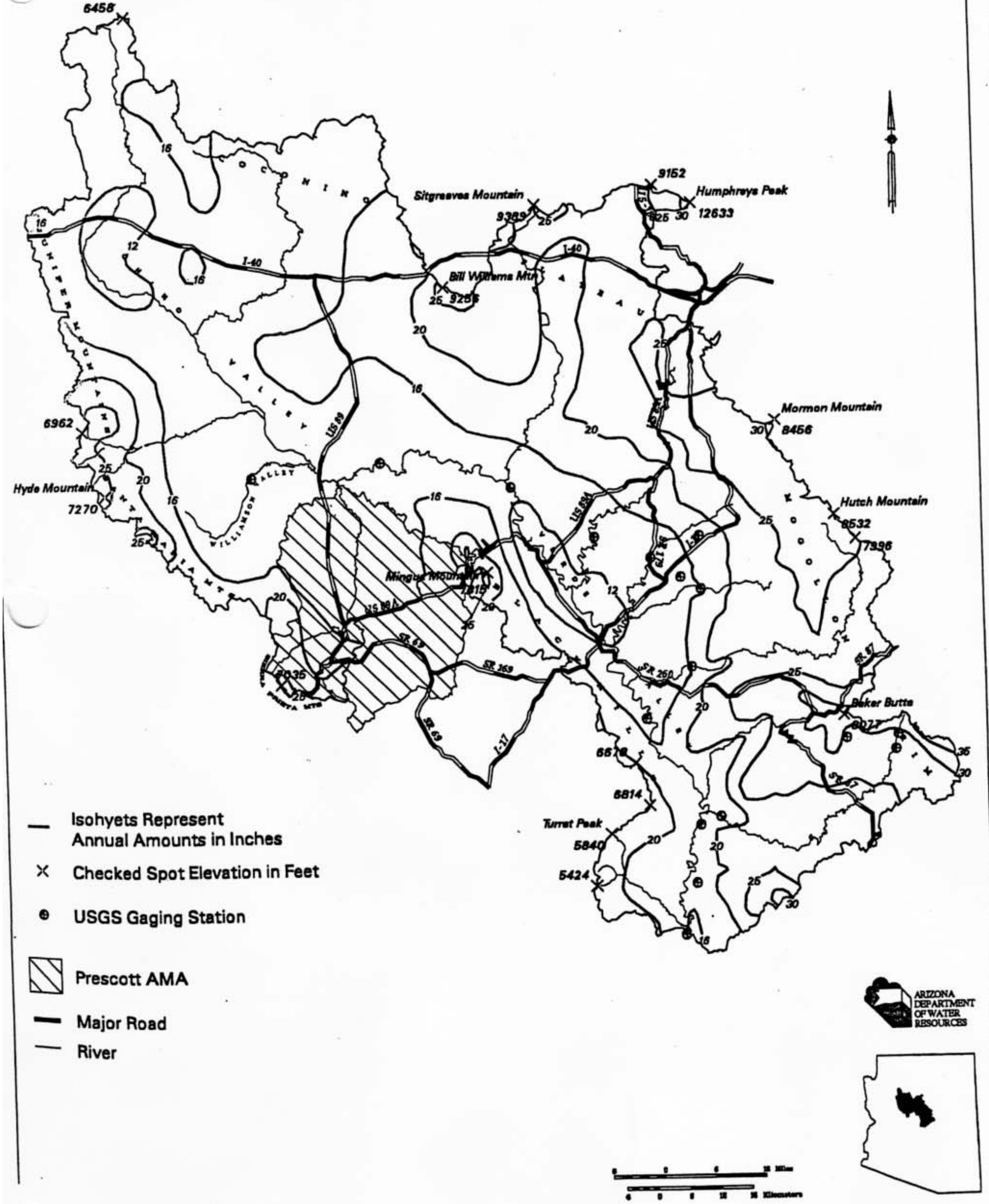
Figure 4.2 - Precipitation in the Verde River Watershed Study Area



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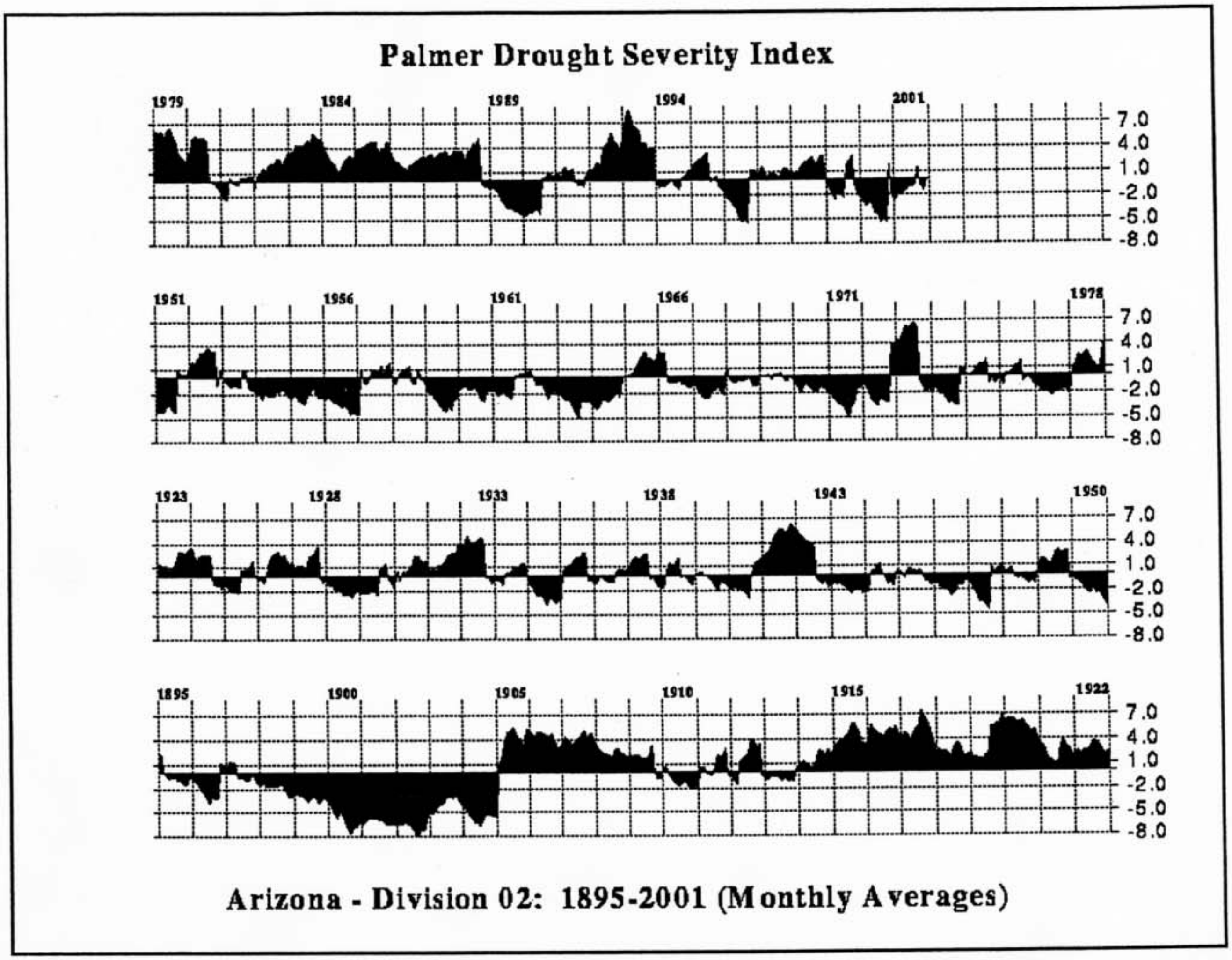

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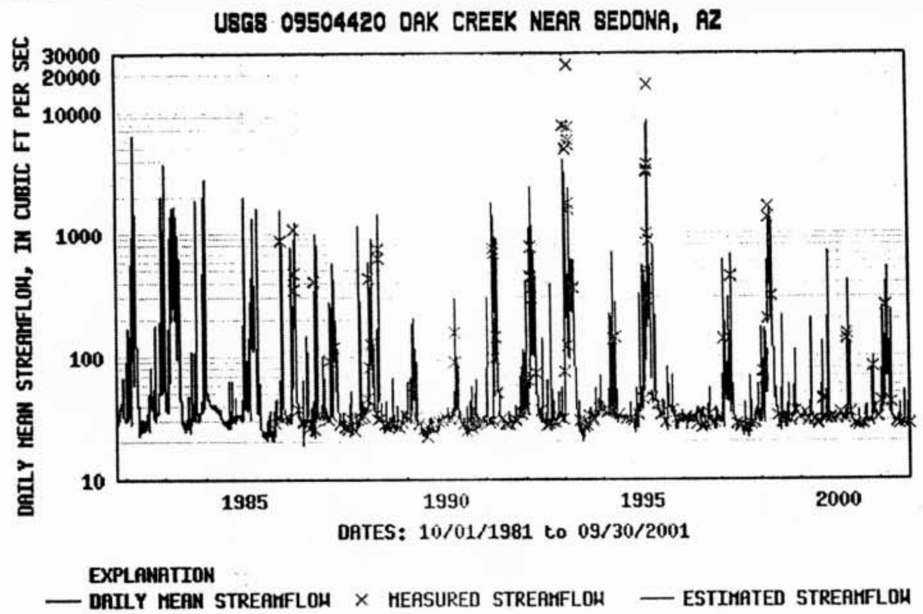
USGS 09504420 OAK CREEK NEAR SEDONA, AZ
DAILY MEAN STREAMFLOW, IN CUBIC FT PER SEC
30000
20000
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1985
1990
1995
2000
DATES: 10/01/1981 to 09/30/2001
EXPLANATION
DAILY MEAN STREAMFLOW
MEASURED STREAMFLOW
ESTIMATED STREAMFLOW

USGS 09504420 OAK CREEK NEAR SEDONA, AZ

PROVISIONAL DATA SUBJECT TO REVISION

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All 3 parameters available at this site
00060 DISCHARGE (DD 01)
00065 GAGE HEIGHT (DD 02)
00045 PRECIPITATION (DD 03)

Output format Graph

Days 7

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DISCHARGE, CUBIC FEET PER SECOND

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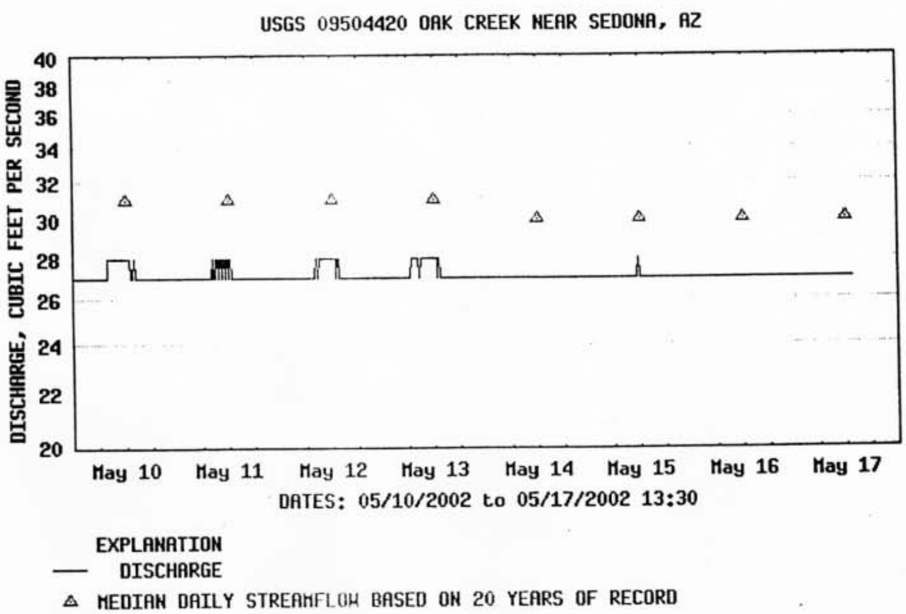

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Daily mean flow statistics for 5/17 based on 20 years of record in ft^3/sec

Current Flow	Minimum	Mean	Maximum	80 percent exceedence	50 percent exceedence	20 percent exceedence
27	27	31.6	46	28.0	30.0	34.8

Percent exceedance means that 80, 50, or 20 percent of all daily mean flows for 5/17 have been greater than the value shown.

GAGE HEIGHT, FEET

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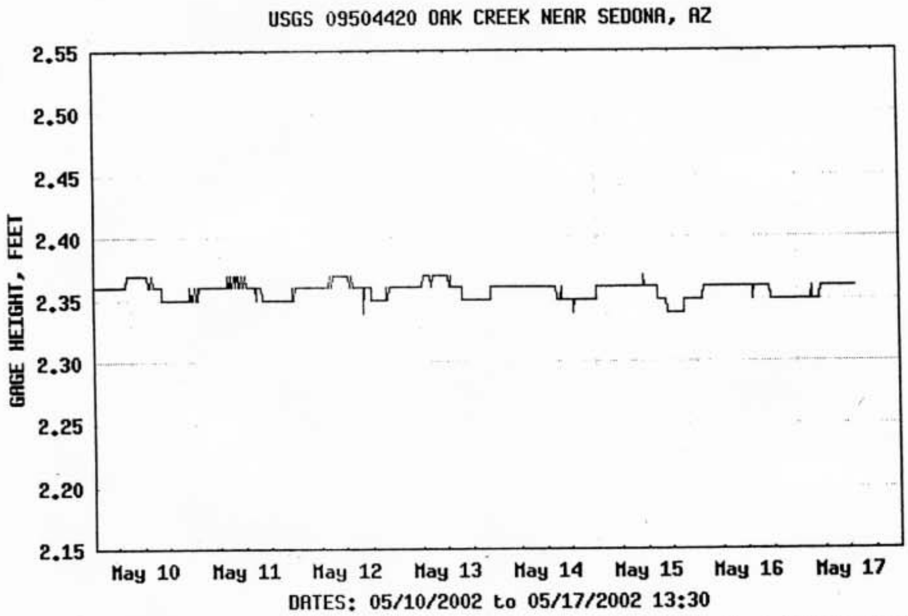

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PRECIPITATION, TOTAL, INCHES

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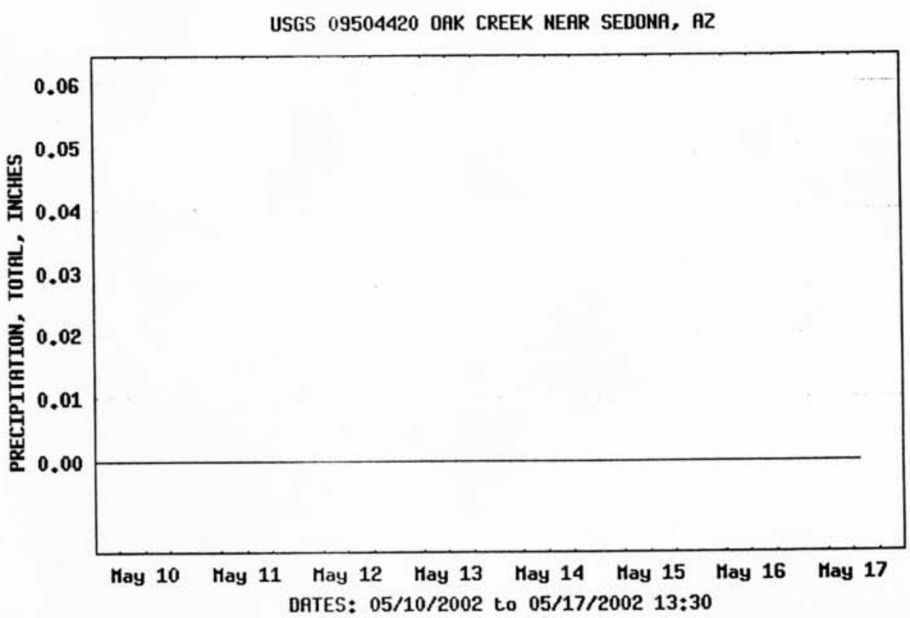

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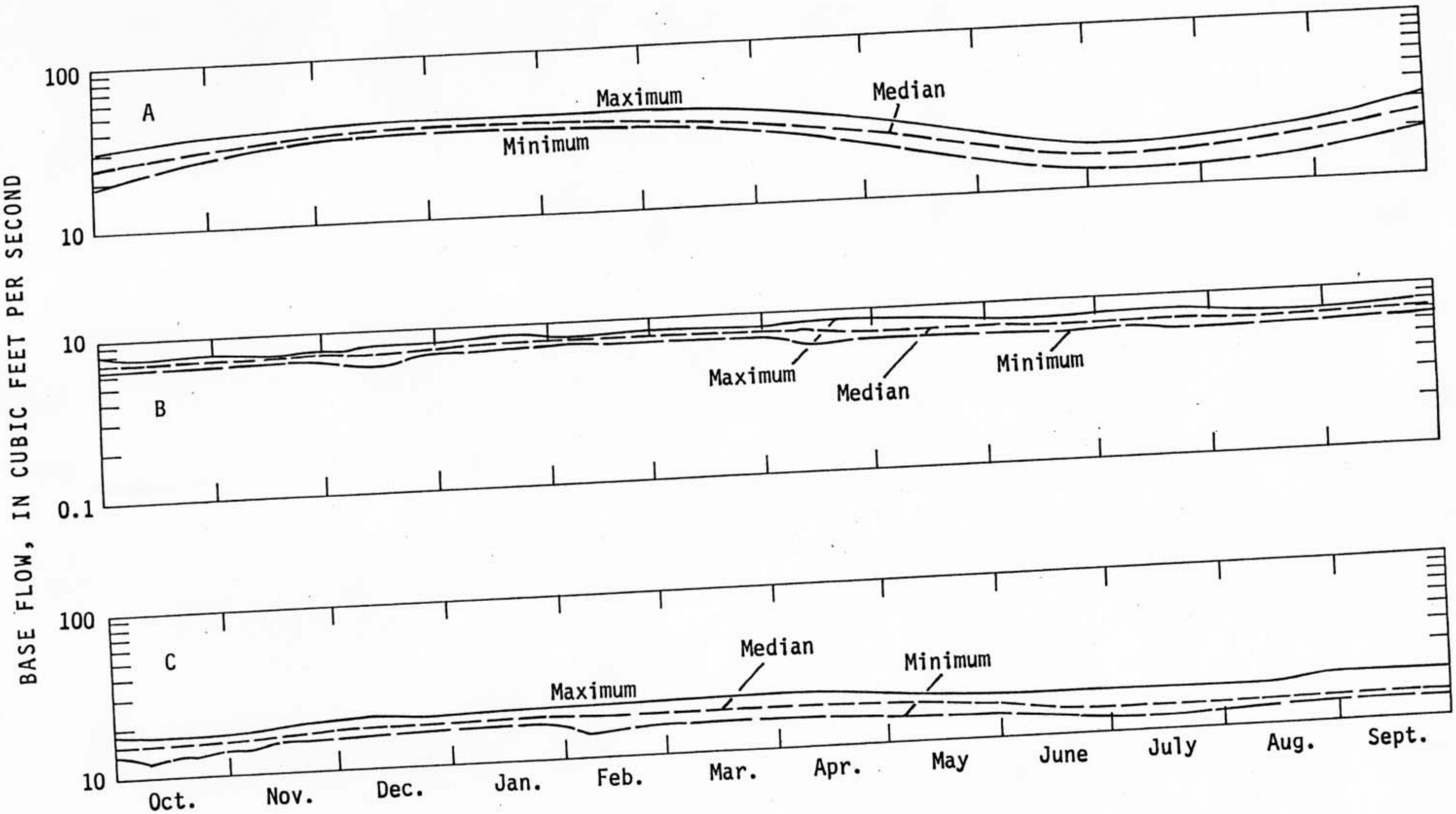


Figure 5.--Distribution of base flow for tributaries of the Verde River. A, Oak Creek near Cornville, 1950-64 and 1966-78. B, Wet Beaver Creek near Rimrock, 1961-78. C, West Clear Creek near Camp Verde, 1966-78.

Groundwater Beneath the Coconino and San Francisco Plateaus

ERROL L. MONTGOMERY, RONALD H. DEWITT,
WILLIAM R. VICTOR, AND EDWIN H. MCGAVOCK

Errol L. Montgomery & Associates, Inc.

The hydrologic sub-basins of the Coconino and San Francisco Plateaus lie on the southern part of the Plateau Uplands Province and are characterized by large thicknesses of nearly flat-lying sedimentary strata. Figure 1 is a regional map that shows the location of the plateaus. The San Francisco sub-basin, which occurs in the southeast part of the area, includes the San Francisco volcanic field and the city of Flagstaff. The Coconino sub-basin occurs in the northwest and includes Havasu Springs, where large amounts of groundwater discharge. The most important boundaries of the sub-basins are the Colorado River on the north and the Verde River on the south (see Figure 1). These rivers are the principal drains for the groundwater systems of the plateaus. The western boundary of the Coconino sub-basin lies along Aubrey Cliffs. The eastern boundary of the sub-basins lies near the Little Colorado River, along regional faults and folds including the East Kaibab Monocline and the northern part of the Mesa Butte fault system.

Locations of the principal cities and towns on the plateaus are shown in Figure 2. The largest population centers are Flagstaff, Williams, Tusayan, and Grand Canyon Village. Sedona lies on a southern erosional slope of the plateaus. Because Sedona obtains groundwater from aquifers that are recharged on the plateaus, groundwater use by Sedona should be included in summaries for the plateaus.

Although this region is often described as a water-short area, groundwater is, in fact, truly abundant. However, the depth to the most favorable aquifers is large, resulting in high costs for groundwater exploration and development programs. These high costs and the lack of understanding about the groundwater systems, particularly for geologic conditions that control the locations of prolific groundwater-yielding zones in the aquifers, have prevented more extensive development.

Presently Developed Groundwater Supplies

Present total water use on the Coconino and San Francisco sub-basins, including Sedona, is about 13,000 acre-feet per year. Of this amount, about 8,000 acre-feet per year is groundwater from wells. Most of the total water use, about 62 percent of water used on the plateaus, occurs at Flagstaff. About 23 percent occurs at Sedona.

Flagstaff

The Flagstaff municipal water supply system obtains groundwater from three well fields and surface water from Upper Lake Mary, a man-made reservoir (Montgomery and DeWitt 1982). Sources of the municipal water supply for Flagstaff are shown in Figure 3. The earliest Flagstaff municipal supply was from springs located in the Inner Basin of the San Francisco Peaks. The pipeline from the springs to Flagstaff was completed in 1899.

Figure 4 shows the amount of water used by Flagstaff for the 50-year period from 1949 through 1999. For the last decade, average total water use by Flagstaff has been about 8,000 acre-feet per year. In the early years, from 1949 through 1955, water was supplied to the city from Upper Lake Mary and from Inner Basin springs. Because water from the springs is of excellent chemical quality and arrives at the city by gravity flow, the city uses water from the springs to the greatest extent possible.

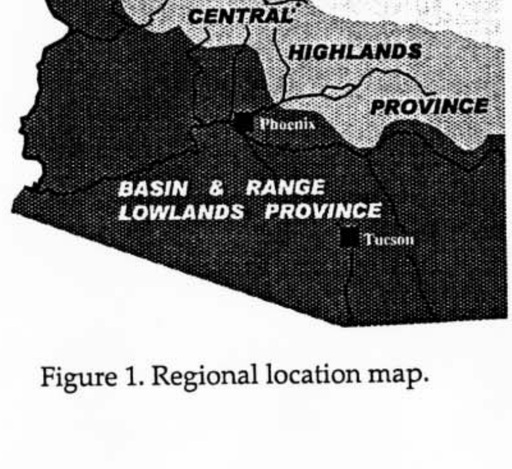
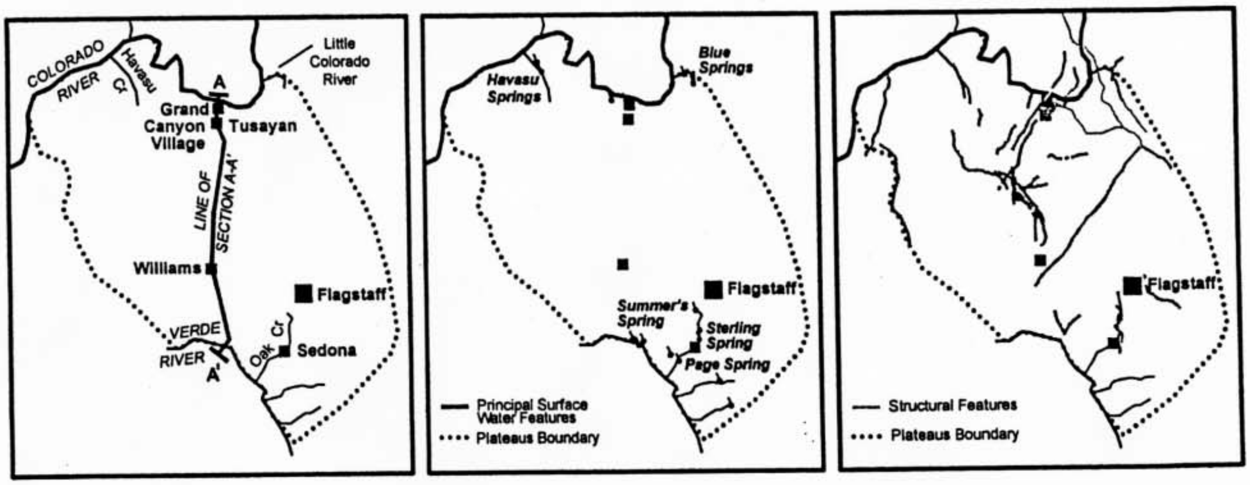


Figure 1. Regional location map.



a b c

Figure 2. Population centers, surface water features, and principal geological structural features.

Flagstaff currently relies heavily on groundwater from municipal well fields (Figure 4). In 1999, only about 1,200 acre-feet or about 15 percent of the water used by the city was obtained from Upper Lake Mary, and about 6,800 acre-feet or 85 percent was groundwater pumped from municipal well fields. Over the last decade, more than half of the water used by Flagstaff has been groundwater. During years of drought, such as 1989, 1990, and 1999 (see Figure 4), Upper Lake Mary may be nearly dry, and a much larger fraction of water is obtained from groundwater.

The dam for Upper Lake Mary was initially constructed in 1940 and 1941. The reservoir presently has a capacity of about 15,600 acre-feet. This reservoir capacity is about twice Flagstaff's annual municipal demand. Lower Lake Mary is a smaller reservoir and is not presently used for municipal supply (see Figure 3). Both reservoirs lie in a complex graben, a geologically structurally depressed zone adjacent to the Anderson Mesa Fault (Montgomery & Associates 1993).

Most inflow to the reservoirs is from snowmelt; the amounts are irregular due to wide variations in winter snowpack. The average annual inflow to Upper Lake Mary is about 7,000 acre-feet, but high and low yearly inflows have ranged from about 300 acre-feet in a year of extreme drought, to as much as 17,500 acre-feet during a year of abundant snowmelt. Water stored in the reservoirs is subject to two large losses: seepage through the bottom, and evaporation. Seepage is the larger loss, through the alluvial and lava-flow rocks that underlie the impoundment. Seepage from Lake Mary passes downward through Kaibab Limestone via fracture systems associated with the Anderson Mesa Fault. Approximately 42 percent of the inflow to Upper Lake Mary is lost to downward leakage (Blee 1988). Evaporation losses account for approximately 28 percent of inflow. Because of these large losses and widely variable inflow, in years of drought, or especially in back-to-back years of drought, the water supply from Lake Mary is not reliable.

Beginning in 1966, the Inner Basin groundwater supply was further developed by construction of production water wells. The groundwater supply from the Inner Basin is vulnerable to drought; when drought conditions cause the water supply from Upper Lake Mary to be threatened, water yield from Inner Basin springs and wells is also small (Montgomery and DeWitt 1982). Water obtained from the Inner Basin in the drought year of 1999 was only about 340 acre-feet (Figure 4). Groundwater in the Inner Basin is stored in a perched aquifer system that lies far above the aquifers normally used for the municipal water supply.

The first development of a large reliable groundwater supply from the Coconino and San Francisco sub-basins occurred in 1956, from the first deep well in what became the Flagstaff Woody Mountain well field (see Figure 3). After geologic analysis, the well was drilled on the downthrown side of the northern extension of the Oak Creek Fault to exploit abundantly fractured rocks that occur along this fault. The Woody Mountain well field now consists of 10 production water wells; individual wells now range from about 250 to 1,000 gallons per minute (gpm). In 1999, a total of about 3,200 acre-feet of groundwater was yielded to the Flagstaff municipal system from these wells (Figure 4).

After the Woody Mountain well field was established, deep wells were also constructed in the Lower Lake Mary area, and these successful wells established the Flagstaff Lake Mary well field. Yields from individual wells also range from about 250 to 1,000 gpm. In 1999, a total of about 3,200 acre-feet of groundwater was obtained from the Lake Mary well field (Figure 4).

Recently, additional groundwater supply has been obtained from two deep wells constructed on the east side of the city.

Other Water Users

Although most of the water usage on the Coconino and San Francisco sub-basins occurs at Flagstaff, substantial amounts are used by Sedona, Williams, Tusayan, and Grand Canyon Village. Sedona uses about 3,000 acre-feet per year. The supply is entirely groundwater obtained from wells. Pumping rates from individual Sedona production wells range from about 250 to 1,000 gpm. Williams presently uses about 600 acre-feet per year. In years of normal precipitation, most of the municipal water has been obtained from local small and drought-vulnerable reservoirs. At present, part of the water supply is obtained from a deep well developed by the city. Tusayan presently uses about 200 acre-feet per year. Most of the water is obtained from local deep wells. Much of the water used by Tusayan in the past was imported from Williams, Flagstaff, and Grand Canyon National Park.

Grand Canyon Village presently uses about 400 acre-feet per year. This water is obtained from Roaring Springs in Bright Angel Canyon, on the north side of the Grand Canyon, and is pumped from deep in the Grand Canyon to the village on the South Rim. Because the source of water supply lies on the north side of the Colorado River, water use by Grand Canyon Village is not included in summaries for the Coconino and San Francisco Plateaus.

Aquifer Systems of the Coconino and San Francisco Plateaus

Figure 5 is a hydrogeologic section for the plateaus that shows the vertical sequence of strata and aquifers that occur between the Colorado and Verde Rivers (see Figure 2a). Geologic conditions shown on the hydrogeologic section are simplified to focus on important groundwater features. The north-south distance shown on the section is about 100 miles. The thickness of the strata is about 1 mile from the top of the plateau to the base of the sedimentary layers.

The most important geologic strata that control groundwater movement and storage, in de-

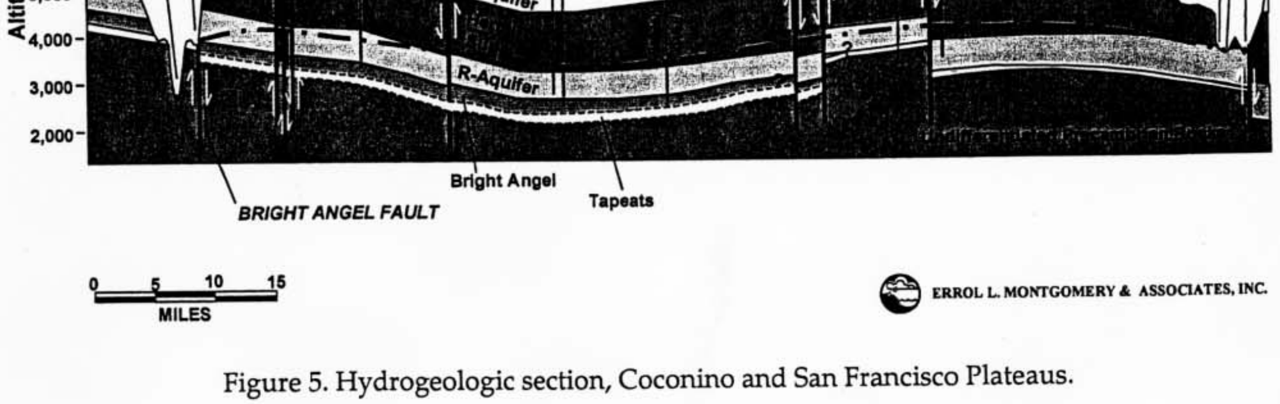


Figure 5. Hydrogeologic section, Coconino and San Francisco Plateaus.

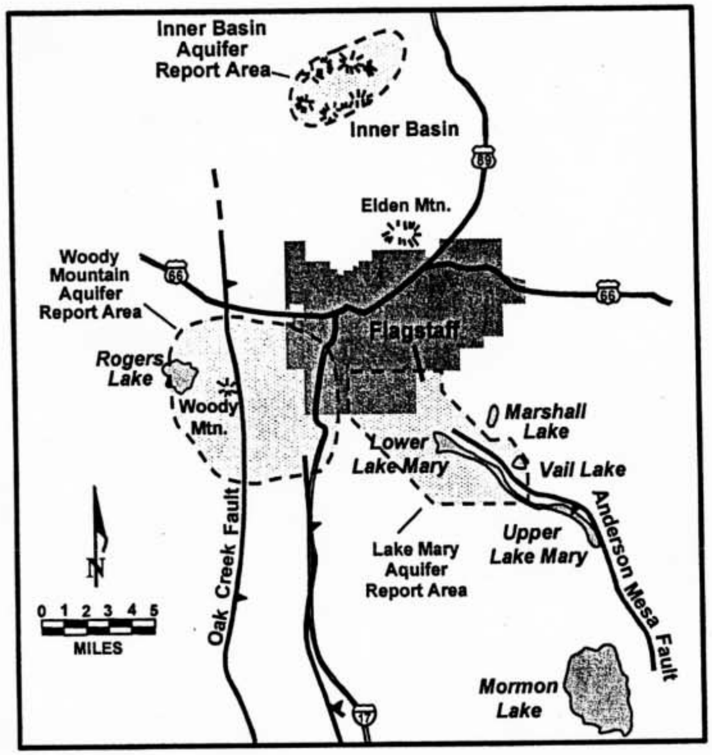


Figure 3. Sources of Flagstaff municipal water supply.

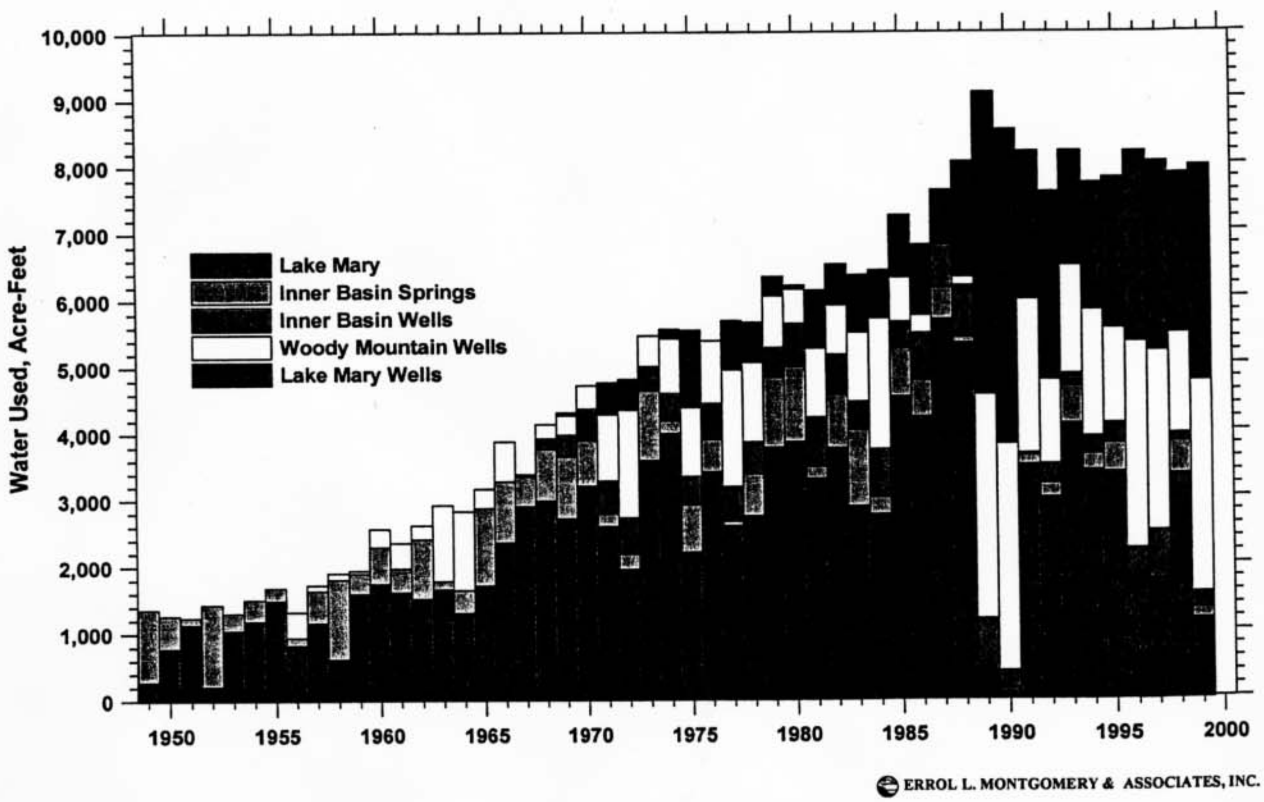


Figure 4. Annual water used, city of Flagstaff.

scending order, are volcanic rocks, the Moenkopi Formation, Kaibab Limestone, the Toroweap Formation, Coconino Sandstone, Hermit Shale and the Supai Group, Redwall Limestone and Muav Limestone, Bright Angel Shale, and Tapeats Sandstone (Figure 5).

The C-aquifer and R-aquifer are the most important systems for the Coconino and San Francisco Plateaus. Both are described as regional aquifer systems; however, the R-aquifer system is by far the most important and is truly regional. Perched aquifers that occur at places above the C- and R-aquifers also contain and transmit small amounts of groundwater. These perched aquifers are thin and discontinuous.

The C-aquifer includes the Coconino Sandstone and adjacent water-bearing strata including at places in the sub-basins, Toroweap Formation, Kaibab Limestone, and Schnebly Hill Formation. The R-aquifer includes the carbonate rocks of the Redwall Limestone and adjacent water-bearing strata such as Muav Limestone, the Martin Formation, and in some cases, the brittle rocks in the lower part of the Supai Group.

The base of the C-aquifer system occurs 1,000 feet or more beneath the top of the plateaus (Figure 5). The depth to the base of the R-aquifer system is 3,000 feet or more. Because of the large depth to the base of the aquifers, most importantly to the base of the R-aquifer, the cost of drilling wells to extract groundwater is unusually large. The cost for a single exploration well to test local conditions in the R-aquifer is commonly several hundreds of thousands of dollars. Construction of a single high-yield water production well from the R-aquifer in the plateaus area may cost more than a million dollars. The depth to the R-aquifer is smaller in the Sedona area, so R-aquifer wells in that area cost less.

Flagstaff obtains most of the groundwater for its municipal supply from the C-aquifer from the Woody Mountain and Lake Mary well fields. Smaller amounts of groundwater are obtained from alluvial, glacial, and volcanic breccia aquifers in the Inner Basin well field. Recently constructed wells at two locations on the east side of the city also penetrate the C-aquifer system. One of these wells is located in the Continental Country Club area in a fractured rock zone associated with four faults that bound crosscutting grabens.

All Sedona wells penetrate and obtain groundwater entirely from the R-aquifer. The most successful Sedona wells are located near large faults and exploit the fractured rock conditions associated with those faults. The recently constructed Williams deep well yields groundwater from the R-aquifer. The pumping rate is reported to be more than 200 gpm. The yield from wells at Tusayan is entirely from the R-aquifer. Pumping rates from individual production wells are reported to range from about 25 to 80 gpm.

Factors Controlling Groundwater Movement

Groundwater moves in sedimentary rocks by passing through openings between the rock particles. Where particles are relatively large, as in the case of sandstone, intergranular spaces may also be relatively large, and groundwater may pass with moderate ease. Sandstones, such as the Coconino Sandstone, commonly comprise useful permeable aquifers.

Where particles are exceedingly small, as for mudstone or shale strata, intergranular spaces are also exceedingly small and groundwater passes only with great difficulty. Therefore, mudstone and shale strata, such as the Hermit Shale, function as barriers to groundwater movement. Intergranular spaces in crystalline rocks, such as many limestone and lava-flow rocks, are also usually exceedingly small. Unless larger openings occur, such as those associated with fractures, crystalline rocks, such as the Redwall Limestone, may also comprise barriers to groundwater movement.

Both the C- and R-aquifer systems consist of brittle rock strata. When geologic movements occur, such as movements on faults, both units have accommodated this movement by fracturing. Abundant fractures in brittle rocks provide pathways for easy groundwater movement. The permeability of sandstone in the C-aquifer, and carbonate rocks in the R-aquifer, is substantially improved where fractures are abundant. Because shale and mudstone strata tend to be ductile rather than brittle, these strata often flex rather than fracture when subjected to geologic movements. Because fractures are less abundant in shale and mudstone strata, such as the Hermit Shale, the ability of these barriers to strongly retard groundwater movement is much less likely to be modified, even where geologic movements have occurred.

When groundwater moves along fractures in carbonate rocks, such as occurs in the R-aquifer, the fractures are often widened by dissolution of soluble carbonate minerals. In some places this widening of fractures has resulted in the creation of interconnected cavern systems and solution-enhanced permeability. Permeability of the Kaibab Limestone, and of carbonate rocks of the R-aquifer, has been greatly increased, at some places, by the presence of solution-enhanced fracture openings. Groundwater development programs for the R-aquifer system should be guided by the results of hydrogeologic investigations for hydrogeologic conditions that provide abundant fractures and solution-enhanced permeability (see Figure 2c).

Figure 6 shows the geologic conditions that result in abundant fractures in brittle strata along large faults. These favorable structural features are present in many parts of the plateau region, and are available for exploitation of large amounts of groundwater from the aquifer systems. These favorable groundwater development zones must be delineated locally by hydrogeologic investigations, and should be explored in the subsurface by construction and testing of exploration wells, prior to construction of more costly production water wells. High-yielding Flagstaff Woody Mountain wells are constructed on the downthrown side of the Oak Creek Fault to exploit the abundantly fractured zone adjacent to the fault, as illustrated in Figure 6. The fractured conditions shown in Figure 6 also occur in the Lake Mary area, adjacent to the Anderson Mesa Fault. Wells constructed to exploit abundant fractures associated with large faults yield as much as 1,000 gpm. Wells located based on other criteria commonly have much smaller yields.

Groundwater Discharge

The amount of groundwater that moves through the C- and R-aquifers can be estimated by examining flow from large springs that occur on the margins of the plateaus, where groundwater discharges to tributaries of the Colorado and Verde Rivers. Locations of points of principal groundwater discharge along the margins of the Coconino and San Francisco Plateaus are shown in Figure 2b. Amounts of discharge are summarized in Table 1.

More than 260,000 acre-feet of groundwater discharges from the margins of the Coconino and San Francisco Plateaus each year. Of this amount, about two thirds discharges to the Colorado River from the R-aquifer system at Blue Springs and Havasu Springs. About one third of the natural groundwater discharge is to the Verde River, from both the C- and R-aquifers.

Discharge to the Colorado River

Blue Springs: Total groundwater discharge from Blue Springs is about 160,000 acre-feet per

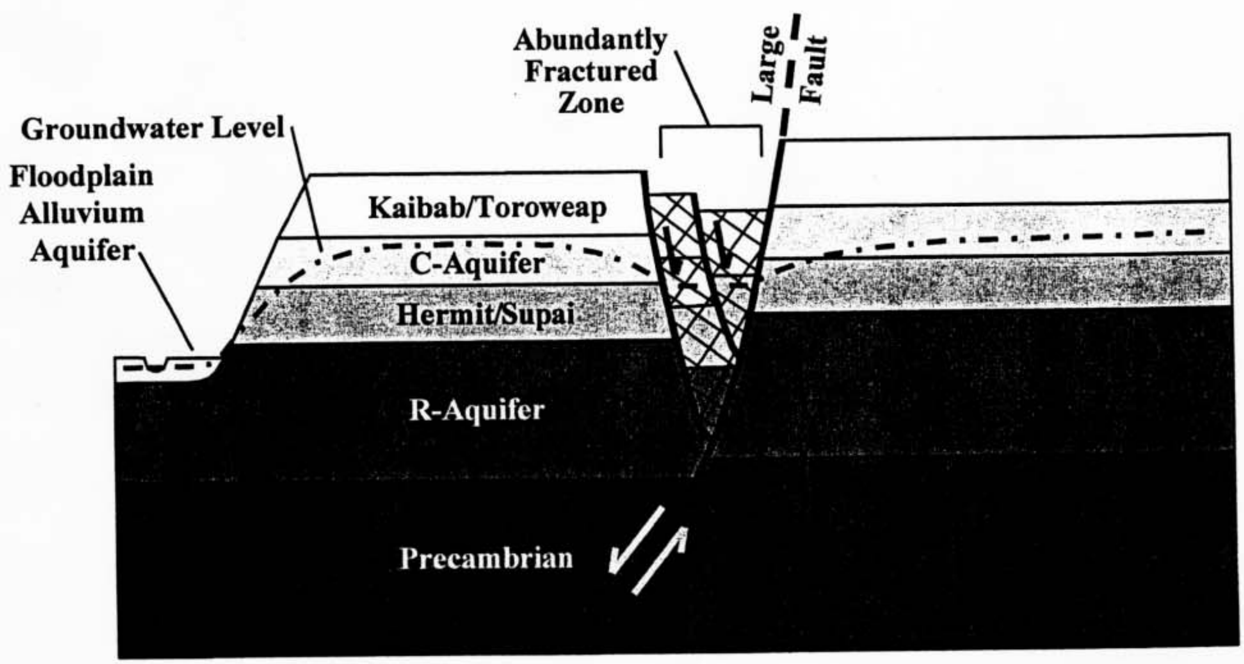


Figure 6. Abundantly fractured zone adjacent to large fault.

Table 1. Principal groundwater discharges from the Coconino and San Francisco Plateaus.

Discharge	Acre-feet per year
To Colorado River	
Blue Springs	120,000
Havasu Springs	47,000
Other springs	not known
Other groundwater discharge	not known
To Verde River	
Summer's Spring	45,000
Oak Creek C-aquifer	10,000
Oak Creek R-aquifer	40,000
Total	262,000

year. This groundwater originates from natural recharge on the Coconino and San Francisco Plateaus and also from the Black Mesa Basin, which lies to the east of the plateaus. Groundwater from the Black Mesa Basin is saline and can be differentiated from less saline groundwater from the plateaus region by analyzing groundwater chemistry from water samples. Results indicate that about 75 percent of the groundwater from Blue Springs, or about 120,000 acre-feet per year, originates from the Coconino and San Francisco subbasins (Loughlin 1983).

The Blue Springs complex is located where the R-aquifer system is near river level, in the lower part of the Little Colorado River canyon. Groundwater movement to the springs occurs along the northern part of the Mesa Butte Fault, along the East Kaibab Monocline, and along faults that cut the lower part of the Little Colorado River canyon (see Figure 2).

Havasu Springs: Total groundwater discharge from the R-aquifer at Havasu Springs is about 47,000 acre-feet per year. Groundwater that issues from Havasu Springs originates from the Coconino Plateau. Havasu Springs is located where the R-aquifer system is near river level, and along the Havasu down-warp, where many faults and fractures occur.

Other Springs: Other smaller springs, including Garden and Hermit Springs, and small perched aquifer springs and seeps, discharge groundwater to the Colorado River from the plateaus, but are not important for the current purpose of summing the total amount of groundwater discharge from the plateaus. Although the amount of groundwater that issues from these springs is small, the springs have environmental importance.

Other groundwater discharge to the Colorado River: Additional groundwater discharges from the plateaus to the Colorado River where rocks of the R-aquifer crop out at river level. These outcrop areas are chiefly near the confluence of Havasu Creek with the Colorado River, but also occur in the lower reaches of Marble Canyon above the confluence of the Little Colorado River with the main stem of the Colorado River. The amount of groundwater discharge is not known.

Discharge to the Verde River

Total groundwater discharge to the Verde River from the Coconino and San Francisco Plateaus is about 95,000 acre-feet per year (Table 1). Of this amount about 10,000 acre-feet per year issues from the C-aquifer and about 85,000 acre-feet per year issues from the R-aquifer.

Verde River near Summer's Spring: Groundwater discharge from the R-aquifer system to the upper reaches of the Verde River, in the vicinity of Summer's Spring, is about 45,000 acre-feet per year. This groundwater is derived from the southern part of the Coconino Plateau. The groundwater discharge occurs where faults and related fractures extend to near the axis of the valley (see Figure 2).

Oak Creek: About 10,000 acre-feet per year of groundwater discharges from the C-aquifer at Sterling Spring, in the upper reaches of Oak Creek, and from gains in base-flow of the creek to about the location of Indian Garden. About 40,000 acre-feet per year issues from the R-aquifer system to the lower part of Oak Creek below Sedona. Much of the discharge occurs at Page Spring. This groundwater originates on the southern part of the San Francisco Plateau. Groundwater movement in the Oak Creek Canyon area is strongly influenced by fractured rock zones along the Oak Creek fault system and related faults in the Sedona area.

Groundwater Circulation and Storage

Groundwater beneath the plateaus originates as recharge from infiltration of rainfall and snowmelt. The long-term average amount of annual recharge must be equal to the amount of groundwater discharge of more than 260,000 acre-feet per year. This rate of recharge is in the magnitude of 4 percent of the total average annual precipitation on the plateaus. Groundwater storage may be in the magnitude of 5 million acre-feet, the product of about 10,000 square miles of plateau area, with an average saturated thickness of 800 feet, and an average specific yield or drainable porosity of 0.1 percent.

In the Flagstaff area, downward-moving recharge water ultimately passes all upper perching horizons and reaches the C-aquifer, where large amounts of groundwater storage occur over limited areas. In the Flagstaff Woody Mountain and Lake Mary well field areas, all rock units from the C-aquifer downward are saturated. Groundwater in the saturated zone of the C-aquifer moves laterally and downward, very slowly in areas of non-fractured rock, and less slowly in areas where abundant fractures occur. At distances of a few miles to a few tens of miles from the Lake Mary and Woody Mountain well field areas, saturated thickness in the C-aquifer diminishes to zero or near zero due to full drainage of the groundwater downward to the R-aquifer system. After groundwater passes downward to the R-aquifer, it provides groundwater storage in the regional system, and moves slowly toward the Colorado and Verde River drains, chiefly along arterial fractured rock aquifer zones related to regional geological structures.

Potential Impacts

One of the principles of groundwater hydrology is that, over the short term, groundwater pumped from wells is obtained solely from groundwater storage in aquifers. Over the long term, the source of groundwater begins to be accounted for as reduction of natural discharge. For the plateaus, reduction of natural discharge must be accounted for chiefly by reduction in groundwater discharge to springs along the Colorado and Verde River drains. Total groundwater used on the plateaus, including Sedona, is presently about 8,000 acre-feet per year. This total use represents about 3 percent or less of the discharge to springs along the Colorado and Verde Rivers, and about 0.2 percent of the estimated groundwater in storage. An analysis of projections given by the Arizona Department of Water Resources (2000) indicates that total groundwater to be used by cities by the year 2010 may be about 12,700 acre-feet per year. This projected total groundwater use represents about 5 percent or less of the discharge to springs along the Colorado and Verde Rivers.

Conclusions

Present groundwater use on the Coconino and San Francisco Plateaus, including Sedona, is about 8,000 acre-feet per year. Total water use, including surface water, is about 13,000 acre-feet per year. Most of the water use is at Flagstaff; most groundwater extraction is presently from the C-aquifer at the Flagstaff Woody Mountain and Lake Mary well fields. The aquifer systems that contain and transmit groundwater in these regions are chiefly the C- and R-aquifers. Although the C-aquifer is presently the most used aquifer and is commonly described as a regional aquifer, it is more properly described as a local aquifer in the Coconino and San Francisco Plateaus. Of the two, the R-aquifer is truly a regional aquifer, and provides about 96 percent of the groundwater that drains from the plateau area. More than 260,000 acre-feet of groundwater issues from the margins of the plateaus to the Colorado and Verde River drains. Most of the groundwater moves in arterial zones along solution-enhanced fracture systems in the R-aquifer. Locations of high-permeability arteries for groundwater movement are controlled by regional geological structural systems. Most successful large-yield wells have been located to exploit fractured rock conditions located along structural features. Comparing the rate of groundwater usage on the plateaus, about 8,000 acre-feet per year, to the natural groundwater discharge rate, more than 260,000 acre-feet, and considering the large amounts of groundwater in storage, indicates that groundwater is truly abundant beneath the plateaus. Because the depth to groundwater in the R-aquifer is large, large costs will be experienced for groundwater exploration and development.

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