Ground-Water Recharge in the Arid and Semiarid Southwestern United States — Climatic and Geologic Framework

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Abstract

Ground-water recharge in the arid and semiarid southwestern United States results from the complex interplay of climate, geology, and vegetation across widely ranging spatial and temporal scales. Present-day recharge tends to be narrowly focused in time and space. Widespread water-table declines accompanied agricultural development during the twentieth century, demonstrating that sustainable ground-water supplies are not guaranteed when part of the extracted resource represents paleorecharge. Climatic controls on ground-water recharge range from seasonal cycles of summer monsoonal and winter frontal storms to multimillennial cycles of glacial and interglacial periods. Precipitation patterns reflect global-scale interactions among the oceans, atmosphere, and continents. Large-scale climatic influences associated with El Niño and Pacific Decadal Oscillations strongly but irregularly control weather in the study area, so that year-to-year variations in precipitation and ground-water recharge are large and difficult to predict. Proxy data indicate geologically recent periods of multidecadal droughts unlike any in the modern instrumental record. Anthropogenically induced climate change likely will reduce ground-water recharge through diminished snowpack at higher elevations, and perhaps through increased drought. Future changes in El Niño and monsoonal patterns, both crucial to precipitation in the study area, are highly uncertain in current models. Land-use modifications influence ground-water recharge directly through vegetation, irrigation, and impermeable area, and indirectly through climate change. High ranges bounding the study area—the San Bernadino Mountains and Sierra Nevada to the west, and the Wasatch and southern Colorado Rocky Mountains to the east—provide external geologic controls on ground-water recharge. Internal geologic controls stem from tectonic processes that led to numerous, variably connected alluvial-filled basins, exposure of extensive Paleozoic aquifers in mountainous recharge areas, and distinct modes of recharge in the Colorado Plateau and Basin and Range subregions.

Introduction

The arid and semiarid southwestern United States is among the fastest growing regions in the country. Because surface-water supplies are limited, exploitation of ground water played an important part in the development of agricultural and urban areas during the twentieth century. Ground-water pumpage in large areas grew to exceed rates of natural recharge starting in the midcentury, revealing effects of overexploitation. These effects included land subsidence, loss of springs and riparian habitat, and declining levels and quality of ground water (Alley and others, 1999; Galloway and others, 1999; Leake and others, 2000).

The current study area comprises about a million square kilometers of Arizona, California, Nevada, New Mexico, Utah, and small parts of Colorado, Idaho, and Oregon (fig. 1). The region is arid to semiarid, except for localized wetter areas in the mountains, and it is bounded on the west by the Sierra Nevada and San Bernadino Mountains, on the east by the Wasatch and southern Rocky Mountains, on the north by the south rim of the upper Snake River drainage, and on the south by the international boundary with Mexico. Hyperarid conditions occur in Imperial Valley and Death Valley of California, and in the Yuma Basin of southwestern Arizona. Relatively wet conditions on the east and west bound the relatively dry region comprising the study area.

Population and total water use have trended upward since the southwestern states were opened for development. Somewhat surprisingly, the fraction of water derived from aquifers started declining in the 1970s (Konieczki and Heilman, 2004). A review of water-use trends between 1950 and 2000 shows that, while agriculture still consumed the largest portion of ground water in study-area states, the fraction of ground-water withdrawals for agriculture declined from 94 percent in 1950 to 80 percent in 2000.

Census data show continuing population growth throughout the study area. During the most recent period for which county-level estimates are available—April 1, 2000, to July1, 2005—the total population in the study area grew 16.5 percent, equivalent to an annual growth rate of 3.0 percent. This rate exceeds the growth rate of the overall U.S. population by a factor of three (fig. 2). Counties with the highest rates of growth during the five-year period include Lyon County, Nevada (greater Reno-Carson City area, 38 percent), Washington County, Utah (Saint George area, 32 percent), Pinal County, Arizona (greater Phoenix area, 28 percent), Riverside

County, California (interior southern California, 26 percent), Clark County, Nevada (Las Vegas area, 24 percent), and Sandoval County, New Mexico (greater Albuquerque area, 19 percent; U.S. Census Bureau, 2006). Historical declines in ground-water levels largely mirror these centers of population and agricultural growth (fig. 3).

Purpose and Scope

Subsequent chapters in this professional paper present (first) a regional analysis of ground-water recharge across the entire study area (chapter B) followed by individual case studies representing different subareas of the geographically diverse region (chapters C–K). The regional analysis includes detailed hydrologic modeling within the framework of a high-resolution geographic-information system. Results from the regional analysis are used to explore both the distribution of ground-water recharge for mean climatic conditions as well as the influence of two climatic patterns—the El Niño-Southern Oscillation and Pacific Decadal Oscillation—that impart a high degree of variability to the hydrologic cycle. Individual case studies in chapters C–K employ a variety of geophysical and geochemical techniques to investigate recharge processes in different geographic subareas, and to relate these processes to local geologic and climatic conditions. All of the case studies made use of naturally occurring tracers to quantify recharge.

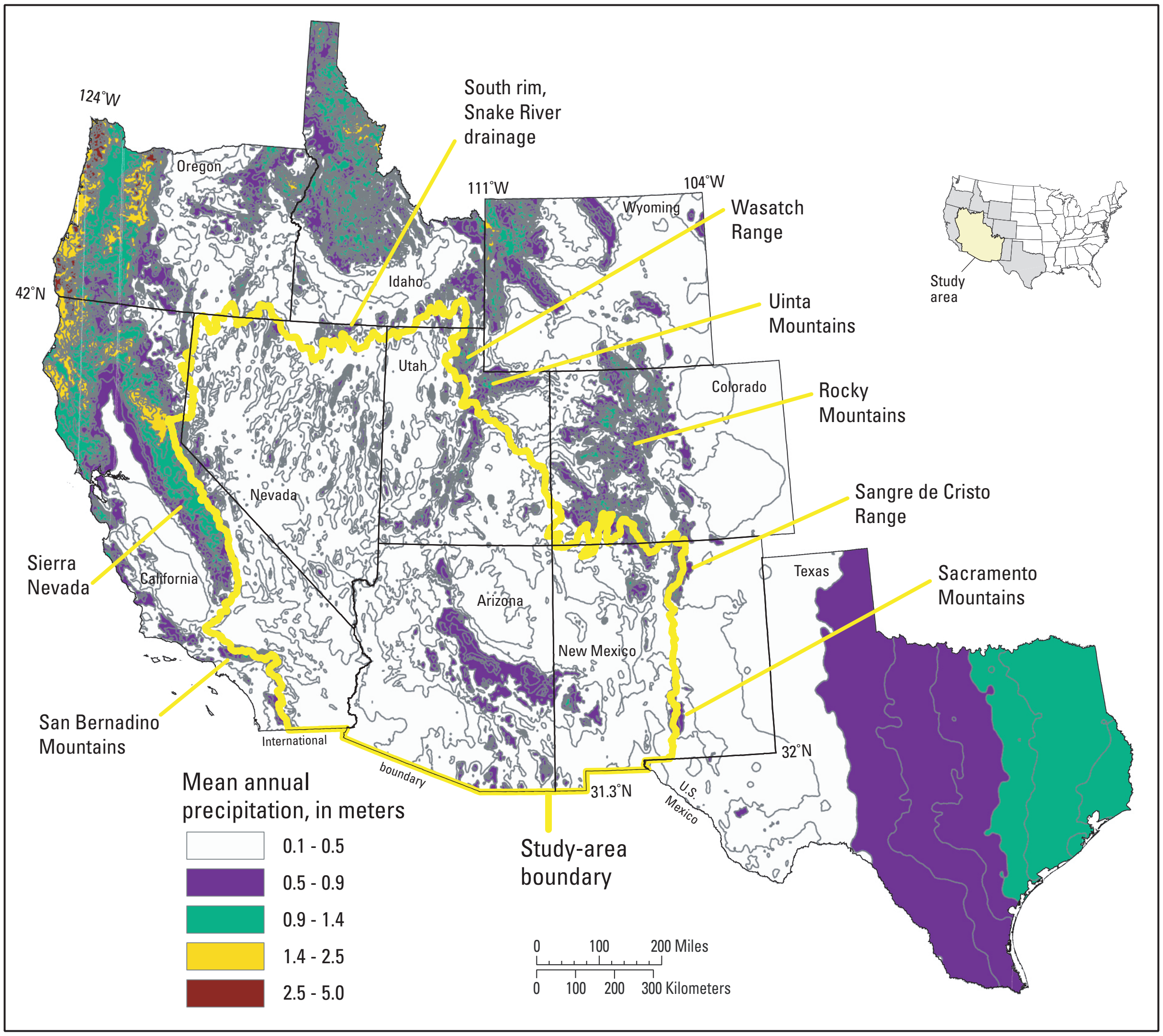

Figure 1. The arid and semiarid southwestern U.S. study area is an interior continental region characterized by generally low precipitation. Mean annual precipitation estimates in the figure were generated with the PRISM (precipitation-elevation regressions on independent slopes) model (Daly and others, 1994) on the basis of 1961–1990 monthly means at NOAA Cooperative Weather Station sites, USDA SNOTEL sites, and selected state stations. Data-poor regions were supplemented by stations with at least 20 years of record. The PRISM model accounts for orographic position, including aspect. From http://www.ocs.orst.edu/prism/state_products/ maps.phtml (last accessed May 25, 2006).

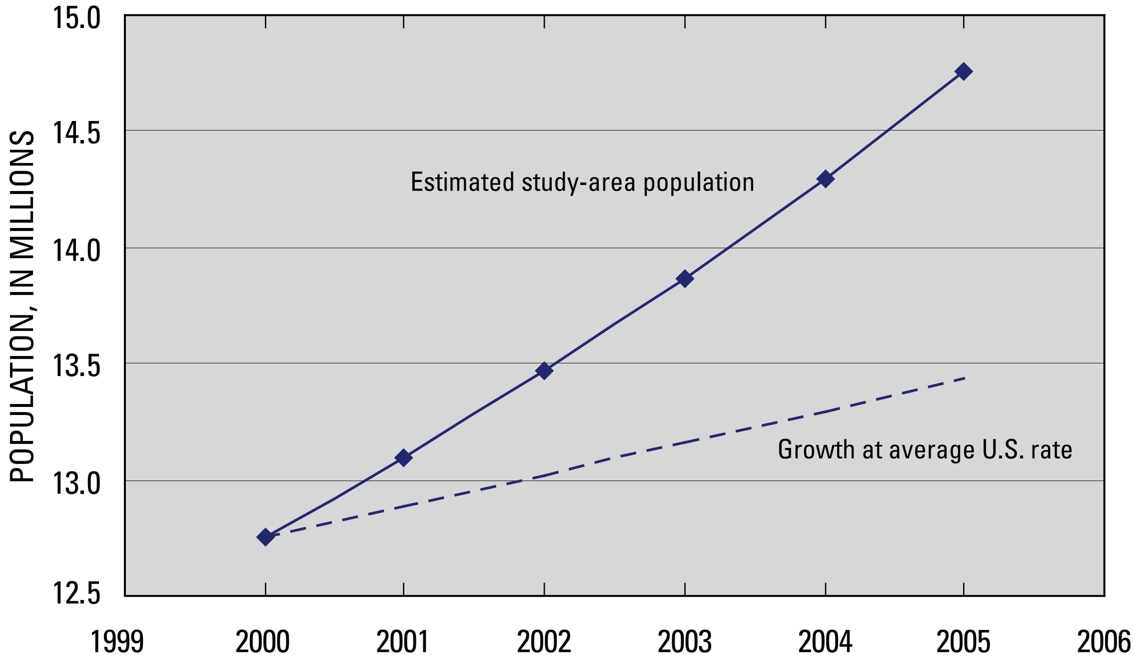

Figure 2. Estimated population of the arid and semiarid southwestern U.S., 2000–2005. Compiled from county-level estimates (U.S. Census Bureau, 2006). Points represent the sum of population estimates for counties having at least half their acerage within the study-area boundary. Dashed line shows theoretical growth at the average rate for the entire United States during the same time period.

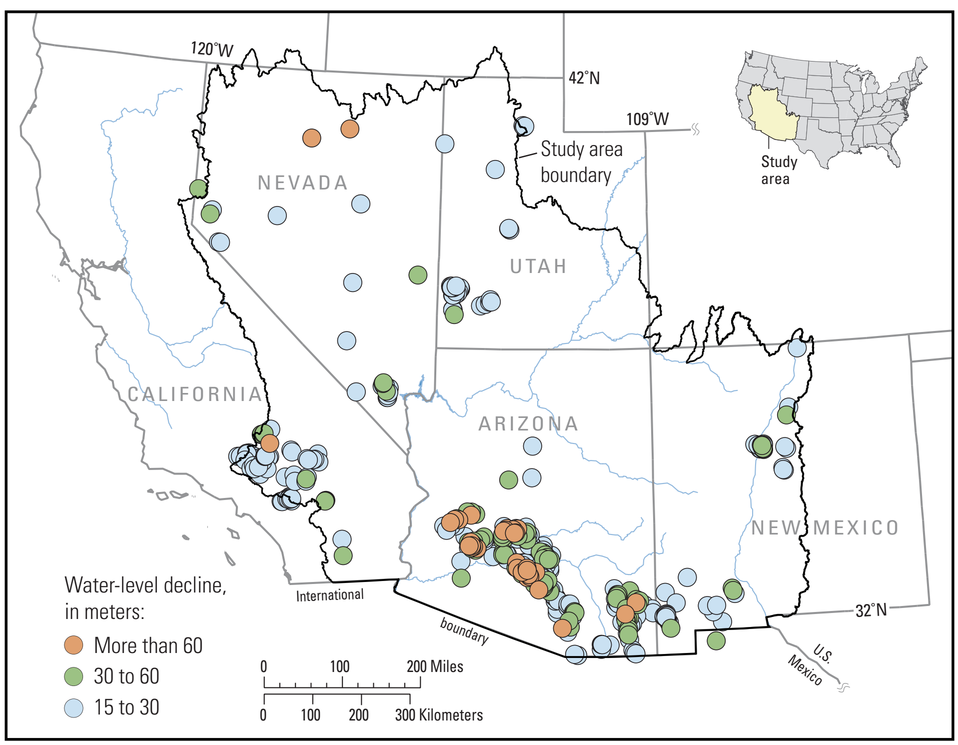

Figure 3. Historic water-level declines in producing aquifers of the arid and semiarid southwestern United States. Water levels have recovered in some areas in response to reduced pumping, optimization, and other management measures. Modified from Leake and others (2000) and Bartolino (2003).

Thermal and geophysical techniques that were developed in the course of the studies are presented in the appendices.

The purpose of this chapter is to provide an overview of climatic and geologic controls on ground-water recharge in the study area. Vegetative and land-use controls also are discussed. Controls on recharge involve a wide range of time scales, from seasonal fluctuations to multimillennial cycles of glaciation and deglaciation. The pluvial periods responsible for much of the ground-water resource in parts of the study area are associated with the growth of massive ice sheets north of the study area. Rates of ground-water recharge during pluvial periods were as much as an order of magnitude higher than at present.

Climatic Framework of Ground-Water Recharge

Mean Circulation, Storms, and Seasonality

The characteristic aridity of the study area results primarily from global circulation patterns and topographic effects. Average atmospheric circulation is roughly aligned with latitude, as manifested most clearly in the tropics (Peixoto and Oort, 1992). Preferential solar heating of equatorial regions with planetary rotation gives rise to Hadley cells, which straddle the intertropical convergence zone (ITCZ). Surface air in the Hadley cells moves obliquely toward the ITCZ, picking up moisture from tropical oceans before rising aloft. Rising air cools by expansion, creating copious "signature" clouds, before diverging poleward. Moisture-depleted air returns earthward at about 30° north and south latitude. Subsiding air warms by compression, reducing relative humidity. Earth’s nonpolar deserts, including the study area, are located within zones of descending dry air at the poleward limits of Hadley cells.

The transport of heat, momentum, and water vapor in the midlatitudes is largely through the emergent action of cyclones, fronts, meandering jets, and planetary waves (Martin, 2006). Nevertheless, winds in the extratropics tend to be westerly. Storms in the study area usually arrive from the Pacific Ocean—particularly in winter, when the area receives most of its precipitation from large-scale frontal systems. In summer, the westerlies weaken. Summer storms form mostly in response to thermally and topographically driven breezes fed by tropical and subtropical moisture entering the region in brief bursts. This general picture of moisture transport is irregularly but recurrently disrupted by storm-track shifts and tropical feeds associated with El Niño-Southern Oscillations and other large-scale interactions between the oceans and atmosphere (Liu and Alexander, 2007).

Moving inland, air masses pass over mountain ranges, losing moisture from orographic lifting. With respect to prevailing storm tracks, the study area is in the rain shadow of its bounding ranges.

Topographic feedback can induce and amplify instabilities. The interaction of prevailing westerlies with the crest of the Sierra Nevada generates cyclones that, given sufficient humidity, bring modest but ecologically critical quantities of rain to the eastern Great Basin in spring and fall (Houghton, 1969).

Large-scale horizontal atmospheric transport is unstable. Storms form at the boundaries of contrasting air masses, which reorganize the air masses to steepen frontal boundaries. The broad band of westerly winds in the midlatitudes, especially over the North Pacific, steers atmospheric disturbances into or around the study area. In summer, an area of persistent high pressure forms west of the study area, at about 30–40° north latitude and 140–150° west longitude. Clockwise rotation around this high-pressure area deflects eastward-moving storms north of the study area. In winter, the high-pressure area weakens and shifts southward. While most storms still miss the study area, their trajectories dip southward, imparting a strong winter-precipitation signal to regional climate. Storms originating in the north Pacific increase in frequency and intensity, as a persistent area of low-pressure near the Aleutian Islands deepens in winter (Houghton, 1969).

Combined with planetary rotation and redistribution of heat, long-range momentum transport gives rise to jet streams in the lower stratosphere (Baldwin and others, 2007). Recent work has focused on a different set of jet streams that form in the lower troposphere, about 0.5 to 2 km above sea level (Ralph and others, 2006). These low-level jets feed narrow plumes of tropical and subtropical moisture to winter storms affecting the study area. These “atmospheric rivers” provide the bulk of precipitation to many of the wettest storms (Kerr, 2006).

Preferential heating of the continent relative to the ocean in summer induces onshore shifts in low-altitude winds. This summer monsoon feeds tropical moisture to convective afternoon thunderstorms formed by thermal updrafts over topographic highs. Monsoonal precipitation often dominates in the southern and eastern portions of the study area.

The Arizona monsoon that affects the study area represents the highly variable northernmost fringe of the much larger, North American Monsoon, centered in northern Mexico (Douglas and others, 1993). Most of the monsoonal moisture reaching the study area comes from the tropical Pacific, although the Gulf of Mexico contributes as well (Hales, 1973; Michaud and others, 1995; Diem and Brown, 2006). The Gulf of California forms a topographic corridor that channels monsoonal “surges” across the southwestern boundary of the study area (Hales, 1972; Brenner, 1974). Monsoonal transport is characterized by gentle breezes in the lower troposphere (Bordoni and others, 2004). Occasionally the transport gains upper-level support, resulting in rapid movement of large quantities of moisture into the study area. Figure 4 shows a monsoonal event that delivered torrential rain to the southeastern part of the study area in 2006 (Magirl and others, 2007). Monsoonal events can deliver precipitation farther west or north than in the selected example, or to nearly the entire study area at once.

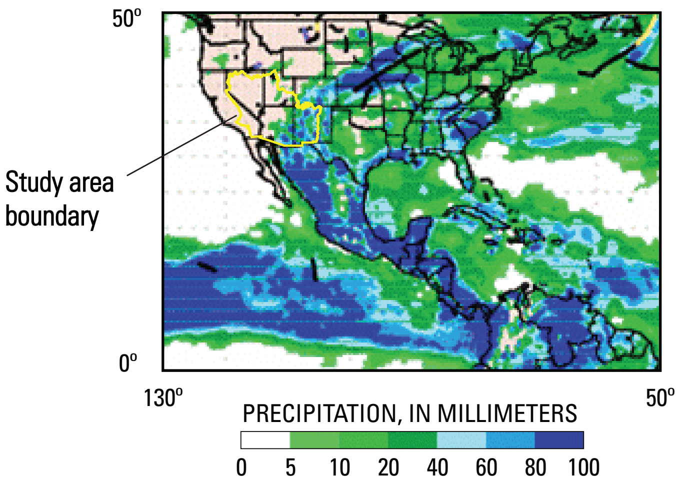

Figure 4. Monsoonal conditions bring rain to the arid and semiarid southwestern U.S. in summer. Example shows total rainfall during August 1–10, 2006, a period of exceptionally heavy monsoonal storm activity. Image derived from National Weather Service, Climate Prediction Center, storm track assessment for August 2006 (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/stormtracks/NHA_200608_full.gif, last accessed October 24, 2006).

The main sources of atmospheric moisture reaching the study area are the tropical and subtropical oceans in summer and the tropical through North Pacific Ocean in winter. Although oceans provide the primary reservoir for atmospheric water vapor, soil moisture represents a secondary reservoir that can add persistence to wet periods by supplying water through evapotranspiration (Entekhabi and others, 1996). Work in the Sahel, the southern border of the Sahara Desert, suggests that soil-moisture and evapotranspiration gradients actively modify surface winds in monsoonally affected arid and semi-arid regions (Taylor and others, 2007).

Walker Circulation, El Niño-Southern Oscillation, and Pacific Decadal Oscillation

Superimposed on seasonal changes in precipitation are longer-acting processes that strongly affect the study area. Free oscillations of the coupled ocean-atmosphere system, known as El Niño-Southern Oscillation (ENSO), produce irregular three-to-seven year cycles in the location of warm Pacific surface waters, polarity of atmospheric-pressure anomalies, and strength and direction of equatorial trade winds (Bjerknes, 1969; Philander, 1990; McPhaden and others, 2006). Under normal conditions, easterly trade winds push warm surface water to the western side of the tropical Pacific. Cool replacement water rising from the depths of the eastern Pacific diminishes the supply of atmospheric moisture to the Americas. Pooling warm water in the western equatorial Pacific is the locus of upwelling moist air, which—after cooling and losing moisture—diverges eastward in the upper troposphere before subsiding downward over the Americas to close the loop (Walker, 1924). The Walker circulation is embedded in and interrupts the Hadley-cell circulation.

The normal mode of Walker circulation results from positive feedback between ocean and atmosphere. Trade winds push warm water to the western Pacific, where rising hot air sustains the trade-wind circulation (Philander, 1990). During the El Niño (or positive) phase of the ENSO cycle, the feedback becomes negative—the trade winds weaken, the pool of warm water migrates east, and the study area becomes wetter (fig. 5). El Niño conditions bring southward adjustments of winter tracks, leading to wetter conditions—particularly in the Great Basin and Mojave Deserts (Menking and Anderson, 2003).

Enhanced precipitation during the positive phase of ENSO cycles forms part of a precipitation dipole, that is, increases in the study area are offset by decreases in the Pacific Northwest (Dettinger and others, 1998). The strength of the ENSO-induced dipole becomes weaker or stronger according to a longer-period fluctuation in the ocean-atmospheric system, the Pacific Decadal Oscillation (PDO; Mantua and others, 1997). The PDO results from multiyear persistence in North Pacific sea-surface temperatures, perhaps from large-scale circulations of surface water (Mantua and Hare, 2002). The PDO imparts decadal-scale variability to

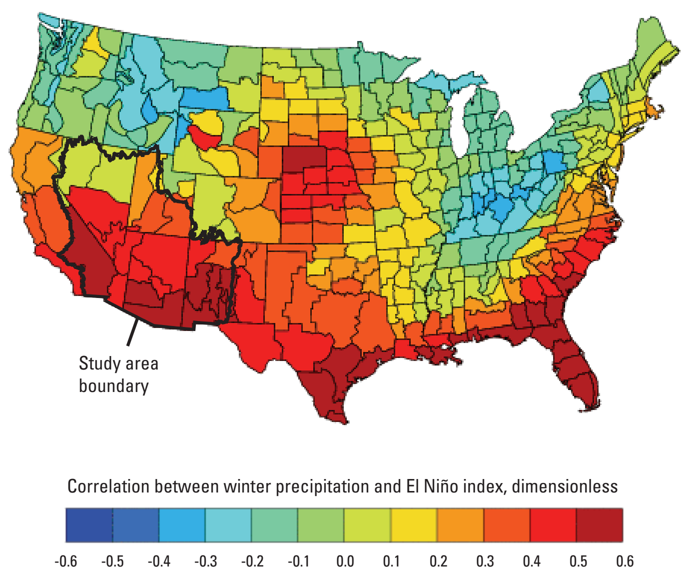

Figure 5. Correlation of the El Niño 3.4 index (positive during El Niño phases of El Niño-southern oscillation cycles) with precipitation from December through March for the period of record (1949–2006). The index is the average anomaly (departure from mean) of equatorial Pacific surface-water temperatures within a region bounded by +5 to -5 degrees latitude and -120 to -170 degrees longitude (Curtis and Adler, 2000). Data from the NOAA Climate Diagnostics Center, http://precip.gsfc.nasa.gov (last accessed December 7, 2006).

North American climatic patterns (Cayan and others, 1998; McCabe and Dettinger, 2002).

Interacting ENSO and PDO processes modulate precipitation and ground-water recharge in the study area (Flint and others, 2004; chapter B, this volume). Ground-water levels near areas of active recharge respond, in a damped fashion, to produce an integrated climatic signal (Dickinson and others, 2004). Ground-water recharge near Tucson, Ariz., during 1977–1998—a period of frequent El Niños and high values of the PDO index—was three times higher than during 1941–1957—a period of more-normal ENSO and PDO index values (Pool, 2005). Spectral analysis shows that ENSO, PDO, and the North American monsoon index modulate ground-water recharge in basins all across the study area (Hanson and others, 2006).

Natural Variability—Pleistocene Pluvials to Holocene Droughts

Glacial-Interglacial Cycles

Variability in the climate system is considerable. The largest variations relevant to ground-water recharge relate to the expansion of continental ice during glacial periods, when the interior southwestern United States became cooler and wetter than it is today (Grayson, 1993). Persistent pluvial conditions caused lakes to form and grow in inland basins. Closed-basin lakes overtopped their divides, coalescing into massive fresh-water seas that covered large parts of the study area (Feth, 1961; Benson, 2004).

The isotopic composition of ground water indicates that much of it represents paleorecharge that occurred prior to the Holocene in drier parts of the study area (Winograd and Thordarson, 1975; Benson and Klieforth, 1988; Eastoe and others, 2004; Izbicki and Michel, 2004; Plummer and others, 2004; Stonestrom and others, 2004). Numerical models of ground-water flow indicate that recharge rates were more than an order of magnitude higher during the last glacial maximum in New Mexico and likely elsewhere in the study area (Sanford and others, 2004). Midlatitude deserts elsewhere contain paleorecharge, although the timing of pluvials was not entirely synchronous on all continents (Edmunds, 1998; Scanlon and others, 2006).

Ice ages almost certainly involve orbital forcing, although changes in atmospheric carbon-dioxide levels, vegetation, and oceanic-atmospheric circulation patterns form a complex web of feedbacks that control the balance of continental ice (Gildor, 2003; Ji and others, 2006; Paillard, 2006; Roe, 2006; Montanez and others, 2007). The initiation of glacial-interglacial cycles three million years ago corresponded to the replacement of persistent El Niño conditions in the tropical Pacific by a modern ENSO mechanism—about the time the Panamanian isthmus formed an eastern limit to tropical Pacific circulation (Ravelo and others, 2006). About four-hundred thousand years ago, the cycle of glaciations and deglaciations changed from a roughly one-hundred thousand year period to a forty-thousand year period. During the last four-hundred thousand years, atmospheric levels of carbon dioxide have fluctuated between 180 and 300 parts per million, in virtual lockstep with global temperatures (Fedorov and others, 2006).

Present circulation patterns tend to steer frontal systems north of the study area, as previously discussed. Paleoclimate models and proxy data indicate that the Laurentide ice sheet split the northern hemisphere jet stream into a polar jet and a low-latitude jet, bringing abundant precipitation to the study area (Antevs, 1948; Kutzbach and Wright, 1985; COHMAP, 1988; Webb and Bartlein, 1992). In addition to storm-track modification, lower temperatures would reduce evapotranspiration rates, further increasing ground-water recharge during glacial periods.

During interglacial periods, ecological succession established xerophytes that were highly adapted for scavenging soil moisture (Walvoord and others, 2002; Walvoord and others, 2004). Vegetation is decisive in determining the near-surface water balance under conditions of high aridity (Gee and others, 1994). The presence and amount of ground-water recharge in most parts of the study area is strongly controlled by plants (Phillips and others, 2004; Scanlon, Levitt, and others, 2005; Seyfried and others, 2005; Sandvig and Phillips, 2006).

Holocene Droughts and Holocene Pluvials

Severe drought gripped the study area during 1999–2004 (chapter C). This drought was the most severe in the United States since the late 1930s and early 1940s (Phillips and Thomas, 2005; Andreadis and others, 2005). Warm, dry conditions extended far beyond the study area. The spatial extent and magnitude of temperature anomalies exceeded those during the Medieval Warm Period (roughly 800–1300 AD), which affected major parts of the Northern Hemisphere (Osborn and Briffa, 2006).

Compared with present-day conditions, large parts of the study area during the past millennium have been characterized by extended, severe droughts with minimal ground-water recharge. Occasional wetter periods with elevated recharge—though shorter and less frequent— also have occurred. Indicators of preinstrumental climate change include plant remains in packrat middens (Betancourt and others, 2000), isotopic variations in lake sediments (Benson and others, 2002), landforms in intermittently deflationary basins (Menking and Anderson, 2003), and annual growth rings in trees and speleothems (Cook and others, 2004; Rasmussen and others, 2006; Leavitt, 2007).

The frequency of drought during the twentieth century is strongly linked to oceanic-atmospheric feedbacks embodied in the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation (McCabe and others, 2004; Benson and others, 2006). Paleoclimate reconstructions based on tree-ring data for the last 1,200 years indicate that extended droughts occurred repeatedly from 900 to 1300 (Cook and others, 2004; Meko and others, 2007). This 400-year period of chronic drought generally had negative PDO index values, and it coincided with the collapse of major agricultural societies within the study area (MacDonald and Case, 2005; Benson and others, 2007).

Though less well resolved, the middle Holocene was also characterized by prolonged drought. Severe drought from 6.5 to 3.8 thousand years before present is evident in the sediments of dry lakes in the western Great Basin (Benson and others, 2002). Desiccation arrived earlier in the Estancia Basin of New Mexico, where blowouts and eolian landforms indicate that ground-water levels started dropping markedly nine thousand years ago (Menking and Anderson, 2003).

Tree-ring data for the past 1,200 years indicate the presence of several pluvial periods during the last 1,200 years. The best characterized of these is a 13-year period of wet conditions that affected the southwestern United States from 1905 to 1917 (Woodhouse and others, 2005). Also, the general climate of the study area was significantly wetter during the early to mid twentieth century than during the earlier part of the record. This trend reversed in the second half of the twentieth century when, despite moderate increases in precipitation, sharply rising temperatures contributed to increasing drought severity across the interior southwest (Andreadis and others, 2005; Andreadis and Lettenmaier, 2006).

Anthropogenic and Land-Cover Controls on Recharge

Global warming of the last few decades is projected to continue (Houghton and others, 2001, 2004; Stainforth and others, 2005; IPCC, 2007; Rahmstorf and others, 2007; Raupach and others, 2007). As currently implemented, global circulation models of climate may underpredict warming due to feedbacks produced by global carbon pools (Scheffer and others, 2006; Torn and Harte, 2006; Zimov and others, 2006; Matthews and Keith, 2007), increasing humidity in the upper troposphere (Soden and others, 2005), and model bias (Shukla and others, 2006). An expected effect of warming is intensification of the hydrologic cycle, reflecting increased heat storage and thermal gradients (Pierrehumbert, 2000; Huang, 2006). Consensus estimates from global circulation models suggest that the intensity of storms in the study area will increase, if not necessarily the total amount of precipitation, as will the frequency and severity of heat waves and droughts (Tebaldi and others, 2006; Hoerling and Eischeid, 2007; Seager and others, 2007). The recent drought, which affected southwest Asia and southern Europe in addition to the study area, corresponded to unprecedented warmth in the western Pacific in 1998-2002 (Hoerling and Kumar, 2003).

Global circulation models that successfully simulate the Aleutian low and north Pacific storm tracks, among other features, suggest that North American storm tracks could shift poleward under a wide range of projected climates (Yin, 2005; Salathé, 2006). Hadley cell enlargement is expected to cause poleward expansion of dry subtropical zones (Lu and others, 2007). However, such shifts in zonal averages produce only small changes in precipitation at mid-latitudes, where agreements between model predictions and measurements are poor (Zhang and others, 2007). The response of El Niño-Southern Oscillation to warming is far more relevant to the study area, if less clear. Models and data suggest that the Walker circulation may weaken with warming (Vecchi and others, 2006). Persistent El-Niño conditions have been predicted under several emissions scenarios (Meehl and others, 2006). The significance of these results is unclear, as close inspection shows that current models have difficulty matching historic ENSO patterns (Lin, 2007). Models of monsoonal precipitation response are likewise uncertain (Webster and others, 1998; Mo and others, 2005).

Climate change is predicted to have a large effect on water resources east of the study area (Small, 2005; Scibek and Allen, 2006; Baettig and others, 2007). The most likely change expected in the study area is a marked shift in precipitation to less snow and smaller snowpack accumulation. The effects of warmer temperatures on snowpack are already evident in earlier runoff generation (Service, 2004; Dettinger, 2005). Snowmelt is highly efficient at generating ground-water recharge, so that a shift from snow to rain will decrease recharge even if total precipitation remains the same (Earman and others, 2006).

Large-scale replacement of native vegetation by urban, suburban, and agricultural land use may have impacted ground-water recharge more than recent changes in climate (Foley and others, 2005). Construction of impermeable areas alters rainfall-runoff relations and location of infiltration (Filippone and Leake, 2005). Irrigation induces ground-water recharge (Stonestrom and others, 2004) and produces evaporative cooling over large regions (Kueppers and others, 2007). Because native vegetation is highly adapted to extracting soil moisture, its replacement by agricultural crops can reverse the direction of water flow in the unsaturated zone, inducing ground-water recharge even in regions of dryland farming (Scanlon, Reedy, and others, 2005).

Considering future climates, anthropogenic emissions may have precluded an imminent return to glacial-pluvial conditions (Crucifix and Berger, 2006; Ruddiman, 2006). Carbon-dioxide levels during the Pliocene suggest that a level of about 400 parts per million will prevent the formation of continental ice sheets in the Northern hemisphere (Sternberg, 2006). Levels of 400 parts per million are expected within ten years under all emissions scenarios (Sarmiento and Gruber, 2002).

Geologic Framework of Ground-Water Recharge

The study area has been subdivided into six geologic subregions to facilitate description of the wide range of conditions present. The areas are the Eastern Great Basin, Western Great Basin, Mojave-Colorado Desert Area, Arizona Sonoran Desert-Mexican Highland Area, Rio Grande Rift-Southwestern New Mexico, and the South-Central Colorado Plateau Area (fig. 6). These areas have been further subdivided into hydrologic units used by the U.S. Geological Survey. The 195 hydrologic units present are shown on figure 6. These units consist of one or more structural basins that have been grouped together for study and accounting purposes. The principal characteristics of the geologic regions are summarized in table 1.

The Eastern Great Basin is an area of internal drainage that receives most of its water supply from precipitation that falls along the Wasatch Front on the eastern side of the subregion. Winter snowfall accumulates in the higher mountains, and much of the annual recharge is derived from spring snowmelt. Mountains along the western and northern borders also provide additional moisture. The central part of the subregion is occupied by several large desert basins, the Great Salt Lake, the Salt Lake Desert, Sevier Desert, and the Escalante Desert. Carbonate rocks are present in much of the Eastern Great Basin, where they form mountains and underlie basin-fill sediments. The carbonate rocks generally are permeable, and relatively high rates of recharge occur in mountains where they are exposed. In some areas, this causes the recharge process to be dominated by in-place recharge in the mountains. Multibasin ground-water flow systems exist where there is a regional ground-water gradient and hydraulic continuity between basins is provided by carbonate rocks.

The Western Great Basin in many ways mirrors the Eastern Great Basin, where much of the water supply comes from precipitation that falls on the Sierra Nevada. Additional moisture is provided by several high mountain ranges along the northeastern and eastern boundaries of the subregion. As with the Eastern Great Basin, most of the annual recharge occurs during the spring snowmelt. A significant difference between the two subregions is the rain shadow that exists along the eastern margin of the Sierra Nevada. Although the eastern margin receives significant runoff from the mountains, local precipitation is much less than it would be without

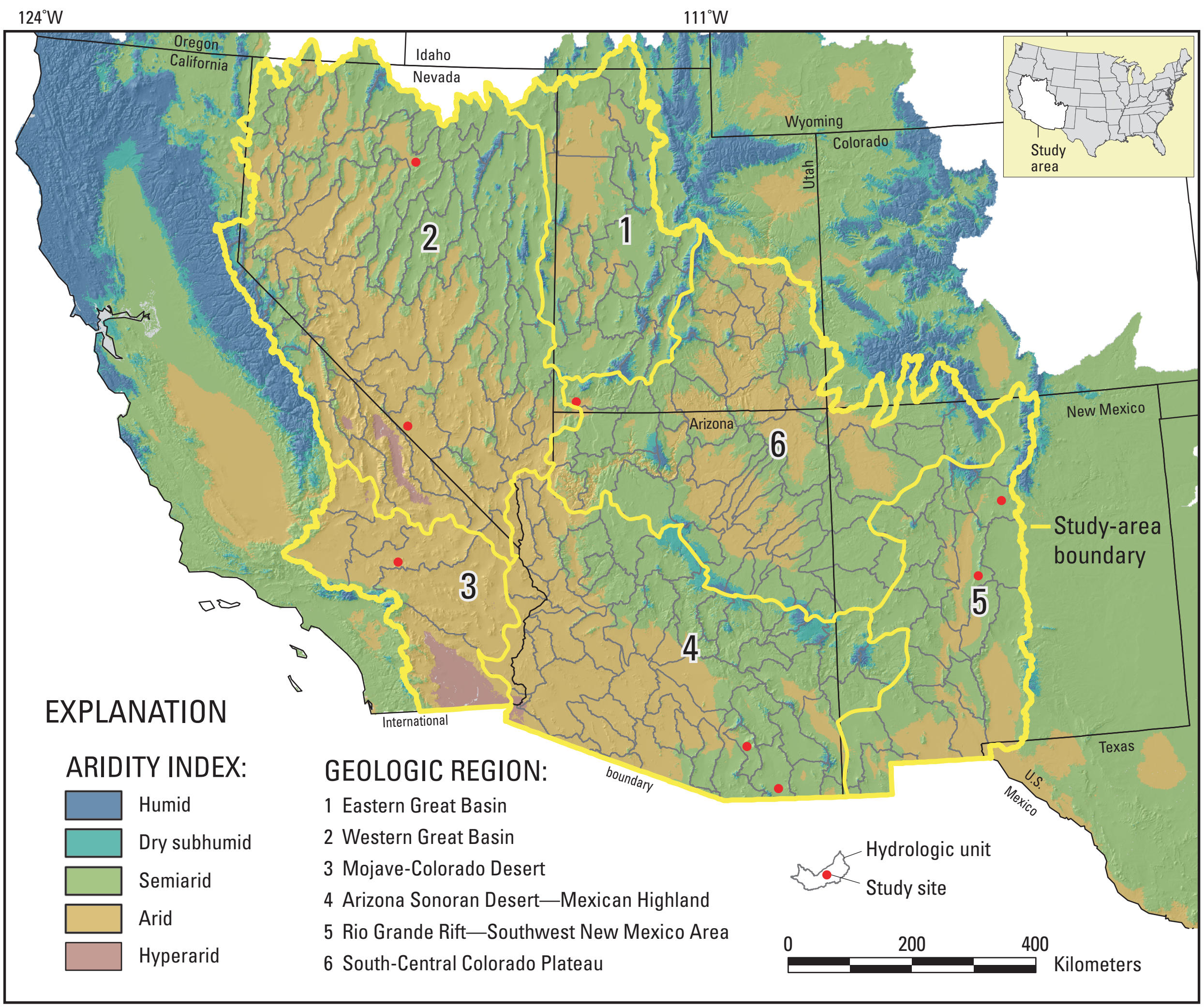

Figure 6. Geologic regions, hydrologic areas, and aridity classification for the southwestern U.S. study area. The aridity index is the ratio of mean annual precipitation to mean annual potential evapotranspiration. Index values ranging from 0 to 0.05 denote hyperarid conditions. Ranges of 0.05–0.2, 0.2–0.5, 0.5–0.65, and greater than 0.65 denote arid, semiarid, dry subhumid, and humid conditions, respectively (UNESCO, 1979).

Table 1. Principal characteristics of geologic subregions.

	Eastern Great Basin	Western Great Basin	Mojave-Colorado Desert	Arizona Sonoran Desert-Mexican Highland	Rio Grande Rift-Southwestern New Mexico	South Central Colorado Plateau
Area, in thousands of square kilometers	106	315	71	204	114	233
Climate classification and number of hydrologic units						
Hyperarid	0	1	1	0	0	0
Arid	7	25	5	24	10	19
Semiarid	12	27	0	27	10	27
Dry subhumid	0	0	0	0	0	0
Humid	0	0	0	0	0	0
Total	19	53	6	51	20	46
Drainage type and principal rivers						
Drainage type	Internal	Internal[1]	Internal	Mostly external, to Colorado River[2]	Mostly external, to Rio Grande[3]	External, to Colorado River
Principal rivers	Jordan R.[4] Logan R.[4] Sevier R.[4] Weber R.[4]	Carson R.[4] Humboldt R.[4] Owens R.[4] Truckee R.[4] Walker R.[4] Colorado R. Muddy R. Virgin R.	Mojave R.[4]	Gila R. Colorado R. Little Colorado R. Salt R.	Rio Grande	Green R. Colorado R.
Location and altitude of highest and lowest points						
Highest point and altitude, in meters	Delano Peak 3,697	Mount Whitney 4,418	San Gorgonio Mountain 3,501	Humphreys Peak 3,682	Wheeler Peak 4,011	Windom Peak 4,295
Lowest point and altitude, in meters	Great Salt Lake 1,281	Death Valley -86	Salton Sea -72	Colorado R. at the Southerly International Boundary 30	Rio Grande near El Paso, Texas 1,140	Colorado R. at Grand Canyon NP[5] 366

[1]Most areas have internal drainage; however, several areas drain to Colorado River.

[2]Most areas drain to Colorado River; however, several areas have internal drainage.

[3]Areas east of continental divide drain to Rio Grande.

[4]River flows to terminal basin.

[5]Colorado River at west boundary of Grand Canyon National Park (NP).

the rain shadow. Carbonate rocks are present in much of the eastern and southeastern part of the subregion. The western and west-central parts of the subregion are underlain mostly by volcanic, intrusive, and metamorphic rocks. Carbonate rocks are present in localized areas. The subregion has been, and still is, undergoing structural extension. This extension has resulted in a basin-and-range topography where generally north-south trending mountain ranges are separated by intervening valleys. The valleys are structural depressions that are partly filled by materials derived from the adjacent mountains. A pronounced regional topographic gradient exists in the southern part of this subregion. The valley floors in the east-central part of the subregion have altitudes of slightly more than 1,830 m. These altitudes decrease to the south and southwest to a low of 86 m below sea level on the Death Valley playa. This gradient exists in an area that is mostly underlain by carbonate rocks and has interbasin ground-water flow. Some of these areas of carbonate rock are highly permeable and readily allow recharge to occur. In these areas the recharge occurs mostly in the mountains.

The Mojave-Colorado Desert subregion occupies southern California south of Panamint and southern Owens Valleys. It is bordered on the west by the southern Sierra Nevada, the western San Bernadino Mountains, and several costal basins. Snowmelt creates substantial amounts of runoff from the two major mountain ranges. Snowmelt runoff in the remainder of the area is minor. The Mexican border, a political division, forms the southern boundary of the current study area, even though the Mojave-Colorado physiographic region extends about 80 km farther south. The western boundary of the Colorado River drainage forms the eastern boundary. The most significant mountain ranges are the southern Sierra Nevada and the San Bernadino Mountains. The Mojave River originates on the northern flank of the San Bernadino Mountains and flows to the north where it terminates at the Soda Lake Playa near the northern boundary of the subregion. Mountain ranges in the rest of the area are relatively small and have little local relief. This area is underlain mostly by intrusive, volcanic, and metamorphic rocks that do not transmit water readily. The structural basins are filled with materials derived from the nearby mountains. Consequently most recharge and ground-water flow occurs in basin-fill deposits.

The Arizona Sonoran Desert-Mexican Highlands subregion occupies the southwestern half of Arizona and includes small areas of southwestern New Mexico and southeastern California. The subregion is bordered on the north by the Colorado Plateau, on the west by the drainage divide of the Colorado River and the Mojave-Colorado Desert Area, on the south by Mexico and on the east by basins of the Rio Grande Rift-Southwestern New Mexico subregion. The subregion contains basin and range structures similar to those in the Eastern and Western Great Basins; however, their orientation differs slightly, and major basin subsidence ended 6–10 million years ago (Anderson and others, 1992, p 13). Extension remains active in the Eastern and Western Great Basins. Consequently, the basin and range topography in the Arizona Sonoran Desert-Mexican Highlands subregion is more mature than in the Eastern and Western Great Basin subregions. The structural basins are more completely filled and, overall, the local relief between valley floors and mountain crests is less. This suggests that the orographic effect that causes much of the precipitation in the higher mountains of the Eastern and Western Great Basin is less of a factor in this subregion. However, monsoonal summer rains are significant in the Arizona Sonoran Desert-Mexican Highlands subregion. These rains are triggered primarily by convective heating and are not as dependent on local relief and the orographic effect as the winter precipitation and snowmelt runoff, which provides most of the water supply in the Eastern and Western Great Basins. The Arizona Sonoran Desert-Mexican Highlands subregion is underlain mostly by intrusive, volcanic, and metamorphic rocks that do not transmit water readily. Consequently, most recharge and ground-water flow occurs in basin-fill deposits.

The Rio Grande Rift-Southwestern New Mexico subregion is along the southeastern boundary of the study area in Central New Mexico. It is bounded on the west by the South-Central Colorado Plateau subregion and the Arizona Sonoran Desert-Mexican Highlands subregion (the western boundary also corresponds roughly with the continental divide), on the south by Mexico, on the east by the Great Plains physiographic province, and on the north by the San Luis Valley. This subregion is traversed by the Rio Grande River, which flows through the down-dropped graben associated with the rift structure. Some of the hydrologic areas drain directly to the Rio Grande River, others are isolated basins. The basin fill is recharged by infiltration of runoff at or near the mountain front and by some direct infiltration of precipitation and snowmelt. Monsoonal summer rains are common in this subregion, and they supply a significant part of the annual recharge. Areas along the Rio Grande can receive recharge from or discharge water to the river depending on the relation between the water table and river stage.

The South-Central Colorado Plateau subregion includes the southwestern part of Utah, most of northern and northeastern Arizona, and the northwestern part of New Mexico. The hydrologic areas are drained externally and are part of the Colorado River drainage. This subregion differs from the others in that its most significant characteristic is a large area of relatively uniform uplift. The uplifted area has been eroded to form the canyon-plateau topography that typifies the subregion. This subregion does not contain the extensive basin-fill deposits characteristic of the other subregions. Alluvium is present as flood-plain deposits, and in some cases as valley floor deposits, but these deposits formed in a canyon or valley that is primarily an erosional feature. Recharge occurs as direct infiltration of precipitation and snowmelt, or as seepage of streamflow into joints, fractures, and pore spaces of consolidated and semiconsolidated rocks.

Evolution of the Geologic Framework

The geologic history and evolution of the arid southwest has produced a framework of igneous and metamorphic rocks, sedimentary rocks and deposits, structures, topography, and landforms that exert strong controls on the occurrence and distribution of recharge. The six subregions that comprise the study area vary in their history and in the way that the geologic framework effects the occurrence and distribution of recharge. Discussion of the evolution of the geologic framework begins in Proterozoic time when basement-rock aquitards were formed beneath most of the study area. This initial event was followed by a series of successive geologic events and processes that extend to the present. The more significant of these events are listed in table 2 (adapted from Chuang and others, 2003). Table 2 also lists the hydrogeologic consequences of the events for each of the six subregions. For any given event, the hydrogeologic consequences sometimes vary between the subregions. Major events in the evolution of the geologic framework affecting the present-day occurrence and distribution of recharge are listed below in chronological order.

Paleozoic Era

During the Paleozoic Era, spatially extensive carbonate units formed in the Eastern and Western Great Basins, and smaller carbonate units formed in the Mojave-Colorado Desert and Arizona Sonoran Desert-Mexican Highland subregions. Today these carbonates constitute regional and locally important aquifers. Extensive exposures of permeable carbonates crop out in the mountains of both Eastern and Western Great Basin subregions. Rainfall and snowmelt in the mountainous areas provides the dominant component of recharge to the carbonate aquifers in these areas.

Mesozoic Era

During the Mesozoic Era, continental sediments and sandstone aquifer units formed in the Colorado Plateau subregion. Most of the present-day recharge in the subregion occurs in the areally extensive eolian sandstone that formed during this time.

Tertiary Period

Onset of extensional faulting began in early Tertiary time in all areas except the Colorado Plateau. The extensional faulting has resulted in the basin and range topography characteristic of most of the study area. The basins have partially filled with alluvial and colluvial deposits that form the basin-fill aquifers. Most of the present-day recharge occurs to aquifers that started forming in the early-to-mid Tertiary. Recharge to the extensive Paleozoic carbonate aquifers is often through basin fill in the Eastern Great Basin. Mountain ranges that formed during Tertiary extension receive more precipitation (in the form of rain and snow) than the intervening valleys. This orographically produced precipitation produces most of the present-day recharge. Active extension continues at present in the Eastern and Western Great Basins.

Pliocene Epoch to Quaternary Period

The regional uplift and desiccation of the Colorado Plateau and integration of drainages included the formation of the Colorado, Gila, and Salt Rivers and formation of the present-day topography. There was also a period of Pleistocene pluvial conditions when lakes were formed throughout the study area, and most drainages supported perennial streams and rivers. The pluvial period ended during the Holocene Epoch, when there was widespread aridification. Playas dried and flow in streams and rivers was reduced or, in some cases, dried up. Ground-water recharge and discharge were reduced in accordance with the degree of aridification. Currently, recharge in the study area appears to be approximately in balance with the natural ground-water discharge. There is little change in ground-water storage except for the depletion caused by pumping.

Hydrogeologic Units

During the evolution of the geologic framework, a series of sedimentary, volcanic, intrusive, and metamorphic rocks was formed throughout the study area. For purposes of this study, these units have been grouped into categories with similar hydrologic properties. The five groups are (1) basin-fill/alluvium, (2) noncarbonate sedimentary rocks, (3) carbonate sedimentary rocks, (4) volcanic rocks, and (5) intrusive and metamorphic rocks. The distribution of these rocks is shown in figure 7, and their characteristics are described in table 3.

Major Aquifers

Throughout the arid and semiarid Southwest, ground water provides a substantial part of the water supply—in some places providing the sole source of water. The U.S. Geological Survey National Atlas delineates five major aquifers in the study area (fig. 8): (1) basin-fill, (2) carbonate-rock, and (3) volcanic-rock aquifers in the Great Basin subregions, (4) Colorado Plateau aquifers in the South-Central Colorado Plateau subregion, and (5) the aquifer system of the Rio Grande Rift-Southwestern New Mexico subregion (comprising mostly basin-fill aquifers).

Basin-fill aquifers are capable of storing large amounts of water that is readily supplied to wells. Basin-fill aquifers are the most common aquifers in the study area and are the dominant aquifer type in all subregions except the Colorado Plateau. Most of the pumpage in the study area is from basin-fill aquifers, and recharge occurs mainly at or near the surrounding mountain fronts. Recharge also occurs where streams flow across alluvial fans and where streams or rivers flow through valley lowlands. During sustained precipitation events, there can also be direct recharge from precipitation.

Basin and range carbonate-rock aquifers occur in the mountains and underlie basin-fill deposits in large parts of the Eastern and Western Great Basin subregions. Where carbonate rocks are present, significant recharge commonly occurs in

Table 2. Hydrogeologic framework of the arid and semiarid southwestern United States

[Adapted from Chuang and others (2003). Dashes denote regional absence or indirect manifestation only though inheritance. Bold italics indicate formation and recharge of current aquifers]

Eon, era, period, or epoch	Geologic process	Hydrologic consequence, by region					
		Eastern Great Basin	**Western Great Basin**	**Mojave-Colorado Desert**	**Arizona Sonoran Desert-Mexican Highland**	**Rio Grande Rift-Southwestern New Mexico**	**South-Central Colorado Plateau**
Proterozoic	Continental basement rocks created	Aquitards form	Aquitards form	Aquitards form	Aquitards form	Aquitards form.	Aquitards form
	Local rift basins open	—	Local ***carbonate aquifers*** form	Local ***carbonate aquifers*** form	Local ***carbonate aquifers*** form	—	Local siliclastic units form
	Continental rifting and truncation	—	Most older basement rocks obliterated	—	—	—	—
Paleozoic	Continental slope and oceanic basin deposition	—	Locally ***thick carbonate aquifers*** form	—	—	—	—
	Passive margin marine shelf deposition	***Thick carbonate aquifers*** form	Locally ***thick carbonate aquifers*** form	—	—	—	—
	Continental and shallow marine deposition	—	—	Thin ***carbonate aquifers*** form	Thin ***carbonate aquifers*** form	Thin ***carbonate aquifers*** form.	Thin ***eolian sand*** and ***carbonate aquifers*** form
	Orogenesis, chiefly contractual	—	—	—	—	—	—
	Overthrusting	Carbonate aquifers disrupted	Carbonate aquifers locally concealed	—	—	—	—
	Deposition of foreland basin wedges	Carbonate aquifers disrupted or concealed	Carbonate aquifers disrupted or concealed	—	—	—	—
	Late Paleozoic uplift, basin formation, regional desiccation	Local evaporites form	—	Local evaporites form	Local evaporites form	—	Highlands erode, basins fill with clastics; local evaporites form
Mesozoic to early Cenozoic	Contractional orogenesis	—	—	—	—	—	—
	Regional uplift, emergence, and erosion in most areas	—	—	—	—	—	—
	Overthrusting	Carbonate aquifer disrupted	Carbonate aquifer disrupted	—	—	—	—
	Arc magmatism and metamorphism	Local plutonic basement forms	Metavolcanic and plutonic basement forms	Plutonic basement forms	Volcanic and plutonic basement forms	—	—
	Orogenisis; sedimentation in foreland basins	Marine clastics deposited	Marine clastics locally deposited	Marine clastics deposited	Marine clastics deposited	—	Marine and non-marine clastics deposited
	Deposition of windblown sand sheets	Local ***sandstone aquifers*** form	—	Quartzites form	Quartzites form		Local ***sandstone aquifers*** form
	Monclinal and block uplift	Local evaporites form	—	—	—	—	Horizontal aquifers disrupted
Tertiary	Activation of transform continental margin	Sinistral faulting	Walker Lane faulting; ***basin-fill aquifers*** form	E. Calif. shear faulting; ***basin-fill aquifers*** form	—	—	Colorado Plateau rotates clockwise
	Eocene extension and calcic-alkaline magmatism	Broad alluvial basin conglomerates, lake-bed sediments, lavas, and welded tuffs form	—	—	—	—	—

Table 2. Hydrogeologic framework of the arid and semiarid southwestern United States.—Continued

Era, period, or epoch	Geologic process	Hydrologic consequence, by region					
		Eastern Great Basin	Western Great Basin	Mojave-Colorado Desert	Arizona Sonoran Desert-Mexican Highland	Rio Grande Rift-Southwestern New Mexico	South-Central Colorado Plateau
Tertiary—Continued	Oligocene-Miocene extensional faulting	Basins form; basement aquitards lifted up in core complexes; structures greatly disrupted in highly extended areas				Basins form; structures disrupted.	—
	Oligocene-Miocene nonmarine horst-and-graben faulting; basin infilling	Fanglomerates and fine-grained axial valley clastics deposited; lakebed sediments, ***landslide-breccia,*** and ***fluvial sand and gravel aquifers*** deposited. ***Bouse and Imperial aquifer***s form in Mojave and Colorado Deserts; ***Bouse aquifer*** forms in the Arizona Sonoran Desert.				Same as Great Basin; ***breccia*** and ***fluvial aquifers*** deposited	—
	Oligocene-Pliocene (chiefly Miocene) hyperextension and core complex formation	Structures broadly disrupted; crystalline rocks lifted up	Structures locally disrupted; crystalline rocks lifted up	Structures broadly disrupted; crystalline rocks lifted up	Structures broadly disrupted; crystalline rocks lifted up	—	—
	Oligocene-Miocene isolation of Colorado Plateau highland	Evaporites and ***carbonate aquifers*** form downgradient from margin	—	—	Evaporites and ***carbonate aquifers*** form down gradient from margin	—	—
	Oligocene-Miocene calcic-alkaline magmatism	Calderas form, ash deposited; ***lava and tuff aquifers*** form locally	***Lava and tuff aquifers*** form locally	—	—	—	—
	Miocene-Quaternary bimodal volcanism	***Welded tuff and basalt aquifers*** form locally	Calderas form; ***welded-tuff, ash, and basalt aquifers*** form	***Basalt aquifers*** form locally	***Basalt aquifers*** form locally	***Welded-tuff, ash, and basalt aquifers*** form	***Basalt aquifers*** form
	Miocene-Quaternary Yellowstone hot-spot and northern Nevada Rift activation	Widespread ash units form	Snake River flood basalts form	—	—	—	—
Pliocene to Quaternary	Tectonic extension and faulting	Lake deposits, ***fanglomerate and fluvial aquifers*** form		Salton Trough created; lake deposits and ***alluvial aquifers*** form	—	—	—
	Continued basin-fill deposition	Playa deposits, ***fanglomerate and fluvial aquifers*** form		Playa deposits, ***fanglomerate and fluvial aquifers*** form		Same as Great Basin; ***alluvial aquifers*** form	—
	Drainage integration and regional dissection	Colorado R. and upper Humboldt R. drainages dissected	Humboldt River form by lake overflows; ***alluvial aquifers*** form	Mojave and Owens Rivers form; ***alluvial aquifers*** form	***Aquifers*** form along Colorado, Gila, Salt, San Pedro, and Bill Williams Rivers	***Productive aquifer clastics*** deposited by Rio Grande	Colorado River drainage dissected
	Uplift of Sierra Nevada and Transverse Ranges	Rain shadow forms; aridity increases	Rain shadow forms; aridity increases	Rain shadow forms; aridity increases	Rain shadow forms; aridity increases	—	—
	Pleistocene pluvial conditions	***Aquifers recharged***; pluvial lakes form; littoral deposits form	***Aquifers recharged***; pluvial lakes form; littoral deposits form	***Aquifers recharged***; playas inundated	***Aquifers recharged***; local dunes form	***Aquifers recharged***; glaciers form	***Aquifers recharged***; local dunes form
	Holocene aridification	Playas desiccated; salt pans and local dunes form	Playas desiccated; local dunes form	Playas desiccated; salt pans and local dunes form	Local dunes form	—	Local dunes form

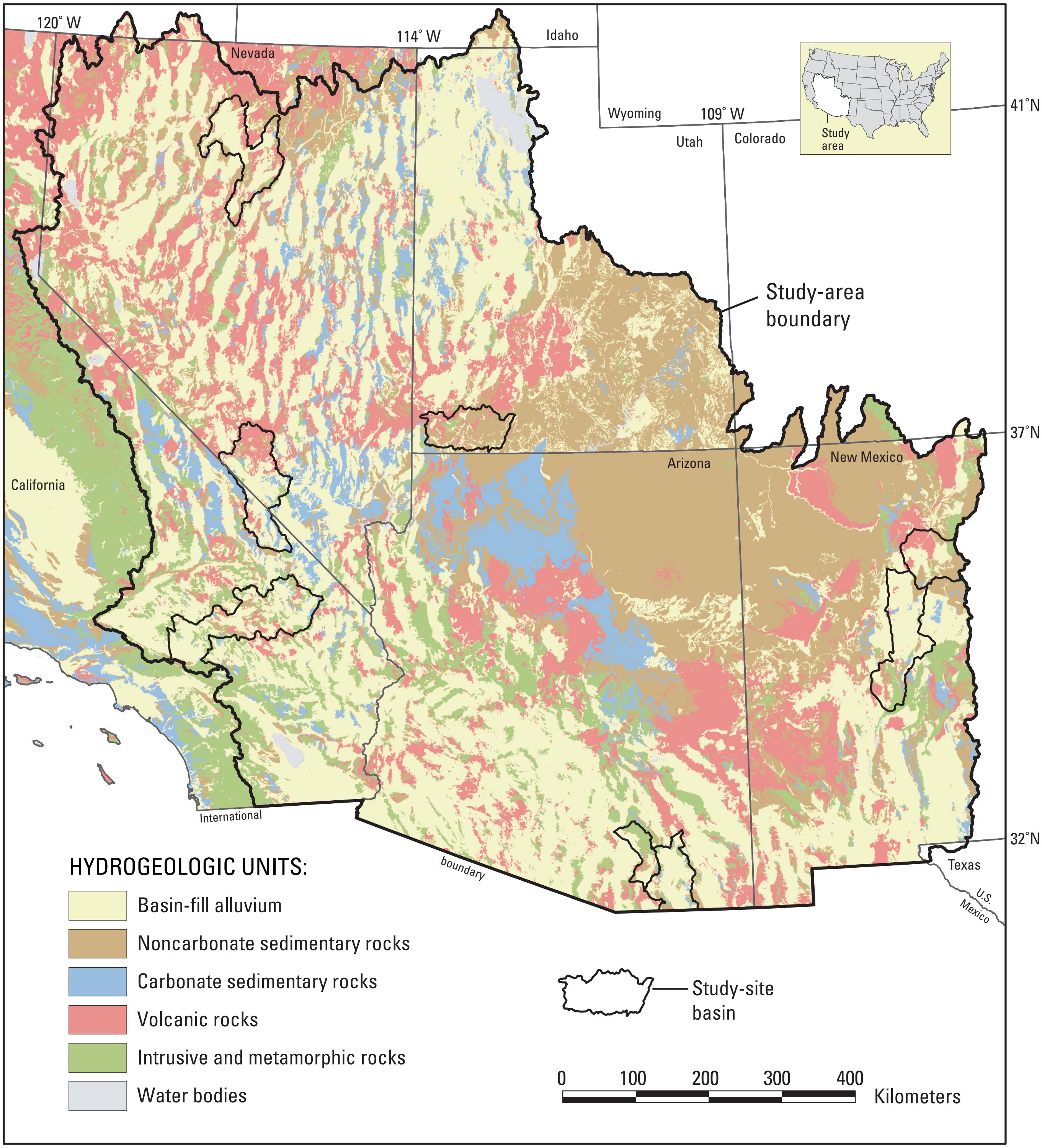

Figure 7. Hydrogeologic units, for the study area, arid and semiarid southweastern United States (from U.S. Geological Survey National Atlas digital data; [http://www.nationalatlas.gov/]).

Table 3. Hydrogeologic units in the arid and semiarid southwestern United States.

[Adapted from Harrill and Prudic, 1998]

Hydrogeologic unit	Generalized geology	Water-bearing characteristics
Basin-fill alluvium	Younger basin-fill deposits consist of unconsolidated to semi-consolidated alluvial fans and pediments (unsorted to poorly sorted silt, sand, gravel, and boulders) in valley lowlands and playas (moderately sorted to well sorted clay, silt, sand, and gravel), and in stream flood plains (moderately sorted to well sorted beds of silt and clay or sand and gravel). Older basin-fill deposits consist of semiconsolidated to consolidated fanglomerate, sandstone, siltstone, mudstone, limestone, and interbedded volcanic rocks.	Younger and older basin-fill deposits form aquifers that yield much of the ground water used in the study area. Excluding flood plain deposits, hydraulic conductivities range approximately from 0.0007 to 43 meters per day (m/d) and average 24 m/d. Conductivities of flood-plain deposits range approximately from 5 to 335 m/d and average 40 m/d. Regional-scale basin-fill aquifers include those in the Basin and Range and Rio Grande aquifer system (fig. 8).
Volcanic rock	Subunit of sedimentary and igneous rocks of late Precambrian to Quaternary age. Flows and flow breccias that range in composition from basalt to rhyolite and silicic welded tuffs. Where these rocks are highly fractured, they form aquifers instead of confining units.	Localized conditions of high permeability characterize this unit. Basalt aquifers occur as individual units and interbedded with basin-fill deposits. Lava flows and welded tuffs at the Nevada Test Site in south-central Nevada are the largest area of volcanic rock aquifers shown on figure 8.
Clastic sedimentary rock	Contains clastic sedimentary rocks of late Precambrain to Quaternary age. Includes siltstone, shale, sandstone, and conglomerate.	Fine-grained clastics (siltstone and shale) form confining units unless highly fractured. Sandstone and conglomerates have permeability from primary porosity and sometimes fractures. An extensive area of clastic sedimentary rocks in the Colorado Plateau (fig. 7) contains sandstone units of the Colorado Plateau aquifers (fig. 8).
Carbonate sedimentary rock	Contains carbonate (and some interbedded clastic) sedimentary rocks of Middle Cambrian to Cretaceous age. Includes interbedded limestone, dolomite, sandstone, and shale. Locally contains some beds of conglomerate and gypsum.	Carbonate-rock units form aquifers in the eastern Great Basin and eastern and south-central parts of the western Great Basin. Ground water flows mostly along joints and fractures. Hydraulic conductivity can be very high in areas that are faulted and fractured.
Igneous and metamorphic rock	Contains sedimentary and igneous rocks of late Precambrian to Quaternary age. Includes fine-grained sedimentary rocks, most volcanic rocks, intrusive rocks, metamorphic rocks, and older crystalline basement.	This unit forms a poorly permeable barrier to ground-water flow. It inhibits flow between hydrographic basins and does not readily yield water to wells. Its occurrence generally corresponds to areas of non-aquifer rocks shown on figure 8.

the mountains but runoff to the adjacent valleys is minor. If a regional hydraulic gradient is present, carbonate-rock aquifers can transmit significant interbasin flow. These aquifers have not been stressed extensively by pumping, however, discharge from large springs supported by these aquifers is almost all allocated for agricultural, municipal, and environmental purposes.

Basin and range volcanic-rock aquifers occur in localized parts of the study area. Not all volcanic rocks function as aquifers, so the area of aquifers shown in figure 8 is smaller than the area of volcanic rock shown in figure 7. The largest area of volcanic-rock aquifer shown in figure 8 is an area of highly fractured welded tuff in south-central Nevada. Basalt flows also form productive volcanic-rock aquifers at several locations, but the size of these aquifers is too small to be shown on figure 8. Volcanic rocks also yield small to moderate amounts of water to a number of domestic wells throughout the study area. Although the amounts of water are generally too small to be considered as part of a major aquifer, the supply is significant to a number of individual users. Most recharge to the volcanic-rock aquifers is from direct infiltration of precipitation or snowmelt in the mountains, or from infiltration of streamflow in the mountains. The recharge occurs through secondary openings, such as joints or fractures. In addition, basalt aquifers often are interbedded with basin-fill alluvium, allowing recharge to the basalt aquifer through the adjoining alluvium.

The Colorado Plateau aquifers occur in southeastern Utah, Northeastern Arizona, and northwestern New Mexico (fig. 8). These aquifers are composed primarily of sandstones of Mesozoic age that transmit water primarily through interconnected joints and fractures. Recharge is primarily by direct infiltration of precipitation and streamflow. The aquifers have not been heavily developed, but some of the water is used for municipal, domestic, and agricultural purposes.

The Rio Grande Rift-Southwestern New Mexico Area aquifer system consists primarily of basin-fill aquifers, but also includes some areas of volcanic rock. Most recharge is supplied by monsoonal storm and snowmelt runoff that infiltrates alluvial materials near the edges of the rift basin. Pumpage from this area is mostly for urban and industrial uses.

Geologic Controls on Recharge Processes

The geologic framework influences the recharge process in three general ways. First, the topography, relief, and orientation of mountain ranges modify the flow of moist air as it moves across mountains and valleys. This modification of airflow influences the occurrence and distribution of precipitation. Second, once the precipitation has fallen, topographic factors such as slope, exposure, and shading determine if the water will tend to remain where it has fallen or move, and if it will be subject to high or low evaporation losses. Third, the permeability of surface and near-surface materials determines

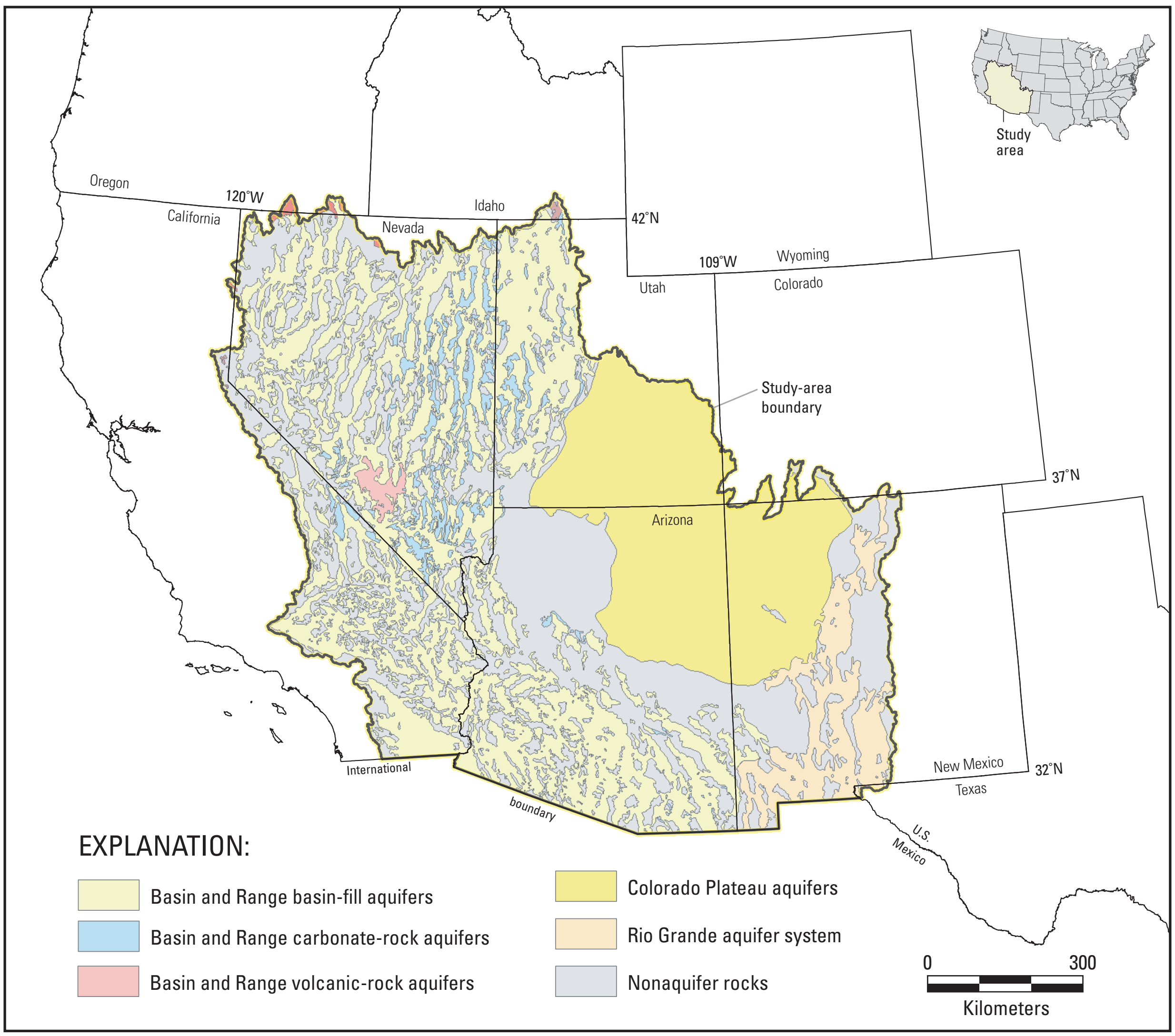

Figure 8. Major aquifers in the arid and semiarid southwestern U.S. study area (from data compiled for the U.S. Geological Survey Ground-Water Atlas of the United States—Whitehead, 1994; Planert and Williams, 1995; Robson and Banta, 1995).

how readily water will infiltrate the land surface and percolate down to the water table.

Topographic factors that influence recharge (fig. 9) include:

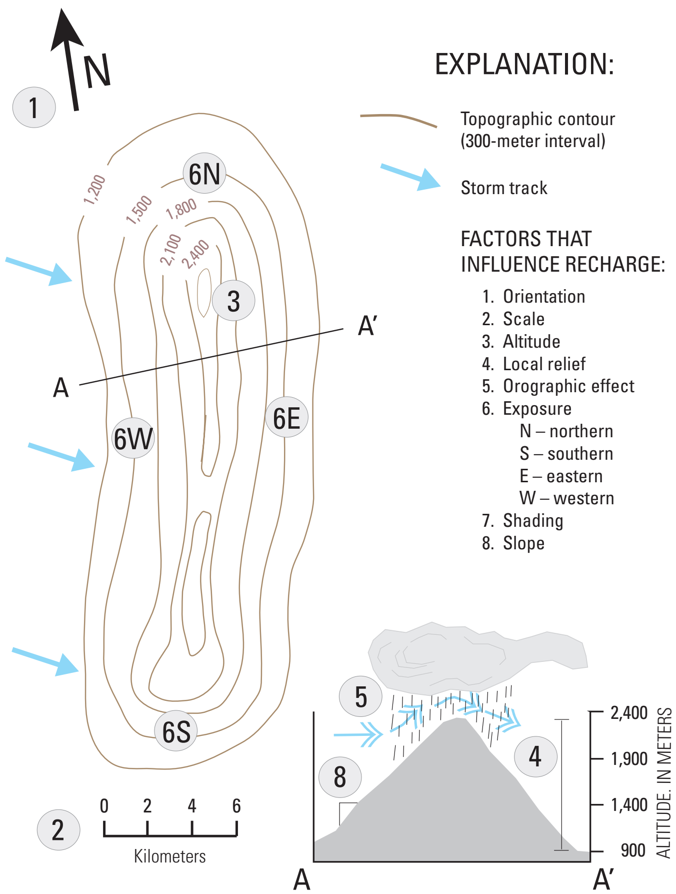

Figure 9. Topographic factors that influence recharge in the arid and semiarid southwestern U.S. study area. Example typifies the Basin and Range subregion.

Orientation

Mountain ranges that are oriented perpendicular to prevailing storm tracks will receive more precipitation than ranges that have a parallel orientation because they present a larger area to the moving moist air masses and are less likely to be bypassed. In addition, when a mountain range is oriented perpendicular to the storm track, the flank of the mountain facing the storm track will receive more precipitation than the leeward side of the mountain, which is in a local rain shadow.

Scale

A large mountain mass will disrupt the flow of a body of moist air more than a small mountain mass will. Therefore, higher rates and larger volumes of precipitation tend to be associated with the larger mountain ranges.

Altitude

The altitude of the crest of a mountain range influences the amount and character of precipitation. Observations throughout the study area indicate that areas of higher altitude receive more precipitation than do areas of lower altitude. The temperature is cooler at higher altitudes; consequently, most high altitude winter precipitation occurs as snow. This snow accumulates during winter and provides snowmelt for spring runoff, which in most areas is the major recharge event of the year.

Local Relief

Local relief, as used in this report, is the difference in altitude between the crest of a mountain range and the adjacent valley floor. This relief is proportional to the vertical distance that air will be forced to rise as it moves across the area. This rise is a key factor in triggering precipitation.

Orographic Effects

The orographic effect happens as air moves across the basin and range topography and rises when crossing mountain ranges. The temperature drops in response to adiabatic cooling that occurs as the air rises. If the air is carrying significant moisture, this drop in temperature will be sufficient to trigger precipitation. Local relief is usually the most significant factor that drives the orographic effect, but other factors, such as altitude, scale, and orientation, also affect the process.

Exposure

Most commonly, exposure is related to the amount of solar radiation that will be retained. A northern exposure (fig. 9, factor 6N) generally retains the lowest amount of solar radiation of all the exposures discussed. In addition, in winter months, when the sun is low in the sky, not only will the incident angle of sunshine on the land surface be lowest, but portions of the exposure also may be shaded for parts of the day, resulting in a lower rate of evapotranspiration. Snow tends to accumulate on northern exposures, and these areas do not dry out as readily as other exposures. Other topographic factors being equal, there will be more water available on the northern exposures to supply recharge.

Southern exposures retain more solar radiation than other exposures, resulting in high amounts of evapotranspiration. Snow melts quickly on the southern exposures, and these areas dry out relatively fast, resulting in less water available for recharge.

East-facing and west-facing exposures retain more solar radiation than the north-facing exposures and less than the south-facing exposures. The solar input varies throughout the day. East-facing exposures retain more solar radiation in the morning than in the afternoon and conversely west-facing exposures retain more solar radiation in the afternoon than in the morning. Evapotranspiration in these areas is not extremely high or low, and the amount of water available to support recharge is about average.

Shading

Shading occurs where the crests of mountain ranges or high peaks cast a shadow on a portion of the mountain. The area that is shaded varies throughout the day as the sun moves across the sky and varies from a minimum at the summer solstice to a maximum at the winter solstice. Consequently, a specific location for factor 7 is not shown on figure 9. Shading also can occur along reaches of deeply incised stream channels, near cliffs, and in areas of steep slope, depending on local conditions. Areas that experience a high incidence of shading have lower rates of evapotranspiration and are more likely to have some water available to generate recharge.

Slope

Slope is a factor that determines if precipitation will remain in place where it falls or will become runoff. The effect of slope on recharge depends on interactions with other factors. For example, if the slope is relatively flat and surface material is permeable, precipitation will mostly remain in place, and water not consumed by evapotranspiration will infiltrate to become recharge. However, if the slope if relatively flat and the surface material is poorly permeable, precipitation will tend to stay in place, but most will be taken up by evapotranspiration and little will infiltrate to become recharge. If the slope is steep and the surface material is permeable, precipitation will be split between recharge occurring in place and runoff. Areas with sufficiently high subsurface permeability, such as carbonate terrains in eastern Nevada, produce little or no runoff even on the steepest slopes. If the slope is steep and the surface material is poorly permeable, most of the excess precipitation will become runoff. Eventually, the runoff will either be taken up by evapotranspiration or generate recharge, depending on the conditions downslope.

For purposes of discussion, the preceding discussion isolated each of the eight topographic factors that influence recharge at the scale of hill slopes to mountain ranges. Under field conditions, the interactions of these factors determine how much water, if any, will be available to supply recharge.

The composition and character of surface and near-surface materials determines if water will infiltrate and percolate to the water table. This discussion will describe conditions at the scale of outcrops. The main factors considered in this report are whether or not there are openings at the land surface capable of accepting infiltration and, where these openings exist, whether or not they are sufficiently interconnected to provide a pathway capable of transporting water from the land surface to the water table.

Consolidated rock openings are mostly formed by joints and fractures (fig. 10*A*). In some rocks, such as limestone, these openings can be enlarged by solution (fig. 10*B*). Hydraulic continuity is created when several sets of fractures intersect and form a network of openings. These features form after the rock has formed so the fracture permeability is a secondary feature. Some rocks have primary permeability that is created when the rock is formed. An example is sandstone in which the grains of sand have been cemented enough to form a consolidated rock, that still has enough open interstices to provide

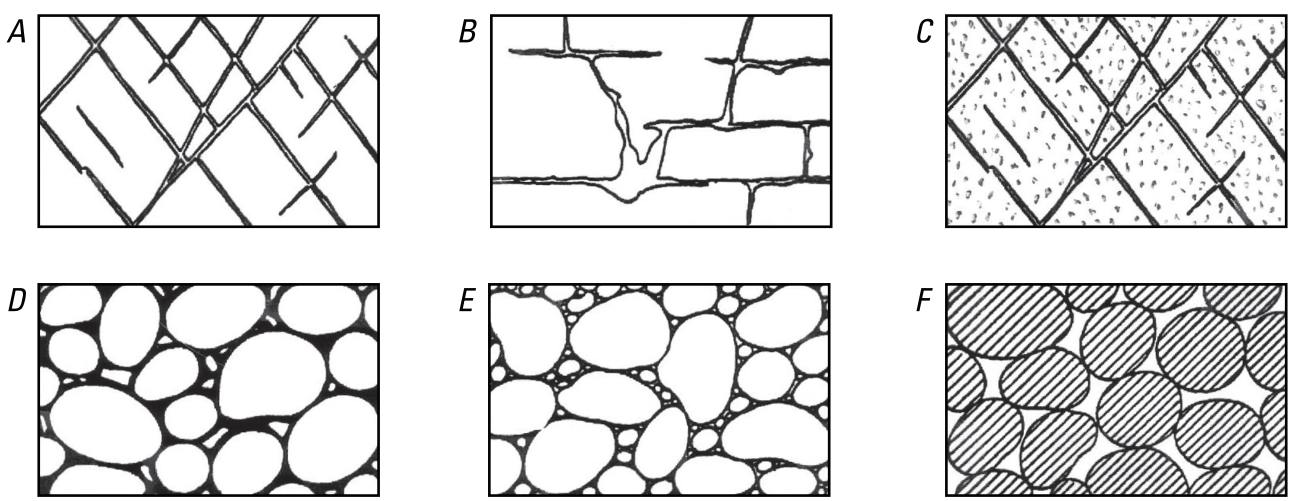

Figure 10. Surface openings that influence infiltration. *A*, rock rendered porous by fracturing; *B*, rock rendered porous by solution; *C*, fractured sandstone that exhibits dual porosity and permeability; *D*, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; *E*, poorly sorted sedimentary deposit having low porosity; *F*, well-sorted sedimentary deposit having high porosity (after Meinzer, 1923).

primary permeability (fig. 10*C*). Some of the sandstone aquifers of the Colorado Plateau have both primary and secondary permeability (fig. 10*D*).

Unconsolidated basin-fill deposits are porous media that may differ in composition, grain size, sorting, and cementation. The most permeable basin-fill deposits are well-sorted coarse-grained materials (fig. 10*F*). Permeability decreases with grain size. Well-sorted fine sand can still transmit a significant amount of water, but finer materials, such as silt and clay, generally act as confining units. Lack of sorting also reduces permeability. Poorly sorted sediments (fig. 10*E*) tend to have permeability representative of the finer-grained materials present. As illustrated for the previously discussed case of sandstone, cementation decreases interstitial space, reducing both porosity and permeability (fig. 10*D*). A type of cementation common in the arid southwest is the formation of caliche that develops because of repeated wetting and drying of the soil. The infiltration from sparse precipitation is often insufficient to support percolation below shallow depths, and the water evaporates as the soil dries. A thin layer of minerals is deposited as evaporation occurs. Each cycle of drying increases the thickness of the mineral deposits and reduces interstitial space. In time, thick layers of impermeable caliche can develop and provide local controls on the occurrence of recharge.

The preceding discussion described examples of the most common types of openings on rock surfaces. A comprehensive discussion of primary and secondary permeability is beyond the scope of this chapter (but see, for example, Watson and Burnett, 1993; Lichtner, 1996; Worthington and others, 2000; Ismat and Mitra, 2001; and Gluyas, 2005). The main point of this general discussion is that all of the various rock-surface openings are components of the hydrogeologic framework and, collectively, they exert strong controls on the recharge process.

The permeability of bedrock also has a major effect on the occurrence and distribution of recharge at a basin-size scale. Figure 11 shows sketches of three topographically similar basins that have different combinations of bedrock permeability and climate.

Figure 11*A* shows an arid basin that has permeable bedrock. Most recharge occurs in the mountains and there is meager runoff onto the alluvial fan. Water percolates deeply in the mountains and moves to the basin fill as subsurface flow. The area of ground-water recharge is separated from the area of ground-water discharge by a zone of lateral ground-water flow.

Figure 11*B* shows an arid basin with poorly permeable bedrock. Recharge in the mountains is small and ground-water flow is limited to a shallow zone of weathered rock. Most of the excess water leaves the mountain as streamflow. Most of the recharge occurs on the alluvial fan, and most of the ground-water flow occurs in the basin fill. The zone of recharge is separate from the zone of ground-water discharge, as before, but the zone of lateral ground-water flow is now smaller.

Figure 11*C* shows a semiarid basin with poorly permeable bedrock. There is more precipitation on the mountain, however, recharge on the mountain remains low (similar to that shown in figure 11*B*) because the recharge is limited by the poor permeability of the bedrock. The excess precipitation leaves the mountain as streamflow and flows across the alluvial fan to the valley lowland. The zone of recharge extends to the valley floor and overlaps the zone of ground-water discharge. There is still a zone of predominantly lateral ground-water flow, but it is smaller than shown in figures 11*A* and 11*B*, and there is recharge and discharge at the upper surfaces of the zone.

The above examples illustrate how a single component of the hydrogeologic framework can exert significant control on the hydrologic regimen of a basin.

The factors that control recharge processes in the Colorado Plateau subregion are the same as those for the rest of the study area; however, the geologic history and the topographic setting differ. The Colorado Plateau has not been subjected to the strong extension and structural deformation that has occurred throughout the rest of the study area. The Colorado Plateau has experienced regional uplift and subsequent downcutting of streams and rivers, which has resulted in a plateau-and-canyon topography where the sedimentary units that underlie the Plateau are mostly flat lying. The geohydrology of part of this subregion was evaluated by Freethy and Cordy (1991), who noted that most of the recharge originates from (1) infiltration of precipitation (including snowmelt) through the unsaturated zone to the water table (fig. 12*A*) and (2) infiltration of streamflow from stream channels into the zone of saturation (fig. 12*B*).

Summary

Aridity in the study area results from the combination of descending dry air at the boundary of the Hadley cell and orographic drying of air masses crossing the bordering mountains. Rainfall in the study area is strongly seasonal, with frontal cyclonic storms mostly occurring in winter and convective and monsoonal rains mostly occurring in summer. The Pacific Ocean is the primary source of moisture to the study area, although the Gulf of Mexico contributes moisture, mostly to the southeastern portion of the study area, during the summer monsoonal season. Precipitation and associated ground-water recharge in the northwestern part of the study area have a significant winter component, whereas the southeastern part of the study area has a strong monsoonal component.

Climatic controls on ground-water recharge are complex and exhibit a large degree of natural variability. Droughts more severe than any in the modern instrumental record are evident in tree-rings and other proxy indicators. Pluvial periods that accompanied recent ice ages produced ground-water recharge rates an order of magnitude higher than present rates in parts of the study area. Isotopic

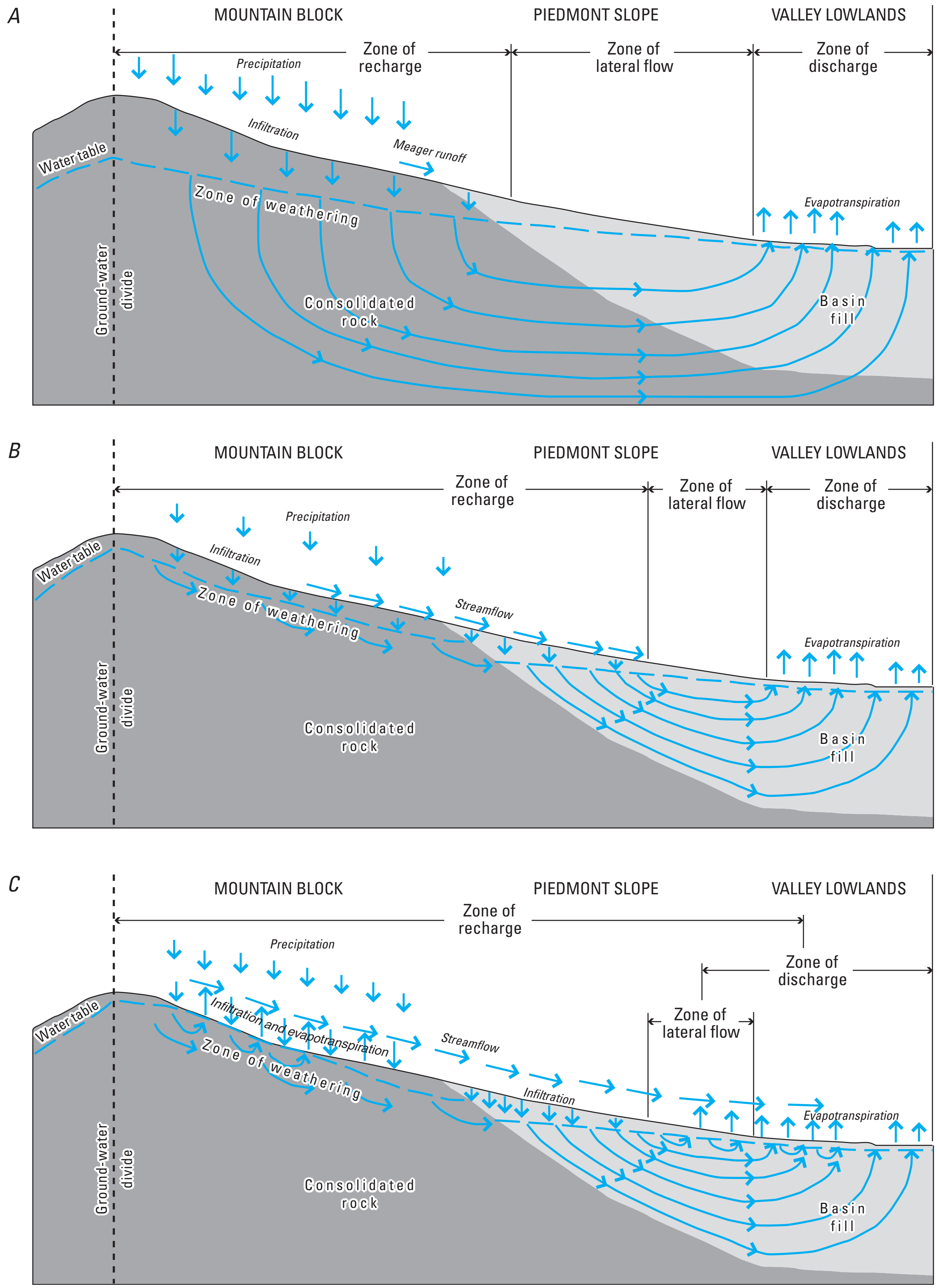

Figure 11. Cross-sections of typical basins showing controls on recharge due to variations in bedrock permeability. *A*, Arid basin having permeable bedrock; *B*, arid basin having poorly permeable bedrock; *C*, semiarid basin having poorly permeable bedrock (from Berger, 2000).

evidence shows that much of the ground-water resource in these areas was recharged during previous geological epochs that were wetter and cooler than today.

Anthropogenic effects are superimposed on natural variability. Projected climate change will likely reduce ground-water recharge through reduced snowpack and perhaps through increased severity of drought. These factors reflect rising temperatures and the possible northward shifting of storm tracks.

Geologic controls on recharge in the study area include the formation of the Sierra Nevada and San Bernadino Mountains that bound the Mojave Desert and Basin and Range to the west and the southern Rocky Mountain Cordillera to the east. Extensional tectonism produced internally drained, alluvial-filled basins and exposed Paleozoic aquifers in mountainous recharge areas in most of the study area. Extensional tectonism did not affect the southern Colorado Plateau; however, it did create differences in predominant modes of recharge. In addition, geologic controls on permeability (through infiltration and subsequent percolation) and topography (through micro-climate) provide important controls on ground-water recharge at smaller scales.

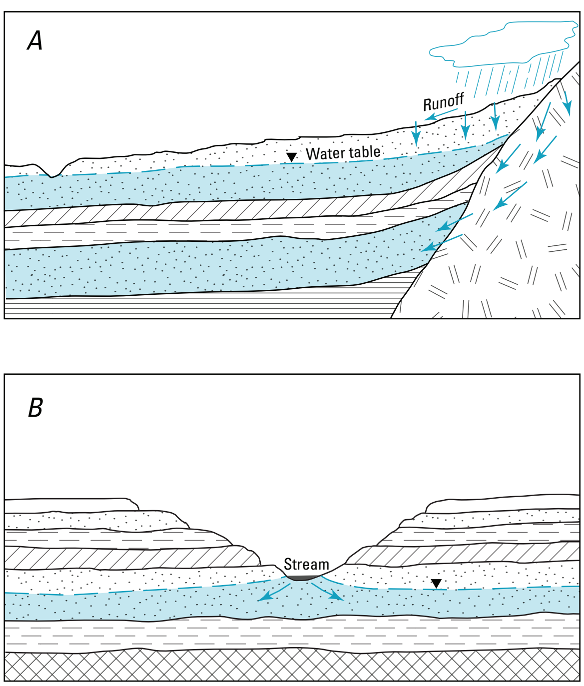

Figure 12. Typical modes of recharge in the Colorado Plateau subregion (adapted from Freethy and Cordy, 1991). *A*, Direct infiltration of precipitation; *B*, seepage from losing reach of stream.

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