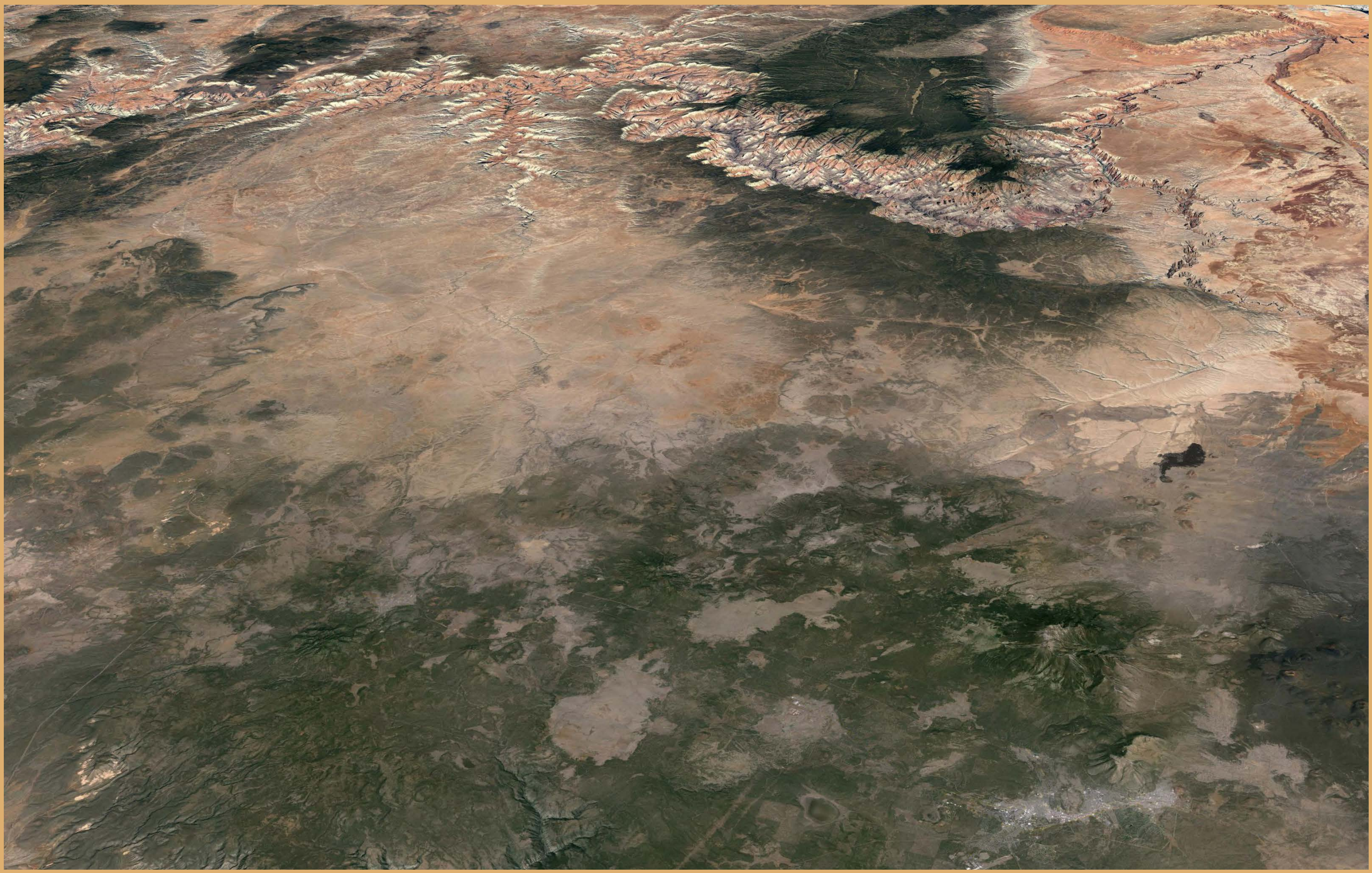
Prepared in cooperation with the Arizona Department of Water Resources and Yavapai County

Simulation of Groundwater Withdrawal Scenarios for the Redwall-Muav and Coconino Aquifer Systems of Northern and Central Arizona



Scientific Investigations Report 2016–5115

U.S. Department of the Interior
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COVER

Elevated, northwest-looking Google Earth view of Flagstaff, Arizona, in the foreground, the Coconino Plateau in the center, and Grand Canyon in the upper part of the image. Image Landsat from Google (2016).

Simulation of Groundwater Withdrawal Scenarios for the Redwall-Muav and Coconino Aquifer Systems of Northern and Central Arizona

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (ac-ft/yr)
cubic hectometer per year (hm^3/yr)	811.03	acre-foot per year (ac-ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
	Specific capacity	
liter per second per meter [(L/s)/m]	4.831	gallon per minute per foot [(gal/min)/ft]
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)
	Leakance	
meter per day per meter [(m/d)/m]	1	foot per day per foot [(ft/d)/ft]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, “North American Vertical Datum of 1988 (NAVD 88)”

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, “North American Datum of 1983 (NAD 83)”

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Simulation of Groundwater Withdrawal Scenarios for the Redwall-Muav and Coconino Aquifer Systems of Northern and Central Arizona

By D.R. Pool

Abstract

The Northern Arizona Regional Groundwater Flow Model was used to estimate the hydrologic changes, including water-level change and groundwater discharge to streams and springs, that may result from future changes in groundwater withdrawals in and near the Coconino Plateau Water Advisory Council study area, Coconino and Navajo Counties, Arizona. Three future groundwater withdrawal scenarios for tribal and nontribal uses were developed by the Coconino Plateau Water Advisory Council and were simulated for the period representing the years from 2006 through 2105. Scenario 1 assumes no major changes in groundwater use except for increased demand based on population projections. Scenario 2 assumes that a pipeline will provide a source of surface water from Lake Powell to areas near Cameron and Moenkopi that would replace local groundwater withdrawals. Scenario 3 assumes that the pipeline extends to the Flagstaff and Williams areas, and would replace groundwater demands for water in the area.

The Coconino Plateau Water Advisory Council withdrawal scenarios primarily influence water levels and groundwater discharge in the Coconino Plateau basin, near the western margin of the Little Colorado River Plateau basin, and the Verde Valley subbasin. Simulated effects of the withdrawal scenarios are superimposed on effects of previous variations in groundwater withdrawals and artificial and incidental recharge. Pre-scenario variations include changes in water-levels in wells; groundwater storage; discharge to streams and springs; and evapotranspiration by plants that use groundwater. Future variations in groundwater discharge and water-levels in wells will continue to occur as a result of both the past and any future changes.

Water-level variations resulting from post-2005 stresses, including groundwater withdrawals and incidental and artificial recharge, in the area of the withdrawal scenarios are primarily localized and superimposed on the regional changes caused by variations in stresses that occurred since the beginning of the initial stresses in the early 1900s through 2005. Withdrawal scenario 1 produced a broad region on the Coconino Plateau where water-levels declined 3–5 feet by 2105, and local areas with water-level declines of 100 feet or more where groundwater withdrawals are concentrated, near the City of Flagstaff Woody Mountain and Lake Mary well fields, and the towns of Tusayan, Williams, and Moenkopi. Water-level rises of 100 feet or more were simulated at areas of incidental recharge near wastewater treatment facilities near Flagstaff, Tusayan, Grand Canyon South Rim, Williams, and Munds Park.

Simulated water-level change from 2006 through 2105 for scenarios 2 and 3 is mostly different from water-level change simulated for scenario 1 at the local level. For scenarios 2 and 3, water levels near Cameron in 2105 where 1–3 feet higher than simulated for scenario 1. Water levels at Moenkopi are more than 100 feet higher due to the elimination of a proposed withdrawal well that was simulated in scenario 1. Scenario 3 eliminates more groundwater withdrawals in the Flagstaff and Williams areas, simulates 1–3 feet less water-level decline than scenario 1 across much of the Coconino Plateau, and water levels that are as much as 50 feet higher than simulated by scenario 1 near withdrawal wells in the Williams and Flagstaff areas.

Scenario 1 simulated the most change in groundwater discharge for the Little Colorado River below Cameron and for Oak Creek above Page Springs where declines in discharge of about 1.3 and 0.9 cubic feet per second (ft^3/s), respectively, were simulated. Other simulated changes in discharge through 2105 in scenario 1 are losses of less than 0.4 ft^3/s at the Upper Verde River, losses of less than 0.3 ft^3/s at Havasu Creek and at Colorado River below Havasu Creek, losses of less than 0.1 ft^3/s at Clear Creek, and increases in flow at the south rim springs and Chevelon Creek of less than 0.1 and 0.3 ft^3/s, respectively. Simulated changes in discharge for scenarios 2 and 3 are less than for scenario 1 because of lower rates of groundwater withdrawal. Scenario 3 resulted in greater groundwater discharge than scenarios 1 and 2 at all major groundwater discharge features from 2006 through 2105 except for Clear and Chevelon Creeks, where the same groundwater discharge was simulated by each of the three scenarios.

Changes in groundwater discharge are expected to occur after 2105 to all major surface features that discharge from the Redwall-Muav and Coconino aquifers because change in aquifer storage was occurring at the end of the simulation in 2105. The accuracy of simulated changes resulting from the Coconino Plateau Water Advisory Council groundwater withdrawal scenarios is dependent on the persistence of several hydrologic assumptions that are inherent in the Northern

Arizona Regional Groundwater Flow Model including, but not limited to, the reasonably accurate simulation of (1) transmissivity distributions, (2) distributions of vertical hydraulic properties, (3) distributions of spatial rates of withdrawal and incidental recharge, (4) aquifer extents, and (5) hydrologic barriers and conduits.

Introduction

The U.S. Geological Survey (USGS) Northern Arizona Regional Groundwater Flow Model (NARGFM; Pool and others, 2011) was constructed for several purposes; one of which was to estimate the hydrologic changes—including changes in water levels and groundwater discharge to streams, springs, and vegetation—that may result from future groundwater withdrawals. The Coconino Plateau Water Advisory Council (CPWAC) would like to better understand the effect of future groundwater withdrawals from the primary aquifers that may occur though the year 2105 and has developed three future withdrawal scenarios for testing using the NARGFM. This report documents the changes in the groundwater-flow system simulated by the NARGFM from 2006 through 2105 using the three scenarios.

The analysis does not include the simulation of changes in the groundwater system that may result from changes in climate and land-use. Past variations in recharge rates are known to be important in the simulation of observed water-level changes in the study area (Pool and others, 2011). The effects of land-use change on the groundwater system are largely unknown and not simulated by NARGFM. Only the groundwater effects caused by changes in groundwater withdrawals from the primary regional aquifers and associated changes in incidental recharge from waste-water treatment facilities are simulated. By focusing only on the effects of changes in groundwater withdrawals, the CPWAC will be able to better assess changes in groundwater discharge and water levels in wells that may result from each of the three withdrawal scenarios. Inclusion of climate scenarios that are beyond the control of CPWAC would likely complicate the analysis and were therefore avoided.

The study area is a small part of the region covered by the NARGFM, which includes most of northern and central Arizona, but also adjacent parts of western New Mexico and southern Utah. The areal extent of the analysis of the effects of the CPWAC withdrawal scenarios is the boundary of the Coconino Plateau Partnership (fig. 1) and adjacent areas, which includes the Coconino Plateau and parts of the watersheds of the Verde and Little Colorado Rivers, and the western part of Navajo County. The Coconino Plateau is a region of uplifted layered sedimentary rock overlain by layered volcanic rocks and dissected by deep canyons. The layered sedimentary rocks are deformed by faulting and uplift. In several alluvial basins drained by the Verde and Salt River systems, the deformation has resulted in thick accumulations of sediments.

Land surface altitudes in the CPWAC study area range from more than 7,000 feet (ft) on San Francisco Mountain, the Mogollon Rim south of Flagstaff, and along the south rim of Grand Canyon to about 3,100 ft at the confluence of Beaver Creek and about 1,500 ft at the Colorado River west of Havasu Creek (fig. 1). North of the Mogollon Rim, the land surface generally slopes gently toward deep canyons at the Little Colorado and Colorado Rivers. To the south of the Mogollon Rim, the land surface drops more steeply to the Verde Valley.

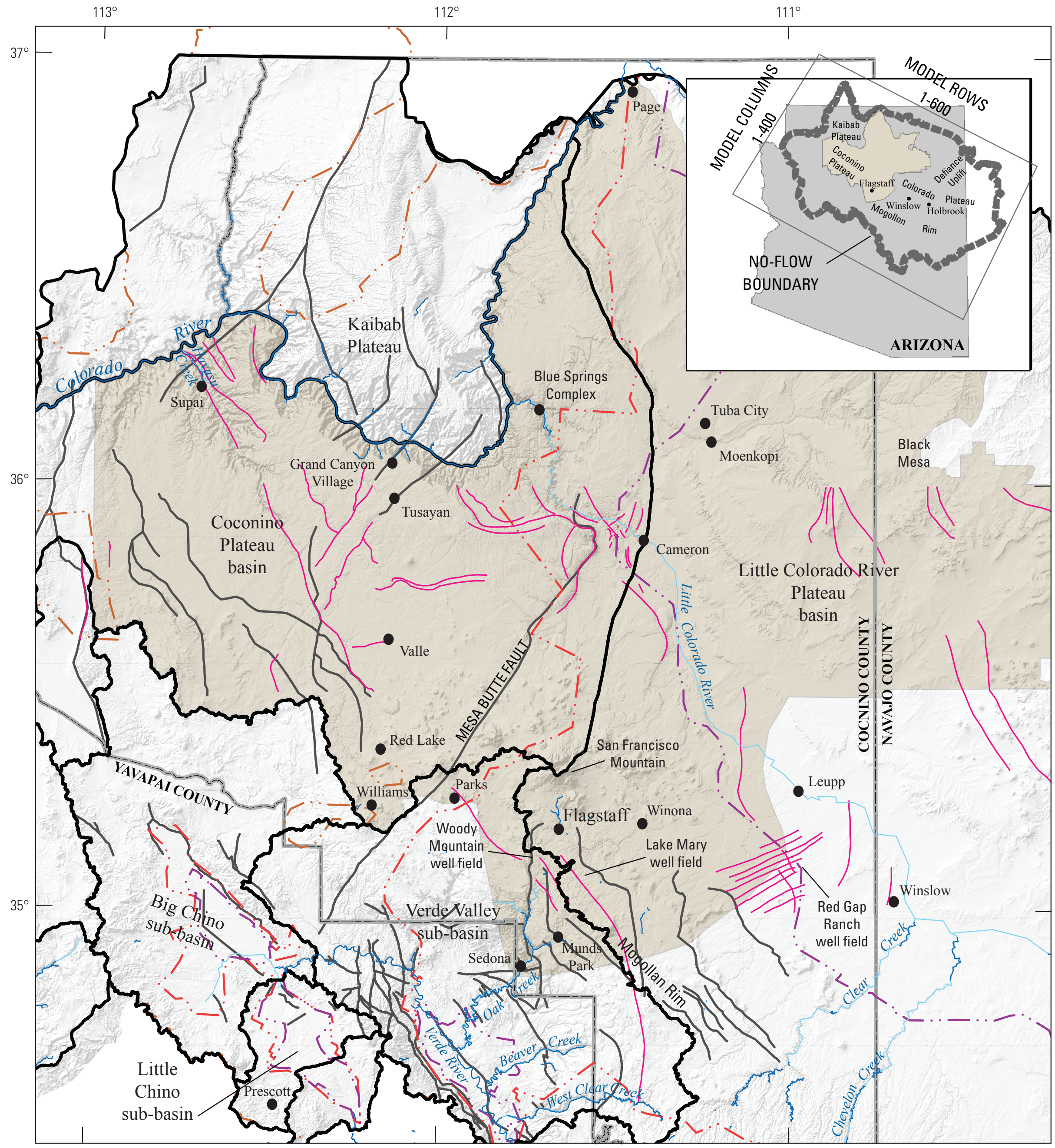
The analysis is restricted to the primary regional Redwall-Muav and Coconino aquifers that are accessed by the major water users in the area. Other, more localized aquifers such as the Navajo Sandstone aquifer at Black Mesa, volcanic rock aquifers near Flagstaff and Williams, and alluvial aquifers along streams are not considered in the analysis

Springs and streams that discharge groundwater from the regional aquifers of the area are included in this analysis. The major rivers in the study area (fig. 1) are the Colorado River and Little Colorado River to the north of the Mogollon Rim, and the Verde River to the south. The perennial streams are largely supplied with groundwater discharge from springs, but flow is also supported by runoff from numerous intermittent and ephemeral streams. Groundwater discharge is also distributed along many stream reaches that gain flow. The primary perennial streams considered in this analysis include the Colorado River, lower and middle parts of the Little Colorado River, the Upper Verde River, and Oak Creek. Streams and springs that are tributaries of the Colorado River and are considered in the analysis include Havasu Creek and several springs at the south rim of Grand Canyon. Streams and springs that are tributaries of the Little Colorado River and are considered in the analysis include the lower perennial parts of Clear Creek and Chevelon Creek. Oak Creek is a tributary of the Verde River.

Climate

The climate of the study area is primarily arid to semiarid with large spatial and temporal variations of temperature and precipitation. Climate conditions are strongly correlated with altitude; moderate summers and severe winters are at higher altitudes, and extreme summer heat and mild winters are at lower altitudes. Microclimates are common in the study area because of local controls on the amount of solar radiation and precipitation reaching the land surface in mountainous terrain and in the deep canyons.

The spatial distribution of precipitation, derived from the Basin Characterization Model of Flint and Flint (2008), is primarily influenced by the direction of approaching winds and orographic uplift of air masses. Average annual precipitation varies from about 7–15 inches in the basins, to about 20–37 inches in the mountains and higher altitudes of the Coconino Plateau. Long term precipitation in the study area is dominated by extended below-average periods of precipitation



County boundaries of the United States, USGS 2000 National Atlas, 1:2,000,000-scale resolution, 2002, USGS; Towns from USGS Geographic Names Information System, 1981. Coordinate System: NAD 1927 UTM Zone 12N. Projection: Transverse Mercator. Datum: North American 1927. False Easting: 500,000.0000. False Northing: 0.0000. Central meridian: -111.0000. Scale factor: 0.9996. Latitude of origin: 0.0000. Units: meters

Perennial streams from Arizona Department of Water Quality, 2015, scale 1:100,000; Groundwater basin and sub-basin boundaries from Arizona Department of Water Resources, 2008, scale 1:100,000; Faults and folds from USGS SIR 2010–5180

EXPLANATION

- **Town or landmark**
- **Simulated stream**
- **Perennial streams**
- **Major faults**
- **Folds**
- **Coconino Plateau Partnership area**
- **ADWR Groundwater basin and subbasin boundary**
- **Coconino County boundary**
- **Model layer 1 active extent**
- **Model layer 2 active extent**
- **Model layer 3 active extent**

0 5 10 20 30 40 MILES

0 10 20 40 60 80 KILOMETERS

Figure 1. Map of the area within the Coconino Plateau Water Advisory Council groundwater withdrawal scenarios, including Arizona Department of Water Resources (ADWR) groundwater basins, model layer extents, and inset map of Arizona showing Northern Arizona Regional Groundwater Flow Model model grid and boundaries.

interspersed with occasional above-average periods of precipitation (Blasch and others, 2006). Annual precipitation is distributed between a summer monsoon period and a winter frontal storms period. The summer monsoon (also known as the North American Monsoon, or the Southwestern, Arizona, or Mexican Monsoon), generally begins in early July and extends through September, and includes precipitation from convective storms that are characteristically short lived (less than a few hours), but can be intense (precipitation greater than 1 in/hr), and localized (tens of square miles). The winter frontal season from November through March produces storms that are characteristically longer (12–48 hr), less intense (precipitation less than 0.25 in/hr), and more regional in extent (hundreds of square miles) than summer convective storms. Precipitation also can fall during October and November as a result of both tropical disturbances from the southern Pacific Ocean and winter frontal storms from the north Pacific. Although precipitation during this period can be a substantial part of the annual total, the atmospheric conditions that result in precipitation do not happen regularly. The average annual rainfall rate is greater than the average annual snowfall rate for all climate stations in the study area. The greater rainfall rate is attributed to warm annual mean temperatures. This greater rate is true in the higher altitudes where the ratio of rainfall to snowfall is about 3 to 1, and in the basins where the ratio is greater.

Average annual temperatures range from about 68 °F in the basins to 43 °F at higher altitudes and are inversely correlated with altitude. Average annual minimum temperatures were recorded as low as 36 °F on the north rim of the Grand Canyon and average annual maximum temperatures have been measured as warm as 78 °F in the Verde Valley. Large differences between the minimum and maximum daily temperatures are characteristic of the area.

Vegetation

The distribution of vegetation in the study area is influenced by temperature and by water availability. Thus, plant communities are distributed on the basis of differences in latitudes, altitudes, and topography. Basins along the Verde and Salt Rivers are inhabited by desert scrub characteristic of the Sonoran desert. Piñon-juniper woodlands and chaparral are primarily present in the middle altitudes (about 3,900–5,600 ft). The predominant type of vegetation at altitudes above 5,600 ft is montane coniferous forest on the Mogollon Rim and across a large region near the San Francisco Mountain, Flagstaff, and Williams. Vegetation that taps groundwater supplies, phreatophytes, occur along perennial and intermittent streams. Important phreatophytes of the area include cottonwood, willow, sycamore, tamarisk, and mesquite.

Land and Water Use

Population—The estimated population of Coconino County was 136,539 in 2013 (U.S. Census Bureau, 2015), which includes most of the area of analysis.

Land Use—Native American reservations account for about 68 percent of the lands in the Coconino Plateau Partnership study area. About 26 percent of the land in the area is publicly owned; 14 percent is managed by the U.S. Department of Agriculture (USDA) Forest Service, 7 percent is managed by the National Park Service, and 4 percent is managed by the State of Arizona. Recreation, forest, cattle and sheep ranching, mining, and urban development are the largest land uses in the region. Privately held lands account for about 7 percent of the total.

Water Use—Groundwater (including spring water) withdrawals in the study area are primarily for industrial and tribal/municipal/domestic water use. Near population centers, groundwater is supplied primarily by private and municipal water companies. Wells are used in some rural areas to obtain groundwater for domestic and stock use. Total well withdrawals in the CPWAC area were about 12,500 acre-ft during 2006–10. About 10,800 acre-ft were withdrawn from the regional aquifers simulated by NARGFM on an annual basis during 2006–10. About 1,700 acre-ft of the total were withdrawn from aquifers other than the regional aquifers simulated by NARGFM. Surface water is also a water supply source at Page, Flagstaff, and Williams. A source of water for Grand Canyon Village is spring discharge from the North Rim of Grand Canyon, which is imported to the study area through a pipeline. A portion of the water used for municipal, tribal, and domestic purposes was returned to the primary regional aquifers as incidental recharge through waste-water treatment facilities and septic systems.

Regional Hydrogeology

Descriptions of the regional hydrogeology of northern Arizona include several elements—aquifers and confining units, rates and distribution of recharge, rates and distributions of discharge, and groundwater flow through the aquifers between recharge and discharge areas. Each of the elements of hydrogeology are briefly discussed in this report. More complete descriptions of each element may be found in Pool and others (2011) and in greater detail in numerous reports for subregions of the study area.

Aquifer Geology and Structure

The stratigraphic sequence in the study area includes Proterozoic metamorphic and igneous rocks that are overlain by a sequence of Cambrian to Permian sedimentary rocks. Late Tertiary volcanic rocks overlay the older rocks in places, especially along the Mogollon Rim. Sequences of late

Tertiary alluvial basin deposits, hundreds to thousands of feet thick, overlie the older rocks in the alluvial basins along the Verde and Salt River drainages. A more complete description of the rock units and aquifers of the study area can obtained from Hart and others (2002), Leake and others (2005), Parker and others (2005), Wirt and others (2005), Blasch and others (2006), Bills and others (2007), and Pool and others (2011).

Aquifers

Most rock units in the study area contain some water-bearing zones. However, structural deformation has reduced the continuity of saturated units across the study area. Groundwater systems of the study area are more complex than is indicated by the fairly simple layering of the rocks that contain the groundwater systems. The complexity is because of variations in stratigraphy, lithology, and geologic structure (Bills and others, 2007). Aquifers are briefly described here but are described in greater detail in the NARGFM report (Pool and others, 2011). Stratigraphic relations of the rock units are shown in figure 7 of Pool and others (2011). The Redwall-Muav aquifer (locally known as the R-M aquifer) and the Coconino multiple aquifer system (locally known as the C aquifer) are the primary aquifers in the study area. The Redwall-Muav and Coconino aquifers are the primary regional aquifers on the Coconino Plateau in the study area (Cooley and others, 1969; Cooley, 1976). Both the Redwall-Muav aquifer and the Coconino aquifer have internal southeast-northwest trending groundwater divides that are coincident with or near the Mogollon Rim, and divide the regional groundwater-flow system into parts that flow northward toward the Colorado and Little Colorado Rivers, and southward toward the Verde and Salt Rivers. Other local aquifers lie adjacent to the regional aquifers and are hydraulically connected including thick alluvial deposits in basins of the Verde River drainage system, thin stringers of Quaternary alluvium along major streams, and fractured Proterozoic sediments, granite, and metamorphic rocks that mainly occur in upland areas (fig. 2). Other local aquifers that are hydraulically disconnected from the regional aquifer system and from each other occur within Proterozoic rocks, the lower Supai Formation, the Coconino Sandstone, the Kaibab Limestone, volcanic rocks, and Quaternary alluvium. These local, isolated aquifers generally are small and thus are unsuitable as long-term water supplies; however, these aquifers are used extensively to meet local water demands. These local disconnected aquifers are taken into consideration in the regional groundwater-flow system because groundwater that discharges from the local aquifers can percolate downward to the underlying regional aquifer system. The downward percolation of water from shallow local aquifers is an important process in the large region covered by volcanic rocks in the Flagstaff, Williams, and much of the Mogollon Rim areas.

Proterozoic Basement

Proterozoic metamorphic and igneous rocks form the underlying confining bed for the Redwall-Muav, Coconino, and basin-fill aquifers, and, in general, do not store or transmit substantial amounts of water. Only in a few areas with significant fracturing is water found in quantities sufficient for withdrawal. One of these areas is along the Inner Gorge of the Grand Canyon where several small springs and seeps discharge from fractured Precambrian granites and metamorphic rocks.

Redwall-Muav Aquifer

The Redwall and Muav Limestones are the primary water-bearing rock units in the region of the Coconino Plateau, and underlie the Coconino aquifer in the remainder of the Colorado Plateau. Cooley (1976) defined the Redwall and Muav Limestone multiple-aquifer system as the saturated to partly saturated and hydraulically connected Redwall, Temple Butte, and Muav Limestones. Other regional studies have broadened the extent of the aquifer to include several hydraulically connected limestone, sandstone, and shale units including the Tapeats Sandstone, Bright Angel Shale, Muav Limestone, Temple Butte Limestone, Martin Limestone, and Naco Formation (McGavock and others, 1986; Parker and others, 2005). The Redwall Limestone occurs throughout the study area and is the upper rock unit of the Redwall-Muav aquifer where the Naco Formation is absent. The Temple Butte Limestone and the Muav Limestone underlie the Redwall Limestone near the Grand Canyon in the area of the Coconino Plateau. South of the Grand Canyon, the Temple Butte Formation thins southward and overlies the Martin Limestone or is absent, and the Muav and Redwall Limestones are in direct contact. The Martin Limestone is mainly in the central and southern part of the plateau and thickens to the south.

The Bright Angel Shale and Tapeats Sandstone underlie the Martin, Temple Butte, and Muav Limestones in the central and western parts of the study area. The Bright Angel Shale is several hundred feet thick; however, it is not a major water-bearing unit because it is composed of very fine-grained sediments that impede the downward migration of water (Huntoon, 1977). Nevertheless, dozens of springs discharge from the Bright Angel Shale in Grand Canyon from fine grained sandstone, sandy siltstone, and bedding plane fractures (Monroe and others, 2005). The Tapeats Sandstone is a major water-bearing unit in places. The Tapeats Sandstone is a continuous unit along the south and north rims of Grand Canyon. South of Grand Canyon, the Tapeats Sandstone is mainly present as isolated erosion remnants overlying Proterozoic rocks. The Tapeats Sandstone is believed to be hydraulically connected to the overlying Redwall and Muav Limestones through faults and fractures, and where the Bright Angel Shale is thin or absent.

Groundwater primarily enters the Redwall-Muav aquifer through downward leakage from overlying units by way of faults, fractures, and other geologic structures that create secondary porosity and conduits for groundwater flow through the lower Supai Formation, which is otherwise primarily a confining unit. Groundwater flow in the aquifer is substantially enhanced by faults, fractures, and solution channels. Areas of substantial faulting and fracturing are (1) along the Mesa Butte Fault Zone; (2) across the Havasu Creek drainage basin from Williams to Supai; (3) along the faults near Tusayan; (4) in the Cameron area coincident with several large monoclines; and (5) south of Flagstaff in association with extensional basins (Cooley, 1976; Ulrich and others, 1984; Billingsley, 2000; Bills and others, 2000; Billingsley and others, 2006). The aquifer is anisotropic and confined in much of the study area. Small parts of the aquifer are unconfined where the aquifer rocks crop out. Wells drilled along extension faults and fractures typically penetrate zones of increased transmissivity because of the solution-enhanced permeability (Errol L. Montgomery and Associates, 1999).

Coconino Aquifer

The Coconino aquifer is the sequence of rock units between the Moenkopi Formation and the lower Supai Formation (McGavock and others, 1986; Bills and others, 2000, 2007; Bills and Flynn, 2002). The primary water producing unit is the Coconino Sandstone; however, the overlying Kaibab and Toroweap Limestones and the underlying Schnebly Hill Formation and upper and middle Supai Formations of the Supai Group can be locally major water producing units (Leake and others, 2005). The lower Supai Formation typically forms a confining unit that separates the Coconino aquifer from the underlying Redwall-Muav aquifer and local Proterozoic crystalline aquifers. West of the Mesa Butte Fault, the primary water-bearing zones of the Coconino aquifer are locally present as perched aquifers (Bills and others, 2007) but are unsaturated across broad regions. The Coconino aquifer thins toward the east, however the exact eastern boundary is uncertain because water-level and geologic data are meager. Groundwater in the Coconino aquifer is unconfined except where the base of the Moenkopi Formation falls below the potentiometric surface across much of the region north of the Little Colorado River. Many wells drilled into the confined part of the aquifer flowed at land surface before significant development of the groundwater supplies (Mann and Nemecek, 1983; Mann, 1976). Groundwater flow in the Coconino aquifer is locally enhanced by fractures and faults (Bills and others, 2000; Hoffmann and others, 2005; Kaczmarek, 2003; Leake and others, 2005).

Alluvial Aquifers

Alluvial basin aquifers are present in basins that lie to the south of the study area but are of minor importance in the CPWAC study area. Alluvial aquifers of local importance include thin stringers of Quaternary flood-plain alluvial and terrace deposits that occur along major streams. Where unsaturated, such as along perennial stream reaches, these highly permeable deposits are effective conduits for the transmission of infiltrated streamflow to the underlying aquifer. Perched aquifers may form locally where the Quaternary alluvium overlies low permeability rocks.

Structure

Regional tectonic stresses have shaped the landscape of the study area, disturbed the stratigraphic sequence, formed basins where sediments accumulated, and formed local zones of weakness that resulted in volcanism. These regional stresses have also influenced the groundwater-flow system through the creation of faults and fractures that can locally be flow barriers or conduits for groundwater flow. Northeast-, north-, and northwest-striking faults and other fractures dominate the structure of the study area (Gettings and Bultman, 2005). Extensional stresses that have weakened the regional pre-Tertiary sediments have enabled large amounts of late Tertiary and Quaternary intrusive and volcanic rocks to reach the surface (Wolfe and others, 1987a,b). In addition, zones of weakness are continuing to expand, lengthen, and deepen, in some areas into canyons, from continued interaction with water. Groundwater movement along the expanded zones of weakness enhances the preferential flow paths through dissolution of carbonate rocks.

Description of the Northern Arizona Regional Groundwater Flow Model

The NARGFM was developed using the USGS groundwater model MODFLOW-2000 (Harbaugh and others, 2000) and MODFLOW-2005 (Harbaugh, 2005). The model grid includes 600 rows and 400 columns of finite-difference cells, each 1-kilometer square, in the horizontal dimension. The model grid is rotated 60° in the counter-clockwise direction about the geographic origin of the grid at Universal Transverse Mercator zone 12 easting 660,000 m and northing 3,580,000 m. Rotation of the grid allows for row and column alignment with the assumed principal directions of the hydraulic conductivity tensor. The origin of the model grid lies at the outer corner of the cell at row 600 and column 1. Model rows are incremented from the cell at row 1, column 1 to row 600 in a southeasterly direction. Model columns are incremented from the cell at row 1, column 1, to column 400 in a northeasterly direction. The model was constructed using units of meters for length and days for time. For this report, descriptions of values in the model are given in units of feet for length and days for time.

NARGFM uses three model layers to simulate the primary hydrogeologic units across the model domain (fig. 2). Model layer 1 represents the upper part of the Coconino aquifer including the Coconino Sandstone and Kaibab Limestone and equivalent units in the Colorado Plateau structural province and adjacent areas, and the upper part of basin fill in the alluvial basins of the transition zone. Model layer 2 represents the lower part of the Coconino aquifer including the upper and middle Supai Formation and equivalent units in the Colorado Plateau structural province and adjacent areas, and the lower part of basin fill in the alluvial basins of the transition zone. Model layer 3 represents the Redwall-Muav aquifer and older crystalline and sedimentary rocks where the Redwall-Muav aquifer is absent across much of the transition zone and eastern part of the Colorado Plateau structural province. For more detail, see Pool and others (2011).

Boundaries of NARGFM include no-flow boundaries at the model margins and internal flow boundaries at perennial streams. No-flow boundaries correspond with low permeability rocks and groundwater divides, and constrain all of the simulated recharge in the model to flow toward discharge at internal flow boundaries and wells. Internal flow boundaries are the primary controls that determine directions of groundwater flow. The distributions of internal flow boundaries relative to areas of variable flux at wells and recharge areas also partly determine the rates of change in discharge that result from the variable flux. The other important factors that determine rates of change are aquifer hydraulic and storage properties.

Within the area of the CPWAC withdrawal scenarios and surrounding areas, the major simulated aquifers are the Coconino aquifer and the Redwall-Muav aquifer. The upper part of the Coconino aquifer is simulated as model layer 1 only where the primary hydrogeologic units are regionally saturated in the Little Colorado River Plateau basin, primarily in the region northeast of the Little Colorado River. The lower part of the Coconino aquifer is simulated as model layer 2 where the upper and middle Supai Formations are regionally saturated in the area east of about Cameron and Williams. In the Verde Valley, model layer 2 includes the saturated parts of the upper and middle Supai Formations outside of the alluvial basin, and the saturated part of the sand and gravel facies of the Verde Formation in the alluvial basin. The Redwall-Muav aquifer is simulated as model layer 3 throughout most of the region of the CPWAC withdrawal scenarios and surrounding areas except for a few areas where the Redwall-Muav aquifer is absent and model layer 3 represents underlying rocks along parts of the Colorado River.

Aquifer properties are represented in the NARGFM using the Layer-Property Flow Package of MODFLOW. Important aquifer properties included in the model are hydraulic conductivity, specific storage, and specific yield. Hydraulic conductivity can be different in the two principal directions of the model grid, along rows and columns. Directions and magnitude of primary hydraulic conductivity directions across the area of the CPWAC withdrawal scenarios is influenced by geologic structure and secondary porosity. Model layer 3 is simulated with values along columns that are as much as 10

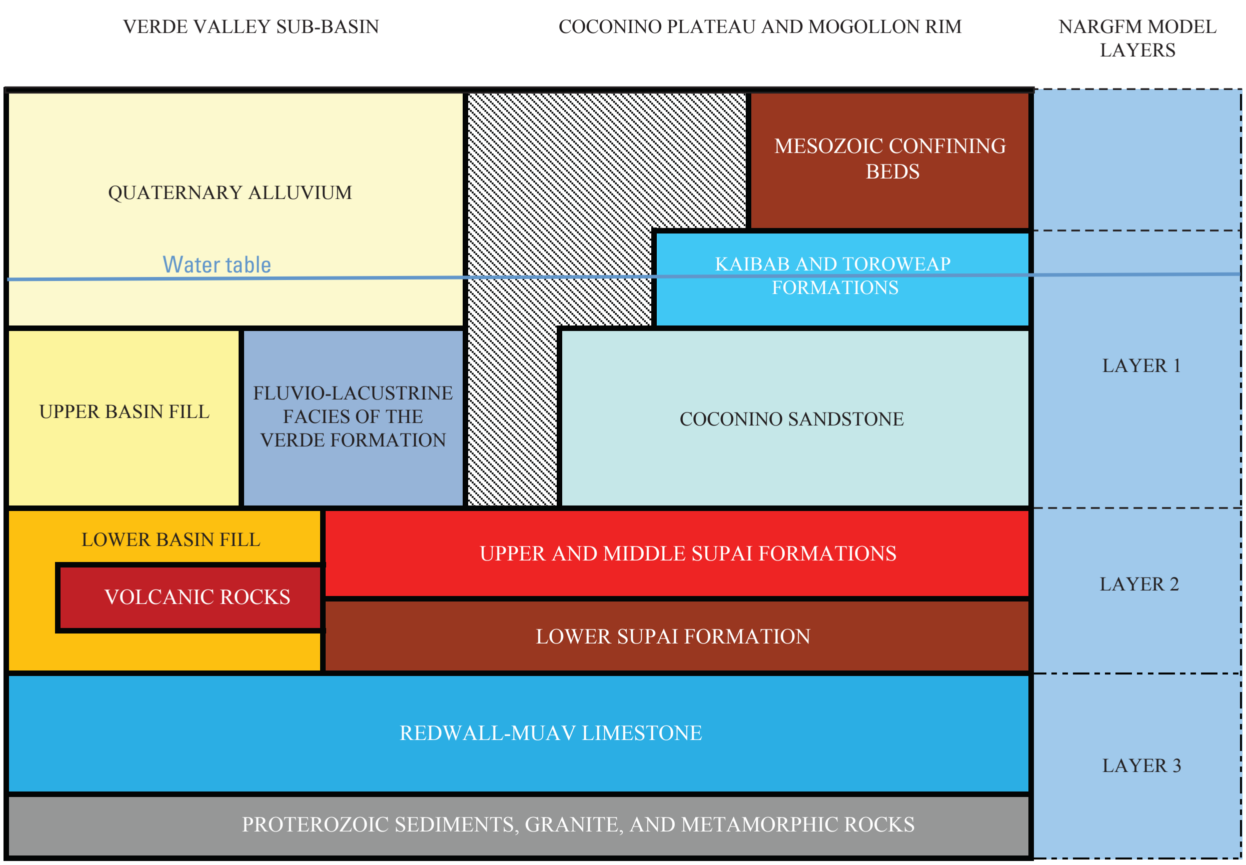


Figure 2. Conceptualized relations among major hydrogeologic units and the Northern Arizona Regional Groundwater-Flow Model (NARGFM) layers.

times the values along rows in the region for the Coconino Plateau. Hydraulic conductivity for model layers 1 and 2 are simulated as equivalent along rows and columns across large regions, but variable in the area of the Mogollon Rim where values along columns in some areas are as much as 5 times the values along rows. In the Oak Creek area, values along rows are locally 3 times greater than along columns. Mean vertical hydraulic conductivity in all layers is lower than mean horizontal hydraulic conductivity along rows and columns. In MODFLOW, specific storage is applied where the aquifer is confined, as indicated by head or water level above the top of the aquifer. The product of specific storage and saturated thickness is the aquifer storage coefficient. The USGS has defined the storage coefficient of an aquifer as, “the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface” (http://water.usgs.gov/admin/memo/GW/gw55.28.html). The mechanisms for these storage changes are compression and decompression of the aquifer skeleton and water. Similarly, specific yield is applied where the aquifer is unconfined, as indicated by head or water level below the top of the aquifer. Specific yield is the quantity of water released per unit volume of the aquifer by gravity drainage from lowering the water table. The uppermost active layer of the three model layers across the area of the CPWAC withdrawal scenarios is simulated as unconfined except in the eastern part of the area where the Moenkopi Formation is an important regional confining unit overlying the Coconino aquifer. In areas where the uppermost active model layers 1 or 2 are simulated as unconfined, underlying model layers 2 and 3 are simulated as confined. Specific yield values for model layers 1 and 2 range from 0.10 to 0.20 in the area of the CPWAC withdrawal scenarios. Low values of specific yield, less than 0.02, are simulated for layer 3 where it is the only active model layer.

Saturated thickness also is an important factor in calculating groundwater movement in the model. Where heads are below the top of the model layer, saturated thickness is the difference between the model-calculated head or water level and the specified bottom of the aquifer. Mean saturated thickness is much larger in layers 2 and 3 than in layer 1 in the area of the CPWAC withdrawal scenarios and surrounding areas.

Discharge of groundwater in NARGFM is simulated as occurring naturally along streams and springs simulated with the stream (Prudic, 1989) and drain packages (Harbaugh, 2005), and through evapotranspiration (ET). The stream package keeps track of available flow and calculates stream stage in each section or reach of stream that crosses a model cell. If leakage of water from the stream exceeds available streamflow, no further leakage is allowed from downstream reaches until the point where there is additional water available to the downstream reaches from tributary inflow or flow of groundwater into the stream. The stream package is used to simulate discharge to streams that have significant reaches where streamflow infiltrates the channel and recharges the aquifer. Groundwater discharged at features simulated using the drain package is permanently removed from the simulated flow system and not available to recharge through downstream stream reaches like in the stream package. The drain package is used to simulate streams and springs that have no important losing reaches. Important discharge features in the region of the CPWAC withdrawal scenarios that are simulated using the stream package include the Verde and Little Colorado Rivers and major perennial tributary streams. Important discharge features that are simulated using the drain package include the Colorado River, Havasu Creek, and several major springs in tributary streams. Input for the stream package includes specification of quantities for each of the stream reaches such as the elevations of the top and bottom of the streambed, streambed conductance, stream width, and Manning’s roughness coefficient. Input for the drain package includes the elevation and conductance of the spring or streambed. ET is simulated in riparian areas where there are shallow depths to the water table along the Verde and Little Colorado Rivers and major perennial tributary streams. Input for each model cell where ET is simulated includes maximum ET rate, elevation of maximum ET rate, and maximum depth of ET. Maximum rates of ET assigned to model cells in the area of the CPWAC withdrawal scenarios and nearby regions were 6.54×10^{-4} ft/d. Elevation of maximum rates of ET were assigned as 4.9 ft below the land surface in the model cell. Maximum depth of ET was simulated as 16.4 ft. For more details on representation of features with the stream, drain, and ET packages in the NARGFM, see Pool and others (2011).

Withdrawal Scenarios

Three future water demand scenarios (fig. 3, appendixes 1–3) for tribal and nontribal uses, including groundwater withdrawals, were developed by the CPWAC for much of Coconino County, all of which lies within the area simulated by the NARGFM. Projected withdrawal rates were developed for each decade from 2006 to 2105 for all three scenarios on the basis of population projections supplied by tribal and nontribal agencies. For the scenario simulations, future withdrawals are assumed to derive from existing exempt and nonexempt wells and many new withdrawal wells that are anticipated to be developed in several areas (fig. 4, table 1). The simulations also include estimated changes in incidental recharge of effluent from sewage plants and golf courses. The simulated scenarios do not included demands on water supplies that are not simulated by NARGFM such as surface water supplies and groundwater supplies from aquifers that are disconnected from the regional aquifers, including the Navajo, Dakota, and other shallow aquifers.

The scenarios include projected groundwater withdrawals from the primary regional aquifers by major water users for each decade from 2010 to 2049 followed by a 55-year period of stable withdrawals from 2050 to 2105. Groundwater withdrawals are simulated from only the regionally extensive

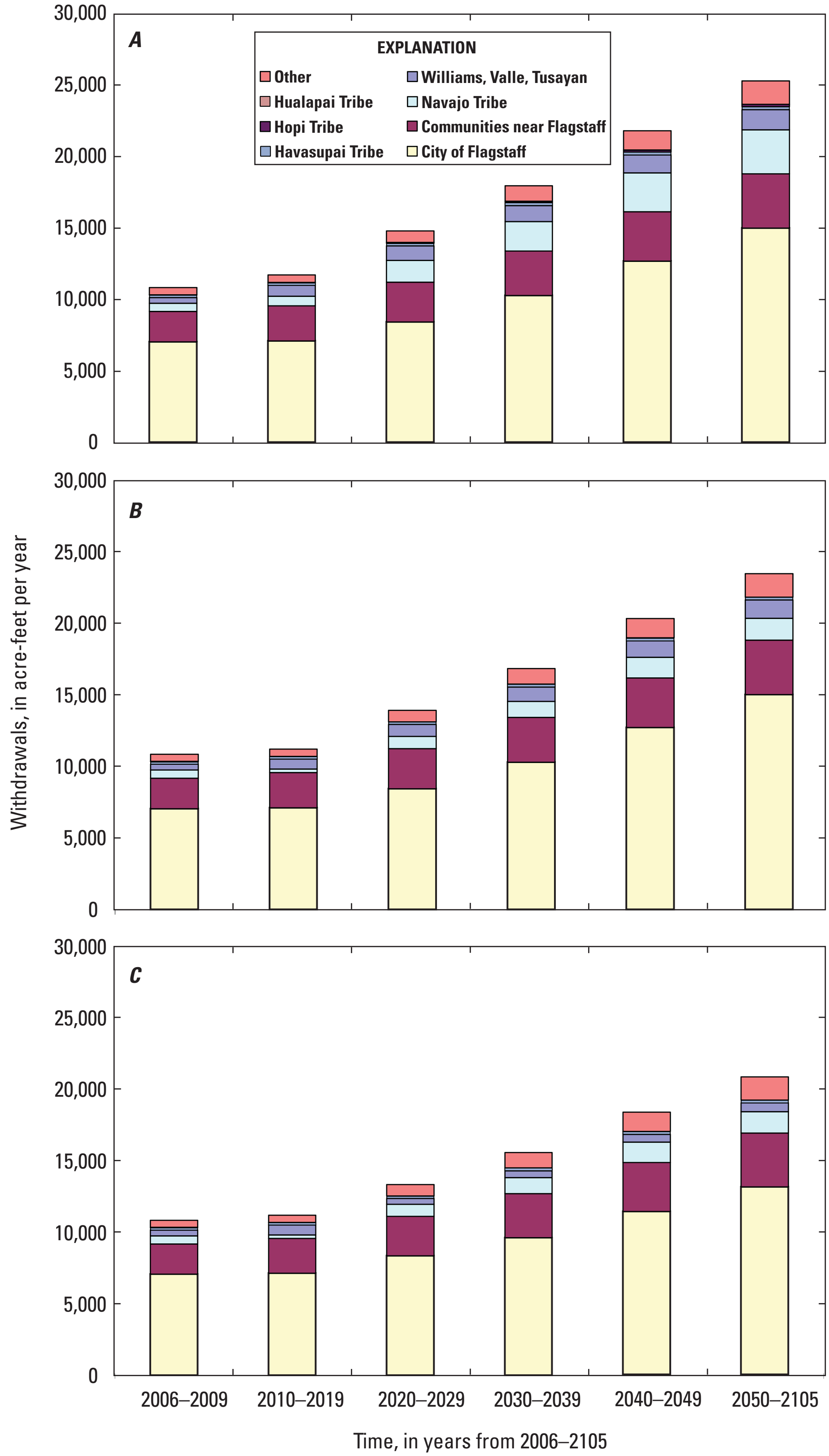


Figure 3. Graphs of projected groundwater withdrawals by major water users for future withdrawal scenarios. (*A*) Scenario 1, (*B*) Scenario 2, and (*C*) Scenario 3.

Coconino and Redwall-Muav aquifers and overlying locally extensive volcanic rock aquifers that likely discharge to the underlying regional aquifers. Most of the wells, from which groundwater withdrawal for each scenario would be derived, lie within two groundwater basins defined by the Arizona Department of Water Resources (ADWR)—the Coconino Plateau basin and the Little Colorado River Plateau basin. Some of the wells lie within the Verde Valley subbasin. Parts of Coconino County that were not included in the scenarios as demand areas are near Sedona in the Verde Valley subbasin, on the Mogollon Rim areas in eastern and southeastern parts of the County, and the Kaibab Plateau north of the Grand Canyon.

In addition to the withdrawal scenarios for the CPWAC area, non-CPWAC area groundwater withdrawals and related incidental recharge also need to be included in the simulations. For each of the three scenarios, non-CPWAC groundwater withdrawals were assumed to remain unchanged from the rates simulated during the final NARGFM stress period, 2000–05. This assumption recognizes that past and future non-CPWAC withdrawals will have future effects on the hydrologic features of interest in the CPWAC area, and simulates the effects of those withdrawals and incidental recharge. This assumption also facilitates the evaluation of groundwater management practices within the CPWAC area separate from change caused by practices outside of the area of interest.

The intent of the scenario simulations is to evaluate changes in water levels in the regional aquifers and changes in groundwater discharge to streams and springs that may result from possible future variations in groundwater withdrawals in the CPWAC area. Future changes, however, will also result from past and future variations in recharge rates and groundwater withdrawals in areas both within and outside of the CPWAC area. These past changes that affect future change make the interpretation of the scenario results more complex. In order to simplify the scenario results, it was advantageous to eliminate the effects of past recharge variations from the analysis. Therefore, the effects of past recharge variations are eliminated from this analysis by simulating pre-2006 conditions using an average-annual recharge rate and using those 2005 ending conditions as the initial conditions for the scenarios. Additional scenarios other than those simulated, would be required to evaluate the post-2005 changes that result from pre-2006 variations in withdrawals and recharge throughout the model area, future variations in withdrawal rates outside of the CPWAC area, and the effects of future variations in recharge rates.

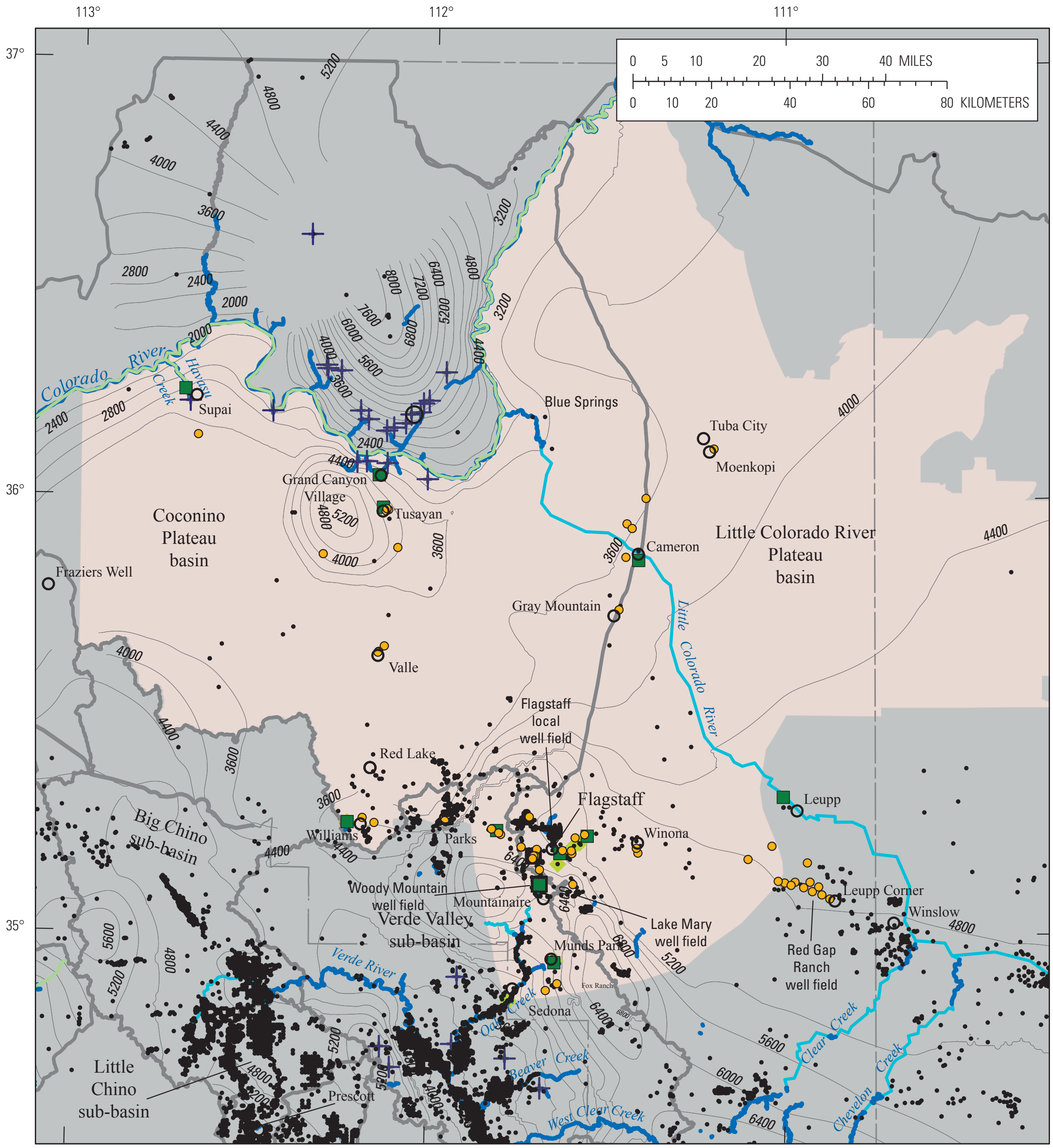
Change resulting from variations in groundwater withdrawals and incidental recharge for both past conditions and future variations in each CPWAC scenario is determined by comparing the changes in water levels and groundwater discharge resulting from each scenario. This type of analysis requires an assumption of a linear system response in the area of interest throughout the simulation for each of the scenarios. Nonlinear changes that may occur include significant changes in the saturated thickness of aquifers and changes in discharge to surface features such as streams, springs, and riparian vegetation. This assumption is likely valid for the CPWAC area because the rates of groundwater withdrawals in the area are a small fraction of the overall water budget or recharge rates. This assumption would not likely be true for some local parts of the NARGFM where withdrawal rates are large in comparison to local groundwater budgets such as in the Little Chino. The CPWAC is most interested in the possible effects of groundwater withdrawals for each scenario during the time period through 2105.

Water Uses

Water use from wells that draw from the Redwall-Muav and Coconino aquifers in the CPWAC scenarios is categorized as tribal and nontribal. Annual tribal withdrawals from these aquifers were less than 10 percent of the nontribal withdrawals prior to 2010. The scenarios anticipate that annual withdrawals by the tribes will increase faster than the nontribal withdrawals during 2010–50, but will remain less than 20 percent of nontribal annual withdrawals.

The largest pre-2010 tribal uses derived from the Redwall-Muav and Coconino aquifers primarily include groundwater withdrawals of a few hundred acre-feet per year (ac-ft/yr) from the Coconino aquifer for the Navajo Tribe in areas near Leupp, Cameron, Bodeway, and at Twin Arrows Casino west of the City of Winslow. Other pre-2010 tribal uses include less than 200 ac-ft/yr from the Redwall-Muav aquifer for the Havasupai Tribe in the western part of the Coconino Plateau and less than 10 ac-ft/yr from nonregional aquifers for the Hualapai Tribe in the western part of the Coconino Plateau. The scenarios anticipate the most potential growth, more than 3,000 ac-ft/yr by 2050, in tribal withdrawals from the Coconino aquifer in the area to the south of Leupp, on the Navajo Nation. Other tribal withdrawals from the Redwall-Muav and Coconino aquifers are anticipated to increase to about 205 ac-ft/yr by 2050. New wells are also anticipated to tap the Redwall-Muav aquifer for the Havasupai Tribe, increasing use to 25 ac-ft/yr, and the Hualapai Tribe, increasing use to 10 ac-ft/yr. Pre-2010 groundwater supplies for the Hopi Tribe were primarily derived from the Navajo aquifer, which is not simulated in the NARGFM. However, a new well is anticipated to derive as much as 170 ac-ft/yr from the Coconino aquifer near Moenkopi for Hopi Tribe use.

The largest users of groundwater from the Coconino and Redwall-Muav aquifers in the scenario area are nontribal. Several thousand acre-feet per year are withdrawn for use by the City of Flagstaff and several water companies near Flagstaff, the City of Williams, and other communities including Tusayan, Valle, and Grand Canyon Village. The City of Flagstaff withdraws the greatest amount of groundwater in the area and derives its supply mostly from the Coconino aquifer in the Woody Mountain well field, Lake Mary well field, and local wells within the city limits, which is known as the Local well field (fig. 4). Groundwater is also withdrawn by Flagstaff from



County boundaries of the United States, USGS 2000 National Atlas, 1:2,000,000-scale resolution, 2002, USGS; Towns from USGS Geographic Names Information System, 1981. Coordinate System: NAD 1927 UTM Zone 12N. Projection: Transverse Mercator. Datum: North American 1927. False Easting: 500,000.0000. False Northing: 0.0000. Central meridian: -111.0000. Scale factor: 0.9996. Latitude of origin: 0.0000. Units: meters

Perennial streams from Arizona Department of Water Quality, 2015, scale 1:100,000; Groundwater basin and sub-basin boundaries from Arizona Department of Water Resources, 2008, scale 1:100,000; Faults and folds from USGS SIR 2010–5180

EXPLANATION

- Town or landmark
- Post-2005 wells added for CPWAC Scenarios
- Simulated incidental recharge at WWTFs
- Simulated incidental recharge at golf course
- Well included in NARGFM and CPWAC Scenarios
- Coconino County boundary
- Coconino Plateau Partnership area
- Spring simulated using the MODFLOW Drain Package (DRN)
- 2006 water-level altitude in uppermost model layer, contour interval = 400 feet
- Stream simulated using the MODFLOW Drain Package (DRN)
- Stream simulated using the MODFLOW Stream Package (STR)
- Perennial streams
- Groundwater basin and subbasin boundary

Figure 4. Map of the generalized groundwater-flow system initial conditions, including existing and projected withdrawal wells and the Arizona Department of Water Resources (ADWR) groundwater basins in the region of the Coconino Plateau Water Advisory Council (CPWAC) groundwater withdrawal scenarios. WWTF, waste-water treament facility.

Table 1. Withdrawal wells that were not included in the original Northern Arizona Regional Groundwater Flow Model, installed after about 2005, and wells projected to be installed from 2006 through 2050.

[Well locations are in North American Datum of 1927 coordinate system, in both Universal Transmercator (UTM) Zone 12 coordinates (meters) and geographic coordinates of latitude and longitude (degrees, minutes, and seconds)].

Well name	UTM Easting	UTM Northing	Latitude	Longitude	Model layer
A-1 Mountain Sub-1 deep	432502	3895252	35° 11' 59.21" N	111° 44' 29.30" W	2
Anasazi Water Co.	398755	3981129	35° 58' 16.08" N	112° 07' 22.42" W	3
Bellmont Flagstaff Meadows	427261	3898447	35° 13' 41.60" N	111° 47' 57.57" W	2
Bellmont A-22-05 36CCC shallow	424956	3899850	35° 14' 26.53" N	111° 49' 29.20" W	3
Bellmont A-22-05 36CCC deep	424956	3899851	35° 14' 26.56" N	111° 49' 29.20" W	3
Bellmont A-21-06 06CBA	426781	3898834	35° 13' 54.04" N	111° 48' 16.68" W	3
Bodaway/Gap	464329	3983982	36° 00' 05.25" N	111° 23' 44.81" W	1
Bodaway/Gap	459482	3977509	35° 56' 34.47" N	111° 26' 57.22" W	1
Cameron 1, NTUA wells	460796	3976325	35° 55' 56.23" N	111° 26' 04.56" W	1
Cameron 2, BIA wells	459194	3968986	35° 51' 57.79" N	111° 27' 07.14" W	1
Canyon Mine	401100	3971500	35° 53' 04.46" N	112° 05' 44.49" W	3
Cedar Valley Water Co. (3 wells)1	462246	3893699	35° 11' 14.41" N	111° 24' 52.82" W	2
Flagstaff Local well field (Dogpound)	445420	3893556	35° 11' 06.99" N	111° 35' 58.07" W	2
Flagstaff Local well field (I40tp)	443025	3894348	35° 11' 32.22" N	111° 37' 32.96" W	2
Flagstaff Local well field (Interchange)	446253	3897563	35° 13' 17.22" N	111° 35' 26.07" W	2
Flagstaff Local well field (Shop)	448675	3898375	35° 13' 44.03" N	111° 33' 50.45" W	2
Flagstaff Local well field(Fort Tuthill)	437162	3889464	35° 08' 52.42" N	111° 41' 23.44" W	2
Flagstaff Local well field(Stonehouse)	436453	3894641	35° 11' 40.30" N	111° 41' 52.89" W	2
Flagstaff Local well field(Sinagua)	445267	3894261	35° 11' 29.84" N	111° 36' 04.28" W	2
Flagstaff Lake Mary well field	445670	3885700	35° 06' 52.02" N	111° 35' 46.32" W	2
Flagstaff Ranch Golf Course 18	435691	3892397	35° 10' 27.29" N	111° 42' 22.40" W	2
Flagstaff Ranch Golf Course 6	436093	3893000	35° 10' 46.96" N	111° 42' 06.67" W	2
Flagstaff Ranch Golf Course 7	435691	3893000	35° 10' 46.87" N	111° 42' 22.57" W	2
Flagstaff Ranch Golf Course 8b	435389	3892296	35° 10' 23.94" N	111° 42' 34.31" W	2
Flagstaff Red Gap Ranch A-20-13 0 25CAA	507505	3884686	35° 06' 24.28" N	110° 55' 3.54" W	1
Flagstaff Red Gap Ranch A-20-13 0 22CDB	504091	3885888	35° 07' 03.37" N	110° 57' 18.38" W	1
Flagstaff Red Gap Ranch A-20-14 0 07CDB	508913	3889105	35° 08' 47.69" N	110° 54' 07.75" W	1
Flagstaff Red Gap Ranch A-20-13 23DBB	506102	3886279	35° 07' 16.02" N	110° 55' 58.91" W	1
Flagstaff Red Gap Ranch A-20-13 21CBA	502282	3886277	35° 07' 16.02" N	110° 58' 29.84" W	1
Flagstaff Red Gap Ranch A-20-13 19DBC	499649	3886078	35° 07' 09.57" N	111° 00' 13.86" W	2
Flagstaff Red Gap Ranch A-20-13 27ACC	504495	3884888	35° 06' 30.90" N	110° 57' 02.43" W	1
Flagstaff Red Gap Ranch A-20-14 31CAA	509118	3883064	35° 05' 31.57" N	110° 53' 59.88" W	1
Flagstaff Red Gap Ranch A-20-13 35AAA	506702	3883883	35° 05' 58.23" N	110° 55' 35.28" W	1

Table 1. Withdrawal wells that were not included in the original Northern Arizona Regional Groundwater Flow Model, installed after about 2005, and wells projected to be installed from 2006 through 2050.—Continued.

Well name	UTM Easting	UTM Northing	Latitude	Longitude	Model layer
Flagstaff Red Gap Ranch A-19-14 05ABD	511137	3882002	35° 04' 57.03" N	110° 52' 40.19" W	1
Flagstaff Red Gap Ranch A-20-12.5 13ACB	497998	3886506	35° 07' 23.45" N	111° 01' 19.09" W	2
Flagstaff Red Gap Ranch A-20-13 25ADA	508308	3885086	35° 06' 37.24" N	110° 54' 31.80" W	1
Flagstaff Red Gap Ranch A-20-13 29ABB	501283	3885485	35° 06' 50.31" N	110° 59' 09.31" W	2
Fort Valley Deep wells (2 wells)1	434568	3902920	35° 16' 08.61" N	111° 43' 09.80" W	2
Fox Ranch	441607	3860447	34° 53' 11.43" N	111° 38' 20.45" W	2
Fox Ranch	438647	3858713	34° 52' 14.53" N	111° 40' 16.57" W	2
Gray Mountain	457438	3955623	35° 44' 43.78" N	111° 28' 14.59" W	1
Hopi Tribe at Moenkopi	481648	3996540	36° 06' 54.58" N	111° 12' 14.09" W	1
Howard Mesa	382088	3969930	35° 52' 05.93" N	112° 18' 21.76" W	1
Hualapai Tribe	277150	3931987	35° 30' 29.74" N	113° 27' 25.69" W	3
Leupp PW-1A	490306	3892082	35°10’ 24.31’’ N	111° 06’23.26’’ W	1
Leupp PW-2B	496398	3895436	35° 12’ 13.32’’ N	111° 02’ 22.45’’ W	1
Leupp PW-3	505425	3891201	35° 09’ 55.84’’ N	110° 56’25.55’’ W	1
Parks Deep well	413022	3901950	35° 15' 31.22" N	111° 57' 22.13" W	3
Patch Karr	397644	3946454	35° 39' 30.36" N	112° 07' 50.78" W	3
Supai Hilltop well	350319	4000488	36° 08' 21.74" N	112° 39' 48.92" W	3
Tusayan 1	398149	3980826	35° 58' 06.02" N	112° 07' 46.47" W	3
Tusayan 2	398345	3981395	35° 58' 24.55" N	112° 07' 38.91" W	3
Valle 1	396215	3945062	35° 38' 44.64" N	112° 08' 46.96" W	3
Valle 2	396014	3944861	35° 38' 38.04" N	112° 08' 54.85" W	3
Winona Casino	461850	3894911	35° 11' 53.70" N	111° 25' 08.68" W	2
Williams A-22-02 28BAD	391995	3902794	35° 15' 51.24" N	112° 11' 14.52" W	3
Bearizona A-22-22 06BBA	395002	3901505	35° 15' 10.55" N	112° 09' 14.94" W	3

[1]More than a single well may be constructed in the vicinity of the site. The projected withdrawal rate from all wells, shown in appendixes 1–3, is simulated at a single well rather than multiple wells, which is unlikely to produce significantly different simulated results of regional water-level change or capture of nearby surface water features.

wells and springs that flow from glacial outwash and volcanic rocks within the inner basin of San Francisco Mountain. The scenarios anticipate that future City of Flagstaff groundwater supplies will continue to be derived from the same areas, but augmented with new wells that tap the Coconino aquifer within city limits and at the Red Gap Ranch well field about 10 miles west of Winslow. Total withdrawals by the City are currently capped at 9,913 ac-ft/yr from the existing sources based on an Adequate Water Supply Determination from ADWR (Erin Young, hydrologist, City of Flagstaff, written commun., 2014). Additional supplies from the new Red Gap well field will be capped at 8,000 ac-ft/yr by agreement with the Navajo Nation (Erin Young, hydrologist, City of Flagstaff, written commun., 2014). Maximum withdrawal rates for the City of Flagstaff for the scenarios are about 15,000 ac-ft/yr during 2051–2105, although as much as 16,500 ac-ft/yr may be withdrawn to meet the Designated Adequate Water Supply, a maximum annual withdrawal rate determined by the State of Arizona Department of Water Resources. Other communities near Flagstaff that use groundwater from the Coconino aquifer include Bellmont, Doney Park (including Timberline and Fernwood areas), Flagstaff Ranch, Forest Highlands, Kachina Village/Mountainaire, Winona, Coconino Estates, Munds Park, and Parks. Additional withdrawal wells are projected to be developed near many of these communities, at Fox Ranch south of Flagstaff, and near Cameron to the north of Flagstaff. The City of Williams is expected to develop new withdrawal wells in the Redwall-Muav aquifer. New withdrawal wells in the Redwall-Muav aquifer are also expected to be developed near the communities of Tusayan, Valle, Red Lake, and Gray Mountain. All nontribal water demands included in the CPWAC scenarios assume a 20 percent water conservation

(Bureau of Reclamation, 2006) over conditions prior to 2010 for the duration of the simulated period.

Many private wells withdraw small amounts of water for domestic and stock use throughout the scenario area. Most of these wells draw water from groundwater in volcanic rocks and other perched water-bearing zones. A few of these wells, however, do draw water from the Coconino aquifer. The withdrawal scenarios include estimates of future withdrawals for the private wells, but only at the wells existing in 2005. Total simulated withdrawal rates for these wells was about 500 ac-ft/yr during 2000–05 in the NARFGM model. The private well withdrawals are divided into three regions for the scenarios, including the corridor between Flagstaff and Williams, the corridor between Williams and Grand Canyon National Park, and all remaining areas. About 50 percent of these well withdrawals are in the Flagstaff to Williams corridor and about 25 percent of the withdrawals are in each of the other two areas.

Scenario 1

Scenario 1 assumes that all water demand will be met by continuing individual, tribal, and municipal groundwater development and that there will be no regional water project to bring a combination of surface-water and groundwater resources to meet water use demands in the CPWAC region by 2050. Scenario 1 has the most groundwater withdrawals of the three scenarios as withdrawals for each major groundwater user or group of users are projected to increase throughout the scenario. Total groundwater withdrawals from the Redwall-Muav and Coconino aquifers within the CPWAC region for scenario 1 increase from about 10,800 ac-ft/yr during 2006–10 to about 25,300 ac-ft/yr beginning in 2050 (fig. 3*A*, appendix 1). Not included in the scenario are about 7,400 ac-ft/yr of groundwater withdrawals from the N aquifer for tribal use.

Under this scenario the tribal demand for water will grow to a rate of 160 gallons per day per capita as tribal communities improve their infrastructure. Most of this new demand will be met by development of existing and new Coconino aquifer wells in the Leupp area. New Coconino aquifer wells will also be drilled in the area of Moenkopi. Other tribal demands for groundwater in the western part of the model domain for the Hualapai and Havasupai Tribes will be minor and developed from the Redwall-Muav aquifer. Withdrawals from the Coconino aquifer near Cameron and Bodaway for the Navajo Tribe are projected to increase during 2010–50 from about 170 to 750 ac-ft/yr and 200 to 820 ac-ft/yr, respectively. Navajo Tribe withdrawals from the Coconino aquifer at and near Leupp are projected to increase from about 200 to 1,000 ac-ft/yr for the same period with the addition of several new wells. Withdrawals for the Hopi Tribe are projected to begin from the Coconino aquifer near Moenkopi before 2020 at a rate of about 30 ac-ft/yr and increase to 170 ac-ft/yr in 2050. Havasupai Tribe withdrawals from the Redwall-Muav aquifer near the western margin of the NARGFM region are projected to increase only slightly, from about 170 ac-ft/yr before 2010 to 200 ac-ft/yr in 2050. Hualapai Tribe withdrawals from the Redwall-Muav aquifer near the western margin of the NARGFM region are projected to increase slightly to only about 10 ac-ft/yr by 2050.

Nontribal demand for water will occur mostly in Flagstaff and in surrounding areas including the Williams, Valle, and Tusayan areas, the region between Winslow and Leupp, and as far south as Munds Park (fig. 1). The City of Flagstaff will continue to develop new wells in the inner city area, including the Local well field, and at Red Gap Ranch, which could be supplying water to the city by 2020. Groundwater development for projected nontribal water demands in the Williams, Valle, and Tusayan areas will come from the Redwall-Muav aquifer. The City of Williams is capped at development of 700 ac-ft/yr from its existing wells in the Redwall-Muav aquifer south of Williams by an agreement with ADWR (Dennis Wells, Williams City Manager, oral commun., 2007). That limit is projected to be nearly attained at 675 ac-ft/yr by about 2050. Additional demands on the Redwall-Muav aquifer in the region between Williams and Grand Canyon are dependent on if, and how, Grand Canyon National Park resolves its maintenance and (or) replacement issues with the trans-canyon pipeline that delivers water from Roaring Springs on the north rim to the south rim, and future development at Tusayan and Valle.

Most of the projected increases in nontribal withdrawals occur in the vicinity of Flagstaff and nearby communities. City of Flagstaff withdrawals, including withdrawals at Red Gap Ranch, increase from about 7,000 ac-ft/yr before 2010 to about 15,000 ac-ft/yr in 2050. Flagstaff withdrawals are distributed among the existing wells at the Woody Mountain, Lake Mary, and Local well fields, the inner basin area of San Francisco Mountain, and new wells at Red Gap Ranch. Reduced withdrawals at the Lake Mary well field of about 900 ac-ft/yr in 2010 are partly replaced by increases in withdrawals from the Local well field. Increases in City of Flagstaff withdrawals after 2019 will be sourced from wells at the Woody Mountain, Local, and Red Gap Ranch well fields, including increases of about 1,300, 2,300, and 4,300 ac-ft/yr, respectively, by 2050. Withdrawals for several other communities near Flagstaff are projected to increase from about 2,100 ac-ft/yr before 2010 to about 3,800 ac-ft/yr in 2050. Withdrawals from stock, domestic, and small industrial wells are projected to increase from about 500 to 1,600 ac-ft/yr by 2050, with about 50 percent of the increase occurring in the region between Flagstaff and Williams.

Scenario 2

Scenario 2 assumes that the proposed Western Navajo Pipeline will provide a source of surface water from Lake Powell to the communities of Cameron, Tuba City, and

Moenkopi, and all nontribal water demands will continue to be met by groundwater development. Under this scenario, there will be limited groundwater development of the Coconino aquifer in the Leupp area to meet projected local demands. Projected nontribal demands for water will be met by development of groundwater from the Coconino aquifer and the Redwall-Muav aquifer as described in scenario 1.

Total groundwater withdrawals from the Redwall-Muav and Coconino aquifers within the CPWAC region for scenario 2 increase from about 10,800 ac-ft/yr during 2006–10 to about 23,400 ac-ft/yr during 2050–2105 (fig. 3*B*, appendix 2). Withdrawals for major groundwater users or group of users increase throughout the scenario with the exception of use by the Navajo and Hopi Tribes, which increase at much reduced rates in comparison to scenario 1 because of the elimination of groundwater withdrawals for tribal use from the Coconino aquifer near Cameron and Moenkopi. Similar to scenario 1, most increases in groundwater withdrawals for scenario 2 result from increases in Flagstaff and nearby community withdrawals. Withdrawals from stock, domestic, and small industrial wells are projected to increase to 1,600 ac-ft/yr, as was assumed for scenario 1. Overall groundwater withdrawals for scenario 2 during 2050–2105 are about 1,900 ac-ft/yr less than those in scenario 1.

Scenario 3

Scenario 3 assumes that there will be a partnership between the tribal and nontribal interests on the Coconino Plateau that make it possible to extend a part of the proposed Western Navajo Pipeline onto the Coconino Plateau to supply projected unmet demands for water in this area by 2050. As part of an appraisal study by the Bureau of Reclamation for the CPWAC, the projected unmet demands for nontribal water on the Coconino Plateau were about 15,800 ac-ft/yr (Bureau of Reclamation, 2006). All other nontribal water demands will continue to be met by groundwater development in the Coconino and Redwall-Muav aquifers.

Total groundwater withdrawals from the Redwall-Muav and Coconino aquifers within the CPWAC region for scenario 3 increase from about 10,800 ac-ft/yr during 2006–09 to about 20,900 ac-ft/yr during 2050–2105 (fig. 3*C*, appendix 3). Withdrawals for major groundwater users or group of users increase throughout the scenario, but at rates that are much reduced in comparison to scenario 1. Similar to scenarios 1 and 2, most of increases in groundwater withdrawals for scenario 3 result from increases in Flagstaff and nearby communities. The reduced rates of groundwater withdrawals to nontribal users would be offset by imported surface water. All of the reduced withdrawals relative to scenario 2 are because of reduced groundwater withdrawals for the Cities of Flagstaff and Williams after 2019. City of Flagstaff withdrawals are reduced over scenarios 1 and 2 by maintaining withdrawal rates at the Local well field at 2020 rates of 2,500 ac-ft/yr during 2030–2105 rather than the greater rates for scenarios 1 and 2. City of Williams withdrawals are eliminated after 2019. Groundwater withdrawals by all private domestic, stock, and industrial wells are unchanged from scenarios 1 and 2. Overall groundwater withdrawals for scenario 3 during 2050 through 2105 are about 4,300 ac-ft/yr less than those in scenario 1.

Additional Scenario Assumptions

A few additional assumptions were required to complete each of the groundwater withdrawal scenarios. Assumptions were applied regarding distributions of withdrawals by small private and stock wells and wells not considered in the scenarios (outside of the CPWAC area of concern); rates of natural, artificial, and incidental recharge; and how to treat loss of withdrawals that occur as a result of model cells that dry during the simulations. Withdrawals from aquifers not included in the NARGFM were not considered in the scenarios. This exclusion primarily included withdrawals from the Navajo aquifer and overlying aquifers in the Black Mesa area. Wells that withdraw water from local perched aquifers, such as in volcanic rocks that overlie the regional Coconino and Redwall-Muav aquifers, were not explicitly simulated in NARGFM. However, these local shallow aquifers were implicitly simulated by assuming discharge from them likely flows into the underlying regional aquifers, and that withdrawals from the shallow aquifers remove water that would otherwise recharge the regional aquifers. Withdrawals from shallow perched aquifers that overlie and discharge to the regional aquifers were therefore included in the scenarios as withdrawals from the regional aquifers.

Small Private and Stock Well Withdrawals

Withdrawals from most small private and stock wells were assumed to vary in the future according to the scenario withdrawal category “Other domestic, stock and small industrial groundwater” (appendixes 1–3). Several additional tribal and private wells were anticipated by CPWAC to be added to this withdrawal category after 2005 (table 1) and were assigned the withdrawal rates for the category “Other domestic, stock and small industrial groundwater”. Additional private wells were included in the simulations for the Canyon Mine located between Valle and Tusayan (fig. 4) and Bearizona Wildlife Park near Williams (appendixes 1–3). The uses of an estimated 44 ac-ft of groundwater withdrawals from the Redwall-Muav aquifer at the Canyon Mine are for the construction of the mine shaft during 2013–16, mining during 2016–22, and reclamation activities during 2023–25. Groundwater use at this site is scheduled to return to zero after 2029. Annual groundwater withdrawals at Bearizona Wildlife Park are estimated as about 120 ac-ft/yr beginning with a well drilled in 2015.

Natural Recharge Rates

Natural recharge rates for the three simulated groundwater withdrawal scenarios are assumed to occur at a constant rate that is equivalent to average-annual rates of natural recharge simulated in NARGFM. Average recharge rates applied to NARGFM were derived from the modified Basin Characterization Model (BCM; Flint and Flint, 2008), which estimates direct monthly recharge that is calculated as the remainder of precipitation after accounting for runoff, evaporation, vegetation requirements, and retention of moisture by soils. The BCM estimates used in NARGFM were modified to include additional recharge through ephemeral channels in alluvial basins that are outside of the area of the CPWAC scenarios. No modifications of BCM recharge estimates were made in the area of the CPWAC scenarios.

Incidental Recharge Rates

Additional assumptions were made regarding projected rates of incidental recharge within and outside of the CPWAC scenario region. Incidental recharge occurs as a result of excess irrigation of golf courses and agricultural fields, and effluent discharged from waste-water treatment facilities (WWTF). This assumption is consistent with the assumed groundwater withdrawal rates outside of the CPWAC area that were previously discussed. For all sources of incidental recharge outside of the CPWAC scenario region, simulated rates of incidental recharge for the period 2000–05 were projected to remain at 2000–05 rates throughout the period of the scenario simulations. Incidental recharge from excess irrigation of golf courses and agriculture within the CPWAC scenario area was assumed to occur during the scenarios at the same rate and locations that it occurred during the 2000–05 NARGFM simulation period. Incidental recharge from discharge of effluent at 13 WWTFs were simulated in the scenarios (table 2). Six of the WWTFs were simulated in the original NARGFM including Munds Park, Kachina Village, City of Williams, Supai Village, and two City of Flagstaff facilities—Rio de Flag and Wildcat Hill (table 2). For the scenario simulations, incidental recharge from an additional 7 WWTFs were included in the scenario simulations including Forest Highland, Flagstaff Ranch, Flagstaff Meadows at Bellmont, Cameron, Leupp, Tusayan, and Grand Canyon Village. These additional WWTFs were not included in the original NARGFM simulations because either the estimated incidental recharge rate for each facility was estimated at less than 50 ac-ft/yr or the facilities did not exist before 2005. Other WWTFs within the CPWAC scenario area at Tuba City and Moenkopi were not simulated because effluent from these facilities is discharged to channels that flow over outcrops of Mesozoic aquifers and confining units that are hydraulically separated from the simulated aquifers and greatly limit any recharge to the simulated aquifers.

Incidental recharge from the WWTFs was assumed to remain as a constant percentage of water demand for each community throughout the simulation period for each scenario (table 2). Water demand and incidental recharge at two facilities, Grand Canyon Village and Forest Highlands, was assumed to remain unchanged through the scenario period. Demand and incidental recharge for the other 11 facilities was assumed to increase with projected demand. Total estimated incidental recharge of wastewater effluent increases from about 5,700 ac-ft/yr during 2006–09 to about 13,000 ac-ft/yr during 2050–2105. Most incidental recharge from wastewater effluent is estimated to occur near the two City of Flagstaff facilities, Rio De Flag and Wildcat Hill, which account for about 80 percent of the total estimated effluent recharge within the CPWAC area throughout the scenario simulation period. Estimated incidental recharge near the City of Flagstaff facilities increases from about 4,900 ac-ft/yr during 2006–09 to about 10,700 ac-ft/yr during 2050–2105. In comparison, total estimated incidental recharge near the other 11 facilities increases from about 900 ac-ft/yr to about 2,400 ac-ft/yr over the same period.

Drying of Model Cells During the Scenario Simulations

Drying of model cells that include well withdrawals outside of the scenario area was allowed to occur, resulting in some areas where much of the withdrawals were eliminated during the scenarios. Fortunately, the withdrawal losses did not cause variations in the simulation results within the area of CPWAC scenarios because the losses were outside of the CPWAC area and common in rate and location for each scenario.

Distributions of some withdrawals within the scenario area were modified from the pre-2006 simulation for the purpose of preventing drying of the pumped model cell and allowing retention of the projected withdrawals throughout the period of the simulation, including the locations of withdrawals at several wells near the Woody Mountain and Lake Mary well fields. Modifications included redistribution of the withdrawals to include deeper layers, and lateral translation of wells to spread the collective cone of depression resulting from a concentrated area of well withdrawals. Withdrawals from all wells at the Woody Mountain well field were expanded from only model layer 2 (lower part of the Coconino aquifer) to include model layer 3 (Redwall-Muav aquifer). Well locations at the Woody Mountain well field were moved as much as 1.5 miles laterally to reduce the concentration of pumping in single model cells. Withdrawals from two wells at the Lake Mary well field were expanded from only model layer 2 to include model layer 3. Withdrawals from several wells outside of the CPWAC scenario area near Holbrook were also relocated to maintain withdrawal rates near the area of CPWAC concern; some were moved as much as 1 mile laterally to reduce the concentration of pumping. Withdrawal distributions at a few wells near Holbrook were expanded from only model layer 1 to include model layers 2 and 3. As

Table 2. Projected and simulated incidental recharge rates at waste-water treament facilities in the Coconino Plateau Water Advisory Council Scenario region for three groundwater withdrawal scenarios.

[Values are in acre-feet per year]

Waste-water treatment facility[1]	Community served[1]	Simulated incidental recharge rate, 2000-2005	Incidental recharge rate as a percent of groundwater demand served[3]	Simulated incidental recharge rate scenarios 1, 2, and 3					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Munds Park Waste-Water Treatment Plant	Munds Park	80	24	24	52	80	108	137	165
Kachina Village Waste-Water Treatment Facility	Kachina Village	213	62	110	220	228	235	243	249
Rio De Flag Waste-Water Treatment Plant	Flagstaff	5,028	50	3,894	4,650	5,306	6,225	7,429	8,573
Wildcat Hill Waste-Water Treatment Plant	Flagstaff	1,239	12	959	1,145	1,307	1,533	1,830	2,112
City of Williams Waste-Water Treatment Plant	Williams	455	49	181	203	226	248	271	292
Supai Village Sewer System	Supai Village	45	26	45	46	46	53	53	53
Forest Highlands Waste-Water Treatment Plant	Forest Highlands	NA[2]	13	72	72	72	72	72	72
Flagstaff Ranch Waste-Water Treatment Plant	Flagstaff Ranch	NA[2]	64	64	80	80	72	64	64
Flagstaff Meadows at Bellmont	Flagstaff Meadows	NA[2]	80	40	68	72	80	100	120
Cameron Waste-Water Treatment Plant	Cameron	NA[2]	18	35	41	66	87	113	146
Leupp Waste-Water Treatment Plant	Leupp	NA[2]	50	100	388	510	632	753	875
Tusayan Waste-Water Treatment Plant	Tusayan	NA[2]	32	24	72	88	104	121	137
Grand Canyon South Rim Waste-Water Treatment Plant	Grand Canyon South Rim	NA[2]	0	186	186	186	186	186	186
Total simulated incidental recharge from waste-water treatment facilities				5,734	7,224	8,267	9,634	11,370	13,042

[1]Additional waste-water treament facilities in Coconino County were not simulated including Moenkopi and Tuba City. Effluent from these facilties is discharged to stream channels that cross the Chinle and Moenkopi Formations, which are assumed an impermeable upper boundary and confining bed for the Northern Arizona Regional Groundwater Flow Model (NARGFM).

[2]Incidental recharge from waste-water effluent was not included in the original NARGFM for these facilities.

[3]Incidental recharge rate as a percent of groundwater demand served is calculated for each facility based on NARGFM simulated rates of recharge and withdrawals during 2000 to 2005 or the most recent reported facility discharge and withdrawals for facilities that were not simulated in the original NARGFM.

a result of the modified distribution of withdrawals, no cells went dry and no withdrawals were lost from the simulation in the area of interest.

Simulated Effects of Withdrawal Scenarios

The simulated effects of the three groundwater withdrawal scenarios are superimposed on the effects of previously simulated changes to the groundwater-flow system that have resulted from variations in groundwater withdrawals and artificial and incidental recharge in the original NARGFM. Effects of the variations include changes in water-levels in wells, groundwater storage, discharge to streams and springs, and ET by plants that use groundwater. Variations in recharge rates were also simulated in the published version of NARGFM (Pool and others, 2011). However, past and possible future recharge variations were not simulated for this analysis because those variations result in much greater change than the variations in the scenarios. A constant rate of average annual-recharge, equivalent to the average recharge during 1940–2005, was simulated for the scenarios. Eliminating recharge variations allows the analysis to focus on the effects of only past variations in withdrawals and incidental recharge and the scenario variations in withdrawals.

Simulation of the scenarios were completed for the period 2006 through 2105 using 10 time steps within 6 stress periods. Pre-2050 stress periods included the 5-year period 2006 through 2009 followed by periods of decade length during 2010 through 2049. Simulation of conditions through 2105 result in only a part of the changes that will occur before a new steady-state groundwater-flow system is attained in the future. If no additional simulated changes in groundwater withdrawal and recharge were too occur after 2105, the groundwater-flow system would eventually reach a new steady-state condition of reduced but constant storage, and reduced discharge to streams, springs, and ET. However, changes that may occur after 2105 are not addressed in this analysis.

Initial Conditions for the Scenarios

The groundwater-flow system simulated by a modified version of the NARGFM at the beginning of 2006 represents initial conditions for simulations of the three withdrawal scenarios (fig. 3). Specifically, the simulated hydraulic heads throughout the model at the end of 2005 are used as the initial hydraulic heads for the scenarios. Modifications to the published NARGFM included simulation of average-annual recharge rates rather than variable recharge rates, and redistribution of withdrawals at the Woody Mountain well field across a slightly greater area for the purpose of maintaining saturated conditions in the uppermost model layer through the scenario period to 2105. The groundwater-flow system at the beginning of 2006 was in a state of change resulting from previous variations in groundwater withdrawals and artificial and incidental recharge. While change had occurred during the simulation of conditions during 1910–2005, the beginning and ending groundwater-flow systems were largely similar. Groundwater in the NARGFM area flows from areas of high rates of recharge in the high altitude areas of the White Mountains, Mogollon Rim, San Francisco Mountain, Defiance Uplift, and Kaibab Plateau toward the primary discharge areas along the major perennial streams including the Colorado, Little Colorado, Verde, and Salt Rivers. Groundwater also discharged to other perennial streams including Clear and Chevelon Creeks near the eastern border of Coconino County, Oak and Sycamore Creeks south of Flagstaff, streams and many springs near the Grand Canyon, and streams at the western extent of the NARGFM. Evapotranspiration of groundwater was minor in comparison to other water-budget components in the CPWAC region. Local cones of depression were established before 2006 in areas of concentrated groundwater withdrawal including the Woody Mountain and Lake Mary wells fields near Flagstaff.

Simulated groundwater budgets at the end of 2005 document the effect of simulated changes in the groundwater-flow system (table 3). Groundwater was being withdrawn from storage in all simulated groundwater basins in the NARGFM at the end of 2005. Rates of storage loss in basins that are partly within the CPWAC area include 85,000 ac-ft/yr in the Coconino Plateau basin, 54,000 ac-ft/yr in the Little Colorado River Plateau basin, and 39,000 ac-ft/yr in the Verde Valley subbasin. The storage loss occurred as a result of the effects of groundwater withdrawals and variations in artificial and incidental recharge before 2006. Storage losses that occurred in 2005 indicate that losses in groundwater discharge to streams and springs will occur after 2005 even if no further changes in withdrawals and recharge occur. These future declines in rates of net discharge to streams and springs in the NARGFM will be less than or equivalent to the simulated rate of storage loss in 2005. Eventually, given no future changes in withdrawals and recharge, a new steady-state groundwater-flow system will result and all of the rates of loss in storage will be replaced by reduced rates of discharge to streams and springs.

Rates of discharge to streams, springs, and ET that were simulated during 2005 will likely decrease during the simulated future withdrawal scenarios as a result of past withdrawals throughout the NARGFM. Reduced streamflow derived from groundwater may also result in greater infiltration of runoff; however, the NARGFM simulates only groundwater processes. Changes in discharge to streams and springs will occur within the groundwater basins that lie nearest to Coconino County including the Coconino Plateau and Little Colorado River Plateau basins and the Verde Valley subbasin. Simulated groundwater discharge in these basins occurs to the Blue Springs and the Lower Little Colorado River, Clear Creek, Chevelon Creek, the Colorado River, numerous springs above the Colorado River, Havasu Creek, and the Verde River and tributary streams including those nearest to the CPWAC

Table 3. Simulated groundwater-flow budgets at the end of 2005 for selected regions of the Northern Arizona Regional Groundwater-Flow Model from Pool and others (2011).

[Values are in acre-feet per year except for cumulative values, which are in acre-feet. N/A, not applicable]

		Verde River Basin groundwater-flow system							
Groundwater Basin	**Upper Agua Fria**	**Little Chino**	**Little Chino and Upper Agua Fria sub-basins**	**Big Chino**	**Big and Little Chino**	**Verde Valley sub-basin above the streamflow-gaging station near Clarkdale**	**Verde Valley sub-basin between the streamflow-gaging stations near Clarkdale and near Camp Verde**	**Verde Valley**	**Verde Canyon**
Arizona Department of Water Resources basin type	**sub-basin**	**sub-basin**	**Prescott Active Management Area**	**sub-basin**	**sub-basins**	**part of sub-basin**	**part of sub-basin**	**sub-basin**	**sub-basin**
Groundwater-budget component									
Inflow									
Natural recharge	1,300	1,800	3,100	31,200	33,000	22,500	46,100	68,600	26,400
Recharge from infiltration of streamflow derived from base flow[1a]	N/A	700	700	1,900	2,600	13,800	24,700	38,500	1,800
Incidental recharge[1b]	2,300	7,000	9,200	4,200	11,200	0	1,600	1,600	0
Groundwater inflow from adjacent areas[1c]	1,000	1,500	1,800	3,500	5,100	8,800	1,700	8,000	33,100
Total Inflow[1d]	4,600	11,000	14,800	40,800	51,800	45,100	74,000	116,700	61,300
Outflow									
Groundwater discharge to streams (base flow)[1e]	N/A	1,800	1,800	18,100	19,900	36,100	62,200	98,400	62,800
Discharge to streams and springs simulated as drains (base flow)[1f]	1,000	0	1,000	0	0	0	0	0	500
Evapotranspiration by phreatophytes[1g]	100	100	200	1,900	2,000	2,600	9,300	11,900	N/A
Groundwater withdrawals	6,400	17,800	24,200	11,200	28,900	200	2,010	19,500	1,600
Groundwater outflow to adjacent areas[1h]	0	2,600	1,800	26,900	29,500	14,900	13,400	25,800	11,400
Total Outflow[1i]	7,500	22,200	28,900	58,100	80,400	53,900	104,200	155,600	76,400
Net groundwater flow to (-) and from (+) adjacent basins[1j]	1,000	1,0002	0	23,4003	24,4003	-6,000	-11,800	-17,800	21,700
Net streamflow[1k]	N/A	1,100	1,100	16,200	17,300	22,300	37,6004	59,9004	61,000
Net rate of groundwater storage change	-2,900	-11,200	-14,100	-17,400	-28,600	-8,800	-30,200	-39,000	-15,200
Cumulative groundwater storage change since predevelopment	-117,100	-586,500	-703,600	116,700	-469,800	242,200	295,500	537,700	201,200

Table 3. Simulated groundwater-flow budgets at the end of 2005 for selected regions of the Northern Arizona Regional Groundwater-Flow Model from Pool and others (2011).—Continued.

	Colorado River Basin groundwater-flow system				Western basins groundwater-flow system				Salt River sub-basins groundwater-flow system		
Groundwater Basin	**Little Colorado**	**Coconino Plateau**	**Peach Springs**	**Kanab Plateau and adjacent areas**	**Burro Creek**	**Fort Rock (Trout Creek)**	**Truxton Wash**	**Western basins[1g]**	**Tonto Creek**	**Salt River Lakes**	**Salt River above the streamflow-gaging station at Roosevelt**
Arizona Department of Water Resources basin type	**basin**	**basin**	**Part of basin that lies outside of Truxton Wash watershed**	**several basins north of the Colorado River**	**sub-basin**	**sub-basin**	**Parts of Peach Springs basin and Wikieup sub-basin**	**simulated groundwater basin[1l]**	**basin**	**basin**	**Salt River Canyon, Black River, and White River sub-basins**
Groundwater-budget component											
Inflow											
Natural recharge	154,900	113,900	5,100	75,200	13,400	14,600	3,300	31,400	39,700	28,300	133,300
Recharge from infiltration of streamflow derived from base flow[1a]	13,100	300	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Incidental recharge[1b]	49,800	500	0	0	0	0	100	100	1,900	1,300	1,200
Groundwater inflow from adjacent areas[1c]	2,600	190,400	5,400	38,100	6,200	1,500	1,700	9,400	26,400	1,900	10,800
Total Inflow[1d]	220,300	305,100	10,500	113,300	19,700	16,100	5,100	40,900	67,900	31,500	145,200
Outflow											
Groundwater discharge to streams (base flow)[1e]	13,100	173,000	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Discharge to streams and springs simulated as drains (base flow)[1f]	300	160,700	7,600	135,900	25,800	13,300	2,900	42,000	84,100	43,200	203,200
Evapotranspiration by phreatophytes[1g]	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Groundwater withdrawals	81,700	800	0	0	400	0	100	500	1,100	1,300	600
Groundwater outflow to adjacent areas[1h]	210,400	25,100	4,900	9,000	0	9,700	3,300	13,000	2,700	200	0
Total Outflow[1i]	305,600	359,500	12,400	145,000	26,100	23,100	6,300	55,500	87,900	44,700	203,700
Net groundwater flow to (-) and from (+) adjacent basins[1j]	-207,900	165,300	600	29,100	6,200	-8,200	-1,600	-3,600	23,600	1,600	10,800
Net streamflow[1k]	0	172,700	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Net rate of groundwater storage change	-85,000	-54,000	-1,900	-31,800	-6,500	-6,900	-1,200	-14,600	-20,100	-13,200	-58,400
Cumulative groundwater storage change since predevelopment	669,500	1,275,100	70,800	1,021,000	130,600	156,700	37,900	325,200	322,400	326,600	1,205,600

1a-Includes the total of simulated streamflow infiltration; all of which is derived from discharge of groundwater to streams (simulated using the MODFLOW Streams Package (STR)) within the groundwater basin and in upgradient groundwater basins.

1b-Includes recharge resulting from excess applied irrigation water derived from surface water and groundwater supplies, discharge from waste-water treatment facilites, and golf courses.

1c- Includes components of groundwater inflow from multiple adjacent basins and sub-basins.

1d-Represents the sum of inflow components including groundwater flow from adjacent basins and reinfiltration and recharge of groundwater discharge to streams in the groundwater basin.

1e-Includes only discharge to streams simulated using the MODFLOW Streams Package (STR).

1f- Streams and springs simulated using the MODFLOW Drain Package (DRN).

1g- Evapotranspiration was simulated in only the Verde River Basin above the streamflow-gaging station near Camp Verde and in the Little Colorado River Basin.

1h- Includes components of groundwater outflow to multiple adjacent basins and sub-basins.

1i- Calculated as Total Inlow minus Total Outflow. Multiple areas of groundwater inflow and outflow may occur for any basin.

1j- Calculated as Groundwater Infow minus Groundwater Outflow.

1k- Calculated as Recharge from infiltration of streamflow derived from base flow minus Groundwater discharge to streams. Both components are simulated using the Streams Package (STR).

1l- Includes the sum of groundwater budget components for the Burro Creek and Fort Rock sub-basins and the parts of the Peach Springs Basin and Wikieup sub-basin within the Truxton Wash watershed.

2- Includes groundwater outflow of about 2,100 ac-ft per yr to the Big Chino sub-basin and inflow from portions of the Big Chino (about 1,000 ac-ft per yr) and Upper Agua Fria sub-basins.

3- Includes the balance of outflow of groundwater to adjacent basins and inflow from adjacent basins, primarily from the Little Chino sub-basin.

4- Does not include diversion of 34,600 acre-ft per year of base flow that is transpired by crops.

region, Sycamore Creek, Oak Creek, Beaver Creek, and West Clear Creek. Discharge to streams in the Little Colorado River Plateau basin—13,100 ac-ft/yr in 2005—primarily occurs along Clear, Chevelon, and Silver Creeks and along the upper reaches of the Little Colorado River. The discharge also infiltrates and recharges in downstream reaches of the stream network. As a result, both discharge and recharge along the streams in the Little Colorado River Plateau basin will change at equivalent rates during scenario simulations.

Scenario Simulation Results

Scenarios 1, 2, and 3 each result in a different set of simulated hydrologic changes within the modeled area. Change simulated by scenario 1 represents change that will occur due to projected increased demand for groundwater without management decisions to limit groundwater withdrawals, using water imported to the area through a proposed pipeline. Change simulated by scenarios 2 and 3 represents change resulting from the proposed pipeline and less groundwater withdrawals than simulated by scenario 1. Scenario 2 includes a limited extent of the pipeline to the Cameron area. Scenario 3 represents the greatest pipeline extent, maximum importation of water to the greatest area, and the least amount of simulated groundwater withdrawals. For this analysis of future water use scenarios developed by the CPWAC, comparisons of hydrologic changes resulting from the scenarios are made for only the region in and near the CPWAC scenario area. Differences in simulated water-level change in the primary aquifers are compared for conditions simulated at the end of 2105 for each scenario. Simulated changes in groundwater discharge to major perennial streams and springs resulting from each scenario are also discussed. The major streams and springs include Havasu Creek, the Colorado River, four simulated springs on the south rim of Grand Canyon, the lower reach of the Little Colorado River below Cameron including Blue Springs, Chevelon Creek, Clear Creek, Oak Creek, and the upper Verde River above the streamflow gaging station near Clarkdale.

Simulated Changes in Water Levels

Simulated water-level change during 2006–2105 in the CPWAC region is discussed for scenarios 1, 2, and 3. Scenario 1 water-level declines are the greatest of the three scenarios because it includes the assumption that no water would be imported to the region and groundwater withdrawals would continue to supply a large portion of the water demand for the area. As a result, scenario 1 includes the greatest increase in groundwater withdrawals. Scenario 1 water-level changes are treated as a baseline for comparison with water-level change resulting from scenarios 2 and 3, which include imported surface water and reduced groundwater withdrawals in the Cameron and Moenkopi areas for scenario 2, and extension of the imported surface water to the Flagstaff and Williams areas and associated reduced groundwater withdrawals for scenario 3.

Scenario 1

Simulated water-level change is dominated by declines of 1 to 5 ft across most of the CPWAC and adjacent areas for scenario 1 during 2006–2105 (fig. 5). Most of the larger changes occur in areas near major withdrawal wells and areas of incidental recharge at major wastewater treatment plants and facilities. In 2105, the simulation predicts water-level declines of more than 100 ft near the Woody Mountain and Lake Mary well fields and the towns of Tusayan and Parks. Maximum declines near Williams and Moenkopi are about 50 ft. Declines of 10 to 50 ft are simulated near other major withdrawal wells near Sedona, Munds Park, Winona, Leupp, and Red Gap Ranch. Water-level rises of more than 100 ft are simulated near the City of Flagstaff Waste-Water Treatment Plants at Wildcat Hill, Rio De Flag, and Grand Canyon Village. Water-level rises of 1 to 10 ft simulated near Clear and Chevelon Creeks result from pre-2006 changes in withdrawals or incidental recharge outside of the scenario area that were continued into the scenario period. Apparent water-level recovery resulted in resaturation of model cells during the scenario simulation in several areas including south of Williams, northwest of Tuba City, small areas near Clear and Chevelon Creeks, and small areas in Verde Valley. Most of the resaturated areas are at the margins of model layers where the layer is thinnest and susceptible to dewatering. Resaturation is caused by changes in well withdrawals and incidental recharge in the scenario relative to the original NARGFM at the end of 2005.

Scenarios 2 and 3

Importing water and eliminating major withdrawal wells after 2009 in the Cameron area resulted in less water-level decline and slightly higher water levels in scenario 2 compared to scenario 1 from 2006 to 2105 (fig. 6*A*). Less water-level decline was simulated and water levels for Scenario 2 were slightly higher than in Scenario 1 across nearly all of the scenario region. In the Cameron areas area, scenario 2 water levels were 1 to 5 ft higher than in scenario 1. Near Moenkopi, a small area of water levels are as much as 10 ft higher due to the elimination of a proposed withdrawal well that was simulated in scenario 1.

The effects of importing water beyond the Cameron area to Flagstaff and Williams and reducing groundwater withdrawals in the area during 2006 to 2105 are shown on a map of the difference in water-level change simulated by scenario 3 in comparison to scenario 1 (fig. 6*B*). Results near Cameron and Moenkopi are similar to scenario 2 because well withdrawals in those areas were similar for both scenarios 2 and 3 and less than in scenario 1. Water levels for scenario 3 are about 1 to 5 ft higher in comparison to scenario 1 across about one-half of the Coconino Plateau between Williams and the Colorado River. Water levels simulated near withdrawal wells in the

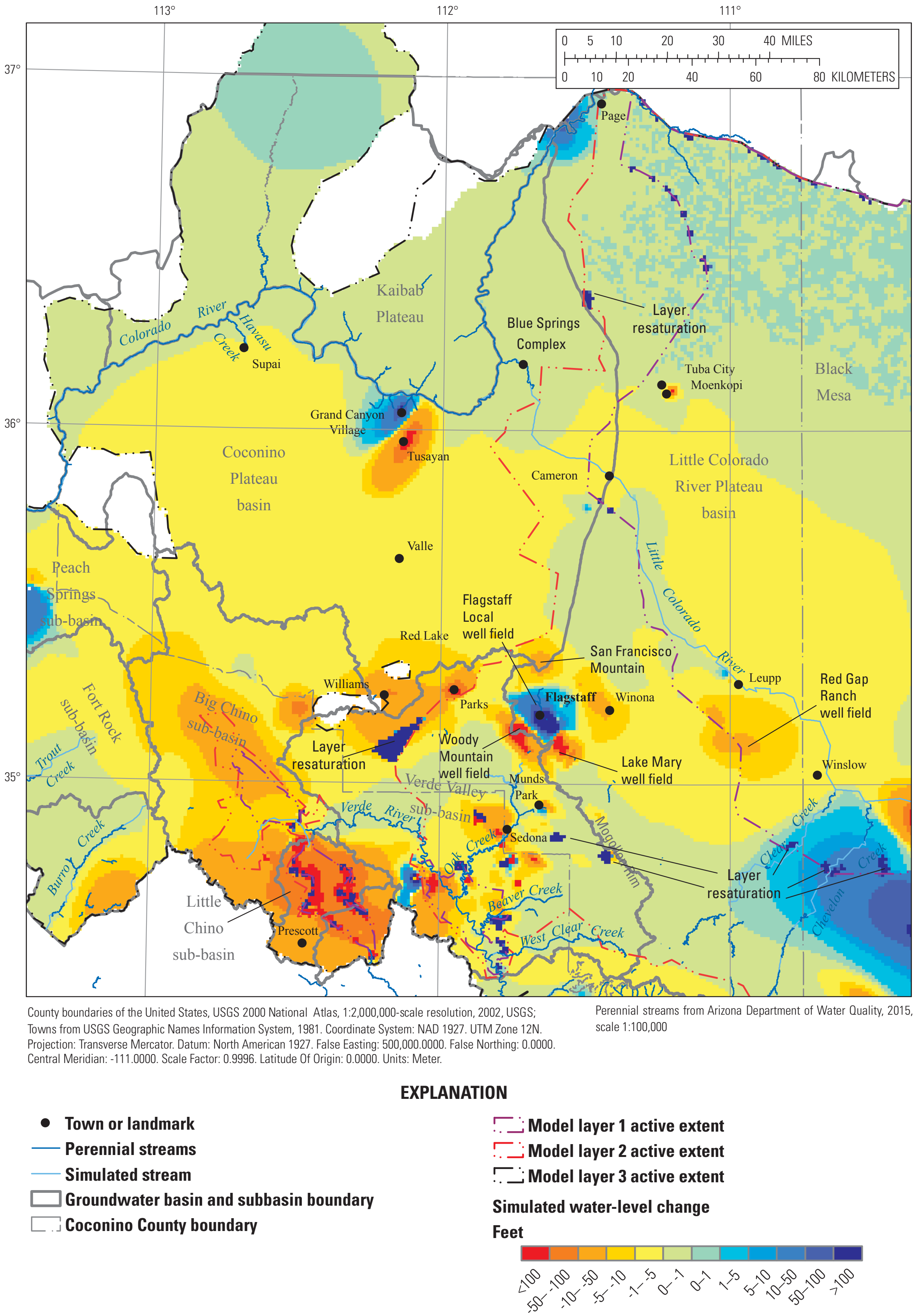
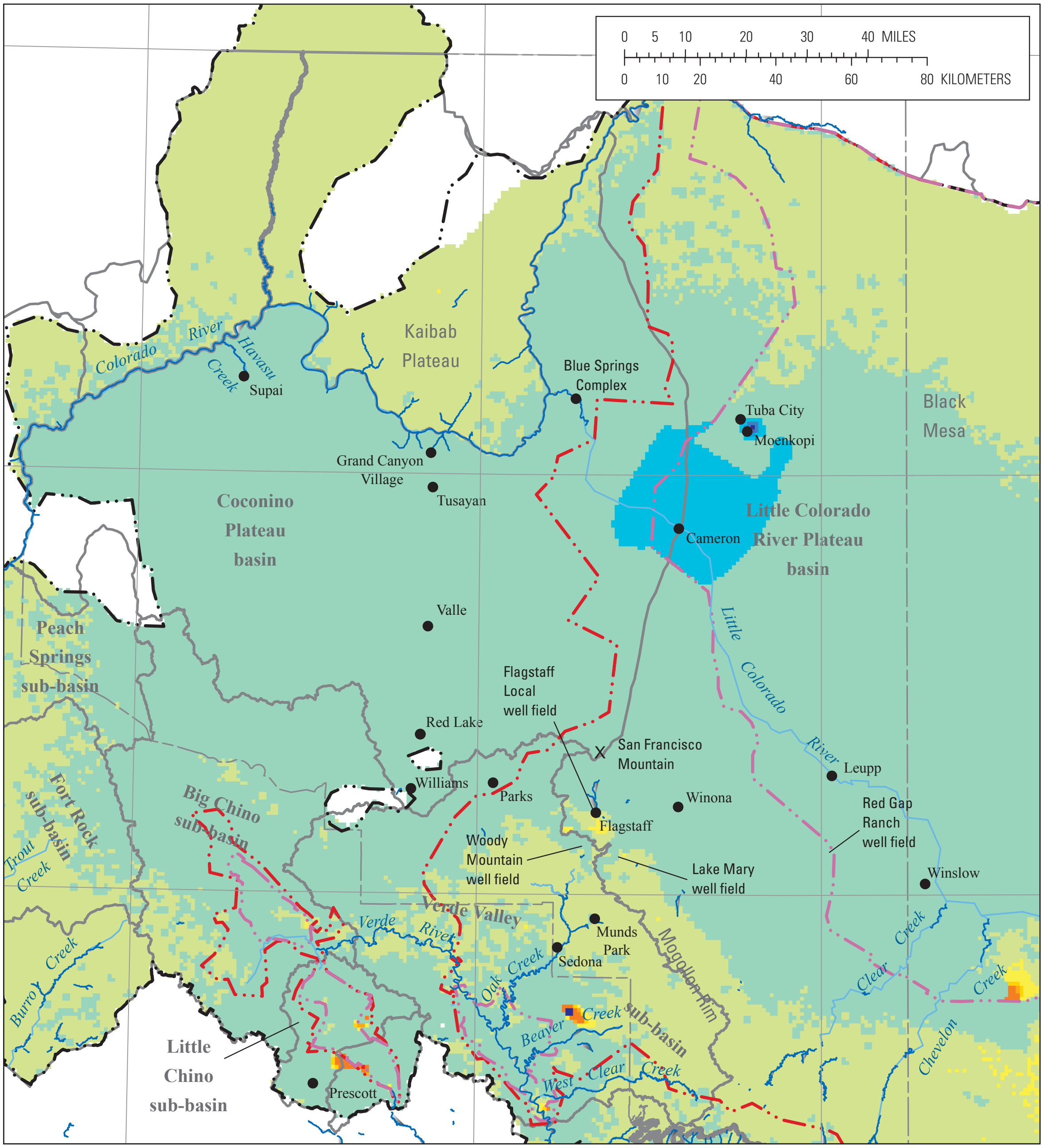


Figure 5. Map of water-level change for scenario 1 in the uppermost model layer from 2006 through 2105 near the Coconino Plateau Water Advisory Council scenario region and surrounding areas, Arizona. ADWR, Arizona Department of Water Resources.

A



County boundaries of the United States, USGS 2000 National Atlas, 1:2,000,000-scale resolution, 2002, USGS; Towns from USGS Geographic Names Information System, 1981. Coordinate System: NAD 1927 UTM Zone 12N. Projection: Transverse Mercator. Datum: North American 1927. False Easting: 500,000.0000. False Northing: 0.0000. Central Meridian: -111.0000. Scale Factor: 0.9996. Latitude Of Origin: 0.0000. Units: Meter

Perennial streams from Arizona Department of Water Quality, 2015, scale 1:100,000; Groundwater basin and sub-basin boundaries from Arizona Department of Water Resources, 2008, scale 1:100,000

EXPLANATION

- Town or landmark
- Perennial streams
- Simulated stream
- Coconino County boundary
- Groundwater basin and subbasin boundary
- Model layer 1 active extent
- Model layer 2 active extent
- Model layer 3 active extent

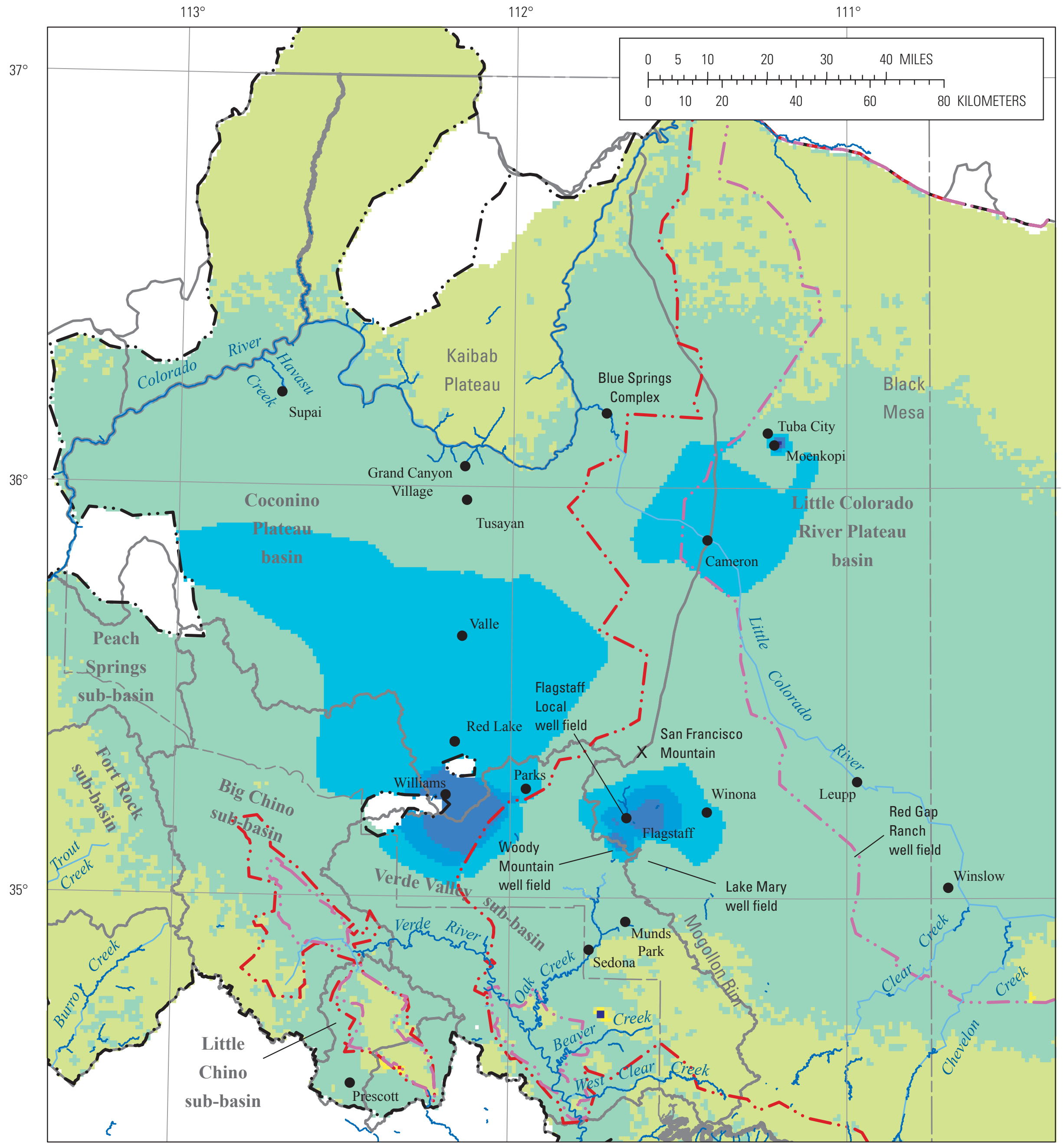
Simulated difference in water levels in Scenario 2 relative to Scenario 1

Feet

<-100, -100 -50, -50 -10, -10 -5, -5 -1, -1 0, 0 1, 1 5, 5 10, 10 50, 50 100, >100

Figure 6. Map of the difference in water-level change in the uppermost model layer compared with scenario 1 from 2006 to 2105 near the Coconino Plateau Water Advisory Council Scenario region and surrounding areas, Arizona for (*A*) Scenario 2 and (*B*) Scenario 3.

B



County boundaries of the United States, USGS 2000 National Atlas, 1:2,000,000-scale resolution, 2002, USGS; Towns from USGS Geographic Names Information System, 1981. Coordinate System: NAD 1927 UTM Zone 12N. Projection: Transverse Mercator. Datum: North American 1927. False Easting: 500,000.0000. False Northing: 0.0000. Central Meridian: -111.0000. Scale Factor: 0.9996. Latitude Of Origin: 0.0000. Units: Meter

Perennial streams from Arizona Department of Water Quality, 2015, scale 1:100,000; Groundwater basin and sub-basin boundaries from Arizona Department of Water Resources, 2008, scale 1:100,000

EXPLANATION

- Town or landmark
- Perennial streams
- Simulated stream
- Coconino County boundary
- Groundwater basin and subbasin boundary
- Model layer 1 active extent
- Model layer 2 active extent
- Model layer 3 active extent

Simulated difference in water levels in Scenario 3 relative to Scenario 1

Feet

<-100, -100 -50, -50 -10, -10 -5, -5 -1, -1 - 0, 0 - 1, 1 - 5, 5 - 10, 10 - 50, 50 - 100, >100

Figure 6.—Continued

vicinity of Williams and Flagstaff are 10 to 50 ft higher than simulated by scenario 1.

Simulated Changes in Groundwater Discharge

Simulated changes in groundwater discharge to streams and springs are discussed for each scenario. Groundwater discharge to streams, springs, and vegetation will decrease as a result of well withdrawals and increase with incidental recharge (Winter and others, 1998; fig. 7). Initial well withdrawals are derived from aquifer storage within the cone of depression around the well, which also creates local groundwater gradients that direct groundwater flow to the well (Barlow and Leake, 2012). The cone of depression is an area of decreased fluid pressure around the well, with the greatest decrease in fluid pressure at the well. As withdrawals from the well continue, the area of reduced fluid pressure expands and ultimately reaches any areas where groundwater discharges to surface features. Withdrawals later in time are derived from a combination of aquifer storage and decreased discharge to surface water features. The effect of incidental recharge is the opposite of well withdrawals, with water first going into storage and increasing discharge to surface features with time.

Simulated distributions of changes in groundwater discharge result from three factors including (1) the distance of each discharge feature to groundwater withdrawal wells or incidental recharge, (2) aquifer transmissivity, and (3) aquifer-storage properties. The rate of discharge change decreases with distance between the withdrawal or recharge and the discharge feature. The rate of discharge change increases with higher aquifer transmissivity and with lower aquifer-storage properties. Rates of discharge change will be greatest for a discharge feature that is hydraulically connected to a highly transmissive confined aquifer.

The NARGFM simulates groundwater discharge to streams, springs, and vegetation. This analysis focuses, however, on changes in discharge to streams and springs, which generally occur before changes in vegetation use. Eventually, given enough time with no further changes in well withdrawals and recharge rates, all of the well withdrawals will be derived from decreased groundwater discharge to surface features, no further change in aquifer storage will occur, and a new steady-state groundwater-flow system will be established. For this analysis, the effects of withdrawals for each scenario are analyzed for the period before 2105, which is long before a new steady-state flow system will be established. Any changes in storage that are simulated in 2105 will eventually, at some future time, result in an equivalent reduction in groundwater discharge to streams and springs.

Simulated changes in groundwater discharge to streams and springs from 2006 to 2105 are discussed for major simulated perennial streams and springs that lie within and nearest to the CPWAC scenario region. These simulated features include the major perennial rivers—Colorado, Little Colorado, and Verde—and tributary streams including Havasu Creek, Clear Creek, Chevelon Creek, Silver Creek, Oak Creek, Sycamore Creek, Beaver Creek, and West Clear Creek. Simulated major springs in the CPWAC region include Havasu Spring, Blue Springs, and five of the major springs on the south rim of Grand Canyon—Royal Arch, Hermit, Monument, Indian Gardens, and Grapevine Springs. Groundwater discharge to all of these features can be captured by groundwater withdrawals or enhanced by artificial or incidental recharge. Groundwater discharge to other surface water features that are hydraulically connected to the Coconino and Redwall-Muav aquifers but not simulated may also change. These features that were not simulated, however, have less groundwater discharge than the simulated features. Simulation of changes in discharge to these features would require a more detailed groundwater flow model.

Simulated changes in discharge occur at each of the major groundwater discharge features for all three scenarios, but most of the change before 2105 is very small (fig. 8). The greatest simulated changes in groundwater discharge occur with scenario 1. The most change is simulated for the Little Colorado River below Cameron (fig. 8*D*) and for Oak Creek above Page Springs (fig. 8*G*) where declines in discharge of about 1.3 and 1.1 cubic feet per second (ft^3/s) occur, respectively. Other simulated changes in discharge through 2105 are losses of less than 0.4 ft^3/s at the Upper Verde River (fig. 8*H*), losses of less than 0.3 ft^3/s at Havasu Creek (fig. 8*A*) and at Colorado River below Havasu Creek (fig. 8*B*), losses of less than 0.1 ft^3/s at Clear Creek, and increases in flow at the south rim springs (fig. 8*B*) and Chevelon Creek (fig. 8*F*) of less than 0.1 and 0.3 ft^3/s, respectively. Simulated changes in discharge for scenarios 2 and 3 are less because of lower rates of groundwater withdrawal with respect to scenario 1.

Scenario 1

Reductions in groundwater discharge occur at most of the major perennial streams and springs near the CPWAC area for scenario 1. However, increases in discharge, both short-term and long-term, occur at some perennial features. The changes at each major discharge feature are discussed including explanations of the simulated change.

The location of the greatest simulated losses in groundwater discharge along the Little Colorado River below Cameron result from several causes, including groundwater withdrawals from the Coconino aquifer in the Cameron and Moenkopi areas, relatively high transmissivity values in the region, and confined aquifer conditions east of Cameron including at a proposed well at Moenkopi. Losses in groundwater discharge to Oak Creek for scenario 1 are primarily the result of nearby large groundwater withdrawals at several wells including those at the Woody Mountain and Lake Mary well fields. The initial simulated increase in flow in Oak Creek, about 0.1 ft^3/s before about 2010, is likely caused by the addition of incidental recharge at the nearby Kachina Village and Munds Park Wastewater Treatment facilities to the simulation. These incidental recharge features were not

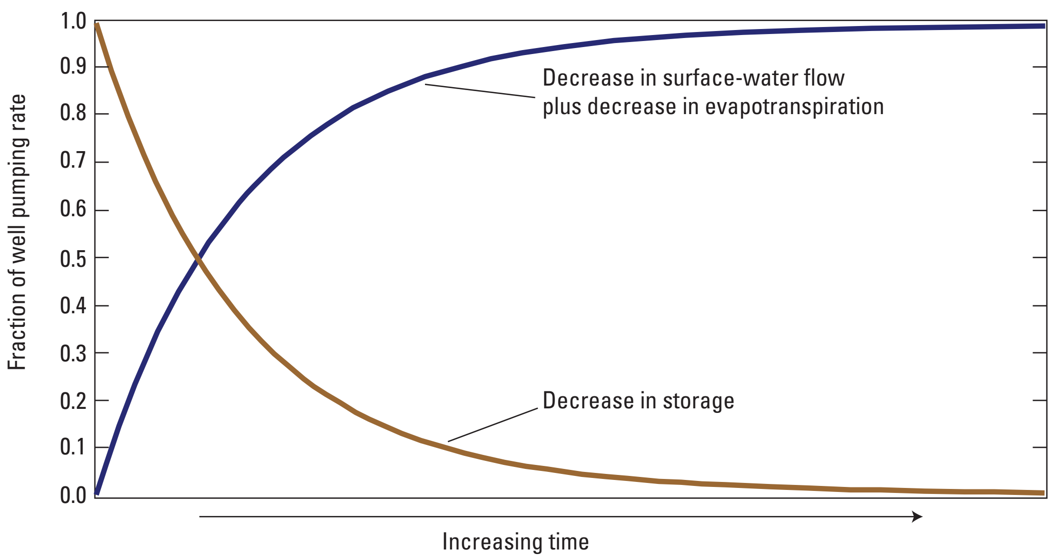


Figure 7. Graph of sources of water, storage or surface-water flow and evapotranspiration, to a pumped well through time.

simulated in the original NARGFM and are a new source of simulated recharge beginning in 2006 for all three scenarios. The maximum decline in flow in Oak Creek of about 1.1 ft^3/s by 2105 is less than 5 percent of the base flow of Oak Creek and well within the typical streamflow measurement error.

Lesser rates of groundwater discharge decline are simulated at Havasu Creek (fig. 8*A*), the Colorado River below Havasu Creek (fig. 8*B*), and Upper Verde River (fig. 8*H*). Simulated declines in flow at Havasu Creek before 2040 are primarily caused by nearby supply wells for the Havasupai Tribe. The longer term decline in discharge of less than 0.3 ft^3/s in 2105, however, is likely caused by distant and regional groundwater withdrawals from the aquifer. The simulated rate of decline for Havasu Creek compared to the present day base flow of Havasu Creek (61 ft^3/s) would be imperceptible. Simulated trends in declining groundwater discharge to the Colorado River below Havasu Creek are similar to those at Havasu Creek and have the same causes, but are slightly less in magnitude. Declines in groundwater discharge of less than 0.4 ft^3/s to the upper Verde River above the streamflow gaging station near Clarkdale are likely a result of both the delayed effects of pre-2006 changes in nearby groundwater withdrawals, and post-2005 scenario 1 changes in distant groundwater withdrawals near Williams. The Redwall-Muav aquifer is simulated as highly transmissive in the region north of the Verde River; as a result distant well withdrawals may capture some groundwater discharge to the Verde River above the streamflow gaging station near Clarkdale. For comparison, the current base flow of the Verde River at Clarkdale is about 69 ft^3/s.

Long-term increases in simulated groundwater discharge (decades or longer duration), occurred for scenario 1 along several of the major perennial streams and springs, including springs at the south rim of Grand Canyon (fig. 8*B*), along Chevelon Creek (fig. 8*F*), and along Clear Creek (fig. 8*E*). The increased discharge at the south rim springs is likely caused by incidental recharge of treated effluent at the wastewater treatment plants at Grand Canyon and Tusayan, which are features that were included in all three scenarios, but were not included in the original NARGFM. The combined increase in flow of the south rim springs (Royal Arch, Hermit, Monument, Indian Gardens, and Grapevine) reaches a simulated maximum of about 0.1 ft^3/s in about the year 2050. From this point on, the simulated change in flow for the combined south rim springs declines to about 0.05 ft^3/s at year 2105.

Increased simulated discharge along Chevelon Creek through the simulated period results from pre-2006 changes in groundwater withdrawals and incidental recharge outside of the CPWAC area. These pre-2006 changes in stresses also are the cause of the simulated water-level recovery in the Chevelon Creek area and areas to the east (fig. 5). The simulated flow increase of about 0.3 ft^3/s by about 2105 represents about an 11 percent increase in the current base flow of Chevelon Creek below the dam. Clear Creek (fig. 8*E*) displays a small increase in discharge before about 2030, which is caused by the same changes in pre-2006 stress that caused the greater and longer-term change in Chevelon Creek discharge. The increase in discharge at Clear Creek is reversed by the effects of nearby groundwater withdrawals after about 2030. This represents less than about 2 percent of the estimated summer base flow of Clear Creek (Leake and others, 2005).

Scenarios 2 and 3

Simulated groundwater discharge for scenarios 2 and 3 reflect the decrease in groundwater withdrawals resulting from importing surface water. Simulated discharge at major perennial streams and springs for scenarios 2 and 3 was greater than scenario 1 at many of the simulated groundwater discharge features (fig. 8). Scenarios 2 and 3 had no influence on simulated groundwater discharge at Clear and Chevelon Creeks from 2006 through 2105 (figs. 8*E*,*F*) because the reduced groundwater withdrawals are distant from those features and any effects may occur later.

Scenario 2, reduced groundwater withdrawals in the Cameron area, produces results similar to scenario 1 for all

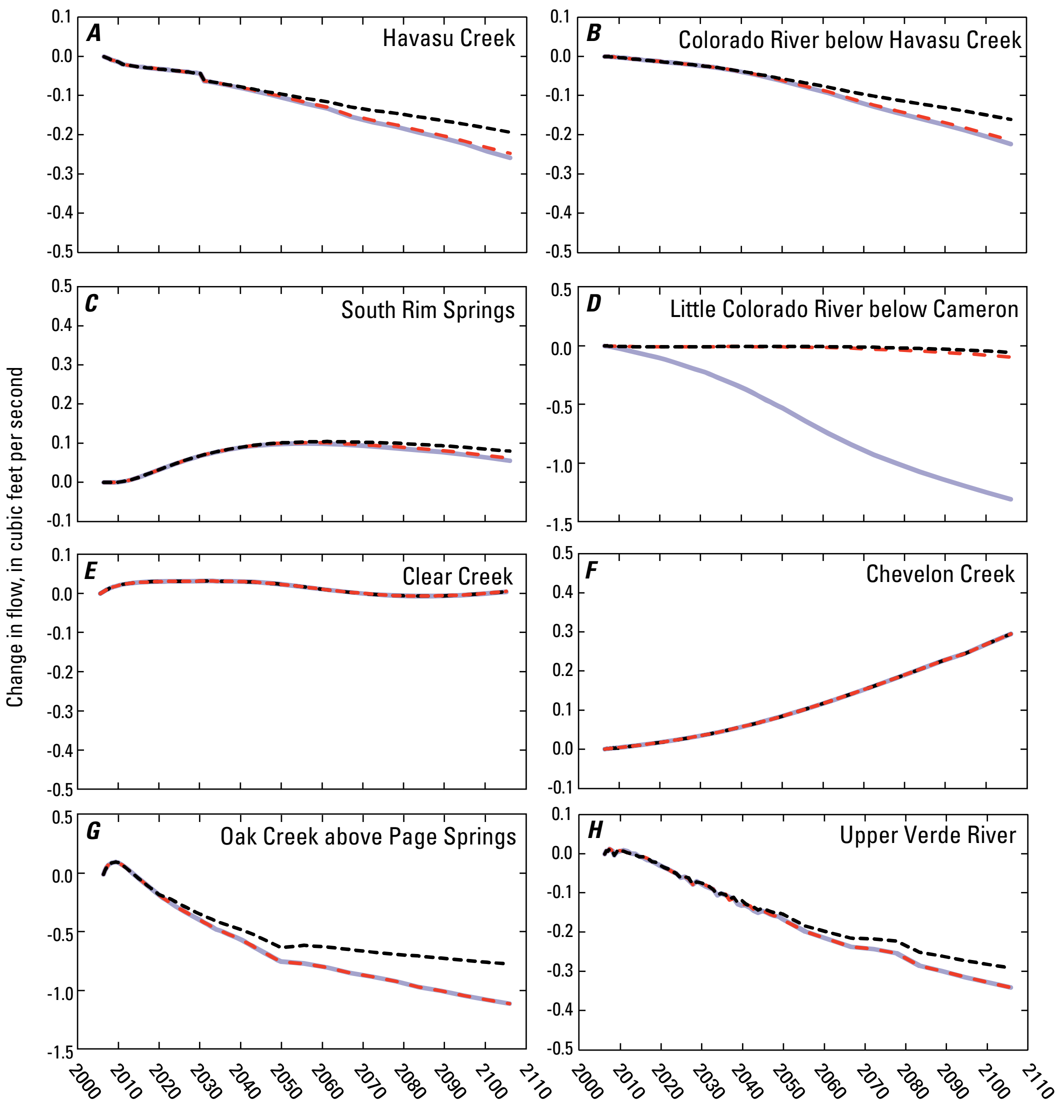


Figure 8. Simulated changes in groundwater discharge to major perennial surface water features from 2006 through 2105 in and near the Coconino Plateau Water Advisory Council scenario region: (*A*) Havasu Creek, (*B*) Colorado River below Havasu Creek, (*C*) major springs at the south rim of Grand Canyon, (*D*) Little Colorado River below Cameron, (*E*) Clear Creek, (*F*) Chevelon Creek, (*G*) Oak Creek above Page Springs, and (*H*) upper part of the Verde River between the streamflow gaging stations near Paulden and near Clarkdale.

major groundwater discharge features except for the perennial reach of the Little Colorado River below Cameron, which is nearest to the reduced withdrawal area. Scenario 2 results in about 0.1 ft^3/s loss in simulated discharge through 2105 in comparison to discharge simulated in 2005, whereas scenario 1 resulted in a loss in discharge of about 1.3 ft^3/s .

Scenario 3 had a broader effect on groundwater discharge across the region because of a greater extent of reduced groundwater withdrawals. Scenario 3 resulted in greater groundwater discharge than scenarios 1 and 2 at all major groundwater discharge features from 2006 through 2105 except for Clear and Chevelon Creeks. The effect on discharge to the Little Colorado River below Cameron was small with respect to scenario 2— about 0.05 ft^3/s more discharge was simulated in 2105—resulting in little change in discharge rate since 2006. Greater groundwater discharge was simulated by scenario 3 in comparison to scenarios 1 and 2 at Havasu Creek, Colorado River below Havasu Creek, Oak Creek above Page Springs, and upper Verde River. In 2105, scenario 3 simulated discharge at Havasu Creek and the Colorado River below Havasu Creek was greater than that simulated by scenarios 1 and 2 by about 0.5 ft^3/s. Scenario 3 simulated groundwater discharge through 2105 at Oak Creek above Page Springs and the upper Verde River was greater than simulated by scenarios 1 and 2 by about 0.05 ft^3/s. Increases in discharge to Oak Creek and the upper Verde River are likely because of reduced simulated groundwater withdrawals near Flagstaff and Williams, respectively. Slightly greater groundwater discharge, about 0.02 ft^3/s, was simulated by scenario 3 in comparison with scenario 1 and 2 at the south rim springs.

Model Limitations

The accuracy of hydrologic change that results from the simulation of the CPWAC withdrawal scenarios is dependent on the persistence of hydrologic assumptions that are inherent in the NARGFM. Major assumptions include, but are not limited to, the reasonably accurate simulation of (1) transmissivity distributions, (2) distributions of hydraulic properties that control interactions between vertically adjacent aquifers, (3) distributions of spatial, including vertical, withdrawal and incidental recharge rates, (4) aquifer extents, and (5) hydrologic barriers and conduits. In addition, no variations in recharge rates were simulated for the scenarios and no attempts were made to predict future recharge rates. Recharge rates were simulated as equivalent to average annual rates simulated for the original NARGFM. Future studies may result in an improved understanding of the groundwater-flow system that could substantially alter the conceptual hydrogeologic model in some areas. Commensurate modifications to the numerical model would be required, resulting in improved simulation of aquifer and stream-aquifer interactions and more reliable estimates of the effects of future groundwater use and management practices.

The accuracy of the simulated scenarios is limited to basin-scale applications and to regions of the model where geologic and hydrologic data are available, including records of steady-state water levels and base flow, and transient changes in water levels, base flow, and withdrawals. Basin-scale applications refer to the simulation of overall water budgets and groundwater flow in a groundwater basin or large part of the basin. Few hydrologic records that document withdrawals and major changes in the hydrologic system are available across some regions of the groundwater flow system that are affected by the CPWAC withdrawal scenarios. The most prominent areas lacking hydrologic data include much of the Coconino Plateau basin, parts of the Little Colorado River Plateau basin, and the Verde Valley subbasin. Future data collection in these areas, especially the Coconino Plateau basin, may alter the current understanding and simulation of the groundwater flow system in those areas. Accordingly, the hydrologic system simulated by the NARGFM should not be considered a simulation of the true system, but a simulation of the system as currently understood and simplified for simulation by using a numerical model. However, the ultimate hydrologic effect of any groundwater withdrawal scenario is limited by the magnitude of the net withdrawals.

Summary

The NARGFM was used to estimate the hydrologic changes—including changes in water levels and groundwater discharge to streams and springs—that may result from future groundwater withdrawals in and near the CPWAC study area in Coconino and Navajo Counties, Arizona. Three future withdrawal scenarios developed by the CPWAC for the 2006 through 2050 period were tested. Simulated water levels resulting from each scenario in 2105 were compared, as were simulated changes in groundwater discharge to major perennial streams and springs.

The NARGFM uses the USGS developed finite-difference code MODFLOW-2005 to simulate groundwater flow within the major aquifers of northern Arizona and parts of adjacent states. The model includes the region of the Colorado Plateau and adjacent areas to the south that include alluvial basins. Three model layers are used to simulate the primary hydrogeologic units across the model domain. Within and surrounding the area of the CPWAC withdrawal scenarios, the major simulated aquifers are the Coconino and Redwall-Muav aquifers. The upper part of the Coconino aquifer, included within model layer 1, is primarily in the region north and east of the Little Colorado River. The lower part of the Coconino aquifer, included within model layer 2, is simulated where the upper and middle Supai Formations are regionally saturated in the region east of a line from Cameron to Williams. Alluvial aquifers are simulated in the adjacent Verde Valley and include the fluvio-lacustrine facies of the Verde Formation, which are simulated within model layer 1, and the sand and gravel facies of the Verde Formation, which are simulated as model layer 2. The Redwall-Muav aquifer is simulated as model layer 3 throughout most of the region of the CPWAC withdrawal scenarios.

The NARGFM simulates aquifer recharge and discharge to streams and springs, and evapotranspiration by phreatophytes. Recharge rates and distributions are derived from a basin characterization model that estimates recharge as direct infiltration. The recharge estimates are modified in alluvial basins to include infiltration along ephemeral stream channels. Discharge to streams and springs are simulated using the MODFLOW stream package for perennial streams within the Verde and Little Colorado River drainage systems, and the MODFLOW drain package for other perennial streams and major springs including the Colorado and Salt Rivers.

Three future groundwater withdrawal scenarios, developed by the CPWAC for tribal and nontribal uses, were simulated for the period 2006–2105. Most of the withdrawal wells for each scenario are within the Coconino Plateau basin and the Little Colorado River Plateau basin. Scenario 1 assumes no major changes in groundwater use except for increased demand based on population projections. Total groundwater withdrawals within the CPWAC region for scenario 1 increase from about 10,800 ac-ft/yr during 2006 through 2009 to about 25,300 ac-ft/yr after 2049 (fig. 3*A*, appendix 1). Scenario 2 assumes that a pipeline will provide a source of surface water from Lake Powell to the communities along the west edge of the Navajo Reservation including Cameron and Moenkopi, and all nontribal water demands will continue to be met by groundwater development. Total groundwater withdrawals within the CPWAC region for scenario 2 increase from about 10,800 ac-ft/yr during 2006 through 2009 to about 23,000 ac-ft/yr after 2049. Most of increases in groundwater withdrawals for scenarios 1 and 2 result from increases for the City of Flagstaff at the Inner City well field and at nearby communities. Scenario 3 assumes that a pipeline extends onto the Coconino Plateau to supply projected unmet demands for water in this area by 2050. Total groundwater withdrawals for scenario 3 are the least of the three scenarios, and increase from about 10,800 ac-ft/yr during 2006 through 2009 to about 23,400 ac-ft/yr after 2049. Similar to scenarios 1 and 2, most of increases in groundwater withdrawals for scenario 3 result from increases near Flagstaff. Overall groundwater withdrawals for scenario 3 after 2049 are about 4,300 ac-ft/yr less than those in scenario 1.

A few additional assumptions were applied to the withdrawal scenarios regarding rates of natural and incidental recharge, rates of projected withdrawals outside of the area of the scenarios, withdrawal rates for exempt wells, and how to handle loss of withdrawals that occur as a result of model cells that dry during the simulations. Natural recharge rates for the three simulated groundwater withdrawal scenarios are assumed to be equivalent to average-annual rates of natural recharge that applied to the NARGFM for the simulation of pre-2006 conditions. This eliminates the effects of natural recharge from the simulated changes and simplifies the analysis. Projected rates of incidental recharge for waste water treatment facilities at 12 communities within the CPAC scenario region were assumed to remain at a constant percentage of water demand from 2000 through 2005. Projected rates of incidental recharge at eight golf courses was constant throughout the simulations. Well withdrawals outside of the CPWAC scenario area were maintained at rates that were simulated in the NARGFM during 2000 through 2005. Drying of model cells that include well withdrawals outside of the scenario area was allowed to occur. Dry models cells and loss of simulated withdrawals at those cells were nearly identical for each scenario and did not greatly affect results. Withdrawals from exempt wells and a few other wells were assumed to vary in the future based on variations in the “other” withdrawal category provided by each scenario. Distributions of withdrawals for some wells within the scenario area, mainly near the City of Flagstaff wells fields and near Holbrook, were modified from the pre-2006 simulation for the purpose of preventing drying of the pumped model cell and retention of the projected withdrawals throughout the period of the simulation. Modifications included redistribution of the withdrawals to include deeper layers and lateral translation of wells to spread the collective cone of depression resulting from a concentrated area of well withdrawals.

The CPWAC withdrawal scenarios primarily influence water levels and groundwater discharge in the Coconino Plateau basin, near the western margin of the Little Colorado River Plateau basin, and the Verde Valley subbasin. Simulated effects of the withdrawal scenarios are superimposed on effects of previous variations in groundwater withdrawals and artificial and incidental recharge. Effects of these pre-scenario variations include changes in water-levels in wells, groundwater storage, discharge to streams and springs, and evapotranspiration by plants that use groundwater. Future variations in groundwater discharge will continue to occur as a result of the past changes.

Water-level variations resulting from post-2005 groundwater withdrawals and incidental and artificial recharge in the area of the withdrawal scenarios are primarily localized and superimposed on the regional changes caused by pre-2006 variations. Withdrawal scenario 1 produced a broad region on the Coconino Plateau where water-levels declined by 1–5 ft by 2105 and local areas with water-level declines of 100 ft or more where groundwater withdrawals are concentrated near the City of Flagstaff Woody Mountain and Lake Mary well fields, and the towns of Tusayan and Parks. Water-level rises of more than 100 ft are simulated near the City of Flagstaff waste-water treatment plants at Wildcat Hill, Rio De Flag, and Grand Canyon Village.

Simulated water-level change from 2006 through 2105 for scenarios 2 and 3, which bring imported surface water to the area and remove some groundwater withdrawals, is mostly different from water-level change at the local level simulated for scenario 1, which includes no imported water to relieve groundwater withdrawals. Scenarios 2 and 3 both eliminate groundwater withdrawals in the reservation areas extending from Lake Powell to, and including, Cameron, where water levels in 2105 were 1 to 5 ft higher than simulated for scenario 1. Water levels at Moenkopi are more than 10 ft higher due to the elimination of a proposed withdrawal well that was simulated in scenario 1. Scenario 3 eliminates more groundwater withdrawals in the Flagstaff and Williams areas; it also simulates 1 to 5 ft less water-level decline than scenario 1 across much of the Coconino Plateau, and 10 to 50 ft higher water levels than simulated by scenario 1 near withdrawal wells in the Williams and Flagstaff areas.

Simulated changes in discharge occur at each of the major groundwater discharge features for all three scenarios, but most of the change before 2105 is very small. Scenario 1, which includes no imported surface water to replace groundwater withdrawals, simulated the most change in groundwater discharge for the Little Colorado River below Cameron and for Oak Creek above Page Springs, where discharge declines about 1.3 and 1.1 ft^3/s , respectively. Other simulated changes in discharge through 2105 in scenario 1 are losses of less than 0.4 ft^3/s at the upper Verde River, losses of less than 0.3 ft^3/s at Havasu Creek and at the Colorado River below Havasu Creek, minimal change at Clear Creek, and increases in flow at the south rim springs and Chevelon Creek of less than 0.1 and 0.3 ft^3/s , respectively. Simulated changes in discharge for scenarios 2 and 3 are less because of lower rates of groundwater withdrawal with respect to scenario 1.

Scenario 3 maintained the greatest simulated rates of groundwater discharge to major streams and springs. The scenario includes the importation of surface water for both tribal and nontribal demand in the CPWAC study area and reduced groundwater withdrawals. Scenario 3 resulted in greater groundwater discharge than scenarios 1 and 2 at all major groundwater discharge features from 2006 through 2105 except for Clear and Chevelon Creeks, where the same groundwater discharge was simulated by each of the three scenarios. Groundwater discharge to the Little Colorado River below Cameron was greatest for scenarios 2 and 3. Scenario 3 resulted in almost no change in discharge after 2005. Scenario 2 resulted in about 0.1 ft^3/s loss in discharge by 2105. Greater flows were simulated by scenario 3 in comparison to scenarios 1 and 2 at Havasu Creek, Colorado River below Havasu

Creek, south rim springs, Oak Creek above Page Springs, and the upper Verde River. However, the increased flows in 2105 in scenario 3 flows over scenario 2 were very small at all of these features, less than about 0.1 ft^3/s. Changes in groundwater discharge will occur after 2105 to all major surface features that discharge from the Redwall-Muav and Coconino aquifers because change in aquifer storage was occurring at the end of the simulation in 2105.

The accuracy of simulated changes resulting from the CPWAC groundwater withdrawal scenarios is dependent on the persistence of several hydrologic assumptions that are inherent in the NARGFM including, but not limited to, the reasonably accurate simulation of (1) transmissivity distributions, (2) distributions of vertical hydraulic properties, (3) distributions of spatial rates of withdrawal and incidental recharge, (4) aquifer extents, and (5) hydrologic barriers and conduits. The model can be improved with knowledge gained from future investigations. Much of the hydrogeology in the simulated area is poorly understood because of limited subsurface investigations and few long-term records of hydrologic change. The most prominent areas lacking hydrologic data include much of the Coconino Plateau basin, parts of the Little Colorado River Plateau basin, and the Verde Valley subbasin. Future data collection in these areas, especially the Coconino Plateau basin, may alter the current understanding and simulation of the groundwater flow system in those areas. Accordingly, the hydrologic system simulated by the NARGFM should not be considered a simulation of the true system, but a simulation of the system as it is currently understood and simplified for simulation by using a numerical model.

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Appendixes

Appendix 1. Groundwater demand scenario 1 developed by the Coconino Plateau Water Advisory Council for the period 2006–2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.

[Values in acre-feet per year]

Category	Area	Water user	Aquifer	Scenario 1 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Municipal, Tribal, and Industrial groundwater withdrawals	Moenkopi/Lower Moenkopi	Hopi Tribe	Coconino	26	34	70	94	127	170
	Havasupai	Havasupai Tribe	Redwall-Muav	170	175	175	200	200	200
	Hualapai	Hualapai Tribe	Other[1]	0	0	1	5	10	10
	Bodaway/Gap	Navajo Tribe	Other[1]/Coconino	169	196	301	445	629	750
	Cameron	Navajo Tribe	Coconino	196	230	371	485	632	819
	Leupp	Navajo Tribe	Coconino	200	230	302	374	446	518
	Leupp wells (Seba Delka, Dilkon, Red Lake, etc.)	Navajo Tribe	Coconino	0	0	50	250	500	500
	Twin Arrows Casino	Navajo Tribe	Coconino	0	9	500	500	500	500
	Inner Basin wells and springs	City of Flagstaff	Coconino	274	700	700	700	700	700
	Lake Mary well field	City of Flagstaff	Coconino	2,576	1,650	1,650	1,650	1,650	1,650
	Woody Mountain well field	City of Flagstaff	Coconino	2,701	2,700	2,954	3,231	3,585	3,968
	Local well field	City of Flagstaff	Coconino	1,475	2,042	2,607	3,176	3,743	4,310
	Red Gap Ranch	City of Flagstaff	Coconino	0	0	500	1,500	3,000	4,348
	Bellmont (Flagstaff Meadows)	Bellmont (Flagstaff Meadows)	Coconino	25	50	75	100	125	150
	Doney Park	Doney Park	Coconino	781	974	1,168	1,362	1,556	1,755
	Flagstaff Ranch	Flagstaff Ranch	Coconino	100	125	125	112	100	100
	Forest Highlands	Forest Highlands	Coconino	570	600	600	600	600	600
	Fox Ranch	Fox Ranch	Coconino	0	10	10	20	20	40
	Fort Valley	Fort Valley	Coconino	0	20	40	60	80	95
	Kachina	Kachina	Coconino	342	354	366	378	390	400
	Mountainare	Mountainare	Coconino	90	99	108	117	125	135
	Mountain Dell Water Company	Mountain Dell Water Company	Coconino	20	23	25	25	30	30
	Parks	Parks	Other[1]/Coconino	200	200	275	350	425	490
	Tusayan	Tusayan	Redwall-Muav	75	225	275	325	375	425
	Valle	Valle	Redwall-Muav	50	117	134	151	168	185
	Williams	City of Williams	Redwall-Muav	280	360	440	520	600	675
	Canyon Mine	Canyon Mine	Redwall	0	4	40	4	0	0
	Williams	Bearazona Wildlife Park	Redwall	0	60	120	120	120	120

Appendix 1. Groundwater demand scenario 1 developed by the Coconino Plateau Water Advisory Council for the period 2006–2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.—Continued.

Category	Area	Water user	Aquifer	Scenario 1 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Other domestic, stock and small industrial groundwater withdrawals	Williams to Grand Canyon area	Stock and domestic	Other[1]/Redwall-Muav	125	130	200	270	340	410
	Flagstaff to Williams area	Stock and domestic	Coconino/Redwall-Muav	250	255	395	535	675	815
	Remaining area	Stock and domestic	Coconino/Redwall-Muav	125	130	200	270	340	410
Non-NARGFM groundwater withdrawals	Hopi	Hopi Tribe	Navajo	64	98	198	265	362	497
	Coppermine	Navajo Tribe	Navajo	62	70	110	163	230	275
	LeChee	Navajo Tribe	Navajo	175	203	310	457	946	946
	Tuba City	Navajo Tribe	Navajo	1,393	1,623	2,603	2,285	4,379	5,648
Total annual groundwater withdrawal				12,514	13,696	17,998	21,099	27,708	32,644
Total annual NARGFM simulated groundwater withdrawal				10,820	11,702	14,777	17,929	21,791	25,278
Annual withdrawals from aquifers not simulated using NARGFM				1,694	1,994	3,221	3,170	5,917	7,366

[1]Aquifers in younger rocks including those of local extent in alluvial and volcanic rocks that may be perched or hydraulically disconnected from the underlying simulated aquifers, but may discharge groundwater to the simulated aquifers.

Appendix 2. Groundwater demand scenario 2 developed by the Coconino Plateau Water Advisory Council for the period 2006–2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.

[Values in acre-feet per year]

Category	Area	Water user	Aquifer	Scenario 2 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Municipal, Tribal, and Industrial groundwater withdrawals	Moenkopi/Lower Moenkopi	Hopi Tribe	Coconino	26	0	0	0	0	0
	Havasupai	Havasupai Tribe	Redwall-Muav	170	175	175	200	200	200
	Hualapai	Hualapai Tribe	Other[1]	0	0	1	5	10	10
	Bodaway/Gap	Navajo Tribe	Other[1]/Coconino	169	0	0	0	0	0
	Cameron	Navajo Tribe	Coconino	196	0	0	0	0	0
	Leupp	Navajo Tribe	Coconino	200	230	302	374	446	518
	Leupp wells (Seba Delka, Dilkon, Red Lake, etc.)	Navajo Tribe	Coconino	0	0	50	250	500	500
	Twin Arrows Casino	Navajo Tribe	Coconino	0	9	500	500	500	500
	Inner Basin wells and springs	City of Flagstaff	Coconino	274	700	700	700	700	700
	Lake Mary well field	City of Flagstaff	Coconino	2,576	1,650	1,650	1,650	1,650	1,650
	Woody Mountain well field	City of Flagstaff	Coconino	2,701	2,700	2,954	3,231	3,585	3,968
	Local well field	City of Flagstaff	Coconino	1,475	2,042	2,607	3,176	3,743	4,310
	Red Gap Ranch	City of Flagstaff	Coconino	0	0	500	1,500	3,000	4,348
	Bellmont (Flagstaff Meadows)	Bellmont (Flagstaff Meadows)	Coconino	25	50	75	100	125	150
	Doney Park	Doney Park	Coconino	781	974	1,168	1,362	1,556	1,755
	Flagstaff Ranch	Flagstaff Ranch	Coconino	100	125	125	112	100	100
	Forest Highlands	Forest Highlands	Coconino	570	600	600	600	600	600
	Fox Ranch	Fox Ranch	Coconino	0	10	10	20	20	40
	Fort Valley	Fort Valley	Coconino	0	20	40	60	80	95
	Kachina	Kachina	Coconino	342	354	366	378	390	400
	Mountainare	Mountainare	Coconino	90	99	108	117	125	135
	Mountain Dell Water Company	Mountain Dell Water Company	Coconino	20	23	25	25	30	30
	Parks	Parks	Other[1]/Coconino	200	200	275	350	425	490
	Tusayan	Tusayan	Redwall-Muav	75	225	275	325	375	425
	Valle	Valle	Redwall-Muav	50	117	134	151	168	185
	Williams	City of Williams	Redwall-Muav	280	360	440	520	600	675
	Canyon Mine	Canyon Mine	Redwall	0	4	40	4	0	0
	Williams	Bearazona Wildlife Park	Redwall	0	60	120	120	120	120

Appendix 2. Groundwater demand scenario 2 developed by the Coconino Plateau Water Advisory Council for the period 2006–2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.—Continued.

Category	Area	Water user	Aquifer	Scenario 2 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Other domestic, stock and small industrial groundwater withdrawals	Williams to Grand Canyon area	Stock and domestic	Other[1]/Redwall-Muav	125	130	200	270	340	410
	Flagstaff to Williams area	Stock and domestic	Coconino/Redwall-Muav	250	255	395	535	675	815
	Remaining area	Stock and domestic	Coconino/Redwall-Muav	125	130	200	270	340	410
Non-NARGFM groundwater withdrawals	Hopi	Hopi Tribe	Navajo	64	0	0	0	0	0
	Coppermine	Navajo Tribe	Navajo	62	0	0	0	0	0
	LeChee	Navajo Tribe	Navajo	175	0	0	0	0	0
	Tuba City	Navajo Tribe	Navajo	1,393	0	0	0	0	0
Total annual groundwater withdrawal				12,514	11,178	13,875	16,781	20,283	23,419
Total annual NARGFM simulated groundwater withdrawal				10,820	11,178	13,875	16,781	20,283	23,419
Annual withdrawals from aquifers not simulated using NARGFM				1,694	0	0	0	0	0

[1]Aquifers in younger rocks including those of local extent in alluvial and volcanic rocks that may be perched or hydraulically disconnected from the underlying simulated aquifers, but may discharge groundwater to the simulated aquifers.

Appendix 3. Groundwater demand scenario 3 developed by the Coconino Plateau Water Advisory Council for the period 2006– 2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.

[Values in acre-feet per year]

Category	Area	Water user	Aquifer	Scenario 3 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Municipal, Tribal, and Industrial groundwater withdrawals	Moenkopi/Lower Moenkopi	Hopi Tribe	Coconino	26	0	0	0	0	0
	Havasupai	Havasupai Tribe	Redwall-Muav	170	175	175	200	200	200
	Hualapai	Hualapai Tribe	Other[1]	0	0	1	5	10	10
	Bodaway/Gap	Navajo Tribe	Other[1]/Coconino	169	0	0	0	0	0
	Cameron	Navajo Tribe	Coconino	196	0	0	0	0	0
	Leupp	Navajo Tribe	Coconino	200	230	302	374	446	518
	Leupp wells (Seba Delka, Dilkon, Red Lake, etc.)	Navajo Tribe	Coconino	0	0	50	250	500	500
	Twin Arrows Casino	Navajo Tribe	Coconino	0	9	500	500	500	500
	Inner Basin wells and springs	City of Flagstaff	Coconino	274	700	700	700	700	700
	Lake Mary well field	City of Flagstaff	Coconino	2,576	1,650	1,650	1,650	1,650	1,650
	Woody Mountain well field	City of Flagstaff	Coconino	2,701	2,700	2,954	3,231	3,585	3,968
	Local well field	City of Flagstaff	Coconino	1,475	2,042	2,500	2,500	2,500	2,500
	Red Gap Ranch	City of Flagstaff	Coconino	0	0	500	1,500	3,000	4,348
	Bellmont (Flagstaff Meadows)	Bellmont (Flagstaff Meadows)	Coconino	25	50	75	100	125	150
	Doney Park	Doney Park	Coconino	781	974	1,168	1,362	1,556	1,755
	Flagstaff Ranch	Flagstaff Ranch	Coconino	100	125	125	112	100	100
	Forest Highlands	Forest Highlands	Coconino	570	600	600	600	600	600
	Fox Ranch	Fox Ranch	Coconino	0	10	10	20	20	40
	Fort Valley	Fort Valley	Coconino	0	20	40	60	80	95
	Kachina	Kachina	Coconino	342	354	366	378	390	400
	Mountainare	Mountainare	Coconino	90	99	108	117	125	135
	Mountain Dell Water Company	Mountain Dell Water Company	Coconino	20	23	25	25	30	30
	Parks	Parks	Other[1]/Coconino	200	200	275	350	425	490
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	Valle	Valle	Redwall-Muav	50	117	134	151	168	185
	Williams	City of Williams	Redwall-Muav	280	360	0	0	0	0
	Canyon Mine	Canyon Mine	Redwall	0	4	40	4	0	0
	Williams	Bearazona Wildlife Park	Redwall	0	60	120	120	120	120

Appendix 3. Groundwater demand scenario 3 developed by the Coconino Plateau Water Advisory Council for the period 2006– 2105 including groundwater demand simulated for the Coconino and Redwall-Muav Aquifers using the Northern Arizona Groundwater Flow Model (NARGFM) and groundwater demand for overlying and disconnected aquifers that are not simulated using NARGFM.

Category	Area	Water user	Aquifer	Scenario 3 water use by simulated decade					
				2006-2009	2010-2019	2020-2029	2030-2039	2040-2049	2050-2105
Other domestic, stock and small industrial groundwater withdrawals	Williams to Grand Canyon area	Stock and domestic	Other[1]/Redwall-Muav	125	130	200	270	340	410
	Flagstaff to Williams area	Stock and domestic	Coconino/Redwall-Muav	250	255	395	535	675	815
	Remaining area	Stock and domestic	Coconino/Redwall-Muav	125	130	200	270	340	410
Non-NARGFM groundwater withdrawals	Hopi	Hopi Tribe	Navajo	64	0	0	0	0	0
	Coppermine	Navajo Tribe	Navajo	62	0	0	0	0	0
	LeChee	Navajo Tribe	Navajo	175	0	0	0	0	0
	Tuba City	Navajo Tribe	Navajo	1,393	0	0	0	0	0
Total annual groundwater withdrawal				12,514	11,178	13,328	15,585	18,440	20,934
Total annual NARGFM simulated groundwater withdrawal				10,820	11,178	13,328	15,585	18,440	20,934
Annual withdrawals from aquifers not simulated using NARGFM				1,694	0	0	0	0	0

[1]Aquifers in younger rocks including those of local extent in alluvial and volcanic rocks that may be perched or hydraulically disconnected from the underlying simulated aquifers, but may discharge groundwater to the simulated aquifers.

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