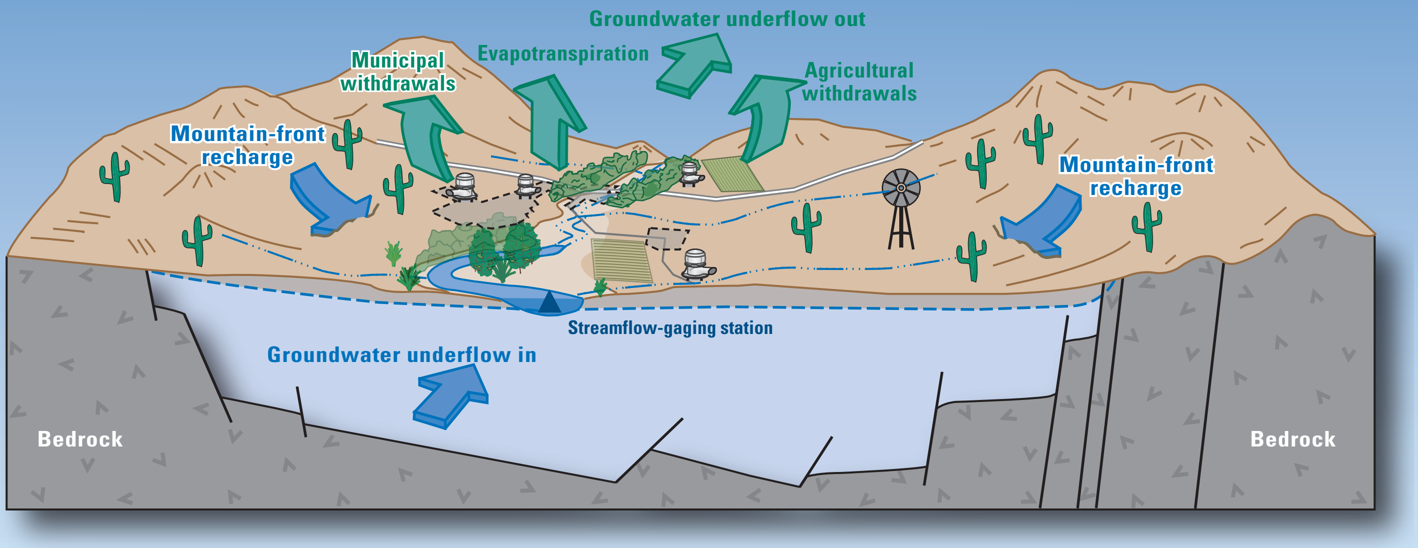
National Water Availability and Use Pilot Program

Water Availability and Use Pilot: Methods Development for a Regional Assessment of Groundwater Availability, Southwest Alluvial Basins, Arizona



Scientific Investigations Report 2011-5071

U.S. Department of the Interior
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FRONT COVER
Generalized block diagram of typical groundwater budget components in the Southwest Alluvial Basins of Arizona.

BACK COVER
The USGS Groundwater Resources Program includes pilot studies of water availability and use in the two areas highlighted on this map; these are comprehensive studies of regional water resources, including groundwater and surface-water use and availability.

National Water Availability and Use Pilot Program

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By Fred D Tillman, Jeffrey T. Cordova, Stanley A. Leake, Blakemore E. Thomas,
and James B. Callegary

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

Suggested citation:
Tillman, F.D, Cordova, J.T., Leake, S.A., Thomas, B.E., and Callegary, J.B., 2011, Water availability and use pilot: methods development for a regional assessment of groundwater availability, southwest alluvial basins, Arizona: U.S. Geological Survey Scientific Investigations Report 2011-5071, 118 p.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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Executive Summary

Arizona is located in an arid to semiarid region in the southwestern United States and is one of the fastest growing States in the country. Population in Arizona surpassed 6.5 million people in 2008, an increase of 140 percent since 1980 (U.S. Census Bureau, 2010a), when the last regional U.S. Geological Survey (USGS) groundwater study was done as part of the Regional Aquifer System Analysis (RASA) program. The alluvial basins of Arizona are part of the Basin and Range Physiographic Province (Fenneman, 1931) and cover more than 73,000 mi^2, 65 percent of the State's total land area. More than 85 percent of the State's population resides within this area (U.S. Census Bureau, 2010b), accounting for more than 95 percent of the State's groundwater use (Tadayon, 2005). Groundwater supplies in the area are expected to undergo further stress as an increasing population vies with the State's important agricultural sector for access to these limited resources.

To provide updated information to stakeholders addressing issues surrounding limited groundwater supplies and projected increases in groundwater use, the USGS Groundwater Resources Program instituted the Southwest Alluvial Basins Groundwater Availability and Use Pilot Program to evaluate the availability of groundwater resources in the alluvial basins of Arizona. The principal products of this evaluation of groundwater resources are updated groundwater budget information for the study area and a proof-of-concept groundwater-flow model incorporating several interconnected groundwater basins. This effort builds on previous research on the assessment and mapping of groundwater conditions in the alluvial basins of Arizona, also supported by the USGS Groundwater Resources Program.

Regional Groundwater Budget

The Southwest Alluvial Basins-Regional Aquifer System Analysis (SWAB-RASA) study produced semiquantitative groundwater budgets for each of the alluvial basins in the SWAB-RASA study area. The pilot program documented in this report developed new quantitative estimates of groundwater budget components using recent (2000–2007) data and methods of data analysis. Estimates of inflow components, including mountain-front recharge, incidental recharge from irrigation of agriculture, managed recharge from recharge facilities, interbasin underflow from upgradient basins, and streamflow losses, are quantified for recent time periods. Mountain-front recharge is the greatest inflow component to the groundwater system and was estimated using two methods: a basin characteristic model and new precipitation information used in a previously developed regression equation. Annual mountain-front recharge for the study area for 1940–2007 estimated by the two methods is 730,000 acre-ft for the basin characteristic model and 643,000 acre-ft for the regression equation, representing 1.5 percent and 1.3 percent of precipitation, respectively. Outflow components, including groundwater withdrawals, evapotranspiration, and interbasin flow to downgradient basins, are also presented for recent time periods. Groundwater withdrawals accounted for the largest share of the water budget, with nearly 2.4 million acre-ft per year withdrawn from the study area in recent years. Evapotranspiration from groundwater was estimated at nearly 1.3 million acre-ft per year for the study area using a newly developed method incorporating vegetation indices from satellite images and land cover information. For water-budget components with temporal variation that could be assessed from available data, estimates for intervening time periods since before development were also developed. An estimate of aquifer storage change, representing both gains to and losses from the groundwater system since before development, was derived for the most developed basins in the study area using available estimates of groundwater-level changes and storage coefficients. An overall storage loss of 74.5 million acre-ft was estimated for these basins within the study area.

Demonstration of a Multibasin Groundwater-Flow Model

A proof-of-concept regional groundwater-flow model was developed to determine if large, multibasin models can

be joined and solved, and to test groundwater budget components developed in the first part of this study. This model builds upon previous Federal and State agency groundwater investigations in the area completed at differing scales. Steady-state groundwater flow was modeled for an area that encompasses more than 2,900 mi^2, including the corridor of connected aquifers extending from the Santa Cruz Basin near the Tubac streamgage north of Nogales, Arizona, through the Tucson and Pinal Active Management Areas to the north. The connected aquifers of Avra and Altar Valleys, the Tucson metropolitan area, and the heavily agricultural area of the Pinal Active Management Area are all included in the modeled area. Steady-state groundwater flow was modeled using information on average in-place recharge and runoff produced during the development of the groundwater budgets. Planned future model refinements include transient simulations based on groundwater-budget components for time periods after widespread groundwater development.

Introduction

The southwestern United States is the fastest growing region in the country, with Arizona consistently among the fastest growing States. The alluvial basins of Arizona contain the major population centers for the State and account for most of the recent and projected population growth. Additionally, the plentiful sunshine in the south-central part of the State has made the area attractive for planned solar-thermal power plants that may require considerable amounts of water. Many basins contain limited or no surface-water resources, leaving groundwater as the principal source of water for all needs. Groundwater withdrawals from the alluvial basins in Arizona accounted for about 45 percent of total water use for the area in 2003 (Tadayon, 2005; Arizona Department of Water Resources, 2006). Competition between agricultural, municipal, and industrial water users over limited water resources, along with increasing awareness of the need for ecological flows to support rivers and riparian communities, makes the need for thorough assessment of water resources of the State an ongoing priority.

The availability of groundwater as a resource is dependent upon many factors, including hydrogeologic setting, groundwater quality, amount and timing of precipitation, and amount and location of groundwater withdrawals. This study, supported by the USGS Groundwater Resources Program, investigates groundwater availability and use in the alluvial basins of Arizona by presenting updated groundwater budgets for the area and by demonstrating a multibasin groundwater-flow model that may indicate a future tool for integrating multibasin groundwater management in the area. The updated groundwater budgets and proof-of-concept flow model build upon previous work done for the Groundwater Resources Program to investigate and communicate groundwater conditions in south-central Arizona.

Purpose and Scope

The purpose of this report is to present results from the USGS Southwest Alluvial Basins (SWAB) Groundwater Availability and Use Pilot Program. The study area comprises the alluvial basins of Arizona, roughly the southern two-thirds of the State (fig. 1). Forty-five groundwater basins defined by the Arizona Department of Water Resources (ADWR) are used as the basis for basin-scale investigations and the presentation of results in this study (fig. 2).

The SWAB Groundwater Availability and Use Pilot Program consists of three parts:

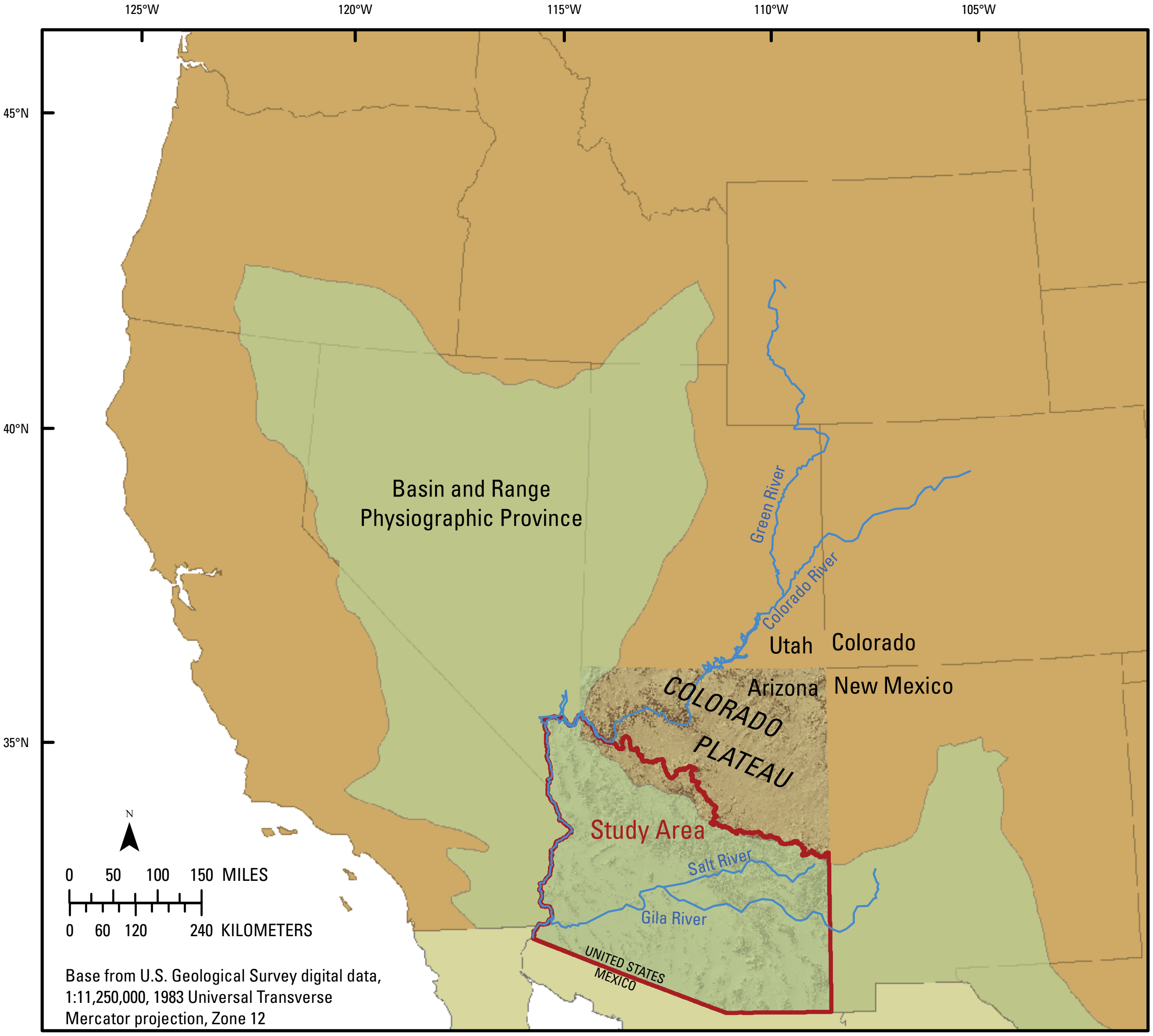
1. Development of methods and indicators for assessment and presentation of regional groundwater conditions in the alluvial basins of Arizona using existing databases,
2. Generation of updated regional groundwater budgets using the most recent available data and methods of data analysis, and
3. Development of a proof-of-concept groundwater-flow model of several interconnected basins in an area heavily dependent upon groundwater.

Methods developed for the first part of the study were discussed in previous publications (Tillman and others, 2007; Tillman and others, 2008), and corresponding results for the most developed basins of the study area are presented in this report.

This report presents a description of the study area, including important physical, climate, population, and water-use characteristics that impact groundwater conditions in the alluvial basins of Arizona. Issues related to groundwater availability and the effects of groundwater use in the SWAB region are also discussed. Indicators of regional groundwater conditions produced from analyses of groundwater-level databases for the most developed basins in the study area are then presented, followed by updated regional groundwater budgets for all basins. Groundwater-budget components investigated in this report include mountain-front recharge from precipitation (including both direct infiltration of precipitation into mountain blocks and the infiltration of water in drainages along mountain fronts), groundwater withdrawals, evapotranspiration, incidental recharge from irrigation of agriculture, managed recharge from recharge facilities, interbasin underflow, streamflow gains and losses, and aquifer storage change. Changes in budget components with time are presented for those basins with available temporal data. The purpose of, and results from, the proof-of-concept groundwater-flow modeling demonstration are then described, followed by a discussion of lessons learned from the SWAB Groundwater Availability and Use Pilot Program and considerations for future work.

Approach and Scale of this Study

The Southwest Alluvial Basins Pilot Project is different in approach and scale from many of the concurrent USGS Regional Groundwater Availability Studies (Reilly and others, 2008; see also http://water.usgs.gov/ogw/gwrp/activities/gw-avail.html). Other USGS groundwater availability studies consist of large-area, detailed, calibrated groundwater modeling efforts (for example, a 12-layer flow model for the Denver Basin study representing 1 alluvial aquifer, 6 bedrock aquifers, and 5 claystone confining units; Banta and others, in press) investigating areas as large as 174,000 mi^2 in the case of the High Plains Aquifer study (Qi and Christenson, 2010). The scale of investigation for the present study is limited to the alluvial basins of the Basin and Range Physiographic Province that lie within the State of Arizona. This study focuses on groundwater only and does not address changes in surface-water conditions, except through an investigation of the streamflow gain and loss groundwater budget component



Base from U.S. Geological Survey digital data, 1:11,250,000, 1983 Universal Transverse Mercator projection, Zone 12

Figure 1. Map of Western United States showing the Basin and Range Physiographic Province (Fenneman, 1931) and the outline of the Southwest Alluvial Basins Study Area within the State of Arizona.

Figure 2. Basin boundaries and basin names within the study area used in this report. Temporal information on groundwater budget components, where available, is presented for each of the "focus" basins highlighted in blue. Focus basins were selected because they represent the variability of climate conditions in the study area and have experienced, or are projected to experience, large population growth.

and through use of the streams package in the groundwater-flow simulation. The approach of this study is to investigate groundwater budgets for the study area using the most recent available data and methods of data analysis. A steady-state, proof-of-concept groundwater-flow model is also developed to illustrate the possibility and usefulness of such a tool and to highlight a potential direction of future work.

Previous Studies

Investigations into the water resources of the alluvial basins of Arizona stretch back to the early part of the 20th century, with work by such luminaries as Oscar E. Meinzer in Paradise Valley (Meinzer and Ellis, 1916) and Willcox Basin (Meinzer and others, 1913), Willis T. Lee in the Salt River Valley (Lee, 1905), and G.E.P. Smith throughout the study area (Smith, 1938). Since those studies were conducted, the USGS, Arizona Department of Water Resources (ADWR), and various local, State, and Federal agencies have all completed numerous groundwater studies at regional, basin, and subbasin scale in the area. A list of additional reading materials that includes many of these studies in the most developed basins of the study area is presented in appendix A (available electronically) of this report, categorized by basin. The most recent USGS regional study of the area, the SWAB-RASA study, is summarized briefly here.

The USGS RASA program began in 1978 following a congressional directive to the Department of the Interior to "…identify the water resources of the major aquifers within the United States…" and to "…establish the aquifer boundaries, the quantity and quality of water within the aquifer, and the recharge characteristics of the aquifer" (Sun and Johnston, 1994). The USGS identified 28 major regional aquifer systems, 25 of which were studied under the RASA program, including the Southwest Alluvial Basins. Investigation and evaluation of the SWAB basins began in 1979, and study results were presented in a series of four USGS Professional Papers that describe the geohydrology of the basins (Anderson and others, 1992), the geochemistry of groundwater in the area (Robertson, 1991), the simulation of groundwater flow in selected basins in the area (Anderson and Freethey, 1995), and a summary of the information presented in the other three reports (Anderson, 1995). The SWAB-RASA studies covered roughly the same area as the current investigation, although basin boundaries for the SWAB-RASA studies were defined somewhat differently from those for the current study and extended into California and New Mexico.

Several geophysical studies were performed during the SWAB-RASA project to evaluate basin structure, basin stratigraphy, aquifer hydrologic properties, and depth to the water table in the study area. Data from the geophysical studies were combined with existing data from various State, Federal, and local water-resources agencies to describe the unconsolidated alluvial deposits that form the principal aquifers of the area. Results of the generalized geologic characterization of the principal aquifers were published in USGS Hydrologic Atlas 663 (Freethey and others, 1986), in addition to Professional Paper 1406-B mentioned above. Predevelopment hydrologic conditions determined from the study were presented in Hydrologic Atlas 664 (Freethey and Anderson, 1986), including predevelopment groundwater-level contours, magnitude and direction of interbasin underflow, and relative magnitudes of inflow and outflow groundwater budget components. Geochemical results indicated the quality of groundwater in much of the study area to be suitable for most uses, although dissolved-solids concentrations were high (greater than 1,000 mg/L) in some areas and trace elements were found in exceedance of maximum contaminant levels (MCLs) for drinking water in small parts of several basins. Groundwater flow was simulated in 12 representative basins in the SWAB-RASA study area. Model results were analyzed to document similarities and differences in basin and regional geohydrology to investigate the feasibility of information transfer from modeled basins to those that were not modeled. All basin flow models were developed using two layers, with the top layer in most basins representing upper basin fill and the lower layer representing lower basin fill.

Acknowledgments

Work reflected in this report was supported by the U.S. Geological Survey's Groundwater Resources Program, Water Availability and Use Pilot Program. Many individuals contributed to the Southwest Alluvial Basins Water Availability and Use Pilot Project, including Doug Rautenkranz, Don Pool, Jesse Dickinson, Marilyn Flynn, Kurt Schonauer, and Cheryl Partin of the USGS Arizona Water Science Center and Ken Hollett, formerly of the USGS. Teri Davis of the Arizona Department of Water Resources provided groundwater-level data from the State of Arizona.

Description of the Study Area

The Southwest Alluvial Basins study area encompasses a wide range of topography, geology, landcover, and precipitation and is located entirely within the boundaries of Arizona. It is bounded in the west by the Colorado River and in the north by watershed boundaries. In the south it is bounded by the U.S.-Mexico border and in the east by the Arizona-New Mexico border. The area under consideration is about 73,600 square miles. Population, land use, and climate strongly influence water availability and quality in the study area, with regulation provided by a mosaic of local, State, Federal, and international laws, compacts, and treaties.

Physiography and Climate

The Southwest Alluvial Basins study area is located in the Basin and Range Lowland, Central Highland, and Plateau Uplands of Arizona (U.S. Geological Survey, 1969; fig. 3).

In the Basin and Range Lowland province, altitudes of the alluvial basins range from less than 100 feet above sea level along the Colorado River near Yuma to greater than 4,000 feet in southeastern Arizona, where some mountains top 10,000 feet. In the Central Highlands, altitudes range from about 500 feet in the west along the Colorado River to greater than 11,000 feet in the east at Mt. Baldy. In the Upland Plateau province, altitudes range from about 1,200 feet at the upstream end of Lake Mead to over 12,000 feet at Humphreys Peak north of Flagstaff. The climate is semiarid, with precipitation varying by altitude (Anderson and others, 1992). Precipitation is also strongly seasonal, with substantial summer rainfall across the entire study area and substantial winter snow accumulation at higher elevations. Snowpack and snowmelt are important in the timing of groundwater recharge, surface-water flow, and reservoir storage volumes (Gottfried and others, 2002; Flint and Flint, 2007b). Annual precipitation ranges from about 3 inches in the lower, western deserts to greater than 44 inches in the mountains of the Highlands. Precipitation varies from summer dominated to winter dominated, depending on location within the study area (Western Region Climate Center, 2010). In the northwest, about 60 percent of precipitation occurs in winter. In the southwest and central portions, about 55 percent of precipitation occurs in winter, and in the southeast, the proportion of precipitation occurring in winter falls below 30 percent. Land cover in the study area is primarily classified as shrub/scrub/herbaceous followed by forest, then agricultural land use (fig. 3). Groundwater-dependent vegetation represents a small fraction of the total land cover.

Geology

The study area is located primarily in the Basin and Range Physiographic Province (Fenneman, 1931), but it also includes what is known as the Transition Zone, which broadly corresponds with the Central Highlands in figure 3 (Wilson and Moore, 1959). The Transition Zone is a geologically complex region in the northeast portion of the study area between the Basin and Range Lowlands Province and the (Colorado) Plateau Uplands. Structurally, the Transition Zone bears resemblances to both the Basin and Range and Colorado Plateau Provinces (Anderson and others, 1992). This zone has undergone episodes of both extension and compression, creating complex faulting as well as severe deformation and uplift. Rocks in the Transition Zone, though highly faulted and displaced, consist primarily of the same sedimentary formations as those found in the Colorado Plateau, with local additions of Miocene and younger basalts and other volcanics and older sedimentary rocks of Cenozoic age (fig. 4). In the Basin and Range Province, the basins were formed by downdropping of mountain blocks along high-angle normal faults (Freethey and others, 1986). The mountain ranges have main axes that typically trend from north-south to northwest-southeast, and they are separated by broad valleys underlain by Cenozoic alluvium and, in certain basins, evaporite deposits (Anderson and others, 1992). Rocks in the mountains of the study area are metamorphic, sedimentary, and igneous, with ages ranging from Precambrian to Cenozoic. Sediments in the basins typically thin to zero thickness at the margins and become thicker toward the center. Maximum thickness of sediments varies widely but in some basins can exceed 10,000 feet (Anderson, 1987). Alluvium tends to grade from coarse (cobbles and gravel) near mountain fronts to fine (silt and clay) near basin centers.

Population Centers and Dynamics

According to the U.S. Census Bureau, Arizona had the second highest population growth rate in the country for the period 2000 to 2009 (U.S. Census Bureau, 2010a). The Phoenix metropolitan area has a population of more than 4 million, while that of Tucson exceeds 1 million. Other population centers within or adjacent to the study area include the twin border cities of Nogales, Arizona, and Nogales, Sonora, Mexico (combined population greater than 200,000); the twin border cities of Douglas, Arizona, and Agua Prieta, Sonora (about 80,000); the twin border cities of San Luis, Arizona, and San Luis Rio Colorado, Sonora (about 173,000); Yuma (about 100,000); Prescott (about 47,000); and Sierra Vista (about 47,000) (Arizona Department of Commerce, 2010; Institución Nacional de Estadística y Geografía, 2010). Population within the study area increased from about 10,000 in 1870 to more than 5 million in 2000, with a projected population of more than 12 million by 2050 (fig. 5; Arizona Department of Commerce, 2010).

Surface Water Resources and Management

The study area lies entirely within the Colorado River Basin, and the Colorado River is the largest surface-water resource within the study area. It enters the study area with 2009 Water Year (10/1/08 to 9/31/09) discharge of more than 9,200,000 acre-ft at the gage below Hoover Dam (USGS Station # 09421500) and exits the study area with 1,400,000 acre-ft of flow at the Northern International Boundary above Morelos Dam (USGS Station # 09522000), the point at which accounting for U.S. deliveries of water to Mexico occurs (U.S. Geological Survey, 2010; estimates based on mean daily discharge). The Colorado River and its reservoirs are managed by the U.S. Bureau of Reclamation (BOR) and the river's water is distributed in the Lower Colorado River Basin to California, Nevada, and Arizona via a network of canals and pipelines primarily for municipal and agricultural use (U.S. Bureau of Reclamation, 2010). The main tributary to the Colorado River in the study area is the Gila River (fig. 6). In eastern Arizona, the east-to-west flowing Gila River is perennial. The Gila River is the largest tributary bringing water into the study area, with annual flow of about 116,000 acre-ft for Water Year 2009 at the gage located at the head of Safford Valley (USGS Station # 09448500), about 40 kilometers west of the New Mexico border, which forms the eastern boundary of the study

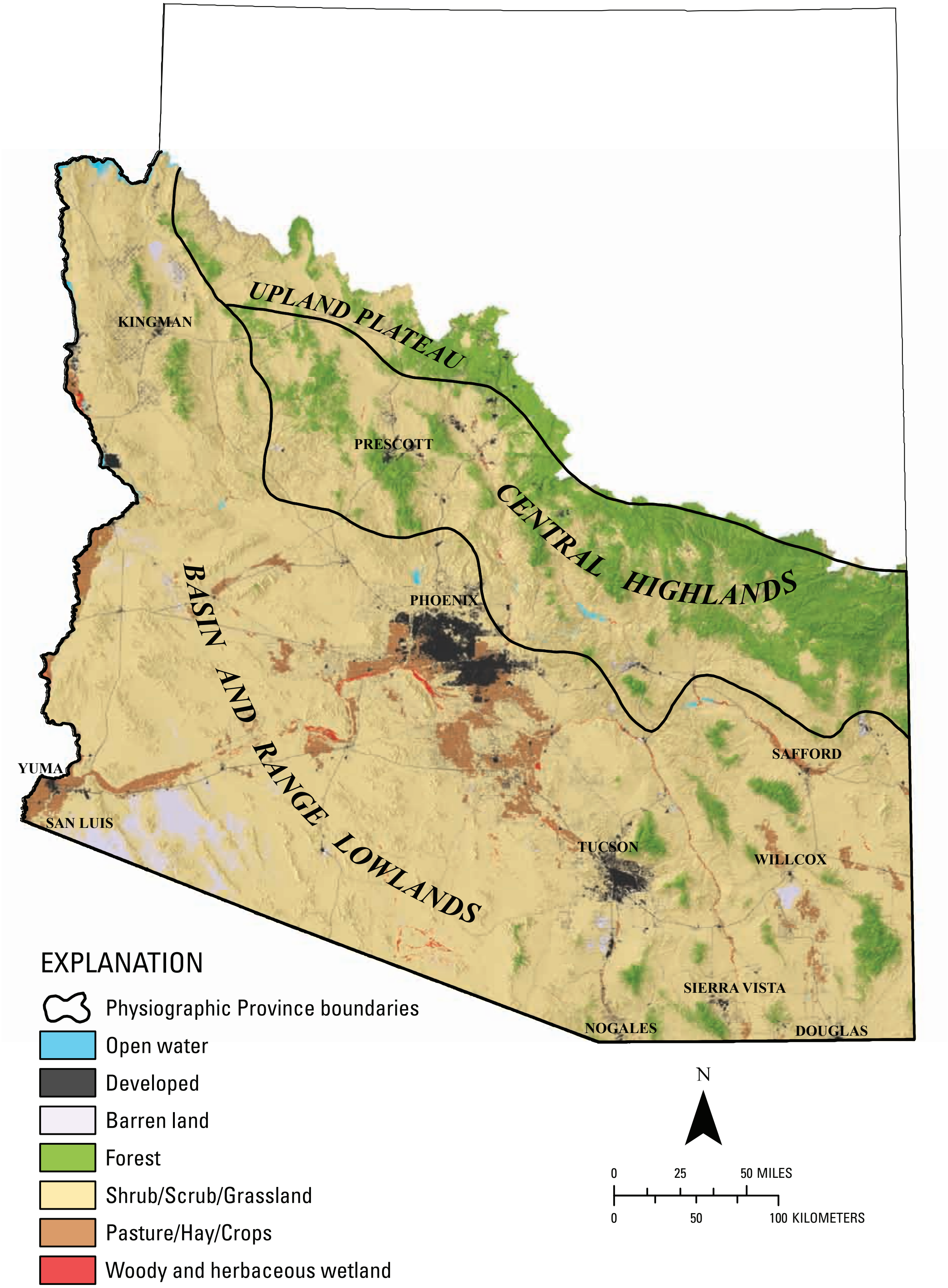


Figure 3. Study area landcover (modified from Multi-Resolution Land Characteristics Consortium, 2010) and physiographic provinces (U.S. Geological Survey, 1969).

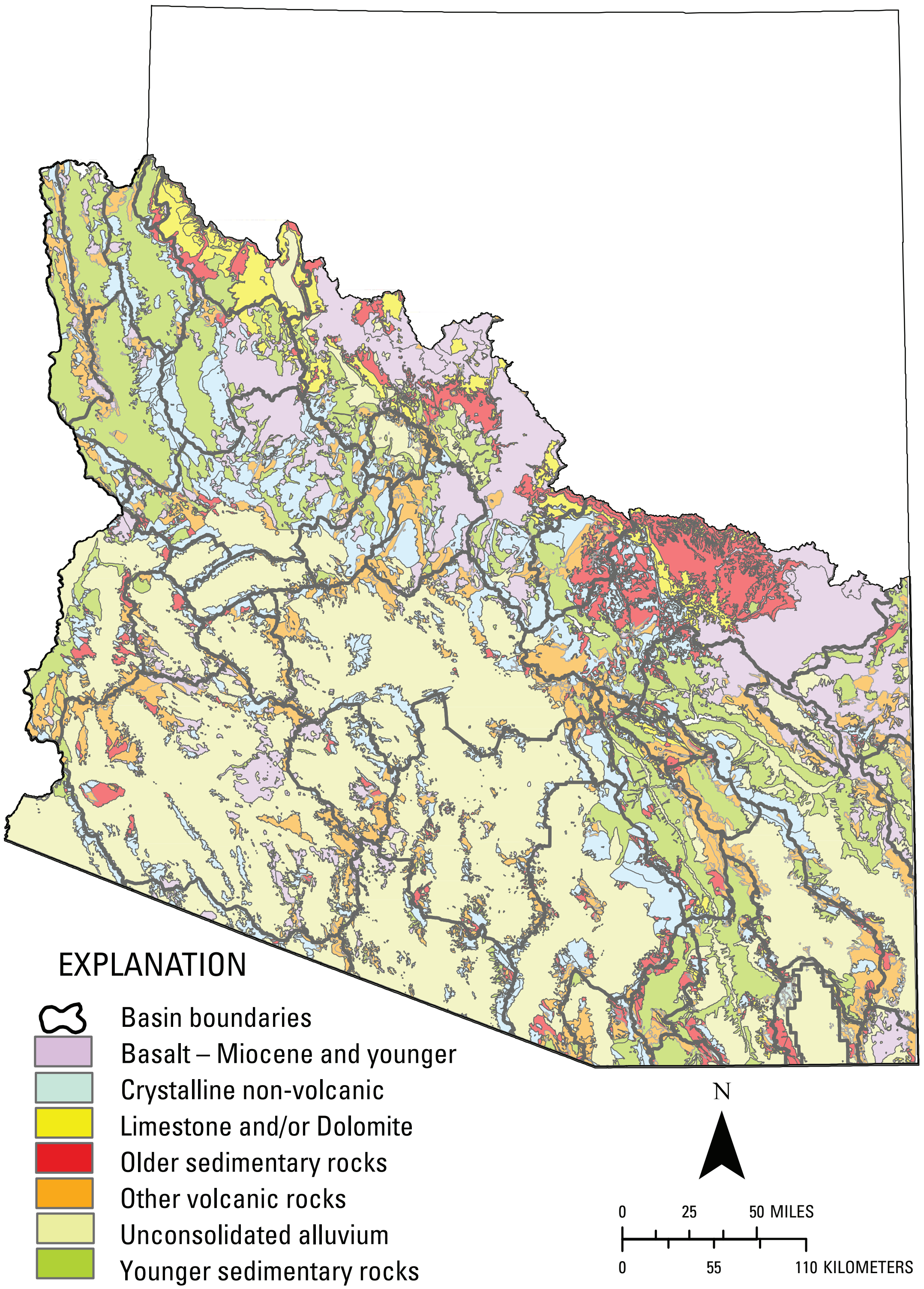


Figure 4. Map of generalized geology of study area, with classifications simplified from Hirschberg and Pitts (2000). Younger sedimentary rocks are of middle Miocene or younger age.

area. From the Ashurst-Hayden Diversion Dam east of Phoenix until it joins the Colorado River a few miles upstream of Yuma, the Gila River is ephemeral or effluent-dependent, with most of its flow being diverted for agricultural or industrial purposes (Arizona Department of Water Resources, 2009d). Draining the Central Highlands and tributary to the Gila River are the Verde and Salt River systems (fig. 6). The Salt and Verde River systems are managed through a series of six reservoirs and one diversion dam for the production of power and water for the Greater Phoenix metropolitan area, as well as for agriculture (Salt River Project, 2010). In southeastern Arizona, the San Pedro and Santa Cruz Rivers are the main rivers (fig. 6). Both are tributary to the Gila, and both are rivers shared between the United States and Mexico. They are now ephemeral or intermittent over much of their length.

Management of surface water in the study area generally falls to State (Arizona Department of Water Resources (ADWR)), Federal (BOR) or quasi-governmental (Central Arizona Project (CAP); Salt River Project) entities. Much of the study area is located within the Gila River Watershed, in which the Gila River adjudication (the determination of the extent and priority of surface-water rights) is ongoing (Judicial Branch of Arizona, 2008). In Arizona, appropriable surface water is defined under Section 45-141 of the Arizona Revised Statutes as water “flowing in streams, canyons, ravines or other natural channels, or in definite underground channels” (Feller, 2007). In the United States, entitlements to Colorado River water are decided by the U.S. Supreme Court multistate compacts, Congressional Acts, and the U.S.-Mexico Treaty of 1944 together with its amendments (Arizona Department of Water Resources, 2006). Together, the compacts, Acts, and the Treaty and its amendments are called the “Law of the River.” In Mexico, water is considered to be a nationally owned resource and is regulated by the Mexican National Water Commission (Comisión Nacional del Agua, 2008). Treaty-bound surface water crossing the U.S.-Mexico border is regulated by the International Boundary and Water Commission, a jointly operated agency that is a branch of the U.S. and Mexican State Departments.

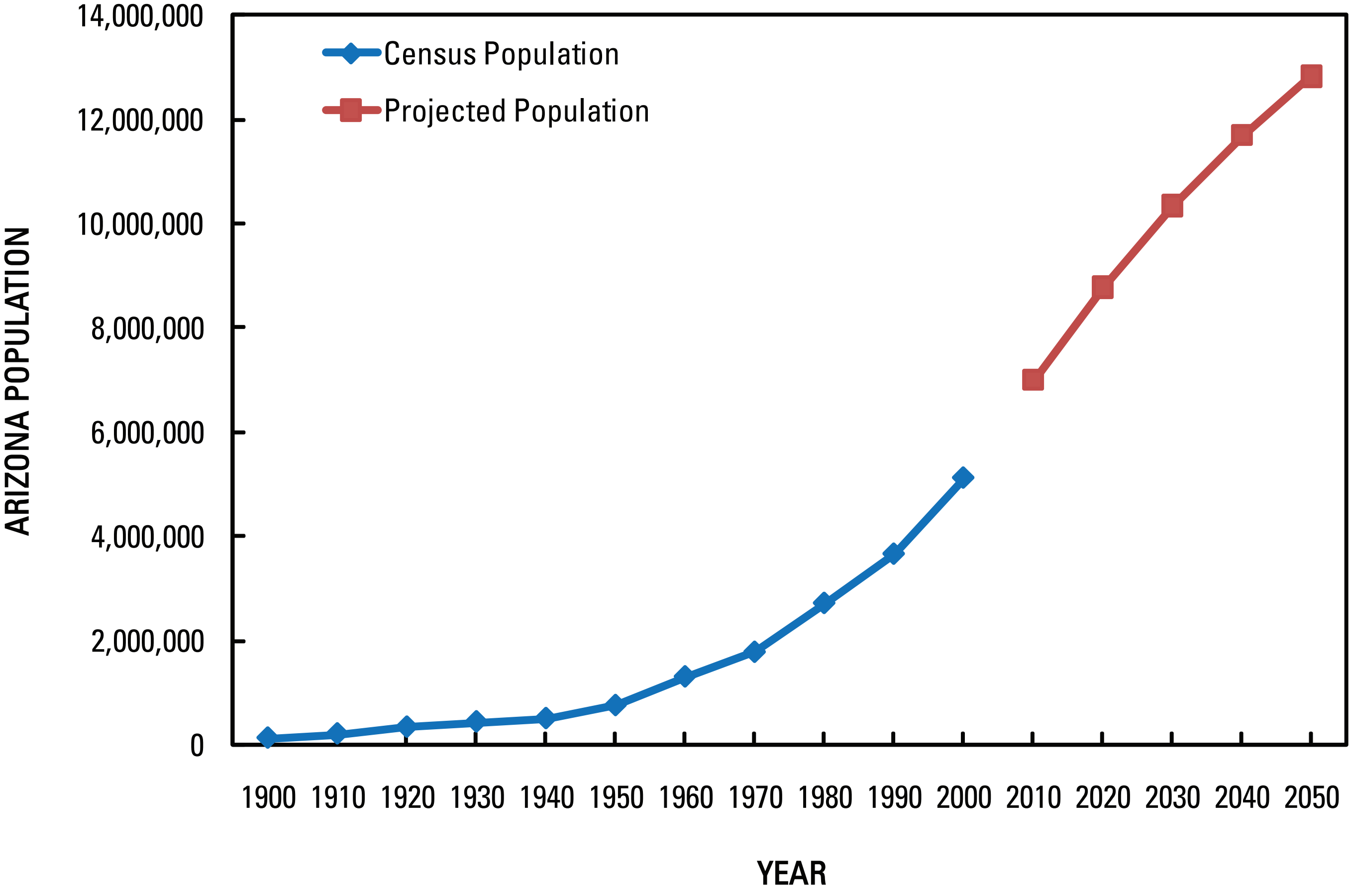


Figure 5. Reported (U.S. Census Bureau, 2009) and projected (Arizona Department of Commerce, 2010) population for the State of Arizona.

Figure 6. Location of major cities (yellow dots), the Central Arizona Project (CAP) canal (light blue lines), and major rivers (dark blue lines) in the study area.

Groundwater Resources and Management

The primary groundwater resources in nearly all basins in the study area are found either within older, unconsolidated basin-fill aquifers or recent stream-alluvium aquifers (Arizona Department of Water Resources, 2006, 2009a–e). Level of groundwater use tends to follow intensity of agriculture and population level. Groundwater is not used extensively in mountainous regions or in the large region immediately adjacent to the U. S.-Mexico border between the Santa Cruz Basin and the Colorado River. This area south of Interstate Highway 8 consists primarily of the Tohono O'odham Reservation and Federal lands including the Cabeza Prieta National Wildlife Refuge, Organ Pipe National Monument, and Barry M. Goldwater Air Force Range. By contrast, along the Lower Colorado, Gila, and Salt Rivers, where most of the population and agriculture in the State is found, groundwater demand is about 1 million acre-ft per year (Arizona Department of Water Resources, 2006, 2009a–e). With regard to management, the State is the primary regulator of groundwater and has three levels of management depending on local groundwater conditions (for example, current or potential overdraft, a condition in which more water is removed from an aquifer than is replenished) (Arizona Department of Water Resources, 2010a). The lowest level of management consists of rules that apply statewide except where superseded by higher levels of management. The next level is applied in Irrigation Non-expansion Areas (INA), in which it has been determined that there is insufficient groundwater to meet growing irrigation demand (Arizona Department of Water Resources, 2009a). There are two INAs in the study area: the Harquahala Basin and a portion of the Douglas Basin. The Douglas INA, created in 1980, includes the majority of the Douglas Basin in areas of highest water use. In the Douglas INA, it is legal to continue to irrigate land that was under irrigation at any time between January 1, 1975, and January 1, 1980 (Arizona Department of Water Resources, 2010b). In the Harquahala INA, which was added later, irrigation rights are based on land under irrigation between January 6, 1976, and January 6, 1981. The highest level of management is applied in Active Management Areas (AMA), because these areas have the most severe overdraft conditions. There are five AMAs in the study area. These are the Prescott, Phoenix, Pinal, Tucson, and Santa Cruz AMAs —locations with growing populations, rapidly declining water tables in some areas, and/or intensive pumping of groundwater for agriculture (Arizona Department of Water Resources, 2009e).

Effects of Development on Groundwater-Reliant Ecological Systems

Some perennial, groundwater-dependent reaches of the Santa Cruz, San Pedro, and Gila Rivers, as well as their tributaries, were longer before development than they are currently (Webb and others, 2007). The factors that affect baseflow and groundwater levels near streams and rivers are complex. The actual effects of the interactions among factors such as geology, recharge, surface water diversions return flow from irrigation, groundwater pumping, and riparian vegetation, are difficult to predict in all but the simplest settings. Groundwater pumping for agricultural and municipal use has brought about water-table declines of as much as hundreds of feet in some locations, with concomitant reductions in baseflow in some streams and rivers (Logan, 2002; Hoffmann and Leake, 2005; Thomas and Pool, 2006). These changes have affected and presumably will continue to affect the composition of riparian areas and aquatic ecosystems throughout the region, given that different plants and terrestrial and aquatic biota have particular requirements for flow regime and depth to water (Collins and others, 1981; Marchetti and Moyle, 2001; Leenhouts and others, 2006; Lake, 2007).

Water Quality

Water quality in surface water and groundwater in the study area varies considerably from good to poor. Some locations heavily affected by human activities have been designated as Arizona Water Quality Assurance Revolving Fund sites with remediation projects having been implemented in a number of areas (Arizona Department of Environmental Quality, 2010). Types of contaminants from both human and natural sources range from *E. coli* and pesticides to arsenic and mercury. Most contaminated surface water and groundwater lie in and downstream of population centers such as Phoenix and Tucson (Arizona Department of Water Resources, 2009a–f). Urban sources of contaminants include industry, wastewater treatment plants, and underground storage tanks. Some contaminated surface waters are located in rural areas with sources such as agriculture (nitrate or microbes), mining (metals), or natural sources such as ore deposits. Exceedances of primary Enviromental Protection Agency drinking-water standards for organic chemicals occur in certain reaches of the Gila, Santa Cruz, and San Pedro Rivers. Some reaches have been designated by the Arizona Department of Environmental Quality as impaired for exceedances of *E. coli* (Arizona Department of Environmental Quality, 2008). In surface water, copper, selenium, low dissolved oxygen, and cadmium are the most common causes of exceedances of designated use standards, but ammonia, mercury, boron, lead, nitrogen, chlorophyll, arsenic, zinc, phosphorus, pesticides, pH, turbidity, and sediment exceedances have also been found (Arizona Department of Environmental Quality, 2008; Arizona Department of Water Resources, 2009a–f). Metal contamination is derived from both natural and anthropogenic sources and is present in many areas where former mines and tailings piles are common. In groundwater, inorganic contaminants such as arsenic and fluoride, which are typically from natural sources, are the most common cause of exceedances of primary drinking water standards in wells, but there are many others. Nitrate from agricultural sources is also a problem in groundwater and surface water (Arizona Department of Water Resources, 2009a–f). Water exceeding the EPA secondary drinking water standard for total dissolved solids (TDS) is found in the Colorado, Gila, and Salt Rivers and in portions of nearly every basin-fill aquifer in the study area (Anning and others, 2007). The regional problem of elevated levels of TDS is underscored by Minute 242, a 1974 agreement between the United States and Mexico that specifically regulates TDS concentrations in Colorado River water delivered to Mexico (Arizona Department of Water Resources, 2009d). Emerging contaminants (those that may have health effects, but are not currently regulated) have been detected in the study area at some of the highest levels in the United States, but comprehensive sampling has not been done and published work indicates that they may be much more widespread than previously thought (Barnes and others, 2002; Barnes and others, 2008). Emerging contaminants include a wide variety of compounds such as flame retardants, pesticides and solvents, drug metabolites including hormones, and antimicrobial compounds used in personal care products. In surface water, suspended sediment is a problem wherever conditions such as construction, vegetation removal, and fire promote erosion and transport (U.S. Department of Agriculture, 2000; Pierson and others, 2007). Drought, rapid population growth, and development augment the naturally high rates of erosion and sediment transport in the study area. Sediment deposition and scour can change the permeability of streambed sediments, thereby altering interactions of groundwater and surface water (Schubert, 2002; Dunkerley, 2008).

Sensitivity of Water Supplies to Climate

Studies of the impact of climate change in the southwestern United States have come to the general conclusion that, as global temperature increases, drier conditions will increasingly dominate across the region (Garfin and Lenart, 2007). Increased evapotranspiration due to rising temperatures will more than likely offset any increase in precipitation with respect to water availability. It is predicted that rainfall will be more skewed to extremes, with the frequency of both large precipitation events and periods of drought increasing. Overall, the effects of climate change are expected to be decreased baseflow in streams and rivers, more catastrophic flooding, and greater erosion, with likely effects on groundwater resources as well (Lenart and others, 2004; Serrat-Capdevila and others, 2007). With increased evapotranspiration, a decline in precipitation during spring months, and consequent decline in surface-water availability, irrigated agriculture will likely become increasingly dependent on groundwater (U.S. Global Change Research Program, 2010).

SWAB Groundwater Availability Issues

Water use in Arizona is dominated primarily by agriculture and secondarily by growing urban populations (Tadayon, 2005). Agriculture is a $6.3-billion industry in the State, comprising more than 7,500 farms and ranches (University of Arizona, 2005). Arizona ranks second in the United States in production of head lettuce, leaf lettuce, romaine lettuce, cauliflower, broccoli, and lemons; third in production of tangerines; and fourth in production of oranges and grapefruit (University of Arizona, 2005). In the study area in 2003, agriculture accounted for nearly 5.3 million acre-ft of water use, or roughly 70 percent of the total 7.6 million acre-ft of water used in the study area (Tadayon, 2005; Arizona Department of Water Resources, 2006). Nearly 46 percent of this agricultural water use was supplied by groundwater, with the remainder supplied by native surface water (in particular, the Colorado River for agriculture near Yuma and in the Parker Basin), Central Arizona Project (CAP) water, and wastewater treatment plant effluent (Tadayon, 2005; Arizona Department of Water Resources, 2006). Nearly all of the agricultural land in Arizona is within the SWAB study area, primarily in the Phoenix, Pinal, and Tucson Active Management Areas (AMAs); in Harquahala INA; in McMullen Valley and Ranegras Plain; along the Gila River in Gila Bend Basin; along the Colorado River in Parker and Yuma Basins; and in the Douglas, Willcox, and Safford Basins in the eastern part of the State (figs. 2, 3). Municipal water use ranks a distant second to agriculture in the study area, with nearly 1.5 million acre-ft used in 2003, of which 39 percent was supplied by groundwater (Tadayon, 2005; Arizona Department of Water Resources, 2006). In the absence of new conservation measures, recent and projected population growth in Arizona (fig. 5) will most likely result in an increase in municipal water use in the State.

Through the Colorado River Compact of 1922 (approved by Arizona in 1944), Arizona is entitled to 2.8 million acre-ft of Colorado River water (Colby and Jacobs, 2007). Construction on the CAP canal and associated facilities began in 1973 and was completed 20 years later at a cost of more than $4 billion (Central Arizona Project, 2010). The CAP canal (fig. 6) stretches 336 miles from Lake Havasu just north of Parker to Tucson and is designed to deliver 1.5 million acre-ft of Arizona's Colorado River allotment to interior basins (Central Arizona Project, 2010). CAP water is used for municipal, industrial, and agricultural purposes and is a source of water for six aquifer recharge projects in the State (Central Arizona Project, 2010).

Although groundwater in the basin-fill aquifers is a major resource for the region, development of this resource can result in some undesirable consequences. In addition to declining groundwater levels discussed in the section "Analysis of Groundwater Conditions Using Groundwater-Level Databases" and loss of groundwater in storage discussed in the section "Regional Groundwater Budgets" in this report, major consequences have included land subsidence and associated earth fissures and reduction in size or flow of surface-connected groundwater features such as streams, springs, wetlands, and areas of evapotranspiration of groundwater by riparian plants.

Land subsidence is the sinking of the land surface. A major cause of land subsidence in the Southwest is drainage of groundwater from the clay and silt sediments in or next to aquifers (Galloway and others, 1999). As groundwater levels in the aquifers decline, the drainage from the clay and silt layers causes them to compact, resulting in lowering of the land surface. Land subsidence causes many problems, including (1) changes in elevation and slope of streams, canals, and drains; (2) damage to bridges, roads, railroads, storm drains, sanitary sewers, canals, and levees; (3) damage to private and public buildings; and (4) failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems. Uneven land subsidence also can cause earth fissures. In the study area, earth fissures associated with land subsidence have been observed to be more than 30 meters deep and several hundred meters in length. One extraordinary fissure in central Arizona is more than 9 miles long (Carpenter, 1993). These features start out as narrow cracks, a few centimeters or less in width. They can intercept surface drainage and erode to widths of several meters at the land surface. Significant amounts of subsidence, with or without associated earth fissures, have been detected in nearly all basins in the study area that have experienced historical groundwater withdrawals for agriculture. For details on locations of recent subsidence detected by satellite imagery, see *http://www.azwater.gov/azdwr/Hydrology/Geophysics/LandSubsidenceMaps.htm* (accessed May 11, 2010). For maps of known earth fissures in the study area, see *http://www.azgs.state.az.us/EFC.shtml* (accessed May 11, 2010).

Loss of streams, springs, wetlands, and riparian evapotranspiration areas can occur as groundwater withdrawals intercept natural groundwater discharge to these features. The effects of groundwater withdrawals on these features depend on aquifer properties, proximity of withdrawals to the features, and time since withdrawals began and normally are proportional to the withdrawal rate. When water is initially withdrawn from a well, all of the water comes from aquifer storage around the well. A cone of depression develops around the well and the gradient of the groundwater head is the driving force for movement of water into the well. If the aquifer is unconfined, nearly all of the storage change is from draining of pore spaces at the water table. As withdrawals continue, the cone of depression will expand to increasing distances from the well. When the cone of depression expands to the vicinity of features such as connected streams, wetlands, rivers, and lakes, the effect is to change the natural gradients that drive water to or from these features. For features that receive groundwater discharge, the effect is to decrease the gradients and groundwater flow to these features. Some features that once received discharge may actually begin to provide recharge. For features that supply water to the aquifer, the effect is to increase the gradients and flow from these features. In either case, there is a loss of available surface water. If the features are riparian areas where plants that use groundwater (phreatophytes) are present, the effect is to lower the water table and reduce the amount of water available to and consumed by the plants, sometimes causing the riparian areas to disappear.

As previously mentioned, the time over which all or nearly all of groundwater withdrawals are supplied by reduced flow in connected features is dependent on the proximity of the withdrawal wells to features that can supply water and the hydraulic properties of the aquifer. In general, wells that are close to connected features will receive water from these features much faster than more distant wells. In cases where wells are tens of miles from connected surface water, the time at which depletion of surface features becomes the dominant source of water to the well can be decades or even centuries after withdrawals begin. If the volume of water withdrawn exceeds the supply that can be captured from connected features, the features may become disconnected, resulting in drying of streams, springs, and wetlands and reduction of areas of riparian evapotranspiration. In that case, withdrawals in excess of the maximum capture will be met by further removal of water from storage in the aquifer. This has been the course of events in the Tucson Basin, with loss of riparian trees along the Santa Cruz River (Webb and others, 2007).

Basin-fill aquifers in the study area that do not have connected surface-water features or groundwater evapotranspiration areas are not susceptible to loss of these features as a result of groundwater withdrawals. Continued groundwater withdrawals in those aquifers will result in possible decrease in underflow to downgradient aquifers, increase in underflow from upgradient aquifers, continued depletion of groundwater storage, or a combination of these effects.

Analysis of Groundwater Conditions Using Groundwater-Level Databases

Several indicators of groundwater conditions were developed for the study area using groundwater-level observations in existing databases. The development and application of these indicators are described in detail in Tillman and others (2008). Briefly, computer programs were written to combine and analyze different groundwater-level datasets, to produce geographic information system (GIS) input files, and to create groundwater-level hydrographs for display of groundwater conditions (Tillman, 2009). These methods result in indicators of groundwater conditions that address different spatial and temporal scales of the aquifer systems. Groundwater-level data from the USGS National Water Information System (NWIS) and the Arizona Department of Water Resources' Groundwater Site Inventory were used for these analyses. The utility of these indicators is that they are based on actual observed groundwater levels (not interpolated groundwater surfaces or groundwater modeling simulations), are easily understood by people with a wide range of backgrounds, and can be presented in a publicly accessible online mapping system (http://az.water.usgs.gov/projects/azgwconditions/index.html). A limitation of these indicators is that conclusions that can be drawn from them are limited by the spatial distribution and temporal frequency of available groundwater-level data. For example, geographic areas with extensive groundwater development generally have more groundwater-level data than other areas. This may lead to a bias toward greater groundwater depths for these areas than are presented for other less developed basins in the SWAB region. Also, groundwater levels may begin to be recorded in a well after groundwater levels in the area have already begun to decline or rise. Estimates of actual groundwater-level declines or rises based on these observations would therefore be underestimated.

Temporal information on groundwater-level declines and rises is presented by dividing the datasets into two groups: a “historical” group with groundwater-level declines or rises that cease to be observed before 1997 and a “recent” set with declines or rises that continue to be observed between 1997 and 2006. Wells may only appear in one group or the other. Groundwater-level observations flagged as pumping were not used in any analysis. Owing to time and budget constraints, groundwater indicators for only the 19 basins with the greatest historical groundwater withdrawals were developed and are presented here. These basins account for more than 96 percent of the estimated groundwater withdrawals in the State through 1987 (Konieczki and Wilson, 1992) and are referred to as the “most developed basins” in this section. For each indicator presented, with the exception of Recent Depth to Groundwater, hydrographs of all wells meeting the selection criteria were visually inspected to ensure a qualitative agreement between the groundwater-level data and the indicator.

Recent Depth to Groundwater

The most recent 2004–06 depth-to-groundwater observations for wells in the most developed basins of the study area (fig. 7) indicate that shallow depths to groundwater (0 to about 50 feet below land surface) are present along the riparian corridors of the San Pedro, Upper Santa Cruz, and Gila Rivers (fig. 6). Numerous deeper depth-to-groundwater observations (>400 feet) are seen in the agricultural areas of Harquahala INA, McMullen Valley, Phoenix AMA, and the western portion of the Tucson AMA. Of the 6,143 wells with one or more groundwater-level observations in the 2004–06 time period, the majority have depths to groundwater of 200 feet or less, with 33 percent from 0 to 100 feet and 23 percent from 100 to 200 feet (fig. 8). However, 570 wells, or 9 percent of wells with observations in this time period, have depths to groundwater of greater than 400 feet. Groundwater may be at greater depths in the higher elevation portions of a basin simply because of topography, limiting the usefulness of depth-to-groundwater as an indicator of groundwater depletion.

Groundwater-Level Decline

Groundwater development in the study area has caused sometimes dramatic groundwater-level declines. Some of these recorded groundwater-level declines occurred only during past time periods, whereas others have continued until more recently. As previously described, two categories of groundwater-level decline were defined for the study area: declines that ceased to be observed before 1997 and declines that continued to be observed from 1997 through 2006 (fig. 9). Note that groundwater-level declines in wells may no longer be observed for several reasons, including that the well has gone dry, that monitoring has ceased at the well, that nearby groundwater withdrawals have been reduced, or that nearby groundwater levels have risen, among others. For these analyses only wells with maximum observed groundwater-level declines of 75 feet or more, with at least three groundwater-level observations defining the decline, are presented (Tillman and others, 2008). The 75-ft threshold was chosen to minimize the presentation of wells with water levels that were oscillating and not truly declining. Significant groundwater declines of more than 350 feet before 1997 are evident in wells in the agricultural areas of Harquahala INA, central and southeastern Phoenix AMA, and Pinal AMA (fig. 9). Although fewer in number, declines of greater than 350 feet continued to be recorded between 1997 and 2006 in McMullen Valley, Phoenix and Pinal AMAs, and Safford Basin. Of the 1,962 wells in the study area that have at least 75 feet of groundwater-level decline in their period of record, 57 percent cease to indicate declines before 1997 (fig. 10). The majority of recorded declines for both time periods were in the 75 to 150 ft range, with a decrease from 17 to 6 percent of the declines greater than 250 ft from the pre-1997 to the 1997-and-after time frames (fig. 10).

Groundwater-Level Rise

Groundwater management actions in the study area, including the importation of CAP water from the Colorado River to interior basins and the retirement of agricultural land, has contributed to rising groundwater levels in wells in some areas (fig. 11). For these analyses only wells with maximum observed groundwater-level rise of 50 feet or more, with at least 3 groundwater-level observations defining the rise, are presented (Tillman and others, 2008). The 50-ft threshold was chosen to minimize the presentation of wells with water levels that were oscillating and not truly rising. Some 300 wells indicate a maximum rise in groundwater levels of at least 50 feet before 1997, including 3 wells with more than 300 feet of recorded groundwater-level rise in Harquahala INA (figs. 11, 12). Many wells in areas with significant pre-1997 declines have seen post-1997 groundwater-level rises, including Harquahala INA, eastern Phoenix AMA, and the Maricopa-Stanfield and Picacho Basins of Pinal AMA (fig. 11). Of the 1,436 wells that showed groundwater-level rise of at least 50 feet during their period of record, 1,130, or 79 percent, continued to rise in 1997 or later (fig. 12). Most of the recorded rise in groundwater levels is in the 50 to 150 ft range (92 percent of rising wells before 1997 and 85 percent of wells continuing to rise during or after 1997).

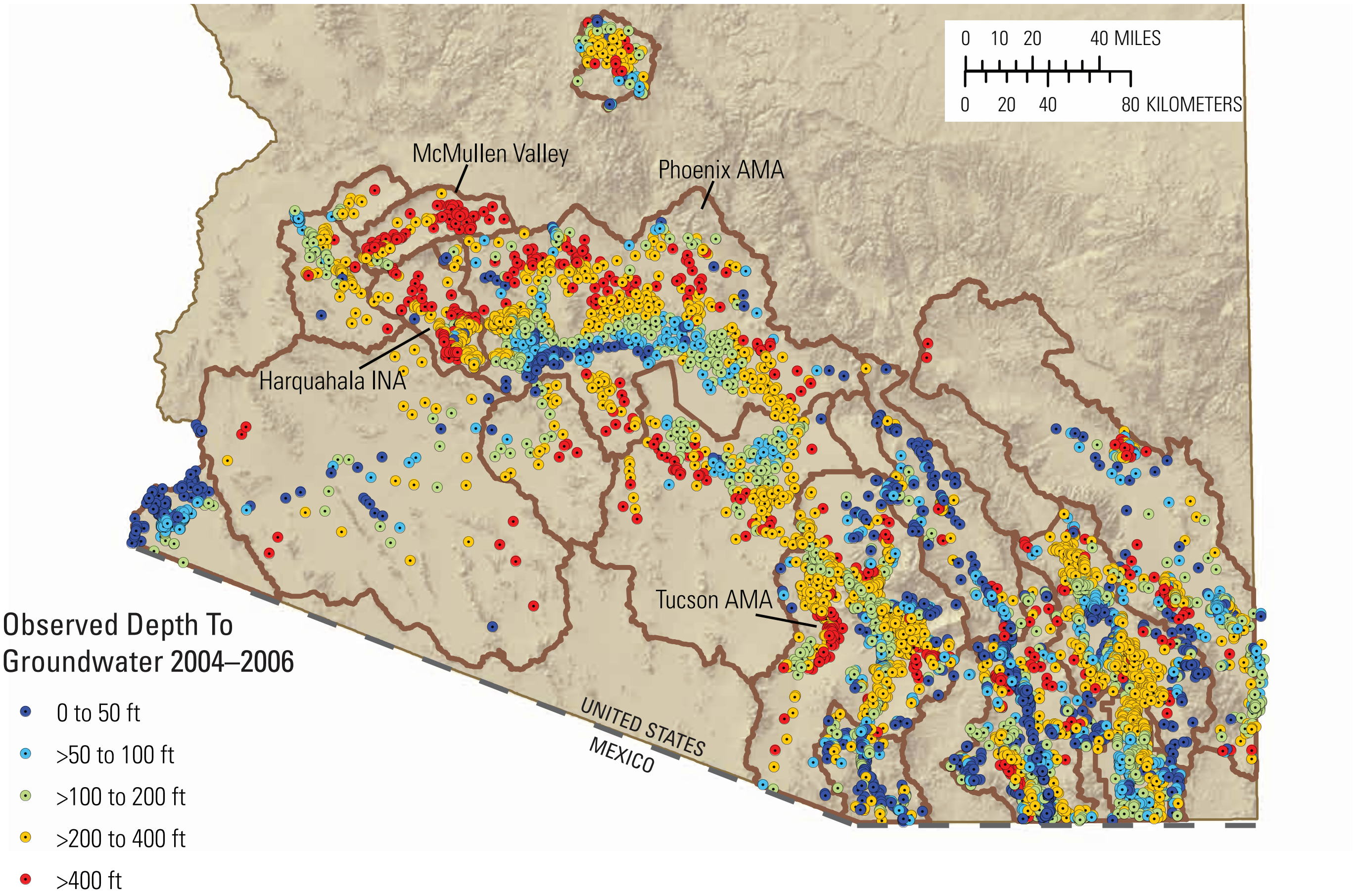


Figure 7. Depth to groundwater in wells with observations between 2004 and 2006 for basins with the most groundwater use (outlined in brown) in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

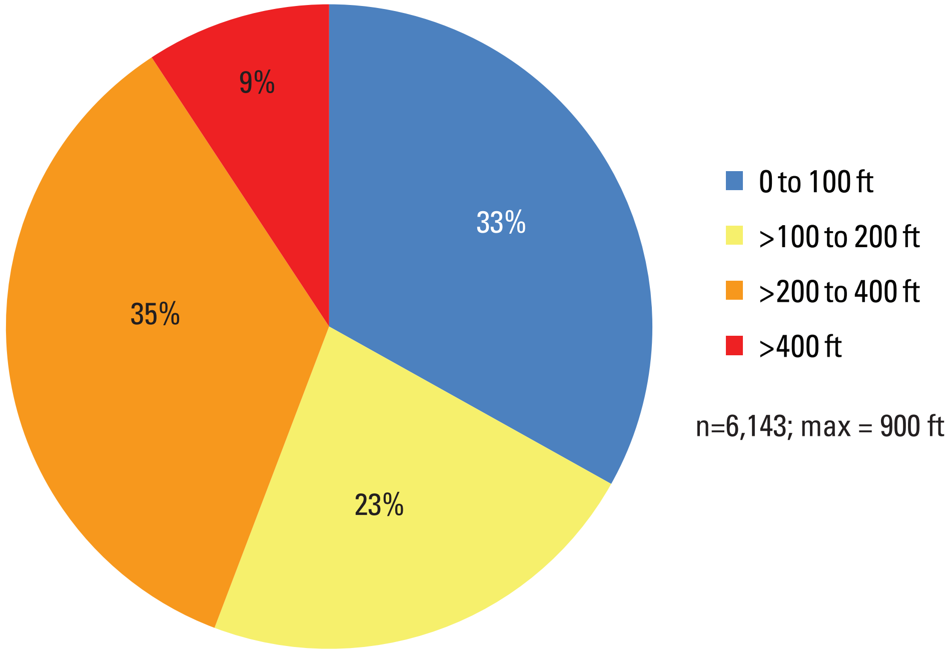


Figure 8. Pie diagram summarizing depth to groundwater in wells with observations between 2004 and 2006 in basins with the most groundwater use in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

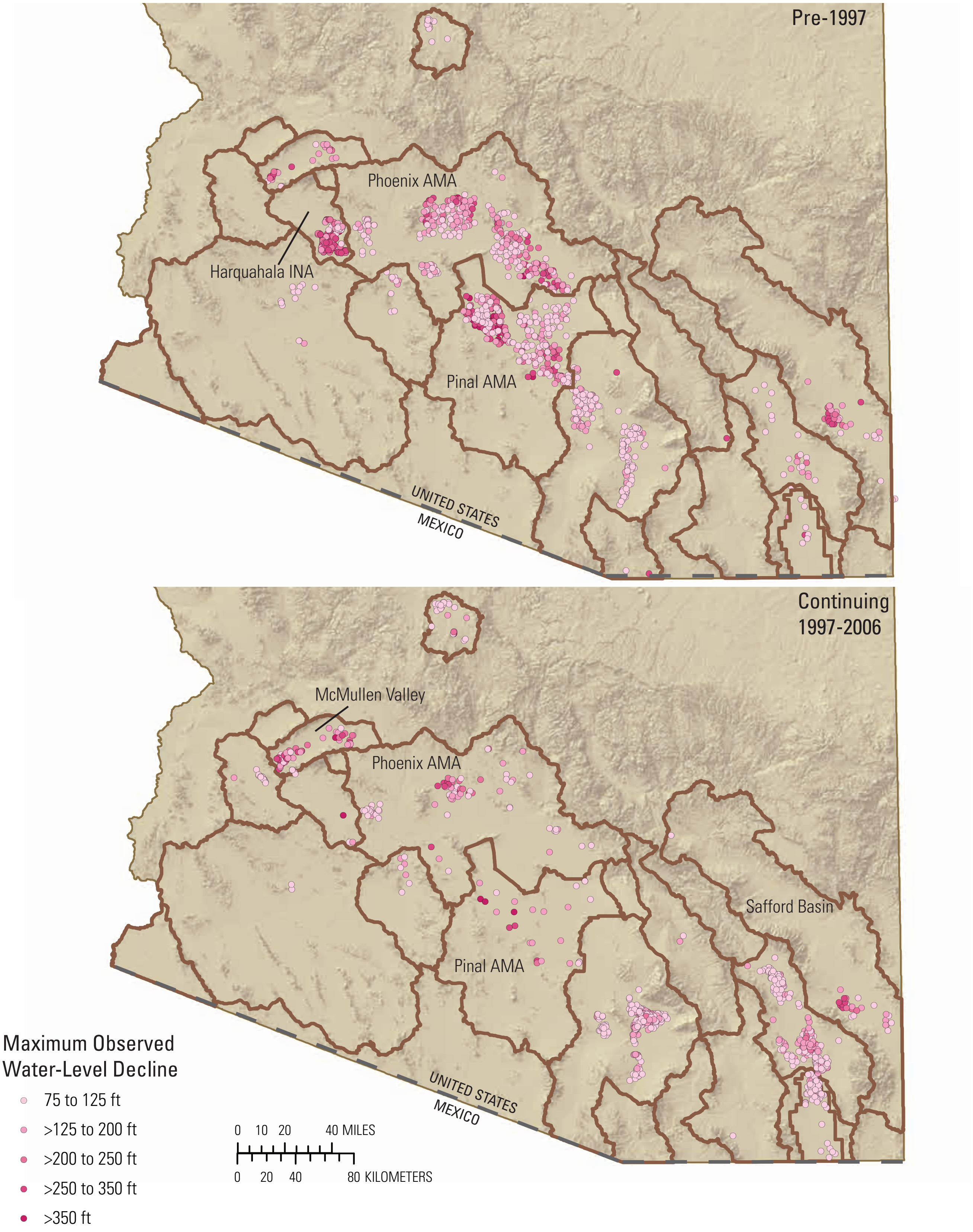


Figure 9. Wells indicating declines in groundwater levels of at least 75 ft ending before 1997 (top) and continuing after 1997 (bottom) for basins with the most groundwater use (outlined in brown) in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

Recent Trends in Groundwater Levels

Although analysis of the magnitude and location of groundwater-level declines and rises in wells is important to understanding groundwater conditions, information on recent trends in groundwater levels may be a better indicator of the current and near-future status of the aquifer system in the SWAB study area. A method was developed for computing linear trends in groundwater level data and presenting these trends as modified Thiessen polygons for visualization (Tillman and others, 2008; Tillman and Leake, 2010). Trends in groundwater levels were computed for wells in the most developed basins of the study area for the time period 1997 through 2006, with the trends classified as falling (water levels declining more than 1 ft per year), rising (water levels rising more than 1 ft per year), or nearly stable (water levels between these two categories; fig. 13). Criteria for inclusion in the recent trends analysis were no observations flagged as pumping, at least three observations during the time period of interest (84 percent of the final wells had more than three observations), and an R^2 of linear fit at least 0.75. Visual inspection of hydrographs for each well in the final trend analysis was performed to ensure that the computed linear trend in groundwater levels qualitatively represented the

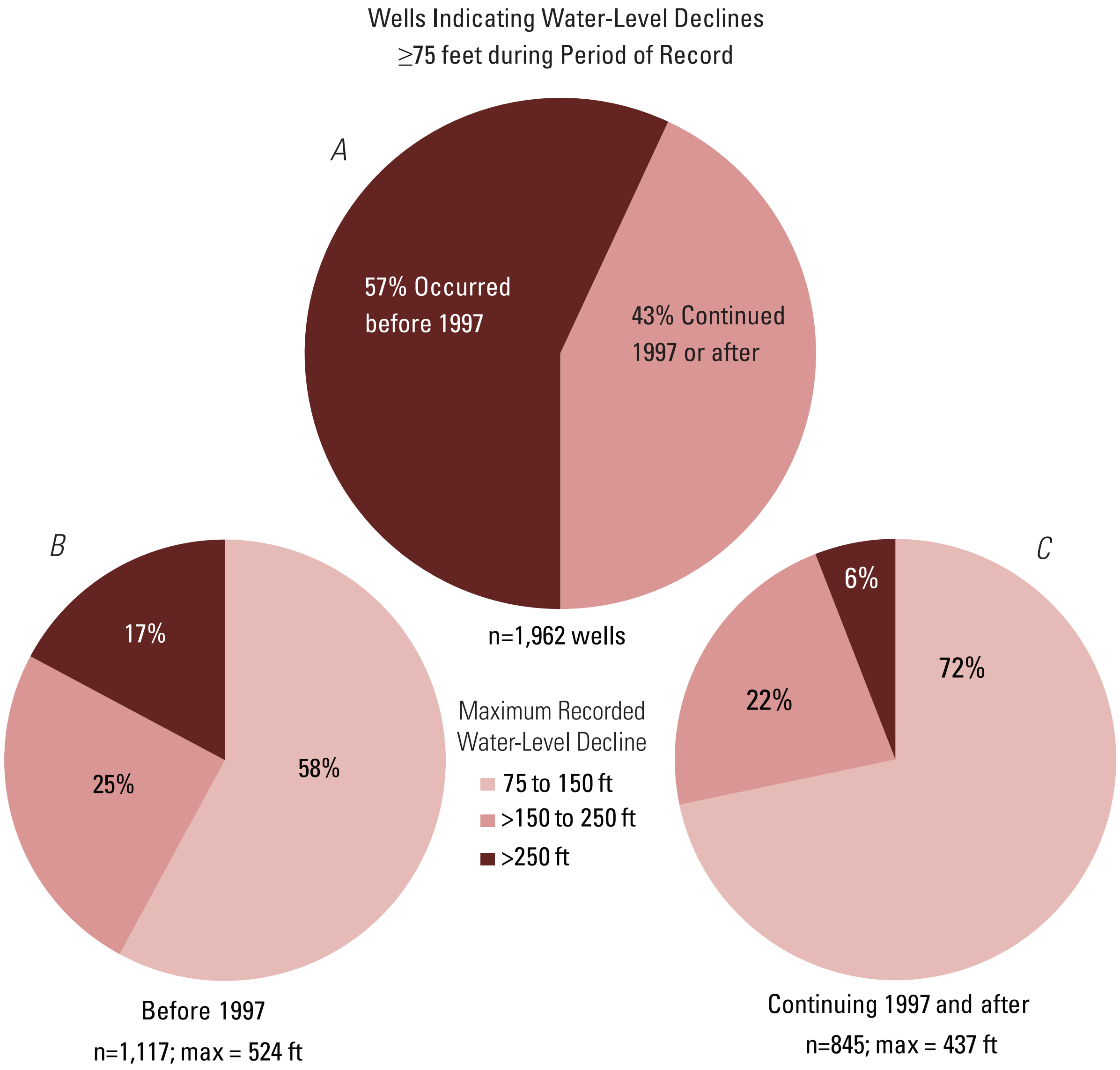


Figure 10. Pie diagrams summarizing wells indicating water-level decline of at least 75 ft in basins with the most groundwater use in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007). *A*, Distribution of wells with decline before and after 1997. Maximum recorded water-level declines observed before 1997 (*B*) and continuing after 1997 (*C*).

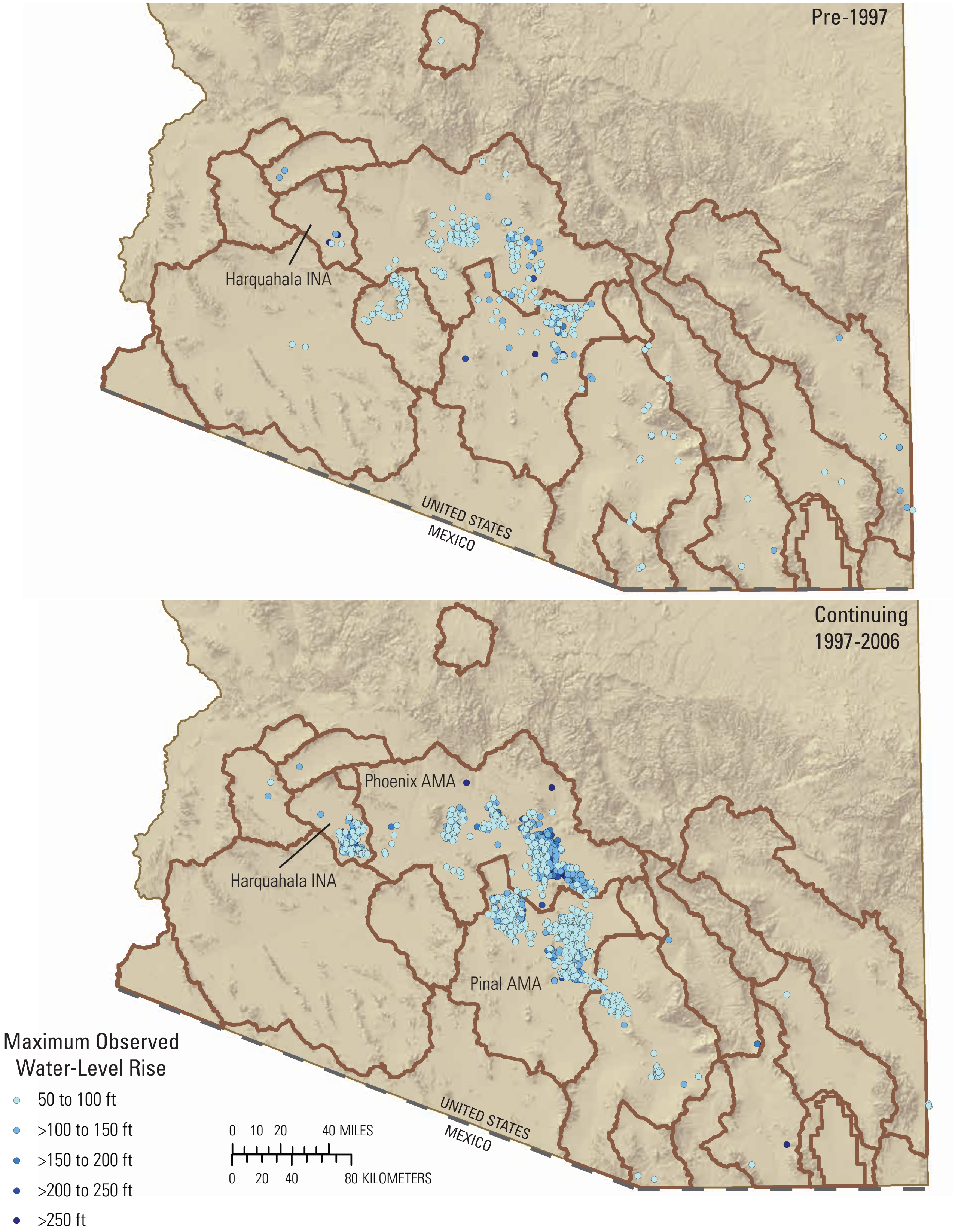


Figure 11. Wells indicating rises in groundwater levels of at least 50 ft ending before 1997 (top) and continuing after 1997 (bottom) for basins with the most groundwater use (outlined in brown) in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

trend in the data. Of the 1,279 wells with data that fit the trend analysis method criteria, 53 percent indicated falling groundwater-level trends (fig. 14). Groups of wells with falling groundwater-level trends are particularly evident in central Tucson AMA, northeastern Pinal AMA, central Phoenix AMA, Gila Bend Basin, McMullen Valley, Prescott AMA, and central Willcox Basin. Areas with rising groundwater-level trends include western Tucson AMA, northwestern Pinal AMA, southeastern Harquahala INA, and portions of eastern Phoenix AMA along the CAP canal (fig. 13; fig. 6).

Regional Groundwater Budget

A water budget states that the rate of change in the water stored in an accounting unit (sample volume) such as an aquifer is determined by the rate at which water flows into that unit minus the rate at which water flows out of it (Healy and others, 2007). A groundwater budget is an accounting of the inflow to, outflow from, and storage change in an aquifer for a select time period (Hollet and others, 1991). A groundwater budget can be used as an indication of whether the aquifer

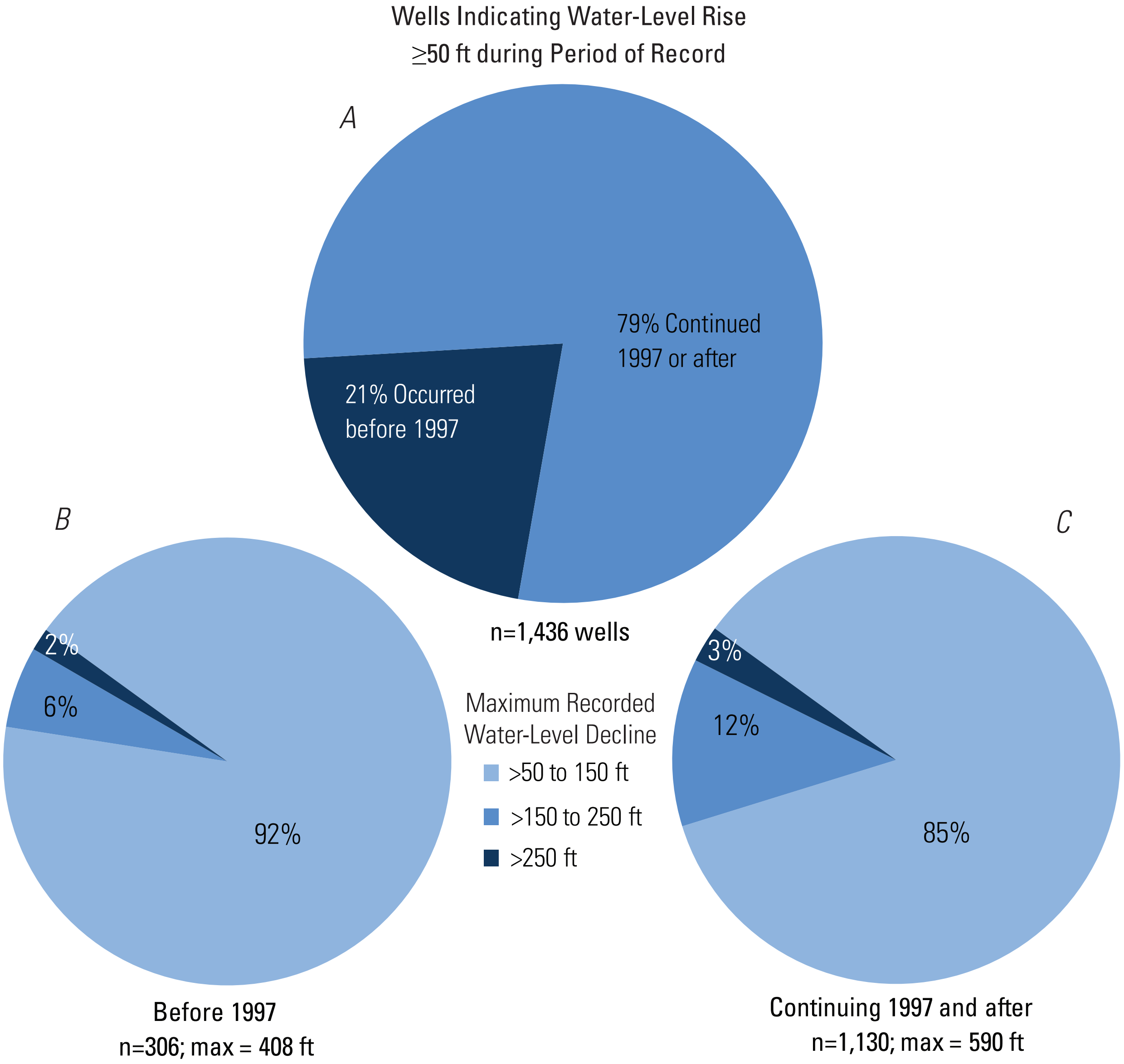


Figure 12. Pie diagrams summarizing wells indicating water-level rise of at least 50 ft in basins with the most groundwater use in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007). *A*, Distribution of wells with rise before and after 1997. Maximum recorded water-level rise observed before 1997 (*B*) and continuing after 1997 (*C*).

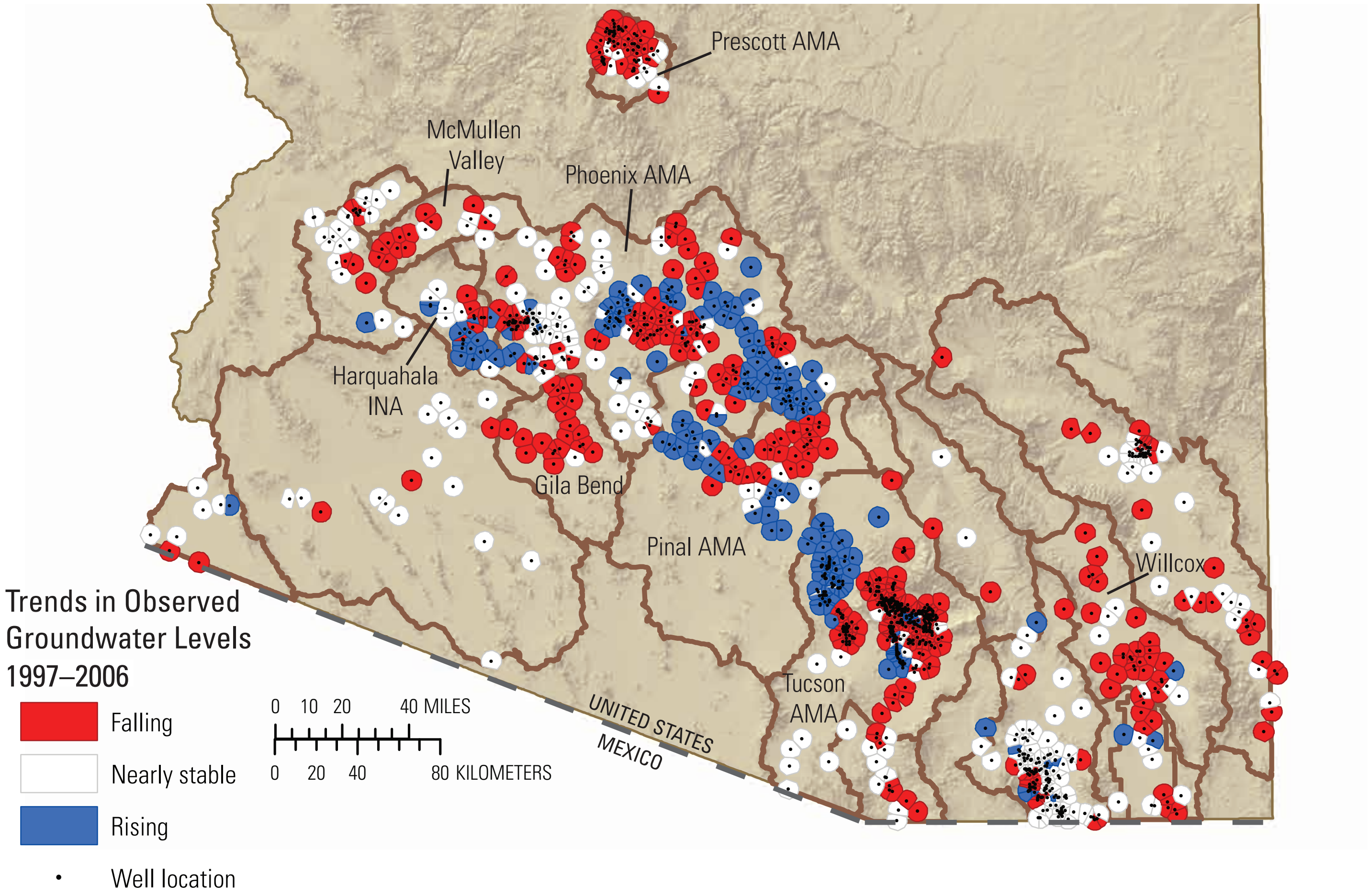


Figure 13. Trends in groundwater levels in wells for observations between 1997 and 2006 for basins with the most groundwater use (outlined in brown) in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

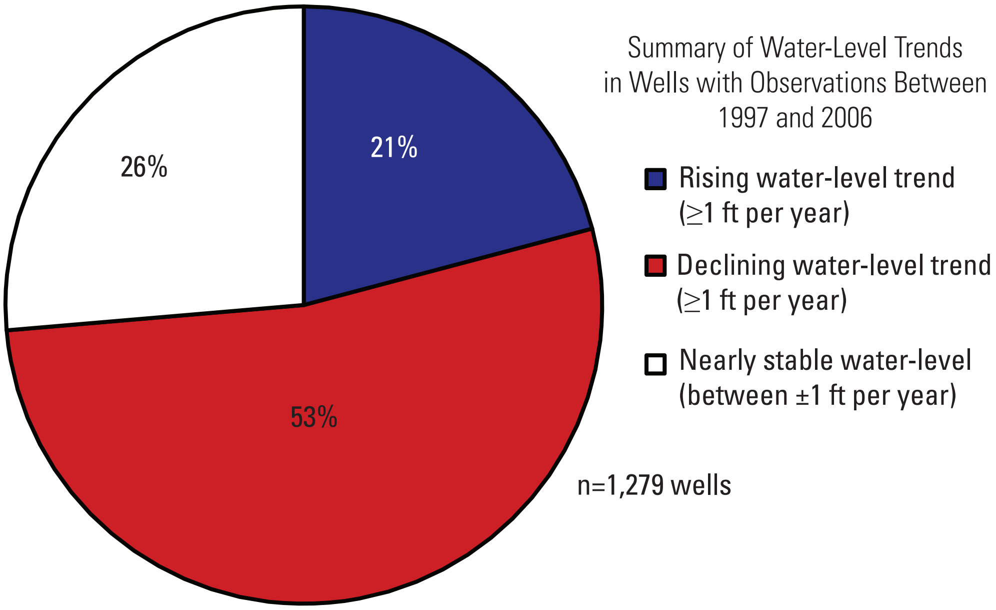


Figure 14. Pie diagram summarizing trends in water levels in wells for the 1997–2006 time period in basins with the most groundwater use in the alluvial basins of Arizona (U.S. Geological Survey, 2010; Arizona Department of Water Resources, 2007).

storage is in a deficit, gaining, or stable condition. If aquifer inflow equals the outflow, then the aquifer is in a steady-state condition or equilibrium, with no change in storage. An aquifer in equilibrium exhibits little or no change in water levels, or it may exhibit fluctuations of water levels with no long-term rise or decline. When the total inflow does not equal the total outflow, the aquifer is in a transient, or nonequilibrium, state and change in the volume of groundwater in storage (increasing or decreasing) is reflected by changes in groundwater levels.

This study presents selected groundwater budget components for the study area related to the groundwater system from before development (circa before 1940) to current conditions (2000–2006). The predevelopment period is considered a time period before large-scale human-induced changes to the groundwater-flow system occurred. This section begins with discussion of precipitation and runoff for the study area. Natural groundwater-budget components considered here include (1) mountain-front recharge, (2) recharge by seepage from streams, (3) evapotranspiration, and (4) underflow. The human-affected components of the groundwater budget are addressed next, including (1) public-supply withdrawals, (2) irrigation withdrawals, (3) incidental recharge from irrigation, and (4) artificial CAP and treated-effluent recharge. These four water-use components of the groundwater budget are presented for 1980 and for 2005. Groundwater is also used for mining and industrial purposes in the study area, but on the basis of 1985 and 2005 data from USGS reports, these groundwater withdrawals represent less than 5 percent of the total groundwater withdrawals in the study area and were not included in this study (Solley and others, 1988; Kenny and others, 2009). Storage change, a result of imbalances between aquifer inflows and outflows, also is addressed.

For this study, several standard and new methods of data interpretation were used to independently calculate the components of the groundwater budget. Existing datasets were compiled to estimate the water-use component of the groundwater budget. A new method using remote-sensing data was used to estimate the evapotranspiration component of the groundwater budget, and a distributed parameter water-balance model was used to estimate groundwater recharge.

Seven basins (or, in the case of AMAs, management areas) in the study area were designated as focus basins. These basins are (1) Detrital Valley, (2) Yuma, (3) Verde River, (4) McMullen Valley, (5) Phoenix AMA, (6) Tucson AMA, and (7) Safford basins (fig. 2). These basins were selected because they represent the variability of climate conditions in the study area and have experienced, or are projected to experience, large population growth that could add stress to the groundwater system. In addition, each of these basins has experienced different levels of urban and agricultural development. Temporal information on groundwater budget components, where available, is presented for each of the focus basins.

Precipitation

Although not strictly a groundwater budget component, precipitation is the original source for all inflows to the groundwater system. Precipitation may be directly recharged to an aquifer through permeable rocks and sediments, may become runoff that then infiltrates to become recharge in the basin, or may provide flow in streams that become recharge sources either as they flow through a basin or as their flow is channeled to agricultural fields or recharge facilities (such as through the CAP). The change in total volume, intensity, and timing of precipitation can have a major impact on the amount of recharge reaching an aquifer. An understanding of changes in precipitation through time for the study area may therefore be considered a first indicator of how inflow components to the groundwater system may have changed through time.

Methods

For this study, PRISM (Parameter-elevation Regressions on Independent Slopes Model) data were used to analyze changes in precipitation in the basins of the study area, as well as to provide precipitation input for recharge and runoff estimations (Daly and others, 1994). Briefly, the PRISM system calculates monthly and annual precipitation estimates (among other climatic parameters) at a 2.49-mi (4-km) grid scale using point-measurement data, a digital elevation model (DEM), and other spatial datasets (Daly and others, 1994). The 2.49-mi grid monthly PRISM precipitation data for the study area were summed over each water year (October through September) between 1940 and 2006. These annual values were then averaged over 10-year periods and over the 1940–2006 period of record, and were summed by basin (table 1)[1].

Results

During the 1940–2006 time period, on average nearly 50 million acre-ft of precipitation fell annually on the Southwest Alluvial Basins study area (table 1). Average annual PRISM precipitation for the 1940–2006 time period in individual 2.49-mi grid cells ranged from a low of 2.8 inches in the Yuma Basin to a high of 40.2 inches in the Salt River Basin, with most grid cells in the study area falling in the range 2.8 to 15 in. (fig. 15). Among the focus basins, the average decadal and 66-year period-of-record PRISM precipitation indicate the higher elevation Verde River Basin in the northern portion of the study area received the most precipitation, whereas the lower elevation Yuma Basin in the southern portion of the study area received the least (fig. 16). The data indicate that the focus basins, located throughout the State, have all experienced similar overall patterns in average decadal precipitation since 1940. During the decades of

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[1] Tables 1–29 are grouped at the end of the report, starting on p.78.

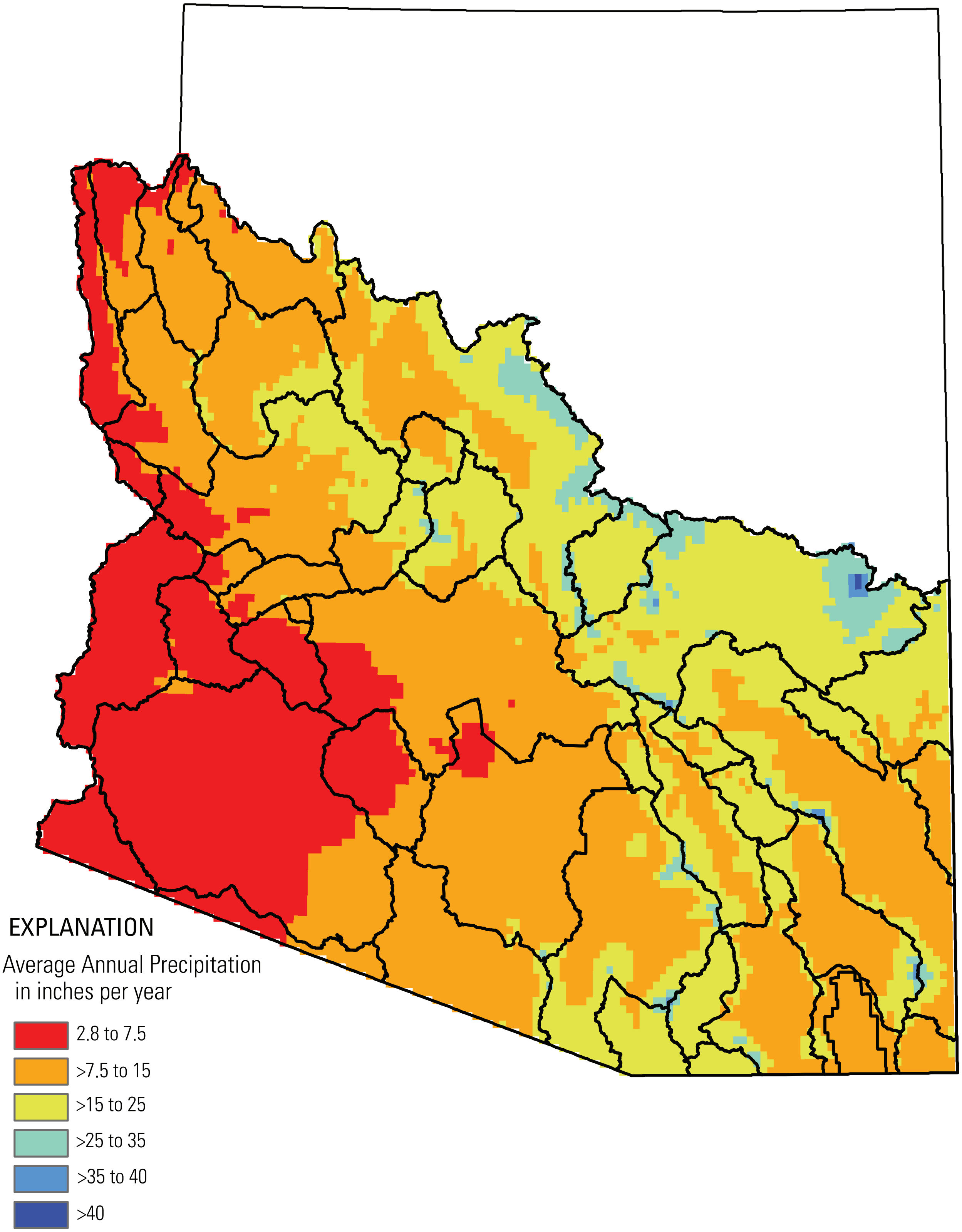


Figure 15. Average annual precipitation (from the Parameter-elevation Regressions on Independent Slopes Model—PRISM) for the Southwest Alluvial Basins study area for 1940–2006 (PRISM, 2008).

1940–49, 1950–59, and 1960–69, most basins received less than average rainfall. From the 1980s through the 1990s, most basins experienced greater than average precipitation, with a return to below average rainfall for the 2000–2006 time period. Although the year of maximum and minimum annual precipitation in the 1940–2006 time period varies somewhat by basin (table 2), for most basins 1941 was the wettest year and 1956 was the driest. This is also true for the Southwest Alluvial Basins study area as a whole, with more than 86 million acre-ft of precipitation in the study area in 1941 and only 24 million acre-ft in 1956. For comparison, the annual PRISM precipitation for 1941 and for 1956 is shown in figures 17 and 18, respectively.

Runoff

As previously discussed, precipitation is the primary source of water entering groundwater systems, either directly as recharge, as recharge from surface water bodies or conveyances, or as previously recharged underflow from adjacent systems. Although the focus of this study is on groundwater budget components, runoff in the study area was investigated to better understand the potential amount of precipitation available for groundwater recharge.

Methods

Runoff was estimated using two different methods: a Basin Characterization Model (BCM; Flint and Flint, 2007a,b) and a multiple-regression equation. The two methods provide independent estimates for comparison, and the results improve the understanding of runoff and general water budgets in the SWAB basins of Arizona. The BCM estimates runoff on the basis of small-area monthly water budgets. A new multiple-regression equation was developed specifically for the study area using streamgaging station data and basin characteristics such as basin area and elevation. Runoff has been measured

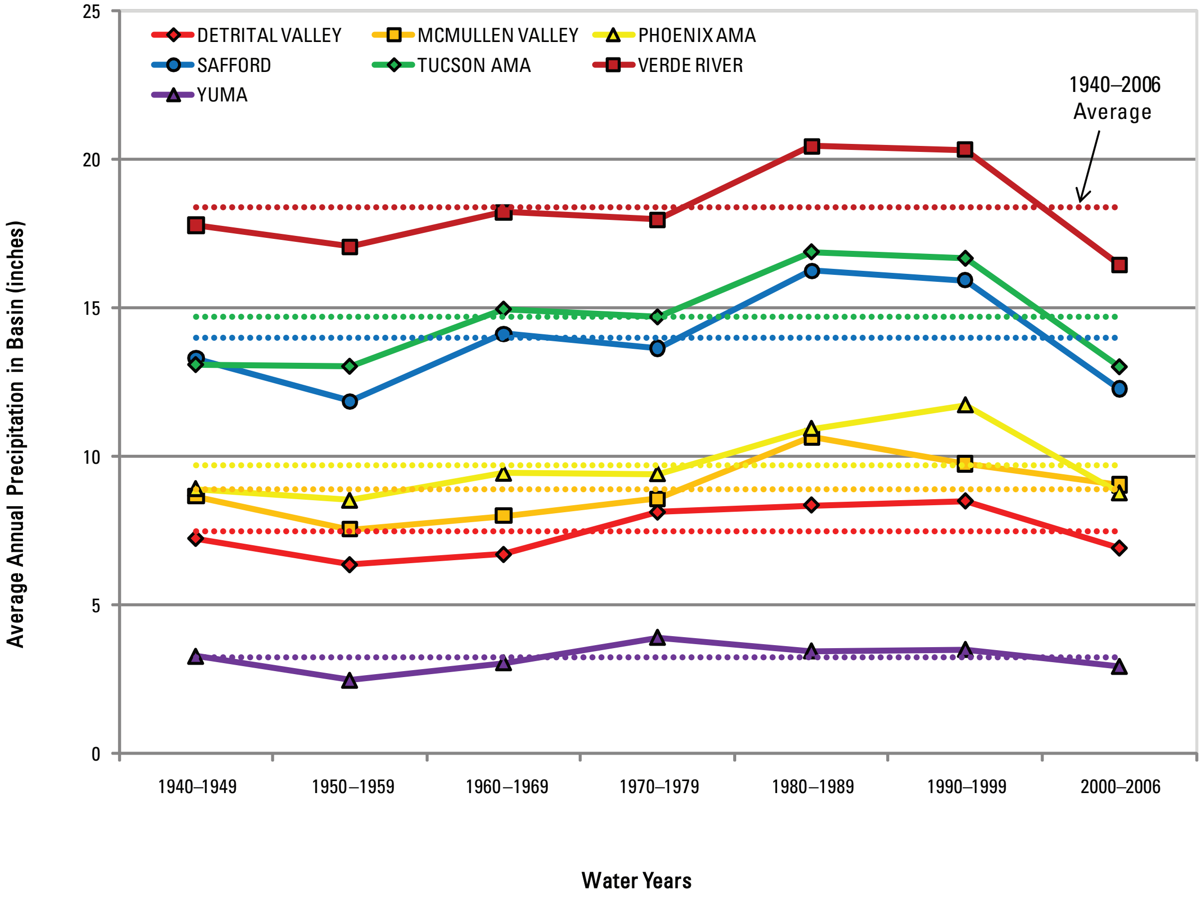


Figure 16. Decadal average annual precipitation (from the Parameter-elevation Regressions on Independent Slopes Model—PRISM) for focus basins in the Southwest Alluvial Basins study area for six 10-year and one 7-year time periods from 1940 through 2006 (PRISM, 2008).

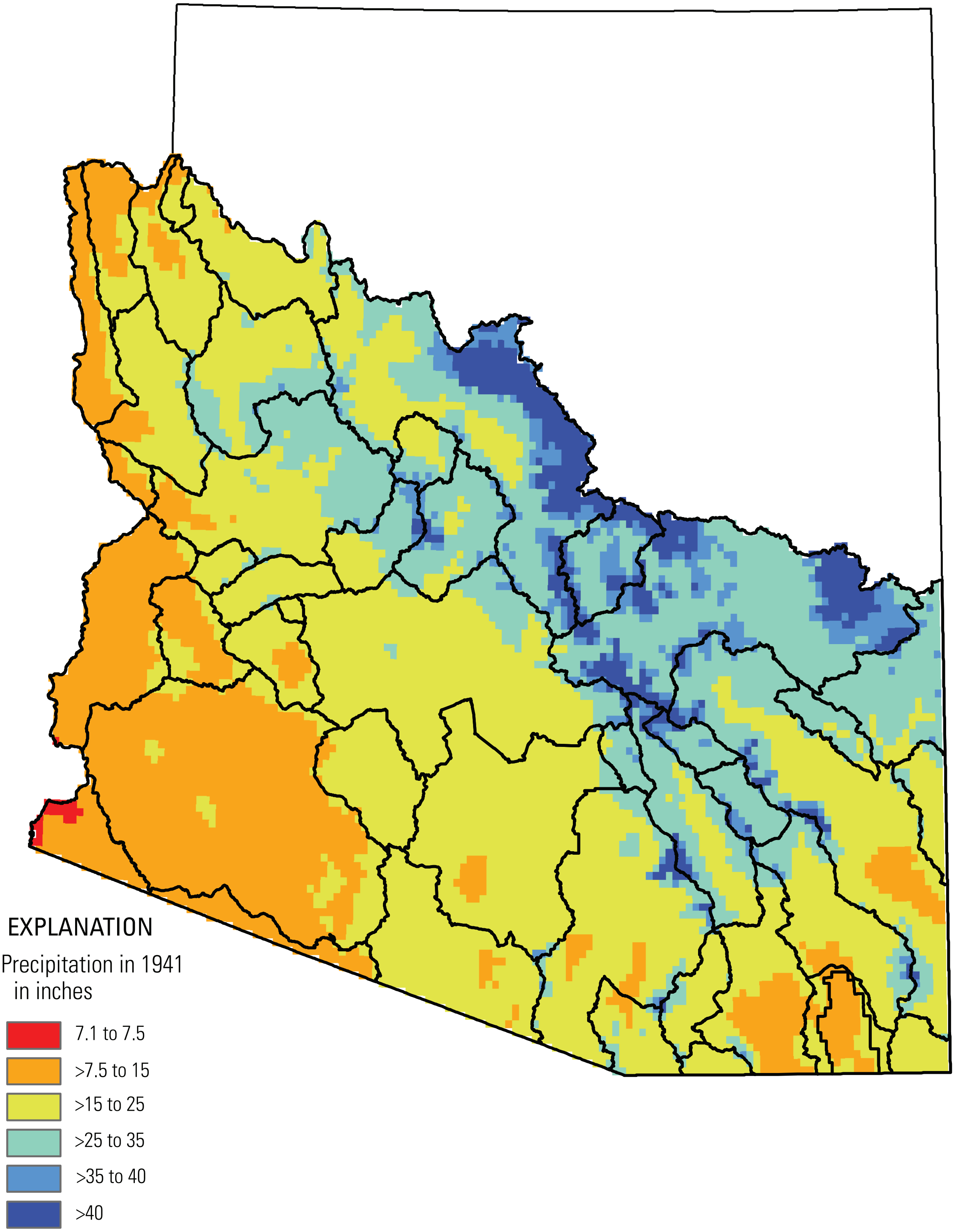


Figure 17. Precipitation (from the Parameter-elevation Regressions on Independent Slopes Model—PRISM) for the Southwest Alluvial Basins study area in 1941, generally representing the maximum annual precipitation in the study area between 1940 and 2006 (PRISM, 2008).

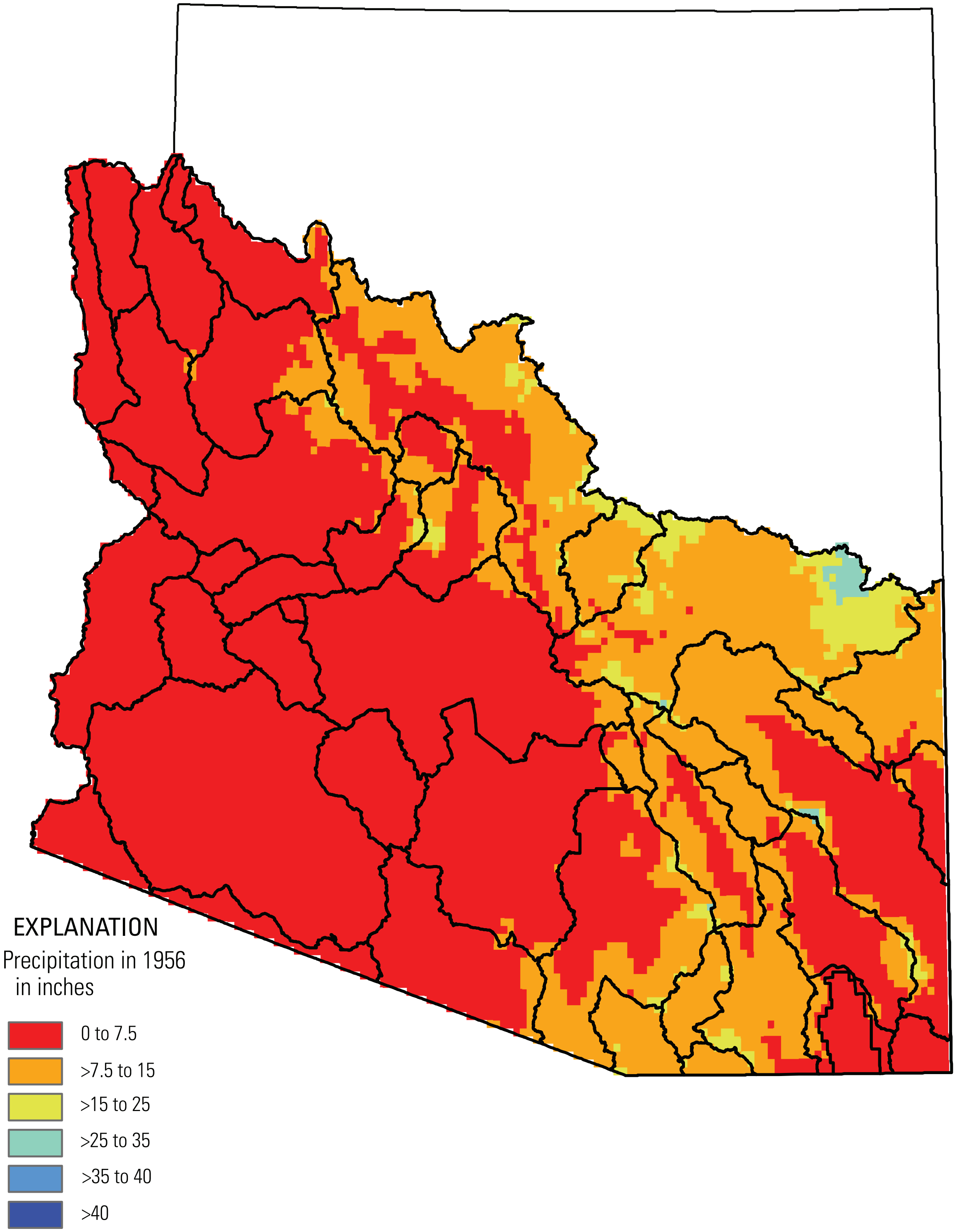


Figure 18. Precipitation (from the Parameter-elevation Regressions on Independent Slopes Model—PRISM) for the Southwest Alluvial Basins study area in 1956, generally representing the minimum annual precipitation in the study area between 1940 and 2006 (PRISM, 2008).

at many streamgaging stations in the study area, and data from 47 streamgaging stations were used in this study to estimate runoff. The drainage areas above these streamgaging stations cover a small portion of the study area (13 percent), so multiple regression was used as an extrapolation technique to estimate runoff throughout the study area.

Runoff was estimated by using both methods for 28 groundwater basins and 3 runoff regions in the study area (fig. 19). Results for the 28 groundwater basins provide detailed descriptions of the distribution of runoff, and results for the 3 runoff regions provide a summary of the regional distribution. Runoff regions were classified for the study area on the basis of similar physical and runoff characteristics. The 3 runoff regions are (1) Western Upland, (2) Central Upland and Northeastern Gila River Basin, and (3) Southeastern Gila River Basin (fig. 19; table 3). The boundary between runoff region 1 (Western Upland) and runoff region 2 (Central Upland and Northeastern Gila River Basin) coincides with the drainage boundary of the Verde River and is primarily based on residuals of preliminary regressions. The boundary between runoff region 2 and runoff region 3 (Southeastern Gila River Basin) cuts across some surface-water drainage boundaries and was selected on the basis of regression residuals and precipitation characteristics. No suitable streamgaging records were located in the Western Lowland region.

Estimation of Runoff from Basin Characterization Model (BCM)

The BCM estimates runoff and in-place recharge using a distributed-parameter water-balance model. The BCM water balance was calculated for 885 ft × 885 ft (270 m × 270 m) cells throughout the study area. For each cell, monthly values of precipitation, maximum and minimum air temperature, and potential evapotranspiration were used to calculate monthly values of the volume of water potentially available for runoff and in-place recharge, together known as available water. In-place recharge is calculated in the BCM as the volume of water for a given time frame that can drain from the soil zone directly into consolidated bedrock or unconsolidated deposits (Flint and Flint, 2007b). The BCM water-balance equation includes available water (AW), precipitation (P), snowmelt (Sm), potential evapotranspiration (PET), snow accumulation (Sa), and soil-water storage (Ss) (Flint and Flint, 2007a,b):

$$AW = P + Sm - PET - Sa + Ss \quad (1)$$

Runoff is calculated as available water in excess of the total soil-water storage capacity (soil porosity multiplied by soil depth). Temperature and precipitation estimates required by the BCM were obtained using PRISM data (Daly and others, 1994). Potential evapotranspiration was estimated with latitude, topographic shading, and air temperature using the Priestley-Taylor equation corrected for vegetated and bare soil areas (Flint and Flint, 2007a). Estimates of the storage capacity of a soil were based on soil texture data from the State Soil Geographic Database (STATSGO; U.S. Department of Agriculture, 1994). The spatial distribution of saturated hydraulic conductivity in bedrock and alluvium was determined using geologic maps. During development of the BCM for the western United States study area of Flint and Flint (2007b), hydraulic conductivity parameters were adjusted to produce results similar to some measured or independently estimated streamflow data. In this study, the BCM was run and results were tabulated; parameters were not further adjusted to fit streamflow data.

Results of the BCM analysis were determined for total areas and mountain areas (defined by geology at land surface; Arizona Geological Survey, 1998) of the 47 streamgaged basins and the 3 runoff regions in the study area. Annual runoff values were computed for the study area from monthly estimates for the 1940–2006 time period. The annual runoff values for the 885 ft × 885 ft grid cells were averaged over the period of record to produce a long-term estimate of runoff. The grid cell period-of-record runoff estimates were then summed over individual streamgage and groundwater basin areas. BCM runoff estimates were also summed over only the mountain areas within these areas for comparison with estimates determined from the regression-runoff equation.

Multiple-Regression Analysis of Runoff

An ordinary least squares (OLS) regression analysis was used to develop an equation for estimating mean annual runoff from available streamflow data. Streamgaging stations were selected from areas in Arizona SWAB basins and one nearby basin in New Mexico (Mogollon Creek nr Cliff, NM) that have sustained runoff from precipitation or snowmelt; the streams selected could be intermittent or perennial, but there had to have been sustained periods of flow during the winter. These areas are generally in the higher elevations of the Arizona SWAB basins, where there is sufficient precipitation and lower levels of evapotranspiration. It was beyond the scope of this study to attempt to develop equations for estimating mean annual runoff in ephemeral streams. Ephemeral-stream runoff is extremely variable spatially and temporally. With current data and techniques, it would be difficult to develop accurate and representative regression equations.

Runoff observed as mean annual flow at each streamgage was the response variable for the regression analysis, and basin and climatic characteristics of the drainage area for the streamgages were investigated as explanatory variables. Streamflow data were obtained from the USGS NWIS database (U.S. Geological Survey, 2010; table 4). Mean annual flow was calculated for the full period of record at each site. Investigating stationarity or lack of trends in flow is important in the application of streamflow statistics (mean flows), especially with the increasing concerns about climate change. To determine if there were any significant trends in annual flow in the study area, a Kendall tau trend test (Conover, 1980) was performed on the data for all 47 streamgages. Results indicate no significant trends (p-value <0.05) in all streamflow records

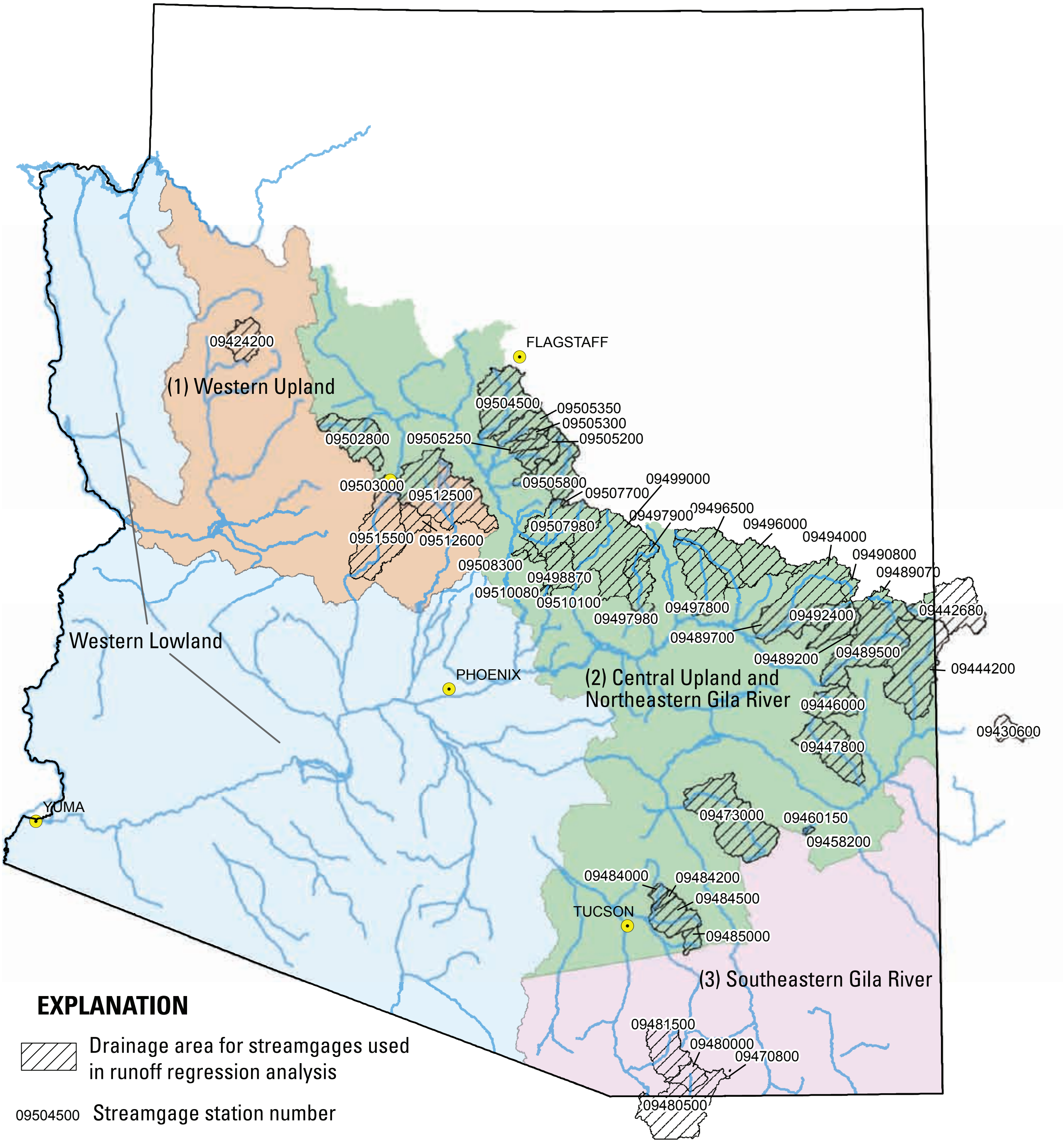


Figure 19. Runoff regions (colored areas) and drainage basin areas (hachured areas) for streamgages used in developing the streamflow regression equation. Streamgages are located at the downstream end of the stream in each drainage area.

with the exception of two sites. Sabino Creek near Tucson had a significant positive trend (p-value = 0.027) and Cherry Creek near Globe had a significant negative trend (p-value = 0.048). These two sites were included in the regression analysis because there does not appear to be any regional pattern to the trends; the sites are located in different parts of the study area and they have different trends (positive and negative).

Two physical basin characteristics were investigated for the analysis: basin drainage area and mean basin elevation, both of which were estimated using geographic information system techniques on 98.4-ft (30-m) digital elevation models (table 4). Basin climatic information of mean annual precipitation was determined from 2.49-mi PRISM data (PRISM, 2008) for the 1940–2006 time period (table 5).

The regression model used for the analysis is the multiplicative or log-transform model. All variables were log transformed to make a linear relation between streamflow and basin characteristics and to satisfy the assumption of homogeneity of variance (homoscedasticity) for the regression analysis. The general form of the regression equation is:

$$\text{Log } Q = a + b\times(\log A) + \text{c}\times(\log B) + ... \tag{2}$$

where Q is mean annual streamflow, A and B are explanatory variables, and a, b, and c are regression coefficients.

Results

An OLS regression equation was developed to estimate mean annual runoff for perennial and intermittent streams within the Basin and Range Physiographic Province in Arizona. An initial model using only basin drainage area as an explanatory variable was able to explain 68 percent of the variability of mean annual streamflow (R^2=0.68; table 6) with a standard error of estimate of 0.319 log units (average standard error of estimate of 80 percent). The addition of basin precipitation and mean basin elevation improved the fit of the equation to an R^2 of 0.90 and a standard error of 0.183 log units (table 6). This three-variable model had a good overall fit to the data, but an investigation of the spatial distribution of residuals (by plotting them on a map of the study area—not shown) revealed a negative bias in two geographic areas. The model significantly overestimated flows in the northwest and southeast parts of the study area. A geographic region variable was added to the model to compensate for this bias. The three runoff regions (fig. 19) are represented in the model by using two dummy variables (R1 and R2) that were coded as follows: region 1 (R1=1, R2=0), region 2 (R1=0, R2=0), and region 3 (R1=0, R2=1). The final regression equation has a coefficient of determination of 0.92 and a standard error of estimate of 0.167 log units (average standard error of 39 percent; table 6).

The final regression equation (table 6) satisfies all the necessary assumptions and requirements of an OLS regression analysis (Draper and Smith, 1981). Plots of the residuals show that they are independent, homoscedastic, and normally distributed. The explanatory variables—drainage area, mean annual precipitation, mean basin elevation, and geographic region variable R2 (region 3)—are all significant at p-values of less than 0.05. The p-value for geographic region variable R1 is 0.17, but including it in the equation substantially improved the regression performance for the 4 streamgages in region 1. In actual flow units (ft^3/s), the average overestimate of flow was 40 percent for the model without an R1 variable, and the average overestimate of flow was 10 percent for the model with the R1 variable. Possible multicolinearity of the explanatory variables (drainage area, mean annual precipitation, and mean basin elevation) was evaluated by calculating a variance inflation factor (VIF) for all combinations of the variables. Multicolinearity does not appear to be a problem in the equation—values of the VIF ranged from 1.10 to 1.65, much lower than upper limits of 5.0 or 10.0 that have been cited as indicating multicolinearity problems (Helsel and Hirsch, 1992).

The performance of the regression model throughout the study area was assessed by comparing regression-estimated streamflows with observed streamflows for the 47 individual streamgaged basins (table 7) and comparing summary results for 3 runoff regions (table 8). Residuals from the regression equation (observed minus regression-estimated mean annual flow) are plotted on a map of the study area (fig. 20). The regression equation has no appreciable regional bias; there are no geographic clusters of positive or negative residuals (fig. 20). The regional precision of the regression equation (magnitude of residuals) is mostly evenly distributed, with a small area of lower precision (larger residuals) in the lower elevations of the Verde River Basin and Salt River Basin subregions (fig. 20, table 7). Two summary statistics were used to evaluate the regional performance of the regression equation in the three runoff regions. The mean residual represents the bias of the estimates and should be near zero to be unbiased. The root mean square error (RMSE) represents the precision of the estimates, with lower values representing a better fit and performance of the method. The mean residual for the multiple regression equation for all of the selected streamgages in the study area is 0.01 and the RMSE is 0.155 (table 8). The regression equation has minimal bias in the three runoff regions; the mean residual ranges from –0.03 to 0.07 (table 8). The precision of the regression estimates is similar throughout the study area, with just a slightly lower precision in the Western Upland region, which has an RMSE of 0.195, as opposed to RMSE values ranging from 0.144 to 0.158 for the other regions and subregions.

Performance of Regression and BCM Estimates of Runoff

Results of the multiple-regression-equation estimates and BCM estimates of runoff were compared for the 47 streamgaged areas, 28 groundwater basins (in which

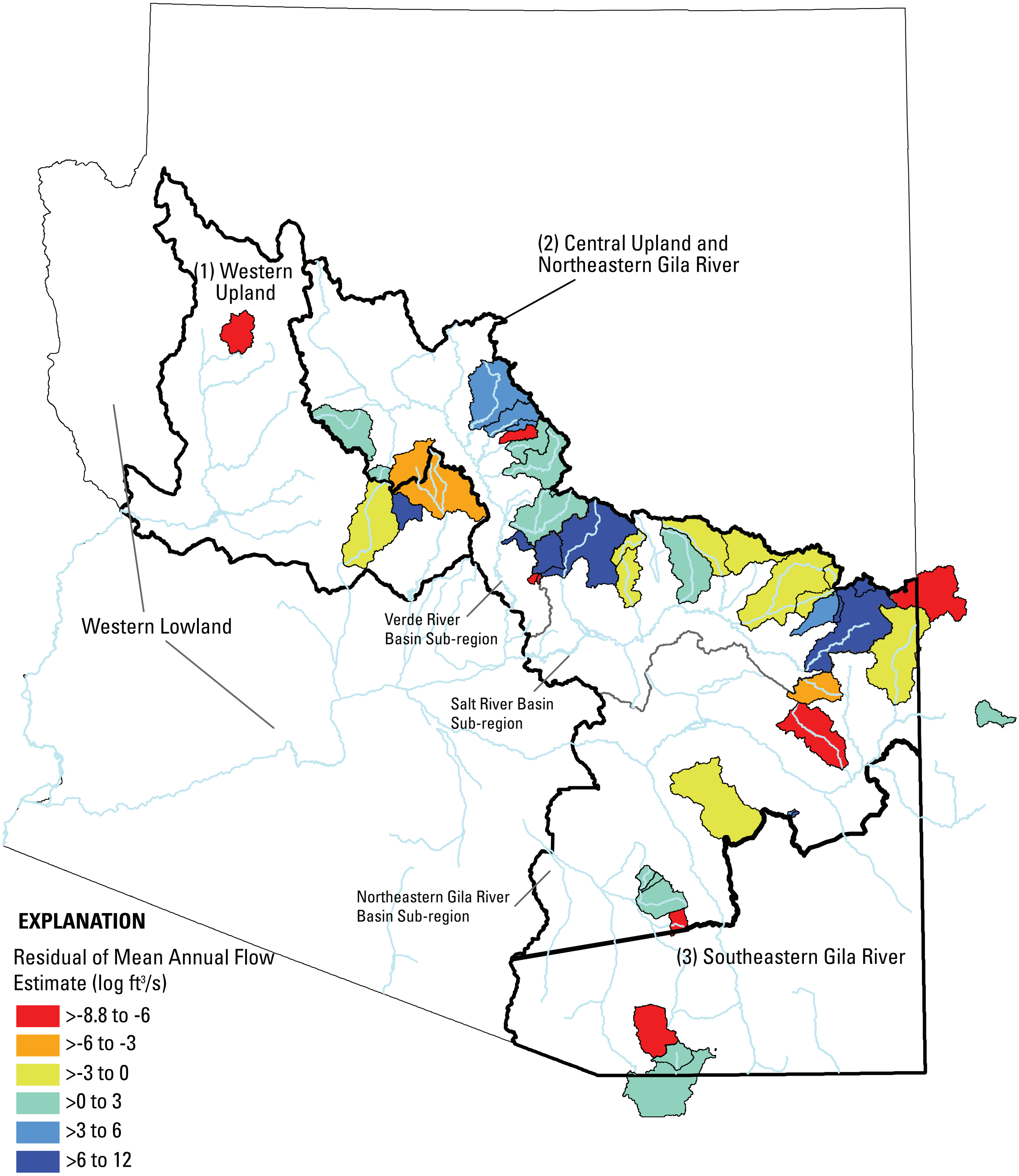


Figure 20. Residual of mean annual flow in 47 streamgaged drainages in the study area, calculated as observed value minus regression-equation-estimated value.

suitable streamgage records were present), and 3 runoff regions (tables 9 through 11). The comparison for the 47 streamgaged areas provides estimates of the accuracy and representativeness of the two methods, because the estimates are compared to observed values at the streamgages. The comparison for the 28 groundwater basins provides a detailed picture of the distribution of estimated runoff in many parts of the SWAB study area. The comparison for the three runoff regions provides a regional summary of the results.

Observed mean annual flow, estimates of mean annual flow from the regression equation and BCM, and differences between observed and estimated flows (residuals) are shown in table 9. The 47 streamgages and associated drainage areas are all in the higher elevation runoff areas of the study area. Residuals, in percent of observed values, range from –79 to 57 percent for regression estimates and from –155 to 91 percent for BCM estimates. The fit between observed and estimated mean annual flow varies according to region and according to the estimation method (regression or BCM) (table 9). Because the regression equation was developed from the observed flows, it generally has a better fit between estimated and observed values than does the BCM.

Comparison of BCM and regression-equation estimates for runoff in the 28 groundwater basins indicates that using BCM results from only mountainous areas of the basins provides more comparable results with the regression equation than using the entire groundwater basin area results (table 10). This is because the runoff regression equation was developed using data from drainage basins in these higher elevation mountain areas. Even comparing mountain-area BCM results with regression-equation results, the regression equation predicts more runoff than the BCM in 25 of the 28 basins, most by a factor of 2 or more (table 10).

Two summary statistics were used to evaluate the fit or performance of the regression equation and the BCM in the runoff regions (table 11). As previously mentioned, the mean residual represents the bias of the estimates and should be near zero if there is no bias. The mean absolute residual represents the precision of the estimates; lower values represent a better fit and performance of the method. The mean residual for all streamgages was –4.7 percent for the regression equation and 28.7 percent for the BCM. The mean absolute residual for all streamgages was 29.1 percent for the regression equation and 46.5 percent for BCM. The bias of estimates from the two methods was appreciably different for each of the three runoff regions, with the regression equation having lower bias than BCM estimates.

Mountain-Front Recharge

Although evapotranspiration exceeds precipitation for most of the year throughout the SWAB study area, there are time periods (particularly during winter months) when evapotranspiration is sufficiently low and locations (particularly in mountain areas) where precipitation is sufficiently large to allow excess water to become aquifer recharge. Recharge to the SWAB aquifer system from precipitation may occur by direct infiltration of water through mountain faults and fractures or through permeable pediment or basin sediments and drainage channels. The term mountain-front recharge is used in this report to identify the recharge of precipitation either directly through mountain blocks or infiltration of precipitation runoff in mountain-front drainages. Total aquifer recharge includes mountain-front recharge along with agricultural return flow, aquifer storage projects, streamflow recharge, and groundwater basin underflow. Methods often employed to estimate groundwater recharge include observational methods such as change in gravity or groundwater levels; monitoring stable isotope and other chemical tracers such as chloride; and mathematical methods including groundwater-flow models, water-balance approaches, and empirical regression relationships (Hogan and others, 2004). In Arizona, the Groundwater Management Act of 1980 requires the Active Management Areas (AMAs) of the State to achieve equilibrium between groundwater withdrawals and total aquifer recharge by 2025 (Colby and Jacobs, 2007), making the estimation of basin-scale recharge a particularly important topic in the study area.

Mountain-front recharge to groundwater was estimated for the alluvial basins in the study area using two independent mathematical methods. First, an empirical regression equation developed for the USGS SWAB-RASA studies was used with new, detailed PRISM precipitation information to update recharge estimations using this Maxey-Eakin-type equation (Maxey and Eakin, 1949; Flint and others, 2004). Second, the BCM was used to produce annual estimates of in-place recharge and runoff. Each of these methods is discussed separately, with the results from both methods compared.

Methods

SWAB-RASA Empirical Recharge Equation

A regression equation relating mountain-front recharge and the total annual volume of precipitation on the watershed was produced by the SWAB-RASA studies of the 1980s (Anderson and others, 1992). The equation is calibrated from recharge values from numerical groundwater models developed during the SWAB-RASA studies, from previous basin-scale studies of recharge, and from water-budget analyses of individual basins and the entire SWAB-RASA study area. An iterative process was employed in which an initial equation was used to estimate mountain-front recharge from precipitation for individual basins. These estimates were then adjusted to balance the water budget of the individual basins and the entire study area, and a new regression equation was produced. After cycles of balancing and modifying, a final equation was produced to estimate mountain-front recharge from precipitation (see Anderson and others, 1992, for more details)

$$\text{Log } Q_{\text{rech}} = -1.40 + 0.98 \log P, \tag{3}$$

where Q_{rech} = total annual volume of mountain-front recharge in a basin (in acre-ft per year) and P = annual basin precipitation (in acre-ft per year) greater than 8 inches per year.

The threshold precipitation value of 8 inches per year accounts for water that is lost to soil-moisture deficits and evapotranspiration. In applying this equation using the 2.49-mi PRISM data, the first 8 inches of precipitation was subtracted from each annual PRISM raster cell, with resulting negative cell values assigned a value of zero. Basin volume of precipitation was then computed by multiplying the remaining cell precipitation by the cell area and summing over individual basin boundaries. This volume, converted to acre-ft, was then used in equation 3.

Recharge Estimates from the Basin Characterization Model

The BCM was used to estimate quantities of water available for generating runoff and in-place recharge within the SWAB study area. As previously described, the BCM estimates these quantities of available water using a water-balance equation for each 885 ft × 885 ft grid cell in the study area. The partitioning of available water into either runoff or in-place recharge by the BCM depends on the saturated hydraulic conductivity of the bedrock and alluvium. Runoff is computed as available water in excess of the total soil-water storage capacity (soil porosity × soil depth). In-place recharge is computed from the available water remaining after runoff minus the field capacity of the soil and occurs at a rate determined by the hydraulic conductivity of the underlying soil or rock. The BCM does not estimate which portion of runoff becomes recharge.

Results

SWAB-RASA Empirical Recharge Equation

For this study, regression equation 3 was used with annual PRISM precipitation data from 1940 through 2006 to estimate mountain-front recharge in the alluvial basins of Arizona. Although the original SWAB-RASA regression equation was developed using maps of contoured average precipitation that were available at the time, using the equation with higher resolution PRISM precipitation estimates is not unreasonable because both the contour maps and PRISM data are based on precipitation measurements. It should be noted, however, that had PRISM data been available at the time of its development, the final SWAB-RASA regression equation might have differed somewhat from equation 3.

Changes in recharge on a decadal scale are presented (table 12) to demonstrate the effect that changing precipitation regimes, including periodic drought or climatic cycles such as El Niño-Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO), may have on aquifer recharge. A 1940–2006 period-of-record average annual estimate of mountain-front recharge is also presented that may better describe the longer term average for the SWAB basins (table 12 and fig. 21). Both the decadal and period-of-record averages of recharge are presented in dimensions of length (inches) and volume (acre-ft), and as a percent of the total PRISM precipitation for the basin (table 12).

Although not a linear function of precipitation, recharge estimated using equation 3 still closely tracks precipitation, with respect to both total volumes and temporal variations. Higher precipitation areas (fig. 15), including the Salt River and Tonto Creek Basins, logically receive the most recharge per unit area, whereas drier areas in the western part of the State receive the least recharge per unit area (table 12 and fig. 21). For the mostly decadal or longer averages in table 12, the percentage of precipitation that becomes recharge is generally less than 2 percent throughout the basins of the study area. Patterns in decadal recharge in the focus basins (fig. 22) follow precipitation trends (fig. 16), with most of the focus basins receiving average or below-average recharge in the 1940s through the 1970s, above average recharge in the 1980s and 1990s, then below average recharge again in the 2000–2006 time period.

Recharge Estimates from the Basin Characterization Model

Monthly in-place recharge and runoff grid cell values from the BCM were summed over each water year, then averaged by decade for the 1940–2006 time period and averaged over the entire 1940–2006 period of record. These decadal and period-of-record estimates of in-place recharge and runoff were then summed by groundwater basin (table 13). To compute total mountain-front recharge for the groundwater basins, 15 percent of BCM runoff was added to BCM in-place recharge (table 14 and fig. 23). Although the amount of runoff that may become recharge will vary by basin and season, a value of 15 percent was chosen based on similar basin-scale studies in Nevada and Utah (Flint and Flint, 2007a,b; Stonestrom and others, 2007). Total basin mountain-front recharge is presented in dimensions of length (in) and volume (acre-ft), and as a percent of the total PRISM precipitation for the basin for both the decadal and period-of-record averages (table 14). Results indicate that basins with higher precipitation receive more recharge than basins with lower precipitation, although the percentage of precipitation that becomes recharge varies from a low of 0 percent in several basins to a high of more than 6 percent in the Tonto Creek Basin for the 1940–2006 average (table 14). For most of the 885 ft × 885 ft grid cells in the study area, the BCM calculated that there was no available water (equation 1) for runoff or in-place recharge. Only in the mainly mountainous areas surrounding the alluvial basins was there sufficient precipitation to provide excess water for recharge (fig. 24). Decadal results for the focus basins (fig. 25) indicate that BCM recharge estimates do not directly track changes in precipitation over the same time periods (fig. 16), likely because the BCM estimates are dependent on such factors as potential evapotranspiration and soil-water storage capacity.

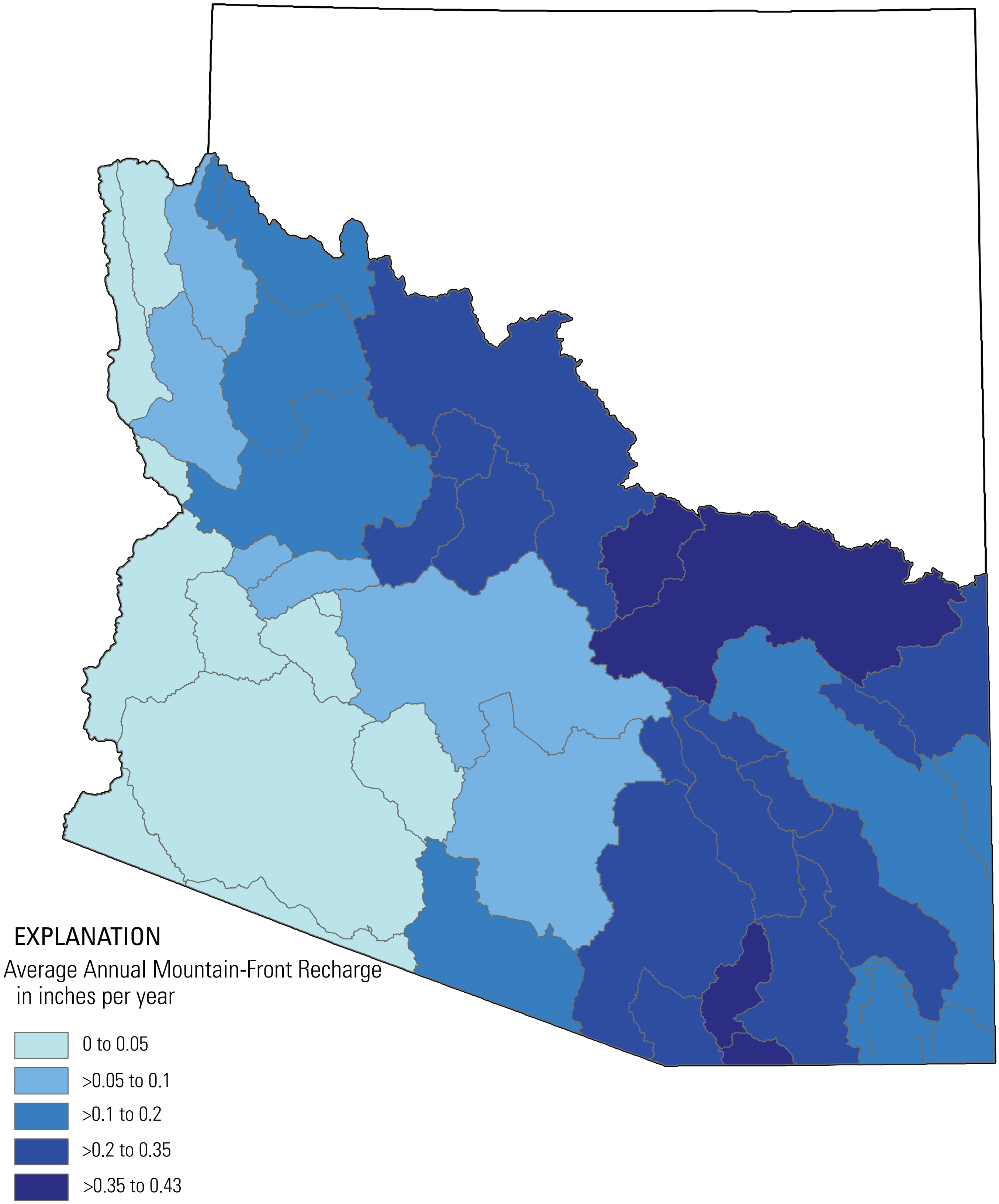


Figure 21. Average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for the 1940–2006 time period by basin.

Comparison of SWAB-RASA Regression and BCM Recharge Estimates

Estimates of recharge produced by the SWAB-RASA regression equation (equation 3) and the BCM are compared for the SWAB basins for the 1940–2006 time period (table 15). For the 45 groundwater basins in the SWAB study area, the SWAB-RASA regression equation estimates more recharge than the BCM in 27 of the 45 groundwater basins, mostly within a factor or 2.4 or less of the BCM estimate (table 15). These 27 basins are mostly in the less mountainous, southern portion of the study area (fig. 24). Ten basins have BCM estimates that exceed SWAB-RASA estimates, half of these by a factor of two or more (table 15). These 10 basins are mostly in the more mountainous portion of the northern part of the study area (fig. 26). Future refinements of the BCM are planned as new information on rock and sediment permeability is obtained. Other recharge estimates reported in the Arizona Department of Water Resources' (ADWR) multivolume Groundwater Atlas (Arizona Department of Water Resources, 2006, 2009a–e) are also reported in table 15 for comparison. Most of the values reported in the Groundwater Atlas refer to estimates by the original SWAB-RASA study (Freethey and Anderson, 1986), which used the same regression equation as in this study (equation 3), but using different precipitation estimates. Note that some ADWR recharge estimates listed in table 15 may include other recharge components and may not be directly comparable to the BCM or regression equation results.

Evapotranspiration

Evapotranspiration (ET) is the set of processes by which water is removed by evaporation from surfaces such as soil and by transpiration from plants, principally via stomata (Hillel, 1998; Mauseth, 1991). In current usage, this definition may or may not include evaporation from water; however, as defined for this study, open-water evaporation

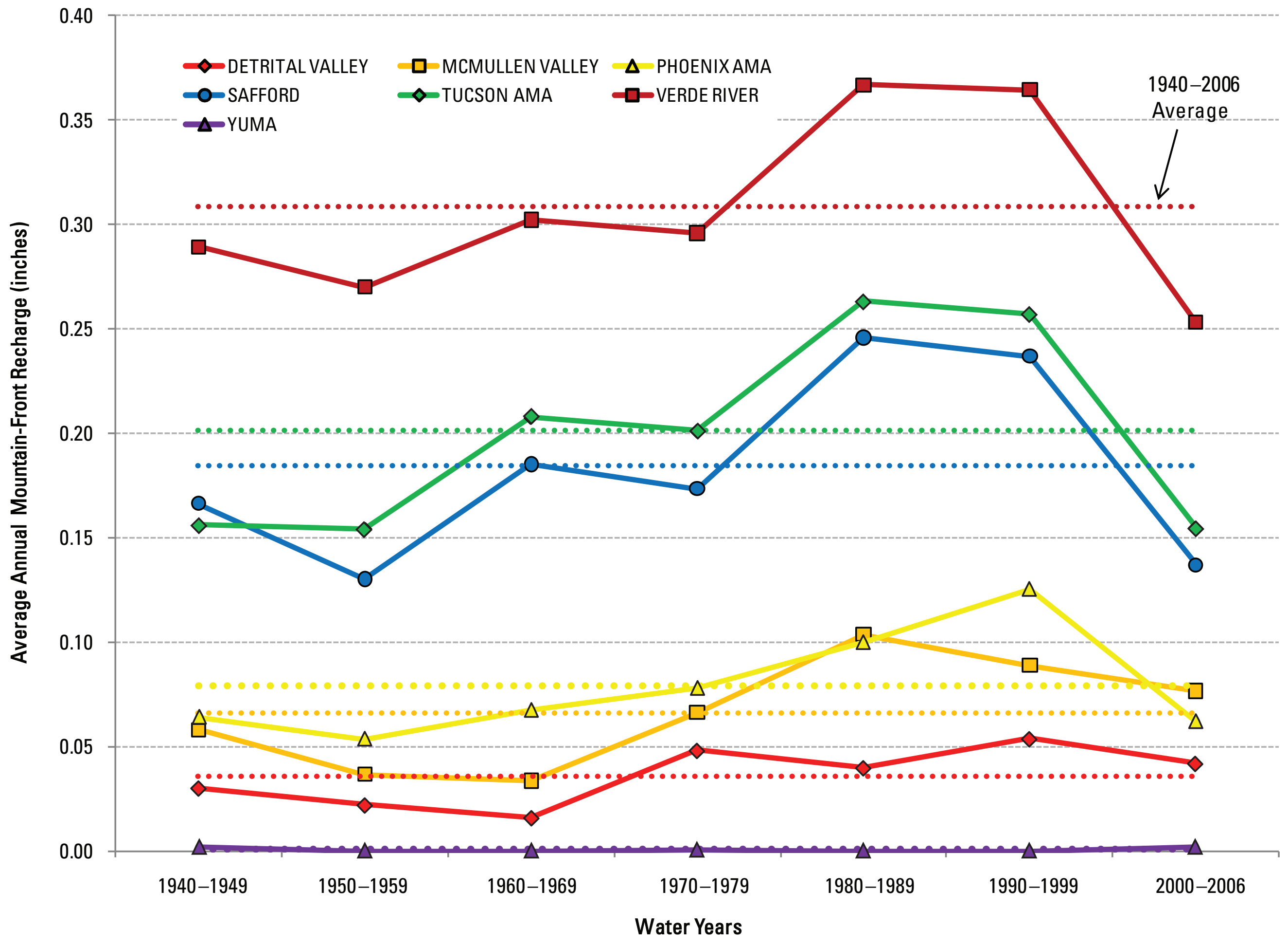


Figure 22. Graph of decadal average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for focus basins for six 10-year and one 7-year time periods from 1940 through 2006.

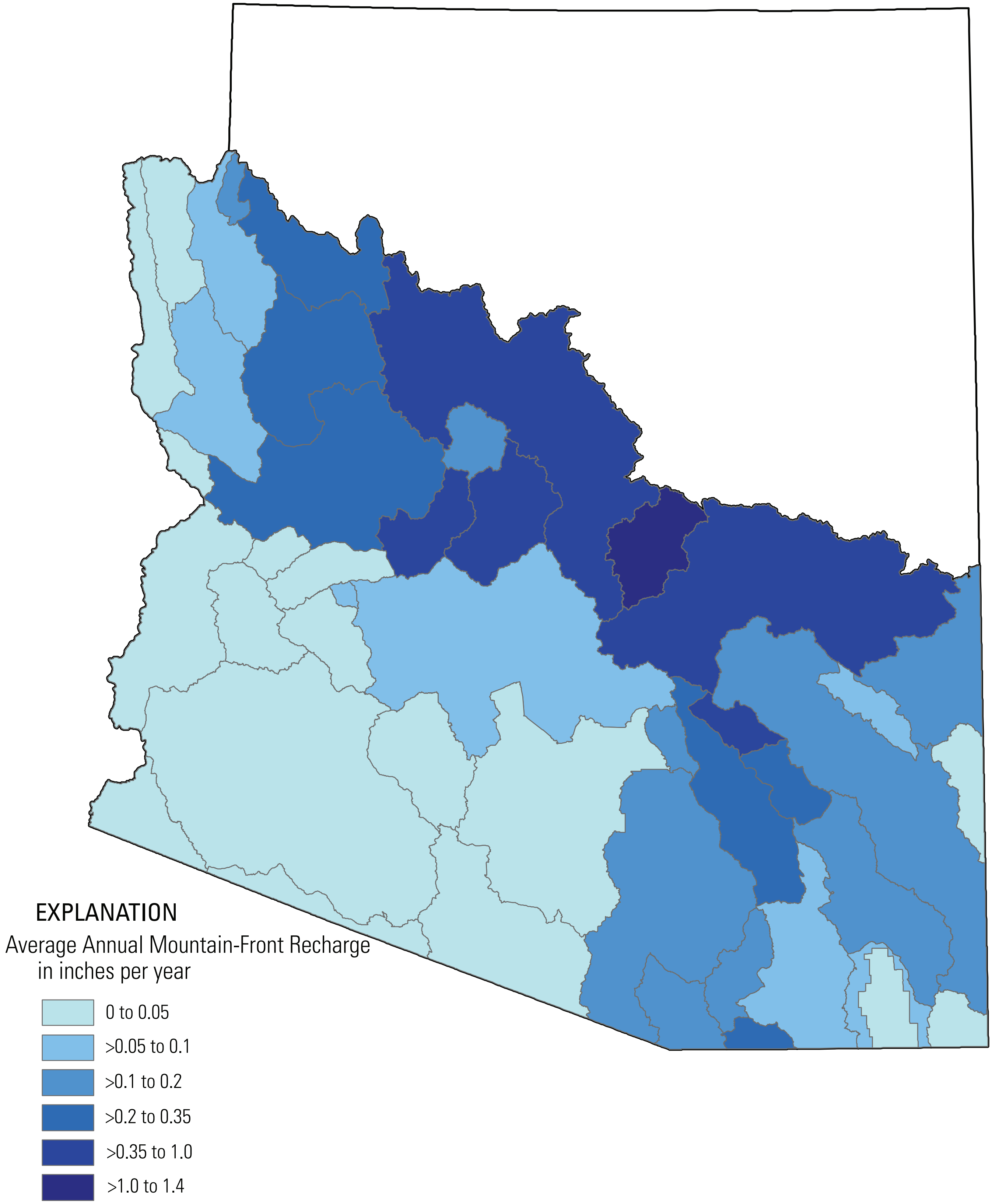


Figure 23. Average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for the 1940–2006 time period, by basin. BCM estimates of mountain-front recharge include in-place recharge plus 15 percent of runoff.

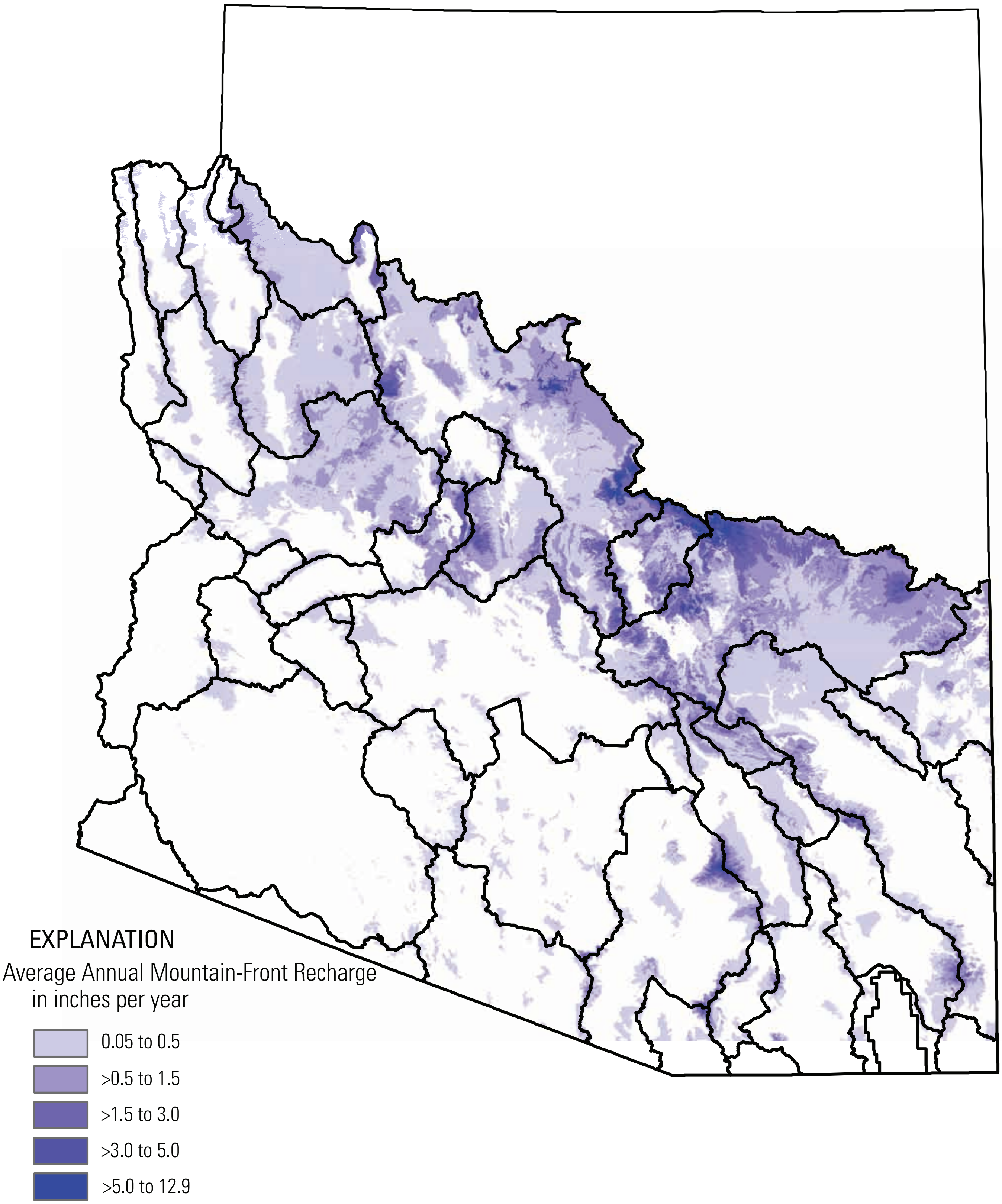


Figure 24. Locations of average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for the 1940–2006 time period.

and evaporation from shallow groundwater are not included. ET is typically a significant component of most water budgets and may be estimated using a variety of methods (Freeze and Cherry, 1979; Goodrich and others, 2000). ET by wetland and riparian vegetation is an important component of groundwater discharge in arid and semiarid areas and was probably the principal discharge component in the study area before large-scale human alteration of groundwater systems (Anderson and others, 1992). Potential ET (PET) is the amount of water that would be removed by ET if the soil water available for ET were unlimited. The goal of this study was to estimate actual ET (AET) from groundwater on an annual basis, but as a step in this process AET was first calculated for the entire study area.

Methods

Annual average AET extracted from groundwater was estimated for the SWAB study area for the period 2000 to 2007 and compared to predevelopment values based on work by Freethey and Anderson (1986). To calculate AET, satellite-based MODIS (Moderate Resolution Imaging Spectroradiometer) enhanced vegetation index (EVI) grid data (Oak Ridge National Laboratory, 2008) were used. Satellite data cover large swaths of the land surface with a repeat rate that is high enough to allow for reasonable estimates of seasonal and annual AET variability (fig. 27). EVI is used because it is a measure of greenness to which ET is directly correlated (Nagler and Glenn, 2009; Nagler and others, 2009). EVI is used instead of more traditional products like the Normalized Difference Vegetation Index (NDVI) because it does not saturate at high levels of greenness (biomass) as does NDVI (Huete and others, 2002). Datasets covering the study area were available for each pass of the satellite (every 16 days) over the period 2000 to 2007 with individual pixel dimensions of 820.21 ft × 820.21 ft (250 m × 250 m). The EVI datasets for each date were stitched together, then substituted into the following equations to calculate AET (mm/day) (Nagler and Glenn, 2009; Nagler and others, 2009):

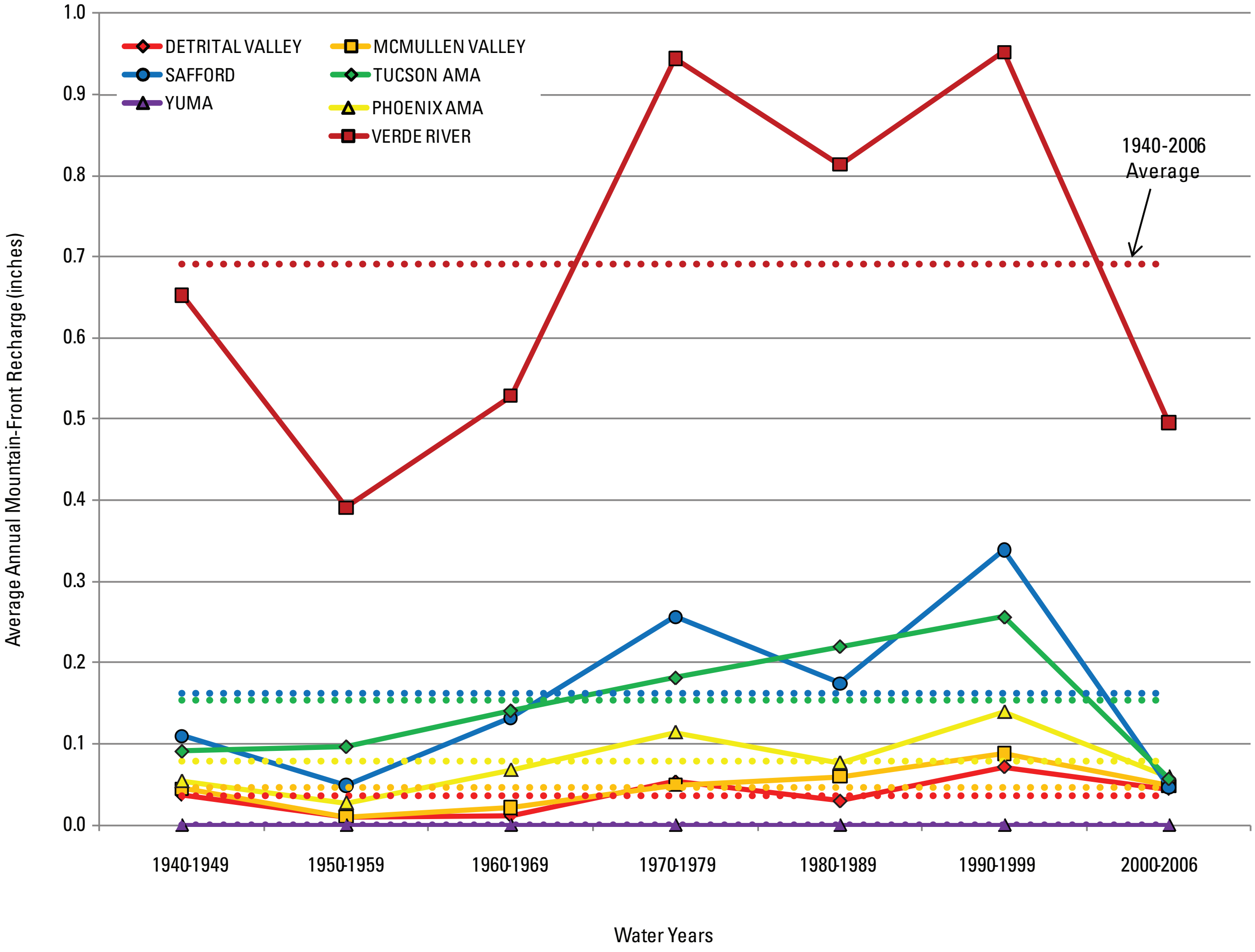


Figure 25. Graph of decadal average annual recharge estimated by the Basin Characterization Model (BCM) for focus basins for six 10-year and one 7-year time periods from 1940 through 2006.

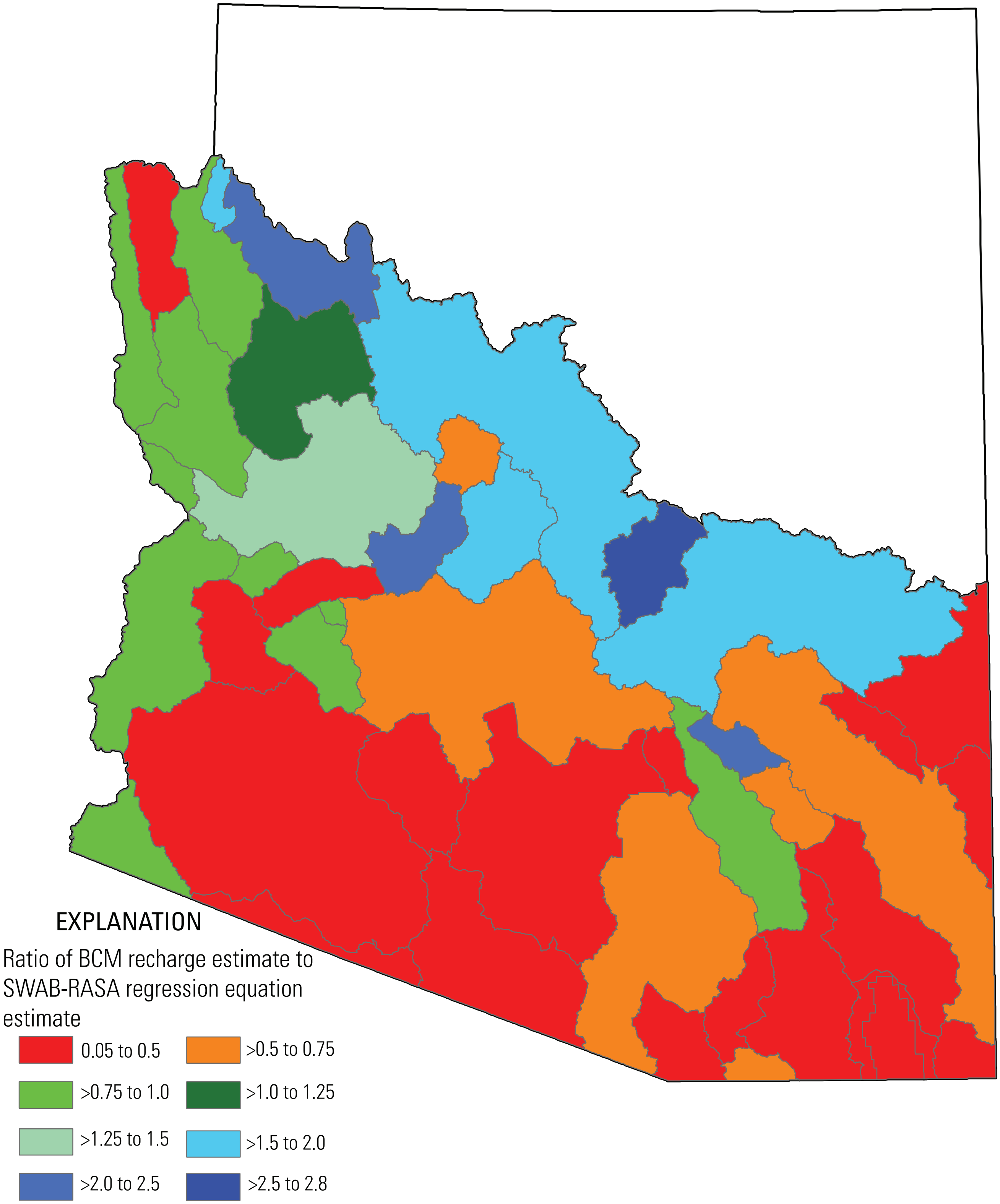


Figure 26. Ratio of mountain-front recharge estimates produced by the Basin Characterization Model (BCM) to estimates from the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation for the 1940–2006 time period, by basin. BCM estimates of mountain-front recharge include in-place recharge plus 15 percent of runoff.

$$AET = 1.22ET_o \times EVI^*, \qquad (4)$$

where ET_o is the "reference crop evapotranspiration" (mm/day) as an average for a period of 1 month and EVI^* is the scaled EVI. ET_o is the evapotranspiration from a standardized vegetated surface (Allen and others, 1998). By substitution it is meant that in each grid, the value of each variable in each pixel was substituted into the appropriate equation using raster mathematics tools in ArcGIS®. ET_o was calculated using a modified Blainey-Criddle relation (Brouwer and Heibloem, 1986):

$$ET_o = p\ (0.46\ T_{\mathrm{mean}} + 8), \qquad (5)$$

where p is mean daily percentage of annual daytime hours and T_{mean} is mean daily temperature, calculated on a monthly basis as:

$$T_{\mathrm{mean}} = \frac{T_{\mathrm{max}} + T_{\mathrm{min}}}{2}\ , \qquad (6)$$

where T_{max} and T_{min} are defined as:

$$T_{\mathrm{max}} = \frac{\text{sum of all } T_{\mathrm{max}} \text{ values during the month}}{\text{number of days of the month}}$$

$$T_{\mathrm{min}} = \frac{\text{sum of all } T_{\mathrm{min}} \text{ values during the month}}{\text{number of days of the month}}$$

Temperature data were obtained from PRISM (2008). EVI was converted to a scaled value (EVI^*) following the method of Nagler and others (2005):

$$EVI^* = 1-(0.542-EVI)/(0.542-0.091), \qquad (7)$$

where 0.542 and 0.091 represent maximum and minimum EVI values, respectively, from a large dataset of riparian plant communities in the southwestern United States (Nagler and others, 2005).

These calculations were done for each pass of the satellite over the study area. Passes occurred approximately every 16 days beginning early in 2000. At the time of download, data were available through Julian day 353 of 2007, with a few days missing in the period of record. For days on which no EVI data were available, estimated AET values were substituted as follows: at the beginning and end of the record, for Julian days 1, 17, 33, and 49 of year 2000 and day 337 in 2007, the average of the same Julian day from years in which data were available was used to fill in missing AET values. Values for averaging were available for these days in all years, with the exception of day 49, which was not available in 2001. Other days missing data, but having EVI data on days before and after, were assigned the average of the ET calculated for the preceding and following days. This process was done for days 225 and 353 in 2000; day 49 in 2001; day 305 in 2003; and days 81 and 113 in 2005. Some computed AET pixel values were outside of the expected range of 0 to 0.59 in. per day (15 mm per day; Tolk and others, 2006). These occurred mainly over areas where snow accumulates for part of the year (values >0.59 in. per day) and where open water or sparse vegetation is present (negative values). Negative values were converted to zero, whereas values >0.59 in. per day were included in basin calculations because they had little overall effect on the basin-scale AET values.

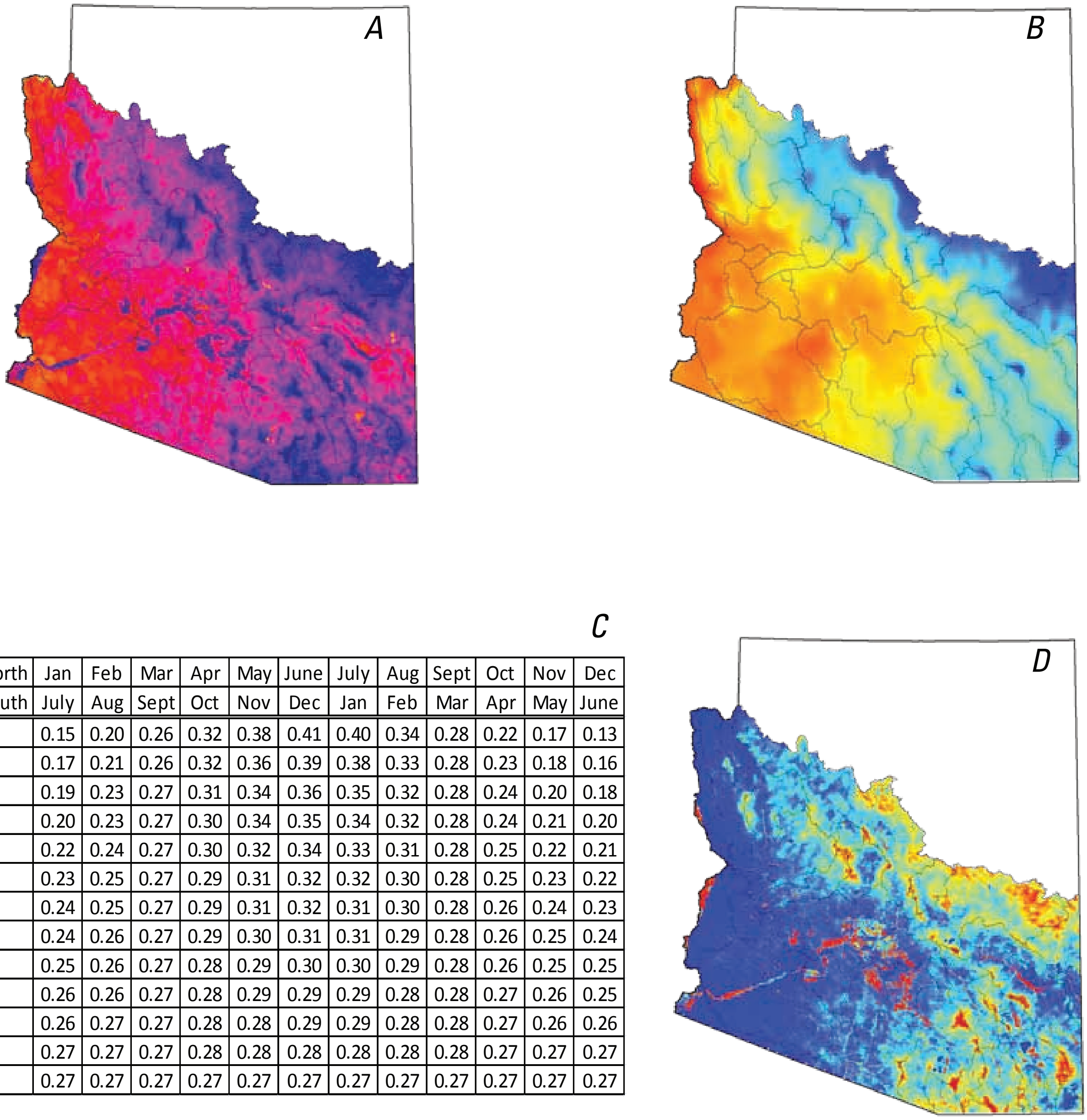
Groundwater ET

Calculation of AET was done for all 820.21-ft (250 m) grid cells in the study area, with results resampled to 164-ft (50 m) grid size. For the purposes of calculating basin groundwater budgets, the amount of AET being extracted only by presumed groundwater-using vegetation was estimated for each basin. Based on an assumption that wetland and other vegetation near surface water primarily use groundwater, AET was summed for all nonagricultural areas within 164 ft (50 m) of named rivers, streams, tributaries, and washes in the study area, as determined from information from the Arizona State Land Department (fig. 28; Arizona State Land Department, 1993). AET in areas falling outside of the 164-feet buffers was also assumed to be from groundwater if land cover in those pixels was classified as woody or herbaceous wetland based on the 2001 98.4-ft (30 m) Multi-Resolution Land Characteristics Consortium land-cover dataset for the study area (fig. 28; Homer and others, 2004). Herbaceous woodland is classified as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 80 percent perennial herbaceous vegetation. Woody wetland is classified as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 20 percent forest or shrubland. It was assumed that these land classifications represent those locations at which all or nearly all water extracted by plants comes directly from groundwater.

Direct precipitation on vegetation has the potential to be at least a partial source of water for AET in the subset areas defined above. A lower bound on estimated groundwater ET for each basin in the study area was developed by subtracting out precipitation (PRISM, 2008) from ET estimates developed in this study.

Results

Minimum and maximum annual volumes of AET from groundwater are summarized by basin for the period 2000 through 2007 in table 16. Maximum values are computed from equations 4 through 7, and minimum values are estimated by subtracting precipitation from each computed ET raster cell. This method of computing minimum AET assumes that all precipitation that falls on the presumed groundwater-using areas is directly used by vegetation, with no losses from runoff or other processes. Most maximum basin AET volumes are greater than minimum volumes by a factor of 2 or less (table 16). Estimated annual AET volumes from groundwater during this time period range from large values in the Salt River Basin (maximum of >176,000 acre-ft in 2005) and the Verde River Basin (maximum of >142,000 acre-ft in 2005) to minimum values of 0 in the Western Mexican Drainage Basin for 2002, 2004, and 2007. Average annual volumes of AET from groundwater for this period are compared with predevelopment AET values adapted from Freethey and Anderson (1986), and with postdevelopment PET values (Flint and Flint, 2007a; table 17). It is assumed that the values from Freethey and Anderson refer to "actual" ET from groundwater and that no direct use of precipitation by plants is accounted for, although these issues are not discussed in their report. Flint and Flint (2007a) calculated PET as described in the "Estimation of Runoff from the Basin Characterization Model (BCM)" section using postdevelopment land-cover information. Estimated predevelopment ET volumes are typically smaller than AET estimated for this study, but in a few basins along the Colorado River and elsewhere, predevelopment ET may be an order of magnitude larger than current estimates. Anderson and



Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60°		0.15	0.20	0.26	0.32	0.38	0.41	0.40	0.34	0.28	0.22	0.17	0.13
55		0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
50		0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.20	0.18
45		0.20	0.23	0.27	0.30	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.20
40		0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35		0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.22
30		0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.30	0.28	0.26	0.24	0.23
25		0.24	0.26	0.27	0.29	0.30	0.31	0.31	0.29	0.28	0.26	0.25	0.24
20		0.25	0.26	0.27	0.28	0.29	0.30	0.30	0.29	0.28	0.26	0.25	0.25
15		0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.25
10		0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
5		0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27
0		0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

Figure 27. Examples of data types used to calculate actual evapotranspiration (ET) where (*A*) is MODIS EVI data (Oak Ridge National Laboratory, 2008), (*B*) is temperature data (PRISM, 2008), (*C*) is mean daily percentage of annual daytime hours based on latitude (Brouwer and Heibloem, 1986), and (*D*) is calculated actual ET from all vegetation types.

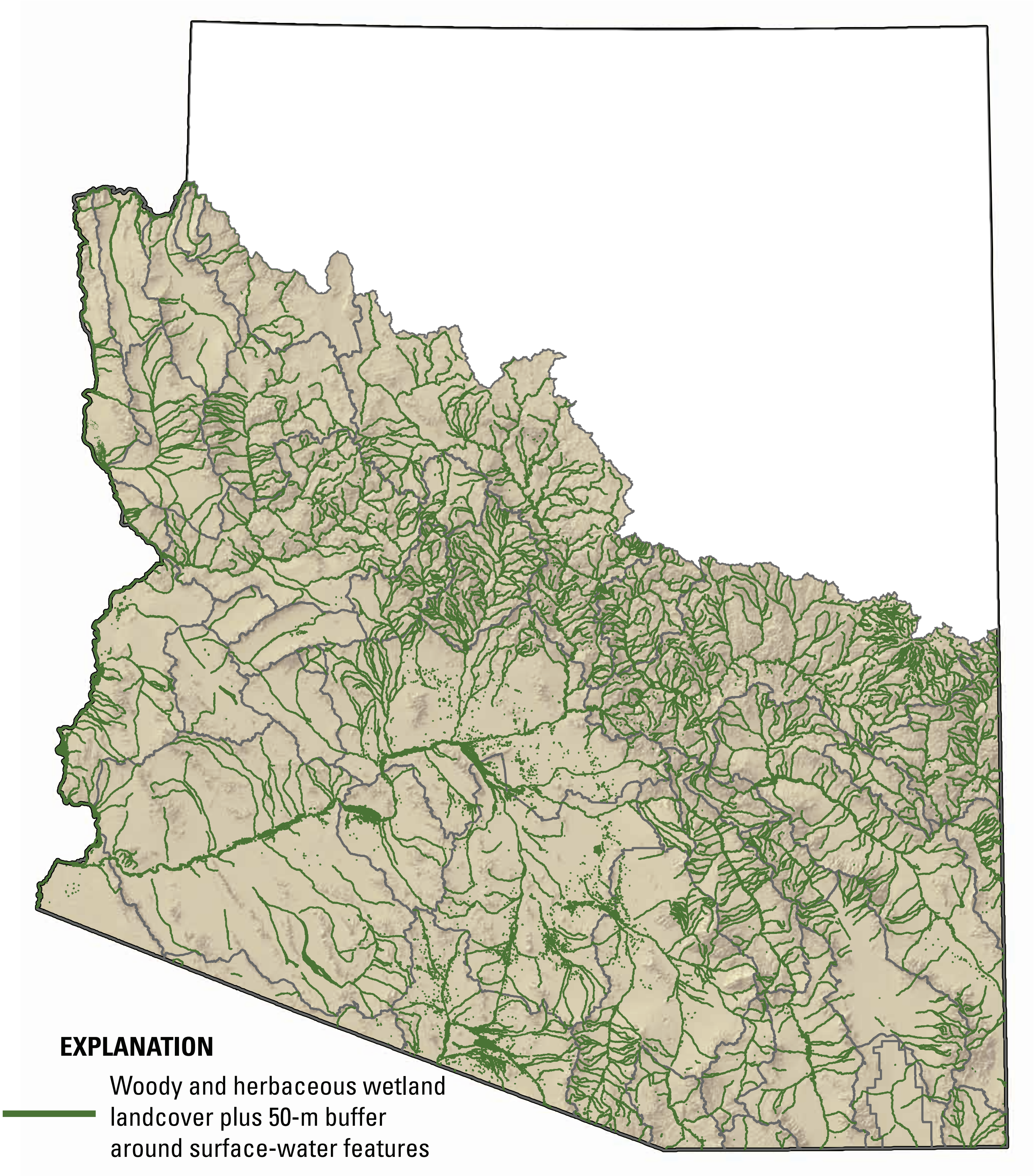


Figure 28. Area classified as primarily groundwater-using vegetation in the Southwest Alluvial Basins (SWAB) study area for evapotranspiration (ET) analyses. Surface-water features include rivers, streams, and tributary washes defined in geographic information system (GIS) coverage (Arizona State Land Department, 1993).

others (1992) suggest that conversion of riparian vegetation to agricultural fields during development may have considerably decreased ET, but the increase in AET in several basins supports the findings of Webb and others (2007) that riparian vegetation has increased over much of the study area. In cases in which predevelopment ET is higher, drought and lowered water tables caused by the interception of flow to riparian areas by pumping may also contribute to this difference. PET is, as expected, greater than 2000–2007 AET values calculated for all basins. A few of the basins in which predevelopment ET is greater than PET are along the Colorado River, where there may have been extensive wetlands and where currently there is large-scale agriculture. Thus, a large decrease in wetland vegetation between predevelopment and postdevelopment (the latter being the condition under which PET was estimated) could explain some of the differences in these values.

Total average seasonal AET rates for the entire study area, and not just groundwater-using areas, (fig. 29) indicate that, in general, the highest rates are found in agricultural areas, with slightly lower rates in mountain forests. The deserts in the western and southwestern parts of the study area along the Colorado River tend to have the lowest AET rates overall. AET peaks in summer, coinciding with yearly highs in temperature and rainfall, but the exact timing varied from basin to basin. In the seven focus basins, minimum and maximum daily rates of groundwater-derived AET for the years 2000–2007 (fig. 30) showed wide variability, from close to zero on some individual days in Detrital Basin to more than 0.14 in/day on some individual days in the Yuma Basin. Differences in these rates among basins are probably related to basin elevation and length of perennial-river reaches within each basin, among other factors.

Groundwater Underflow

The direction of groundwater flow within a basin is dictated by the hydraulic-head distribution, which is influenced by the location and magnitude of aquifer recharge and discharge, and by aquifer properties. The quantity of groundwater flow between basins depends on each basin's geometry, the hydraulic gradient between the basins, and the hydraulic conductivity of the materials within and separating the basins. The rate of groundwater underflow between basins in the study area was estimated. For this study it was assumed that the principal aquifers near the basin boundaries were unconfined.

Methods

As part of the SWAB-RASA study, the rate and direction of groundwater underflow under steady-state conditions were estimated for the SWAB-RASA groundwater basins for pre-1940 conditions (Freethey and Anderson, 1986). For the current study, these predevelopment underflow volumes and directions were disaggregated from SWAB-RASA groundwater basin boundaries to ADWR groundwater basin boundaries (fig. 31). Both basin delineations share some common boundaries, with similar inflow and outflow locations. The inflows and outflows from the SWAB-RASA basins were matched with the corresponding inflows and outflows of the ADWR groundwater basins.

The groundwater underflow component of a groundwater budget can be calculated using a calibrated numerical groundwater flow model. Creating a groundwater flow model simulating rates of groundwater underflow for the entire study area was beyond the scope of this study. As a result a Darcy's Law approach using available groundwater-level data was used to calculate volumes of groundwater underflow between the basins. For current and recent (circa 1980) conditions, average groundwater levels from wells near basin boundaries compiled from the USGS and ADWR groundwater databases for 1975–1980 and 2001–2005 were used to calculate hydraulic gradients between the basins for the two time periods. Wells with similar depths and groundwater levels for each adjacent basin were used in the calculation. The minimum numbers of wells in the estimation was two wells in each basin. The ADWR Arizona Water Atlases (Arizona Department of Water Resources, 2009a–e) were used to infer groundwater flow directions in each basin.

Darcy's Law is expressed as

$$Q = -KA\left(\frac{dH}{dL}\right) \tag{8}$$

where

Q = Discharge in ft^3/s
K = Hydraulic conductivity in ft/s
H= Hydraulic head in ft
L = length in ft
A = Cross sectional area of flow in ft^2.

Darcy's Law can also be expressed using transmissivity in place of K

$$T = Kb \tag{9}$$

where

T = Transmissivity in ft^2/s
b = Aquifer thickness in ft.

Darcy's Law expressed in the terms of transmissivity becomes

$$Q = -TW\left(\frac{dH}{dL}\right) \tag{10}$$

where

Q = Discharge in ft^3/s
T = Transmissivity in ft^2/s
W = Width of flow in ft

For current and recent conditions, it was assumed that the transmissivity term T was the same as in predevelopment conditions (despite possible water-level decline or rise) and

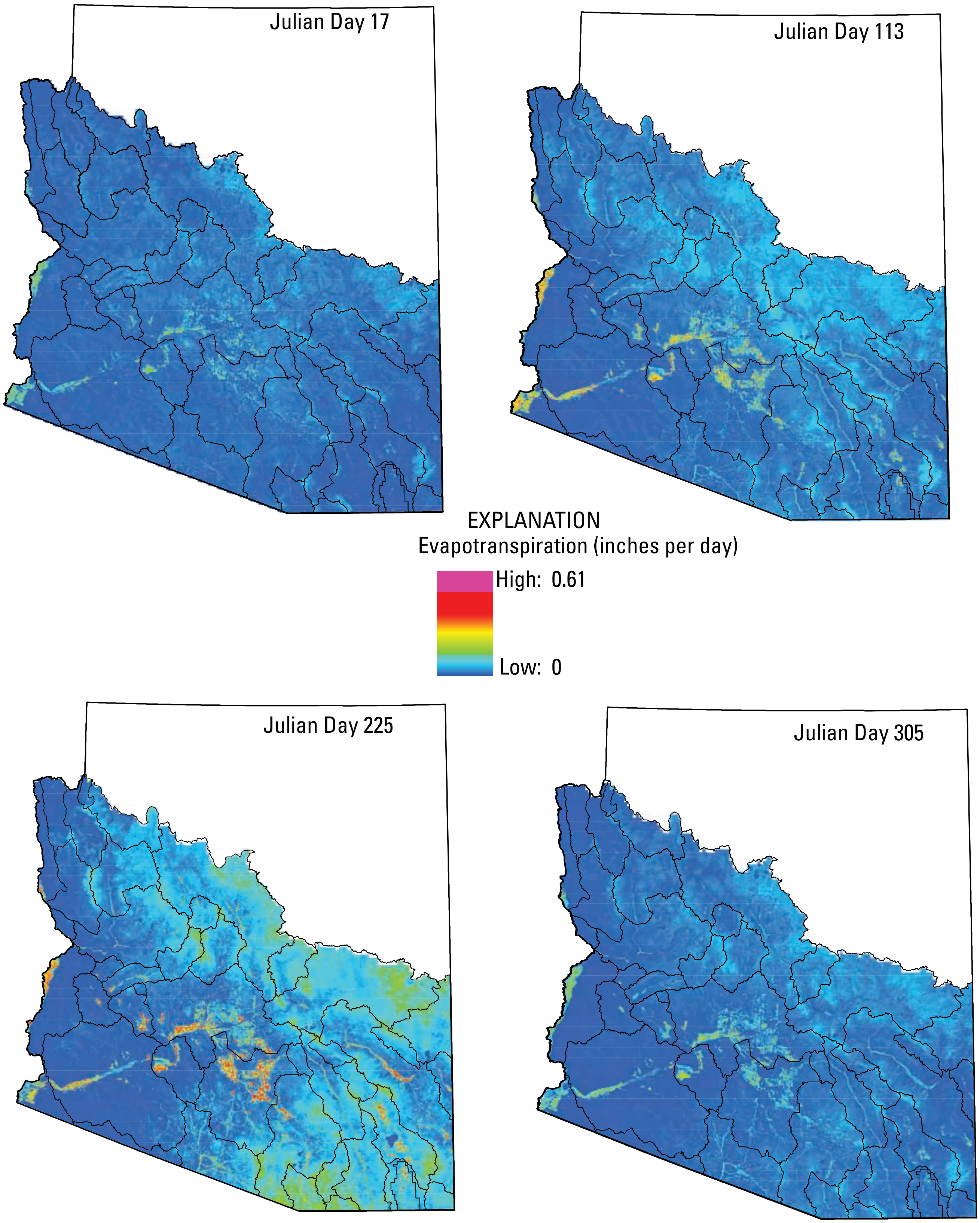


Figure 29. Seasonal variation in evapotranspiration (ET) for all vegetation types. Each date shows the average ET rate for each pixel on that date over the period 2000–2007.

that the only component of the groundwater underflow equation that changed between the time periods was the hydraulic gradient (*dH/dL*). An estimate of the transmissivity term *T* was back-calculated from the hydraulic gradient (*dH/dL*) and the steady-state discharge value *Q* from predevelopment estimates (Freethey and Anderson, 1986). For current conditions, the new hydraulic gradient (*dH/dL*) was calculated from water levels and then used in equation 10. For the Active Management Areas that have published groundwater models, the modeled values of groundwater inflow and outflow were used for the current conditions. Predevelopment estimates for underflow were used for current and recent conditions in basins that have not experienced significant groundwater development.

Results

The largest groundwater underflow component from the study area during predevelopment and current times was underflow out of the Yuma Basin, mainly through subsurface flow in the Colorado River channel (table 18). The inflow component into the overall SWAB study area did not change between predevelopment and current conditions because

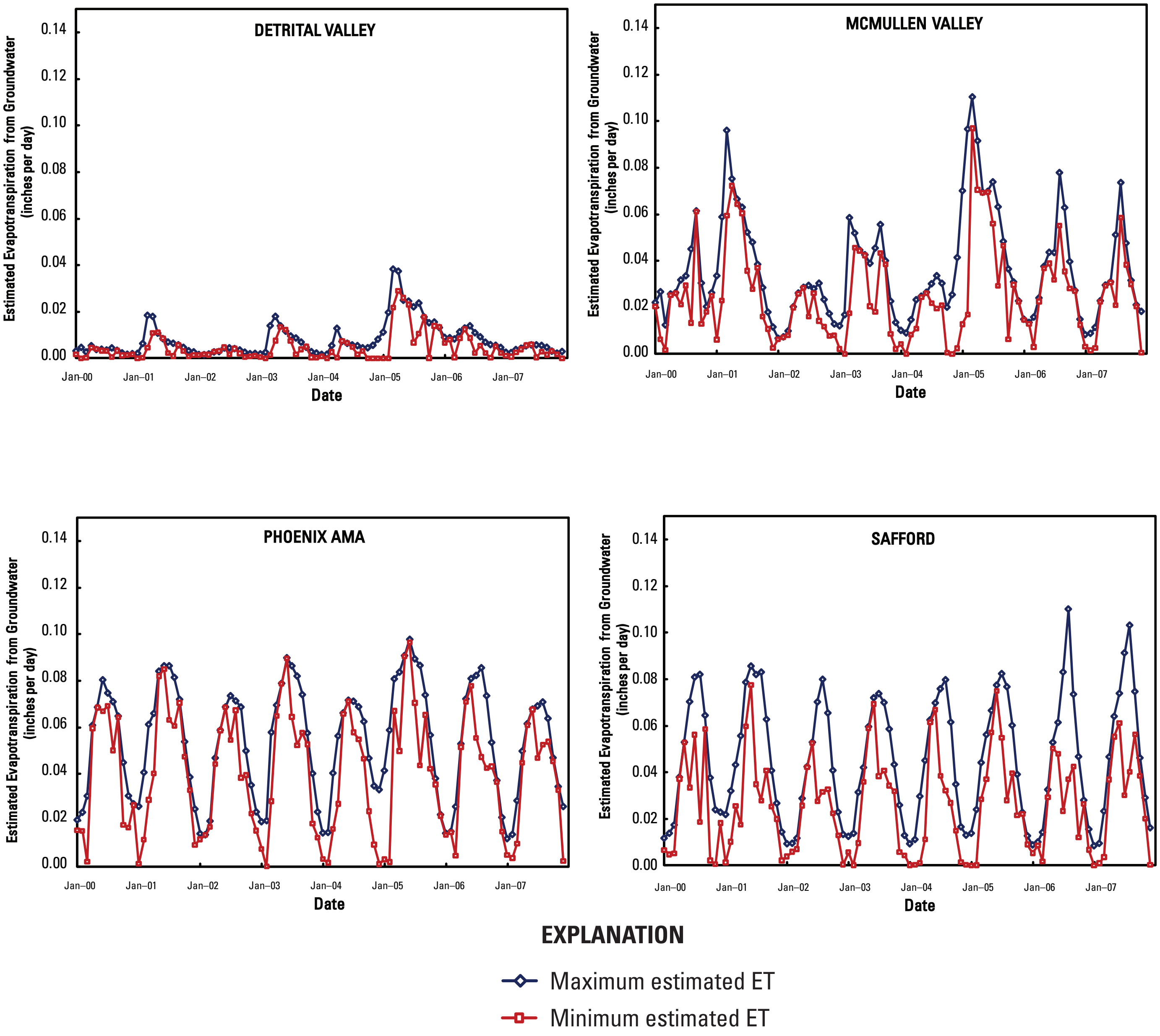


Figure 30. Graphs showing estimated maximum and minimum monthly evapotranspiration (ET) rate from groundwater for focus basins from 2000–2007. Focus basin locations shown on figure 2.

eastern portions of the Duncan Valley and Morenci basins remain undeveloped. Other basins on the study area margins remain fairly undeveloped, and the rates of groundwater underflow to and from these basins have not changed substantially. A change in the direction of groundwater underflow was observed in the Pinal and Phoenix AMAs, which is consistent with the observations of Konieczki and English (1979) and Anderson (1995).

Groundwater Recharge by Seepage from Streams

The interaction of groundwater systems with streams and rivers in arid regions is complex and can vary both spatially and temporally. Hydrologic controls on flow in rivers and streams may come from the timing and location of runoff from precipitation, from groundwater entering or exiting the stream through the stream channel, from the effects of capture from nearby groundwater withdrawals, or from a combination of these events. Geology also exerts control on these systems because flow in a stream or river may seep into the ground as alluvial basins deepen, only to reemerge in the streambed as bedrock rises near the land surface at basin boundaries.

Seepage from streams can be a substantial source of recharge in the Southwest Alluvial Basins of Arizona. Typically, seepage is estimated using several methods: (1) determining maximum amounts of streamflow available for downstream seepage from individual streamgaging stations, (2) determining differences in streamflow between two or

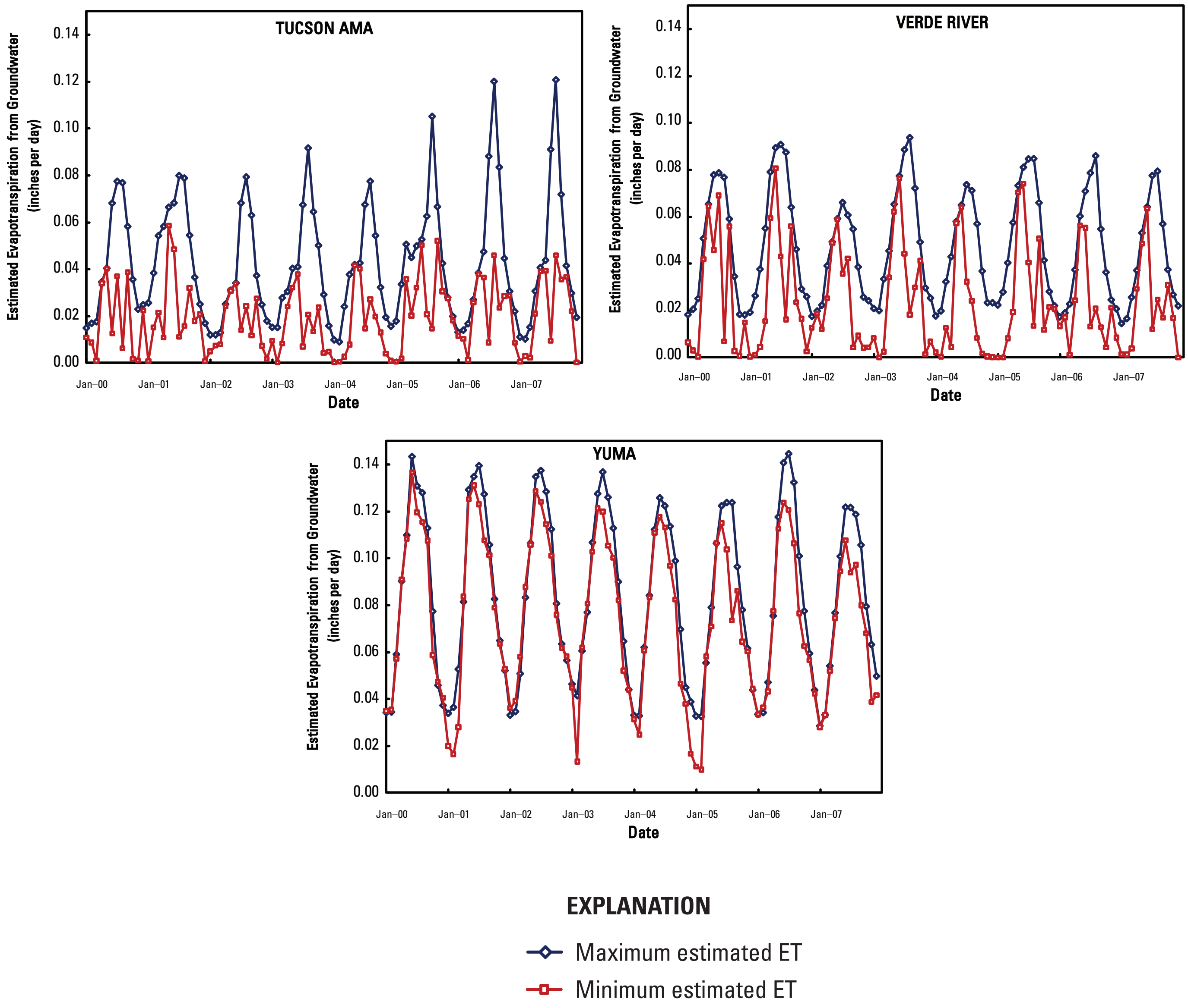


Figure 30.—Continued.

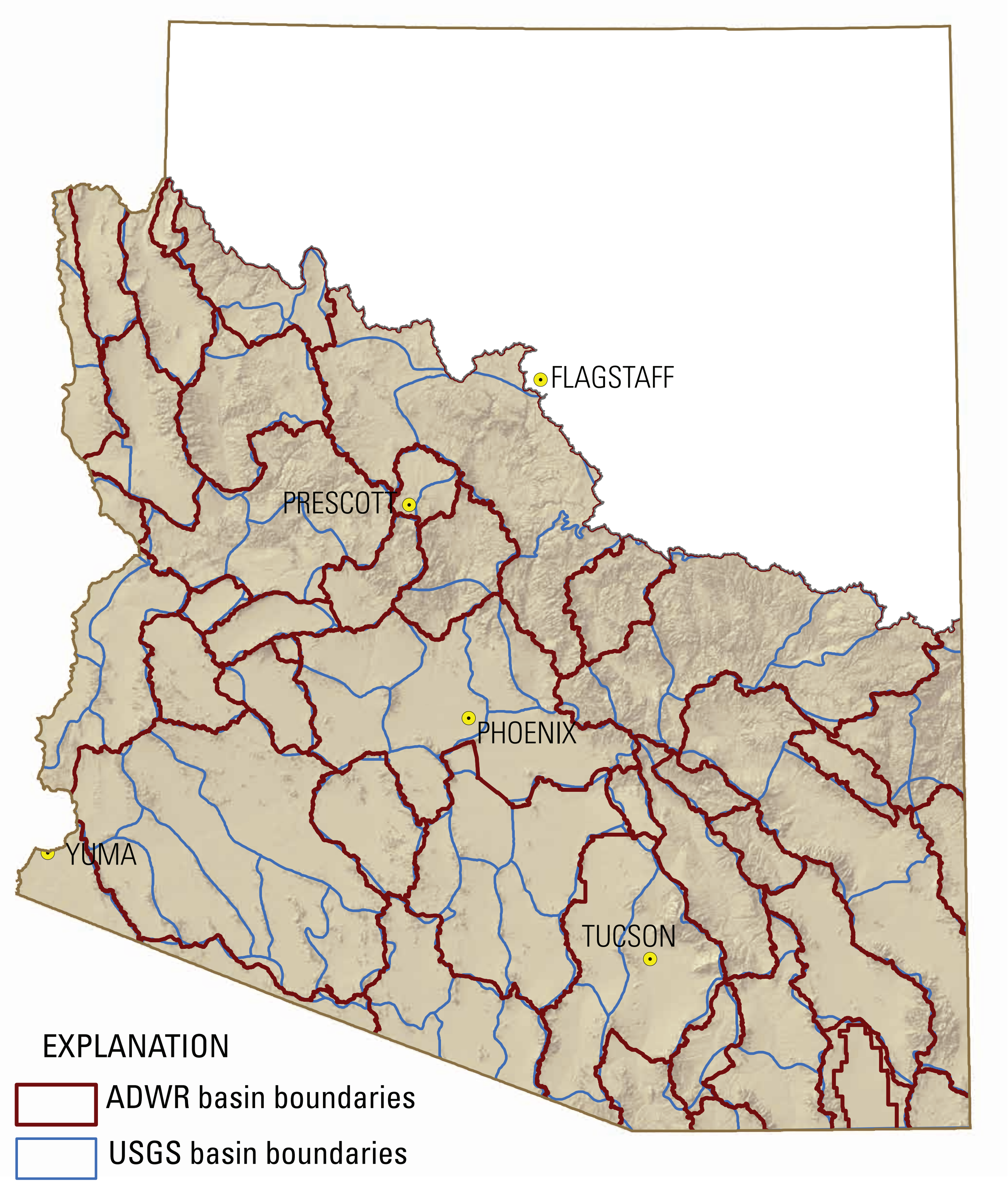


Figure 31. Differences in groundwater basins used in Arizona Department of Water Resources (ADWR) and U.S. Geological Survey (USGS) studies.

more streamgages on the same stream, (3) measuring flow at selected locations during baseflow conditions and determining the differences in measured flows (gains or losses), (4) directly measuring seepage using soil-moisture sensors, and (5) using indirect chemical or physical characteristics such as isotopes, chemical constituents, electrical conductivity, gravity, or temperature (Stonestrom and others, 2007). Methods (1) and (2) were used in this study to investigate the potential recharge to aquifers by seepage from streams. Methods (3), (4), and (5) were beyond the scope of this study.

Methods

Streamflow data from 75 streamgages were evaluated for this study to determine if suitable data exist for estimating aquifer recharge from seepage (table 19). Only gages on streams and rivers internal to the study area were used in this analysis. Flow in the Colorado River was not analyzed owing to the difficulty of determining the effects of diversions, dams, and agricultural return flow on total flow in the river. The 75 streamgage areas were placed into two categories based on estimated flows upstream of the gage as a result of topology and geology: (1) gain; flows generally increase in magnitude with distance downstream, and (2) loss; flows generally decrease in magnitude as drainage area increases (table 19). Aquifer recharge from seepage losses are likely minimal on the stream reaches above gages classified as gaining, and recharge from seepage losses can be substantial on the stream reaches above gages classified as losing. Recharge by seepage from streams was evaluated and estimated by comparing streamflow data at 75 streamgaging stations (table 19). Differences in daily mean flows and monthly flows between streamgages were calculated for the 18 streams with multiple gages (table 20). These differences (gains or losses) were evaluated for magnitudes and seasonal relations.

Results

The differences in flows (gains or losses) between streamgages on all the streams were spatially and temporally variable (table 20). Of the 18 streams with multiple gages, 10 streams had mostly gaining flow between the streamgages, indicating minimal or no seepage in those reaches (table 20). Four streams (Hassayampa River, Gila River, Santa Cruz River, and San Pedro River) had a combination of gains and losses between streamgages, and four streams had mostly losses between gages (New River, Tanque Verde Creek, Pantano Wash, and Rillito River). The differences in daily mean flows and monthly flows on these eight streams were extremely variable, showing both gains and losses from day to day. Runoff from tributaries between streamgages was likely a complicating factor. Even in seasons with minimal precipitation and tributary runoff, it was difficult to discern consistent losses that could be translated into seepage losses.

Mean annual streamflow was calculated for the 75 single streamgage sites and summarized by the region in which the runoff and seepage occur (fig. 32). Data from only 28 downstream streamgages are presented in table 21, because these records summarize flow from above the gage. These flows were assumed to be the amount of flow that is potentially available for seepage downstream of the streamgage and define an upper limit to the volume of aquifer recharge from the stream. Some potential reductions in the volume of streamflow that could become aquifer recharge include shallow infiltration of streamflow and subsequent evapotranspiration, evaporation from the stream surface itself, impoundment by dams, and irrigation diversions. Mean annual volumes of flow available for seepage were calculated for two periods: (1) a predevelopment period (with no dams or irrigation diversions) and (2) a postdevelopment period, when several dams impound water on major streams (table 21).

The study area can be broadly classified into three types of runoff and seepage regions: (1) runoff, (2) seepage, and (3) runoff/seepage (fig. 32). The high-elevation areas in the northern part of the study area have mostly runoff with little seepage to groundwater. The low-elevation areas in the central and western parts of the State have little runoff and mostly seepage. The eastern part of the State has a combination of runoff from mountains and seepage in valleys. Most of the runoff from the high-elevation regions is accounted for by streamgages at the downstream ends of the regions. In the internal drainages of regions 1, 3, 4, 7, and 8 (fig. 32), only part of the streamflow available for seepage is measured by streamgages. Thus, the streamflow available for seepage was only estimated in a few basins in these five regions (table 22).

In the postdevelopment period, about 95 percent of the runoff from the three runoff regions (fig. 32) is impounded and stored behind dams. During the predevelopment period: (1) about 108,000 acre-ft of water was available for seepage in the lower part of region 2 (table 22), (2) about 1,200,000 acre-ft of runoff from regions 5 and 6 (table 22) was available for seepage downstream from these regions, and (3) about 412,000 acre-ft of runoff from region 7 was available for seepage in region 4 (fig. 32; table 22), presuming minimal seepage along rivers before entering region 4. The 1,555,000 acre-ft of predevelopment available seepage water in region 4 that came from outside regions is reduced to about 90,000 acre-ft of available water in the postdevelopment period. There are no dams on the internal drainages in the other internal regions, so the predevelopment estimate of streamflow available for seepage is approximately equal to the postdevelopment estimate. Although insufficient data were available to estimate aquifer gains or losses from/to streamflow on an individual groundwater basin scale, the information presented in table 22 provides a useful upper bound on aquifer recharge from streamflow for the study area. Estimates of predevelopment aquifer recharge from streamflow and aquifer discharge to streamflow developed by the SWAB-RASA study (Anderson and others, 1992) are presented in table 23 for reference for stream reaches in

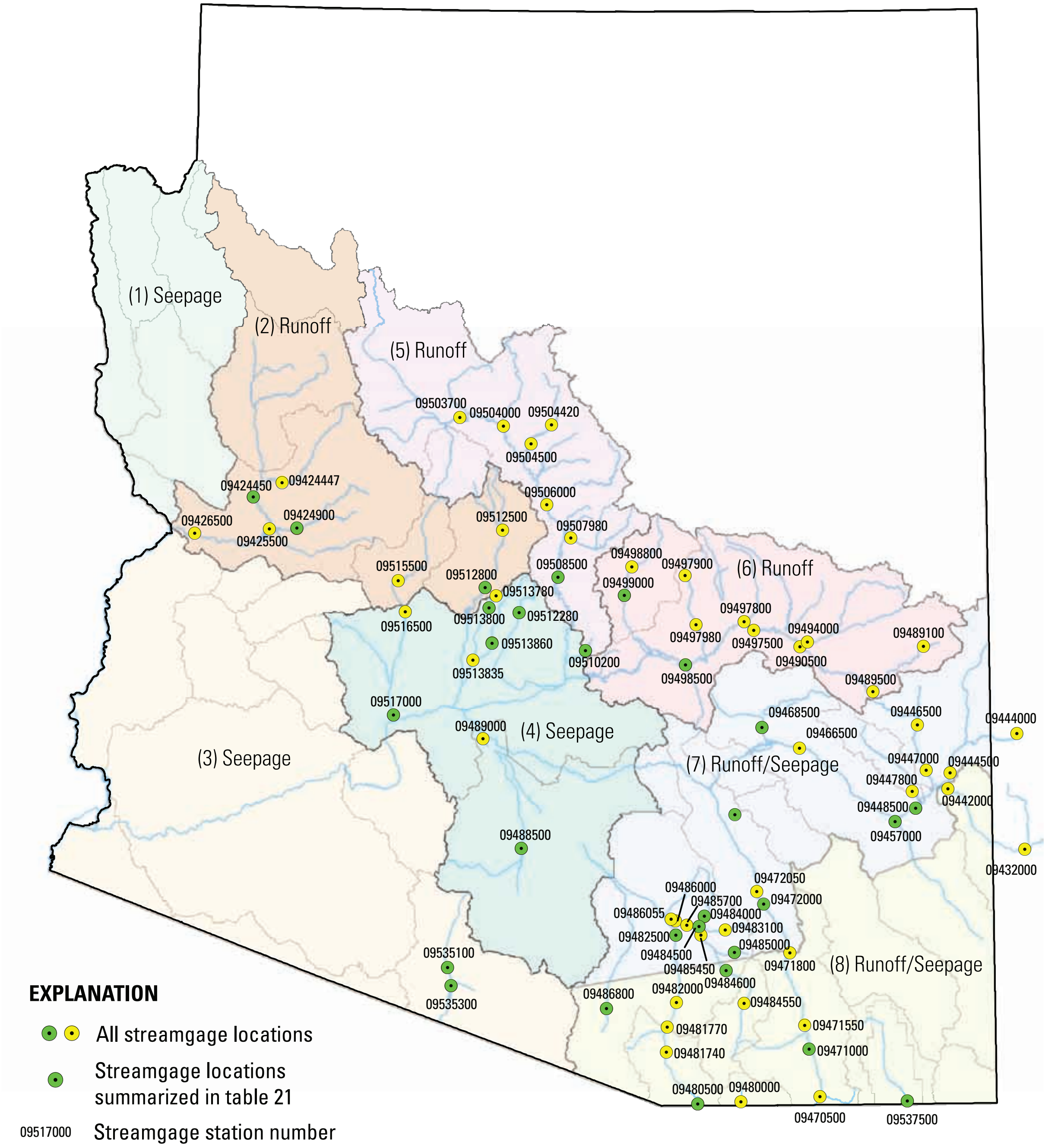


Figure 32. Location of streamflow gages used in analysis of stream seepage and classification of runoff/seepage regions in the Southwest Alluvial Basins of Arizona.

which infiltration was a significant part of the predevelopment water budget (fig. 33).

Irrigation and Public Supply Water Use Data Collection in the Southwest Alluvial Basins

Anthropogenic water use is a significant component of the groundwater budgets in select basins in the study area. Information on anthropogenic water use in Arizona was collected historically by the USGS, with the task more recently divided between ADWR and USGS. These water-use data have been reported in a variety of publications over time. The USGS in Arizona collected and compiled water-use data by USGS groundwater basins (fig. 31) from the 1900s through 1991 (Anning and Duet, 1994). More recently, annual groundwater and surface-water withdrawal data for irrigation and public supply are collected and compiled in each of the five AMAs by ADWR, with the USGS performing the collection and compilation for areas outside of the AMAs. Beginning in 1950, the USGS, as part of a national program on water use, has collected, compiled, and reported groundwater and surface-water withdrawals every 5 years. These reports contain withdrawal data for the categories of public supply, irrigation, mining, thermoelectric power, domestic, commercial, and industrial uses (Solley and others, 1983, 1988). From 1981 through 1990, the USGS and ADWR cooperatively prepared a series of reports titled “Summary of Ground-Water Conditions in Arizona” that summarize the groundwater withdrawal data by USGS groundwater basins. Recently, ADWR has published these data in Water Atlases (Arizona Department of Water Resources, 2006, 2009a–e). Groundwater withdrawals for urban turf irrigation were not included in the irrigation analysis because some of these urban turf irrigation withdrawals are accounted for in the groundwater withdrawals for public supply. Detailed estimates of turf acreage were also not available for the study area.

Methods

Published datasets from the ADWR and the USGS were used to estimate the groundwater and surface-water withdrawals for irrigation and public supply for 1980 and 2005 in the SWAB study area. The water-usage tables in the ADWR Water Atlases report groundwater and surface-water withdrawals since 1971, with projections to 2050. Before 1990, only one average groundwater and one average surface-water withdrawal value were presented for each ADWR basin for a 5-year period. Starting in 1991, water-usage data were subdivided into three categories: municipal, industrial, and irrigation. Whereas most ADWR and USGS-delineated groundwater basins share similar boundaries, the majority of ADWR basins comprise several USGS groundwater basins (fig. 31). To make comparisons between the 1980 and 2005 groundwater and surface-water withdrawals, 1980 withdrawal data were disaggregated from USGS basins and reaggregated by ADWR groundwater basins. To calculate the 1980 groundwater withdrawals for the same categories available for the 2005 data, it was assumed that the proportions of water withdrawals in each ADWR basin for each use remained constant for the time period 1991 to 1995. The proportional water-use categories were then multiplied by the average of the 5-year period for 1975 to 1980 to estimate municipal and irrigation withdrawals for 1980.

Irrigation

The 1980 groundwater and surface-water withdrawals for irrigation for the study area including the AMAs were obtained from the ADWR Water Atlas series (Arizona Department of Water Resources, 2006, 2009a–e), with the exception of three basins. The Colorado River comprises the western boundaries of the Yuma, Parker, and Lower Gila basins in the southwest part of the study area, and these three basins receive surface water diverted from the Colorado River. These surface-water diversions are metered by the USGS. Although the surface-water diversions are included in the ADWR Water Atlas series (Arizona Department of Water Resources, 2006, 2009a–e), the same surface water diversion value is reported for each of the three basins, which is highly unlikely. As a result, the 1980 surface-water diversions for the Yuma, Parker, and Lower Gila basins were obtained from USGS-metered surface-water diversions instead of from the Water Atlases.

The 2005 groundwater and surface-water withdrawal data for irrigation in the non-AMA ADWR groundwater basins were obtained from the USGS Arizona Water Use Program Web site (U.S. Geological Survey, 2009a). For the five AMAs, groundwater and surface-water withdrawal data were obtained from the ADWR Active Management Area Assessment Web site (Arizona Department of Water Resources, 2009f). Although the focus of this report is on groundwater budgets in the study area, surface-water withdrawals for irrigation for both time periods were included in the analysis in order to estimate incidental aquifer recharge from irrigation (see “Incidental Recharge from Irrigation Water Use” section below).

Public Supply

The 1980 groundwater withdrawal data were obtained from the ADWR Water Atlas series (Arizona Department of Water Resources, 2006, 2009a–e). The 2005 public-supply groundwater withdrawal data from all areas with the exception of the AMAs were obtained from the USGS Arizona Water Use Program Web site (U.S. Geological Survey, 2009a). For the five AMAs, public-supply groundwater withdrawal data were obtained from the ADWR Active Management Area Assessment Web site (Arizona Department of Water Resources, 2009f).

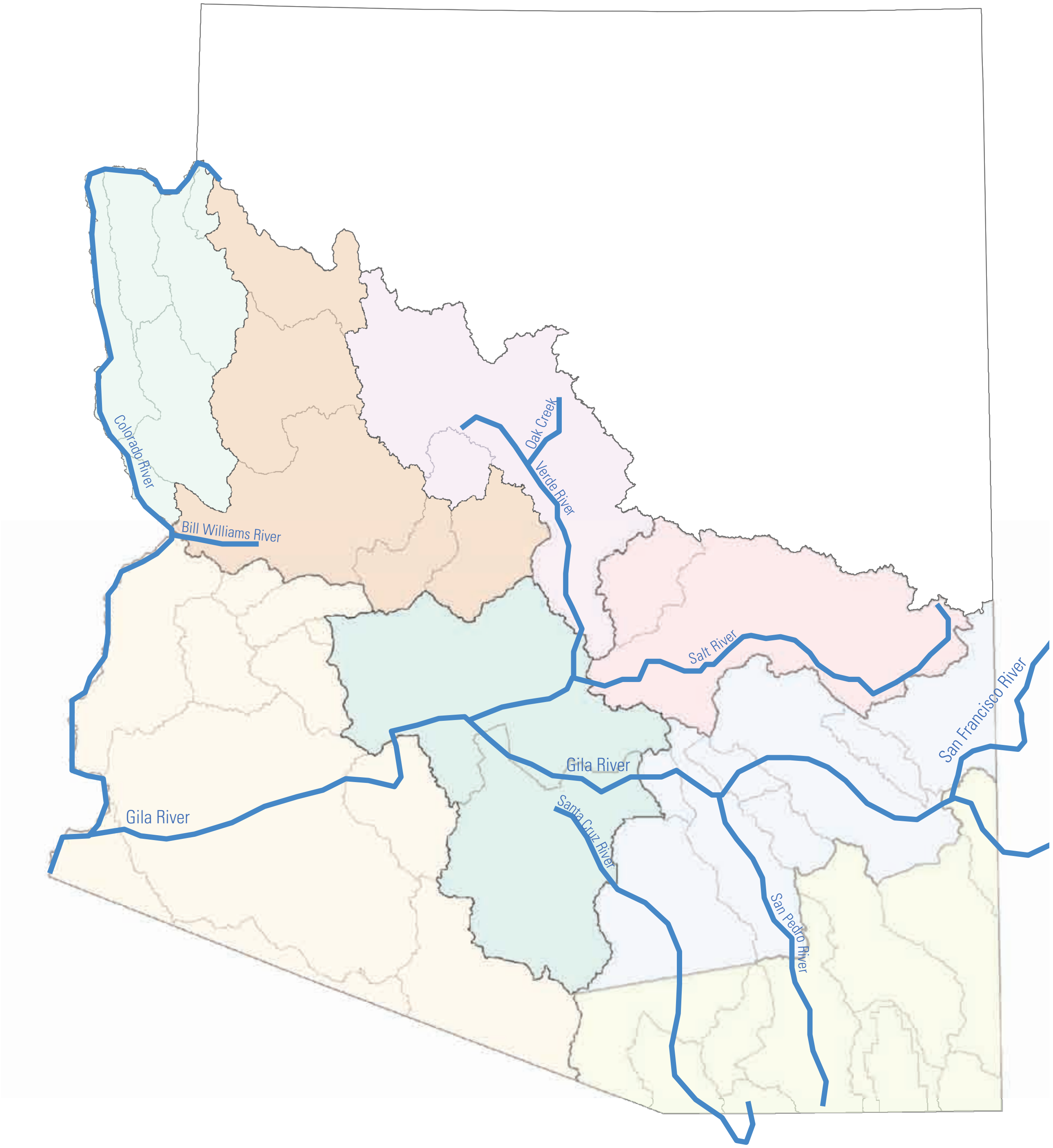


Figure 33. Stream reaches in the study area in which infiltration was a significant part of the predevelopment water budget (adapted from Anderson and others, 1992).

Results

Groundwater and surface-water withdrawals for irrigation for 1980 and 2005 are presented in acre-ft in table 24 for 28 basins in which data were available. Groundwater and surface-water withdrawals for public supply for 1980 and 2005 are presented in acre-ft in table 25 for all 45 basins (with Douglas INA data included with the Douglas Basin). Withdrawals for some basins are reported as "less than 300 acre-ft" or "less than 1,000 acre-ft." Total groundwater and surface-water withdrawals reported in the text, figures, and tables are the summation of the values greater than 300 acre-ft or greater than 1,000 acre-ft. The rounding criteria of Tadayon (2005) were used to present the groundwater and surface-water withdrawal data:

- Values from 300 to <1,000 acre-ft are presented to the nearest 50 acre-ft.
- Values from 1,000 to <10,000 acre-ft are presented to the nearest 100 acre-ft.
- Values from 10,000 to <100,000 acre-ft are presented to the nearest 500 acre-ft.
- Values from 100,000 to <1.0 million acre-ft are presented to the nearest 1,000 acre-ft.
- Values of 1.0 million acre-ft and greater are presented to the nearest 5,000 acre-ft.

Irrigation

The largest volumes of groundwater withdrawals for irrigation during 1980 were in the Phoenix and Pinal AMAs (fig. 34 and table 24). Outside of the AMAs, the Lower Gila Basin had the largest groundwater withdrawals for irrigation. For 1980, total groundwater withdrawals in the study area in basins with groundwater irrigation withdrawals greater than 1,000 acre-ft were 3.6 million acre-ft. For 2005, total groundwater withdrawals in the study area in basins with irrigation groundwater withdrawals greater than 1,000 acre-ft were 1.9 million acre-ft (fig. 34 and table 24). The greatest declines in groundwater withdrawals for the time period of 1980 through 2005 were in the Phoenix and Pinal AMAs, whereas groundwater withdrawals increased the most in the Ranegras Plain Basin. As in 1980, the largest groundwater withdrawals for irrigation in 2005 were in the Pinal and Phoenix AMAs. Outside of the AMAs, the Gila Bend Basin had the largest groundwater withdrawals for irrigation purposes.

In 1980 and 2005, the Yuma basin had the greatest amount of surface-water withdrawals for irrigation, followed by the Phoenix AMA (table 24). Increases in surface-water withdrawals for irrigation occurred in the Tucson AMA, Harquahala INA, and Pinal AMA between 1980 and 2005 (table 24). These increases in surface-water withdrawals from the three basins are from the importation of surface water through the CAP canal. Surface-water withdrawals have decreased the most in the Gila Bend Basin, from 102,000 acre-ft in 1980 to 55,500 acre-ft in 2005.

Public Supply

Total withdrawals of groundwater in 1980 for public supply in basins with withdrawals greater than 300 acre-ft was 480,000 acre-ft (table 25). The Phoenix AMA had the greatest public-supply groundwater withdrawals, followed by the Tucson AMA and Lake Havasu Basin in 1980 (fig. 35, table 25). Twenty-nine of the 45 basins had withdrawals less than 300 acre-ft for public-supply. The Yuma basin had the greatest withdrawals for public supply in 1980 outside of the AMAs.

Total withdrawals of groundwater in 2005 for public supply in basins with withdrawals greater than 300 acre-ft were 526,000 acre-ft. Lake Mohave had the largest withdrawals for public supply outside of the AMAs in 2005 (fig. 35 and table 25). The Phoenix AMA was the only basin that showed a decrease in public-supply groundwater withdrawals between 1980 and 2005. This decrease in groundwater withdrawals is primarily from the increased use of surface water from the CAP for public supply in the Phoenix AMA. Groundwater withdrawals for public supply in the Prescott AMA, Lake Mohave, and Pinal AMA basins each increased by 10,000 acre-ft or more between 1980 and 2005.

Incidental Recharge from Irrigation Water Use

Not all water withdrawn for irrigation purposes is used consumptively by plants; some of this water is lost in the conveyance system, during deep percolation, and as recharge to the aquifer. For this study, potential incidental recharge from irrigation is defined as irrigation water that is not used by the crop for consumptive use. The irrigation efficiency was used to estimate the maximum potential recharge from irrigation water use and is defined as the crop consumptive water requirement divided by the total quantity of water withdrawn for irrigation (Tadayon, 2005). The irrigation efficiencies in the study area differ depending upon the type of irrigation system used by the grower. Irrigation efficiencies for the SWAB study area are shown in table 26 (S. Tadayon, oral commun., 2009).

Methods

To estimate the quantity of irrigation water that percolates to the aquifer as recharge, total water withdrawals for irrigation (from both groundwater and surface water sources)

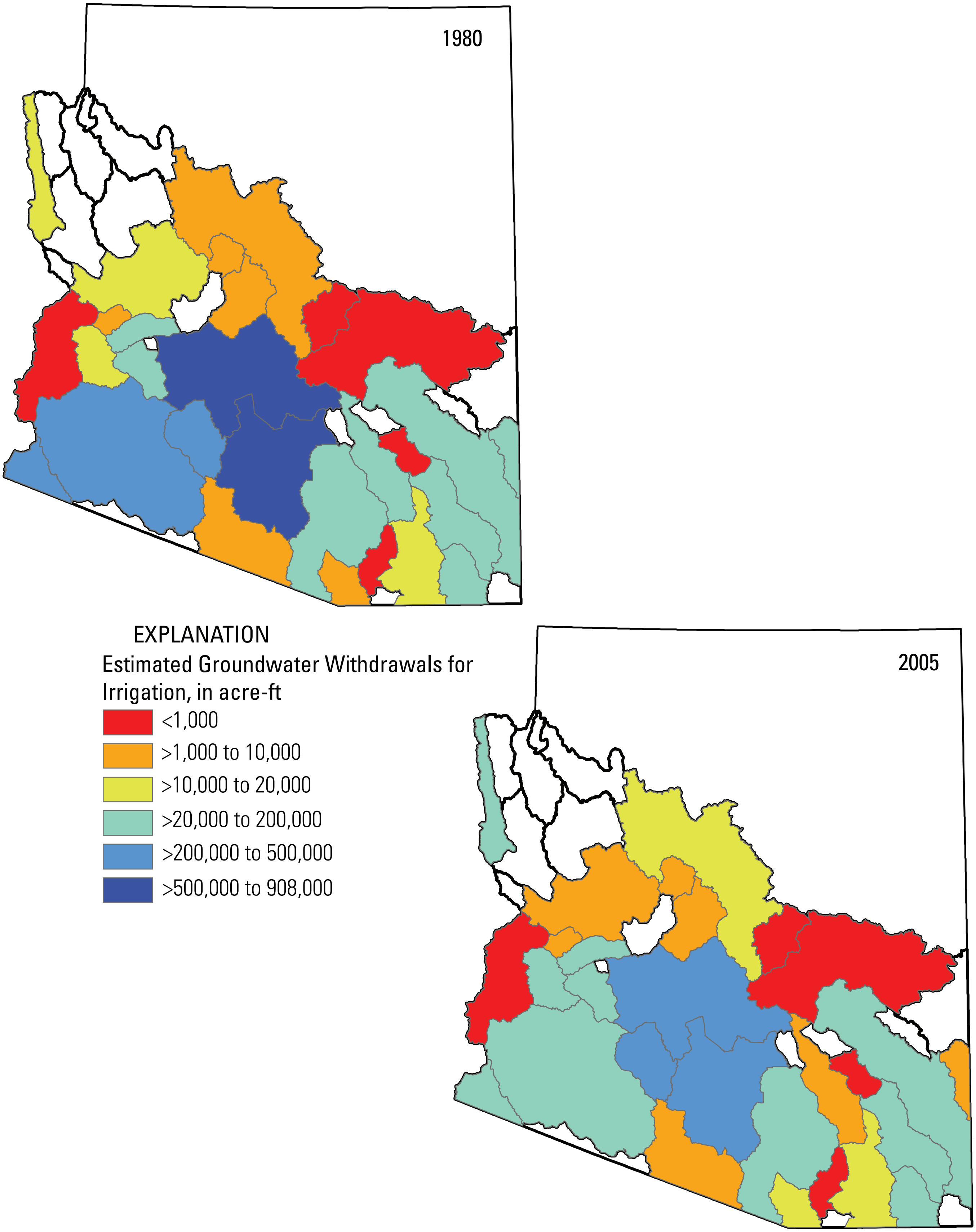


Figure 34. Estimated groundwater withdrawals for irrigation in 1980 and 2005. Uncolored basins have no reported data.

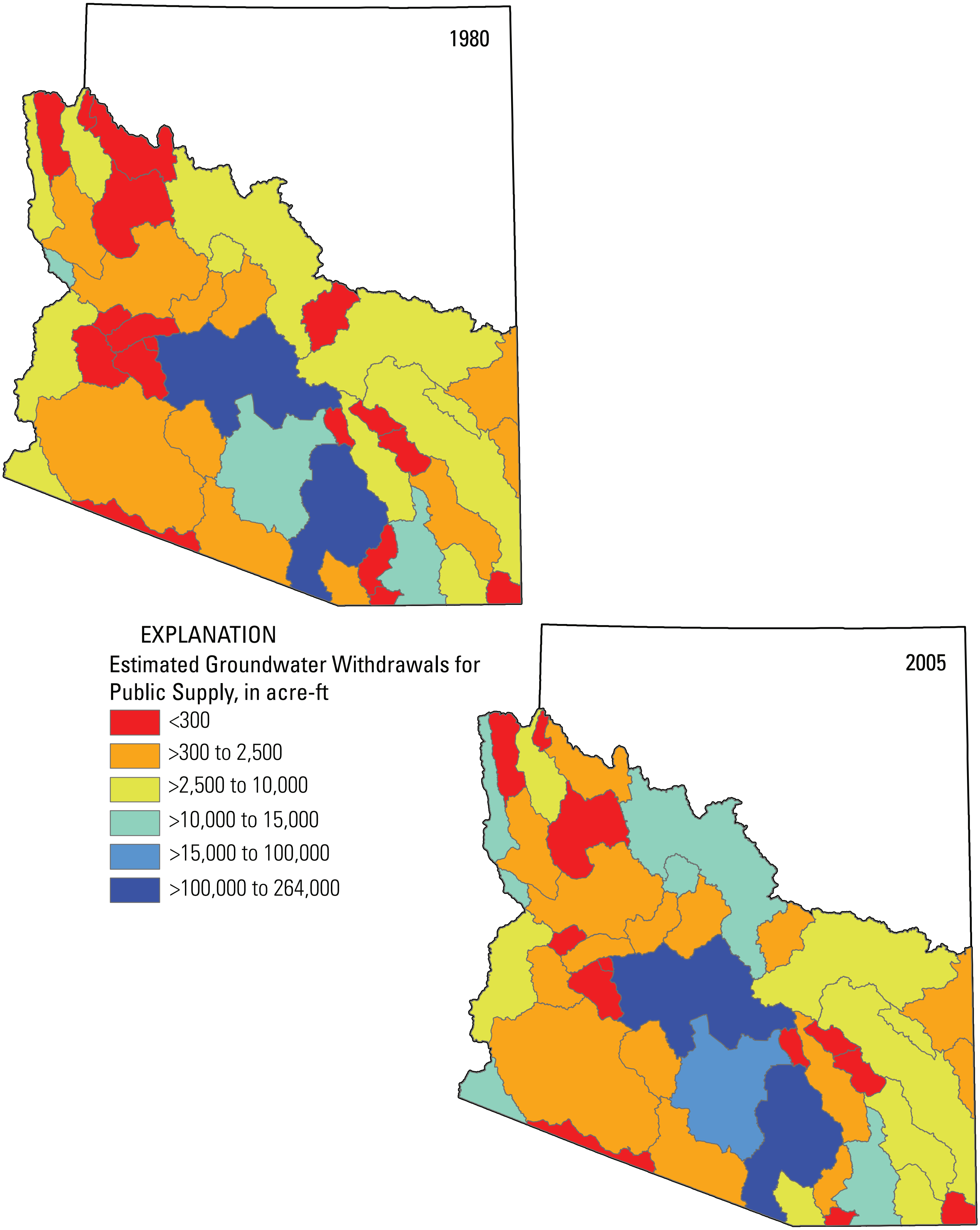


Figure 35. Estimated groundwater withdrawals for public supply in 1980 and 2005.

for each basin were first multiplied by an inefficiency coefficient (1 minus the irrigation efficiency). This value represents the maximum quantity of water that is available for recharge from irrigation.

Information on irrigation system type and irrigation volume of water applied was not available for 1980, so 1985 acreage by irrigation system and volume of water applied by eight-digit Hydrologic Unit Code (HUC) were obtained from the USGS National Water-Use Data Archive Web site (U.S. Geological Survey, 2009b). The eight-digit HUC basins are similar to the ADWR basins and were applicable for this study. A weighted average for irrigation efficiency was computed based on the eight-digit HUC irrigation types for acreages of known irrigation systems. Water-use data collected by the USGS for irrigation in the ADWR basins were used to estimate the maximum potential recharge from irrigation water use for 2005. As part of the annual data collection by the USGS, for each ADWR groundwater basin outside of the AMAs, the irrigation system, crop type, and acreage are reported. For the AMA basins, water withdrawals were obtained from the ADWR Water Atlas series (Arizona Department of Water Resources, 2006, 2009a–e). For basins outside of the AMAs where sufficient data about irrigation systems and acreage were available, the losses from each type of irrigation system were computed and then summed for each basin. For the AMAs, an overall efficiency of 60 percent was used, assuming that the majority of the irrigated fields in the AMAs are flooded.

For three basins, the Phoenix AMA, Lower Gila Basin, and Yuma Basin, there are drainage wells that needed to be considered. The main purpose of these drainage wells is to keep the water table from rising to the root zone to allow for the flushing of excess salts (Tadayon, 2005). In the Phoenix AMA, the Lower Gila Basin, and Yuma Basin, the volumes of shallow groundwater withdrawn from the drainage wells are metered, and these volumes were subtracted from the maximum potential recharge from irrigation for both the 1980 and 2005 time periods.

Results

The estimates of maximum potential incidental recharge from irrigation for 1980 and 2005 are presented in acre-ft (table 27). In 1980, the greatest estimates of maximum potential incidental recharge were for the Phoenix and Pinal AMAs (fig. 36 and table 27). The total estimated volume of maximum potential incidental recharge to the aquifer from irrigation in 1980 in basins with irrigation withdrawals greater than 1,000 acre-ft was 2.0 million acre-ft (table 27). In 2005, the greatest estimates of maximum potential incidental recharge were also for the Phoenix and Pinal AMAs (fig. 36 and table 27). The total estimated volume of maximum potential incidental recharge to the aquifer from irrigation in 2005 in basins with irrigation withdrawals greater than 1,000 acre-ft was 1.6 million acre-ft (table 27).

Recharge from the Central Arizona Project

An additional inflow to the groundwater budgets of some alluvial basins is intentional recharge of surface water delivered by the Central Arizona Project (CAP) into the study area. Construction of the CAP canal began in 1973 and was completed in 1993. The CAP canal allows Arizona to use a portion of its Colorado River allotment in interior basins. The water delivered by the CAP canal (CAP water) is used for municipal, industrial, and irrigation uses, as well as providing water for aquifer recharge and storage facilities in the study area. Storage of CAP water in Underground Storage Facilities (USF) or Ground Water Savings Facilities (GSF) is administered by the ADWR. CAP water delivered to a USF is often recharged to the aquifer by an injection well or a percolation basin. Some USFs discharge CAP water into ephemeral streambeds for aquifer recharge. CAP water is also delivered to GSFs, where it is transferred to users such as irrigation districts who would otherwise pump groundwater. For more information on the storage of CAP water, readers are referred to Colby and Jacobs, 2007.

Methods

Information on the volumes of CAP water delivered to GSF and USF facilities is collected by the ADWR for accrual of recharge credits. All of the permitted recharge facilities for CAP water are located in the Phoenix, Tucson, and Pinal AMAs. These three AMAs have a combined annual permitted storage capacity at both USFs and GSFs of 2.1 million acre-ft (Arizona Department of Water Resources, 2006, 2009a–e).

Results

The annual volume of CAP water delivered to USFs at the end of the 2005 calendar year includes delivery of 94,000 acre-ft to the Phoenix AMA and 141,000 acre-ft to the Tucson AMA (D. Kusel, written commun., 2009). This total volume of 235,000 acre-ft represents the maximum amount of recharge from surface-water deliveries from the CAP to USFs.

Artificial Recharge from Treated Effluent

Another small component of the groundwater budgets in several alluvial basins in the study area is treated effluent from municipalities that recharges the aquifer. The treated effluent can recharge through seepage after its release to an infiltration basin or watercourse such as a channel, or it can be recharged directly through injection wells.

Methods

The volumes of treated effluent discharged into unlined impoundments or injection wells in alluvial basins in the study

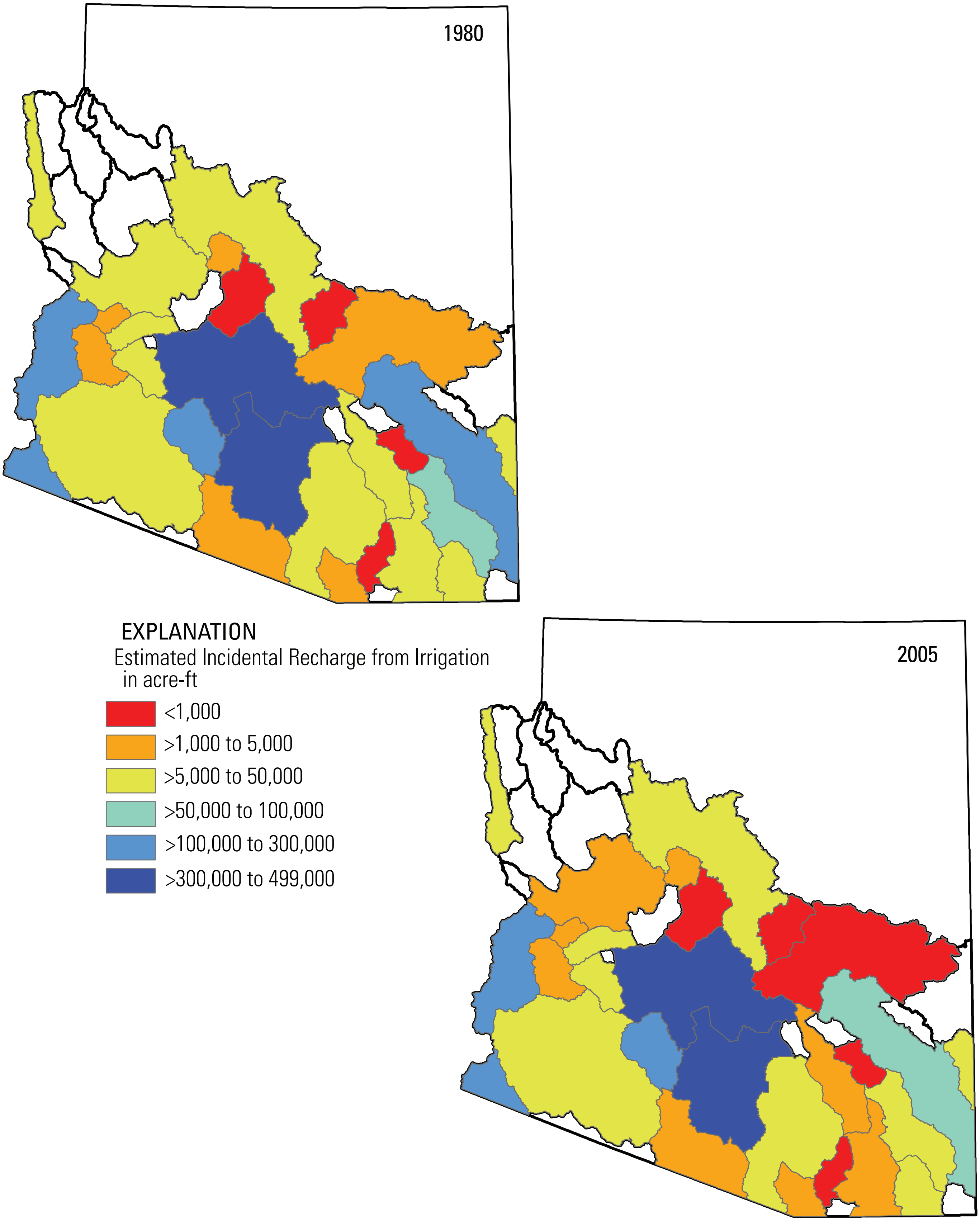


Figure 36. Estimated potential incidental recharge from irrigation water use in 1980 and in 2005. Uncolored basins have no reported data.

area were provided by ADWR personnel (K. M. Lacroix, written commun., 2009). Additional information on the Upper San Pedro Basin, Tucson AMA, Santa Cruz AMA, and the Prescott AMA was obtained from published reports (table 28). The volumes of treated effluent discharge in table 28 represent the maximum potential volumes of recharge to the aquifer. Although a portion of this treated effluent actually becomes aquifer recharge, some portion is also lost to evaporation.

Results

Maximum estimated aquifer recharge from treated effluent was greatest in the AMAs (fig. 37, table 28), with the highest volume being 34,000 acre-ft in the Phoenix AMA. In the Phoenix AMA, an additional approximately 140,000 acre-ft of treated effluent is delivered to the Palo Verde nuclear power station for cooling of the plant's reactors and is not available for recharge (Colby and Jacobs, 2007). The Upper San Pedro Basin had the greatest estimated recharge from treated effluent outside of the AMAs (fig. 37, table 28).

Change in Aquifer Storage Since Before Development

In many basins in the SWAB study area, the imbalance between aquifer recharge and aquifer discharge (particularly groundwater withdrawals), has led to large decreases in aquifer storage. An estimate of total change in aquifer storage between predevelopment times and post-2000 conditions was produced using published groundwater-level information and depth-to-groundwater data. This method of estimating aquifer storage change does not rely on the accuracy of other groundwater budget components and is thus independent of any uncertainties in their estimation.

Methods

The change in aquifer storage since before development was estimated for the most developed basins in the SWAB area. Although estimates were not developed for all 45 groundwater basins in the study area, the 15 basins investigated account for more than 85 percent of the total historical groundwater withdrawals for the State through 1987 (Konieczki and Wilson, 1992) and therefore represent most of the change in aquifer storage within the study area. Estimating the change in aquifer storage since before development for the most developed SWAB basins in Arizona involved basic hydrologic analyses of historical and recent groundwater-level surfaces. Literature sources for predevelopment groundwater levels in the SWAB basins were located. Maps in these reports were scanned and georeferenced into a geographic information system (GIS) and the groundwater-level information was digitized. Well records also were searched to determine if groundwater-level observations were available for the predevelopment era and if so, these data were added to the predevelopment maps in GIS. A surface of predevelopment groundwater levels was created from all available historical groundwater information using interpolation methods such as inverse distance weighting or nearest neighbor (Cressie, 1993). Recent groundwater-level surfaces were generated in a similar manner using current and recent (since 2000) groundwater observations contained in the USGS and ADWR databases. A subtraction of the current groundwater-level surface from the predevelopment surface in GIS produced a layer of groundwater-level change since predevelopment times. Storage coefficients were obtained from previously published reports. Depending on the type of aquifer, the storage coefficients may be specific yield or the product of specific storage and thickness. Aquifer storage change since before development was then computed as the product of the storage-coefficient value and the change in water level.

Results

In some areas of the most developed SWAB basins, a lack of predevelopment information precluded determination of change in groundwater levels and storage since predevelopment times. As previously described, groundwater levels from predevelopment reports and maps were augmented with observations from the NWIS and ADWR databases, where appropriate. In certain areas, however, there was no information on predevelopment conditions and, consequently, no estimate of aquifer storage change could be computed. Total aquifer storage change since before development for the study area, therefore, is probably underestimated.

Aquifer storage change since predevelopment times for the SWAB basins of Arizona is presented graphically in units of feet of water (fig. 38) and in a table as volume of change (table 29). Areas with large declines in groundwater levels, such as the heavily agricultural area of the Pinal AMA, have seen accompanying large declines in aquifer storage (fig. 38; see fig. 2 for basin names). Some wells in the Pinal AMA have recorded declines in groundwater observations of more than 500 feet since the mid-1940s (Tillman and others, 2007). The large land area under development along with large amounts of historical groundwater withdrawals in the Phoenix AMA have resulted in more than 30 million acre-ft of estimated aquifer storage depletion in this basin (table 29). The computed total volume of 74.5 million acre-ft of groundwater lost from storage for the basins covering about 85 percent of recorded groundwater withdrawals through 1987 is comparable to other published estimates of 92.0 million acre-ft (Robson and Banta, 1995) and 100 million acre-ft (Anderson and others, 1992) for the entire SWAB-RASA study area through 1980. Comparisons from this study with aquifer storage change estimates from recently reported modeling results include 5.3 million acre-ft versus 6.9 million acre-ft (Mason and Bota, 2006) for the Tucson AMA and 899,000 acre-ft versus 704,000 acre-ft (Pool and others, 2011) for the Prescott AMA.

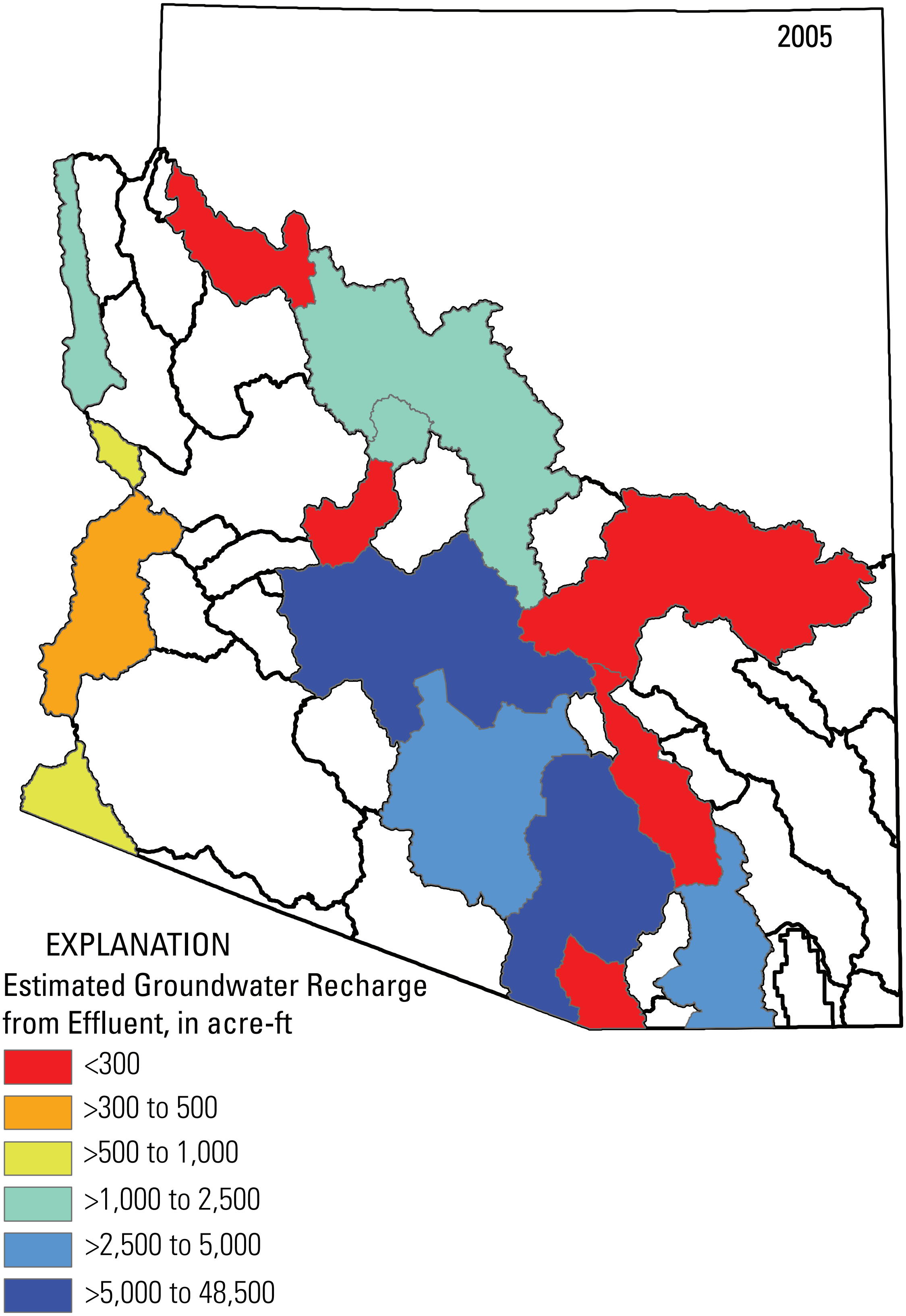


Figure 37. Estimated potential groundwater recharge from treated effluent in 2005. Uncolored basins have no reported data.

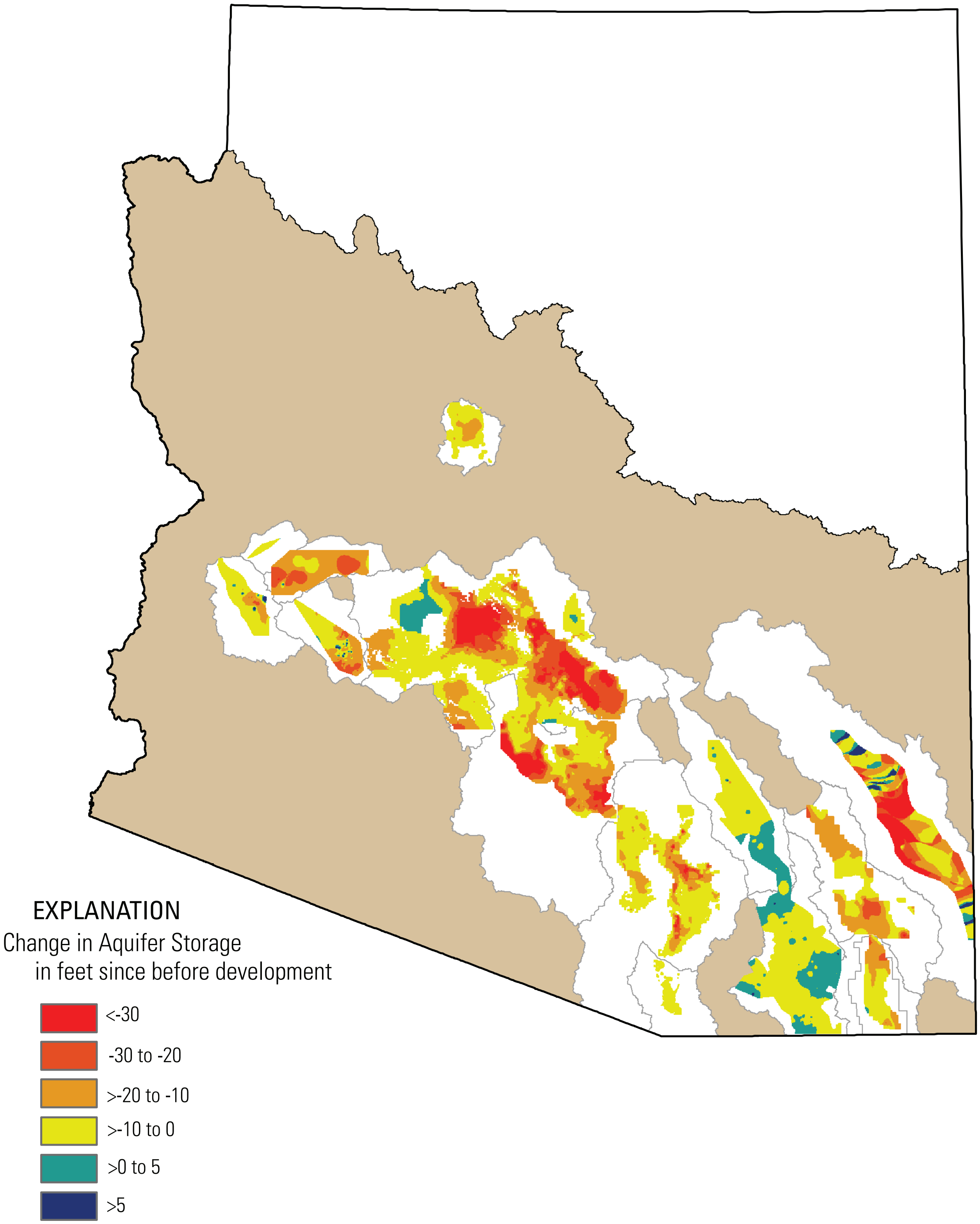


Figure 38. Estimate of change in aquifer storage from before development (circa 1940) to present (2000–2006) for the most developed alluvial basins in Arizona. Storage change estimate does not include loss of storage from land subsidence. Negative values represent removal of groundwater from aquifer storage and positive values indicate addition of groundwater to aquifer storage. Estimation method based on water-level change over period of development and assumed storage coefficients. Predevelopment or present-day data unavailable for white areas inside of most developed basins.

Regional Groundwater Budget Summary

The alluvial basins in Arizona have experienced significant population growth since the USGS SWAB-RASA studies in 1980. Currently, groundwater accounts for about 50 percent of water used in these alluvial basins (Tadayon, 2005). The stress on groundwater supplies in the alluvial basins is expected to increase with projected population growth. The USGS Groundwater Resources Program instituted the SWAB Groundwater Availability and Use Pilot Program to evaluate the availability of groundwater resources in the alluvial basins of Arizona. Updated data and new methods of data analysis were used to evaluate groundwater budget components for each of the alluvial basins in Arizona for predevelopment and modern time periods.

Inflows to the SWAB aquifer system during predevelopment times occurred from three sources: mountain-front recharge, streamflow infiltration, and groundwater underflow into the study area. The largest components of the predevelopment groundwater budget were mountain-front recharge and streamflow infiltration, together accounting for nearly 1.4 million acre-ft per year (fig. 39). Estimates of mountain-front recharge remain roughly the same between predevelopment and current conditions (fig. 39). Although inflows into the SWAB aquifer system from streamflow infiltration for current conditions is reduced owing to damming of rivers and reduced streamflow resulting from groundwater pumping, incidental recharge from irrigation, effluent, and intentional recharge of some of the Colorado River water delivered through the CAP canal system has the potential to offset much of this loss. Nearly 1.9 million acre-ft of incidental recharge may be available for groundwater in the study area (fig. 39).

Outflow from the SWAB aquifer system for predevelopment times occurred mainly through two processes: evapotranspiration and groundwater underflow out of the alluvial basins. Some groundwater discharge to streamflow also probably occurred along reaches of the Bill Williams and Gila River that were formerly perennial to the Colorado River. Modern conditions in the SWAB aquifer systems are defined by the addition of the large human-induced outflow component of groundwater withdrawals. The total annual estimated outflow from the SWAB aquifer system for the predevelopment time period is estimated to be about 1.3 million acre-ft and for the current time period about 3.7 million acre-ft (fig. 39). The largest groundwater budget component during either time period was groundwater withdrawals for public supply and irrigation, estimated to be about 2.4 million acre-ft.

Individual components of the groundwater budget for both predevelopment and modern time periods were estimated independently of each other, with no attempt made to balance inflows and outflows. Differences in the methods and data sources, as well as the uncertainty in each of the individual groundwater budget components, results in a net imbalance during predevelopment time periods, even though groundwater inflow and outflow should be equal during this long-term steady-state era. Development of the aquifer systems, however, produced an imbalance between inflows and outflows (mainly groundwater withdrawals), resulting in an estimated loss of aquifer storage of 74.5 million acre-ft between predevelopment and modern times for the most developed basins in the study area (fig. 39).

Demonstration of a Multibasin Groundwater-Flow Model for South-Central Arizona

A proof-of-concept steady-state numerical groundwater-flow model was developed for a large, multibasin area in the south-central portion of the SWAB study area (fig. 40). The goal in developing this simplified model was to determine if reasonable simulation of the hydrologic systems of several alluvial basins connected only by narrow constrictions was possible and to test the groundwater budget component of recharge developed in this study. Basins with areas selected for the multibasin proof-of-concept model include Tucson and Pinal AMAs, where the most developed areas were modeled. All modeling was accomplished using the three-dimensional groundwater-flow model MODFLOW 2005 (Harbaugh, 2005). The model area comprises more than 2,900 square miles and includes the urban Tucson metropolitan area as well as agricultural areas in the Picacho and Maricopa-Stanfield Basins of the Pinal AMA (fig. 40), which have seen some of the greatest declines in groundwater levels in the State (fig. 9). The model was constructed using existing hydrogeologic frameworks for the Tucson and Santa Cruz AMAs, modification of a previously unpublished framework for the Picacho Basin in the Pinal AMA, and a new framework developed from limited well logs and published geohydrologic reports for the Maricopa-Stanfield Basin, also in the Pinal AMA.

Geohydrologic Conditions in the Model Area

The model study area consists of the Santa Cruz River drainage from south of the Santa Cruz River at Tubac, AZ streamgage (site 09481740) in the Santa Cruz AMA; the Tucson Basin near the City of Tucson and Avra Valley of the Tucson AMA; the Picacho and Maricopa-Stanfield Basins of the Pinal AMA; and a small portion of the Phoenix AMA surrounding the Gila River (fig. 40). The length of the model area along the Santa Cruz River is 153 miles, and the total area encompasses 2,943 square miles. A roughly 4-mile-wide constriction in the basin alluvium between the Silverbell and Picacho Mountains separates the model area into two main parts at the boundary between the Tucson and Pinal AMAs. Basins in the model area consist of alluvial material surrounded by mountain bedrock, but only the basin-fill sediments are sufficiently transmissive to groundwater to be considered aquifers

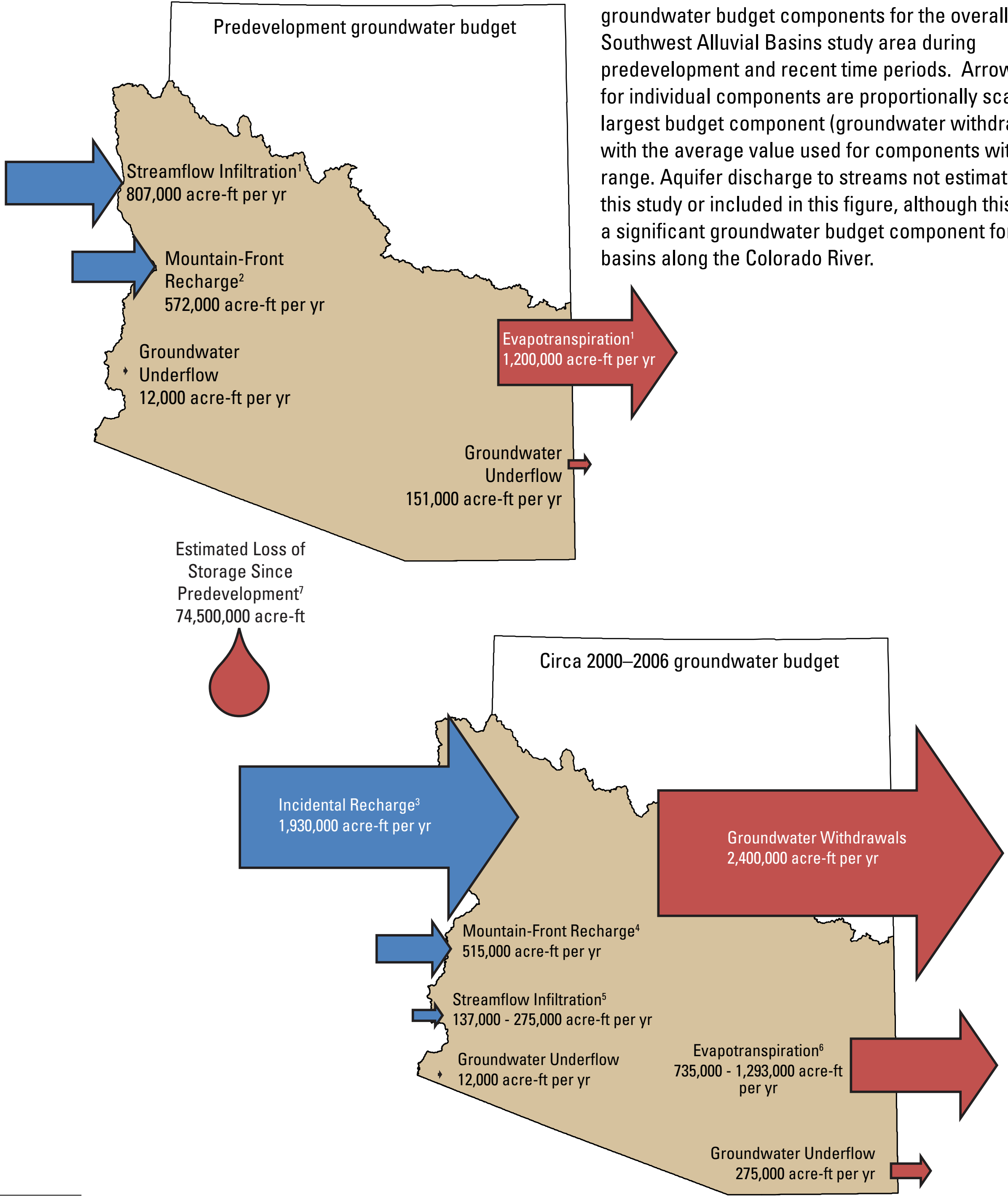


Figure 39. Summary of independently estimated groundwater budget components for the overall Southwest Alluvial Basins study area during predevelopment and recent time periods. Arrow sizes for individual components are proportionally scaled to largest budget component (groundwater withdrawals), with the average value used for components with a range. Aquifer discharge to streams not estimated in this study or included in this figure, although this may be a significant groundwater budget component for some basins along the Colorado River.

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[1] Adapted from Anderson (1995) for study area.

[2] Predevelopment mountain-front recharge estimate from SWAB-RASA regression equation results for 1940–1949.

[3] Incidental recharge estimate includes the sum of recharge from treated effluent greater than 300 acre-ft per year, maximum potential recharge from irrigation greater than 1,000 acre-ft per year, and recharge from CAP deliveries to managed recharge facilities, all for the 2005 calendar year.

[4] Recent mountain-front recharge estimate from SWAB-RASA regression equation results for 2000–2006.

[5] Range of recent streamflow infiltration is 50–100% of streamflow available for recharge in table 21.

[6] Range of recent evapotranspiration from minimum and maximum average 2000–2007 estimates in table 16.

[7] Estimate of total groundwater storage depletion from analysis of groundwater level changes.

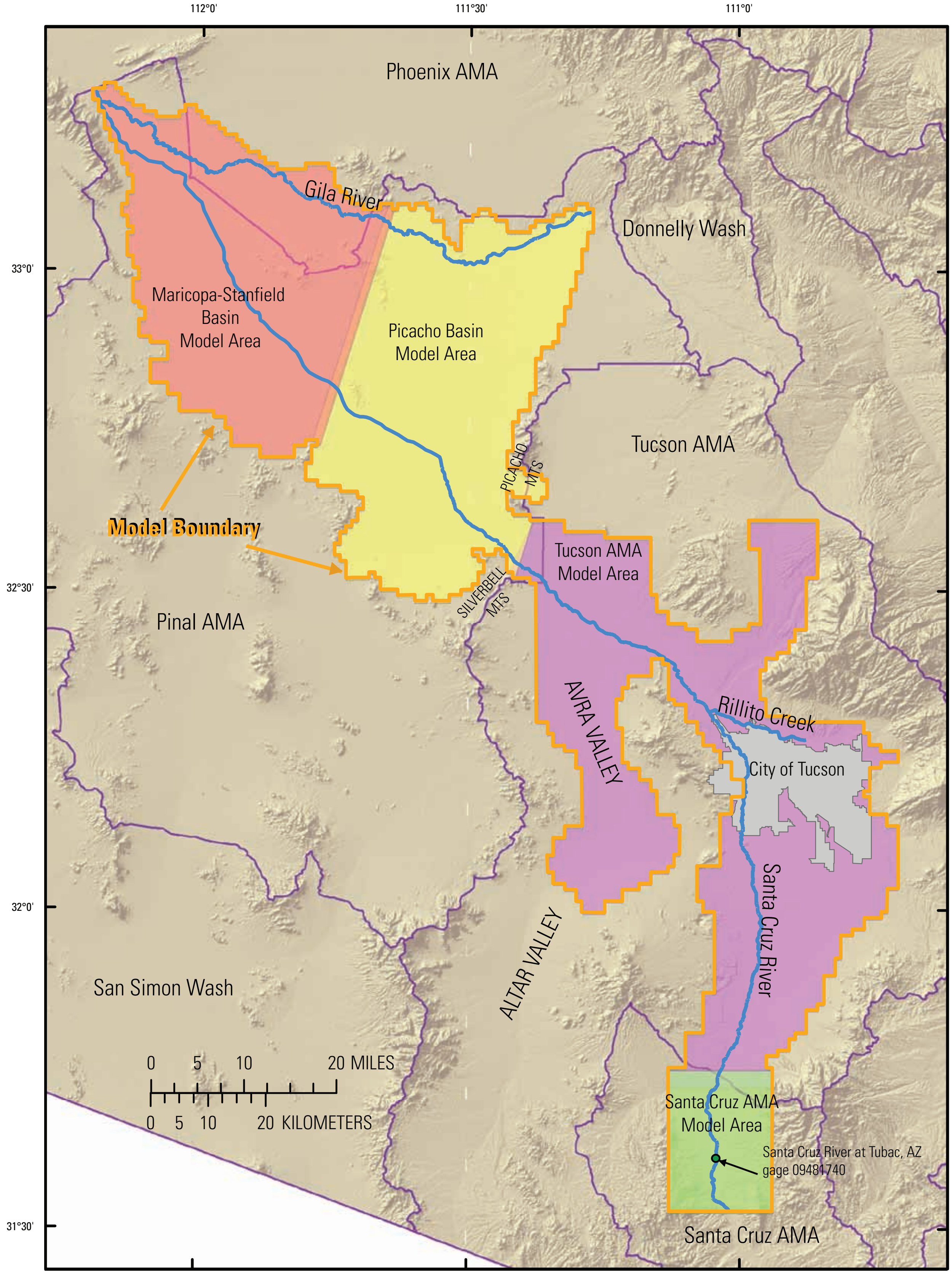

Figure 40. Map of proof-of-concept model area indicating model boundary and component model areas used in creating model framework.

and only these areas are modeled in this study. Predevelopment groundwater flow in the area generally followed the Santa Cruz River drainage, with northerly flow in the Santa Cruz AMA and most of the Tucson AMA, and northwesterly flow through the basins of the Pinal AMA (Anderson and others, 1992).

Pre-Basin and Range sediments overlie consolidated rocks in the basins and are Tertiary in age. These sediments consist of moderately to highly consolidated deposits that range from silt, clay, and claystone to gravel and conglomerate (Anderson and others, 1992). The Basin and Range disturbance in the late Tertiary formed structural basins that subsequently filled with erosional material from tens to more than 11,000 feet thick (Hanson and Benedict, 1994; fig. 41). Deposition of sediments occurred at different rates throughout the area, leading to variability in thickness, areal extent, and grain size. Basin-fill sediments in the area are often divided into two or more units based on grain size, color, degree of consolidation or deformation, stratigraphic position, clast type, and water-bearing characteristics (Anderson and others, 1992). Generally, lower basin-fill sediments are more highly consolidated and finer grained than the upper basin-fill sediments. In the deeper basins they are also more likely to contain mudstone and evaporate deposits. Lower basin-fill sediments are generally indicative of deposition during a topographically closed-basin period, with upper basin fill representing a transition period from closed to integrated drainage basins (Anderson and others, 1992). The lower basin fill comprises the Pantano Formation and the lower and middle Tinaja beds in the Tucson area (Anderson, 1987). The upper basin fill is generally more coarse grained than the lower basin fill, consisting mainly of gravel, sand, and clayey silt (Anderson and others, 1992; Hanson and Benedict, 1994). The upper basin fill is equivalent to the upper Tinaja beds and Fort Lowell Formation in the Tucson area (Anderson, 1987). Stream alluvium overlies basin-fill sediments along the present surface-drainage system and generally consists of flood-plain material and alluvial-fan deposits (Anderson and others, 1992). More detailed descriptions of the hydrogeology of basins in the study area are provided in the “Description of the Study Area” section of this report.

Annual precipitation in the Tucson and Pinal AMAs averages 14.7 and 9.7 inches, respectively, for the 1940–2006 time period (see table 1), with most rainfall occurring in higher elevations. Recharge to the SWAB aquifer system from precipitation may occur by direct infiltration of water through mountain faults and fractures or through permeable pediment or basin sediments and drainage channels. Mountain-front recharge estimates in the Tucson and Pinal AMAs are 1.4 and 0.8 percent of precipitation, respectively, for the SWAB-RASA regression equation and 0.9 and 0.2 percent of precipitation, respectively, for the BCM (see tables 12 and 13). Major surface drainages in the model area include the north-flowing Santa Cruz River, the west-flowing Gila River, and their tributaries.

Model Characteristics

The purpose of this model was to demonstrate the ability to reasonably simulate steady-state groundwater conditions in multiple, large alluvial basins in the study area connected by narrow constrictions and to evaluate the recharge estimate produced during this study. This model was designed as a proof-of-concept only, and does not seek to capture all heterogeneity in the model area. No calibration was done on the model, and existing model input files were combined to create input files for much of the model area, as described below.

The conceptual model for the proof-of-concept model is based on interpretations from previous USGS and ADWR studies (Hardt and Cattany, 1965; Hanson and others, 1990; Hanson and Benedict, 1994; Pool and others, 2001; Mason and Bota, 2006). The numerical model uses existing model framework input files from the ADWR Tucson AMA model (Mason and Bota, 2006), from a portion of the ADWR Santa Cruz AMA model (Nelson, 2007), and from an unpublished USGS model for the Picacho Basin of the Pinal AMA. To develop the model framework for the Maricopa-Stanfield Basin of the Pinal AMA, limited available well records and hydrogeologic information in Hardt and Cattany (1965) were used to estimate breaks between model layers. The numerical model for the entire model area uses three layers to simulate the aquifer system in the area. From land surface downward, model layer 1 represents the Ft. Lowell Formation and recent stream alluvium, layer 2 represents the upper and middle Tinaja beds, and layer 3 represents the Pantano Formation. Layer 1 was modeled as a water table aquifer, layer 2 as fully convertible between unconfined and confined aquifer conditions, and layer 3 as confined. Areally, the model was discretized into 0.386 square mile (1 square km) grid cells, requiring 141 vertical columns and 197 horizontal rows to cover the model area.

Boundary conditions for the flow model include groundwater underflow into the model area from the south, recharge from precipitation estimated by the BCM, and internal head-dependent boundaries along streams simulated using the Stream Package. Recharge from precipitation in the model area was estimated using the 1940–2006 average annual in-place recharge estimate from the BCM (see table 13). Given that most BCM-estimated recharge in the study area occurs across areas of mountain bedrock (see fig. 24) and that the model area mostly covers the alluvial portions of the basins, the BCM-estimated recharge from mountainous areas that drain into the model area was applied to the uppermost active model cells adjacent to the mountainous areas (fig. 42). The BCM recharge estimates represent net precipitation that reaches the aquifer, and no direct evapotranspiration from groundwater was simulated in the model. Groundwater underflow into the model domain occurs from the south in two locations: through the Santa Cruz River drainage and from Altar Valley into Avra Valley, just west of Tucson (figs. 40, 42). Underflow of 10,200 and 13,800 acre-ft per year,

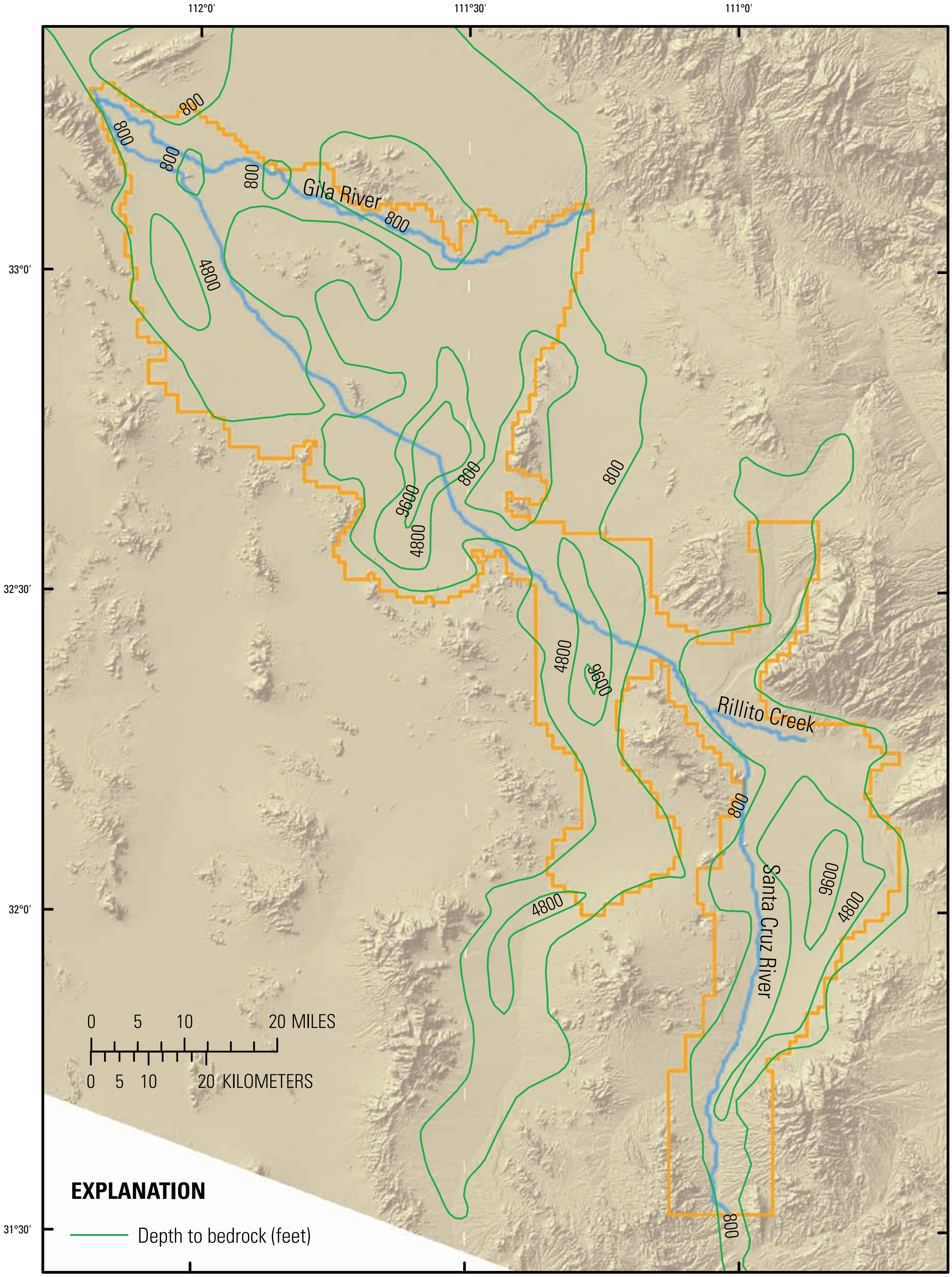

Figure 41. Thickness of alluvial sediments in proof-of-concept model area (Richard and others, 2007). Model boundary delineated with orange line.

magnitudes taken from the ADWR Tucson and Santa Cruz AMA model results (Nelson, 2007; Mason and Bota, 2006), was applied to Avra Valley and the Santa Cruz River using the Well Package. Four of the model cells where underflow was applied at the Santa Cruz River, however, went dry during the simulation, resulting in underflow of only 9,200 acre-ft per year instead of 13,800 acre-ft per year at that location. The Stream Package (STR1; Prudic, 1989) was used to simulate interaction of the aquifer with the Santa Cruz River, the Gila River, and Rillito Creek (fig. 40). Flow between streams and aquifers in the model is computed by Darcy's Law using the difference between the head in the stream and the head in the aquifer beneath the streambed (Prudic, 1989). Streams may either gain water from or discharge water to the aquifer beneath the streambed, depending upon the gradient of the head difference. Furthermore, STR1 keeps track of water in the stream and allows stream reaches to go dry when all streamflow is lost to the aquifer or diverted. Groundwater discharge can result in streamflow reaches without flow from upstream reaches. The current channel location of the Santa Cruz River was used from the southern end of the model area up through the Tucson AMA. Flow in the Santa Cruz River through the Pinal AMA is ephemeral and occurs in a mostly undefined channel, although a defined channel was present before widespread agricultural development in the area. The location of the remaining presently undefined channel of the Santa Cruz River through the Pinal AMA was estimated using historical topographic maps. A stream network in the model was developed using the five segments shown on figure 42. Segments are groups of "reaches" of streams in model cells traversed by the stream. Streambed top elevation was estimated from a digital elevation model at the select control points shown on figure 42. Elevation for reaches in between control points were computed using linear interpolation of elevation at the two nearest control points. Streambed top elevations ranged from 3,215 ft at the upper end of segment 1 to 995 ft at the lower end of segment 5. Streambed bottom elevations were assumed to be 3.28 ft below the top elevation in each reach. All stream reaches were in connection with layer 1 of the model. Streambed conductance for each reach varied as a function of the length of the stream reach and assumed stream width and streambed vertical hydraulic conductivity. Average streambed conductance values for reaches in segments 1–5 were 49,300, 46,900, 63,900, 64,900, and 65,800 ft^2/day, respectively. Inflows to Rillito Creek and the Gila River were set at 1 and 100 cubic feet per second, respectively (fig. 42). With the exception of those described above, all other model boundary conditions were simulated as no-flow boundaries.

Existing model parameter input files were rescaled and merged to provide input for hydraulic conductivity and transmissivity for the ADWR Santa Cruz and Tucson AMAs (fig. 43; Nelson, 2007; Mason and Bota, 2006) and for the Picacho Basin of the Pinal AMA (unpublished USGS model). A different set of uniform hydraulic conductivity and transmissivity values was used for each of the three model layers in the Maricopa-Stanfield Basin of the Pinal AMA, based on values for the same layer from the deeper portion of the nearby Picacho Basin (fig. 43). Properties for each of these model layers in the Maricopa-Stanfield Basin were assigned based on the assumptions of homogeneity and isotropy.

Results of Simulation

Simulated hydraulic heads from the uncalibrated, proof-of-concept steady-state model were qualitatively compared to published predevelopment groundwater-level contours (Freethey and Anderson, 1986) and found to be similar in magnitude and direction of hydraulic gradients (fig. 44). Use of BCM estimates appears to provide sufficient recharge to the system. The qualitative satisfactory steady-state solution to the simulated system indicates that the narrow constriction between multiple, deep alluvial basins does not appear to present numerical challenges.

Implications for Future Work

The ability of the proof-of-concept groundwater-flow model to numerically solve the interconnected aquifer system in the model area and the qualitative success of matching predevelopment hydraulic heads indicates that modeling all interconnected basins in the SWAB study area could be feasible. A fully calibrated groundwater-flow model of the entire SWAB study area capable of transient simulations would allow testing of other groundwater budget component estimates developed in this study. An integrated, multibasin model could be used to provide information on the likely effects of management actions (related to groundwater withdrawals or artificial recharge, for example) in one basin or management area on groundwater levels or streamflow in other connected basins.

Considerations for Assessment of Groundwater Availability

Early studies of groundwater in the area (for example, Lee, 1905) were resource assessments intended to provide information for development of water supplies in a manner that could sustain a growing economy in the region. By the latter half of the 20th century, many investigations focused on estimating groundwater flow quantities and aquifer properties that could improve understanding of observed aquifer response to stress from groundwater withdrawals, and prediction of future responses to continued resource development. Water-budget estimates by the SWAB-RASA study (Freethey and Anderson, 1986) have been used by a number of subsequent studies and models of individual basins. This study updates many of the SWAB-RASA water-budget estimates and presents a groundwater model of multiple basins as a proof of concept with respect to use of these updated estimates to model groundwater systems and predict responses to changing conditions.

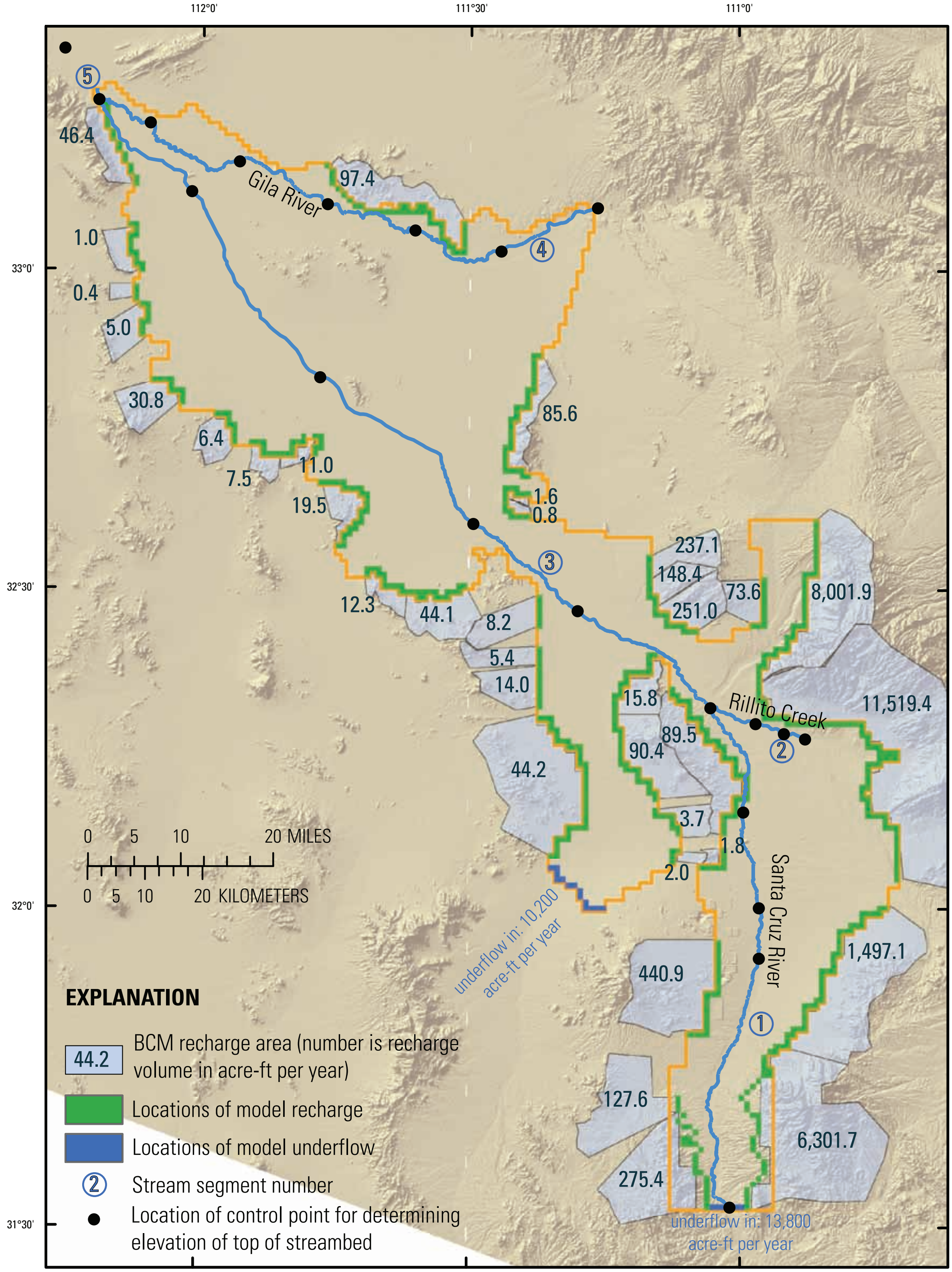

Figure 42. Aggregated areas of Basin Characterization Model (BCM) recharge estimates and model cell locations where the recharge was applied, locations of groundwater underflow entering the model area, locations of streams and stream segments, and location of control points for determining streambed elevation. Model boundary delineated with orange line.

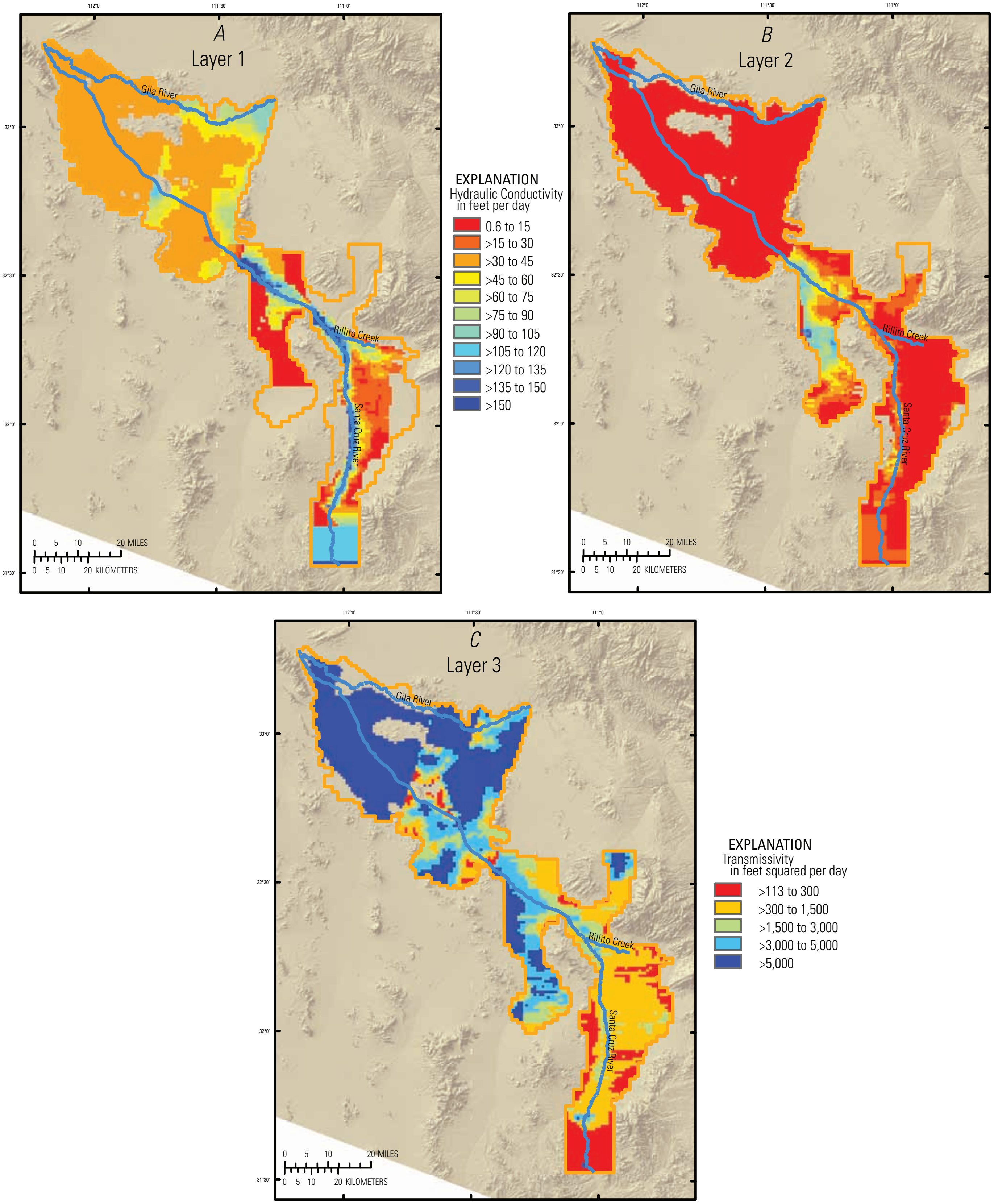

Figure 43. Hydraulic conductivity (*A* and *B*) and transmissivity (*C*) values for the three model layers.

Though many past studies have attempted to estimate the amount of recoverable groundwater in storage in basin-fill aquifers in the study area, Alley (2007) points out that such assessments may not be meaningful in practice with respect to water availability. Recovery of the full quantity of groundwater in aquifer storage by wells may be infeasible for economic and other reasons. Also, deleterious consequences of withdrawals, including land subsidence, earth fissures, and depletion of surface water, may occur with extraction of only a small fraction of the volume of water in storage. However, knowledge of water-budget components, including natural and anthropogenic recharge to and discharge from groundwater systems, is important in understanding potential long-term effects of development of groundwater resources in the study area. Some considerations for future work in quantifying select water-budget components are given in the following section, and considerations for future groundwater flow models are given in the section entitled "Simulation of Groundwater Flow."

Estimation of Water-Budget Components

Natural Groundwater Recharge

This component, including mountain-front recharge from precipitation and stream seepage, is difficult to estimate in the SWAB study area because it is highly variable through space and time. Site-specific studies can be done to quantify recharge in select ephemeral channels where most of the recharge occurs (Stonestrom and others, 2007), but it is difficult to extrapolate meaningful basin-scale budget estimates from site-scale study estimates. Temporal variations in recharge occurring on scales ranging from days to multiple decades further confound the extrapolation of budget estimates from studies spanning a few years. The approach taken by this study using the BCM is an improvement over site-scale studies in that it is regional in nature and it links climate to surface processes (runoff) and subsurface processes (in-place recharge). In the study area, however, the pathway for much of the recharge to groundwater is from later, downgradient infiltration of runoff. More work is needed to quantify the amount of BCM-generated runoff that becomes recharge. Additional calibration of BCM-generated runoff using streamflow data also would help with future studies.

Anthropogenic Groundwater Recharge

This component includes managed aquifer recharge (MAR) for storage in the subsurface, as well as incidental recharge from agriculture and other activities. MAR projects include generally reasonable estimates of amounts recharged, but incidental recharge is more difficult to quantify. Future studies that quantify components such as percolation of excess irrigation water and losses from canals, sewers, and other conveyances will improve future groundwater budget investigations.

Natural Groundwater Discharge to the Surface

This component includes discharge to streams, rivers, lakes, springs, wetlands, and plants that use groundwater. When the discharge is to surface water features, the possibility exists that some of the discharged water may reenter the aquifer in another location, with a net loss by evaporation and transpiration while the water was at or near the surface. This study used remotely sensed information to estimate actual evapotranspiration (AET) from groundwater. A major challenge of using this approach in the study area is that areas of groundwater discharge by evapotranspiration often occur in narrow bands along watercourses. The width of these bands can be smaller than the pixel sizes for remotely sensed data. Future improvements in resolution of these data will help in quantifying AET in the study area.

Anthropogenic Groundwater Discharge

This component consists mostly of withdrawal of water by wells, but in agricultural areas with shallow water tables, features such as drainage ditches that intercept shallow groundwater have been installed for the purpose of keeping the water table below the root zone of crops. In the AMAs in the study area, records of withdrawals for nonexempt wells (pumping rate of 35 gallons per minute or greater) are required. These records have been and will continue to be valuable for quantitative groundwater studies. A lack of such detailed records outside AMAs complicates groundwater use estimates in these areas. Therefore, continued work on water use such as has been documented by Tadayon (2005) will be important for future assessments.

Groundwater Flow Between Basins

This component, sometimes referred to as "underflow," includes groundwater flow into a basin-fill aquifer from an upgradient basin and groundwater flow out to a downgradient basin. These components are difficult to estimate with accuracy, but they commonly are thought to be smaller than many other components. As indicated in the section "Groundwater Underflow," estimates of this component are sometimes made using Darcy's Law (equation 8). Problems with this approach include poorly known terms for use in Darcy's Law, including the hydraulic gradient, the geometry of the subsurface link between basins, and the transmissivity or hydraulic conductivity of that link. In future groundwater models that link multiple basins, groundwater flow between the hydraulically connected basins will be an internal component that can be computed from the model.

Past estimates of many of the components listed here have been long-term averages. There is increasing interest in the study area to understand how components vary at time scales ranging from intraannual to multidecadal. Quantification of variations in components at smaller time scales may

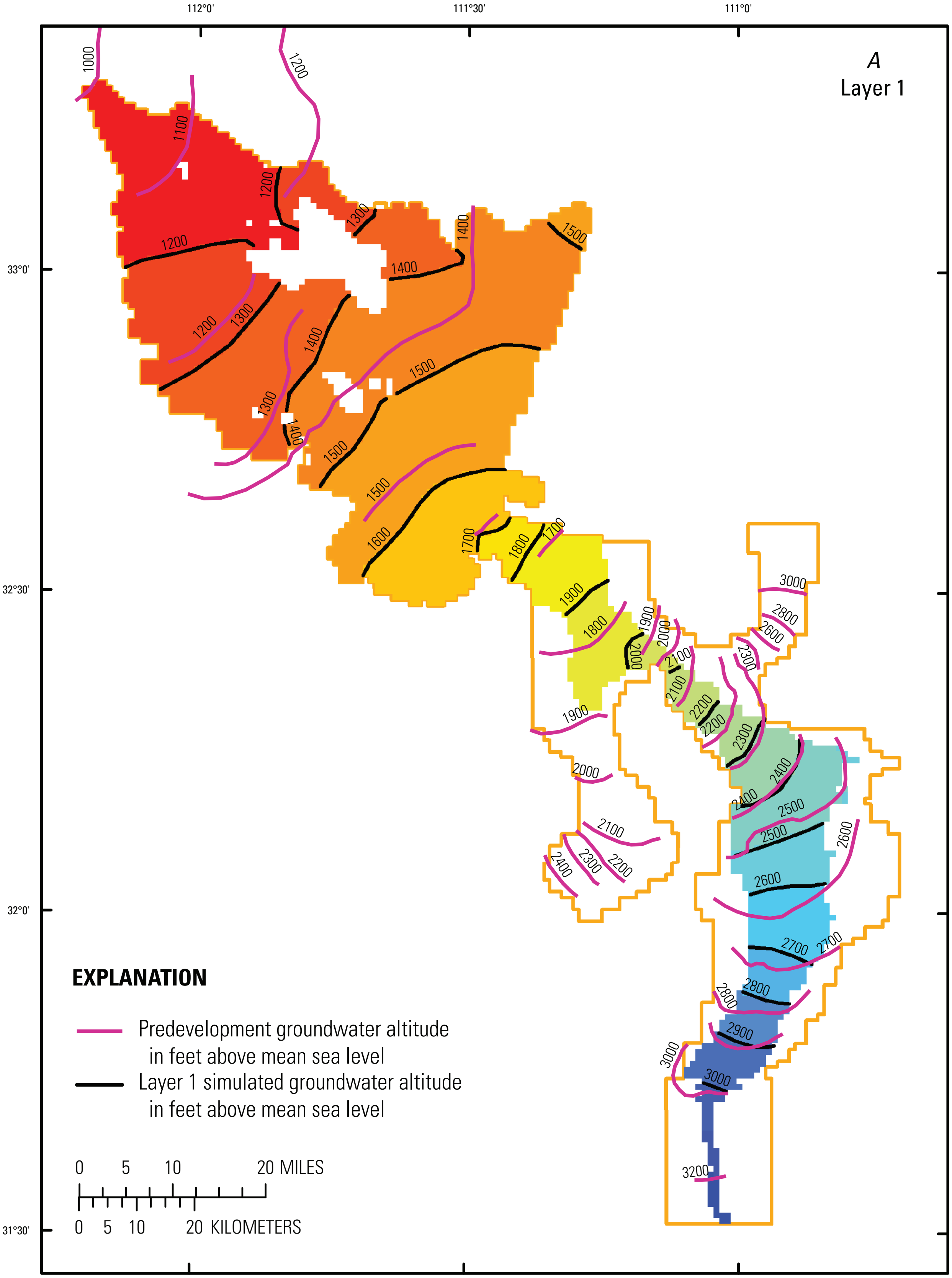

Figure 44. Groundwater levels simulated by the uncalibrated steady-state model for model layers 1 (*A*), 2 (*B*), and 3 (*C*), with comparison to published predevelopment groundwater levels from Freethey and Anderson (1986).

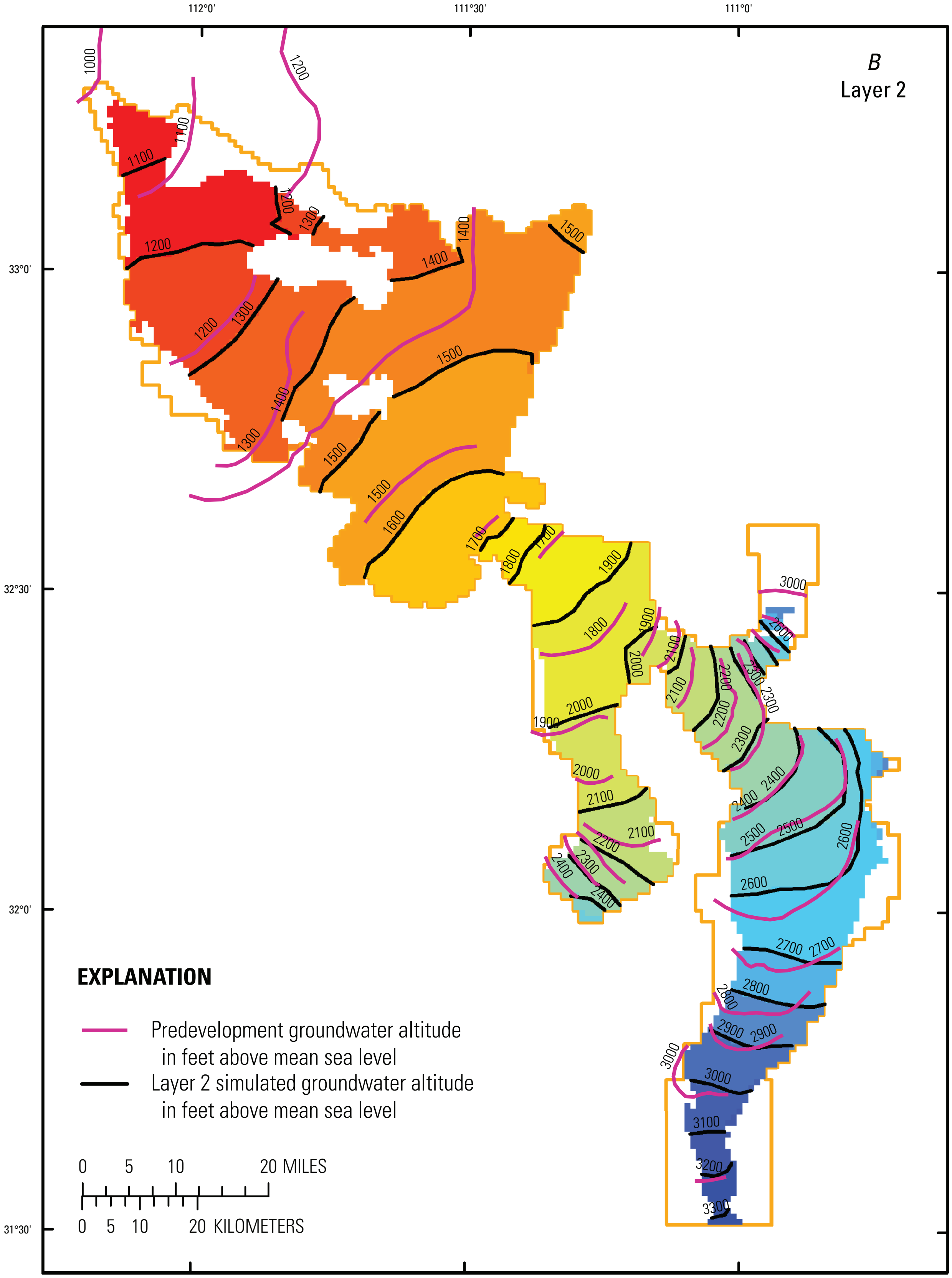

Figure 44.—Continued.

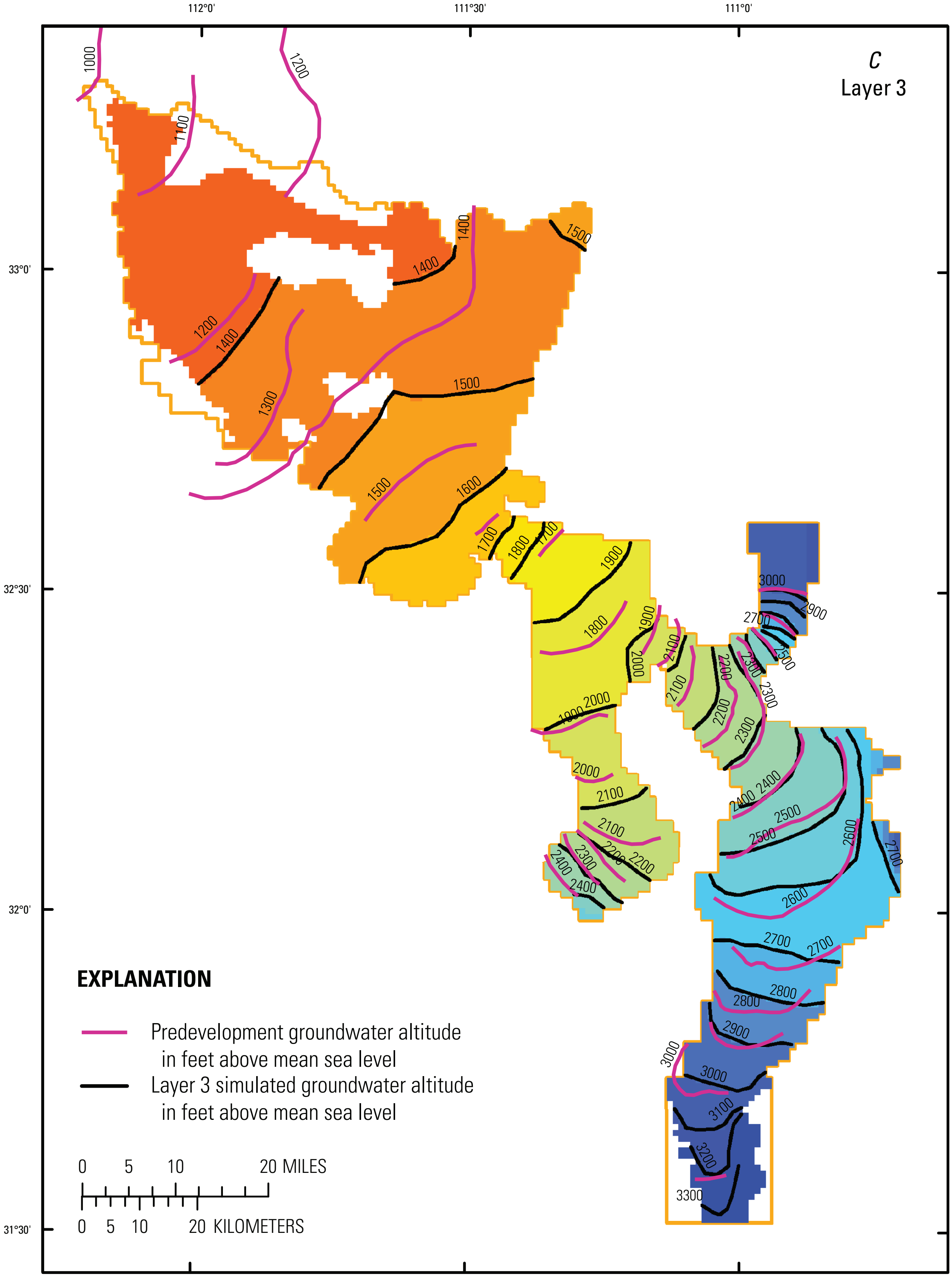

Figure 44.—Continued.

be important for certain studies, such as in understanding the functioning of groundwater-dependent ecosystems.

Simulation of Groundwater Flow

Groundwater models have been developed for the AMAs as well as for many of the basin-fill aquifers outside of the AMAs. The earliest models were made using electrical analog methods. Most subsequent models have used finite-difference computer model codes, including various versions of MODFLOW (for example, Corkhill and Hill, 1990; Corell, 1992; Mason and Bota, 2006; Pool and Dickinson, 2006; Erwin, 2007; Nelson, 2007). With increasing computer capabilities, horizontal discretization has been decreasing from cell sizes of about 1 square mile in early models to less than one quarter of that size in some more recent models. At least three layers are commonly used to represent different hydrogeologic units in the basin fill.

Limited testing by this project indicates that linked-basin models are feasible. Such an approach may be beneficial in the future to understand how development in one basin may affect groundwater resources in adjacent basins. Few past transient models have included calculations of release of water from storage attributed to inelastic compaction of the aquifer system (permanent land subsidence), including groundwater models of the Tucson Basin (Hanson and Benedict, 1994) and Avra Valley (Hanson and others, 1990). The Subsidence and Aquifer-System Compaction Package (SUB-WT; Leake and Galloway, 2007) for use in simulating water-table aquifers with MODFLOW is particularly applicable for groundwater simulations of aquifers in the study area. That package can be used in future MODFLOW-based models in which there is a need to compute vertical compaction and resulting land subsidence.

Future models would benefit from the inclusion of detailed climate data to better understand how climate variability and climate change may affect groundwater resources. Such models could be used to evaluate both direct and indirect effects of a different climate. A direct effect might be the reduction of recharge to an aquifer system and an indirect effect might be increased groundwater withdrawals because of a climate-related shortage of surface-water supplies. These models will likely be less deterministic in nature and take a more stochastic approach, investigating a range of potential future groundwater withdrawal, recharge, and streamflow scenarios.

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Appendix 1. Supplemental Information—Additional References Organized by Basin

This list of supplemental references is published only electronically, in the online version of this report at http://pubs.usgs.gov/sir/2011/5071/.

Tables 1–29

Table 1. Average annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation estimates for the Southwest Alluvial Basin study area in Arizona for time periods indicated.

	1940–49		1950–59		1960–69		1970–79	
Basin name	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**
AGUA FRIA	15.8	1,064,000	15.5	1,045,000	17.8	1,200,000	17.4	1,170,000
ARAVAIPA CANYON	16.3	448,000	14.9	412,000	17.3	477,000	17.9	493,000
BIG SANDY	13.2	1,399,000	12.8	1,354,000	13.7	1,452,000	13.8	1,469,000
BILL WILLIAMS	12.0	2,139,000	11.4	2,035,000	12.3	2,198,000	12.8	2,287,000
BONITA CREEK	15.1	368,000	14.7	357,000	16.1	392,000	15.5	377,000
BUTLER VALLEY	8.0	122,000	6.9	106,000	7.6	116,000	8.4	128,000
CIENEGA CREEK	17.7	579,000	17.7	581,000	20.0	657,000	19.2	630,000
DETRITAL VALLEY	7.3	346,000	6.4	304,000	6.7	320,000	8.1	387,000
DONNELLY WASH	14.7	229,000	13.6	212,000	14.9	233,000	15.6	243,000
DOUGLAS	13.4	282,000	12.7	267,000	14.1	296,000	14.0	295,000
DOUGLAS INA	11.8	350,000	10.9	323,000	12.4	367,000	11.9	354,000
DRIPPING SPRINGS WASH	16.5	333,000	15.7	316,000	17.7	357,000	18.0	363,000
DUNCAN VALLEY	11.9	348,000	10.0	293,000	12.6	370,000	12.2	359,000
GILA BEND	7.7	529,000	5.9	406,000	7.4	507,000	7.3	499,000
HARQUAHALA INA	6.5	266,000	5.8	238,000	6.5	266,000	6.9	283,000
HUALAPAI VALLEY	9.3	600,000	8.5	553,000	9.1	588,000	9.7	627,000
LAKE HAVASU	5.4	73,000	4.7	64,000	4.7	63,000	5.9	80,000
LAKE MOHAVE	5.8	302,000	5.1	265,000	5.1	269,000	6.3	330,000
LOWER GILA	5.9	2,300,000	4.6	1,787,000	5.5	2,152,000	6.0	2,348,000
LOWER SAN PEDRO	15.1	1,305,000	14.3	1,235,000	16.1	1,397,000	16.8	1,457,000
MCMULLEN VALLEY	8.7	300,000	7.6	262,000	8.0	277,000	8.6	297,000
MEADVIEW	8.9	90,000	7.8	79,000	8.8	89,000	9.9	100,000
MORENCI	17.6	1,498,000	16.2	1,385,000	18.4	1,569,000	17.3	1,479,000
PARKER	4.6	546,000	4.0	472,000	4.3	517,000	5.0	591,000
PEACH SPRINGS	11.7	883,000	11.2	839,000	12.4	933,000	12.9	972,000
PHOENIX AMA	8.9	2,565,000	8.5	2,452,000	9.4	2,713,000	9.4	2,709,000
PINAL AMA	8.7	1,909,000	8.6	1,869,000	10.1	2,213,000	9.6	2,104,000
PRESCOTT AMA	14.7	378,000	15.4	394,000	16.7	427,000	16.0	410,000
RANEGRAS PLAIN	5.9	287,000	5.3	259,000	5.9	285,000	6.6	321,000
SACRAMENTO VALLEY	8.7	740,000	8.3	704,000	8.6	729,000	9.4	799,000
SAFFORD	13.3	3,372,000	11.9	3,008,000	14.1	3,582,000	13.7	3,460,000
SALT RIVER	20.3	5,659,000	19.1	5,322,000	21.2	5,910,000	21.9	6,113,000
SAN BERNARDINO VALLEY	14.3	296,000	11.9	245,000	15.0	309,000	14.2	294,000
SAN RAFAEL	17.8	217,000	17.9	218,000	19.2	234,000	18.6	227,000
SAN SIMON WASH	10.3	1,251,000	9.6	1,174,000	12.4	1,511,000	11.0	1,346,000
SANTA CRUZ AMA	15.7	598,000	16.1	614,000	18.4	705,000	17.6	673,000
TIGER WASH	8.5	34,000	7.3	29,000	7.8	31,000	8.3	33,000
TONTO CREEK	21.1	1,074,000	20.8	1,059,000	21.9	1,115,000	22.8	1,160,000
TUCSON AMA	13.1	2,709,000	13.1	2,697,000	15.0	3,093,000	14.7	3,039,000
UPPER HASSAYAMPA	14.7	618,000	15.1	635,000	15.9	668,000	16.2	678,000
UPPER SAN PEDRO	13.9	1,343,000	13.6	1,319,000	15.3	1,486,000	15.3	1,479,000
VERDE RIVER	17.8	5,376,000	17.1	5,158,000	18.2	5,510,000	18.0	5,431,000
WESTERN MEXICAN DRAINAGE	6.9	225,000	6.0	195,000	7.8	255,000	6.9	224,000
WILLCOX	14.2	1,443,000	12.8	1,309,000	14.8	1,507,000	14.3	1,455,000
YUMA	3.3	139,000	2.5	105,000	3.1	130,000	3.9	166,000

Table 1. Average annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation estimates for the Southwest Alluvial Basin study area in Arizona for time periods indicated.—Continued

	1980–89		1990–99		2000–2006		1940–2006	
Basin name	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**	**(inches)**	**(acre-ft)**
AGUA FRIA	19.6	1,321,000	19.9	1,342,000	14.8	999,000	17.4	1,170,000
ARAVAIPA CANYON	19.8	546,000	20.7	573,000	14.8	408,000	17.5	483,000
BIG SANDY	14.6	1,546,000	14.5	1,542,000	11.5	1,218,000	13.5	1,435,000
BILL WILLIAMS	14.4	2,576,000	14.3	2,562,000	11.7	2,083,000	12.7	2,277,000
BONITA CREEK	19.0	463,000	17.8	435,000	15.1	368,000	16.2	395,000
BUTLER VALLEY	9.9	152,000	9.5	145,000	8.6	132,000	8.4	129,000
CIENEGA CREEK	22.5	738,000	21.1	693,000	17.2	563,000	19.4	638,000
DETRITAL VALLEY	8.4	399,000	8.5	405,000	6.9	330,000	7.5	357,000
DONNELLY WASH	16.9	265,000	17.4	272,000	12.0	188,000	15.1	237,000
DOUGLAS	16.2	340,000	14.8	311,000	12.4	261,000	14.0	295,000
DOUGLAS INA	14.6	431,000	12.8	378,000	11.1	328,000	12.3	363,000
DRIPPING SPRINGS WASH	19.4	391,000	20.0	404,000	13.4	271,000	17.4	351,000
DUNCAN VALLEY	15.2	446,000	14.4	423,000	12.0	351,000	12.6	371,000
GILA BEND	8.4	576,000	8.4	574,000	6.5	447,000	7.4	508,000
HARQUAHALA INA	7.6	309,000	7.8	319,000	7.2	294,000	6.9	282,000
HUALAPAI VALLEY	10.0	649,000	10.2	657,000	8.4	541,000	9.4	605,000
LAKE HAVASU	7.0	94,000	7.3	98,000	5.9	79,000	5.8	79,000
LAKE MOHAVE	7.1	371,000	7.3	383,000	6.0	313,000	6.1	319,000
LOWER GILA	6.0	2,355,000	5.9	2,285,000	5.1	1,986,000	5.6	2,182,000
LOWER SAN PEDRO	18.9	1,638,000	19.0	1,642,000	13.3	1,153,000	16.3	1,415,000
MCMULLEN VALLEY	10.7	370,000	9.8	338,000	9.1	313,000	8.9	308,000
MEADVIEW	9.7	99,000	10.0	101,000	8.3	85,000	9.1	92,000
MORENCI	21.0	1,791,000	19.9	1,696,000	17.8	1,518,000	18.3	1,564,000
PARKER	5.9	706,000	5.6	672,000	4.6	544,000	4.9	580,000
PEACH SPRINGS	12.8	966,000	12.4	929,000	10.6	799,000	12.1	908,000
PHOENIX AMA	10.9	3,146,000	11.7	3,374,000	8.8	2,524,000	9.7	2,795,000
PINAL AMA	10.8	2,352,000	10.9	2,382,000	8.7	1,896,000	9.7	2,113,000
PRESCOTT AMA	18.4	471,000	17.9	458,000	14.3	367,000	16.3	417,000
RANEGRAS PLAIN	7.4	360,000	6.9	336,000	6.0	291,000	6.3	306,000
SACRAMENTO VALLEY	10.4	877,000	10.5	888,000	8.3	700,000	9.2	780,000
SAFFORD	16.3	4,120,000	16.0	4,041,000	12.3	3,113,000	14.0	3,547,000
SALT RIVER	25.0	6,978,000	23.0	6,425,000	18.7	5,227,000	21.4	5,980,000
SAN BERNARDINO VALLEY	15.6	322,000	13.7	284,000	11.6	240,000	13.9	286,000
SAN RAFAEL	21.8	267,000	20.6	252,000	17.8	217,000	19.2	234,000
SAN SIMON WASH	12.0	1,461,000	11.8	1,438,000	10.5	1,274,000	11.1	1,354,000
SANTA CRUZ AMA	20.8	793,000	20.3	775,000	16.2	618,000	17.9	685,000
TIGER WASH	10.3	41,000	9.6	38,000	9.2	36,000	8.7	34,000
TONTO CREEK	24.6	1,253,000	23.7	1,207,000	18.2	928,000	22.0	1,122,000
TUCSON AMA	16.9	3,490,000	16.7	3,445,000	13.0	2,693,000	14.7	3,038,000
UPPER HASSAYAMPA	18.1	758,000	17.8	748,000	13.7	576,000	16.0	673,000
UPPER SAN PEDRO	17.4	1,689,000	16.1	1,563,000	13.5	1,311,000	15.1	1,462,000
VERDE RIVER	20.5	6,181,000	20.3	6,145,000	16.5	4,973,000	18.4	5,565,000
WESTERN MEXICAN DRAINAGE	7.7	250,000	7.9	258,000	6.2	202,000	7.1	231,000
WILLCOX	17.1	1,749,000	16.8	1,712,000	13.4	1,371,000	14.8	1,513,000
YUMA	3.5	146,000	3.5	149,000	2.9	125,000	3.3	138,000

Table 2. Maximum and minimum annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation by basin between 1940 and 2006.

Basin name	Maximum annual precipitation (inches)	Year of maximum	Minimum annual precipitation (inches)	Year of minimum
AGUA FRIA	31.5	1983	7.3	2002
ARAVAIPA CANYON	31.7	1941	9.6	1956
BIG SANDY	24.5	1941	5.0	1996
BILL WILLIAMS	23.8	1941	3.9	1956
BONITA CREEK	26.6	1941	10.0	1947
BUTLER VALLEY	19.0	1941	1.6	1956
CIENEGA CREEK	31.5	1983	12.1	1956
DETRITAL VALLEY	15.7	2005	1.8	2002
DONNELLY WASH	30.1	1941	6.4	2002
DOUGLAS	20.2	1983	7.4	1956
DOUGLAS INA	18.1	1985	5.5	1956
DRIPPING SPRINGS WASH	33.7	1941	7.4	2002
DUNCAN VALLEY	21.3	1941	6.1	1956
GILA BEND	16.5	1941	2.2	1956
HARQUAHALA INA	16.1	1941	0.7	1956
HUALAPAI VALLEY	17.1	2005	2.9	1996
LAKE HAVASU	15.2	2005	0.5	1956
LAKE MOHAVE	15.0	2005	1.0	1956
LOWER GILA	13.2	1941	1.4	1956
LOWER SAN PEDRO	28.3	1941	8.4	2002
MCMULLEN VALLEY	20.7	1941	2.1	1956
MEADVIEW	17.6	2005	2.5	2002
MORENCI	29.5	1941	11.4	1951
PARKER	12.4	2005	0.7	1956
PEACH SPRINGS	20.9	2005	4.1	1996
PHOENIX AMA	21.3	1941	3.6	1956
PINAL AMA	18.1	1941	5.0	2002
PRESCOTT AMA	28.4	1983	7.9	2002
RANEGRAS PLAIN	14.7	1941	1.2	1956
SACRAMENTO VALLEY	18.1	2005	2.3	1956
SAFFORD	23.8	1941	7.5	1956
SALT RIVER	35.7	1941	12.0	2002
SAN BERNARDINO VALLEY	20.2	1941	5.6	1956
SAN RAFAEL	31.0	1983	12.9	1956
SAN SIMON WASH	19.1	1984	4.9	2002
SANTA CRUZ AMA	29.2	1983	10.5	1956
TIGER WASH	20.6	1941	1.7	1956
TONTO CREEK	37.2	1941	8.5	2002
TUCSON AMA	24.8	1984	8.0	1956
UPPER HASSAYAMPA	28.1	1983	6.1	1956
UPPER SAN PEDRO	23.4	1966	9.1	1947
VERDE RIVER	32.2	1941	8.7	2002
WESTERN MEXICAN DRAINAGE	13.8	1979	1.7	2002
WILLCOX	22.6	1966	7.6	1956
YUMA	8.2	1941	0.3	1956

Table 3. Characteristics of runoff regions in the Southwest Alluvial Basins of Arizona.

Runoff region[1]	Area, in square miles		Mean annual precipitation[3]		Mean elevation, in feet	
	Total area	Mountain area[2]	Total area	Mountain area[2]	Total area	Mountain area[2]
Western Upland	8,797	6,557	14	15	4,118	4,331
Central Upland and Northeastern Gila River	22,534	15,853	17	18	4,497	4,824
Southeastern Gila River	10,460	4,204	15	17	4,525	4,932
Western Lowlands	31,792	10,112	8	8	1,921	2,413

[1] Runoff regions shown in figure 19.

[2] Mountain area in a basin is the higher elevation area composed of bedrock.

[3] Mean annual precipitation is from 1940–2006 Parameter-elevation Regressions on Independent Slopes Model (PRISM) data.

Table 4. Streamflow-gaging stations used for runoff regression analysis.

[See figure 19 for streamflow-gaging station locations and figure 20 for sub-region locations.]

Gaging station number	Gaging station name	Period of record	Gage datum (ft)	Drainage area (mi^2)	Mean annual precipitation[1] (in)	Mean basin elevation (ft)	Observed mean annual streamflow (ft^3/s)
1) WESTERN UPLAND RUNOFF REGION							
09424200	Cottonwood Wash trib nr Kingman	1964-1978	4,544	139	13.1	5,361	4.7
09512500	Agua Fria River nr Mayer	1940-2007	3,435	585	14.5	4,938	22.7
09512600	Turkey Creek nr Cleator	1979-1990	3,140	89	16.5	5,256	19.0
09515500	Hassayampa River nr Wickenburg	1946-1982	2,238	416	16.1	4,534	24.3
2) CENTRAL UPLAND AND NORTHEASTERN GILA RIVER RUNOFF REGION							
Verde River Basin Sub-region							
09502800	Williamson Valley Wash nr Paulden[2]	1965-2007	4,455	255	12.3	5,135	15.7
09503000	Granite Creek nr Prescott[2]	1932-2007	5,203	39	16.5	5,906	6.5
09504500	Oak Creek nr Cornville	1940-2007	3,471	354	20.2	6,112	86.6
09505200	Wet Beaver Creek nr Rimrock	1962-2007	4,019	110	20.2	6,555	31.9
09505250	Red Tank Draw nr Rimrock	1958-1978	3,921	51	19.7	6,083	7.2
09505300	Rattlesnake Canyon nr Rimrock	1958-1980	4,869	25	21.0	6,453	8.9
09505350	Dry Beaver Creek nr Rimrock	1961-2007	3,694	144	20.3	6,165	42.4
09505800	West Clear Creek nr Camp Verde	1965-2007	3,629	241	20.2	6,627	61.1
09507700	Webber Creek nr Pine	1960-1974	5,531	5	25.6	7,008	2.5
09507980	East Verde River nr Childs	1962-2007	2,500	327	20.2	5,246	64.1
09508300	Wet Bottom Creek nr Childs	1968-2007	2,320	36	17.9	4,918	14.1
09510080	West Fork Sycamore Creek nr Sunflower	1961-1974	3,999	10	21.9	5,322	2.0
09510100	East Fork Sycamore Creek nr Sunflower	1961-1986	4,140	5	20.5	5,203	1.0
Salt River Basin Sub-region							
09489070	North Fork of East Fork Black River nr Alpine	1965-1978	8,652	39	21.5	9,045	12.7
09489200	Pacheta Creek at Maverick	1958-1980	7,851	17	24.1	8,596	8.9
09489500	Black River blw pumping nr Point of Pines	1953-2007	5,725	556	20.6	8,058	202.6
09489700	Big Bonito Creek nr Fort Apache	1958-1981	5,909	114	24.4	8,074	67.2
09490800	North Fork White River nr Greer	1965-1978	8,373	41	26.5	9,521	24.6
09492400	East Fork White River nr Fort Apache	1958-2007	6,050	39	26.3	8,189	34.3
09494000	White River nr Fort Apache	1958-2007	4,367	630	22.0	7,247	164.1
09496000	Corduroy Creek nr Show Low	1952-2005	5,000	206	16.6	6,371	23.6
09496500	Carrizo Creek nr Show Low	1952-2007	4,751	441	16.8	6,325	46.1
09497800	Cibecue Creek nr Chrysotile	1960-2007	3,199	289	17.2	5,738	43.9
09497900	Cherry Creek nr Young	1963-1977	4,951	62	21.4	5,991	10.1
09497980	Cherry Creek nr Globe	1965-2007	3,199	200	19.4	5,538	32.0
09498870	Rye Creek nr Gisela	1966-1985	2,730	122	16.7	4,281	26.6
09499000	Tonto Creek abv Gun Creek nr Roosevelt	1941-2007	2,523	672	19.1	5,082	149.6
Northeastern Gila River Basin Sub-region							
09430600	Mogollon Creek nr Cliff, NM	1967-2007	5,440	74	21.8	7,772	30.4
09442680	San Francisco River nr Reserve, NM	1959-2007	5,279	332	15.6	7,799	25.4
09444200	Blue River nr Clifton	1968-2007	4,160	505	16.8	6,847	66.0
09446000	Willow Creek nr Morenci	1945-1967	4,970	155	15.8	6,237	13.7
09447800	Bonita Creek nr Morenci	1981-2007	3,501	302	13.7	5,246	11.6
09458200	Deadman Creek nr Safford	1967-1993	4,951	5	15.8	7,372	1.8
09460150	Frye Creek nr Thatcher	1989-2007	5,581	4	18.7	8,150	1.8
09473000	Aravaipa Creek nr Mammoth[2]	1931-2007	2,346	537	14.3	4,570	34.8
09484000	Sabino Creek nr Tucson[2]	1932-2007	2,720	35	22.4	6,070	13.4
09484200	Bear Creek nr Tucson	1959-1974	2,671	17	20.6	6,070	4.7
09484500	Tanque Verde Creek at Tucson[2]	1941-2007	2,470	219	16.1	4,377	23.5
09485000	Rincon Creek nr Tucson	1987-2007	3,120	44	19.7	5,105	6.0
3) SOUTHEASTERN GILA RIVER RUNOFF REGION							
09470800	Garden Canyon nr Fort Huachuca[2]	1960-2007	5,400	8	16.0	6,237	1.3
09480000	Santa Cruz River nr Lochiel	1949-2007	4,619	82	15.7	5,089	3.6
09480500	Santa Cruz River nr Nogales	1931-2007	3,704	511	15.8	4,879	25.4
09481500	Sonoita Creek nr Patagonia	1930-1972	3,819	207	16.9	4,925	8.1

[1] Mean annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation for 1940–2006.

[2] Period of record has some missing years.

Table 5. Characteristics of the Southwest Alluvial Basins of Arizona.

[Runoff regression analysis performed on basins in all runoff regions except Western Lowland, where no acceptable gaged streams were located.]

Runoff region[1]	Basin name[2]	Area, in square miles		Mean annual precipitation[4] in inches		Mean basin elevation, in feet	
		Total area	Mountain area[3]	Total area	Mountain area[3]	Total area	Mountain area[3]
Western Upland	Agua Fria	1,263	1,180	17.1	17.3	4,028	4,057
	Big Sandy	1,988	1,346	13.3	14.2	4,590	4,947
	Bill Williams	3,350	2,432	12.5	13.3	3,238	3,531
	Peach Springs	1,409	1,120	11.9	12.0	4,974	4,965
	Upper Hassayampa	787	478	15.8	17.2	3,760	4,155
Central Upland and Northeast Gila River	Prescott AMA	480	220	16.1	17.9	5,244	5,605
	Verde River	5,662	4,564	18.2	19.3	5,272	5,512
	Salt River	5,232	4,784	21.2	21.8	5,703	5,922
	Tonto Creek	955	774	21.8	22.9	4,745	5,136
	Aravaipa Canyon	517	341	17.2	17.9	4,603	4,770
	Bonita Creek	457	257	16.1	16.3	5,237	5,431
	Donnelly Wash	293	216	14.9	14.8	2,812	2,786
	Dripping Springs Wash	378	312	17.1	17.2	3,561	3,668
	Lower San Pedro	1,624	901	16.1	17.7	3,667	4,098
	Morenci	1,599	1,283	18.2	18.5	6,136	6,264
	Safford north	2,980	1,398	15.1	18.1	3,995	4,792
	Tucson AMA north	2,356	804	14.0	17.9	2,989	3,909
Southeastern Gila River	Cienega Creek	615	316	19.2	20.1	4,801	4,972
	Douglas	394	275	13.9	14.5	4,866	5,021
	Douglas INA	555	10	12.2	13.0	4,210	4,369
	Duncan Valley	550	245	12.5	13.6	4,336	4,774
	Safford south	1,772	660	13.5	16.5	4,397	5,242
	San Bernardino Valley	387	308	13.8	14.1	4,542	4,630
	San Rafael	229	88	19.0	20.1	5,368	5,789
	Santa Cruz AMA	716	394	17.7	19.1	4,008	4,316
	Tucson AMA south	1,515	692	17.4	19.6	3,666	4,120
	Upper San Pedro	1,816	567	15.0	17.5	4,642	5,249
	Willcox	1,911	648	14.7	17.9	4,936	5,770
Western Lowland	Detrital Valley	892	321	7.4	8.4	2,820	3,417
	Hualapai Valley	1,213	484	9.2	9.8	3,490	4,006
	Lake Havasu	252	161	5.7	6.2	1,348	1,627
	Lake Mohave	980	475	6.0	7.0	1,689	2,363
	Meadview	190	60	9.0	10.5	3,598	4,856
	Sacramento Valley	1,587	670	9.0	10.3	2,807	3,527
	Butler Valley	288	87	8.2	9.6	2,011	2,553
	Gila Bend	1,284	518	7.3	8.0	1,289	1,734
	Harquahala INA	766	215	6.8	7.5	1,542	1,979
	Lower Gila	7,309	2,392	5.5	6.1	1,029	1,378
	McMullen Valley	649	181	8.7	9.8	2,344	2,765
	Parker	2,229	722	4.8	5.1	1,017	1,349
	Ranegras Plain	912	325	6.2	6.6	1,509	1,834
	San Simon Wash	2,284	572	11.0	12.1	2,330	2,774
	Tiger Wash	74	39	8.6	8.7	2,413	2,596
	Western Mexican Drainage	610	276	7.0	6.9	1,262	1,388
	Yuma	792	92	3.3	3.8	421	977
	Phoenix AMA	5,386	1,597	9.6	12.0	1,693	2,348
	Pinal AMA	4,096	925	9.6	10.7	1,893	2,373

[1] Runoff region is shown in figure 19.

[2] Basins are shown in figure 2.

[3] Mountain area in a basin is the higher elevation area composed of bedrock.

[4] Mean annual Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation for 1940–2006.

Table 6. Improvement of fit of multivariate regression equation by additional explanatory variables and final form of equation.

[Streamflow and basin characteristics at 47 streamflow gages used in the regression analysis.]

Q[1] =	a	b	c	d	e	f	Coefficient of determination (R^2)	s^2 (log units)	s (average percent)
A	-2.026	0.710					0.68	0.319	80
A + P	-11.269	0.869	3.318				0.88	0.194	46
A + P + E	-12.782	0.880	2.704	0.957			0.90	0.183	43
A + P + E + R1 + R2	-11.508	0.871	2.529	0.727	-0.133	-0.305	0.92	0.167	39

Degrees of freedom	Final runoff regression equation[1]
42	Log Q = -11.508+0.871(logA)+2.529(logP)+0.727(logE)-0.133(R1)-0.305(R2)

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[1] Form of regression equation is Log Q = a + b×(logA) + c×(logP) + d×(logE) + e×(R1) + f×(R2), where Q = mean annual flow (m3/s), A = drainage area (km2), P = mean annual precipitation (mm), E = mean basin elevation (m), R1 and R2 represent runoff region.

[2] s is the standard error of estimate.

Table 7. Comparison of streamflow predictions by regression equation to observed data.

Gaging station name	Mean annual flow (log ft³/s)		
	Observed	Regression estimate	Residual (observed value – estimated value)
WESTERN UPLAND RUNOFF REGION			
Cottonwood Wash trib nr Kingman	0.67	0.60	0.07
Agua Fria River nr Mayer	1.36	1.48	-0.12
Turkey Creek nr Cleator	1.28	0.92	0.36
Hassayampa River nr Wickenburg	1.39	1.44	-0.05
CENTRAL UPLAND AND NORTHEASTERN GILA RIVER RUNOFF REGION			
Verde River Basin Sub-region			
Williamson Valley Wash nr Paulden	1.20	1.13	0.07
Granite Creek nr Prescott	0.81	0.78	0.03
Oak Creek nr Cornville	1.94	1.85	0.09
Wet Beaver Creek nr Rimrock	1.50	1.43	0.07
Red Tank Draw nr Rimrock	0.86	1.09	-0.24
Rattlesnake Canyon nr Rimrock	0.95	0.92	0.03
Dry Beaver Creek nr Rimrock	1.63	1.52	0.11
West Clear Creek nr Camp Verde	1.79	1.73	0.05
Webber Creek nr Pine	0.40	0.53	-0.13
East Verde River nr Childs	1.81	1.77	0.03
Wet Bottom Creek nr Childs	1.15	0.79	0.36
West Fork Sycamore Creek nr Sunflower	0.31	0.54	-0.23
East Fork Sycamore Creek nr Sunflower	-0.02	0.17	-0.19
Salt River Basin Sub-region			
NF of East Fork Black River nr Alpine	1.10	1.21	-0.11
Pacheta Creek at Maverick	0.95	0.99	-0.04
Black River blw pumping nr Point of Pines	2.31	2.13	0.18
Big Bonito Creek nr Fort Apache	1.83	1.72	0.11
North Fork White River nr Greer	1.39	1.47	-0.08
East Fork White River nr Fort Apache	1.53	1.40	0.14
White River nr Fort Apache	2.22	2.22	0.00
Corduroy Creek nr Show Low	1.37	1.47	-0.07
Carrizo Creek nr Show Low	1.66	1.74	-0.08
Cibecue Creek nr Chrysotile	1.64	1.58	0.07
Cherry Creek nr Young	1.01	1.25	-0.24
Cherry Creek nr Globe	1.51	1.56	-0.06
Rye Creek nr Gisela	1.42	1.13	0.30
Tonto Creek abv Gun Creek nr Roosevelt	2.18	1.97	0.20

Table 7. Comparison of streamflow predictions by regression equation to observed data.—Continued

Gaging station name	Mean annual flow (log ft^3/s)		
	Observed	Regression estimate	Residual (observed value – estimated value)
Northeastern Gila River Basin Sub-region			
Mogollon Creek nr Cliff, NM	1.48	1.42	0.07
San Francisco River nr Reserve, NM	1.40	1.62	-0.22
Blue River nr Clifton	1.82	1.82	0.00
Willow Creek nr Morenci	1.14	1.28	-0.14
Bonita Creek nr Morenci	1.07	1.32	-0.25
Deadman Creek nr Safford	0.26	0.00	0.27
Frye Creek nr Thatcher	0.26	0.16	0.09
Aravaipa Creek nr Mammoth	1.54	1.54	0.00
Sabino Creek nr Tucson	1.13	1.09	0.04
Bear Creek nr Tucson	0.67	0.72	-0.05
Tanque Verde Creek at Tucson	1.37	1.32	0.05
Rincon Creek nr Tucson	0.78	0.98	-0.20
SOUTHEASTERN GILA RIVER RUNOFF REGION			
Garden Canyon nr Fort Huachuca	0.10	-0.12	0.22
Santa Cruz River nr Lochiel	0.56	0.66	-0.10
Santa Cruz River nr Nogales	1.41	1.34	0.06
Sonoita Creek nr Patagonia	0.91	1.08	-0.17

Table 8. Comparison of streamflow predictions by regression equation for runoff regions.

[See figures 19 and 20 for locations of runoff regions and sub-regions.]

Runoff region		Number of streamflow gages in region	Mean residual (log ft^3/s)	Root mean square error (log ft^3/s)
WESTERN UPLAND		4	0.07	0.195
CENTRAL UPLAND AND NORTHEASTERN GILA RIVER RUNOFF REGION	Verde River Basin Sub-region	13	0.00	0.158
	Salt River Basin Sub-region	14	0.02	0.144
	Northeastern Gila River Basin Sub-region	12	-0.03	0.148
SOUTHEASTERN GILA RIVER		4	0.00	0.151
all runoff regions		47	0.01	0.155

Table 9. Observed and estimated mean annual flow at streamflow-gaging stations in the Southwest Alluvial Basins of Arizona.

[BCM is Basin Characterization Model.]

Runoff region[1]	Gaging station number	Gaging station name	Mean annual flow, in cubic feet per second			Residual, in percent of observed value	
			Ob-served	Regression estimated[2]	BCM estimated	Regression	BCM
Western upland	09424200	Cottonwood Wash trib nr Kingman	4.67	3.88	1.77	17	62
	09512500	Agua Fria River nr Mayer	22.71	30.02	18.43	-32	19
	09512600	Turkey Creek nr Cleator	19.06	8.48	11.76	56	38
	09515500	Hassayampa River nr Wickenburg	24.35	27.55	27.02	-13	-11
Central Upland and Northeast Gila River	09502800	Williamson Valley Wash nr Paulden	15.75	13.42	3.71	15	76
	09503000	Granite Creek nr Prescott	6.45	6.00	0.68	7	89
	09504500	Oak Creek nr Cornville	86.67	70.98	111.01	18	-28
	09505200	Wet Beaver Creek nr Rimrock	31.91	26.84	24.21	16	24
	09505250	Red Tank Draw nr Rimrock	7.24	12.36	8.98	-71	-24
	09505300	Rattlesnake Canyon nr Rimrock	8.95	8.12	6.85	9	23
	09505350	Dry Beaver Creek nr Rimrock	42.44	33.20	40.81	22	4
	09505800	West Clear Creek nr Camp Verde	61.12	54.03	51.53	12	16
	09507700	Webber Creek nr Pine	2.50	3.53	1.69	-41	32
	09507980	East Verde River nr Childs	64.17	59.33	19.79	8	69
	09508300	Wet Bottom Creek nr Childs	14.11	6.00	4.86	57	66
	09510080	West Fork Sycamore Creek nr Sunflower	2.04	3.53	2.86	-73	-40
	09510100	East Fork Sycamore Creek nr Sunflower	0.96	1.41	0.93	-47	3
	09489070	NF of East Fork Black River nr Alpine	12.72	16.24	28.34	-28	-123
	09489200	Pacheta Creek at Maverick	8.88	9.89	5.05	-11	43
	09489500	Black River blw pumping nr Point of Pines	202.79	134.20	225.55	34	-11
	09489700	Big Bonito Creek nr Fort Apache	67.29	52.27	39.89	22	41
	09490800	North Fork White River nr Greer	24.65	29.31	30.68	-19	-24
	09492400	East Fork White River nr Fort Apache	34.27	25.07	20.67	27	40
	09494000	White River nr Fort Apache	164.22	164.92	199.97	-0	-22
	09496000	Corduroy Creek nr Show Low	23.58	27.90	28.98	-18	-23
	09496500	Carrizo Creek nr Show Low	46.13	55.09	18.49	-19	60
	09497800	Cibecue Creek nr Chrysotile	43.93	37.43	8.73	15	80
	09497900	Cherry Creek nr Young	10.14	17.66	8.07	-74	20
	09497980	Cherry Creek nr Globe	32.02	36.37	14.51	-14	55
	09498870	Rye Creek nr Gisela	26.57	13.42	67.82	49	-155
	09499000	Tonto Creek abv Gun Creek nr Roosevelt	149.72	94.29	56.46	37	62
	09430600	Mogollon Creek nr Cliff, NM	30.39	26.13	(3)	14	(3)
	09442680	San Francisco River nr Reserve, NM	25.37	42.02	(3)	-66	(3)
	09444200	Blue River nr Clifton	66.00	66.39	52.99	-1	20
	09446000	Willow Creek nr Morenci	13.72	19.07	5.60	-39	59
	09447800	Bonita Creek nr Morenci	11.63	20.84	2.81	-79	76
	09458200	Deadman Creek nr Safford	1.83	1.06	0.27	42	85
	09460150	Frye Creek nr Thatcher	1.81	1.41	0.61	22	66
	09473000	Aravaipa Creek nr Mammoth	34.84	34.61	9.21	1	74

Table 9. Observed and estimated mean annual flow at streamflow-gaging stations in the Southwest Alluvial Basins of Arizona.—Continued

[BCM is Basin Characterization Model.]

Runoff region[1]	Gaging station number	Gaging station name	Mean annual flow, in cubic feet per second			Residual, in percent of observed value	
			Observed	Regression estimated[2]	BCM estimated	Regression	BCM
Central Upland and Northeast Gila River	09484000	Sabino Creek nr Tucson	13.42	12.36	4.45	8	67
	09484200	Bear Creek nr Tucson	4.69	5.30	1.70	-13	64
	09484500	Tanque Verde Creek at Tucson	23.49	20.84	11.36	11	52
	09485000	Rincon Creek nr Tucson	6.03	9.53	3.97	-58	34
South-eastern	09470800	Garden Canyon nr Fort Huachuca	1.26	0.71	0.12	44	91
	09480000	Santa Cruz River nr Lochiel	3.64	4.59	0.42	-26	89
	09480500	Santa Cruz River nr Nogales	25.44	22.25	([3])	13	([3])
	09481500	Sonoita Creek nr Patagonia	8.08	12.01	6.07	-49	25

[1] See figure 19 for location of runoff regions.

[2] See table 6 for description of regression equation.

[3] BCM results not available for gaged site.

Table 10. Comparison of basin runoff estimates using the Basin Characterization Model (BCM) and regression equation.

[---, not applicable.]

Runoff region[1]	Basin name[2]	Runoff from BCM, in inches		Runoff from regression equation[4], in inches	
		Total area	Mountain area[4]	Total area	Mountain area[3]
Western upland	Agua Fria	0.78	0.85	---	0.86
	Big Sandy	0.39	0.55	---	0.59
	Bill Williams	0.49	0.68	---	0.37
	Peach Springs	0.15	0.19	---	0.39
	Upper Hassayampa	0.53	0.86	---	0.97
Central Upland and Northeast Gila River	Prescott AMA	0.20	0.45	---	2.00
	Verde River	1.33	1.64	---	1.61
	Salt River	1.78	1.96	---	2.30
	Tonto Creek	1.04	1.30	---	2.99
	Aravaipa Canyon	0.24	0.35	---	1.68
	Bonita Creek	0.14	0.24	---	1.51
	Donnelly Wash	0.13	0.17	---	0.75
	Dripping Springs Wash	0.40	0.45	---	1.27
	Lower San Pedro	0.26	0.46	---	1.30
	Morenci	0.71	0.87	---	1.88
	Safford north	0.18	0.36	---	1.44
	Tucson AMA north	0.17	0.50	---	1.30
South-eastern Gila River	Cienega Creek	0.22	0.42	---	1.18
	Douglas	0.02	0.02	---	0.53
	Douglas INA	0.00	0.00	---	0.55
	Duncan Valley	0.04	0.08	---	0.44
	Safford south	0.18	0.49	---	0.67
	San Bernardino Valley	0.05	0.07	---	0.45
	San Rafael	0.16	0.40	---	1.54
	Santa Cruz AMA	0.20	0.36	---	0.89
	Tucson AMA south	0.14	0.30	---	0.87
	Upper San Pedro	0.04	0.13	---	0.79
	Willcox	0.35	1.00	---	0.88

[1] Runoff region shown on figure 19.

[2] Basins shown on figure 2.

[3] Mountain area in a basin is the higher elevation area composed of bedrock.

[4] Regression equation shown in table 6.

Table 11. Statistics of fit between observed and estimated mean annual streamflow at gaged sites for runoff regions in the Southwest Alluvial Basins study area.

[BCM is Basin Characterization Model.]

Runoff region[1]	Number of streamflow gages in region	Mean residual, in percent		Mean absolute residual, in percent	
		Regression[2]	BCM[3]	Regression[2]	BCM[3]
Western Upland	4	6.8	27.1	29.4	32.6
Central Upland and Northeast Gila River	39	-5.8	25.6	28.7	47.4
Southeastern Gila River	4	-4.6	68.0	32.8	51.0
all regions	47	-4.7	28.7	29.1	46.5

[1] Runoff regions shown in figure 19.

[2] Regression residual is observed streamflow minus regression estimated streamflow. Regression equation is shown in table 6.

[3] BCM residual is observed streamflow minus BCM estimated streamflow.

Table 12. Average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for time periods indicated.

	1940–1949			1950–1959		
Basin name	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	0.24	16,000	1.5	0.24	16,000	1.5
ARAVAIPA CANYON	0.26	7,000	1.6	0.22	6,000	1.4
BIG SANDY	0.17	18,000	1.3	0.16	17,000	1.3
BILL WILLIAMS	0.13	24,000	1.1	0.13	23,000	1.1
BONITA CREEK	0.22	5,000	1.4	0.21	5,000	1.4
BUTLER VALLEY	0.04	1,000	0.6	0.02	0	0.3
CIENEGA CREEK	0.30	10,000	1.7	0.30	10,000	1.7
DETRITAL VALLEY	0.03	1,000	0.4	0.02	1,000	0.3
DONNELLY WASH	0.22	3,000	1.4	0.18	3,000	1.3
DOUGLAS	0.17	4,000	1.3	0.15	3,000	1.2
DOUGLAS INA	0.12	3,000	1.0	0.10	3,000	0.9
DRIPPING SPRINGS WASH	0.26	6,000	1.7	0.24	5,000	1.6
DUNCAN VALLEY	0.13	4,000	1.1	0.08	2,000	0.8
GILA BEND	0.04	3,000	0.5	0.01	1,000	0.2
HARQUAHALA INA	0.03	1,000	0.4	0.01	1,000	0.2
HUALAPAI VALLEY	0.06	4,000	0.7	0.05	3,000	0.6
LAKE HAVASU	0.02	0	0.3	0.00	0	0.1
LAKE MOHAVE	0.02	1,000	0.3	0.01	1,000	0.2
LOWER GILA	0.02	9,000	0.4	0.01	2,000	0.1
LOWER SAN PEDRO	0.23	20,000	1.5	0.20	18,000	1.4
MCMULLEN VALLEY	0.06	2,000	0.7	0.04	1,000	0.5
MEADVIEW	0.06	1,000	0.7	0.05	0	0.5
MORENCI	0.29	24,000	1.6	0.25	21,000	1.5
PARKER	0.01	1,000	0.2	0.00	0	0.0
PEACH SPRINGS	0.12	9,000	1.0	0.11	8,000	1.0
PHOENIX AMA	0.06	18,000	0.7	0.05	15,000	0.6
PINAL AMA	0.06	13,000	0.7	0.05	10,000	0.5
PRESCOTT AMA	0.21	6,000	1.5	0.23	6,000	1.5
RANEGRAS PLAIN	0.02	1,000	0.4	0.00	0	0.1
SACRAMENTO VALLEY	0.05	5,000	0.6	0.05	4,000	0.6
SAFFORD	0.17	42,000	1.2	0.13	33,000	1.1
SALT RIVER	0.36	100,000	1.8	0.33	90,000	1.7
SAN BERNARDINO VALLEY	0.20	4,000	1.4	0.13	3,000	1.1
SAN RAFAEL	0.34	4,000	2.0	0.34	4,000	2.0
SAN SIMON WASH	0.08	9,000	0.7	0.07	8,000	0.7
SANTA CRUZ AMA	0.24	9,000	1.5	0.25	10,000	1.5
TIGER WASH	0.05	0	0.5	0.03	0	0.3
TONTO CREEK	0.39	20,000	1.9	0.39	20,000	1.9
TUCSON AMA	0.16	32,000	1.2	0.15	32,000	1.2
UPPER HASSAYAMPA	0.20	8,000	1.3	0.22	9,000	1.4
UPPER SAN PEDRO	0.17	17,000	1.3	0.17	16,000	1.2
VERDE RIVER	0.29	87,000	1.6	0.27	81,000	1.6
WESTERN MEXICAN DRAINAGE	0.02	1,000	0.3	0.01	0	0.2
WILLCOX	0.19	19,000	1.3	0.15	15,000	1.2
YUMA	0.00	0	0.1	0.00	0	0.0

Table 12. Average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for time periods indicated.—Continued

Basin name	1960–1969			1970–1979		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	0.30	20,000	1.7	0.29	19,000	1.7
ARAVAIPA CANYON	0.29	8,000	1.7	0.30	8,000	1.7
BIG SANDY	0.18	19,000	1.3	0.19	20,000	1.4
BILL WILLIAMS	0.14	25,000	1.2	0.16	29,000	1.3
BONITA CREEK	0.25	6,000	1.5	0.23	6,000	1.5
BUTLER VALLEY	0.02	0	0.3	0.05	1,000	0.7
CIENEGA CREEK	0.37	12,000	1.9	0.35	12,000	1.8
DETRITAL VALLEY	0.02	1,000	0.2	0.05	2,000	0.6
DONNELLY WASH	0.22	3,000	1.5	0.25	4,000	1.5
DOUGLAS	0.19	4,000	1.4	0.18	4,000	1.4
DOUGLAS INA	0.14	4,000	1.1	0.12	3,000	1.0
DRIPPING SPRINGS WASH	0.30	6,000	1.8	0.31	7,000	1.8
DUNCAN VALLEY	0.15	4,000	1.2	0.14	4,000	1.1
GILA BEND	0.03	2,000	0.4	0.03	2,000	0.4
HARQUAHALA INA	0.01	0	0.2	0.03	1,000	0.4
HUALAPAI VALLEY	0.05	3,000	0.6	0.08	5,000	0.8
LAKE HAVASU	0.00	0	0.0	0.02	0	0.3
LAKE MOHAVE	0.00	0	0.1	0.02	1,000	0.4
LOWER GILA	0.01	5,000	0.2	0.02	6,000	0.3
LOWER SAN PEDRO	0.26	22,000	1.6	0.28	24,000	1.7
MCMULLEN VALLEY	0.03	1,000	0.4	0.07	2,000	0.8
MEADVIEW	0.06	1,000	0.7	0.09	1,000	0.9
MORENCI	0.32	26,000	1.6	0.28	23,000	1.6
PARKER	0.00	0	0.0	0.01	1,000	0.2
PEACH SPRINGS	0.14	11,000	1.1	0.16	12,000	1.2
PHOENIX AMA	0.07	19,000	0.7	0.08	22,000	0.8
PINAL AMA	0.08	17,000	0.8	0.07	16,000	0.8
PRESCOTT AMA	0.27	7,000	1.7	0.25	7,000	1.6
RANEGRAS PLAIN	0.00	0	0.1	0.02	1,000	0.4
SACRAMENTO VALLEY	0.04	3,000	0.4	0.08	6,000	0.8
SAFFORD	0.19	47,000	1.3	0.17	44,000	1.3
SALT RIVER	0.39	107,000	1.8	0.41	113,000	1.8
SAN BERNARDINO VALLEY	0.22	4,000	1.4	0.20	4,000	1.4
SAN RAFAEL	0.39	5,000	2.2	0.37	5,000	2.1
SAN SIMON WASH	0.13	16,000	1.0	0.10	12,000	0.9
SANTA CRUZ AMA	0.32	12,000	1.7	0.30	11,000	1.7
TIGER WASH	0.02	0	0.2	0.06	0	0.6
TONTO CREEK	0.42	21,000	1.9	0.44	23,000	2.0
TUCSON AMA	0.21	43,000	1.4	0.20	41,000	1.4
UPPER HASSAYAMPA	0.24	10,000	1.5	0.25	10,000	1.5
UPPER SAN PEDRO	0.21	21,000	1.4	0.21	21,000	1.4
VERDE RIVER	0.30	91,000	1.7	0.30	89,000	1.6
WESTERN MEXICAN DRAINAGE	0.03	1,000	0.4	0.03	1,000	0.4
WILLCOX	0.20	21,000	1.4	0.19	19,000	1.3
YUMA	0.00	0	0.0	0.00	0	0.0

Table 12. Average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for time periods indicated.—Continued

Basin name	1980–1989			1990–1999		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	0.36	24,000	1.8	0.37	24,000	1.8
ARAVAIPA CANYON	0.36	10,000	1.8	0.39	11,000	1.9
BIG SANDY	0.21	22,000	1.4	0.21	23,000	1.5
BILL WILLIAMS	0.20	35,000	1.4	0.20	36,000	1.4
BONITA CREEK	0.34	8,000	1.8	0.30	7,000	1.7
BUTLER VALLEY	0.07	1,000	0.8	0.07	1,000	0.8
CIENEGA CREEK	0.45	15,000	2.0	0.41	13,000	1.9
DETRITAL VALLEY	0.04	2,000	0.5	0.05	3,000	0.6
DONNELLY WASH	0.29	4,000	1.6	0.30	5,000	1.7
DOUGLAS	0.25	6,000	1.7	0.21	5,000	1.5
DOUGLAS INA	0.21	6,000	1.3	0.15	4,000	1.1
DRIPPING SPRINGS WASH	0.35	7,000	1.9	0.37	8,000	1.9
DUNCAN VALLEY	0.23	7,000	1.5	0.20	6,000	1.4
GILA BEND	0.05	3,000	0.6	0.05	3,000	0.6
HARQUAHALA INA	0.03	1,000	0.4	0.04	2,000	0.5
HUALAPAI VALLEY	0.07	5,000	0.7	0.09	6,000	0.9
LAKE HAVASU	0.02	0	0.2	0.03	0	0.4
LAKE MOHAVE	0.02	1,000	0.3	0.03	2,000	0.5
LOWER GILA	0.02	7,000	0.3	0.02	7,000	0.3
LOWER SAN PEDRO	0.34	30,000	1.8	0.34	30,000	1.8
MCMULLEN VALLEY	0.10	4,000	1.0	0.09	3,000	0.9
MEADVIEW	0.07	1,000	0.7	0.09	1,000	0.9
MORENCI	0.39	32,000	1.8	0.36	29,000	1.7
PARKER	0.01	1,000	0.2	0.01	1,000	0.2
PEACH SPRINGS	0.15	12,000	1.2	0.15	11,000	1.2
PHOENIX AMA	0.10	29,000	0.9	0.13	36,000	1.1
PINAL AMA	0.09	21,000	0.9	0.10	23,000	1.0
PRESCOTT AMA	0.33	8,000	1.8	0.31	8,000	1.8
RANEGRAS PLAIN	0.03	1,000	0.4	0.02	1,000	0.3
SACRAMENTO VALLEY	0.08	7,000	0.7	0.10	8,000	1.0
SAFFORD	0.25	62,000	1.5	0.24	60,000	1.5
SALT RIVER	0.50	137,000	2.0	0.44	122,000	1.9
SAN BERNARDINO VALLEY	0.24	5,000	1.5	0.18	4,000	1.3
SAN RAFAEL	0.48	6,000	2.3	0.43	6,000	2.2
SAN SIMON WASH	0.12	15,000	1.0	0.12	15,000	1.0
SANTA CRUZ AMA	0.39	15,000	1.9	0.38	14,000	1.9
TIGER WASH	0.08	0	0.8	0.08	0	0.7
TONTO CREEK	0.50	25,000	2.0	0.47	24,000	2.0
TUCSON AMA	0.26	54,000	1.6	0.26	53,000	1.5
UPPER HASSAYAMPA	0.30	12,000	1.6	0.30	12,000	1.6
UPPER SAN PEDRO	0.28	27,000	1.6	0.24	23,000	1.5
VERDE RIVER	0.37	111,000	1.8	0.36	110,000	1.8
WESTERN MEXICAN DRAINAGE	0.04	1,000	0.5	0.05	1,000	0.5
WILLCOX	0.27	28,000	1.6	0.26	27,000	1.6
YUMA	0.00	0	0.0	0.00	0	0.0

Table 12. Average annual mountain-front recharge estimated by the Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation and Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation data for time periods indicated.—Continued

	2000–2006			1940–2006		
Basin name	**Average annual recharge (in)**	**Average annual volume of recharge (acre-ft)**	**Percent of PRISM precipitation**	**Average annual recharge (in)**	**Average annual volume of recharge (acre-ft)**	**Percent of PRISM precipitation**
AGUA FRIA	0.22	15,000	1.5	0.29	19,000	1.7
ARAVAIPA CANYON	0.21	6,000	1.4	0.29	8,000	1.7
BIG SANDY	0.12	13,000	1.1	0.18	19,000	1.4
BILL WILLIAMS	0.13	24,000	1.2	0.16	28,000	1.2
BONITA CREEK	0.22	5,000	1.4	0.25	6,000	1.5
BUTLER VALLEY	0.06	1,000	0.7	0.05	1,000	0.6
CIENEGA CREEK	0.28	9,000	1.7	0.35	12,000	1.9
DETRITAL VALLEY	0.04	2,000	0.6	0.04	2,000	0.5
DONNELLY WASH	0.14	2,000	1.1	0.23	4,000	1.5
DOUGLAS	0.14	3,000	1.2	0.18	4,000	1.4
DOUGLAS INA	0.10	3,000	0.9	0.14	4,000	1.1
DRIPPING SPRINGS WASH	0.17	4,000	1.3	0.29	6,000	1.8
DUNCAN VALLEY	0.13	4,000	1.1	0.15	4,000	1.2
GILA BEND	0.02	1,000	0.3	0.03	2,000	0.4
HARQUAHALA INA	0.04	1,000	0.5	0.03	1,000	0.4
HUALAPAI VALLEY	0.06	4,000	0.7	0.07	4,000	0.7
LAKE HAVASU	0.03	0	0.5	0.02	0	0.3
LAKE MOHAVE	0.04	2,000	0.6	0.02	1,000	0.3
LOWER GILA	0.02	6,000	0.3	0.02	6,000	0.3
LOWER SAN PEDRO	0.18	15,000	1.3	0.26	23,000	1.6
MCMULLEN VALLEY	0.08	3,000	0.8	0.07	2,000	0.7
MEADVIEW	0.07	1,000	0.8	0.07	1,000	0.7
MORENCI	0.30	24,000	1.6	0.32	26,000	1.6
PARKER	0.02	2,000	0.4	0.01	1,000	0.2
PEACH SPRINGS	0.10	8,000	1.0	0.13	10,000	1.1
PHOENIX AMA	0.06	18,000	0.7	0.08	23,000	0.8
PINAL AMA	0.05	11,000	0.6	0.07	16,000	0.8
PRESCOTT AMA	0.20	5,000	1.4	0.26	7,000	1.6
RANEGRAS PLAIN	0.03	2,000	0.5	0.02	1,000	0.3
SACRAMENTO VALLEY	0.06	5,000	0.7	0.07	6,000	0.7
SAFFORD	0.14	35,000	1.1	0.18	46,000	1.3
SALT RIVER	0.32	88,000	1.7	0.39	109,000	1.8
SAN BERNARDINO VALLEY	0.12	2,000	1.0	0.19	4,000	1.3
SAN RAFAEL	0.34	4,000	2.0	0.39	5,000	2.1
SAN SIMON WASH	0.09	11,000	0.9	0.10	12,000	0.9
SANTA CRUZ AMA	0.25	10,000	1.6	0.31	12,000	1.7
TIGER WASH	0.08	0	0.8	0.05	0	0.6
TONTO CREEK	0.31	16,000	1.7	0.42	22,000	1.9
TUCSON AMA	0.15	32,000	1.2	0.20	41,000	1.4
UPPER HASSAYAMPA	0.18	8,000	1.3	0.24	10,000	1.5
UPPER SAN PEDRO	0.17	16,000	1.2	0.21	20,000	1.4
VERDE RIVER	0.25	76,000	1.5	0.31	93,000	1.7
WESTERN MEXICAN DRAINAGE	0.02	1,000	0.3	0.03	1,000	0.4
WILLCOX	0.17	17,000	1.2	0.21	21,000	1.4
YUMA	0.00	0	0.1	0.00	0	0.0

Table 13. Average annual in-place recharge and runoff estimated by the Basin Characterization Model (BCM).

Basin name	1940–1949 Average annual in-place recharge (in)	1940–1949 Average annual runoff (in)	1950–1959 Average annual in-place recharge (in)	1950–1959 Average annual runoff (in)
AGUA FRIA	0.38	0.41	0.23	0.27
ARAVAIPA CANYON	0.17	0.16	0.03	0.08
BIG SANDY	0.20	0.30	0.09	0.19
BILL WILLIAMS	0.17	0.34	0.09	0.27
BONITA CREEK	0.02	0.05	0.01	0.03
BUTLER VALLEY	0.04	0.03	0.01	0.00
CIENEGA CREEK	0.07	0.05	0.11	0.18
DETRITAL VALLEY	0.03	0.04	0.01	0.00
DONNELLY WASH	0.08	0.06	0.01	0.01
DOUGLAS	0.05	0.01	0.02	0.00
DOUGLAS INA	0.00	0.00	0.00	0.00
DRIPPING SPRINGS WASH	0.57	0.21	0.27	0.07
DUNCAN VALLEY	0.01	0.02	0.00	0.00
GILA BEND	0.01	0.01	0.00	0.00
HARQUAHALA INA	0.02	0.01	0.00	0.00
HUALAPAI VALLEY	0.07	0.04	0.03	0.01
LAKE HAVASU	0.04	0.01	0.00	0.00
LAKE MOHAVE	0.02	0.04	0.00	0.00
LOWER GILA	0.00	0.00	0.00	0.00
LOWER SAN PEDRO	0.19	0.18	0.09	0.08
MCMULLEN VALLEY	0.04	0.02	0.01	0.00
MEADVIEW	0.12	0.07	0.04	0.03
MORENCI	0.06	0.59	0.03	0.45
PARKER	0.00	0.00	0.00	0.00
PEACH SPRINGS	0.27	0.16	0.15	0.08
PHOENIX AMA	0.05	0.06	0.02	0.03
PINAL AMA	0.01	0.00	0.00	0.00
PRESCOTT AMA	0.13	0.15	0.08	0.11
RANEGRAS PLAIN	0.00	0.00	0.00	0.00
SACRAMENTO VALLEY	0.08	0.10	0.03	0.02
SAFFORD	0.09	0.10	0.04	0.06
SALT RIVER	0.61	1.40	0.35	1.16
SAN BERNARDINO VALLEY	0.02	0.05	0.01	0.01
SAN RAFAEL	0.13	0.07	0.10	0.09
SAN SIMON WASH	0.01	0.01	0.01	0.00
SANTA CRUZ AMA	0.06	0.04	0.13	0.20
TIGER WASH	0.05	0.00	0.01	0.00
TONTO CREEK	1.11	0.71	0.77	0.61
TUCSON AMA	0.08	0.06	0.08	0.09
UPPER HASSAYAMPA	0.50	0.31	0.36	0.26
UPPER SAN PEDRO	0.04	0.02	0.04	0.02
VERDE RIVER	0.45	1.34	0.27	0.81
WESTERN MEXICAN DRAINAGE	0.01	0.01	0.00	0.00
WILLCOX	0.08	0.23	0.05	0.25
YUMA	0.00	0.00	0.00	0.00

Table 13. Average annual in-place recharge and runoff estimated by the Basin Characterization Model (BCM). —Continued

	1960–1969		1970–1979	
Basin name	**Average annual in-place recharge (in)**	**Average annual runoff (in)**	**Average annual in-place recharge (in)**	**Average annual runoff (in)**
AGUA FRIA	0.35	0.85	0.62	1.17
ARAVAIPA CANYON	0.06	0.23	0.28	0.29
BIG SANDY	0.09	0.29	0.34	0.62
BILL WILLIAMS	0.12	0.39	0.35	0.70
BONITA CREEK	0.02	0.13	0.08	0.19
BUTLER VALLEY	0.01	0.02	0.04	0.03
CIENEGA CREEK	0.12	0.38	0.17	0.23
DETRITAL VALLEY	0.01	0.03	0.05	0.05
DONNELLY WASH	0.07	0.21	0.18	0.20
DOUGLAS	0.05	0.03	0.09	0.01
DOUGLAS INA	0.00	0.00	0.00	0.00
DRIPPING SPRINGS WASH	0.57	0.68	0.97	0.51
DUNCAN VALLEY	0.02	0.07	0.02	0.04
GILA BEND	0.02	0.02	0.01	0.00
HARQUAHALA INA	0.01	0.01	0.01	0.01
HUALAPAI VALLEY	0.03	0.04	0.11	0.07
LAKE HAVASU	0.00	0.01	0.03	0.01
LAKE MOHAVE	0.00	0.01	0.01	0.03
LOWER GILA	0.00	0.01	0.00	0.00
LOWER SAN PEDRO	0.17	0.34	0.33	0.33
MCMULLEN VALLEY	0.02	0.03	0.05	0.02
MEADVIEW	0.12	0.07	0.27	0.12
MORENCI	0.06	0.67	0.11	0.78
PARKER	0.00	0.00	0.00	0.00
PEACH SPRINGS	0.14	0.12	0.63	0.20
PHOENIX AMA	0.05	0.14	0.09	0.17
PINAL AMA	0.02	0.04	0.02	0.02
PRESCOTT AMA	0.10	0.14	0.24	0.36
RANEGRAS PLAIN	0.00	0.01	0.00	0.00
SACRAMENTO VALLEY	0.03	0.05	0.09	0.10
SAFFORD	0.10	0.23	0.22	0.26
SALT RIVER	0.56	1.77	1.11	2.45
SAN BERNARDINO VALLEY	0.02	0.13	0.02	0.06
SAN RAFAEL	0.21	0.25	0.29	0.16
SAN SIMON WASH	0.03	0.08	0.03	0.03
SANTA CRUZ AMA	0.10	0.31	0.15	0.18
TIGER WASH	0.02	0.02	0.05	0.01
TONTO CREEK	1.09	1.07	1.65	1.56
TUCSON AMA	0.11	0.23	0.16	0.17
UPPER HASSAYAMPA	0.44	0.53	0.70	0.71
UPPER SAN PEDRO	0.06	0.07	0.09	0.04
VERDE RIVER	0.35	1.18	0.69	1.72
WESTERN MEXICAN DRAINAGE	0.01	0.02	0.00	0.00
WILLCOX	0.08	0.41	0.10	0.35
YUMA	0.00	0.00	0.00	0.00

Table 13. Average annual in-place recharge and runoff estimated by the Basin Characterization Model (BCM). —Continued

Basin name	1980–1989 Average annual in-place recharge (in)	1980–1989 Average annual runoff (in)	1990–1999 Average annual in-place recharge (in)	1990–1999 Average annual runoff (in)
AGUA FRIA	0.49	0.93	0.55	1.39
ARAVAIPA CANYON	0.18	0.23	0.43	0.57
BIG SANDY	0.18	0.33	0.34	0.80
BILL WILLIAMS	0.22	0.46	0.33	0.94
BONITA CREEK	0.07	0.18	0.12	0.33
BUTLER VALLEY	0.04	0.05	0.07	0.14
CIENEGA CREEK	0.23	0.30	0.23	0.34
DETRITAL VALLEY	0.03	0.02	0.05	0.11
DONNELLY WASH	0.06	0.07	0.21	0.28
DOUGLAS	0.04	0.00	0.15	0.05
DOUGLAS INA	0.00	0.00	0.00	0.00
DRIPPING SPRINGS WASH	0.65	0.27	1.11	0.87
DUNCAN VALLEY	0.01	0.03	0.05	0.08
GILA BEND	0.00	0.00	0.04	0.02
HARQUAHALA INA	0.02	0.02	0.06	0.05
HUALAPAI VALLEY	0.05	0.01	0.11	0.14
LAKE HAVASU	0.05	0.04	0.12	0.13
LAKE MOHAVE	0.02	0.03	0.04	0.12
LOWER GILA	0.00	0.00	0.01	0.01
LOWER SAN PEDRO	0.29	0.25	0.45	0.54
MCMULLEN VALLEY	0.05	0.06	0.07	0.12
MEADVIEW	0.10	0.05	0.27	0.16
MORENCI	0.11	1.00	0.13	0.99
PARKER	0.01	0.01	0.02	0.02
PEACH SPRINGS	0.23	0.11	0.57	0.23
PHOENIX AMA	0.06	0.11	0.11	0.23
PINAL AMA	0.02	0.01	0.03	0.02
PRESCOTT AMA	0.17	0.24	0.18	0.30
RANEGRAS PLAIN	0.01	0.01	0.02	0.05
SACRAMENTO VALLEY	0.06	0.06	0.11	0.26
SAFFORD	0.14	0.20	0.28	0.36
SALT RIVER	0.90	2.51	1.01	2.22
SAN BERNARDINO VALLEY	0.01	0.03	0.03	0.08
SAN RAFAEL	0.36	0.22	0.35	0.24
SAN SIMON WASH	0.03	0.02	0.04	0.04
SANTA CRUZ AMA	0.21	0.26	0.20	0.29
TIGER WASH	0.07	0.04	0.13	0.17
TONTO CREEK	1.44	1.16	1.54	1.58
TUCSON AMA	0.19	0.18	0.21	0.29
UPPER HASSAYAMPA	0.55	0.60	0.65	0.97
UPPER SAN PEDRO	0.10	0.05	0.12	0.09
VERDE RIVER	0.57	1.61	0.68	1.80
WESTERN MEXICAN DRAINAGE	0.00	0.00	0.01	0.01
WILLCOX	0.11	0.44	0.15	0.57
YUMA	0.00	0.00	0.00	0.00

Table 13. Average annual in-place recharge and runoff estimated by the Basin Characterization Model (BCM). —Continued

	2000–2006		1940–2006	
Basin name	**Average annual in-place recharge (in)**	**Average annual runoff (in)**	**Average annual in-place recharge (in)**	**Average annual runoff (in)**
AGUA FRIA	0.32	0.48	0.42	0.80
ARAVAIPA CANYON	0.03	0.03	0.18	0.24
BIG SANDY	0.17	0.22	0.20	0.40
BILL WILLIAMS	0.22	0.41	0.21	0.50
BONITA CREEK	0.01	0.02	0.05	0.14
BUTLER VALLEY	0.04	0.04	0.04	0.04
CIENEGA CREEK	0.06	0.09	0.15	0.23
DETRITAL VALLEY	0.04	0.05	0.03	0.04
DONNELLY WASH	0.04	0.06	0.09	0.13
DOUGLAS	0.08	0.02	0.07	0.02
DOUGLAS INA	0.00	0.00	0.00	0.00
DRIPPING SPRINGS WASH	0.31	0.09	0.65	0.40
DUNCAN VALLEY	0.00	0.01	0.02	0.04
GILA BEND	0.00	0.00	0.01	0.01
HARQUAHALA INA	0.01	0.00	0.02	0.01
HUALAPAI VALLEY	0.07	0.04	0.07	0.05
LAKE HAVASU	0.02	0.01	0.04	0.03
LAKE MOHAVE	0.02	0.04	0.02	0.04
LOWER GILA	0.00	0.00	0.00	0.00
LOWER SAN PEDRO	0.08	0.06	0.24	0.26
MCMULLEN VALLEY	0.04	0.03	0.04	0.04
MEADVIEW	0.11	0.06	0.15	0.08
MORENCI	0.06	0.53	0.08	0.72
PARKER	0.00	0.00	0.00	0.01
PEACH SPRINGS	0.25	0.15	0.32	0.15
PHOENIX AMA	0.05	0.07	0.06	0.12
PINAL AMA	0.00	0.00	0.01	0.01
PRESCOTT AMA	0.07	0.11	0.14	0.21
RANEGRAS PLAIN	0.00	0.00	0.01	0.01
SACRAMENTO VALLEY	0.05	0.06	0.06	0.09
SAFFORD	0.04	0.04	0.14	0.18
SALT RIVER	0.42	0.89	0.72	1.81
SAN BERNARDINO VALLEY	0.02	0.03	0.02	0.05
SAN RAFAEL	0.06	0.05	0.22	0.16
SAN SIMON WASH	0.01	0.01	0.02	0.03
SANTA CRUZ AMA	0.05	0.09	0.13	0.20
TIGER WASH	0.07	0.02	0.06	0.04
TONTO CREEK	0.75	0.57	1.21	1.06
TUCSON AMA	0.05	0.03	0.13	0.15
UPPER HASSAYAMPA	0.35	0.31	0.51	0.54
UPPER SAN PEDRO	0.04	0.01	0.07	0.04
VERDE RIVER	0.36	0.92	0.49	1.36
WESTERN MEXICAN DRAINAGE	0.00	0.00	0.01	0.01
WILLCOX	0.05	0.14	0.09	0.35
YUMA	0.00	0.00	0.00	0.00

Table 14. Average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for time periods indicated.

[Total estimated recharge includes in-place recharge plus 15% of BCM-estimated runoff.]

Basin name	1940–1949			1950–1959		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	11.2	30,000	2.8	6.8	18,000	1.7
ARAVAIPA CANYON	4.8	5,000	1.2	1.2	1,000	0.3
BIG SANDY	6.2	26,000	1.9	3.0	13,000	0.9
BILL WILLIAMS	5.7	40,000	1.9	3.3	24,000	1.2
BONITA CREEK	0.7	1,000	0.2	0.5	0	0.1
BUTLER VALLEY	1.1	1,000	0.6	0.2	0	0.1
CIENEGA CREEK	1.9	2,000	0.4	3.6	5,000	0.8
DETRITAL VALLEY	0.9	2,000	0.5	0.2	0	0.1
DONNELLY WASH	2.3	1,000	0.6	0.2	0	0.1
DOUGLAS	1.2	1,000	0.4	0.4	0	0.1
DOUGLAS INA	0.0	0	0.0	0.0	0	0.0
DRIPPING SPRINGS WASH	15.4	12,000	3.7	7.0	6,000	1.8
DUNCAN VALLEY	0.3	0	0.1	0.0	0	0.0
GILA BEND	0.3	1,000	0.1	0.0	0	0.0
HARQUAHALA INA	0.5	1,000	0.3	0.1	0	0.0
HUALAPAI VALLEY	2.0	5,000	0.9	0.7	2,000	0.3
LAKE HAVASU	1.0	1,000	0.7	0.0	0	0.0
LAKE MOHAVE	0.7	1,000	0.5	0.0	0	0.0
LOWER GILA	0.1	1,000	0.0	0.0	0	0.0
LOWER SAN PEDRO	5.4	18,000	1.4	2.7	9,000	0.7
MCMULLEN VALLEY	1.1	2,000	0.5	0.3	0	0.1
MEADVIEW	3.4	1,000	1.5	1.2	0	0.6
MORENCI	3.7	12,000	0.8	2.6	8,000	0.6
PARKER	0.1	0	0.1	0.0	0	0.0
PEACH SPRINGS	7.3	22,000	2.5	4.0	12,000	1.4
PHOENIX AMA	1.4	16,000	0.6	0.7	8,000	0.3
PINAL AMA	0.2	2,000	0.1	0.1	1,000	0.1
PRESCOTT AMA	3.8	4,000	1.0	2.6	3,000	0.7
RANEGRAS PLAIN	0.1	0	0.1	0.0	0	0.0
SACRAMENTO VALLEY	2.5	8,000	1.1	0.9	3,000	0.4
SAFFORD	2.8	28,000	0.8	1.2	12,000	0.4
SALT RIVER	20.8	228,000	4.0	13.4	147,000	2.8
SAN BERNARDINO VALLEY	0.6	1,000	0.2	0.2	0	0.1
SAN RAFAEL	3.6	2,000	0.8	2.9	1,000	0.6
SAN SIMON WASH	0.3	1,000	0.1	0.2	1,000	0.1
SANTA CRUZ AMA	1.6	2,000	0.4	4.0	6,000	1.0
TIGER WASH	1.3	0	0.6	0.2	0	0.1
TONTO CREEK	30.8	62,000	5.8	22.0	44,000	4.2
TUCSON AMA	2.3	19,000	0.7	2.5	20,000	0.7
UPPER HASSAYAMPA	13.9	23,000	3.7	10.1	17,000	2.6
UPPER SAN PEDRO	1.1	4,000	0.3	1.0	4,000	0.3
VERDE RIVER	16.6	197,000	3.7	9.9	118,000	2.3
WESTERN MEXICAN DRAINAGE	0.2	0	0.1	0.0	0	0.0
WILLCOX	2.8	11,000	0.8	2.2	9,000	0.7
YUMA	0.0	0	0.0	0.0	0	0.0

Table 14. Average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for time periods indicated. —Continued

[Total estimated recharge includes in-place recharge plus 15% of BCM-estimated runoff.]

Basin name	1960–1969			1970–1979		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	12.1	32,000	2.7	20.2	54,000	4.6
ARAVAIPA CANYON	2.5	3,000	0.6	8.3	9,000	1.8
BIG SANDY	3.5	15,000	1.0	11.0	46,000	3.1
BILL WILLIAMS	4.5	32,000	1.5	11.5	81,000	3.5
BONITA CREEK	1.1	1,000	0.3	2.8	3,000	0.7
BUTLER VALLEY	0.4	0	0.2	1.2	1,000	0.6
CIENEGA CREEK	4.6	6,000	0.9	5.1	7,000	1.1
DETRITAL VALLEY	0.3	1,000	0.2	1.4	3,000	0.7
DONNELLY WASH	2.5	2,000	0.7	5.3	3,000	1.3
DOUGLAS	1.5	1,000	0.4	2.3	2,000	0.7
DOUGLAS INA	0.0	0	0.0	0.0	0	0.0
DRIPPING SPRINGS WASH	17.1	14,000	3.8	26.5	21,000	5.8
DUNCAN VALLEY	0.7	1,000	0.2	0.7	1,000	0.2
GILA BEND	0.6	2,000	0.3	0.2	1,000	0.1
HARQUAHALA INA	0.2	0	0.1	0.3	1,000	0.2
HUALAPAI VALLEY	1.0	2,000	0.4	3.2	8,000	1.3
LAKE HAVASU	0.1	0	0.1	0.7	0	0.5
LAKE MOHAVE	0.1	0	0.1	0.4	1,000	0.3
LOWER GILA	0.1	2,000	0.1	0.1	1,000	0.1
LOWER SAN PEDRO	5.7	19,000	1.4	9.7	33,000	2.3
MCMULLEN VALLEY	0.5	1,000	0.3	1.3	2,000	0.6
MEADVIEW	3.3	1,000	1.5	7.4	3,000	3.0
MORENCI	4.1	14,000	0.9	5.7	19,000	1.3
PARKER	0.0	0	0.0	0.1	1,000	0.1
PEACH SPRINGS	3.9	12,000	1.2	16.9	50,000	5.1
PHOENIX AMA	1.7	20,000	0.7	2.9	33,000	1.2
PINAL AMA	0.6	6,000	0.3	0.7	6,000	0.3
PRESCOTT AMA	3.1	3,000	0.7	7.5	8,000	1.8
RANEGRAS PLAIN	0.0	0	0.0	0.1	0	0.1
SACRAMENTO VALLEY	0.9	3,000	0.4	2.8	9,000	1.2
SAFFORD	3.3	33,000	0.9	6.5	65,000	1.9
SALT RIVER	20.9	230,000	3.9	37.5	413,000	6.8
SAN BERNARDINO VALLEY	1.0	1,000	0.3	0.7	1,000	0.2
SAN RAFAEL	6.3	3,000	1.3	8.0	4,000	1.7
SAN SIMON WASH	0.9	5,000	0.3	0.9	4,000	0.3
SANTA CRUZ AMA	3.8	6,000	0.8	4.4	7,000	1.0
TIGER WASH	0.6	0	0.3	1.3	0	0.6
TONTO CREEK	31.7	64,000	5.7	48.0	96,000	8.3
TUCSON AMA	3.6	29,000	0.9	4.6	37,000	1.2
UPPER HASSAYAMPA	13.2	22,000	3.3	20.5	34,000	5.0
UPPER SAN PEDRO	1.9	7,000	0.5	2.5	9,000	0.6
VERDE RIVER	13.4	160,000	2.9	24.0	285,000	5.3
WESTERN MEXICAN DRAINAGE	0.3	0	0.1	0.1	0	0.1
WILLCOX	3.6	14,000	1.0	3.9	16,000	1.1
YUMA	0.0	0	0.0	0.0	0	0.0

Table 14. Average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for time periods indicated. —Continued

[Total estimated recharge includes in-place recharge plus 15% of BCM-estimated runoff.]

Basin name	1980–1989			1990–1999		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	16.1	43,000	3.2	19.2	51,000	3.8
ARAVAIPA CANYON	5.5	6,000	1.1	13.0	14,000	2.5
BIG SANDY	5.8	24,000	1.6	11.6	48,000	3.1
BILL WILLIAMS	7.2	51,000	2.0	11.9	84,000	3.3
BONITA CREEK	2.5	2,000	0.5	4.3	4,000	1.0
BUTLER VALLEY	1.2	1,000	0.5	2.3	1,000	1.0
CIENEGA CREEK	7.0	9,000	1.2	7.1	9,000	1.3
DETRITAL VALLEY	0.7	1,000	0.4	1.8	3,000	0.8
DONNELLY WASH	1.8	1,000	0.4	6.4	4,000	1.5
DOUGLAS	1.0	1,000	0.3	3.9	3,000	1.0
DOUGLAS INA	0.0	0	0.0	0.0	0	0.0
DRIPPING SPRINGS WASH	17.5	14,000	3.6	31.4	25,000	6.2
DUNCAN VALLEY	0.4	0	0.1	1.4	2,000	0.4
GILA BEND	0.1	0	0.0	1.0	3,000	0.5
HARQUAHALA INA	0.6	1,000	0.3	1.6	3,000	0.8
HUALAPAI VALLEY	1.3	3,000	0.5	3.3	8,000	1.3
LAKE HAVASU	1.5	1,000	0.9	3.4	2,000	1.9
LAKE MOHAVE	0.5	1,000	0.3	1.6	3,000	0.9
LOWER GILA	0.0	1,000	0.0	0.3	4,000	0.2
LOWER SAN PEDRO	8.4	29,000	1.8	13.4	46,000	2.8
MCMULLEN VALLEY	1.5	2,000	0.6	2.2	3,000	0.9
MEADVIEW	2.6	1,000	1.1	7.4	3,000	2.9
MORENCI	6.7	22,000	1.3	7.1	23,000	1.4
PARKER	0.2	1,000	0.1	0.5	2,000	0.3
PEACH SPRINGS	6.1	18,000	1.9	15.3	45,000	4.9
PHOENIX AMA	1.9	22,000	0.7	3.5	40,000	1.2
PINAL AMA	0.5	4,000	0.2	0.7	6,000	0.3
PRESCOTT AMA	5.3	5,000	1.1	5.7	6,000	1.3
RANEGRAS PLAIN	0.2	0	0.1	0.8	2,000	0.5
SACRAMENTO VALLEY	1.6	5,000	0.6	3.7	12,000	1.4
SAFFORD	4.4	44,000	1.1	8.6	86,000	2.1
SALT RIVER	32.5	357,000	5.1	34.1	375,000	5.8
SAN BERNARDINO VALLEY	0.4	0	0.1	1.1	1,000	0.3
SAN RAFAEL	9.9	5,000	1.8	9.8	5,000	1.9
SAN SIMON WASH	0.8	4,000	0.3	1.2	6,000	0.4
SANTA CRUZ AMA	6.4	10,000	1.2	6.2	9,000	1.2
TIGER WASH	1.9	0	0.7	4.0	1,000	1.7
TONTO CREEK	41.1	82,000	6.6	45.1	91,000	7.5
TUCSON AMA	5.6	45,000	1.3	6.5	53,000	1.5
UPPER HASSAYAMPA	16.3	27,000	3.6	20.1	33,000	4.4
UPPER SAN PEDRO	2.7	10,000	0.6	3.3	13,000	0.8
VERDE RIVER	20.7	246,000	4.0	24.2	288,000	4.7
WESTERN MEXICAN DRAINAGE	0.0	0	0.0	0.4	1,000	0.2
WILLCOX	4.6	18,000	1.1	6.0	24,000	1.4
YUMA	0.0	0	0.0	0.0	0	0.0

Table 14. Average annual mountain-front recharge estimated by the Basin Characterization Model (BCM) for time periods indicated. —Continued

[Total estimated recharge includes in-place recharge plus 15% of BCM-estimated runoff.]

Basin name	2000–2006			1940–2006		
	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation	Average annual recharge (in)	Average annual volume of recharge (acre-ft)	Percent of PRISM precipitation
AGUA FRIA	9.9	26,000	2.6	13.8	37,000	3.1
ARAVAIPA CANYON	0.9	1,000	0.2	5.4	6,000	1.2
BIG SANDY	5.1	21,000	1.7	6.7	28,000	2.0
BILL WILLIAMS	7.1	50,000	2.4	7.3	52,000	2.3
BONITA CREEK	0.3	0	0.1	1.8	2,000	0.4
BUTLER VALLEY	1.3	1,000	0.6	1.1	1,000	0.5
CIENEGA CREEK	1.9	2,000	0.4	4.6	6,000	0.9
DETRITAL VALLEY	1.1	2,000	0.6	0.9	2,000	0.5
DONNELLY WASH	1.3	1,000	0.4	2.9	2,000	0.8
DOUGLAS	2.1	2,000	0.7	1.8	1,000	0.5
DOUGLAS INA	0.0	0	0.0	0.0	0	0.0
DRIPPING SPRINGS WASH	8.3	7,000	2.4	18.0	14,000	4.1
DUNCAN VALLEY	0.1	0	0.0	0.5	1,000	0.2
GILA BEND	0.0	0	0.0	0.3	1,000	0.2
HARQUAHALA INA	0.4	1,000	0.2	0.5	1,000	0.3
HUALAPAI VALLEY	1.9	5,000	0.9	1.9	5,000	0.8
LAKE HAVASU	0.4	0	0.3	1.1	1,000	0.7
LAKE MOHAVE	0.7	1,000	0.5	0.6	1,000	0.4
LOWER GILA	0.0	0	0.0	0.1	1,000	0.1
LOWER SAN PEDRO	2.4	8,000	0.7	7.0	24,000	1.7
MCMULLEN VALLEY	1.2	2,000	0.5	1.2	2,000	0.5
MEADVIEW	3.0	1,000	1.4	4.1	2,000	1.8
MORENCI	3.4	11,000	0.8	4.8	16,000	1.0
PARKER	0.1	0	0.0	0.1	1,000	0.1
PEACH SPRINGS	6.8	20,000	2.5	8.7	26,000	2.9
PHOENIX AMA	1.5	17,000	0.7	2.0	22,000	0.8
PINAL AMA	0.1	1,000	0.0	0.4	4,000	0.2
PRESCOTT AMA	2.2	2,000	0.6	4.4	4,000	1.1
RANEGRAS PLAIN	0.0	0	0.0	0.2	0	0.1
SACRAMENTO VALLEY	1.5	5,000	0.7	2.0	7,000	0.9
SAFFORD	1.2	12,000	0.4	4.1	41,000	1.2
SALT RIVER	14.0	154,000	2.9	25.2	277,000	4.7
SAN BERNARDINO VALLEY	0.5	0	0.2	0.7	1,000	0.2
SAN RAFAEL	1.8	1,000	0.4	6.2	3,000	1.3
SAN SIMON WASH	0.2	1,000	0.1	0.7	3,000	0.2
SANTA CRUZ AMA	1.6	2,000	0.4	4.1	6,000	0.9
TIGER WASH	1.8	0	0.8	1.6	0	0.7
TONTO CREEK	21.2	43,000	4.6	34.9	70,000	6.3
TUCSON AMA	1.5	12,000	0.4	3.9	32,000	1.0
UPPER HASSAYAMPA	10.1	17,000	2.9	15.1	25,000	3.7
UPPER SAN PEDRO	1.0	4,000	0.3	2.0	7,000	0.5
VERDE RIVER	12.6	150,000	3.0	17.5	209,000	3.8
WESTERN MEXICAN DRAINAGE	0.0	0	0.0	0.2	0	0.1
WILLCOX	1.7	7,000	0.5	3.6	15,000	1.0
YUMA	0.0	0	0.0	0.0	0	0.0

Table 15. Comparison of Basin Characterization Model (BCM) and Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation estimates of average annual mountain-front recharge for the 1940–2006 time period.

[Recharge estimates by Arizona Department of Water Resources (ADWR) also provided for comparison.]

Basin name	BCM average annual volume of in-place recharge (acre-ft)	SWAB-RASA equation average annual volume of recharge (acre-ft)	ADWR estimates of annual recharge[1] (acre-ft)	ADWR ground-water atlas volume number	Citation for ADWR estimate
AGUA FRIA	29,000	19,000	9,000	5	Freethey and Anderson, 1986
ARAVAIPA CANYON	5,000	8,000	7,000 - 16,700 7,000	3	Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
BIG SANDY	22,000	19,000	22,000	4	Freethey and Anderson, 1986
BILL WILLIAMS	38,000	28,000	32,000	4	Freethey and Anderson, 1986
BONITA CREEK	1,000	6,000	9,000	3	Freethey and Anderson, 1986
BUTLER VALLEY	1,000	1,000	< 1,000 1,060	7	Freethey and Anderson, 1986 Herndon, 1985
CIENEGA CREEK	5,000	12,000	8,500 - 25,500 11,000	3	Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
DETRITAL VALLEY	1,000	2,000	1,000	4	Freethey and Anderson, 1986
DONNELLY WASH	1,000	4,000	3,000	3	Freethey and Anderson, 1986
DOUGLAS	1,000	4,000	15,500[2]	3	Anderson and Freethey, 1995 Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
DOUGLAS INA	0	4,000			
DRIPPING SPRINGS WASH	13,000	6,000	3,000 9,000	3	Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
DUNCAN VALLEY	0	4,000	14,200 6,000 8,000	3	Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986 Arizona Water Commission, 1975
GILA BEND[3]	1,000	2,000	37,000 10,000	7	Freethey and Anderson, 1986 Arizona Water Commission, 1975
HARQUAHALA INA	1,000	1,000	<1,200[4] 1,000 <1,000[4]	7	Anderson and Freethey, 1995 Freethey and Anderson, 1986 Arizona Water Commission, 1975
HUALAPAI VALLEY	4,000	4,000	3,000 2,000 - 2,500	4	Freethey and Anderson, 1986 Remick, 1981
LAKE HAVASU	0	0	35,000[5]	4	Freethey and Anderson, 1986
LAKE MOHAVE[6]	1,000	1,000	183,000	4	Freethey and Anderson, 1986
LOWER GILA	1,000	6,000	88,000 >9,000	7	Freethey and Anderson, 1986 Arizona Water Commission, 1975
LOWER SAN PEDRO	21,000	23,000	29,000 25,000 24,000	3	Anderson and Freethey, 1995 Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
MCMULLEN VALLEY	1,000	2,000	1,000 1,000	7	Freethey and Anderson, 1986 Arizona Water Commission, 1975
MEADVIEW	2,000	1,000	4,000	4	Freethey and Anderson, 1986
MORENCI	7,000	26,000	15,000	3	Freethey and Anderson, 1986
PARKER[6]	1,000	1,000	241,000[6]	7	Freethey and Anderson, 1986
PEACH SPRINGS	24,000	10,000	not available		
PHOENIX AMA	17,000	23,000	24,100	8	Arizona Department of Water Resources, 1999a
PINAL AMA	3,000	16,000	82,750[8]	8	Arizona Department of Water Resources, 2004

Table 15. Comparison of Basin Characterization Model (BCM) and Southwest Alluvial Basins-Regional Aquifer System-Analysis (SWAB-RASA) regression equation estimates of average annual mountain-front recharge for the 1940–2006 time period. —Continued

[Recharge estimates by Arizona Department of Water Resources (ADWR) also provided for comparison.]

Basin name	BCM average annual volume of in-place recharge (acre-ft)	SWAB-RASA equation average annual volume of recharge (acre-ft)	ADWR estimates of annual recharge[1] (acre-ft)	ADWR groundwater atlas volume number	Citation for ADWR estimate
PRESCOTT AMA	4,000	7,000	7,000	8	Timmons and Springer, 2006
RANEGRAS PLAIN	0	1,000	5,000 5,500 <1,000 1,000	7	Arizona Department of Water Resources, 1994 Arizona Department of Water Resources, 1990 Freethey and Anderson, 1986 Arizona Water Commission, 1975
SACRAMENTO VALLEY	5,000	6,000	1,000 4,000	4	Rascona, 1991 Freethey and Anderson, 1986
SAFFORD	34,000	46,000	105,000	3	Freethey and Anderson, 1986
SALT RIVER	201,000	109,000	178,000	5	Freethey and Anderson, 1986
SAN BERNARDINO VALLEY	0	4,000	9,000	3	Freethey and Anderson, 1986
SAN RAFAEL	3,000	5,000	5,000	3	Freethey and Anderson, 1986
SAN SIMON WASH	3,000	12,000	11,000	7	Freethey and Anderson, 1986
SANTA CRUZ AMA	5,000	12,000	61,050[7]	8	Arizona Department of Water Resources, 1999b
TIGER WASH	0	0	<1,000	7	Freethey and Anderson, 1986
TONTO CREEK	62,000	22,000	17,000 37,000	5	Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
TUCSON AMA	27,000	41,000	60,800[7]	8	Arizona Department of Water Resources, 1999c
UPPER HASSAYAMPA	22,000	10,000	8,000	5	Freethey and Anderson, 1986
UPPER SAN PEDRO	7,000	20,000	35,750	3	Arizona Department of Water Resources, 2005
VERDE RIVER	147,000	93,000	197,770	5	Blasch and others, 2006 Arizona Department of Water Resources, 1994 Freethey and Anderson, 1986
WESTERN MEXICAN DRAINAGE	0	1,000	1,000	7	Freethey and Anderson, 1986
WILLCOX	9,000	21,000	47,000 46,000 15,000	3	Anderson and Freethey, 1995 Freethey and Anderson, 1986 Arizona Department of Water Resources, 1994
YUMA	0	0	213,000[5]	7	Freethey and Anderson, 1986

[1] ADWR recharge estimates may include basin underflow, streamflow infiltration, or other components not directly comparable to the SWAB-RASA equation or BCM results.

[2] Includes Douglas and Douglas INA basins.

[3] Includes Gila River flood events and infiltration of water impounded behind Painted Rock Dam (Arizona Department of Water Resources, 1994.)

[4] Includes Tiger Wash Basin.

[5] Presumably includes recharge from Colorado River.

[6] Recharge comes principally from infiltration of Colorado River water.

[7] Includes groundwater inflow.

[8] Primary source of natural recharge is streambed recharge along the Gila and Santa Cruz Rivers.

Table 16. Maximum and minimum estimated annual volumes of actual evapotranspiration from groundwater, summarized by basin.

Volume of Estimated Actual Evapotranspiration from Groundwater (acre-ft)

	2000		2001		2002		2003	
Basin name	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
AGUA FRIA	23,400	41,200	23,600	40,400	15,900	31,400	24,500	49,400
ARAVAIPA CANYON	5,500	15,500	7,500	15,300	6,300	13,400	7,000	15,200
BIG SANDY	13,800	22,800	14,900	23,800	12,900	20,200	15,900	29,900
BILL WILLIAMS	36,700	56,700	39,700	54,800	31,100	44,100	34,300	62,300
BONITA CREEK	2,400	6,400	3,300	7,400	2,100	6,700	3,300	7,500
BUTLER VALLEY	200	400	400	600	200	300	300	700
CIENEGA CREEK	3,600	9,600	4,000	9,500	3,700	8,700	2,900	8,900
DETRITAL VALLEY	600	1,000	1,100	1,600	600	800	1,200	2,300
DONNELLY WASH	3,900	6,500	5,300	7,600	3,900	5,800	4,100	7,000
DOUGLAS	300	900	300	900	200	700	200	500
DOUGLAS INA	800	2,100	1,000	2,100	800	1,900	600	1,500
DRIPPING SPRINGS WASH	3,400	7,400	4,500	8,400	3,500	6,400	4,200	8,500
DUNCAN VALLEY	3,100	5,600	3,800	6,800	2,600	6,500	3,500	5,400
GILA BEND	24,200	29,300	31,000	29,800	26,200	29,500	21,300	27,600
HARQUAHALA INA	1,500	2,000	2,200	2,400	1,100	1,500	1,800	2,700
HUALAPAI VALLEY	800	1,700	1,300	2,500	700	1,200	1,700	3,500
LAKE HAVASU	1,900	2,400	1,900	2,100	1,900	2,400	1,700	2,700
LAKE MOHAVE	27,900	38,100	30,900	40,200	33,400	40,400	30,100	41,200
LOWER GILA	36,000	47,100	34,900	40,500	34,800	40,800	35,300	51,200
LOWER SAN PEDRO	27,600	54,100	36,200	54,100	31,300	48,500	30,000	50,800
MCMULLEN VALLEY	1,200	1,700	2,000	2,000	900	1,100	1,300	2,100
MEADVIEW	300	600	900	1,200	1,700	2,000	2,300	2,900
MORENCI	17,000	41,200	15,100	40,000	14,800	43,200	16,400	43,700
PARKER	25,700	43,400	27,000	38,900	27,700	44,800	26,200	46,100
PEACH SPRINGS	2,000	3,600	3,000	4,700	2,900	4,400	3,600	6,400
PHOENIX AMA	84,300	106,900	95,000	102,600	80,500	97,500	94,000	125,100
PINAL AMA	42,500	61,500	49,200	60,000	38,600	51,100	44,800	63,300
PRESCOTT AMA	5,100	10,000	5,700	9,200	4,500	8,200	5,200	10,900
RANEGRAS PLAIN	600	800	1,000	1,400	400	500	400	1,000
SACRAMENTO VALLEY	4,600	6,800	6,000	8,900	4,300	6,100	6,800	12,800
SAFFORD	46,300	82,200	54,000	79,200	41,800	71,300	52,800	82,100
SALT RIVER	78,700	164,700	73,400	159,800	67,400	153,000	74,000	172,400
SAN BERNARDINO VALLEY	1,200	3,900	2,000	4,700	1,900	4,800	1,100	3,000
SAN RAFAEL	500	1,400	600	1,500	500	1,300	500	1,400
SAN SIMON WASH	37,600	58,700	41,900	57,500	24,000	36,200	41,700	66,900
SANTA CRUZ AMA	4,400	9,700	4,900	9,400	5,200	9,700	4,200	10,300
TIGER WASH	500	800	600	900	200	400	500	1,100
TONTO CREEK	17,900	31,600	15,900	31,600	15,100	27,600	16,300	34,800
TUCSON AMA	26,900	62,200	31,900	61,000	24,600	53,300	23,300	62,300
UPPER HASSAYAMPA	14,200	24,500	15,700	23,000	10,600	18,000	12,700	26,500
UPPER SAN PEDRO	9,200	22,400	12,100	22,600	10,800	20,500	9,400	19,600
VERDE RIVER	70,300	122,800	71,900	118,400	62,100	107,700	73,300	140,400
WESTERN MEXICAN DRAINAGE	100	300	100	300	0	100	100	300
WILLCOX	10,800	26,100	14,300	27,000	11,800	26,500	13,400	24,500
YUMA	7,900	12,300	7,700	10,400	8,200	12,500	7,700	12,600

Table 16. Maximum and minimum estimated annual volumes of actual evapotranspiration from groundwater, summarized by basin. —Continued

	2004		2005		2006		2007	
Basin name	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
AGUA FRIA	12,500	41,300	30,900	55,700	17,700	37,900	16,700	34,400
ARAVAIPA CANYON	5,700	15,600	9,700	18,800	6,900	16,400	8,000	16,700
BIG SANDY	9,400	23,100	19,400	33,900	15,300	28,100	14,200	25,100
BILL WILLIAMS	22,100	51,000	43,900	73,700	34,400	59,400	32,700	52,800
BONITA CREEK	2,200	7,200	3,400	8,300	2,600	8,200	3,600	8,800
BUTLER VALLEY	100	400	800	1,400	400	700	100	300
CIENEGA CREEK	3,400	8,800	4,100	8,600	3,900	10,100	3,900	10,000
DETRITAL VALLEY	600	1,600	3,700	6,200	1,400	2,500	700	1,200
DONNELLY WASH	3,200	6,700	6,200	9,700	4,900	8,200	4,400	7,100
DOUGLAS	200	700	400	900	200	900	300	1,000
DOUGLAS INA	600	1,800	1,200	2,200	800	2,400	1,100	2,700
DRIPPING SPRINGS WASH	3,000	7,600	6,200	10,700	4,200	8,400	3,600	7,300
DUNCAN VALLEY	3,000	7,400	4,400	8,500	2,300	7,700	3,500	7,900
GILA BEND	10,900	16,000	29,700	36,000	28,700	33,300	25,500	30,100
HARQUAHALA INA	700	1,800	3,400	5,100	1,400	2,000	900	1,500
HUALAPAI VALLEY	800	2,100	5,000	8,100	2,300	4,100	1,600	2,700
LAKE HAVASU	1,300	2,400	2,000	3,700	2,000	2,800	1,700	2,400
LAKE MOHAVE	26,600	38,500	31,800	44,100	27,900	40,100	30,600	39,500
LOWER GILA	23,600	40,500	58,700	86,100	42,800	57,900	37,500	49,700
LOWER SAN PEDRO	26,100	49,900	39,200	61,700	33,100	57,600	36,000	58,500
MCMULLEN VALLEY	700	1,400	2,500	3,700	1,500	2,000	1,200	1,700
MEADVIEW	2,300	3,100	2,900	3,700	2,500	3,200	2,300	2,900
MORENCI	12,000	42,400	16,400	43,900	11,700	43,400	12,900	46,100
PARKER	21,800	41,500	29,600	54,300	24,200	44,600	21,200	40,100
PEACH SPRINGS	2,600	5,000	4,500	7,600	3,100	5,700	2,700	5,000
PHOENIX AMA	67,600	104,200	104,700	146,300	84,300	110,100	75,900	97,600
PINAL AMA	36,700	58,200	60,900	86,500	54,800	75,700	49,700	70,700
PRESCOTT AMA	3,600	8,900	6,500	12,200	4,200	9,900	4,100	8,900
RANEGRAS PLAIN	200	800	2,300	3,900	800	1,500	400	800
SACRAMENTO VALLEY	3,500	7,900	10,900	19,200	6,400	10,500	4,000	6,500
SAFFORD	40,200	81,100	58,800	91,600	45,900	85,600	54,100	93,400
SALT RIVER	52,000	158,200	80,700	176,300	62,800	165,200	61,700	166,300
SAN BERNARDINO VALLEY	900	3,900	3,600	7,100	1,800	6,400	1,800	5,800
SAN RAFAEL	400	1,400	600	1,400	700	1,700	600	1,600
SAN SIMON WASH	36,100	63,500	52,600	77,700	40,900	64,100	44,300	68,200
SANTA CRUZ AMA	4,200	9,000	5,900	10,900	5,700	11,800	5,000	10,500
TIGER WASH	200	700	1,000	1,800	700	1,000	400	800
TONTO CREEK	9,400	28,600	17,600	33,900	13,100	29,200	13,100	29,900
TUCSON AMA	21,600	55,100	38,200	73,000	33,500	69,500	32,000	67,100
UPPER HASSAYAMPA	7,300	21,500	17,100	29,900	12,000	22,400	10,700	21,300
UPPER SAN PEDRO	8,700	18,900	12,000	21,600	10,900	25,100	10,700	24,000
VERDE RIVER	46,800	117,800	74,500	142,100	55,900	119,400	56,100	115,500
WESTERN MEXICAN DRAINAGE	0	300	400	900	100	300	0	100
WILLCOX	8,900	26,700	16,000	30,800	12,100	30,800	12,700	31,000
YUMA	6,800	11,500	6,700	11,700	7,400	12,300	6,700	11,700

Table 17. Comparison of maximum and minimum estimated annual volume of actual evapotranspiration (AET) for the 2000–2007 time period (this study) to predevelopment ET and potential ET.

	2000–2007 Average annual AET (acre-ft)		Predevelopment ET[1] (acre-ft)	Potential ET[2] (acre-ft)
Basin name	**Minimum**	**Maximum**		
AGUA FRIA	20,700	41,500	10,400	150,400
ARAVAIPA CANYON	7,100	15,900	4,800	53,400
BIG SANDY	14,500	25,900	18,400	115,200
BILL WILLIAMS	34,400	56,900	22,600	234,000
BONITA CREEK	2,900	7,600	500	29,700
BUTLER VALLEY	300	600	<100	5,200
CIENEGA CREEK	3,700	9,300	<100	30,200
DETRITAL VALLEY	1,200	2,200	<100	43,100
DONNELLY WASH	4,500	7,300	4,000	24,300
DOUGLAS	300	800	17,000	4,500
DOUGLAS INA	900	2,100	included in Douglas estimate	11,600
DRIPPING SPRINGS WASH	4,100	8,100	9,800	29,100
DUNCAN VALLEY	3,300	7,000	4,300	38,900
GILA BEND	24,700	29,000	35,000	91,000
HARQUAHALA INA	1,600	2,400	100	12,800
HUALAPAI VALLEY	1,800	3,200	<100	35,900
LAKE HAVASU	1,800	2,600	40,400	26,800
LAKE MOHAVE	29,900	40,300	153,800	120,200
LOWER GILA	38,000	51,700	72,300	305,400
LOWER SAN PEDRO	32,400	54,400	25,000	165,700
MCMULLEN VALLEY	1,400	2,000	100	8,600
MEADVIEW	1,900	2,500	<100	9,900
MORENCI	14,500	43,000	16,900	131,800
PARKER	25,400	44,200	233,000	175,100
PEACH SPRINGS	3,100	5,300	1,200	30,300
PHOENIX AMA	85,800	111,300	104,100	334,100
PINAL AMA	47,200	65,900	34,900	219,700
PRESCOTT AMA	4,900	9,800	2,400	30,900
RANEGRAS PLAIN	800	1,300	<100	17,100
SACRAMENTO VALLEY	5,800	9,800	1,000	83,200
SAFFORD	49,200	83,300	104,700	272,100
SALT RIVER	68,800	164,500	37,100	438,400
SAN BERNARDINO VALLEY	1,800	5,000	7,500	27,200
SAN RAFAEL	600	1,500	2,800	4,900
SAN SIMON WASH	39,900	61,600	9,600	191,700
SANTA CRUZ AMA	4,900	10,200	11,100	31,200
TIGER WASH	500	900	<100	5,400
TONTO CREEK	14,800	30,900	6,000	85,800
TUCSON AMA	29,000	62,900	53,200	233,900
UPPER HASSAYAMPA	12,500	23,400	6,000	74,600
UPPER SAN PEDRO	10,500	21,800	21,600	80,800
VERDE RIVER	63,900	123,000	65,200	352,000
WESTERN MEXICAN DRAINAGE	100	300	<100	6,300
WILLCOX	12,500	27,900	45,000	81,700
YUMA	7,400	11,900	54,000	24,900

[1] Predevelopment ET values adapted from Freethey and Anderson (1986).

[2] Potential ET values used in Basin Characteristic Model (BCM; Flint and Flint, 2007a). Values are average over 1971–2000 time period and are summed over same area as maximum and minimum ET estimates.

Table 18. Estimated groundwater inflow to and outflow from alluvial basins in Arizona for time periods indicated.

[Values in acre-ft (rounded). INA, Irrigation Non-Expansion Area; AMA, Active Manangement Area.]

Basin name	Predevelopment Conditions[1]		2005 Conditions		Data source for 2005 conditions
	IN	OUT	IN	OUT	
	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	
AGUA FRIA	0	0	0	0	Arizona Department of Water Resources, 2009c Freethey and Anderson, 1986
ARAVAIPA CANYON	0	200	0	200	Freethey and Anderson, 1986
BIG SANDY	300	1,000	300	1,000	Freethey and Anderson, 1986
BILL WILLIAMS	1,000	300	1,000	300	Freethey and Anderson, 1986
BONITA CREEK	0	6,300	0	6,300	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
BUTLER VALLEY	0	300	0	300	Freethey and Anderson, 1986
CIENEGA CREEK	0	2,300	0	2,300	Freethey and Anderson, 1986
DETRITAL VALLEY	0	700	0	700	Freethey and Anderson, 1986
DONNELLY WASH	0	100	0	100	Freethey and Anderson, 1986
DOUGLAS	0	3,000	0	1,900	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
DOUGLAS INA	Included in Douglas Basin				Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
DRIPPING SPRINGS WASH	0	200	0	200	Freethey and Anderson, 1986
DUNCAN VALLEY	12,000	200	12,000	200	Freethey and Anderson, 1986
GILA BEND	5,000	2,000	7,500	2,000	Arizona Department of Water Resources, 2009d Freethey and Anderson, 1986
HARQUAHALA INA	800	800	700	500	Arizona Department of Water Resources, 2009d Freethey and Anderson, 1986
HUALAPAI VALLEY	300	3,800	300	3,800	Freethey and Anderson, 1986
LAKE HAVASU	600	500	600	500	Freethey and Anderson, 1986
LAKE MOHAVE	0	300	0	300	Freethey and Anderson, 1986
LOWER GILA	2,000	1,000	2,000	600	Arizona Department of Water Resources, 2009d Freethey and Anderson, 1986
LOWER SAN PEDRO	1,400	0	1,400	0	Freethey and Anderson, 1986
MCMULLEN VALLEY	0	800	0	700	Freethey and Anderson, 1986
MEADVIEW	0	3,800	0	3,800	Freethey and Anderson, 1986
MORENCI	0	200	0	200	Freethey and Anderson, 1986
PARKER	400	200	900	200	Freethey and Anderson, 1986
PEACH SPRINGS	0	0	0	0	Arizona Department of Water Resources, 2009b Freethey and Anderson, 1986
PHOENIX AMA	28,300	5,000	20,500	30,500	Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Corkhill and Hill, 1990 Freihoefer and others, 2009
PINAL AMA	15,000	36,800	54,300	18,800	Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Corkhill and Hill, 1990 Freihoefer and others, 2009
PRESCOTT AMA	0	500	0	1,400	Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Timmons and Springer, 2006
RANEGRAS PLAIN	300	400	300	860	Arizona Department of Water Resources, 2009d Freethey and Anderson, 1986
SACRAMENTO VALLEY	0	4,000	0	2,000	Anning and others, 2006 Freethey and Anderson, 1986

Table 18. Estimated groundwater inflow to and outflow from alluvial basins in Arizona for time periods indicated. —Continued

[Values in acre-ft (rounded). INA, Irrigation Non-Expansion Area; AMA, Active Manangement Area.]

Basin name	Predevelopment Conditions[1]		2005 Conditions		Data source for 2005 conditions
	IN	OUT	IN	OUT	
	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	Groundwater underflow (acre-ft)	
SAFFORD	9,300	0	6,300	0	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
SALT RIVER	0	0	0	0	Arizona Department of Water Resources, 2009c Freethey and Anderson, 1986
SAN BERNARDINO VALLEY	0	500	0	500	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
SAN RAFAEL	0		0	1,000	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
SAN SIMON WASH	1,800	500	1,800	500	Arizona Department of Water Resources, 2009d Freethey and Anderson, 1986
SANTA CRUZ AMA	9,500	13,900	8,100	24,000	Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Mason and Bota, 2006 Nelson, 2007
TIGER WASH	0	0	0	0	Freethey and Anderson, 1986
TONTO CREEK	0	0	0	0	Arizona Department of Water Resources, 2009c Freethey and Anderson, 1986
TUCSON AMA	19,000	15,900	26,000	14,500	Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Mason and Bota, 2006 Nelson, 2007
UPPER HASSAYAMPA	0	500	0	500	Freethey and Anderson, 1986
UPPER SAN PEDRO	0	1,000	0	1,000	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
VERDE RIVER	2,400	0	1,400	0	Arizona Department of Water Resources, 2009a Arizona Department of Water Resources, 2009e Freethey and Anderson, 1986 Timmons and Springer, 2006
WESTERN MEXICAN DRAINAGE	0	2,400	0	2,400	Freethey and Anderson, 1986
WILLCOX	0	0	0	0	Arizona Department of Water Resources, 2009a Freethey and Anderson, 1986
YUMA	1,000	141,000	600	266,000	Freethey and Anderson, 1986 Dickinson and others, 2006 Hill, 1993

[1] Source for all predevelopment data: Freethey and Anderson (1986).

Table 19. Streamflow gages used in analysis of aquifer recharge from stream seepage.

Runoff/ seepage region[1]	Gaging station number	Gaging station name	Period of record	Drainage area, in square miles	Mean annual flow, in cubic feet per second	Gain or loss in flow above gage
2	09424447	Burro Creek nr Bagdad	1980–2008	611	95.0	gain
2	09424450	Big Sandy River nr Wikeiup	1966–2008	2,742	92.8	gain
2	09424900	Santa Maria River nr Bagdad	1966–2008	1,129	56.2	gain
2	09425500	Santa Maria River nr Alamo	1939–1966	1,439	31.0	gain
2	09426500	Bill Williams River at Planet	1927–1946	5,054	152.0	loss
2	09512500	Agua Fria River nr Mayer	1940–2008	585	22.8	gain
2	09512800	Agua Fria River nr Rock Springs	1970–2008	1,111	81.2	gain
2	09515500	Hassayampa River at box damsite nr Wickenburg	1938–1982	417	24.4	gain
2	09516500	Hassayampa River nr Morristown	1938–2008	796	26.5	gain
3	09535100	San Simon Wash nr Pisinimo	1972–2008	569	3.6	loss
3	09535300	Vamori Wash at Kom Vo	1972–2007	1,250	9.9	loss
4	09488500	Santa Rosa Wash nr Sells	1955–1980	1,782	11.0	loss
4	09489000	Santa Cruz River nr Laveen	1940–2008	8,581	18.1	loss
4	09512280	Cave Creek nr Cave Creek	1980–2008	83	6.3	gain
4	09513780	New River nr Rock Springs	1962–2008	68	12.4	gain
4	09513800	New River at New River	1961–1982	83	14.0	loss
4	09513835	New River at Bell Road nr Peoria	1968–1993	185	14.0	loss
4	09513860	Skunk Creek nr Phoenix	1960–2008	65	1.5	loss
4	09517000	Hassayampa River nr Arlington	1959–2008	1,471	62.5	loss
5	09503700	Verde River nr Paulden	1963–2008	2,150	44.7	gain
5	09504000	Verde River nr Clarkdale	1915–2008	3,124	181.0	gain
5	09504420	Oak Creek nr Sedona	1981–2008	233	81.3	gain
5	09504500	Oak Creek nr Cornville	1940–2008	355	86.5	gain
5	09506000	Verde River nr Camp Verde	1934–2008	4,645	408.0	gain
5	09507980	East Verde River nr Childs	1961–2008	331	63.4	gain
5	09508500	Verde River blw Tangle Creek abv Horseshoe Dam	1930–2008	5,494	455.0	gain
5	09510200	Sycamore Creek nr Fort McDowell	1960–2008	164	26.3	gain
6	09489100	Black River nr Maverick	1963–1982	315	141.0	gain
6	09489500	Black River nr Point of Pines	1953–2008	560	202.7	gain
6	09490500	Black River nr Fort Apache	1912–2008	1,232	392.0	gain
6	09494000	White River nr Fort Apache	1917–2008	632	164.2	gain
6	09497500	Salt River nr Chrysotile	1924–2008	2,849	646.0	gain
6	09497800	Cibeque Creek nr Chrysotile	1959–2008	295	44.0	gain
6	09497900	Cherry Creek nr Young	1963–1978	62	10.2	gain
6	09497980	Cherry Creek nr Globe	1965–2008	200	32.1	gain
6	09498500	Salt River nr Roosevelt	1910–2008	4,306	877.0	gain
6	09498800	Tonto Creek nr Gisela	1965–1975	430	120.0	gain
6	09499000	Tonto Creek abv Gun Creek nr Roosevelt	1940–2008	675	150.0	gain
7	09430500	Gila River nr Gila, NM	1928–2008	1,864	157.0	gain

Table 19. Streamflow gages used in analysis of aquifer recharge from stream seepage.—Continued

Runoff/ seepage region[1]	Gaging station number	Gaging station name	Period of record	Drainage area, in square miles	Mean annual flow, in cubic feet per second	Gain or loss in flow above gage
7	09431500	Gila River nr Redrock, NM	1930–2008	2,829	242.0	gain
7	09432000	Gila River blw Blue Creek nr Virden	1927–2008	3,203	211.0	gain
7	09442000	Gila River nr Clifton	1910–2008	4,010	202.0	gain
7	09444000	San Francisco River nr Glenwood	1927–2008	1,653	87.5	gain
7	09444500	San Francisco River at Clifton	1910–2008	2,763	219.0	gain
7	09446500	Eagle Creek nr Double Circle Ranch nr Morenci	1945–1967	377	25.9	gain
7	09447000	Eagle Creek nr Morenci	1944–2008	622	65.4	gain
7	09447800	Bonita Creek nr Morenci	1981–2008	302	11.6	gain
7	09448500	Gila River at Head of Safford Valley	1920–2008	7,896	462.0	gain
7	09457000	San Simon River nr Solomon	1931–1982	2,192	12.0	loss
7	09466500	Gila River at Calva	1929–2008	11,470	372.0	loss
7	09468500	San Carlos River nr Peridot	1930–2008	1,026	59.1	gain
7	09472000	San Pedro River nr Redington	1931–1996	2,927	44.0	loss
7	09472050	San Pedro River at Redington Bridge	1940–2008	3,096	31.6	loss
8	09482500	Santa Cruz River at Tucson	1915–1981	2,222	23.0	loss
8	09483100	Tanque Verde Creek nr Tucson	1960–1996	43	8.9	loss
8	09484500	Tanque Verde Creek at Tucson	1940–2008	219	23.7	loss
8	09484600	Pantano Wash nr Vail	1959–2008	457	6.3	gain
8	09485000	Rincon Creek nr Tucson	1952–2008	45	6.0	gain
8	09484000	Sabino Creek nr Tucson	1932–2008	35	13.4	gain
8	09485450	Pantano Wash nr Broadway	1998–2008	599	3.9	loss
8	09485700	Rillito River at Dodge	1987–2008	871	28.0	loss
8	09486000	Rillito River nr Tucson	1915–1983	918	14.0	loss
8	09486055	Rillito River nr LaCholla	1990–2008	922	13.7	loss
8	09486800	Altar Wash nr Three Points	1966–2008	463	5.4	loss
8	09470500	San Pedro River nr Palominas	1930–2008	737	30.3	gain
8	09471000	San Pedro River nr Charleston	1913–2008	1,234	53.8	gain
8	09471550	San Pedro River nr Tombstone	1967–2008	1,740	49.0	gain
8	09471800	San Pedro River nr Benson	1966–2008	2,490	35.2	loss
8	09480000	Santa Cruz River at Lochiel	1949–2008	82	3.6	gain
8	09480500	Santa Cruz River at Nogales	1931–2008	533	25.3	loss
8	09481740	Santa Cruz River at Tubac	1995–2008	1,192	33.6	loss
8	09481770	Santa Cruz River nr Amado	2003–2008	1,461	14.4	loss
8	09482000	Santa Cruz River nr Continental	1940–2008	1,682	22.7	loss
8	09484550	Cienega Creek nr Sonoita	2001–2008	198	1.9	gain
8	09537500	Whitewater Draw nr Douglas	1916–2008	1,023	9.0	loss

[1] Runoff/seepage region shown in figure 32.

Table 20. Streams with multiple gages used for analysis of aquifer recharge from stream seepage.

Runoff region[1]	River	Number of gages on stream	Gain or loss in flow between gages
Western Upland	Santa Maria River	2	gain
	Agua Fria River	2	gain
	Hassayampa River	3	gain/loss
Western Lowland	New River	3	loss
Central Upland and Northeastern Gila River	Verde River	4	gain
	Oak Creek	2	gain
	Black River	3	gain
	Salt River	2	gain
	Cherry Creek	2	gain
	Tonto Creek	2	gain
	Gila River	6	gain/loss
	San Francisco River	2	gain
	Eagle Creek	2	gain
	Tanque Verde Creek	2	loss
	Pantano Wash	2	loss
	Rillito River	3	loss
Southeastern Gila River	Santa Cruz River	7	gain/loss
	San Pedro River	6	gain/loss

[1] Runoff region shown in figure 19.

Table 21. Estimated volume of mean annual streamflow, which represents water potentially available for recharge by seepage from streams for predevelopment (pre-dam) and modern (post-dam) time periods in basins of the Southwest Alluvial Basins in Arizona.

[Although 75 streamgages were analyzed in this study, results from only 28 streamgages downstream of the 47 others are presented in this table as they integrate flow information from all upstream gages.]

Runoff region[1] (source area)	Streamflow gages in runoff basin	Seepage region[1] (seepage area)	Mean annual streamflow available for seepage[2]	
			Pre-dam (acre-ft)	Post-dam (acre-ft)
2	Big Sandy River nr Wikeiup (09424450)[3]	2	67,200	0
	Santa Maria River nr Bagdad (09424900)[3]		40,700	0
2	Hassayampa River nr Arlington (09517000)	4	45,300	45,300
	Agua Fria River nr Rock Springs (09512800)[4]		58,800	0
3	San Simon Wash nr Pisinimo (09535100)	3	2,600	2,600
	Vamori Wash at Kom Vo (09535300)		7,200	7,200
4	Cave Creek nr Cave Creek (09512280)	4	4,600	4,600
	New River at New River (09513800)		10,100	10,100
	Skunk Creek nr Phoenix (09513860)		1,100	1,100
	Santa Rosa Wash nr Sells (09488500)		8,000	8,000
5	Verde River blw Tangle Creek abv Horseshoe Dam (09508500)[5]	4	329,000	0
	Sycamore Creek nr Fort McDowell (09510200)		19,000	19,000
6	Tonto Creek abv Gun Creek nr Roosevelt (09499000)[6]	4	108,600	0
	Salt River nr Roosevelt (09498500)[6]		635,000	0
7	San Carlos River nr Peridot (09468500)[7]	4	42,800	0
	Gila River at head of Safford Valley (09448500)[7,8]		335,000	0
	Aravaipa Creek nr Mammoth (09473000)		25,200	25,200
	San Simon River nr Solomon (09457000)		8,700	0
7	San Pedro River nr Redington (09472000)		32,000	32,000
	Pantano Wash nr Vail (09484600)		4,500	4,500
	Tanque Verde Creek at Tucson (09484500)	7	17,100	17,100
	Rincon Creek nr Tucson (09485000)	7	4,400	4,400
	Sabino Creek nr Tucson (09484000)		9,700	9,700
	Santa Cruz River at Tucson (09482500)		16,700	16,700
8	San Pedro River nr Charleston (09471000)	8	38,900	38,900
	Whitewater Draw nr Douglas (09537500)		6,500	6,500
	Santa Cruz River nr Nogales (09480500)		18,300	18,300
	Altar Wash nr Three Points (09486800)		3,900	3,900

[1] Runoff and seepage regions shown in figure 32.

[2] The mean annual volumes of streamflow are from measured flows at gaging stations. These values represent the maximum amount of water available for seepage downstream of the gage.

[3] Streamflow is now stored in Alamo Lake (Alamo Dam built in 1968).

[4] Streamflow is now stored in Lake Pleasant (Waddell Dam built in 1920s and raised in 1992).

[5] Streamflow is now stored in Horseshoe Reservoir (Horseshoe dam built in 1911).

[6] Streamflow is now stored in Theodore Roosevelt Lake (Roosevelt Dam built in 1911).

[7] Streamflow is now stored in San Carlos Reservoir (Coolidge dam built in 1928).

[8] Runoff in the upper Gila basin includes runoff from the Morenci and Bonita Creek basins in Arizona and the upper Gila basin in New Mexico. Runoff becomes seepage in the Safford north basin and the Phoenix AMA basin.

Table 22. Volumes of mean annual streamflow available for recharge by seepage from streams in runoff regions of the Southwest Alluvial Basins in Arizona.

Runoff region[1] (source area)	Seepage region[1] (seepage area)	Mean annual streamflow available for seepage[2]	
		Pre-dam (acre-ft)	Post-dam (acre-ft)
2	2 (lower watershed)	107,900	0
2	4	52,050	45,300
5 and 6	4	1,091,600	19,000
7[3]	4	411,700	25,200

[1] Runoff and seepage regions shown in figure 32. In the internal drainages of regions 1, 3, 4, and 8, much of the streamflow available for seepage is not measured by streamgages and is thus not summarized in this table.

[2] The mean annual volumes of streamflow are from measured flows at gaging stations. These values represent the maximum amount of water available for seepage downstream of the gage.

[3] Presumes most of the flow measured by gage 09448500 on the Gila River and flow measured by three tributaries (table 21) flows through the region and then seeps into region 4 downstream.

Table 23. Estimates of predevelopment groundwater recharge from and discharge to streams in the Southwest Alluvial Basins of Arizona. Estimates adapted from SWAB-RASA studies (Freethey and Anderson, 1986).

Basin name	Predevelopment groundwater recharge from streamflow	Predevelopment groundwater discharge to streamflow
	acre-ft per year	acre-ft per year
Agua Fria	12,880	4,275
Aravaipa Canyon	0	2,000
Big Sandy	0	2,200
Bill Williams	1,000	9,800
Bonita Creek	235	2,115
Butler Valley	0	0
Cienega Creek	0	8,500
Detrital Valley	0	0
Donnelly Wash	900	0
Douglas	0	2,000
Douglas INA	estimates included in Douglas Basin	
Dripping Springs Wash	7,000	0
Duncan Valley	0	3,250
Gila Bend	31,200	0
Harquahala INA	0	0
Hualapai Valley	0	0
Lake Havasu	37,403	0
Lake Mohave	161,550	0
Lower Gila	128,745	0
Lower San Pedro	4,600	0
McMullen Valley	0	0
Meadview	0	0
Morenci	2,528	19,280
Parker	232,625	0
Peach Springs	0	0
Phoenix AMA	73,730	0
Pinal AMA	21,260	0
Prescott AMA	0	2,225
Ranegras Plain	0	0
Sacramento Valley	8,563	0
Safford	45,470	0
Salt River	2,084	160,220
San Bernardino Valley	0	1,000
San Rafael	175	0
San Simon Wash	0	0
Santa Cruz AMA	700	0
Tiger Wash	0	0
Tonto Creek	0	17,040
Tucson AMA	7,625	0
Upper Hassayampa	0	1,500
Upper San Pedro	1,600	7,000
Verde River	4,056	60,300
Western Mexican Drainage	0	0
Willcox	0	0
Yuma	21,775	0

Table 24. Estimated annual groundwater and surface-water withdrawals for irrigation in alluvial basins in Arizona where data are available for time periods indicated.

[Values in acre-ft (rounded). INA, Irrigation Non-Expansion Area; AMA, Active Manangement Area; < less than; ≥ greater than or equal to; NR, not reported.]

Basin name	1980 Groundwater withdrawals (acre-ft)	1980 Surface-water withdrawals (acre-ft)	1980 Total irrigation withdrawals (acre-ft)	2005 Groundwater withdrawals (acre-ft)	2005 Surface-water withdrawals (acre-ft)	2005 Total irrigation withdrawals (acre-ft)
Agua Fria	1,500	NR	≥1,500	1,400	NR	≥1,400
Aravaipa Canyon	<1,000	<1,000	<1,000	<1,000	<1,000	<1,000
Bill Williams Wash	17,000	NR	≥17,000	5,400	NR	≥5,400
Butler Valley	3,400	NR	≥3,400	9,800	NR	≥9,800
Cienega Creek	<1,000	NR	<1,000	<1,000	NR	<1,000
Douglas[1]	87,000	NR	≥87,000	40,500	NR	≥40,500
Duncan Valley	20,500	16,000	36,500	7,200	14,500	22,000
Gila Bend	273,000	102,000	375,000	287,000	55,500	343,000
Harquahala INA	110,000	NR	≥110,000	43,500	44,500	88,000
Lake Mohave	14,500	47,000	61,500	26,000	72,500	98,500
Lower Gila	429,000	328,000	757,000	118,000	349,000	467,000
Lower San Pedro	21,500	<1,000	<22,400	10,000	<1,000	<11,000
McMullen Valley	119,000	NR	≥119,000	81,000	NR	≥81,000
Parker	<1,000	594,000	<595,000	<1,000	614,000	<615000
Phoenix AMA	908,000	601,000	1,509,000	354,000	632,000	986,000
Pinal AMA	830,000	276,000	1,106,000	370,000	584,000	954,000
Prescott AMA	5,200	3,200	8,400	2,100	1,200	3,300
Ranegras Plain	10,500	NR	≥10,500	27,500	NR	≥27,500
Safford	176,000	86,000	262,000	90,500	103,000	194,000
Salt River	<1,000	6,000	<7,000	<1,000	<1,000	<1,000
San Simon Wash	3,500	NR	≥3,500	3,900	NR	≥3,900
Santa Cruz AMA	7,500	NR	≥7,500	12,000	NR	≥12,000
Tonto Creek	<1,000	<1,000	<2,000	<1,000	<1,000	<1,000
Tucson AMA	117,000	<1,000	<118,000	68,500	41,000	110,000
Upper San Pedro	13,500	4,300	18,000	14,500	2,300	17,000
Verde River	9,000	16,000	25,000	11,000	18,000	29,000
Willcox	199,000	NR	≥199,000	182,000	NR	≥182,000
Yuma	239,000	689,000	928,000	96,000	729,000	825,000

[1] Withdrawal values include withdrawals from Douglas INA.

Table 25. Estimated annual groundwater withdrawals for public supply for alluvial basins in Arizona for time periods indicated.

[Values in acre-ft (rounded). INA, Irrigation Non-Expansion Area; AMA, Active Manangement Area; < less than.]

Basin name	1980 Public supply groundwater withdrawals (acre-ft)	2005 Public supply groundwater withdrawals (acre-ft)
AGUA FRIA	1,400	1,800
ARAVAIPA CANYON	<300	<300
BIG SANDY	<300	<300
BILL WILLIAMS	500	800
BONITA CREEK	2,700	3,300
BUTLER VALLEY	<300	<300
CIENEGA CREEK	500	600
DETRITAL VALLEY	<300	<300
DONNELLY WASH	<300	<300
DOUGLAS[1]	5,400	5,300
DRIPPING SPRINGS WASH	<300	<300
DUNCAN VALLEY	600	600
GILA BEND	800	800
HARQUAHALA INA	<300	<300
HUALAPAI VALLEY	4,800	9,100
LAKE HAVASU	13,000	13,500
LAKE MOHAVE	6,000	21,000
LOWER GILA	1,800	1,700
LOWER SAN PEDRO	3,000	2,300
MCMULLEN VALLEY	<300	500
MEADVIEW	<300	<300
MORENCI	1,000	1,700
PARKER	3,000	3,800
PEACH SPRINGS	<300	400
PHOENIX AMA	264,000	226,000
PINAL AMA	11,500	39,500
PRESCOTT AMA	4,600	14,600
RANEGRAS PLAIN	<300	400
SACRAMENTO VALLEY	1,000	2,300
SAFFORD	3,000	3,500
SALT RIVER	5,000	4,100
SAN BERNARDINO VALLEY	<300	<300
SAN RAFAEL	<300	<300
SAN SIMON WASH	900	1,000
SANTA CRUZ AMA	2,500	9,000
TIGER WASH	<300	<300
TONTO CREEK	1,600	2,500
TUCSON AMA	103,000	104,000
UPPER HASSAYAMPA	2,200	2,500
UPPER SAN PEDRO	15,000	17,500
VERDE RIVER	10,000	15,500
WESTERN MEXICAN DRAINAGE	<300	<300
WILLCOX	2,000	2,800
YUMA	8,600	13,500

[1] Withdrawal values include withdrawals from Douglas INA.

Table 26. Irrigation system efficiencies assumed for the Southwest Alluvial Basins study area.

Irrigation system type	Efficiency[1]
Drip	90%
Sprinkler and Center Pivot	80%
Flood	60%

[1] S. Tadayon, oral commun., 2009.

Table 27. Estimated annual recharge from irrigation in alluvial basins in Arizona for time periods indicated.

[Values in acre-ft (rounded); INA, Irrigation Non-Expansion Area; AMA, Active Manangement Area; < , less than.]

Basin name	1980 Irrigation incidental recharge (acre-ft)	2005 Irrigation incidental recharge (acre-ft)
Agua Fria	<1,000	<1,000
Aravaipa Canyon	<1,000	<1,000
Bill Williams Wash	5,100	2,200
Butler Valley	1,400	2,000
Cienega Creek	<1,000	<1,000
Douglas[1]	22,000	8,500
Duncan Valley	14,500	8,500
Gila Bend	121,000	137,000
Harquahala INA	37,500	31,000
Lake Mohave	27,000	39,500
Lower Gila	19,000	22,500
Lower San Pedro	9,000	2,400
McMullen Valley	40,500	27,500
Parker	238,000	258,000
Phoenix AMA	499,000	347,000
Pinal AMA	442,000	394,000
Prescott AMA	3,400	1,700
Ranegras Plain	2,100	2,800
Safford	105,000	74,000
Salt River	1,400	<1,000
San Simon Wash	1,400	1,600
Santa Cruz AMA	3,000	5,000
Tonto Creek	<1,000	<1,000
Tucson AMA	46,500	37,500
Upper San Pedro	6,200	4,900
Verde River	10,000	11,000
Willcox	66,000	41,500
Yuma	230,000	169,000

[1] Includes incidental recharge from Douglas INA.

Table 28. Estimated annual recharge from treated effluent in alluvial basins in Arizona for 2005.

[AMA, Active Manangement Area; < , less than.]

Basin name	2005 Estimated recharged effluent (acre-ft)	Data source
LAKE HAVASU	600	Arizona Department of Water Resources[1]
LAKE MOHAVE	1,100	Arizona Department of Water Resources[1]
LOWER SAN PEDRO	<300	Arizona Department of Water Resources[1]
PARKER	400	Arizona Department of Water Resources[1]
PEACH SPRINGS	<300	Arizona Department of Water Resources[1]
PHOENIX AMA	34,000	Arizona Department of Water Resources[1]
PINAL AMA	4,000	Arizona Department of Water Resources[1]
PRESCOTT AMA	2,200	Arizona Department of Water Resources[1], City of Prescott (2007)
SALT RIVER	<300	Arizona Department of Water Resources[1]
SANTA CRUZ AMA	<300	Arizona Department of Water Resources[1], Pima County (2006)
TUCSON AMA	48,500	Arizona Department of Water Resources[1], Pima County (2006)
UPPER HASSAYAMPA	<300	Arizona Department of Water Resources[1]
UPPER SAN PEDRO	3,000	Arizona Department of Water Resources[1], Upper San Pedro Partnership (2006)
VERDE RIVER	1,100	Arizona Department of Water Resources[1]
YUMA	600	Arizona Department of Water Resources[1]

[1] K. M. Lacroix, written comun., 2009.

Table 29. Estimated change in groundwater storage since predevelopment times for the most developed basins in the Southwest Alluvial Basins study area.

[Storage change estimate does not include loss of storage from land subsidence. Negative values represent removal of groundwater from aquifer storage. Estimation method based on water-level change over period of development and assumed storage coefficients.]

Basin name	Storage change (acre-ft)
BUTLER VALLEY	-159,000
DOUGLAS	-92,000
DOUGLAS INA	-1,622,000
HARQUAHALA INA	-1,984,000
LOWER SAN PEDRO	-380,000
MCMULLEN VALLEY	-4,413,000
PHOENIX AMA	-30,250,000
PINAL AMA	-11,047,000
PRESCOTT AMA	-899,000
RANEGRAS PLAIN	-993,000
SAFFORD	-12,089,000
SANTA CRUZ AMA	-66,000
TUCSON AMA	-5,317,000
UPPER SAN PEDRO	-461,000
WILLCOX	-4,691,000

Produced in the Menlo Park Publishing Service Center, California
Manuscript approved for publication May 12, 2011
Text edited by Peter Stauffer
Layout and design by Judy Weathers

Tillman and others—**Water Availability and Use Pilot: Methods Development for a Regional Assessment of Groundwater Availability, Southwest Alluvial Basins, Arizona**—Scientific Investigations Report 2011-5071