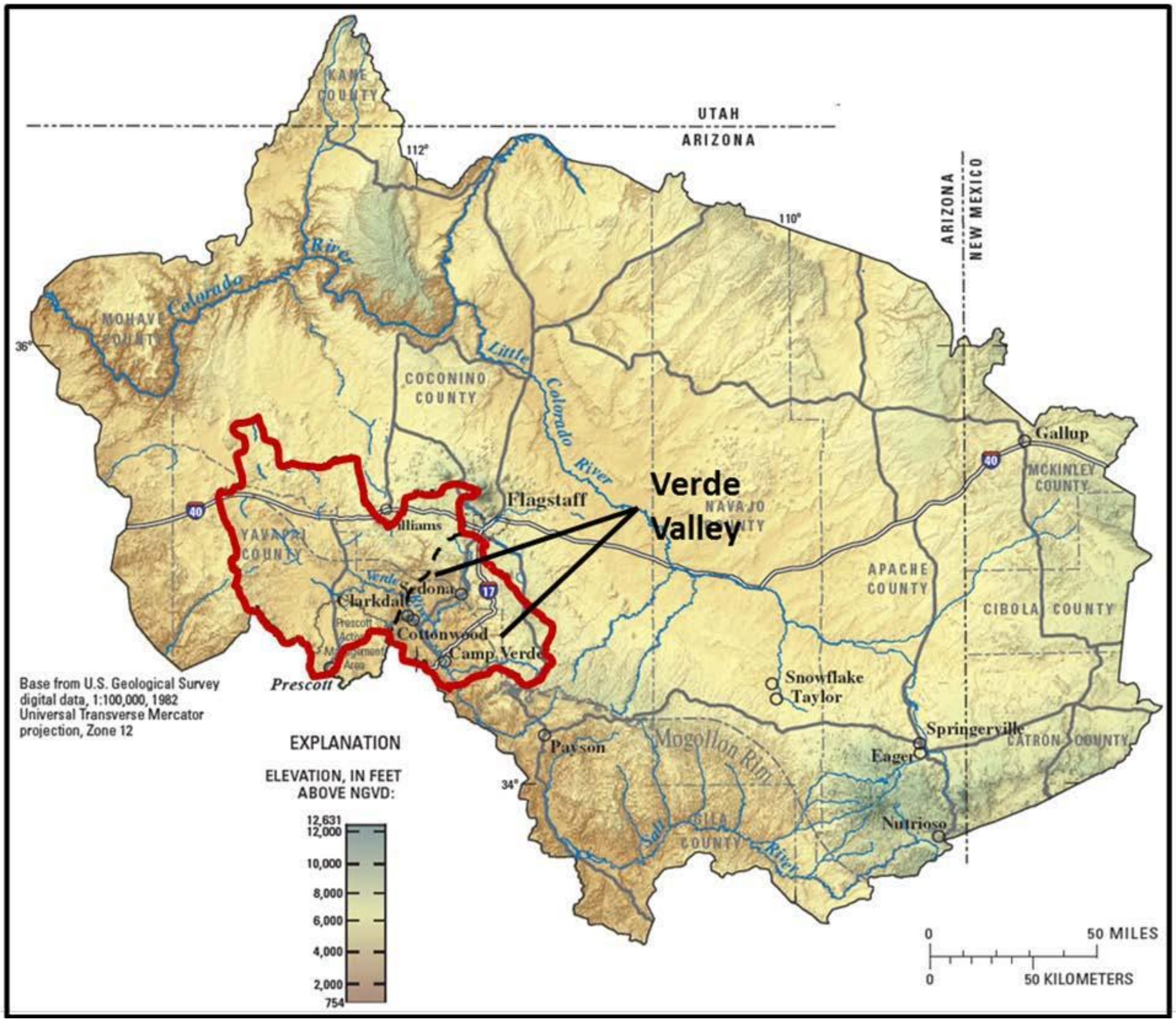


Figure 7.10. Map showing the area of the Northern Arizona regional groundwater-flow model. Red line outlines the upper and middle Verde River watersheds. Dashed black line is approximate northwest boundary of the Verde Valley study area. (After Pool and others, 2011).

Results are given for each of the three layers that NARGFM simulates in the Verde Valley. Figure 7.11 depicts the layers and the conceptual relations among the hydrogeologic units they simulate.

Critical observations and implications of these three reports for water-resource management in the Verde Valley sub-basin are: (1) The aquifer system, the Verde River, its perennial tributaries, and the shallow groundwater that supports riparian vegetation in the vicinity of these waterways are connected. (2) Pumping of groundwater within the Verde Valley sub-basin eventually depletes the flow of the Verde River and its perennial tributaries as well as the supply of shallow groundwater that supports riparian vegetation. Conversely, artificial recharge to the aquifer can augment streamflow and the supply of shallow groundwater that supports riparian vegetation. (3) Past and current pumping has not yet fully affected river flow and evapotranspiration.

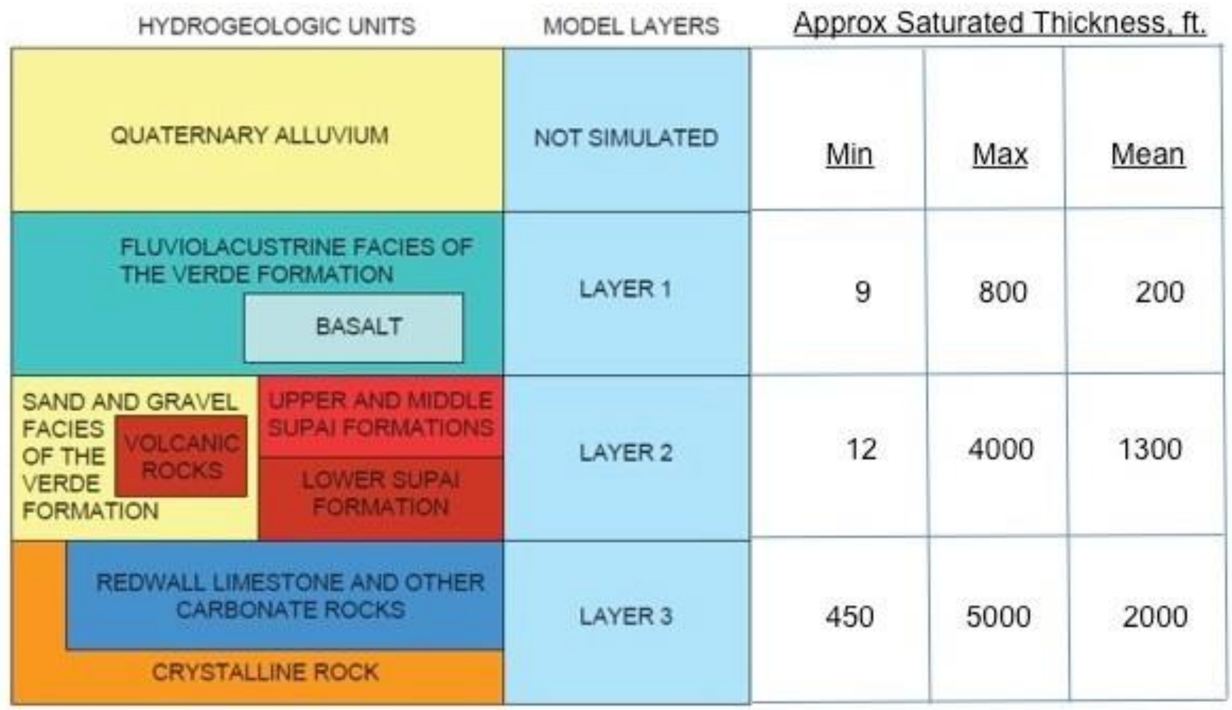


Figure 7.11. Conceptual relations among hydrogeologic units and layers 1,2, and 3 as simulated in the NARGFM for the Verde Valley. (Leake and Pool, 2010).

Figures 7.12 through 7.18 portray via colored maps the computed reduction within the Verde Valley of both base flow and of groundwater available to support riparian vegetation as a fraction of the rate of continuous pumpage of a well, for periods of 10, 50, and 100 years from model layers 1 (Figures 7.12 through 7.14) and 2 (Figures 7.15 through 7.17), and as a fraction of the rate of continuous pumpage for 100 years from model layer 3 (Figure 7.18). Conversely, the maps also portray the computed augmentation of both base flow and the groundwater supporting riparian vegetation as a fraction of the rate of artificial recharge. The computed depletion or augmentation of streamflow is proportional to the pumping rate or the augmentation rate whether those rates are 10, or 1, or 0.5 acre-feet per year.

Ten individual color bands, in sequence of increasing wavelength, from dark blue to red, correspond to either (1) incremental depletion of base flow and groundwater supporting riparian vegetation as a consequence of pumping from a well or (2) augmentation of base flow and groundwater supporting riparian vegetation from artificial recharge. For example, dark blue, at the low end of the color sequence, corresponds to a fraction of 0 to 0.1 of either the pumping rate or the recharge rate; red, at the high end of the color sequence, corresponds to a fraction of 0.9 to 0.10 of either the pumping rate or the recharge rate. (Note: Multiply fraction of the pumping rate by 100 to express the value as percentage of the pumping rate. For example: a fraction of 0.3 of the pumping rate equals 30 percent of the pumping rate).

Warmer colors on the maps denote (1) areas in which pumping from wells acts more rapidly to reduce the groundwater component of streamflow (base flow) and the groundwater that supports riparian vegetation; and (2) areas in which artificial recharge acts more rapidly to increase the groundwater component of streamflow (base flow) and the groundwater that supports riparian vegetation. In contrast the areas of cooler colors on the maps denote (1) areas in which pumping from wells acts less rapidly to reduce the groundwater component of streamflow (base flow) and the groundwater that supports riparian vegetation; and (2) areas in which artificial recharge acts less rapidly to increase the groundwater component of streamflow (base flow) and the groundwater that supports riparian vegetation.

The rate of response to either pumping or artificial recharge of stream flow and groundwater discharge to riparian vegetation at any locality depends upon both the distance of the pumping or artificial recharge from surface-water features and the local hydrologic properties of the aquifers. For example, all of the maps (Figures 7.12 through 7.18) show that streamflow in the Verde River is expected to respond more rapidly to either pumping or artificial recharge that occurs close to the Verde River near Camp Verde than to pumping or artificial recharge that occurs close the Verde River due west of Cornville. Differences such as this reflect differing aquifer properties.

For simplicity, only computed depletion by pumping from a well is discussed below, but computed augmentation by artificial recharge via the same well would give equal but inverse results.

The colored areas of Figures 7.12 through 7.14 show the area of NARGFM layer 1, which simulates the saturated zone of the upper, fluviolacustrine (stream, marsh, and lake deposits) part of the Verde Formation. Pumpage of a single hypothetical well (black star) located along Interstate 17 near exit 289, about 2.5 miles north of AZ 260, and pumped at a consistent annual rate from layer 1 would be estimated to reduce both base flow and the supply of groundwater that supports riparian vegetation by a fraction of 0.6 to 0.7 (60 to 70 percent) of the pumping rate after 10 years (Figure 7.12), by a fraction of 0.8 to 0.9 (80 to 90 percent) of the pumping rate) after 50 years (Figure 7.13),and by a fraction of 0.9 to 1.0 (90 to 100 percent) of the pumping rate after 100 years (Figure 7.14).

To state it in an alternative way: If the continuous pumping rate of the well is 10 acre-feet per year, pumping from the well does not immediately affect streamflow. However, pumping eventually extracts groundwater that would otherwise have discharged to stream(s), and after 10 years of continuous pumping the redirection of groundwater from the stream(s) to the well would total between 6 and 7 acre-feet per year. After 50 years of continuous pumping the redirection to the well would total between 8 and 9 acre-feet per year. After 100 years of continuous pumping the redirection to the well would total between 9 and 10 acre-feet per year, and thereafter would approach ever more closely 10 acre-feet per year; through the well's remaining life all of the water the well produces (10 acre-feet per year) replaces groundwater that once supported streamflow and riparian vegetation.

The colored areas of Figures 7.15 through 7.17 show the area of NARGFM layer 2, which simulates predominantly sand, gravel and volcanic rocks in the deeper part of the Verde Formation to the southwest and the saturated part of the red sandstone and mudstone formerly referred to the Supai Formation beneath the Verde Formation as well as to the north and east. Note that layer 2 extends to the Mogollon Rim, far to the north and east of layer 1. Accordingly, the area of Figures 7.15 through 7.17 is far larger than the area of Figures 7.12

and 7.13, and the map scales differ accordingly. Layer 1 overlies only the southwestern-most part of layer 2.

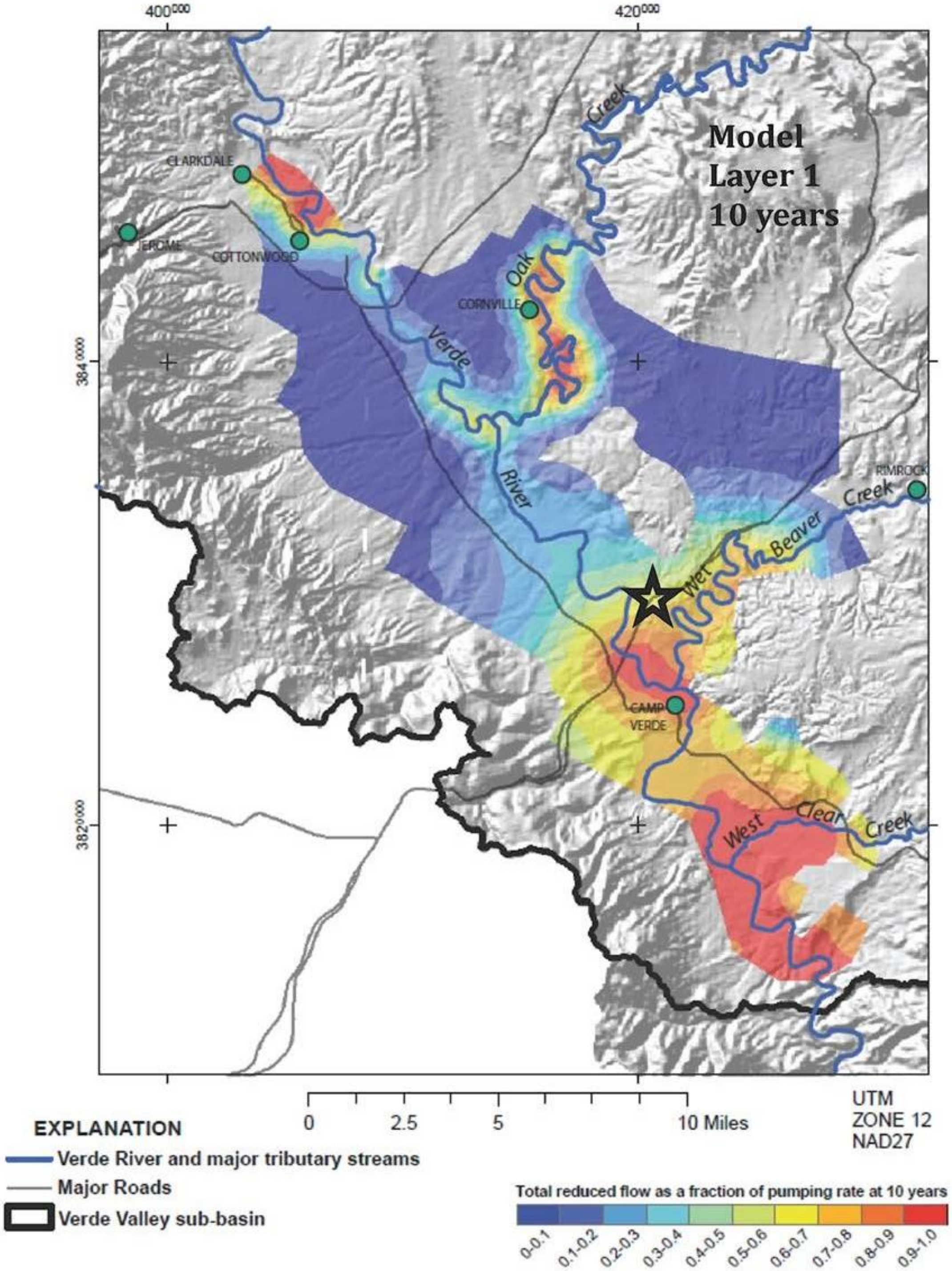


Figure 7.12. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 1 at a constant rate for 10 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 10 years at the location indicated by the black star would derive between 60 and 70 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Leake and Poole (2010).

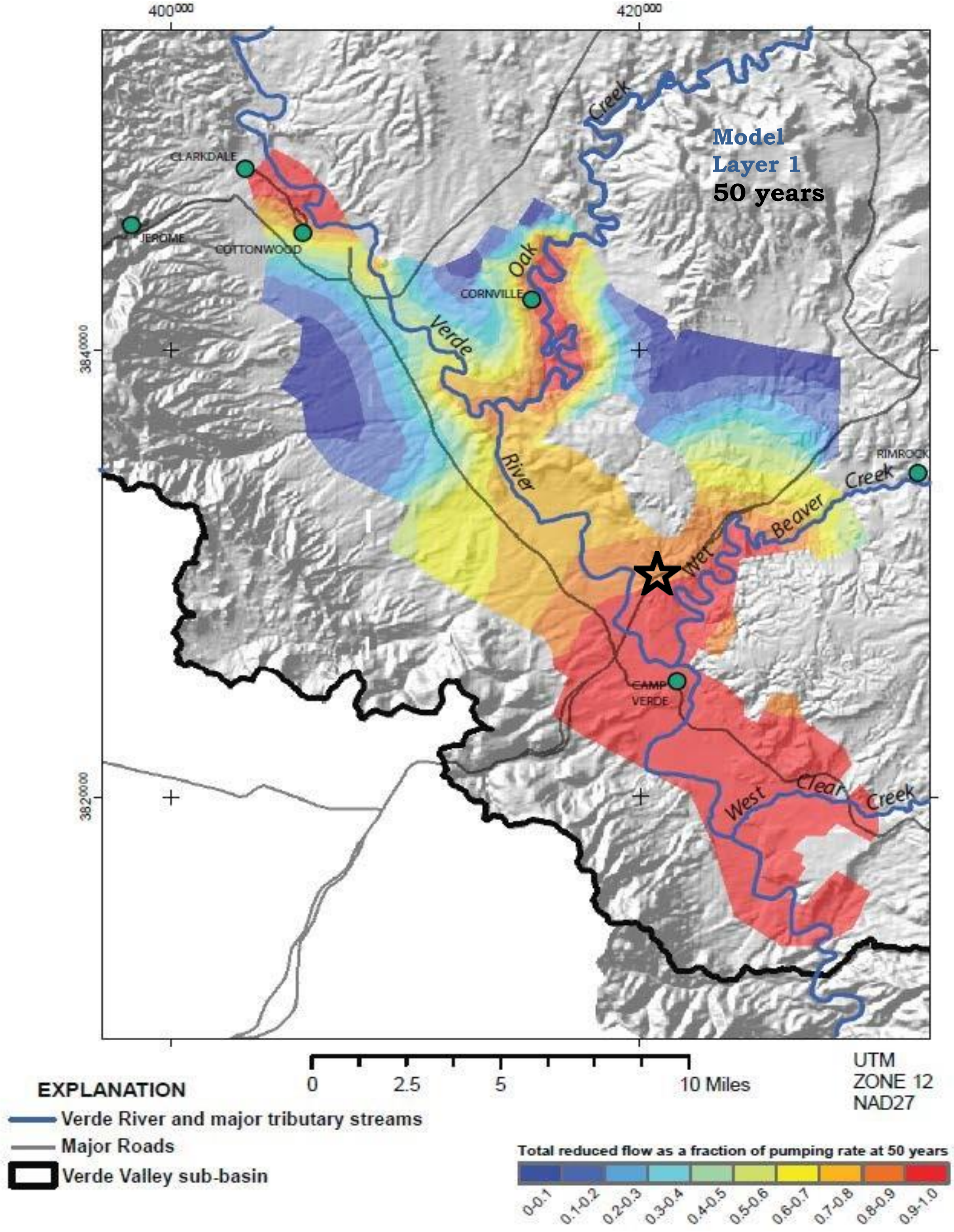


Figure 7.13. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 1 at a constant rate for 50 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 50 years at the location indicated by the black star would derive between 60 and 70 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Leake and Poole (2010).

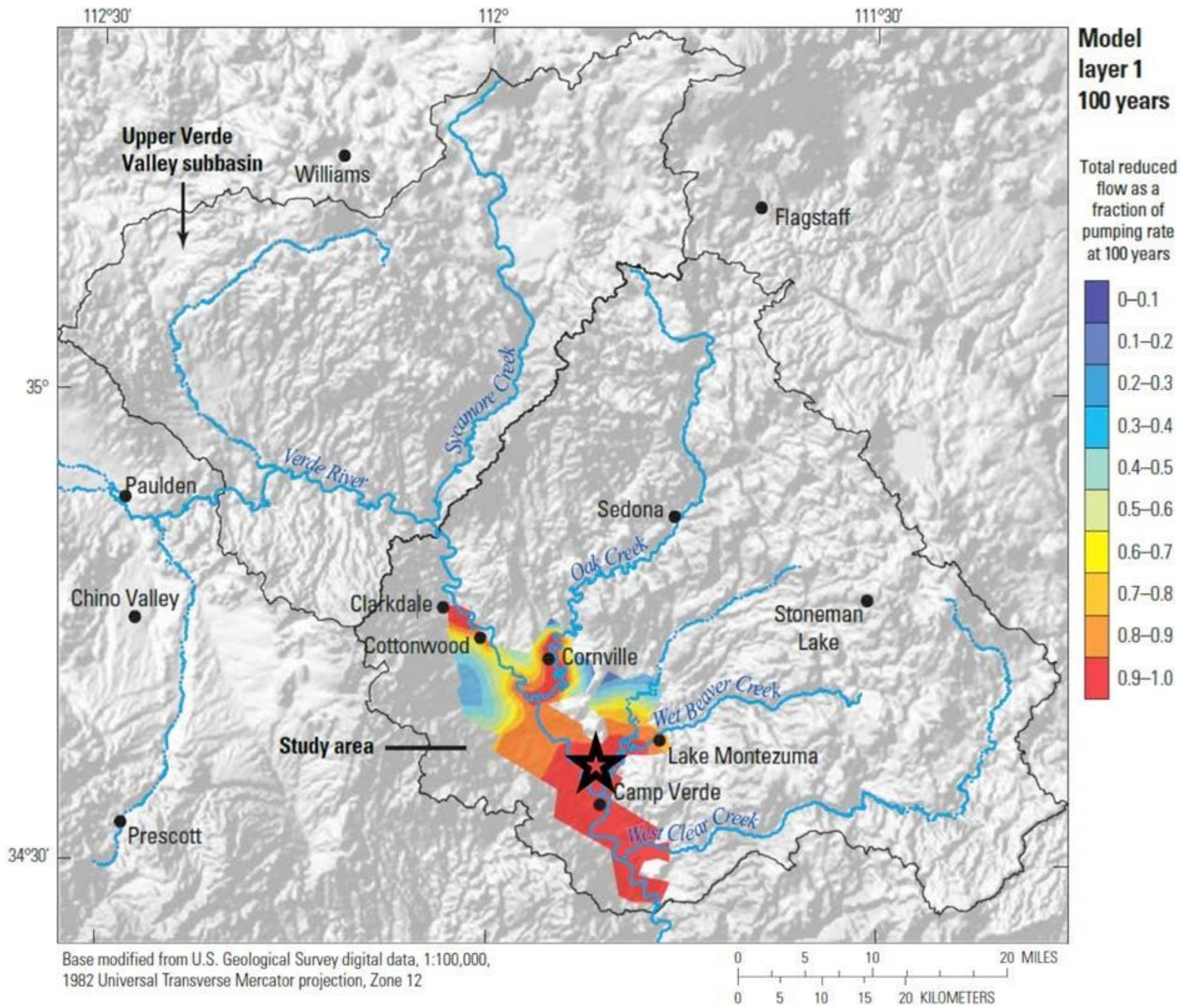


Figure 7.14. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 1 at a constant rate for 100 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 100 years at the location indicated by the black star would derive between 90 and 100 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Garner and others (2013).

Pumpage from layer 2 of a single hypothetical well (black star in Figures 7.15 through 7.17,) located along Interstate 17 near exit 289 and pumped at a consistent annual rate would be estimated to reduce base flow and the groundwater supporting riparian vegetation by between approximately 40 and 50 percent of the pumping rate after 10 years, by approximately 80 percent of the pumping rate after 50 years, and by between 90 and 100 percent after 100 years.

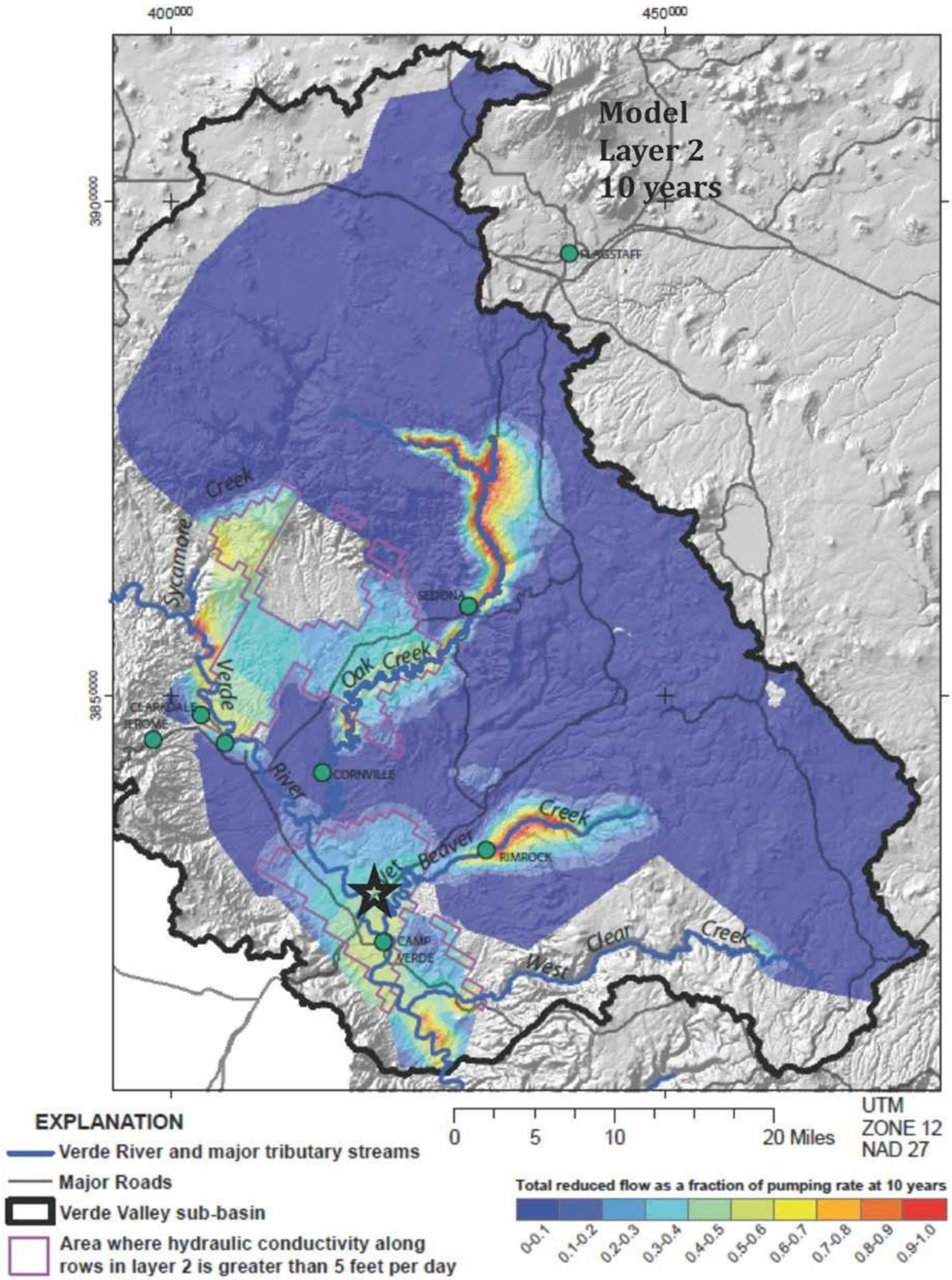


Figure 7.15. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 2 at a constant rate for 10 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 10 years at the location indicated by the black star would derive between 40 and 50 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Leake and Pool (2010).

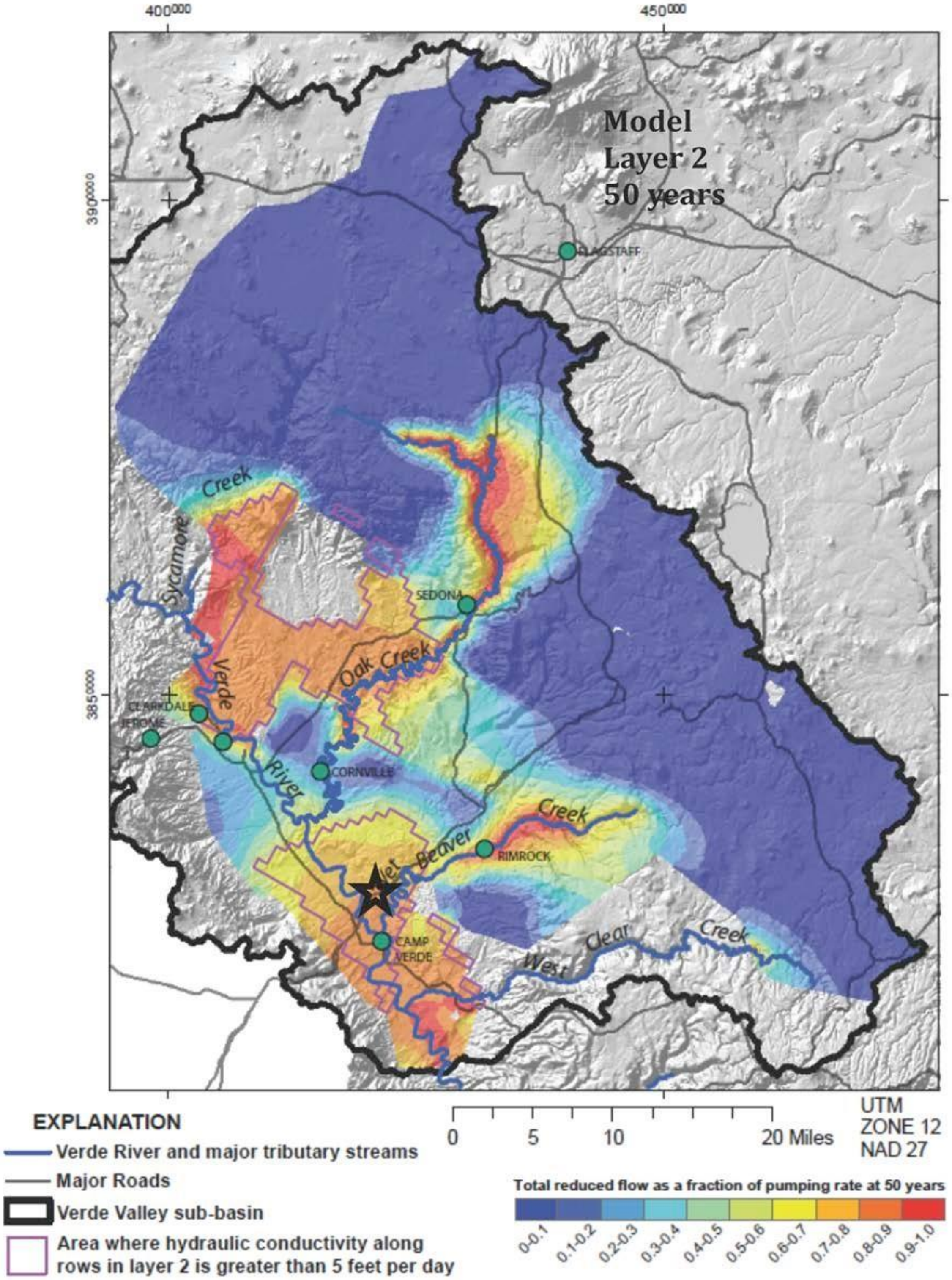


Figure 7.16. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 2 at a constant rate for 50 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 50 years at the location indicated by the black star would derive approximately 80 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Leake and Pool (2010).

The colored area of Figure 7.18 shows the area of NARGFM layer 3. It covers the Verde Valley as well as the adjacent upper part of the Verde Valley sub-basin. The major hydrogeologic units simulated in layer 3 are, where saturated, the Redwall Limestone and any underlying carbonate or other sedimentary rocks and, beneath them, the crystalline Precambrian basement rocks.

Pumpage from layer 3 of a single hypothetical well (black star in Figure 7.18) located along Interstate 17 near exit 289 and pumped at a consistent annual rate would be expected to reduce base flow and the groundwater supporting riparian vegetation by between 90 and 100

percent after 100 years.

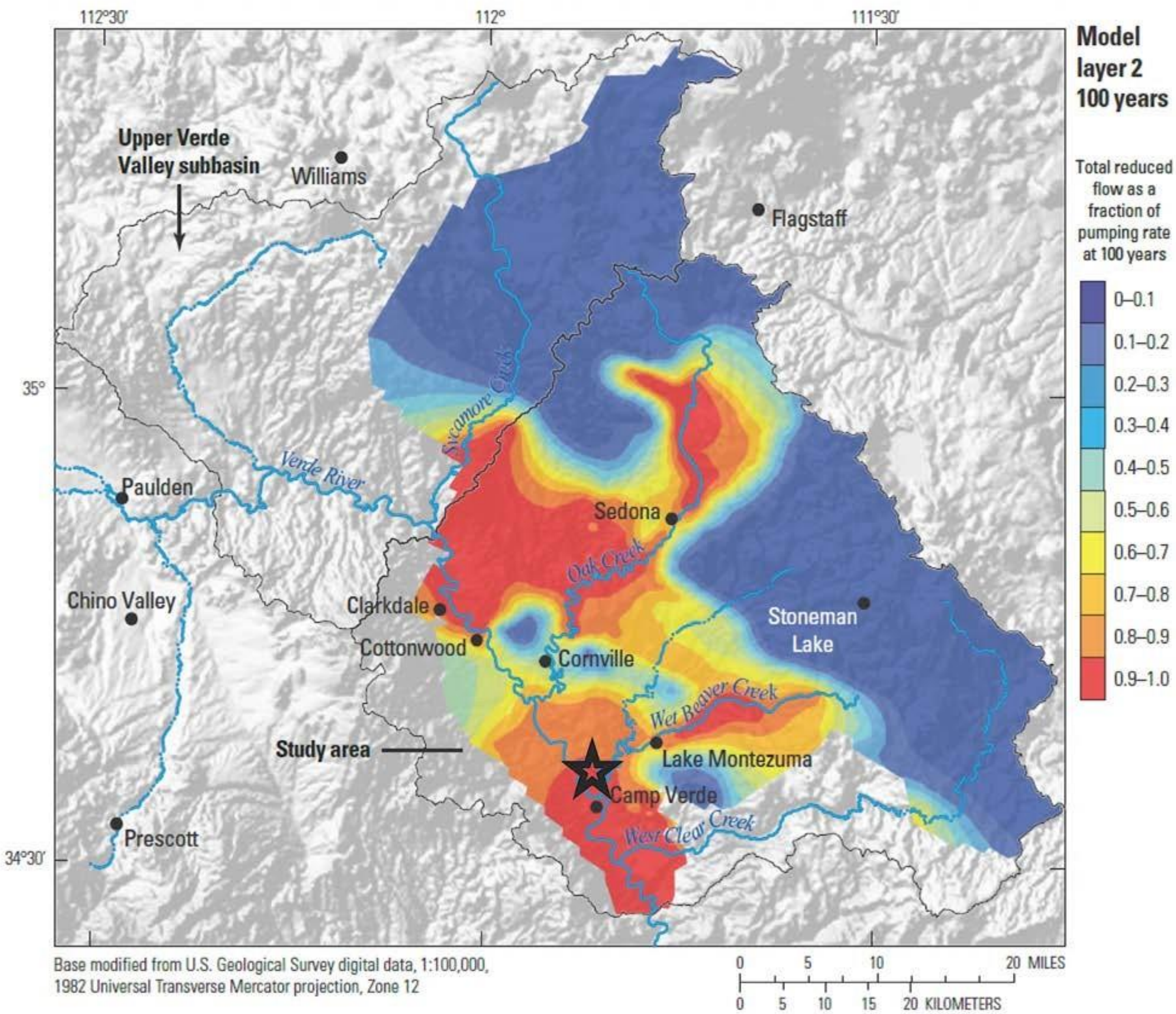


Figure 7.17. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 2 at a constant rate for 100 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 100 years at the location indicated by the black star would derive between 90 and 100 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Garner and others (2013).

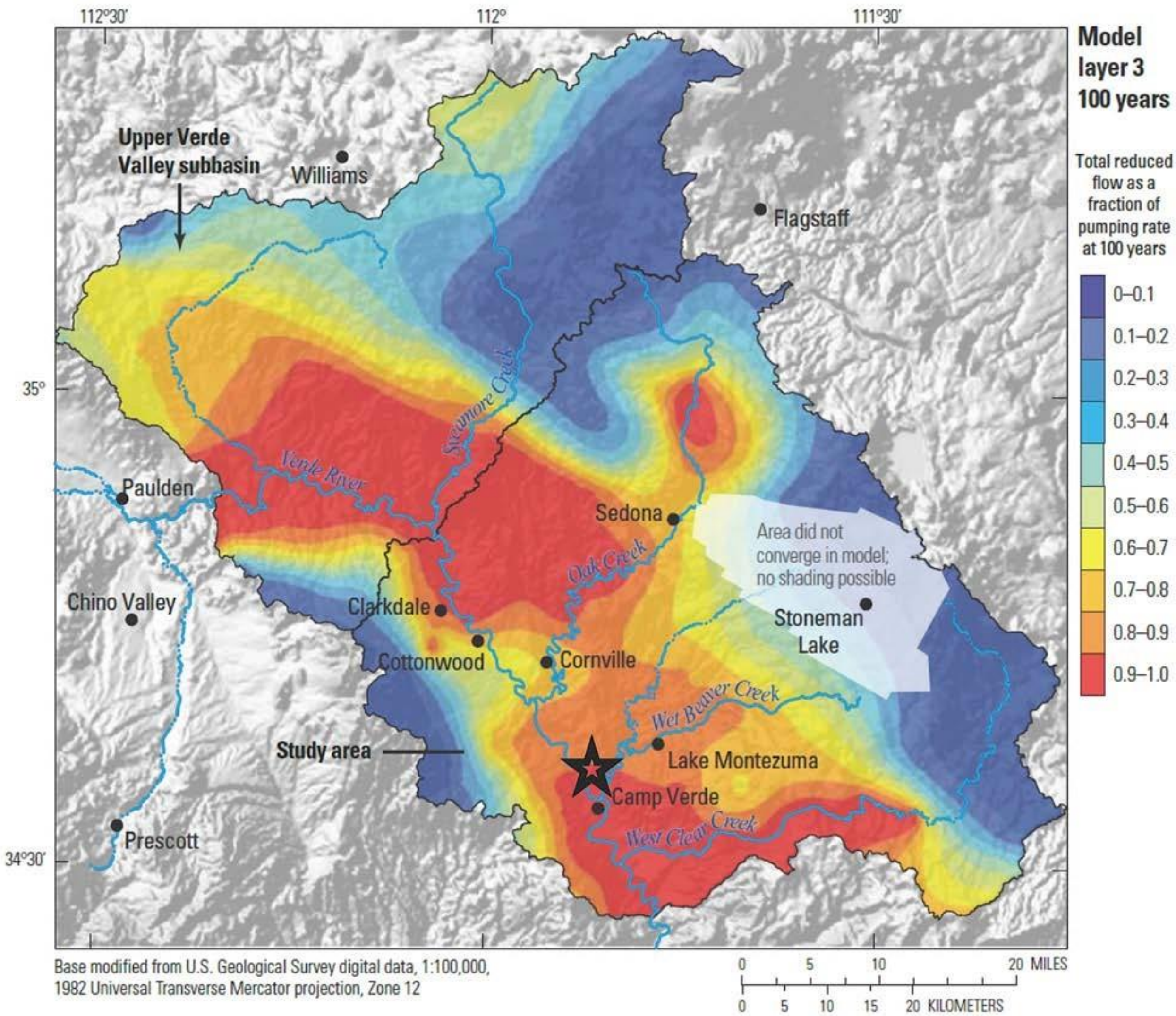


Figure 7.18. Computed reduction in both base flow and groundwater discharge to riparian vegetation as a fraction of the pumping rate from NARGFM layer 3 at a constant rate for 100 years. The color at any location represents the fraction of pumping by a well at that location that would be derived from depletion of both base flow and groundwater discharge to riparian vegetation. For example, a single well pumped continuously for 100 years at the location indicated by the black star would derive between 90 and 100 percent of its pumped water from the depletion of both base flow and groundwater discharge to riparian vegetation. After Garner and others (2013).

Human Effect on Base Flow in the Verde Valley

Garner and others (2013) applied the NARGFM to explore the effect of human activity throughout the NARGFM area (Figure. 7.10) on Verde River base flow in the Verde Valley. Human effect in this instance is identified as net groundwater withdrawal and equals the rate in acre- feet per year of groundwater pumping minus the rate of incidental and artificial recharge.

The power of the NARGFM for this analysis is that it provides for the first time a well-documented tool that enables examination of the effect of regional human stress (net groundwater withdrawal) on the groundwater system of the Verde Valley. Specifically, the model enables us to isolate the effect of human stress governing base flow from the overarching effect of decadal-scale climatic variation on natural recharge of the groundwater system (Figure 7.19).

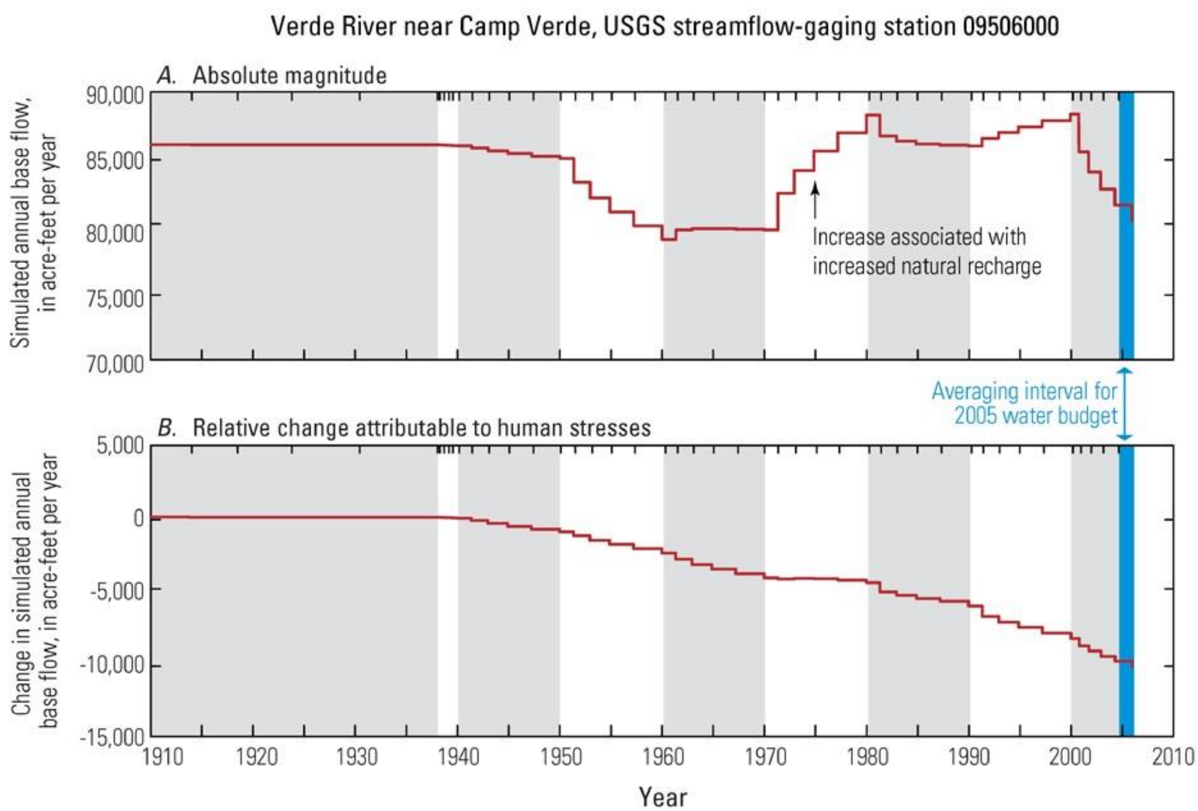


Figure 7.19. Plots of base flow simulated by NARGFM in the Verde River at the Camp Verde stream gage for the 1910–2005 model run. (A) Absolute magnitude of base flow. (B) Relative change in base flow attributable solely to human stress. Gray and white bars indicate stress periods applied to model; tick marks at tops of panels denote time steps within modeled stress periods. (Garner and others, 2013, Figure 15).

Change in Base Flow—1910 Through 2005

Years 1910 through 2005 coincide with the time period for which the NARGFM was calibrated. Thus, the model run for this period—the full transient NARGFM model run (Pool and others, 2011)—is the starting run for analyzing the effect of regional human stress (net groundwater withdrawal) on the groundwater system of the Verde Valley, including production of base flow. In this run, for the period 1910 through 2005, the magnitude and timing of human stresses as well as variation in natural recharge are based on analysis of the best available records as evaluated by Pool and others (2011). These records include decadal-scale variation in pumpage, incidental and artificial recharge, streamflow, and groundwater levels as well as decadal-scale estimates of natural recharge based on analysis of topography, soils, geology, vegetation, and records of such seasonal parameters as evapotranspiration, precipitation and other atmospheric conditions.

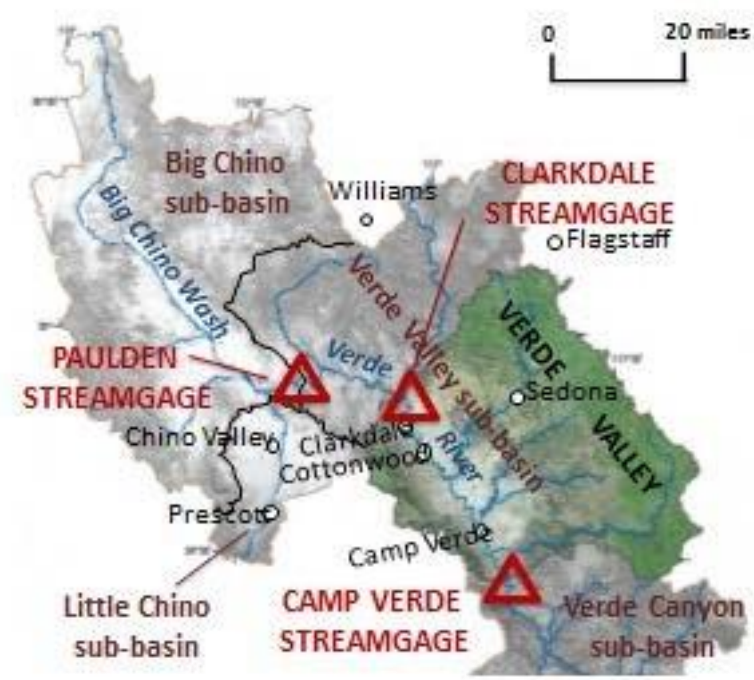


Figure 7.20. Map showing the Big Chino, Little Chino, Verde Valley, Verde Canyon (part) sub-basins, the Verde River, and the USGS Paulden, Clarkdale, and Camp Verde stream gages. Green overprint marks the Verde Valley, which coincides with the part of the Verde River watershed bounded by the Clarkdale and Camp Verde stream gages. (Modified from Figure 1 of Garner and others, 2013).

The consumptive use of water derived from diversion of streamflow for crop irrigation in the Verde Valley was held at a constant rate of 10,000 acre-feet per year.

An additional model run, the so-called natural-conditions run, was required in order to isolate the effects of human stress. Thus, for the 1910 through 2005 time period, the documented decadal-scale variation in natural recharge was maintained, but the evaluated human stresses—groundwater pumping, incidental and artificial recharge—were omitted. The simulated effects of human stresses across the model area on the Verde Valley groundwater system were obtained by subtracting the results of one model run from the other. Selected results attribute solely to human stress are expressed as relative simulated change in net groundwater withdrawal of groundwater and base flow at the Paulden, Clarkdale, and Camp Verde stream gages (Figure 7.20) are given in Table 7.1 and Figure 7.21.

Simulated change in annual base flow attributable solely to human stress decreased steadily from 1910 through 2005 (Figure 7.21). During this period human stress increased steadily, as represented as net groundwater withdrawal (Table 7.1). By 2005 the simulated depletion in base flow at the Paulden, Clarkdale, and Camp Verde stream gages (Figure 7.21) is approximately 4,800, 4,900, and 10,200 acre-feet per year, respectively. The net depletion of base flow within the Verde Valley (equals simulated change in base flow at the Camp Verde stream gage minus simulated change in base flow at the Clarkdale stream gage) by the end of 2005 is approximately 5,300 acre-feet per year.

	Clarkdale Stream gage			Camp Verde Stream gage			Verde Valley		
Year	A ΔNet GW with-drawal above gage, Af/y	B ΔBase flow at gage, Af/y	ΔA/B, Percent	C ΔNet GW with-drawal above gage, Af/y	D ΔBase flow at gage, Af/y	ΔC/D, Percent	C-A ΔNet GW with-drawal	D-B ΔBase flow	Δ(C-A)/(D-B), Percent
1910	0	0	0	0	0	0	0	0	0
1913	200	-10	-2	200	0	-2	0	0	0
1930	200	-10	-2	200	-10	-2	0	0	0
1938	2,700	-50	-2	2,700	-40	-1	0	0	0
1941	9,300	-220	-2	11,300	-230	-2	2,000	-10	0
1951	18,200	-1,200	-7	18,800	-1,300	-7	600	-100	-17
1961	20,000	-2,700	-14	21,100	-2,900	-14	1,100	-200	-18
1971	20,800	-3,600	-17	24,600	-4,300	-17	3,800	-700	-18
1981	19,100	-3,500	-18	28,100	-5,100	-18	9,000	-1,600	-18
1991	17,800	-3,900	-22	31,000	-6,800	-22	13,200	-2,900	-22
2005	20,000	-4,900	-25	37,800	-10,200	-27	17,800	-5,300	-30

Table 7.1. Simulated annual change attributable solely to historic human stress, 1910 through 2005, in net groundwater withdrawal above the Clarkdale and Camp Verde stream gages and in the Verde Valley, acre-feet per year; in base flow at the Clarkdale and Camp Verde stream gages and in the Verde Valley, acre-feet per year; and in base flow as percentage of net groundwater withdrawal. Derived from data (rounded herein) of Table 1.2 of Garner and others (2013).

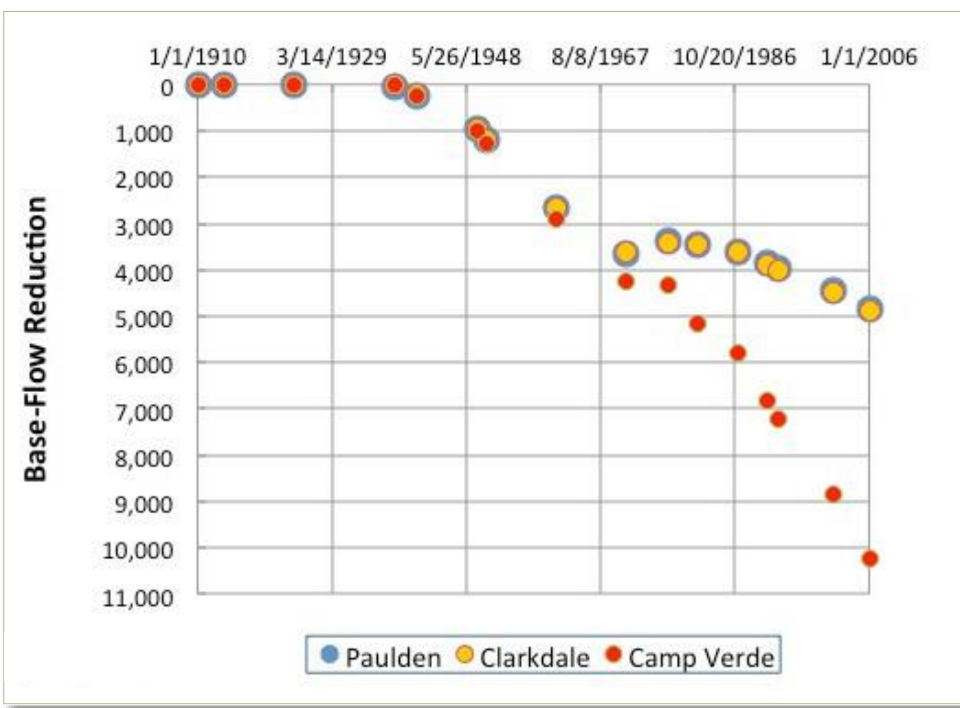


Figure 7.21. Change in base flow (acre-feet per year owed solely to human stress, represented as net groundwater withdrawal, 1910 through 2005, at the Paulden, Clarkdale, and Camp Verde stream gages. Derived from data (rounded herein) Table 1.2 of Garner and others (2013). Graph courtesy of William Meyer.

Notably, the depletion of base flow at the Paulden and Clarkdale stream gages is virtually identical (Figure 7.21) during the 1910 through 2005-time period. The onset of divergence in base-flow depletion at the Camp Verde stream gage with respect to base-flow depletion at the Paulden and Clarkdale stream gages is approximately coincident with the onset of substantial groundwater pumping in the Verde Valley that began in about 1941. Thereafter the divergence steadily increases.

During the 1910 through 2005-time period, the rate of depletion of base flow as a percentage of net groundwater withdrawal increased. In 2005, the simulated annual depletion of base flow at the Clarkdale stream gage was 25 percent of the increase of net groundwater withdrawal above the gage; the annual depletion of base flow at the Camp Verde stream gage was 27 percent of the increase of net groundwater withdrawal above the gage. The depletion of base flow within the Verde Valley in 2005 was 30 percent of the net groundwater withdrawal in the Verde Valley (Table 7.1).

Forward-Looking Simulations - 2006 Through 2109

Three forward-looking (predictive) model runs from 2006 through 2109 were also undertaken to explore the effect on future base flow of both past and hypothetical future human stress. The hypothetical human stresses in the three predictive runs were:

(1) net groundwater withdrawal for 2005 was gradually decreased by 15 percent through 2059 and then held constant through 2109;
(2) net groundwater withdrawal was held unchanged through 2109 at the same rates and at the same locations as in 2005;
(3) net groundwater withdrawal for 2005 was gradually increased by 15 percent through 2059 and then held constant through 2109.

No attempt was made in these runs to estimate future variation of climate. In order to isolate the effects of human stress, the natural-conditions run was extended from 2006 through 2109 using the long-term average value of natural recharge during 1910 through 2005, 59,000 acre-feet per year.

The attempted pumping could not be fully achieved in any of the three forward-looking model runs because some model cells became dry during the runs, especially in the Verde Valley. There the realized pumping in the three model runs fell short of the attempted pumping by approximately 2,700 to 2,900 acre-feet per year as model cells went dry.

It is important to understand that the forward-looking runs do not predict any reasonably expected reality in future water demand or future locations of population growth or pumping. Instead, they were designed simply to explore how groundwater pumping throughout the model area affects the Verde Valley's hydrologic system and Verde River streamflow. Indeed, even the most aggressive of the three forward-looking runs understates by more than 70 percent the unmet water demand estimated for the Verde Valley in 2050 by the Central Yavapai Highlands Water Resources Management Study (see Phase 1 Results at http://www.yavapai.us/bc-wac/cyhwrms/).

Among the three predictive runs, depletion of base flow from 2006 through 2109 ranged from approximately 2,700 to 3,800 acre-feet per year at the Clarkdale stream gage, 5,400 to 8,600 acre-feet per year at the Camp Verde stream gage, and from 2,600 to 4,800 acre-feet per year in the Verde Valley. Hereafter, discussion of forward-looking runs is given only for the run that gave intermediate results—run 2, in which maintenance of 2005 pumping locations and magnitudes was attempted unchanged from 2006 through 2109.

	Clarkdale Stream gage			Camp Verde Stream gage			Verde Valley		
Year	A ΔNet GW with-drawal above gage, Af/y	B ΔBase flow at gage, Af/y	A/B, Percent	C ΔNet GW with-drawal above gage, Af/y	D ΔBase flow at gage, Af/y	C/D, Percent	C-A ΔNet GW with-drawal Af/y	D-B ΔBase flow Af/y	Δ(C-A)/(D-B), Percent
2005	20,000	-4,900	-24	37,800	-	-27	17,700	-5,400	-31
2010	20,100	-5,100	-25	37,200	-	-29	17,100	-5,800	-34
2019	20,100	-5,700	-28	36,900	-	-33	16,900	-6,700	-40
2029	20,100	-6,100	-30	36,500	-	-36	16,500	-7,200	-44
2039	20,100	-6,400	-32	36,500	-	-39	16,400	-7,700	-47
2049	19,900	-6,800	-34	35,800	-	-41	16,000	-8,000	-50
2059	19,900	-7,100	-36	35,300	-	-43	15,400	-8,300	-54
2084	19,900	-7,700	-39	34,800	-	-47	14,800	-8,800	-59
2109	19,600	-8,200	-42	34,400	-	-51	14,800	-9,200	-62

Table 7.2. Simulated annual change attributable solely to unchanged human stress, 2005 through 2109, in net groundwater withdrawal above the Clarkdale and Camp Verde stream gages and in the Verde Valley, acre-feet per year; in base flow at the Clarkdale and Camp Verde stream gages and in the Verde Valley, acre-feet per year; and in base flow as percentage of net groundwater withdrawal. Derived from data (rounded herein) of Table 1.4 of Garner and others (2013). Deviation of values for net groundwater withdrawal from the 2005 value reflects reduction of attempted pumpage owing to development of dry cells and the related simulated variation in incidental and artificial recharge.

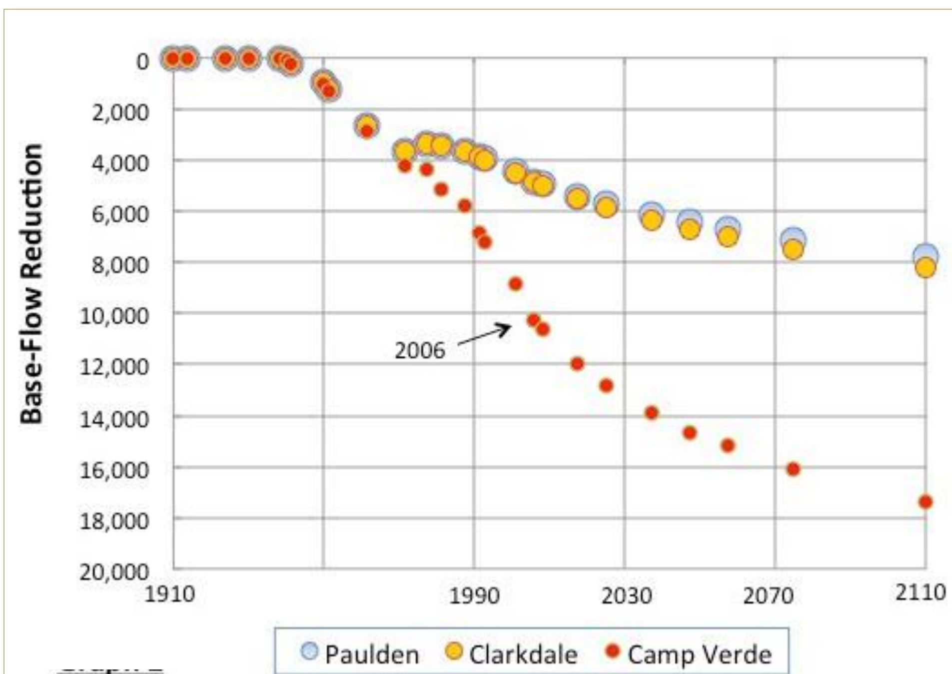


Figure 7.22. Change in base flow (acre-feet per year) owed solely to human stresses, represented as net groundwater withdrawal, 1910 through 2109, at the Paulden, Clarkdale, and Camp Verde stream gages. Based on simulated historic human stresses, 1910 through 2005, and an attempted hypothetical condition of unchanged human stress 2006 through 2109. Derived from data of Tables 1.2 and 1.4 of Garner and others (2013). Graph courtesy of William Meyer.

Figure 7.22 portrays human-induced depletion of base flow from 1910 through 2109 at the Paulden, Clarkdale, and Camp Verde stream gages. For 1910 through 2005, the simulated depletion of base flow is based on the historical records of pumpage, incidental and artificial recharge, streamflow, and groundwater levels that were used for model calibration. The graphed results through 2005 are identical to those of Figure 7.21. Predicted human-induced depletions of base flow, 2006 through 2109, at the Paulden, Clarkdale, and Camp Verde stream gages are approximately, 3,000, 3,300, 7,200 acre-feet per year. Model-predicted total human-induced depletions of base flow at the three stream gages from 1910 through 2109 are, respectively, approximately 7,900, 8,200, and 17,400 acre-feet per year. Model-predicted total human-induced depletion of base flow from 1910 through 2109 in the Verde Valley is approximately 9,200 acre-feet per year (Table 7.2).

During the period from 2006 through 2109, the rate of depletion of base flow as a percentage of net groundwater withdrawal continued to increase from its 2005 values (Table 7.2). Model-predicted total human-induced reductions of base flow as a percentage of net groundwater withdrawal at the Clarkdale and Camp Verde stream gages and within the Verde Valley from 1910 through 2109 are, respectively, 42, 51, and 62 percent.

Human Effect on Depth to Groundwater in the Verde Valley

Garner and others (2013) also applied the NARGFM to examine the human-induced change in depth to the water table. The results are given in a single map (Figure 7.23) that portrays the relative change in the altitude of the water table in the Verde Valley predicted by the forward-looking model run in which the attempt was to hold the 2005 pumping locations and net groundwater withdrawal rates (human stresses) constant through 2109. The report notes that "*maps for the decreased-human-stress and increased-human-stress conditions demonstrated a spatial pattern very similar to that for the unchanged-human-stress condition*" and thus they were not presented in the USGS report. The map portrays simulated water-table declines of more than 100 feet in the vicinity of Cottonwood, Sedona, along Dry Beaver Creek about six miles east of the Village of Oak Creek, in the Woody Ridge area southwest of Flagstaff, and in the Lake Mary area southeast of Flagstaff. Except for the area along Dry Beaver Creek these areas are in or near population centers that are served by either municipal or private water providers.

The same model run showed several areas in which the simulated water-table elevation increased by ten or more feet—in the general vicinity of Jerome in the westernmost part of the Verde Valley, three areas in the headwaters region of the Beaver Creek and West Clear Creek drainages in the east-central part of the Verde Valley, and in the vicinity of Flagstaff just north of the Verde Valley. These increases in simulated water-table elevation seem anomalous and may be a consequence of the USGS modelers' operating decision that simulated pumping would cease for the remainder of the run for any model cell simulated as going dry. A model cell going dry, especially early in the run, may have allowed simulated groundwater to enter back into the cell, producing a simulated elevation of the water table (B.D. Garner, personal communication, October 13, 2017). Supporting this hypothesis, some of the blue areas in Figure 7.23 show associated dry cells at the end of the simulation.

Conclusions and Inferences

The new USGS report (Garner and others, 2013) gives, for the first time, publicly-available numerical documentation of the effect that human water acquisition in northern Arizona has had and will continue to have on Verde River streamflow and the future accessibility of groundwater to sustain the Verde Valley's citizens and communities.

Groundwater pumping, both above the Clarkdale stream gage and in the Verde Valley, that became substantial in the 20th century, began to affect base flow in the same years in which pumping began and will continue to affect base flow well into the future. In 2005, the rate of human-induced depletion of base flow at the Clarkdale stream gage, as a percentage of net groundwater withdrawal above the gage that year, was 27 percent. The rate of depletion of base flow in the Verde Valley at that time was 30 percent of the rate of net groundwater withdrawal within the Verde Valley. By the end of 2109, the predicted rates (from the model run that attempted to hold 2005 rates and locations of net groundwater withdrawal unchanged through 2109) of human-induced depletion of base flow as percentages of net groundwater withdrawal above the Clarkdale stream gage and within the Verde Valley had increased to 42 and 62 percent, respectively. The progressive decrease in Verde River base flow, both historically and in the future, is in accord with the well-established concept of streamflow depletion.

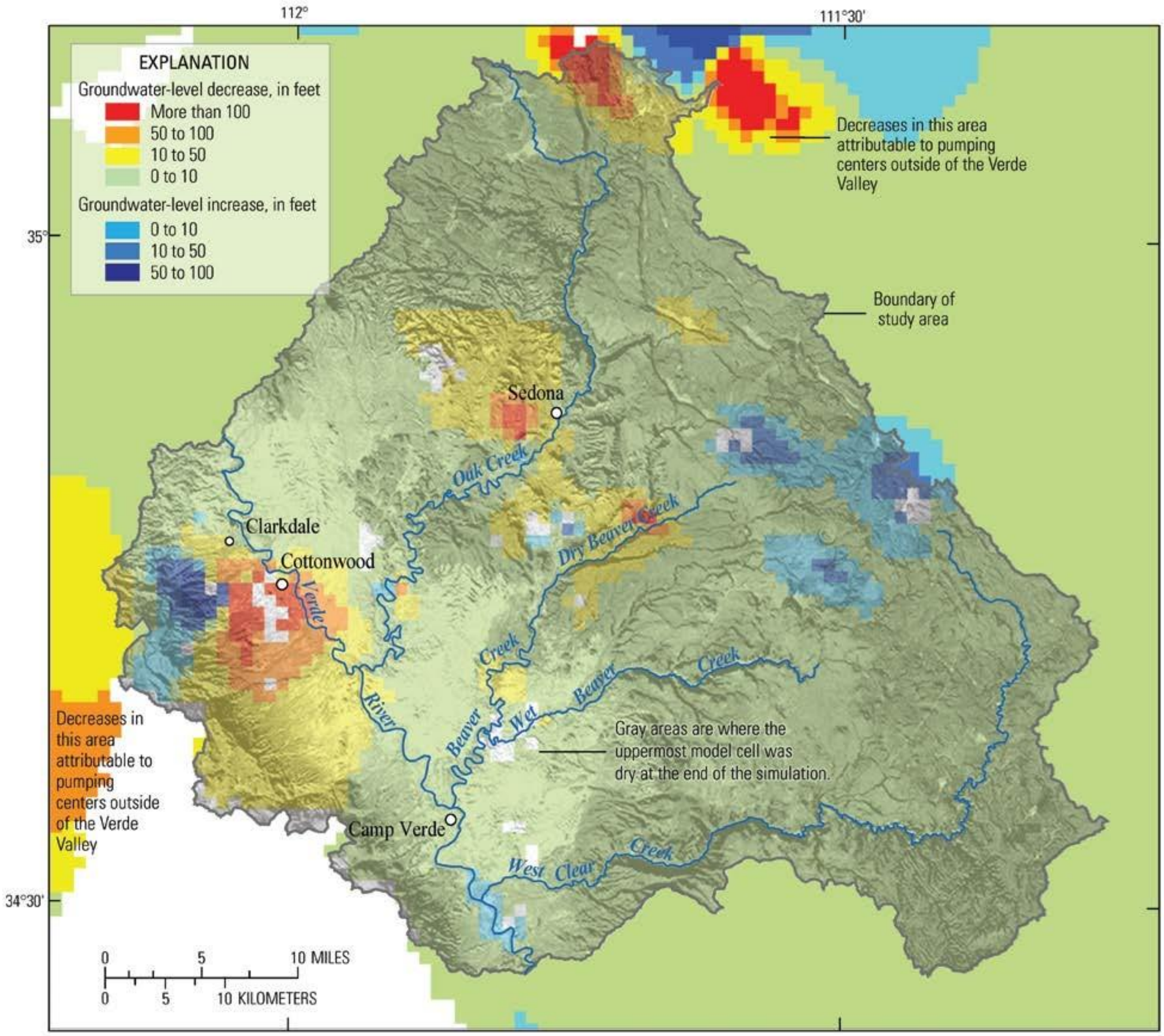


Figure 7.23. Map showing relative changes in water-table altitude attributed solely to human stresses simulated in the model run in which the 2005 pumping locations and net groundwater withdrawal rates (human stresses) were, insofar as possible, held constant through 2109. Values used to produce this map are from the uppermost layer of the model. (Garner and others, 2013, Figure 10).

Change in base flow is critical because the year-round (perennial) flow of the Verde River is dependent on maintaining the river's base flow. Without its base flow, the Verde, like so many other once-perennial rivers in Arizona, would flow only after storms or at times of voluminous snow melt.

The nearly identical model-estimated base-flow depletion at the Paulden and Clarkdale stream gages through time indicates that loss of base flow at the Paulden gage is transmitted essentially intact to the Clarkdale gage. This reflects the near absence of human water acquisition in the watershed area between the two gages. The USGS report notes that although the human stresses that caused the base-flow reduction at the Clarkdale stream gage *"likely are mostly located in areas of the Verde River groundwater basin up-gradient from the Clarkdale gage, some could have been located in other groundwater basins."*

The same hypothetical scenario in which the human stresses on the groundwater system were unchanged after 2005 predicted increased depth to groundwater by 2110 of more than 100 feet in the vicinity of Cottonwood, near Sedona, along Dry Beaver Creek near the Village of Oak Creek, in the Woody Ridge area southeast of Flagstaff, and in the Lake Mary area southeast of Flagstaff. Increasing depth of the water table, of course, causes some once-active water wells to become dry.

Clearly the Verde River is at risk, and groundwater to support future populations will become ever more difficult and more expensive to acquire. The issues, which involve citizens and municipalities in both the upper and middle Verde River basin, are compelling and demand timely solution. Now is the time to plan and implement actions to preserve the Verde River system.

Chapter 8: The Verde River Ecosystem-Riparian and Aquatic Habitat

Chapter 8. The Verde River Ecosystem – Riparian and Aquatic Habitat

The Verde River watershed is outstanding for the extent and inter-connection of perennial surface water and associated riparian habitat In Arizona. Together they provide high quality habitat for fish and other wildlife. Many miles of permanently flowing rivers and riparian habitat have been lost in Arizona due to dams, diversions, and groundwater pumping (Figure 8.1); thus, the extent and connection of habitat in the Verde basin is of state-wide importance. The north-south orientation of the Verde River makes it a preferred flyway for migrating birds that use riparian areas for rest stops and feeding grounds. Breeding bird density is also very high. Carrothers and Johnson (1970) found densities in excess of 1,000 pairs of breeding birds per 100 acres in certain cottonwood stands in the Verde Valley. Native fish still occupy many areas in the Verde River and its perennial tributaries. Much of the Verde River supports natural resources that are unique and irreplaceable on an ecoregional basis and also provides outstanding recreational value (Sullivan and Richardson 1993).

Vegetation that grows adjacent to a river is termed **riparian**. Examples are cottonwood and willow trees and cattails and horsetail plants. Common riparian vegetation consists of mixed broadleaf and cottonwood willow communities, streamside wetlands, and marshlands. Important species include cattail, bulrush, Freemont cottonwood, Goodding willow, Arizona sycamore, and Arizona alder. Riparian vegetation requires shallow groundwater and/or moist soils, along with periodic flooding for germination and survival. Riparian vegetation arranges itself along a river and across the floodplain in response to depth to groundwater and flooding frequency (Figures 8.2A, 8.2B, and 8.3). Healthy riverine ecosystems are comprised of the full complement of riparian and aquatic habitats, which evolved with and are maintained by the natural flow regime.

Riparian vegetation covers much less than 1 percent of the land surface in Arizona yet is extremely important to the livelihood of many species. In semi-arid regions of North America (such as the Verde River basin), the role of riparian areas is disproportionate to their size (Patten 1998). Until the 1890s, the Verde River floodplain zone was over a mile wide in places, creating a matrix of marshes and sloughs that provided habitat for a variety of plants and animals. Agricultural and residential development have occurred along the banks of the river in the Verde Valley, restricting the river's floodplain to some extent; yet, an extensive and well-connected perennial stream with perennial tributaries, functioning floodplain, and continuous riparian vegetation remains.

Riparian areas serve many functions that benefit humans and wildlife, which have been documented in numerous studies. (See http://ag.arizona.edu/extension/riparian/)

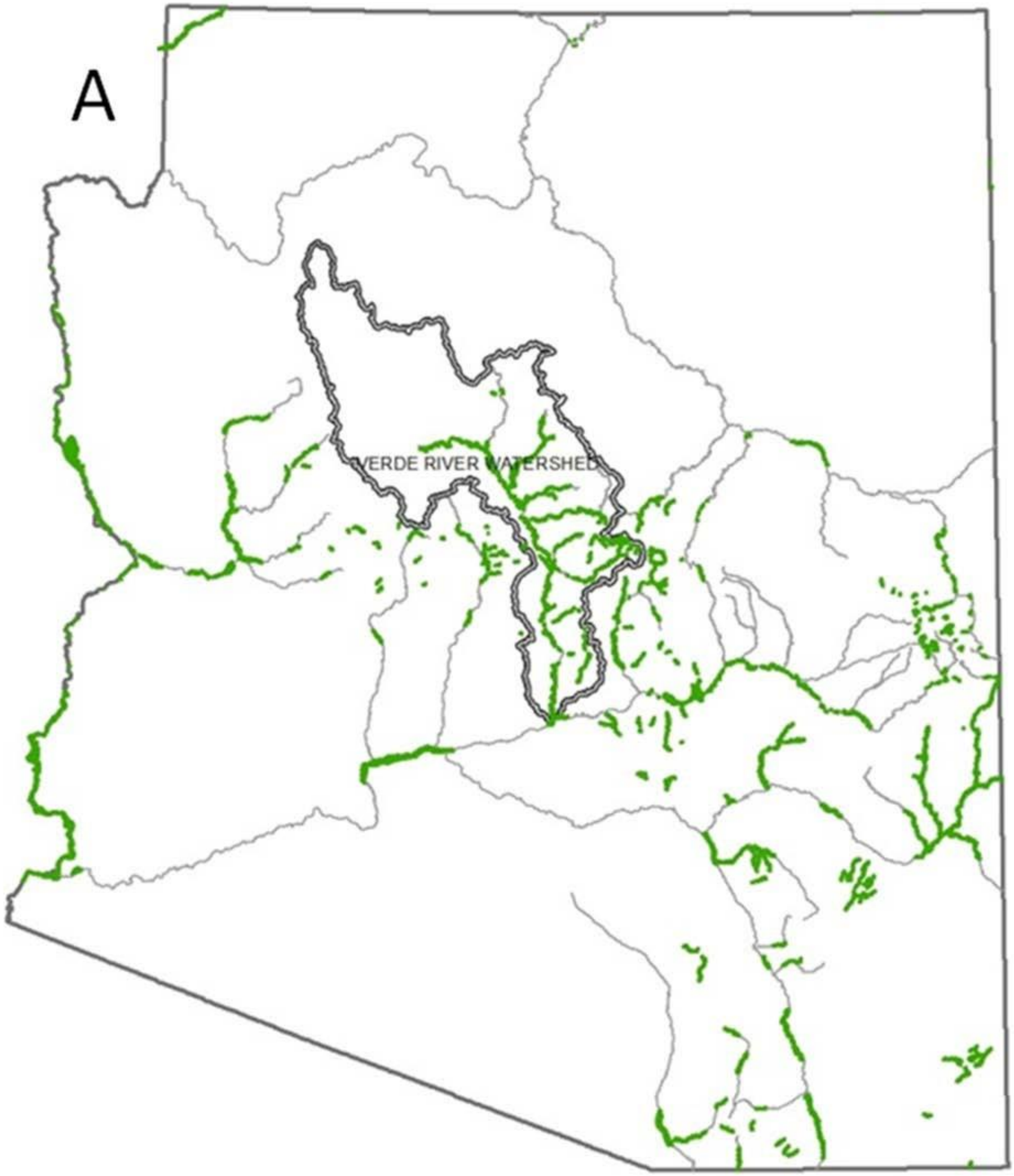


Figure 8.1. Map of Arizona showing extent of remaining riparian vegetation along major rivers (green lines). Verde River watershed outline is shown. The riparian habitat in the Verde River watershed is some of the most extensive and connected in the state. *Data source: Riparian vegetation from ALRIS http://www.land.state.az.us/alris/*

Figure 8.2A. Verde River near Dead Horse Ranch State Park.

In this photo, aquatic vegetation is growing in the water and emerging from the water. Low-stature younger trees grow near the channel and taller trees more distant from the channel. Large trees may persist adjacent to the channel, but often are removed by large floods, such as the flood that occurred in 1993.

Photo courtesy: Jeanmarie Haney

Figure 8.2B. Verde River near Dead Horse Ranch State Park.

Mature cottonwood trees on a high terrace of the floodplain. This level was accessed by water during the 1993 flood, but depth and velocity of the water were not sufficient to uproot these trees.

Photo courtesy: Jeanmarie Haney

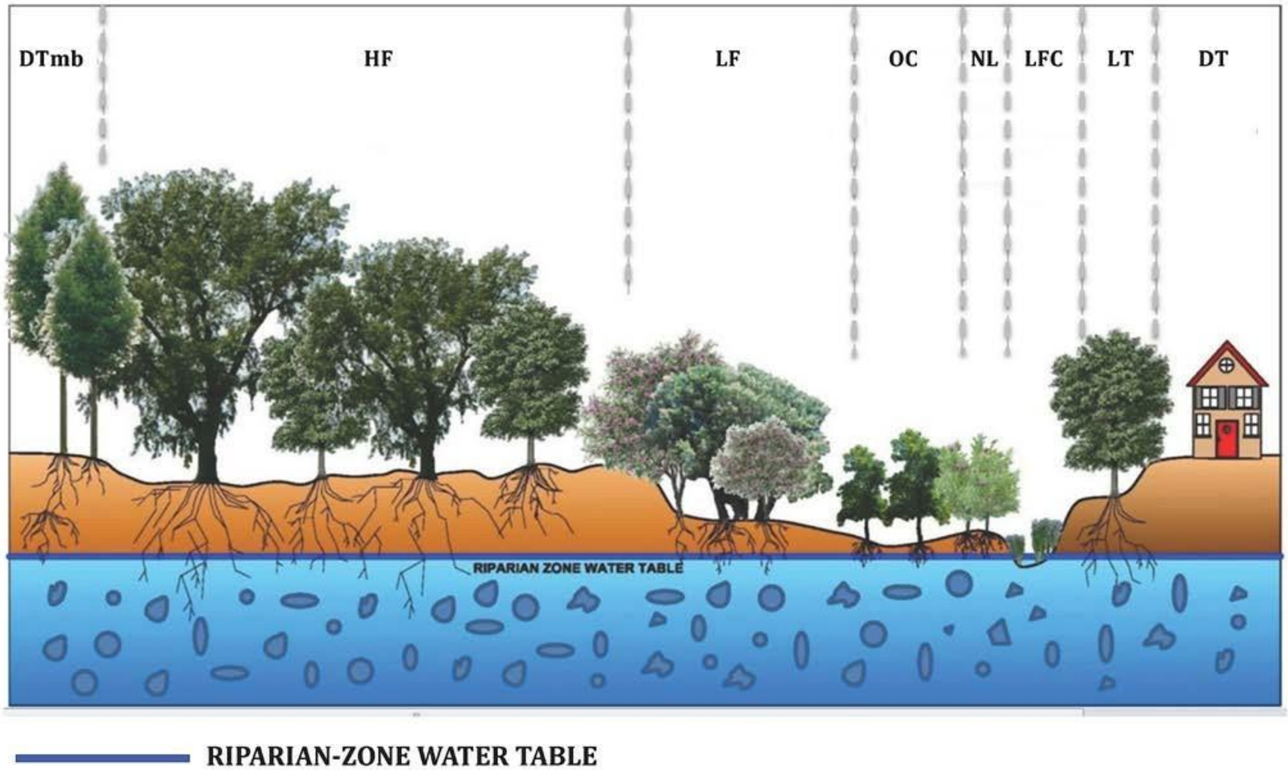


Figure 8.3. Cross section showing how riparian vegetation arranges itself across the floodplain in response to depth to water and flood frequency. DTmb, developed terrace with mesquite bosque; HF, high floodplain with mature riparian forest containing cottonwood, Gooddings willow, ash, hackberry, boxelder; LF, low floodplain with desert willow, tamarisk, adult cottonwoods that have survived flooding; OC, overflow channel with young cottonwoods; NL, natural levee with dense young willows; LFC, low-flow channel with herbaceous wetland vegetation; LT, low terrace; DT, developed terrace.

Plants and animals living in the river itself are called **aquatic species**. Examples are fish, frogs, watercress, and aquatic insects. These species require the permanent presence of water to survive. Aquatic species occupy various **habitats** in the stream (Figures 8.4A and 8.4B). Habitats vary depending, for example, on factors such as water velocity, water depth, water temperature, type of sediment on the bottom of the stream, stream bank vegetation and overhang, and amount of sun reaching the water surface. At different times in its life cycle, from new-born to adult, a species may have different habitat needs. Healthy riverine ecosystems are comprised of the full complement of riparian and aquatic habitats, which evolved with and are maintained by the natural flow regime. These ecosystems are dynamic, are well adjusted to floods, and depend on perennial streamflow and shallow depth to groundwater. Although hardy in many ways, these systems are sensitive to human alterations, and if certain thresholds are crossed, the delicate balance required to maintain these systems is lost.

Figure 8.4A. Verde River aquatic habitats near Dead Horse Ranch State Park.

Riffle: fast, shallow water with a rocky bottom. (This riffle is 70% dewatered due to upstream irrigation diversion.)

Figure 8.4B. Verde River aquatic habitats near Dead Horse Ranch State Park.

Pool or glide: slower, deeper water with sandy or silty bottom.

Photos courtesy: Jeanmarie Haney

Riffle: fast, shallow water with a rocky bottom.

Pool or glide: slower, deeper water with sandy or silty bottom.

Native Fish in Arizona

The Verde River is part of the Gila River basin. The Gila River rises in the Black Range of New Mexico and crosses Arizona in a generally westerly direction, passing through mountain ranges and valleys on its way to the Colorado River near Yuma. The Gila River is one of the largest desert rivers in the world. Once mostly perennial, it has lost its natural perennial flow through much of its course in Arizona due to irrigation, surface water diversions, groundwater pumping, and one large water-storage reservoir (San Carlos Reservoir). The Verde River is tributary to the Salt River, which joins the Gila River near Phoenix.

The Gila River basin shares many of its aquatic species with the Colorado River; the Gila and Colorado rivers in particular share many distinctive large-river species. However, out of roughly 30 native species found in the Gila River basin, an impressive 20% are endemic, meaning these species are found nowhere else in the world. The Verde River is home to two of these endemic species – the spikedace and loach minnow, although these species have not been seen in the Verde in recent years.

For thousands of years, Arizona's native fish adapted to life in habitats ranging from small springs to the raging torrents of the Colorado River. They survived drought and flood and extreme temperature variations. But these species have not adapted well to human-imposed alterations of their environment. Habitat loss and alteration, and the introduction of non-native fish species, have caused sharp declines in many native fish populations (Minkley and Deacon 1991). Out of the 36 fish species native to Arizona, one species is already extinct, 34 have been identified as Species of Greatest Conservation Need in Arizona, and 21 have been federally listed as endangered or threatened. Several species are no longer found in the state but exist elsewhere in the Colorado River Basin. Although native fish species may seem insignificant, especially the small minnow types, they are a unique and irreplaceable part of Arizona's natural heritage. A special and important part of Arizona's heritage could easily disappear if more native fish species are lost.

Conservation efforts by state and federal wildlife agencies are attempting to establish refugia for native fish species, but pressure from development, non-native fish species, and the desire for sport fishing provide challenges for native fish recovery efforts. The upper Verde and specific reaches of the Verde's perennial tributaries, such as Sycamore Creek, Oak Creek, Wet and Dry Beaver Creeks, West Clear Creek, and Fossil Creek, provide opportunities for native fish recovery.

Verde River Plants and Animals

Many aquatic, terrestrial, arboreal (tree) and aerial animal species depend directly or indirectly on the Verde River and its tributaries. In fact, Arizona's Heritage Data Management System (AGFD 2009) lists 43 riparian or aquatic species in the Verde River basin, including 11 with federal protected status.

Native fish populations in the upper Verde River are among the most diverse in Arizona. The river's headwaters represent a critical location for the Gila Riverine fish community type. The reach from Paulden to Clarkdale currently supports one of the best remaining native fisheries in Arizona with eight native species likely extant. This represents the second-highest native fish richness in Arizona.

Historically the Verde River supported sixteen native fish species; only ten remain including the federally endangered Razorback Sucker and Colorado Pikeminnow, as well as the threatened Spikedace and Gila Chub. A number of introduced non-native sport fish draw anglers to the Verde River in the Verde Valley.

> Emergent marsh: Non-woody plant communities growing in year-round standing shallow water along pond and river edges. The plants are rooted in the water and grow upright out of the water's surface up to 6 feet tall. Marsh plants are especially adapted to soil that is saturated with water. Many other plants are unable to tolerate these saturated soils and do not grow in these areas. Marsh plants do not tolerate dry soil conditions.

The Verde River and its major tributaries (Oak Creek, Beaver Creek, and West Clear Creek) contain some of the most extensive acreage of Fremont cottonwood-Goodding willow and mixed broadleaf riparian forest remaining in Arizona. This plant community has a globally imperiled status. In addition, emergent marsh, a very rare habitat type in Arizona, exists at Tavasci marsh and at smaller streamside locations throughout the Verde Valley. Important species in addition to Fremont cottonwood and Goodding willow include cattail, bulrush, spikerush, Arizona sycamore, Arizona alder, velvet ash, netleaf hackberry, and box elder. These riparian and marsh habitats are critical for bird migration and breeding.

The Verde River riparian zone is an important flyway for migratory birds and supports a high density of breeding birds; over 200 resident and neo-tropical migratory bird species have been recorded (Haney and others, 2008, Chapter 5). Species such as the federally endangered Southwestern Willow Flycatcher and the Yellow-billed Cuckoo depend on the river's woody riparian forests of cottonwood, willow and ash. Other species include the Peregrine Falcon, Desert Bald Eagle, Summer Tanager, Osprey, Vermillion Flycatcher, Blue-throated Hummingbirds, and Great Blue Herons. The Verde River supports the largest number of Bald Eagle nesting sites of any river in the state. The Audubon Society has designated four Important Bird Areas (IBAs) in the Verde watershed, based on the abundance and diversity of birds using the area. These are: the Upper Verde River State Wildlife Area IBA; Tuzigoot IBA; Lower Oak Creek IBA; and Watson and Willow Lakes Ecosystem IBA.

The Verde River is one of three Arizonan rivers that sustain populations of river otter. The southwestern river otter sub-species historically occurred in the middle Verde. Its current status is not known and is confounded by the introduction of a sub-species from Louisiana in the early 1980s. Nonetheless, the Verde remains one of three river systems in Arizona that has river otter. The Verde River and its tributaries also support a robust beaver population.

A number of other rare or sensitive riparian-dependent species still occur in the middle Verde, including common blackhawk, which reaches the northern limit of its range in the Verde Valley, and nests in cottonwood trees within the canyon. Where the Verde empties onto the broader floodplain near Clarkdale, dense patches of cottonwood, willow, and saltcedar support southwestern willow flycatcher and western yellow-billed cuckoo. Belted kingfisher, rare in Arizona, is also found nesting in the area.

Other State Wildlife Species of Concern observed in the Verde Basin include Lowland Leopard Frog, Northern Leopard Frog, Peregrine Falcon, Common Black-Hawk, Bobolink, Belted Kingfisher, Navajo Mexican Vole, Western Red Bat, and Narrow-headed Gartersnake.

The Page springsnail is found only at the Page Springs spring complex, from which several main springs and other minor springs arise.

The West Fork of Oak Creek, a tributary of Oak Creek, is another perennial stream in the Verde Basin that provides fish and wildlife habitat. Oak Creek Canyon is a popular destination, second only to the Grand Canyon.

Wet Beaver Creek is a perennial stream with one major tributary, Dry Beaver Creek. Wet Beaver Creek flows through secluded canyons and the Wet Beaver Wilderness Area before flowing through Montezuma Well and Montezuma Castle, eventually reaching the Verde River near Camp Verde. Wet Beaver Creek provides habitat for stocked trout as well as dense riparian vegetation for numerous species of songbirds. The perennial waters in the Wet Beaver Wilderness attract large numbers of wildlife, including elk, deer, bear, mountain lion, and a variety of smaller mammals, reptiles, and birds.

West Clear Creek is another important perennial stream with headwaters originating from Willow and Clover Creeks. West Clear Creek flows through the 13,600-acre West Clear Creek Wilderness Area and provides extensive riparian habitat along canyon bottoms. Dominant vegetation includes cottonwood, sycamore, and alder along with some ash, willow, walnut and wild grape along the riparian zone. The creek attracts anglers with its stocked populations of trout and smallmouth bass.

Fossil Creek is a unique warm-water perennial stream that supports one of the most diverse riparian areas in Arizona. Fossil Creek flows from a complex of springs that supply a constant 20,000 gallons per minute of 72-degree Fahrenheit water. Over thirty species of trees and shrubs and over a hundred species of birds have been observed along Fossil Creek's riparian area. In 2004, federal and state agencies completed an extensive restoration of Fossil Creek to remove invasive fish species and have since successfully reintroduced native fish species. In March 2009 Fossil Creek became the second Arizona stream to receive federal designation as a Wild and Scenic River.

The exotic saltcedar is found throughout the Verde Valley occurring in small (<1 acre) monotypic patches or as an understory component of cottonwood-willow and mixed broadleaf riparian forests. Tree of heaven appears to be on the increase (J. Agygoos, Coconino NF, pers. comm.) occurring locally in small patches (<1 acre), particularly near urban areas.

Verde River Water Needs

Many demands are placed on rivers, and the Verde River is no exception. The Verde River and its tributaries range from nearly pristine, such as in the upper Verde canyon and the upper reaches of tributaries, to the Verde Valley, where the Verde is a working river, delivering irrigation water to fields and lawns through a complex system of diversion dams, ditches, and laterals. Groundwater provides drinking water for city and household wells throughout the Verde watershed. The same groundwater relied upon by humans also furnishes year-round base flow to the Verde River. There has also been gravel mining in the river channel (no longer practiced) and alterations in the urban environment which constrain the Verde River channel while at the same time increasing storm runoff from urban "hardscapes".

When addressing the question of how much water a river needs, scientists first consider the river's natural flow regime, and work to mimic that regime to the extent possible, given the realities of the developed world. However, natural systems are highly complex and variable and human impacts increase the complexity. Although the full flow regime typically can't be realized on a "working" river, particular values desired by society can be considered and maintained through a flow management approach.

There are no large dams on the Verde River upstream from the Verde Valley; thus, the flood regime is relatively unaltered. However, base flows have been altered by human activities described above. Further alteration, in the form of decreased volume of base flow, is expected through time (Chapter 7). Understanding the natural flow regime and how it supports Verde River plants and animals is a first step towards managing the Verde River in an ecologically sustainable manner.

The Verde River ecosystem evolved in tune with the natural flows that occur throughout the year—the large floods, moderate floods, and base flows that vary in magnitude, timing, frequency, and duration from year to year. This full range of streamflow is needed to maintain a river ecosystem in a proper functioning condition. This is because various flow events throughout the year provide cues to plants and animals to begin activities related to reproduction and growth. For example, the spring high flows flush dead plant litter from river banks and sand bars and create a clean, moist surface for cottonwood seeds to land and germinate. If the spring high flows come too early or too late, the seeds are not available, and cottonwood germination will not occur. Birds such as the southwest willow flycatcher and yellow-billed cuckoo migrate into the area and begin building nests, with chick rearing taking place when a high density of specific types of insects is available for food. Many of those insects morphed from an aquatic life stage, likely cued by some aspect of the flow regime. High flows also cue fish to spawn when aquatic habitat availability and food sources are the most beneficial for survival of the young. Species life-cycle dependence on the flow regime is shown schematically in Figure 8.5. The water needs of riparian and wetland plants and native wildlife and fish are discussed below.

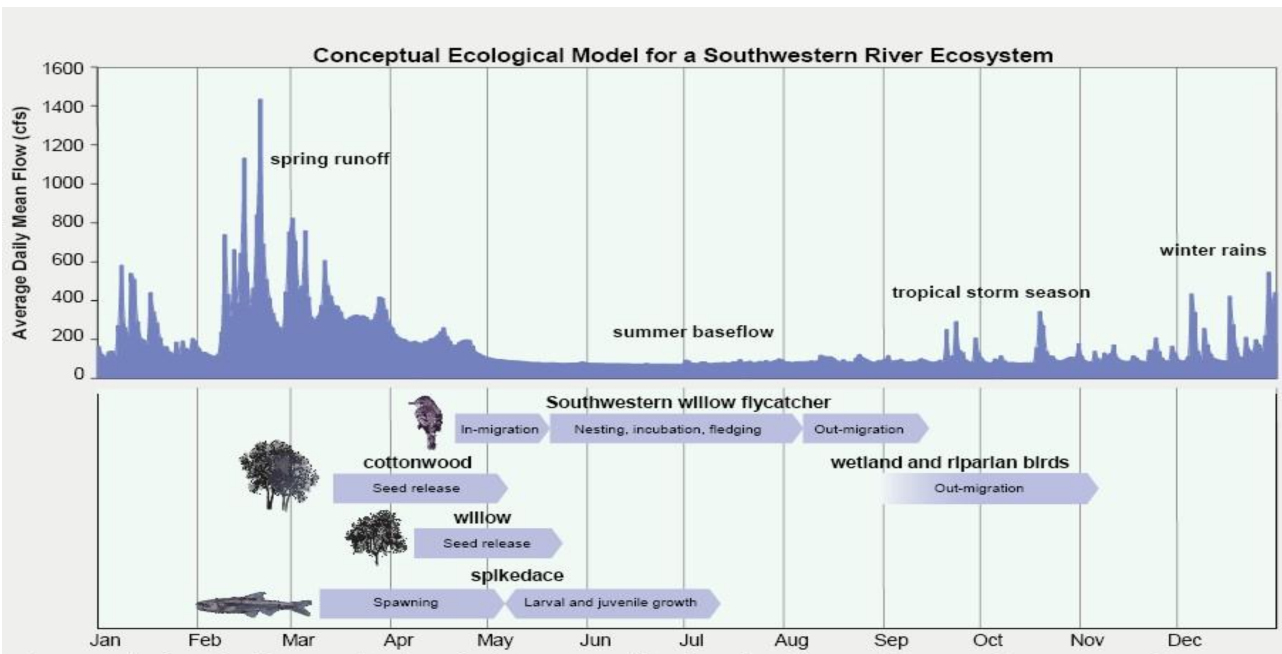


Figure 8.5. Conceptual ecological-flows model for the Verde River. The dark blue is average daily flow. The bottom window shows species life-cycle events that rely on river flows.

Riparian Trees and Groundwater

Riparian forest response to stream flow regime and depth-to-groundwater fluctuations have been extensively studied in southwestern rivers (e.g. Leenhouts and others, 2006; Haney and others, 2008). Cottonwood and willow trees rely primarily on groundwater and are sensitive to fluctuating water table levels. Declines of one meter have killed cottonwood and willow saplings; mature trees have been killed by drops of one meter that were abrupt and permanent. Mesquite and tamarisk, on the other hand, are deeper-rooted species that can switch between rain-fed soil water and groundwater, giving them a higher tolerance to water stress. Studies on the San Pedro River in southeast Arizona have higher tolerance to water stress. Studies on the San Pedro River in southeast Arizona have demonstrated that cottonwood and willow trees thrive along perennial river reaches where depth to groundwater is less than 6.5 feet, and annual groundwater level fluctuation is less than 1 foot (Leenhouts and others, 2006, Table 16). Shallow depth to groundwater adjacent to the river relies on a permanently flowing stream. If streamflow permanence declines, so does groundwater level.

More intermittent flows, deeper groundwater levels, and larger groundwater-level fluctuations all are linked with: 1) declines in cottonwood and willow abundance; 2) decreases in structural diversity; and 3) increases in non-native species such as tamarisk. If threshold values are exceeded for these parameters, native water-loving plants such as cottonwood and willow are likely to be replaced by more drought-tolerant plants, such as desert willow and mesquite, and the non-native invasive tamarisk (Haney and others, 2008, Chapter 4). The riparian forest is likely to shift from tall trees to short trees or shrub lands. This type of conversion is shown in Figure 8.6.

Structural diversity: vertical "layering" of plants at different heights and horizontal "patches" of varying plant species groupings and openings. Structural diversity promotes resiliency – the ability to recover from disturbances such as floods – by providing plant diversity and a variety of habitats for animal species.

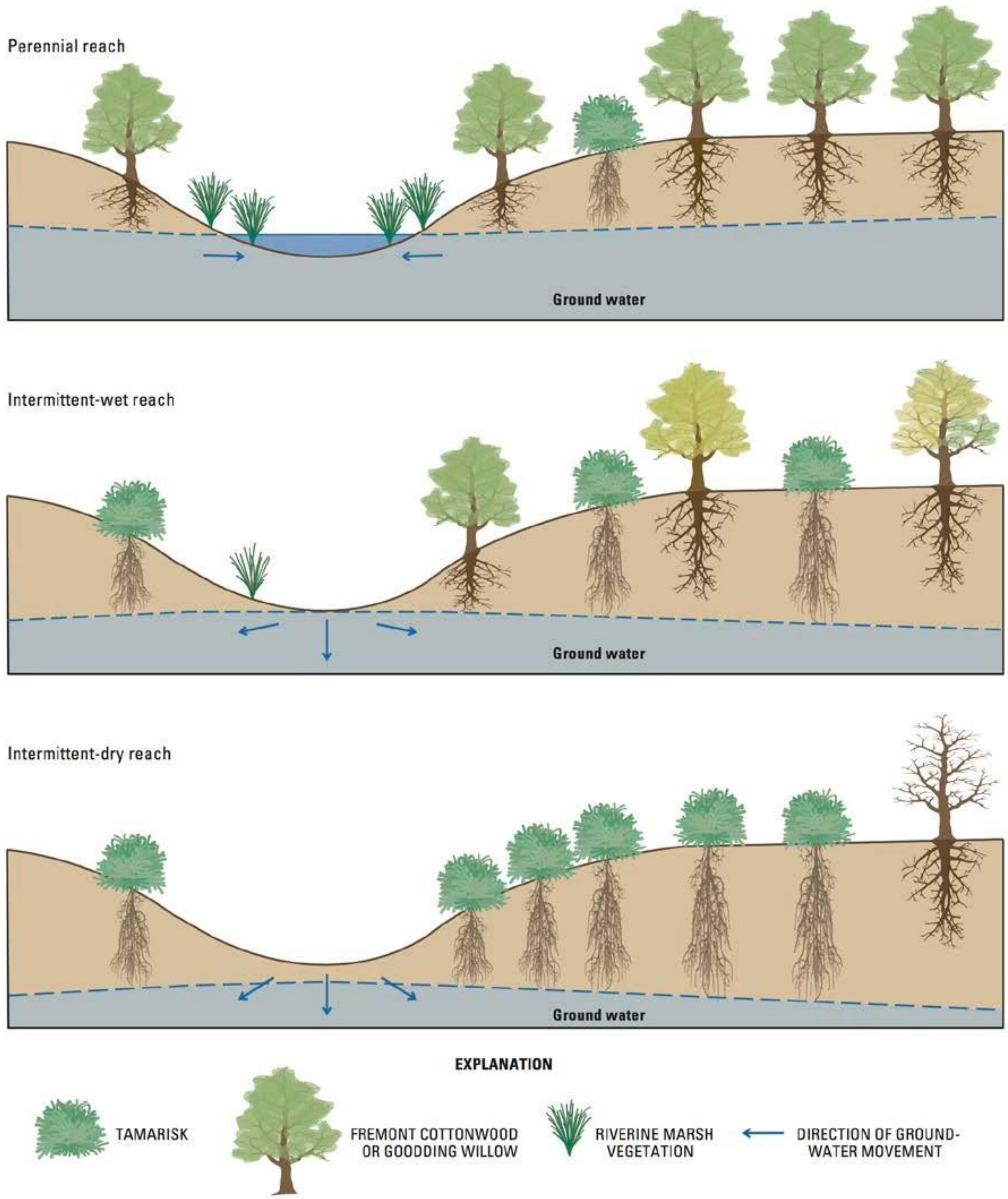


Figure 8.6. Schematic illustration of vegetation and groundwater response to decreasing permanence of streamflow. As streamflow permanence decreases from 100% of the time, a river reach will transition from perennial (year-round flow) to intermittent (seasonal flow only) to possibly ephemeral (flow only in response to runoff). These flow conditions each correspond to an associated groundwater-level condition, with groundwater becoming increasingly disconnected from the stream. A perennial stream flows year-round because it has a permanent connection to the groundwater. Intermittent flow can occur across a range from intermittent—wet (shallow groundwater at or just below the stream bottom, with flow during much of the year other than summer) to intermittent-dry (groundwater is below the stream bottom much of the year with flow occurring for only a few months during the spring of wet years, when groundwater level rises). An ephemeral stream has lost its groundwater connection throughout the year – groundwater is 10s to 100s of feet below the stream bottom. Plant composition shifts from water-loving hydric plants that have their roots in groundwater to mesic plants that can utilize both groundwater and soil water from rainfall to xeric plants that rely solely on soil water from rainfall. Numerous river reaches in Arizona have undergone this transition over the past 150 years. (From Leenhouts and others, 2006, Figure 41.)

Wetland Plants and Groundwater

Wetland plants (Figure 8.7) are highly sensitive to declines in surface-water level. If base flow were to decline, the extent of saturated soils would shrink. Wetland vegetation would shift closer to the channel where it is at higher risk of flood scour. This response can be observed currently on portions of the Verde that have been substantially dewatered by irrigation dams, such as between Tuzigoot Bridge and 10th Street Bridge in Cottonwood. If perennial flow became intermittent and channel soils drier, the abundance of wetland plants would decline sharply. Plant community composition would shift from plants such as cattail, rush and spike rush to plants such as Bermuda grass (Haney and others, 2008, Chapter 4). In addition, species diversity would decrease as the number of no-flow days per year increased.

Figure 8.7. A small wetland along a bend in the channel, near Dead Horse Ranch State Park. The wetland plant community is directly dependent on perennial flow and shallow groundwater level.

Photo courtesy: Jeanmarie Haney

Native Wildlife

Experts predict that loss of wetland and riparian plants and development of more dry-adapted plant communities would have predictable consequences for wildlife owing to habitat change (Haney and others, 2008). Reductions in the extent and diversity of riparian habitat would likely lead to declines in the populations of several bird species. The southwestern willow flycatcher, an endangered species, is riparian-dependent and prefers the high-density foliage of cottonwood-willow forests for nesting. The health of the species thus is linked with the health of these forests. Another bird of concern, the yellow-billed cuckoo (Figure 8.8), also breeds in riparian woodlands and requires large patches of mature forest. Both birds are insect eaters and would likely be affected if reductions in base flow led to declines in insect populations. Because many of the insects have an aquatic phase in their life cycle, it is easy to see how stream flow, riparian tree health, and bird health are tied together.

Other birds likely to be affected by habitat reduction caused by reduced river flow are wetland species such as the common yellowthroat, Virginia rail, sora, and least bittern (Haney and others, 2008, Chapter 5). These birds are closely associated with cattail marshes.

Figure 8.8. A yellow-billed cuckoo watches vigilantly from a cottonwood tree.

Photo courtesy: Anna Fasoli

Figure 8.9. An otter is seen swimming in the Verde River near Dead Horse Ranch State Park during a high flow event in February 2008.

Photo courtesy: Jeanmarie Haney

There are three aquatic mammal species found in the Verde Valley: beaver, muskrat, and river otter (Figure 8.9). These species require perennial flow and would not respond well to loss of flow, especially during the dry summer months. Beavers, which depend on cottonwoods and willows, would likely suffer from the loss of these trees. Otters benefit from pools created by beaver dams and would probably be affected by a decrease in beavers.

Fish

As discussed above, native fish are facing increasingly difficult times, with habitat alteration and introduced non-native species being the biggest concerns. Native fish did not evolve with the dominantly Mississippi River Basin fish that were introduced by humans and now invade their habitat. Thus the native fish have not evolved mechanisms to avoid predation by these invasive species nor are they good at competing with non-natives species for food. Native fish did evolve with the natural flow regime, so when the flow regime is altered from natural conditions, experts believe that the non-native fish are given additional competitive edge (e.g. Minckley and Meffe 1987).

Experts predict that populations of most fish would decline with base-flow declines, and would disappear with major flow reduction except at a few isolated springs (Haney and others, 2008, e.g. Figure 6-5). Habitat loss would affect spawning, juvenile, and adult life stages with specific effects dependent on habitat needs. Some native fish species show a strong preference for specific habitats—such as riffles versus pools—for various life stages. Population size for riffle specialists would be expected to decrease first, as riffles would be the first dewatered habitat. Pool dwellers, such as chub and sucker, would persist longer with reduction in base flow. The speckled dace depends on riffles and would likely suffer significantly with reductions in this habitat type. Roundtail chub occupies pools adjacent to swifter riffles and runs, so initially would be less affected by flow reduction. But the models show populations of these fish, along with other pool-dwelling native species such as the speckled dace and Sonora sucker (Figure 8.10), would ultimately decline with a substantial loss of base flow. Loss of riffle habitat would also reduce the chances of restoring Verde River natives, such as the threatened spikedace. Reduced base flow could also damage the Verde River's value as a sport fishery, with higher water temperatures, lower dissolved oxygen content, and reduced visibility affecting the abundance, size, and catchability of sport fish.

Figure 8.10. Two of the Verde River's ten species of native fish. Top photo is speckled dace (John Rinne) and bottom photo is Sonora sucker (U.S. Forest Service).

Shrinking aquatic habitat is also likely to threaten reptiles and amphibians. Conditions that result in disconnected pools that concentrate predators would likely expose amphibians, such as the lowland leopard frog, to more predation in and between pools. The Verde's two species of garter snakes depend on fish and frogs for their diet, along with streamside plants for cover, and would likely decline along with those groups.

Finding Balance

River ecological systems are sensitive and have thresholds related to stream flow and depth to groundwater. If thresholds are crossed - too little or too much - these systems will change how they function; services valuable to human communities may be lost (Figure 8.11).

The question then becomes, how do we make wide-ranging water-management decisions in a manner that meets human needs and keeps the Verde River flowing? The first step is to continue scientific research with the goal of quantifying how much water the river needs to maintain a desired ecological condition. Then, societal discourse leads to decisions on what level of ecological condition should be maintained, given consequences and trade-offs of various actions. Good leadership provides opportunities to manage water in a smart manner that considers both the desired ecological condition and human needs.

Scientific study, societal exploration, and informed decision making is at the root of environmental flows, an approach that attempts to manage water for both humans and nature. Many communities around the world have been applying the environmental flows concept and approach to maintain river ecosystems while also meeting human needs for water supply, flood control, power, and transportation. Additional information on the environmental flows approach can be found at: www.conservationgateway.org/topic/environmental-flows.

Environmental flows: the provision of water within rivers and groundwater systems to sustain healthy ecosystems and the goods and services that humans derive from them.

Figure 8.11. A flowing, floatable river in Arizona is a rare sight. In addition to supporting valuable and irreplaceable habitat for wildlife, the flowing Verde River provides unparalleled recreational activities for humans, including boating, fishing, swimming, bird watching, hiking, and the simple experience of cooling off in a wet shady place on a hot summer day. It is a certainty that no one in the Verde watershed wants to lose the miracle of a flowing river. Sound science, societal discourse, and good leadership can find the balance necessary to maintain river flow.
Photo courtesy: Jim Duffield

Chapter 9: Perennial Flow of the Verde River: Is It at Risk?

Chapter 9: Perennial Flow of the Verde River: Is It At Risk?

Stream capture resulting from current and future groundwater pumping in the Verde Valley, the Big Chino sub-basin, and the Prescott Active Management Area (PrAMA) poses a substantial long-term threat to perennial flow of at least sections of the Verde River. In this chapter we examine:

- Estimated current water supply and future water demand in the upper and middle Verde River watersheds
- Potential effects of depletion of Verde River streamflow by groundwater pumping
- Actions that could lessen the effects of streamflow depletion by groundwater pumping

Potential Future Groundwater Demand in the Upper and Middle Verde Watersheds

Virtually all water for domestic, industrial, and commercial use throughout the upper and middle Verde River watersheds is pumped from thousands of water wells. These wells draw from aquifers that are hydrologically connected to the Verde River and whose groundwater provides the base flow that keeps the Verde River flowing year-round. Water for agricultural irrigation is an additional demand and is supplied in substantial part by diversion of streamflow.

In 2008, Yavapai County, the Arizona Department of Water Resources, and the U.S. Bureau of Reclamation initiated the Central Yavapai Highlands Water Resources Management Study (CYHWRMS) to "*identify projected water use needs and then outline water resources and management strategies to the defined future needs of communities in the Central Yavapai Highlands*" (see project overview at http://www.yavapai.us/bc-wac/cyhwrms/).

CYHWRMS projections completed in 2010 estimate substantial increases in population and water demand from 2006 to 2050 (Table 9.1).

Area	2006 Population	2050 Population	2006 Water Supply ac-ft/yr	2050 Water Demand ac-ft/yr	2050 Unmet Demand ac-ft/yr	2050 Unmet Demand cfs (rounded)
PrAMA	121,629	352,940	25,416	57,411	31,995	44
Big Chino sb	9,124	58,379	10,012	13,159	3,148	4
Verde Valley sb	70,281	183,073	36,675	46,811	10,136	14
Total	201,034	594,392	72,103	117,381	45,279	62

Table 9.1. Summary, from data of Central Yavapai Highlands Water Resources Management Study, Phase-1 (CYHWRMS, 2010), of estimated 2006 population and water supply in study area sub-basins, and projected 2050 population and unmet water demand (2050 water demand beyond quantities supplied in 2006). PrAMA, Prescott Active Management Area, includes Little Chino and Upper Agua Fria sub-basins; sb, sub-basin. See Figure 6.3 for location of sub-basins and PrAMA. From Phase 1 Results, CYHWRMS Demand Analysis Summary Table Part 2 at http://www.yavapai.us/bc-wac/cyhwrms/.

The intent of the CYHWRMS Phase-1 study was to address unmet water demand related to the demands of municipal and domestic use, commercial and industrial use, and agricultural use. Water for maintenance of streamflow was essentially ignored.

Potential New Water Demand in the Little Chino Sub-basin

The CYHWRMS Phase-1 analysis reports an estimated unmet water demand in 2050 in the PrAMA of 31,995 ac-ft/yr (44 cfs; Table 9.1). Part of the PrAMA is in the Little Chino Sub-basin of the upper Verde River watershed, and part is in the Upper Agua Fria Sub-basin, which is outside of the upper and middle Verde River watersheds (Figure 6.3). CYHWRMS planning areas that are entirely within the Little Chino Sub-basin (City of Prescott, Town of Chino Valley, and some adjacent unincorporated areas) bear an estimated unmet 2050 water demand of at least 20 cfs. The other planning areas in the PrAMA (including the municipalities of Prescott Valley and Dewey-Humboldt) acquire either all or part of their water from the Little Agua Fria Sub-basin or from both the Little Chino and Upper Agua Fria Sub-basins (Figure 6.3). Thus 20 cfs represents a minimum estimate for unmet 2050 water demand in the Little Chino Sub-basin.

Potential New Water Demand in the Big Chino Sub-Basin

The CHYWRMS estimate of unmet water demand in 2050 for the Big Chino Sub-basin is 3,148 ac-ft/yr. This estimated unmet demand in 2050 reflects an estimated increase from 1,681 ac-ft/yr in 2006 to 8,989 ac-ft/yr in 2050 in municipal/domestic water needs offset by an estimated 50 percent reduction (4,162 ac-ft/yr) in water use for agricultural irrigation. However, there are potential additional demands for Big Chino groundwater that could eventually materialize either in full or in part and thus merit consideration.

Arizona State law provides for importation at an unspecified future time of approximately 18,000 ac-ft/yr of groundwater from the Big Chino Sub-basin to the municipalities of the PrAMA. Importation of a part of that 18,000 ac-ft/yr requires formal retirement of irrigation of formerly irrigated land in the Big Chino Sub-basin. Combining an 18,000 ac-ft/yr exportation of groundwater to the PrAMA, a 3,148 ac-ft/yr unmet CYHWRMS phase-1demand in 2050, and an offset to those demands from retirement of all remaining irrigation (4,162 ac-ft/yr) would give a resulting eventual unmet demand of 16,986 ac-ft/yr (23 cfs) for the Big Chino Sub-basin.

Possible additional future demand in the Big Chino Sub-basin stems from potential development in the Big Chino and Williamson Valleys beyond that projected by CHYRWMS phase 1. Approximately the lower 16 miles of Williamson Valley Wash and the lower 34 miles of Big Chino Wash flow through a broad basin filled with alluvial and volcanic deposits that host the basin-fill aquifer, or, as identified in Figure 9.1, the principal aquifer in the alluvial portion of the basin. About ⅞ of the area directly overlying the basin-fill aquifer, or about 235 square miles, consists of contiguous private land and State Trust land. The terrain is primarily grassland with gentle relief, and groundwater occurs throughout at depths that range from a few feet to several hundred feet (Blasch and others, 2006; Schwab, 1995).

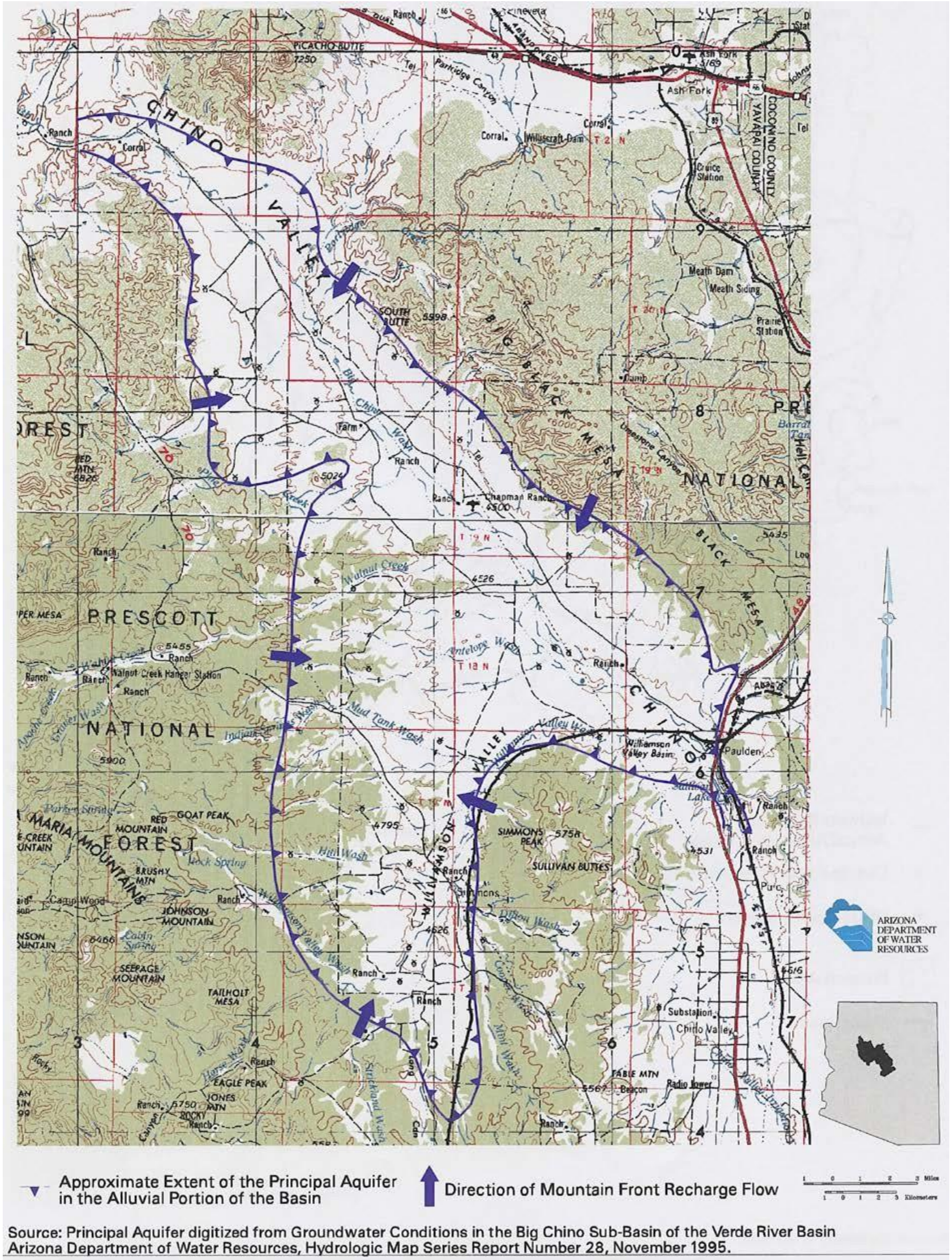


Figure 9.1. Principal aquifer in the alluvial portion of the Big Chino Sub-basin (ADWR, 2000, Figure 4.3).

Development of all the private and State Trust land that overlies the basin-fill aquifer could result in completion of about 75,000 homes if the average density were one home for every two acres. To be conservative, let us consider the addition of ⅔ of that number, or 50,000 homes. If one acre-foot of water could supply water for four homes—an optimistic target for Arizona—a single home would use, on average, 223 gallons per day. For an average of 2.5 persons per household that rate of consumption would equal 89 gallons per person per day. Total annual consumption for 50,000 such homes would be 12,500 acre-feet per year or approximately 17 cfs. There is no assurance, of course, that all or even part of this private and State Trust land will be developed at some future time. However, with its mild climate, moderate topographic relief, and available groundwater, it comprises a vast area of desirable land that could be developed with relative ease.

Potential New Water Demand in the Verde Valley Sub-basin

The CYHWRMS estimate for increased water demand by 2050 in the Verde Valley Sub-basin is 10,136 ac-ft/yr (14 cfs). This represents a 130 percent increase in municipal/domestic (household) water demand from 2006 to 2050 to address an estimated 260 percent growth in Verde Valley population by 2050. It is notable that these estimates incorporate water savings by 2050 from a reduction by 2050 of approximately 5,900 ac-ft/yr (8cfs) in water for agricultural irrigation.

Summary of Potential Water Demands In the Upper and Middle Verde River Watersheds

CYHWRMS postulates unmet water demands in 2050 of 14,555 ac-ft/yr or more (20 cfs or more) in the Little Chino Sub-basin, 3,148 ac-ft/yr (4 cfs) in the Big Chino Sub-basin, and 10,136 ac-ft/yr (14 cfs) in the Verde Valley Sub-basin. Potential additional future demands in the Big Chino Valley that were not considered in the CYHWRMS phase-1 analysis are: (1) legally sanctioned importation of approximately 18,000 ac-ft/yr (25 cfs) of groundwater from the Big Chino Valley to the PrAMA to alleviate over-pumping of the Little Chino Sub-basin aquifer system and to support continuing development; and (2) the possibility of eventual intensive development in the Big Chino Sub-basin that could demand as much as 12,500 ac-ft/yr (17 cfs) or more of Big Chino Sub-basin groundwater.

The Role of Pumping From Wells in Meeting Water Demand in the Upper and Middle Verde River Watersheds

The water demands of both the Verde Valley and the PrAMA for virtually all municipal and domestic use are supplied by groundwater pumped from wells. From the mid-20th century through 2011 the number of wells recorded within the Verde Valley in the Arizona Department of Water Resources well registry grew to 6,436 (Figure 9.2), and doubtless the number has continued to increase. Similarly, the number of wells in the PrAMA increased from mid-20th century through 2006 to 11,854 (Figure 9.3) (http://www.azwater.gov/AzDWR/WaterManagement/AMAs/PrescottAMA/Overview.htm#VirtualTour) and continues to increase.

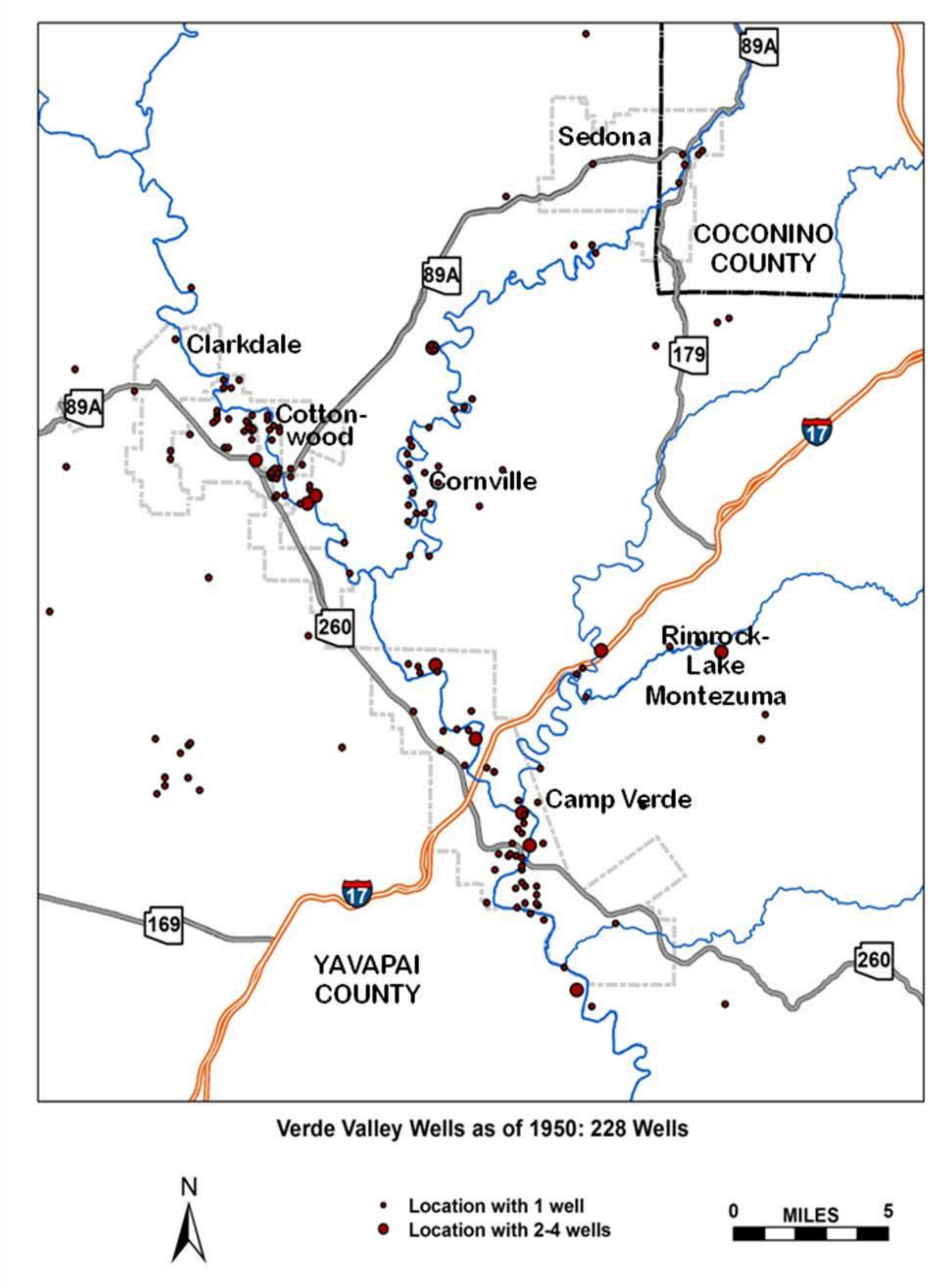
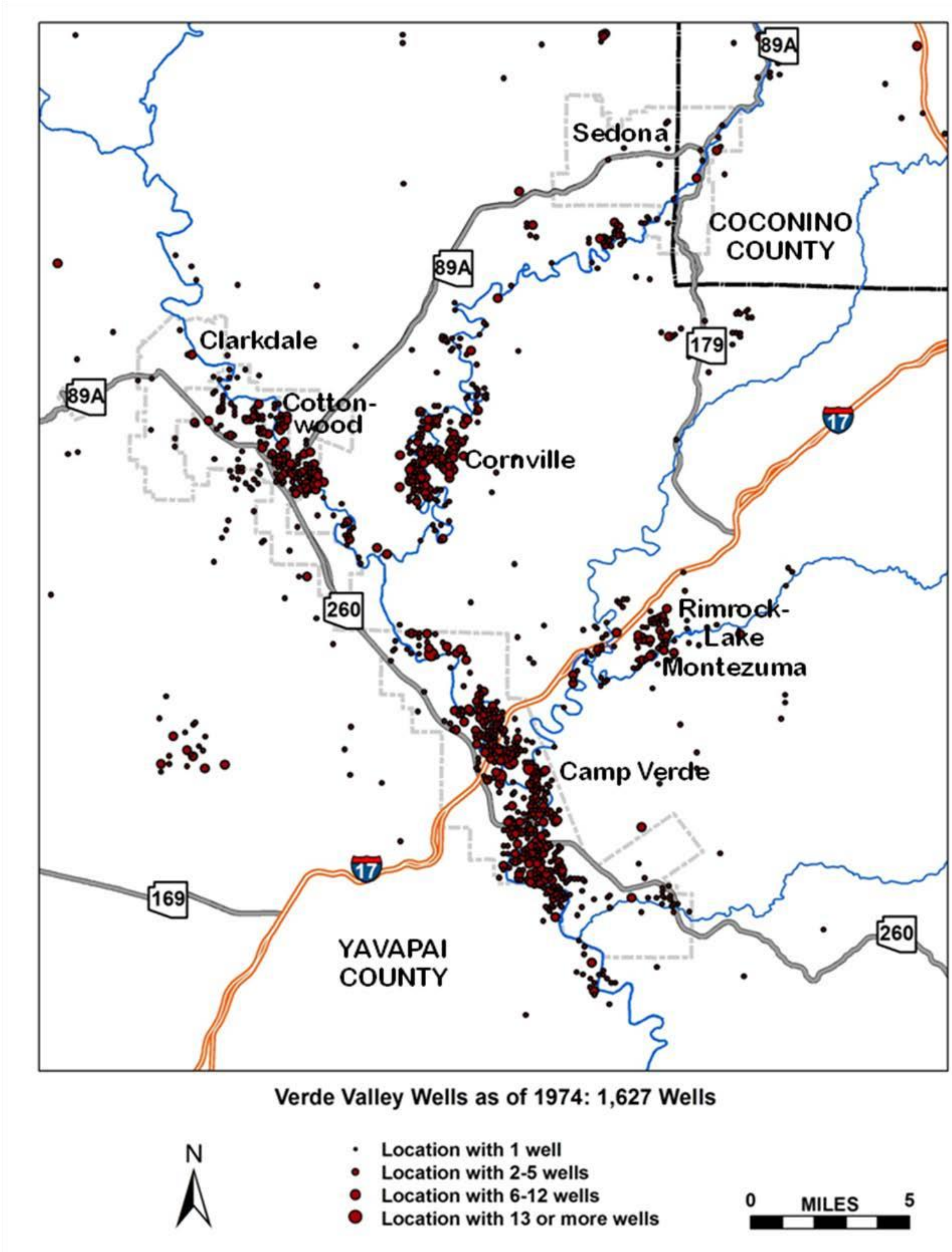

89A
Sedona
COCONINO
COUNTY
89A
Clarkdale
179
89A
Cotton-
wood
17
Cornville
260
Rimrock-
Lake
Montezuma
Camp Verde
17
169
YAVAPAI
COUNTY
260
Verde Valley Wells as of 1950: 228 Wells
N
Location with 1 well
Location with 2-4 wells
0
MILES
5

Figure 9.2A.


89A
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89A
Cotton-
wood
17
Cornville
260
Rimrock-
Lake
Montezuma
Camp Verde
17
169
260
YAVAPAI
COUNTY
Verde Valley Wells as of 1974: 1,627 Wells
N
Location with 1 well
Location with 2-5 wells
Location with 6-12 wells
Location with 13 or more wells
0
MILES
5

Figure 9.2B.

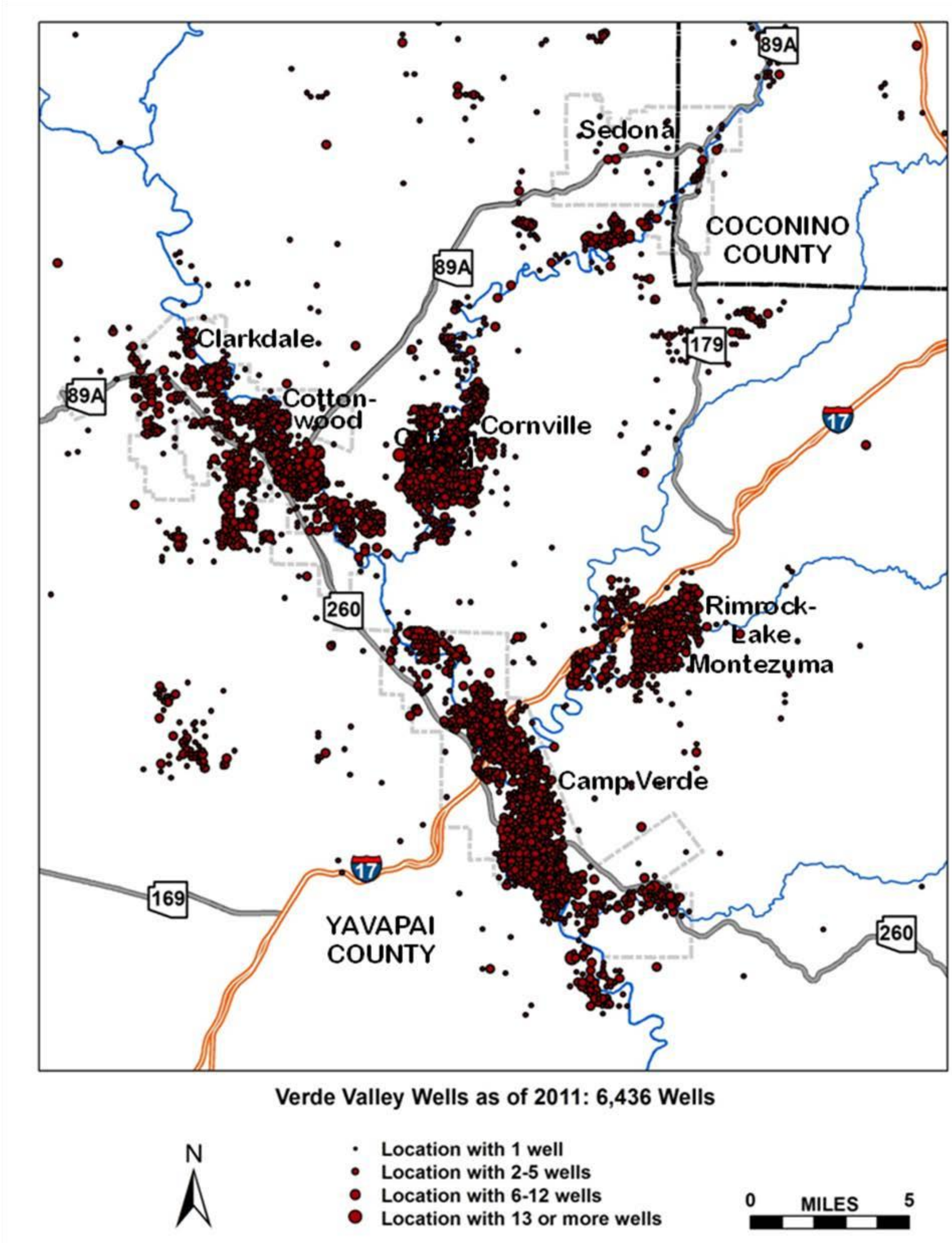

Figure 9.2C.

Figure 9.2. Maps showing number and distribution of registered water wells in the Verde Valley: A. 1950, 228 wells; B. 1974, 1,627 wells; C. 2006, 6,436 wells. Maps prepared by Salt River Project from Arizona Department of Water Resources well registry.

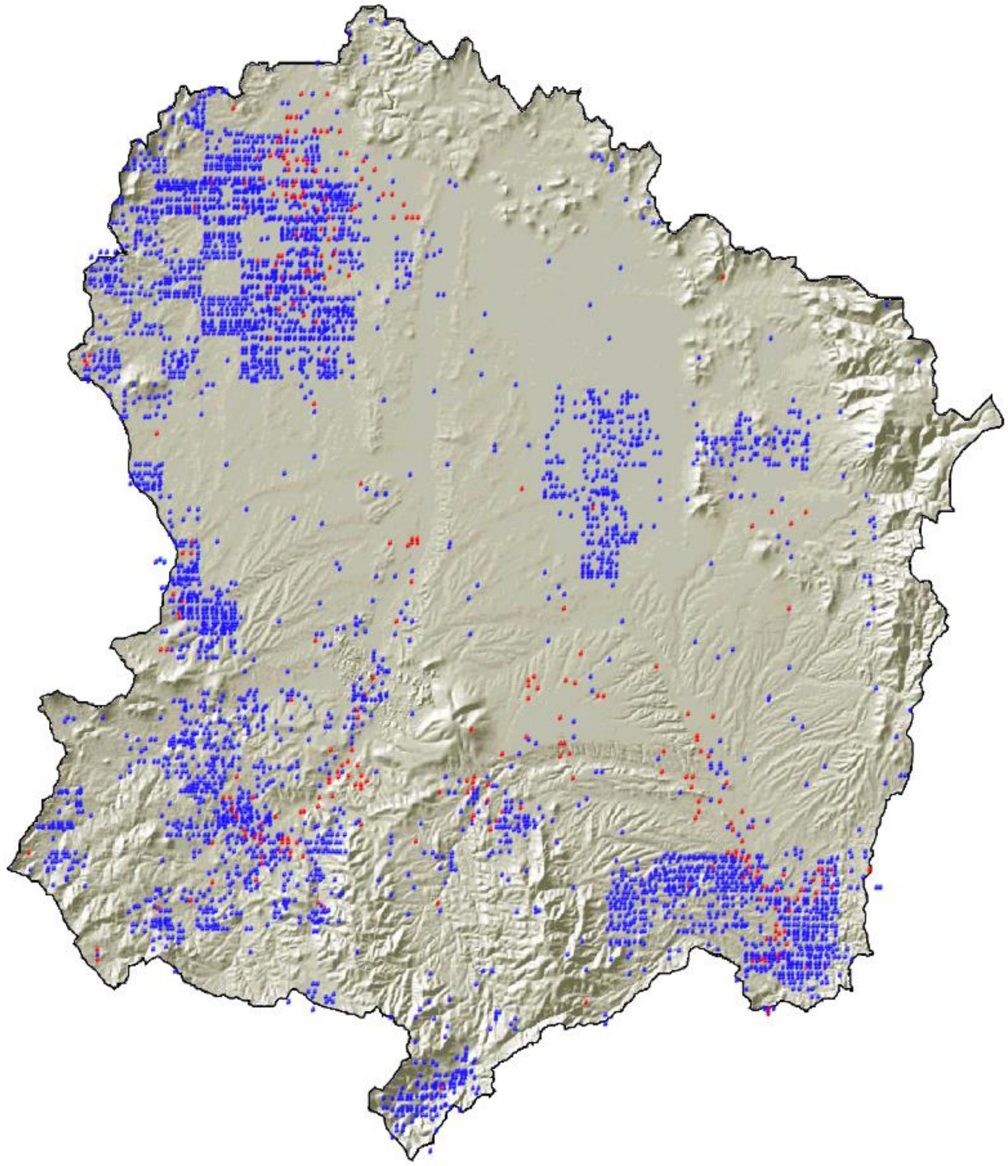

Figure 9.3. Locations of 11,854 water wells in the PrAMA in 2006.
(http://www.azwater.gov/AzDWR/WaterManagement/AMAs/PrescottAMA/Overview.htm#VirtualTour)

Surface water as streamflow in the Verde River watershed is fully appropriated, either for irrigation or for delivery to water customers in Maricopa County. Thus, there is no additional legally available surface water to meet future water demands. Importantly, the full impact of many of these wells on base flow in the Verde River has not yet been fully realized.

Barring the unlikely possibility of acquiring additional water imported from an area outside of the Verde River watershed, increased groundwater pumping is virtually the sole source of new water to meet existing and new demands.

Eventual Effect of Capture from Past, Current, and Potential New Water Demands on Verde River Base Flow

Stream gages on the Verde River provide a record of the river's base flow for the period of record since the gages were installed. Decreases in base flow may reflect one or more of several processes: stream depletion resulting from groundwater pumping, drought, and diversion of streamflow for irrigation. If streamflow measured at a stream gage decreases to zero, it means that the reach of the river in which the stream gage is located is no longer perennial (i.e., it no longer flows year-round). Zero streamflow has not occurred so far at any of the Verde River stream gages, but it is a potential future consequence of our development and water-management policies.

In this section, we explore potential changes in base flow at four USGS stream gages (Figure 9.4) located on the Verde River. They are the:

- Verde River Near Paulden, AZ (09503700, in operation from 1963 to the present, referred to herein as the Paulden stream gage)
- Verde River Near Clarkdale, AZ gage (09504000, in operation from 1915 to 1921 and 1965 to present, referred to herein as the Clarkdale stream gage)
- Verde River Below Camp Verde. AZ (09505550, in operation from late 1971 through 1978, referred to herein as the White Bridge stream gage)
- Verde River Near Camp Verde, AZ (09506000, in operation 1934 to 1945 and 1988 to present, referred to herein as the Camp Verde stream gage).

Groundwater Model Results—Extended effects of Past, Current and Future Groundwater Pumping

Streamflow depletion by groundwater pumping in the Verde River watershed as determined by application of the USGS Northern Arizona Regional Groundwater Flow Model (NARGFM) is discussed in Chapter 7. An important aspect of the NARGFM is that it enables us to isolate the effect of human stress governing base flow from the overarching effect of decadal-scale climatic variation on natural recharge of the groundwater system. Human stress in this context refers to the rate of groundwater pumping from wells within the area of the model minus the rate of return of water to the groundwater system from agricultural and artificial recharge.

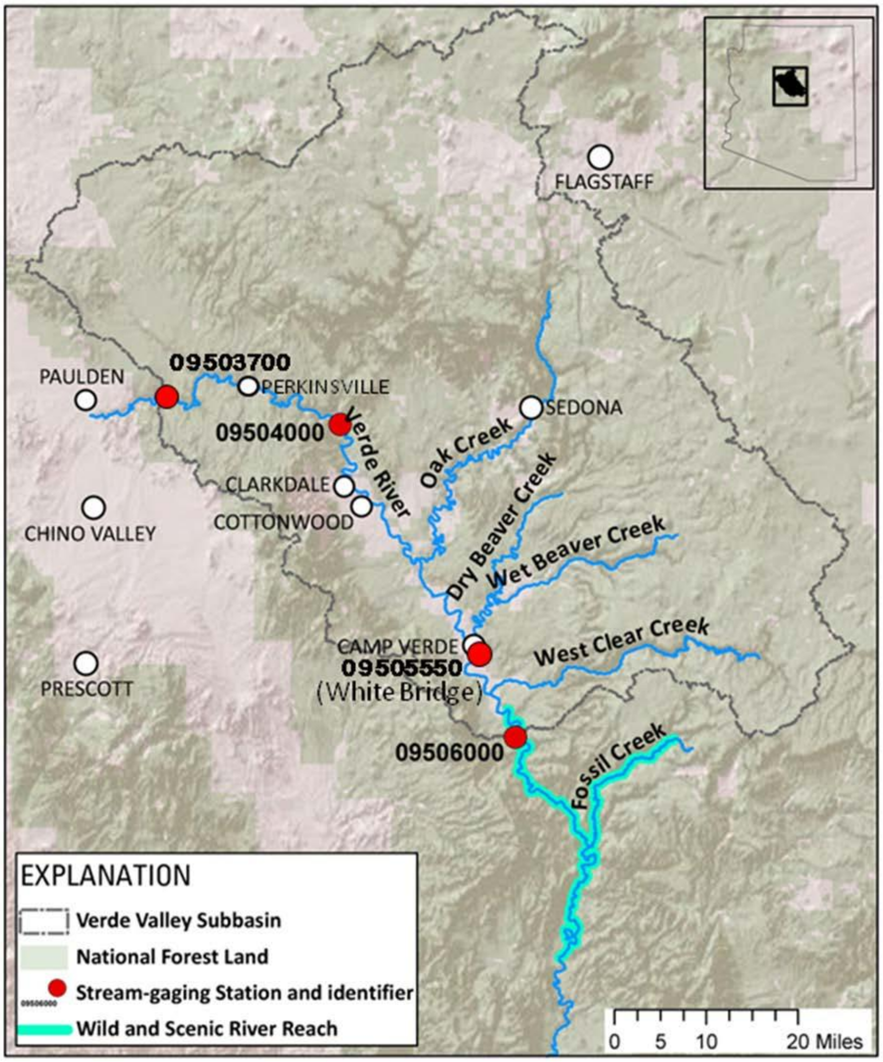

Figure 9.4. Map showing the Verde Valley sub-basin, the Verde River and some of its major tributaries, and the locations of the USGS stream gages: Verde River Near Paulden, AZ (09503700, or Paulden stream gage); Verde River Near Clarkdale, AZ (09504000, or Clarkdale stream gage); Verde River Below Camp Verde, AZ (09505550, or White Bridge stream gage, in operation from late 1971 through 1978); and Verde River Near Camp Verde, AZ (09506000, or Camp Verde stream gage).

Simulated decrease in base flow, cfs, attributable solely to human stress Human stress held at 2005 rate from 2006 through 2109			
Time Period	Paulden Stream gage	Clarkdale Stream gage	Camp Verde Stream
1910 through 2005	6.7	6.7	14.1
2006 through 2109	4.1	4.6	9.9
1910 through 2109	10.8	11.3	24.0

Table 9.2. Decrease in base flow, in cfs, at the Paulden, Clarkdale, and Camp Verde stream gages owing solely to human stress (groundwater pumping minus incidental and artificial recharge) as simulated by the Northern Arizona Regional Groundwater Flow Model of Pool and others (2011). Data are from Tables 1.2 and 1.4 of Garner and others (2013).

Table 9.2 gives the decrease in base flow owed solely to human stress as simulated by the NARGFM. Results for the period 2006 through 2109 are predictive and are based on the unrealistic condition that groundwater pumping and associated artificial and incidental recharge remained at their 2005 levels and locations during the 104 years from the beginning of 2006 through the end of 2109. Nevertheless the results give a sense of the timing of decrease of base flow along the Verde River as a consequence of pumping groundwater. Groundwater moves slowly through the aquifer system, and the full effect of pumping from wells on base flow may be substantially delayed.

Future Water Demand in the Verde River Basin and Its Relation to the Stream Gage Records

The average annual contribution of base flow measured at the Paulden gage represents about 30 percent of the base flow entering the Verde Valley as measured at the Clarkdale gage (Blasch and others, 2006, Table 6). For this analysis summer base flow is of primary concern because, owing to irrigation demands in the Verde Valley, as well as naturally occurring evapotranspiration, summer is the time of lowest Verde River base flow. In the five years from 2010 through 2014 summer base flow (lowest average flow for seven or more days) at the Paulden stream gage was 18 cfs or less. Flows of 18 cfs or less occurred for totals ranging from 6 to 44 days during spring and summer months—mid-April to early September (Figure. 9.5).

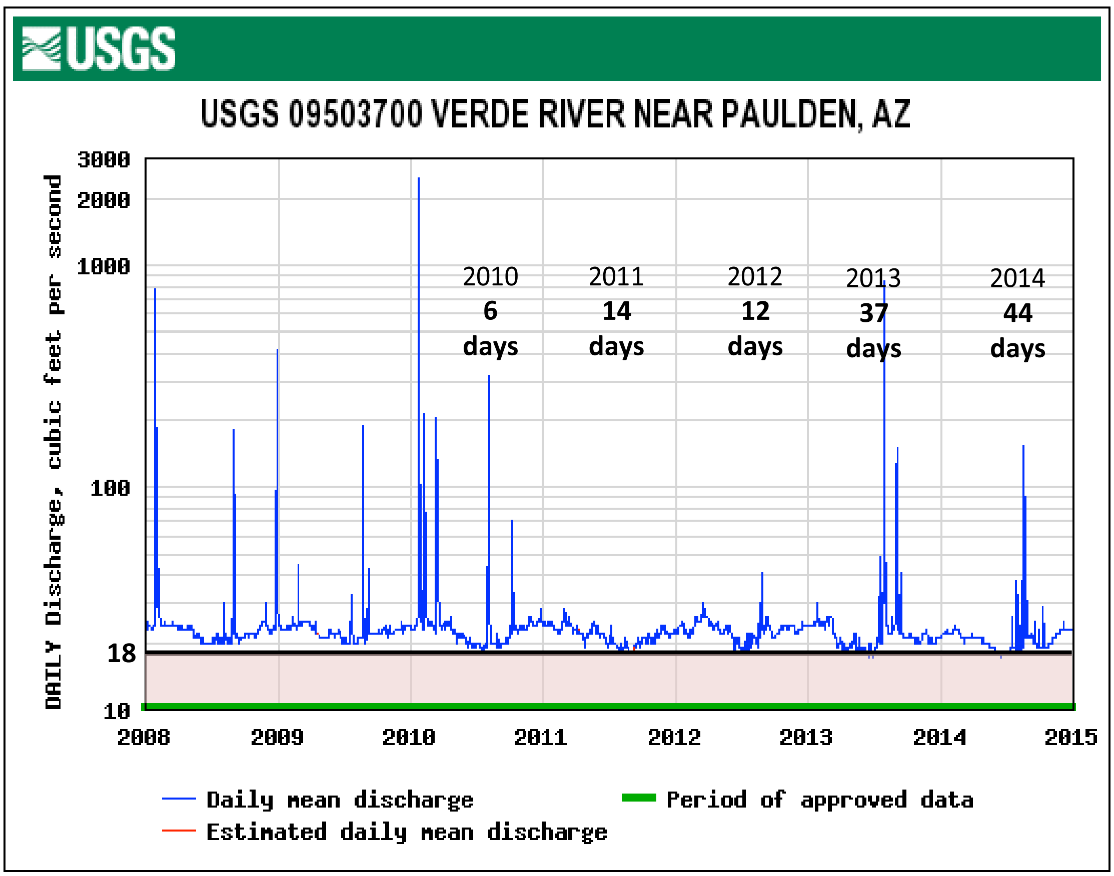

Figure 9.5. Record of mean daily discharge at the Paulden stream gage from January 1, 2006 through December 31, 2014. Measured daily discharge was 18 cfs or (rarely) less for totals ranging from 6 to 44 days in the springs and summers of 2010 through 2014.

Monthly streamflow measurements made under the Water Sentinels Program of the Grand Canyon Chapter of the Sierra Club from 2007 through March 2012 (Pawlowski, 2013) consistently show summer streamflow values of less than 18 cfs on the Verde River just above Perkinsville. During this period of measurements, the lowest measured streamflow values, occurring during July or August, decreased progressively from 17 cfs in 2007 to 8 cfs in 2011. As shown in Figure 6.7, base flow decreases downstream along the reach of the Verde River from the Paulden stream gage downstream for about 14 miles to Perkinsville. An eventual base- flow depletion of 18 cfs at the Paulden stream gage owing to groundwater pumping in the PrAMA and Big Chino Valley would eliminate perennial flow in this reach; this now-perennial reach would then flow only in response to runoff from storms or snowmelt. In the reach below Perkinsville, base flow increases rapidly owing to discharge of groundwater to the river.

We postulate for the Verde Valley, all other factors being unchanged, that new groundwater pumpage would eventually cause a reduction in Verde River summer low-flow values of at least 32 cfs: reduction of 18 cfs of base flow entering the Verde Valley at the Clarkdale stream gage plus 14 cfs of base-flow reduction from additional pumpage within the Verde Valley to meet the unmet 2050 water demand postulated by the CYHWRMS study. Thirty-two cfs is a minimum value for streamflow depletion as the full effect of capture by past and present pumping in the upper and middle Verde River watersheds has not yet shown up in the stream gage records. No doubt eventual runs of the NARGFM will clarify the timing of future base-flow reductions along the Verde River. In the meantime, we can be assured that reduction of base flow will continue, especially in the absence of serious commitment to protecting the groundwater that provides it.

Figure 9.6 shows the record of the stream gage near Camp Verde (09506000; see Figure 9.4 for location) for the period from 2004 through 2014. Summer low flows of 32 cfs or less occurred for 1 to 20 days during six of those years. Had summer base flow already been reduced by 32 cfs, the Verde River at the stream gage would have been dry during those days. This stream gage is within the Verde River Wild and Scenic River reach below Camp Verde. It is also located downstream from all of the Verde River irrigation diversions in the Verde Valley and their surface-water returns to the river system.

The USGS stream gage near White Bridge (09505550; Verde River below Camp Verde, Arizona), collected continuous streamflow data from late 1971 through 1978 (Figure 9.7). No longer in operation, the stream gage was located within the southern part of the area in which Verde Valley irrigation diversions and their surface-water returns occur. If summer low-flow discharge had already been reduced by 32 cfs, the Verde River at the stream gage would have been dry for between zero and 95 days during six of the eight summers in which the gage was in operation.

At each of these stream gages on the river in the southern Verde Valley, the hypothetical number of days of zero streamflow understates the eventual threat to the river's perennial flow because the full effect of capture by past and present pumping in the upper and middle Verde River watersheds has not yet shown up in the stream gage records. Again, without the application of groundwater modeling, we cannot speculate on exactly when the effects of past and future pumping, or of future pumping, will materialize—only that they assuredly will appear.

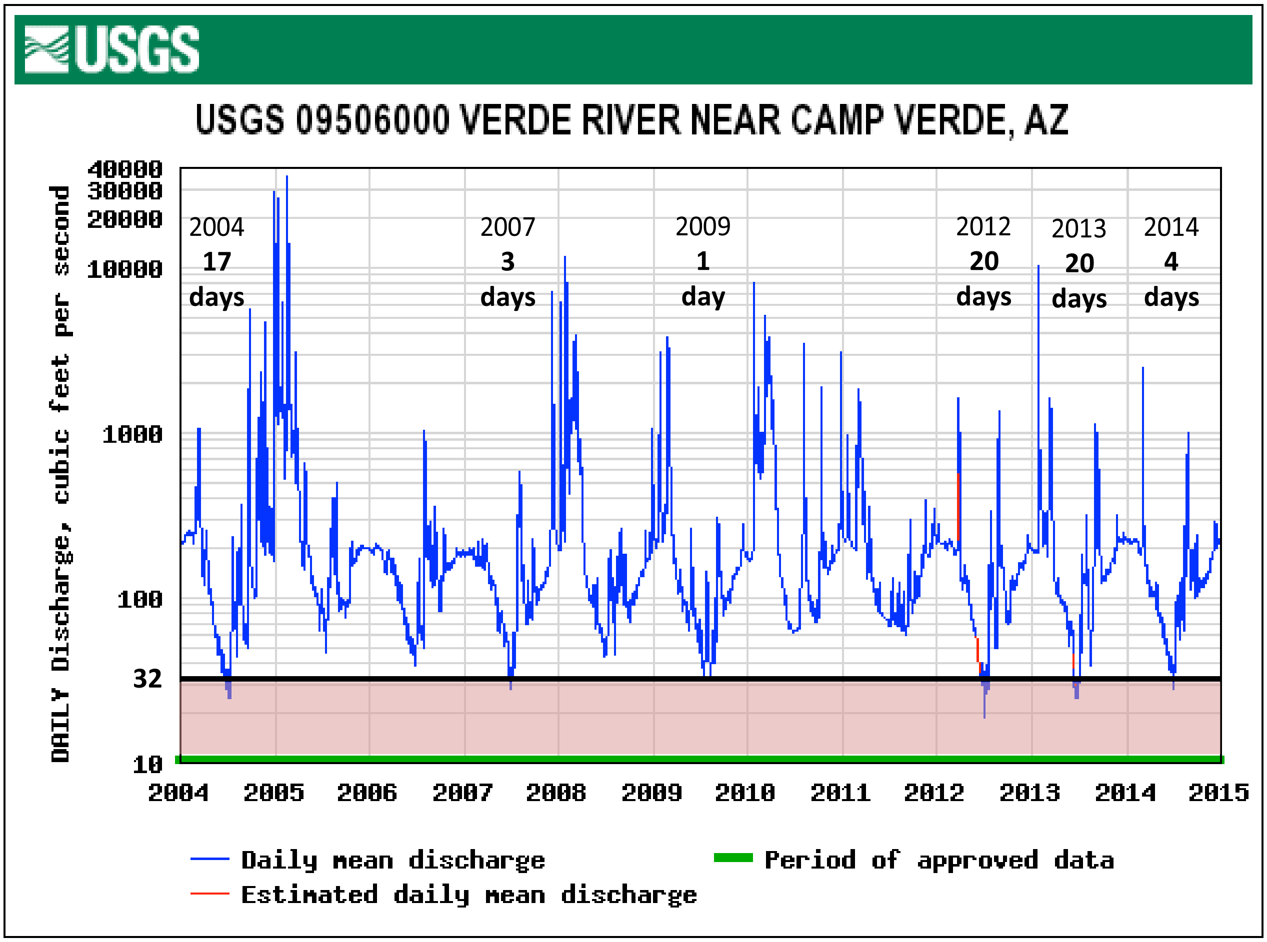

Figure 9.6. Streamflow record of USGS stream gage 09506000 Verde River near Camp Verde, Arizona from 2004 through 2014. Parts of the daily mean discharge record within the colored bar represent days when there would have been no streamflow if streamflow had already been reduced by 32 cfs. Hypothetical days of no flow in 2004, 2007, 2009, and 2012 through 2014 ranged from 1 to 20.

The summer discharge measurements at these two stream gages either now or in a hypothetical future reflect the combined effects of climate, groundwater pumping throughout the watershed, and irrigation diversions. In a hypothetical future time when summer base flow could be greatly reduced, water needed for irrigation would be greatly reduced or nonexistent. On the other hand, increasing the efficiency of agricultural diversions, managing our groundwater more effectively, and/or a substantially wetter climate could help maintain river flow during irrigation seasons. Not all of the effects of past and present pumping have shown up yet in measurements of river flow. However, the effects of past, present, and future management of our Verde River basin water resources can doom the river as we know it. If we wait to address our water-resource management practices until parts of the river cannot sustain the essential water requirements for human, habitat, and wildlife needs, it will be too late. We will have lost an invaluable resource.

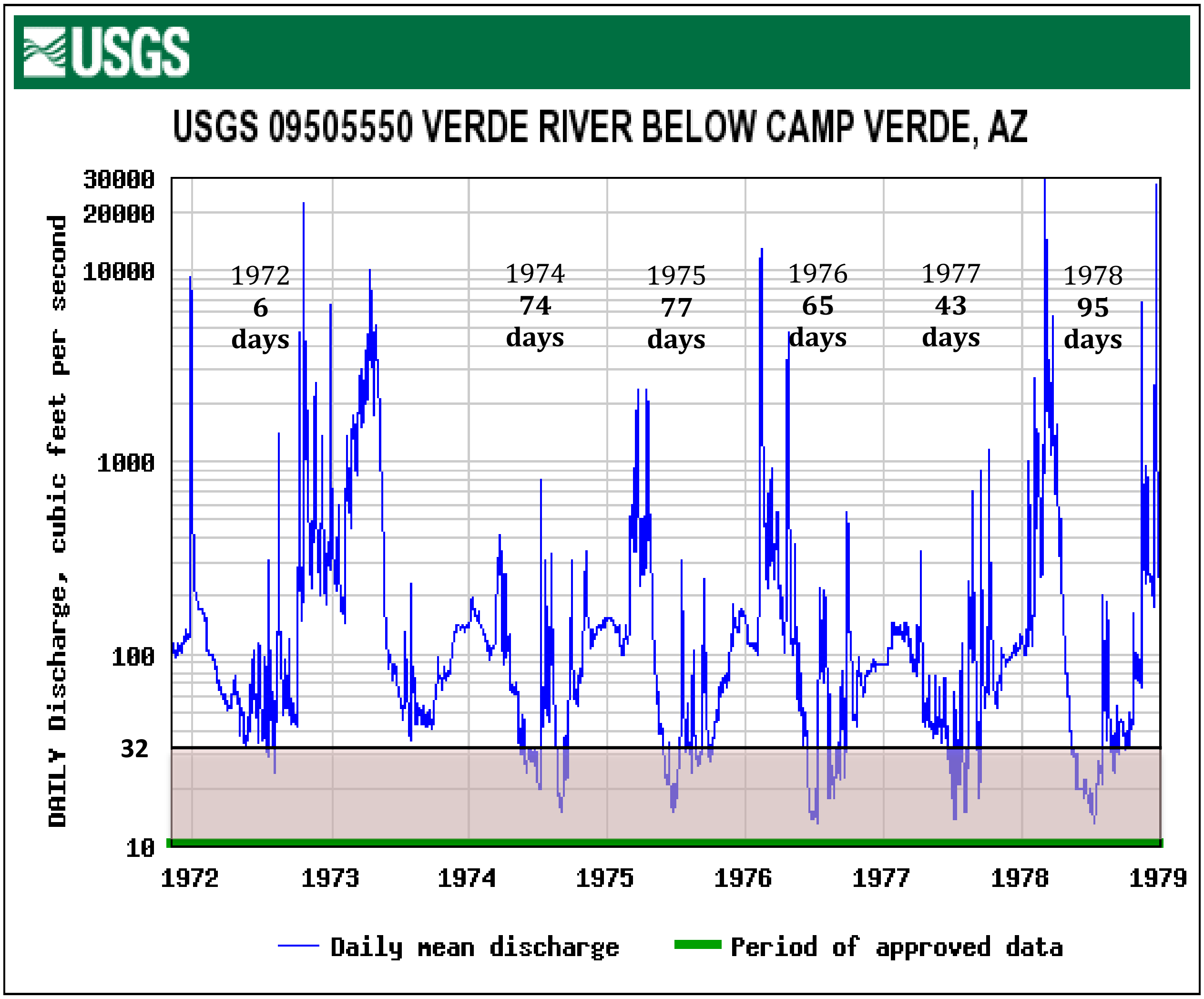

Figure 9.7. Streamflow record of USGS stream gage 09505550 Verde River below Camp Verde, Arizona (actually at White Bridge in Camp Verde), 1972 through 1978. Parts of the daily mean discharge record within the colored bar represent days when there would have been no streamflow if streamflow had already been reduced by 32 cfs. The gage recorded continuous stream-discharge measurements from late 1971 through 1978. Hypothetical days of no flow in 1972 and in 1974 through 1978 ranged from 6 to 95.

What Might the Future Hold?

Reports of the U.S. Geological Survey clearly show that pumping of groundwater that began in these areas in the 1900s has lowered and will continue to lower groundwater tables and to decrease perennial streamflow. Unmitigated additional pumping will amplify both effects.

Development of housing, infrastructure, and business to support an ever-growing population is generally recognized as the backbone of our economy. Unfortunately, further groundwater pumping is the only obviously available source of new water to meet the future water needs for this growth. The ever-greater likelihood of a warming climate adds to the challenge of supplying water to meet future demand.

What are some of the expected eventual consequences of pumping ever more groundwater to supply future needs?

- Dry stretches and irreparable damage to the Verde River.
- Loss of surface-water use by water-right holders that include agricultural irrigators in the Verde Valley and, farther downstream, irrigators and municipalities in parts of Maricopa County.
- Loss of riparian habitat and associated wildlife.
- Increasing loss of once-productive domestic wells as water tables decline.
- Necessity to deepen or relocate some currently productive municipal wells.

Maintaining a healthy Verde River and supplying the water needs of future generations requires that we both reduce our dependence on groundwater and find ways to augment our groundwater supply in order to offset our future pumping demands.

What tools might we apply regionally, as connected watershed communities, to protect our shared groundwater and live within our means?

- Conservation, especially by installation of or conversion to low water-use landscaping (xeriscaping) and maximizing water-use efficiency in our homes.
- Maximized use of treated wastewater for groundwater recharge, irrigation, or other non-potable use (for example, treated wastewater returned via purple pipe for toilet flushing).
- Roof-top rainwater harvesting at residences and businesses. Average annual rainfall ranges from about 13 inches in Chino Valley, Cottonwood, and Camp Verde to about 18 inches in Prescott and Sedona. One inch of water harvested from rainfall on a single 1,000 square-foot roof would provide approximately 560 gallons of water that could be used for non-potable uses such as yard irrigation, laundry, or toilet flushing. An alternative where geologic conditions permit would be aquifer recharge via dry wells that capture roof drainage from the downspouts.
- Collection of runoff from hard surfaces such as roads, driveways, and parking areas in residential developments and business lots or business parks could be substantial and, water-quality permitting, would most likely be directed to aquifer recharge.
- Capture of floodwater runoff to support aquifer recharge, for example, via check dams along normally dry washes where geologic conditions would permit infiltration or by diversion to infiltration basins.
- Purchase of development rights (also known as conservation easement) programs to financially compensate willing landowners for not developing their land. This is a tool that can benefit both landowners and communities while simultaneously protecting groundwater, wildlife habitat, and farming or ranching.

Regional application of any one of these tools has cost and is insufficient by itself to fully prevent further decline of water tables. Further, each requires, to varying degree, technical evaluation, public acceptance, political support, and regulatory change. However, meeting the costs and applying these tools as appropriate across the upper and middle Verde River watersheds may reduce or eliminate a need to apply stringent regulation of groundwater pumping as the only workable tool. Application of such tools is surely preferable to failing to meet the future water needs of our citizens and losing the esthetic, ecological, recreational, and economic benefits of a free-flowing, perennial Verde River.

Speculation about the impact of the future unmet demands of CYHWRMS on the actual flow at these stream gages is, of course, hypothetical. In fact, the issue is more complicated. A warmer and drier climate will negatively affect base flow and summer streamflow. Pumping that has already occurred will continue to diminish base flow into the future. On the plus side, exciting work is underway in the Verde Valley to increase both the efficiency of the Verde Valley's irrigation diversions and of the irrigation they supply to crops. In addition, growing commitment by some municipalities within our watersheds to maximize reuse of treated wastewater and promote conservation to partly offset our demand on groundwater is a welcome step.

Our valued river is at risk. We must protect our groundwater. We can't wait. Delay will make protecting the year-round flow of the Verde River ever more difficult, and inaction will doom it. Political foresight and will are required!

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