Overview of Ground-Water Recharge Study Sites

By Jim Constantz, Kelsey S. Adams[1] , and David A. Stonestrom

Abstract

Multiyear studies were done to examine meteorologic and hydrogeologic controls on ephemeral streamflow and focused ground-water recharge at eight sites across the arid and semiarid southwestern United States. Campaigns of intensive data collection were conducted in the Great Basin, Mojave Desert, Sonoran Desert, Rio Grande Rift, and Colorado Plateau physiographic areas. During the study period (1997 to 2002), the southwestern region went from wetter than normal conditions associated with a strong El Niño climatic pattern (1997–1998) to drier than normal conditions associated with a La Niña climatic pattern marked by unprecedented warmth in the western tropical Pacific and Indian Oceans (1998–2002). The strong El Niño conditions roughly doubled precipitation at the Great Basin, Mojave Desert, and Colorado Plateau study sites. Precipitation at all sites trended generally lower, producing moderate- to severe-drought conditions by the end of the study. Streamflow in regional rivers indicated diminishing ground-water recharge conditions, with annual-flow volumes declining to 10–46 percent of their respective long-term averages by 2002. Local streamflows showed higher variability, reflecting smaller scales of integration (in time and space) of the study-site watersheds. By the end of the study, extended periods (9–15 months) of zero or negligible flow were observed at half the sites. Summer monsoonal rains generated the majority of streamflow and associated recharge in the Sonoran Desert sites and the more southerly Rio Grande Rift site, whereas winter storms and spring snowmelt dominated the northern and westernmost sites. Proximity to moisture sources (primarily the Pacific Ocean and Gulf of California) and meteorologic fluctuations, in concert with orography, largely control the generation of focused ground-water recharge from ephemeral streamflow, although other factors (geology, soil, and vegetation) also are important. Watershed area correlated weakly with focused infiltration volumes, the latter providing an upper bound on associated ground-water recharge. Estimates of annual focused infiltration for the research sites ranged from about 10^5 to 10^7 cubic meters from contributing areas that ranged from 26 to 2,260 square kilometers.

Introduction and Scope

The Colorado River, Rio Grande, and other regional drainages dominate the hydrographic landscape of the arid and semiarid southwestern United States (chapter A, this volume). These perennial rivers, together with their major tributaries, comprise a natural network distributing recent precipitation from mountain highlands to distant locations. The shear number of minor tributaries and isolated channels in which flow is ephemeral warrants investigation for generating potentially important amounts of infiltration and ground-water recharge. Process-based understanding of ephemeral flow, infiltration, and associated recharge is needed to quantify where, when, and how much these events contribute to ground-water resources.

Investigations at eight study sites across the arid and semiarid southwestern United States (“Southwest” hereafter) examined streamflow, infiltration, and ground-water recharge during a multiyear campaign (nominally 1997–2002). Study sites were in Arizona (two Sonoran Desert sites), California (one Mojave Desert site), New Mexico (two Rio Grande Rift sites), Nevada (one Mojave Desert and one Great Basin site), and Utah (one Colorado Plateau site; fig. 1; for desert boundaries see fig. 6, chapter A, this volume). Satellite images show each tributary (or basin) in relation to the regional drainage (fig. 2). In addition to the primary characteristic of ephemeral flow, each study site had regionally specific characteristics, resulting in observations of recharge-producing conditions over a range of hydrogeologic settings.

This chapter briefly reviews the literature on focused ground-water recharge from ephemeral infiltration and introduces the study sites, providing context for the chapters that follow. A synopsis of climatic conditions that were observed during the study indicates that streamflow and recharge in dry environments are sensitive to climatic fluctuations, and it demonstrates the value of multiyear data.

Previous Work

Since antiquity, irrigators of arid lands have realized that seepage losses occur when water is routed through unlined channels to distant fields (Gulhati and Smith, 1967). A scientific approach to the sequential processes of infiltration, percola-

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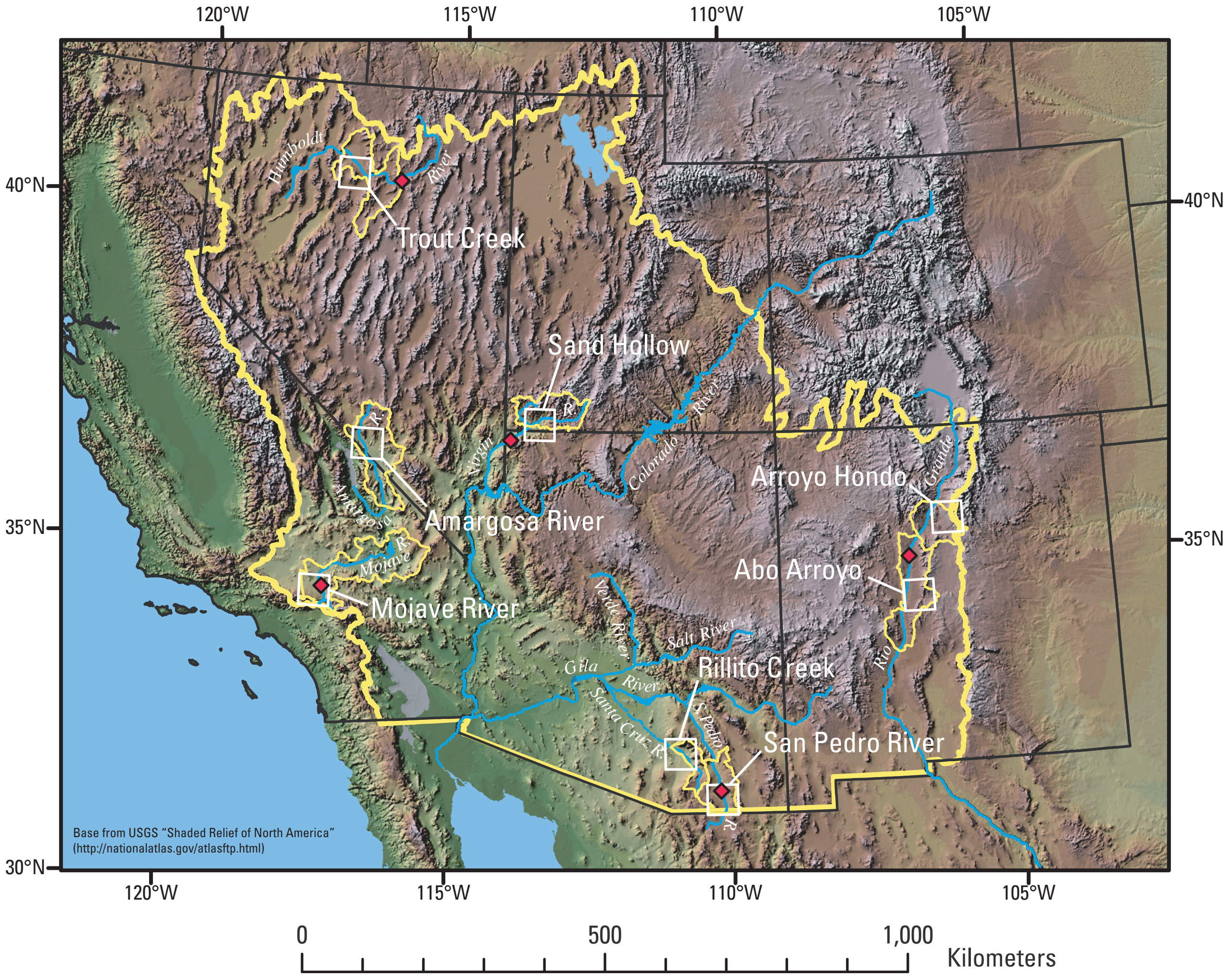
[1] Now with Engeo Incorporated, San Ramon, California (kadams@engeo.com).

tion, and ground-water recharge began with the pioneering work of Henry Darcy in the mid 1800s (Darcy, 1856). Following the dawn of quantitative hydrology, engineers and scientists studied these processes under a variety of rubrics, including consumptive use, transmission losses, and surface-water—ground-water interactions. Interest in recent years has included the deliberate enhancement of ground-water recharge by capturing ephemeral flow with engineered structures and by introducing reclaimed or imported water into channels that would otherwise be dry (Colby and Jacobs, 2006).

During the past quarter century, studies around the world have contributed greatly to the understanding of ground-water recharge in arid regions (Scanlon and others, 2006). Examples include studies in Africa (Crerar and others, 1988), Australia (Allison and Hughes, 1978), Chile (Houston, 2002), Mexico (Ponce and others, 1999), the Middle East (Levin and others, 1980), and India (Rangarajan and Athavale, 2000), in addition to the Southwest (Hogan and others, 2004). Yet few studies address the challenge of quantifying recharge from channels in which a perennial trickle of water is suddenly interrupted by a once-in-a-decade flash flood.

Early studies of focused infiltration in the Southwest were performed at budding population centers including Albuquerque, New Mex., Las Vegas, Nev., and Tucson, Ariz. As these centers grew, in part due to favorable water-resource availability, many formerly remote stream channels from upland basins became concrete-lined flood-control structures draining suburban communities. Early work partitioned streamflow losses into evapotranspiration (ET) and ground-water recharge (Troxell, 1936). Such studies are of value today as much for their historical information on changing land-use patterns as for their insights on recharge processes.



Base from USGS "Shaded Relief of North America" (http://nationalatlas.gov/atlasftp.html)

Figure 1. General locations of the focused ground-water-recharge study sites (white squares) are indicated within the overall arid and semiarid southwestern United States study area (thick yellow outline). Squares, labeled by the study-site names, indicate locations of the satellite images shown on figure 2. The thin yellow outlines indicate locations of the corresponding hydrologic basins that were simulated by using the basin-scale recharge model (chapter B, this volume). Red diamonds indicate locations of the streamflow-gaging stations for which multidecadal data were used in analyzing regional trends (see fig. 9 and table 2)

Early work examined hydrodynamic processes, such as the role of sediment transport in ephemeral-streamflow hydraulics (Leopold and Miller, 1961), in addition to the influence of geology and topography in generating ephemeral flow (Hely and Peck, 1964). Quantifying the amount of ground-water recharge from ephemeral mountain runoff proved to be an important but difficult task (Crippen, 1965).

There are few multiyear studies. Exceptions include long-term studies at the U.S. Department of Agriculture (USDA) Walnut Gulch catchment in southeastern Arizona (Renard 1970, Renard and others, 1993). Studies initiated in 1953 to quantify watershed processes in arid regions continue today (Goodrich and others, 2004). These studies showed that ephemeral-flow events, though brief, can be effective in producing ground-water recharge. A long-term study by the U.S. Geological Survey over three decades showed that roughly 70 percent of ephemeral streamflow was lost to infiltration before leaving the Tucson Basin in south-central Arizona (Burkham, 1970). More recently, multiyear investigations at the Nevada Test Site in southern Nev., have showed that runoff and infiltration events can produce deep percolation beneath small washes that rarely flow (LeCain and others, 2002). This latter study used heat as an indicator of deep percolation, an approach applied at six of the study sites.

Naturally occurring hydrologic tracers such as chloride, heat, and isotopes have been used to quantify ground-water recharge by examining ground-water chemistry at the basin scale (Dettinger, 1989; Anderholm, 2000) and by examining focused recharge at smaller scales (Stonestrom and others, 2003). Due to advances in computational analysis, field measurements are increasingly complemented by numerical modeling of watershed-runoff (Maurer, 2002) and unsaturated-zone heat, fluid, and solute transport (Walvoord and others, 2004). This latter study used modeling and observations to show that climate and vegetational changes that occur on multimillennial time scales can determine the presence or absence of ground-water recharge.

Obtaining accurate observations of hydrological processes in arid regions is inhibited by the high-energy nature of ephemeral channels, the long time scales of climatic fluctuations, and the difficulty of methodological research and development in remote areas. Such challenges contribute to a general lack of information on focused infiltration and associated ground-water recharge in arid regions throughout the world.

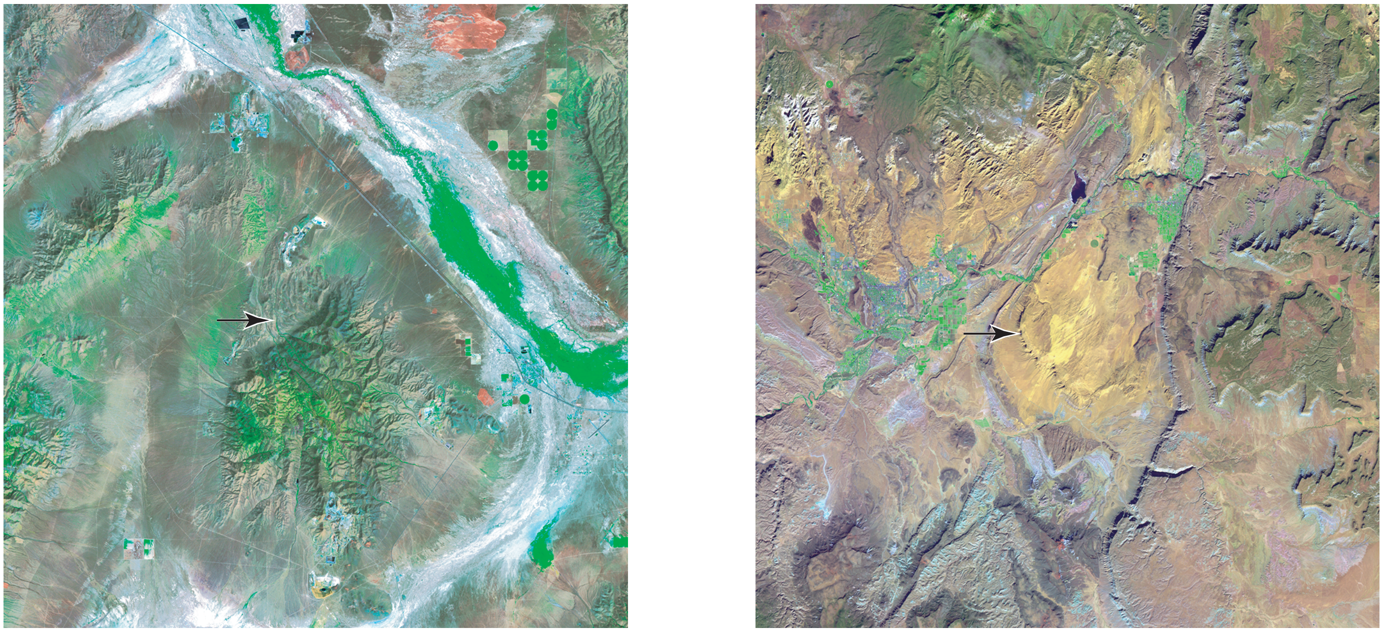
Although sufficiently accurate streamflow data can provide information on streamflow losses, measurement error generally is larger in dry-region streams than in their humid-region counterparts due to the flashy nature of streamflow and unstable geometry of alluvial channels. Direct determinations of channel losses during ephemeral flow often are impractical due to unstable channel conditions. Considerable effort in the present study concerned the development of thermal methods for estimating losses in channels with ephemeral flow (Constantz and others, 2001; Constantz and others, 2002; Blasch and others, 2004; Niswonger and others, 2005). Geophysical and environmental-tracer methods, which provide time-integrated indications of deep percolation and ground-water recharge, also were advanced (Parker and Pool, 1998; Izbicki and others, 2002; Hoffmann and others, 2003; Stonestrom and others, 2003; Heilweil and others, 2006).

In subhumid and humid regions, watershed size and geology correlate closely with mean annual runoff and base flow, both of which provide indicators of recharge when used in regression models (Nolan and others, 2007). Such relations are more elusive in arid regions. Correlations between watershed area and streamflow for short periods of record are little better than what would occur by chance, as shown by watersheds in the Mojave Desert (fig. 3*A*). Factors including mountain-block permeability, topographic aspect with respect to prevailing storm tracks, vegetational dynamics, and meteorologic granularity (spottiness) become increasingly important with increasing aridity. The relatively high levels of climatic variability in the Southwest, including multiyear droughts, can bias all but the longest records. This is evident in the Mojave Desert example, where restricting analysis to basins with at least 20 years of record improves the correlation considerably (fig. 3*B*).

Infiltration and recharge are less uniformly distributed in arid regions than in humid regions. Arid-region recharge tends to be more concentrated in space—in permeable mountain terrains, beneath losing stream channels, and at contacts between impermeable bedrock and alluvium. Figure 4 shows a conceptual diagram contrasting distributed recharge in humid regions with the focused recharge in arid regions. The volume of infiltration (water entering the subsurface, given by the area under the green infiltration-rate curve) is greater than the volume of percolation beneath the root zone (the area under the dotted black line) due to evapotranspiration, which returns a higher fraction of infiltrating water to the atmosphere in arid regions than in humid regions. Large plants in arid regions can concentrate water around their stems, creating focused infiltration (fig. 4*B*). Ground-water recharge (solid orange line), refers to flow across the water table, into the saturated zone.

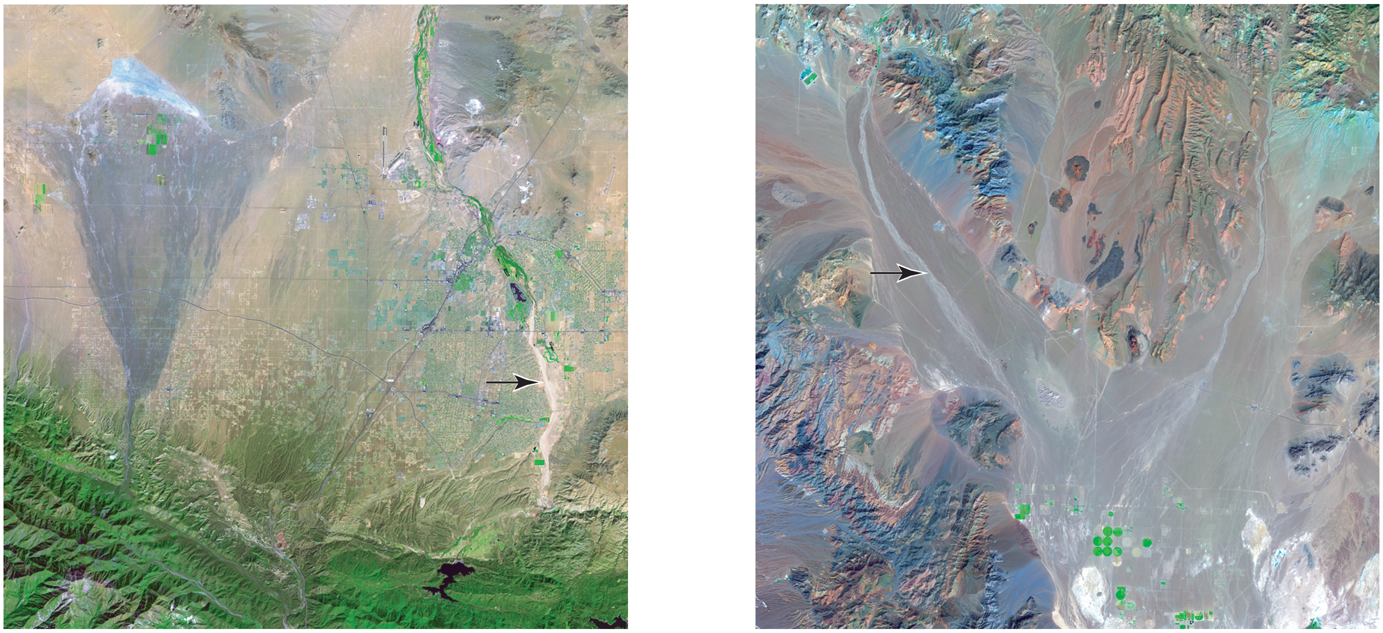
Percolating water from line sources (stream channels) spreads laterally as it moves downwards toward the water table, but the rate of horizontal spreading diminishes quickly if infiltration proceeds in sufficiently homogeneous, deep unsaturated zones (Philip, 1983). Once the wetting front connects to the water table, creating mounded conditions, lateral flow becomes dominant once again. Impermeable horizons, such as buried clay and caliche-rich layers, can cause lateral spreading at intermediate depths (Nimmo and others, 2002).

Together with mountain-block infiltration (chapter B, this volume), stream-channel infiltration at the mountain front and downstream in alluvial-filled basins is hypothesized to be the dominant process of ground-water recharge in most of the study area. Geochemical and isotopic studies show that recharge from ephemeral streamflow is focused beneath large channels (Claassen, 1985; Woocay and Walton, 2004). Distributed recharge has been documented, nevertheless, beneath woody vegetation receiving high amounts of precipitation—ponderosa-pine associations on the upper west flank of the



Trout Creek, Nevada

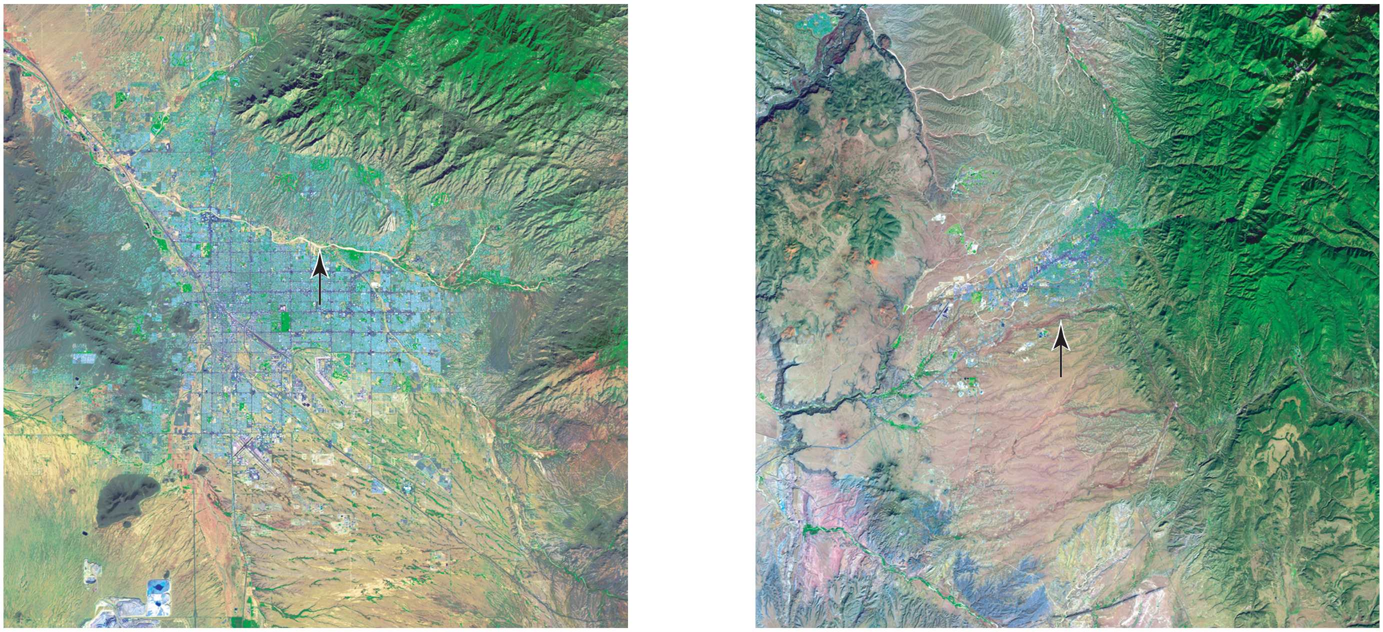
Sand Hollow, Utah



Mojave River, California

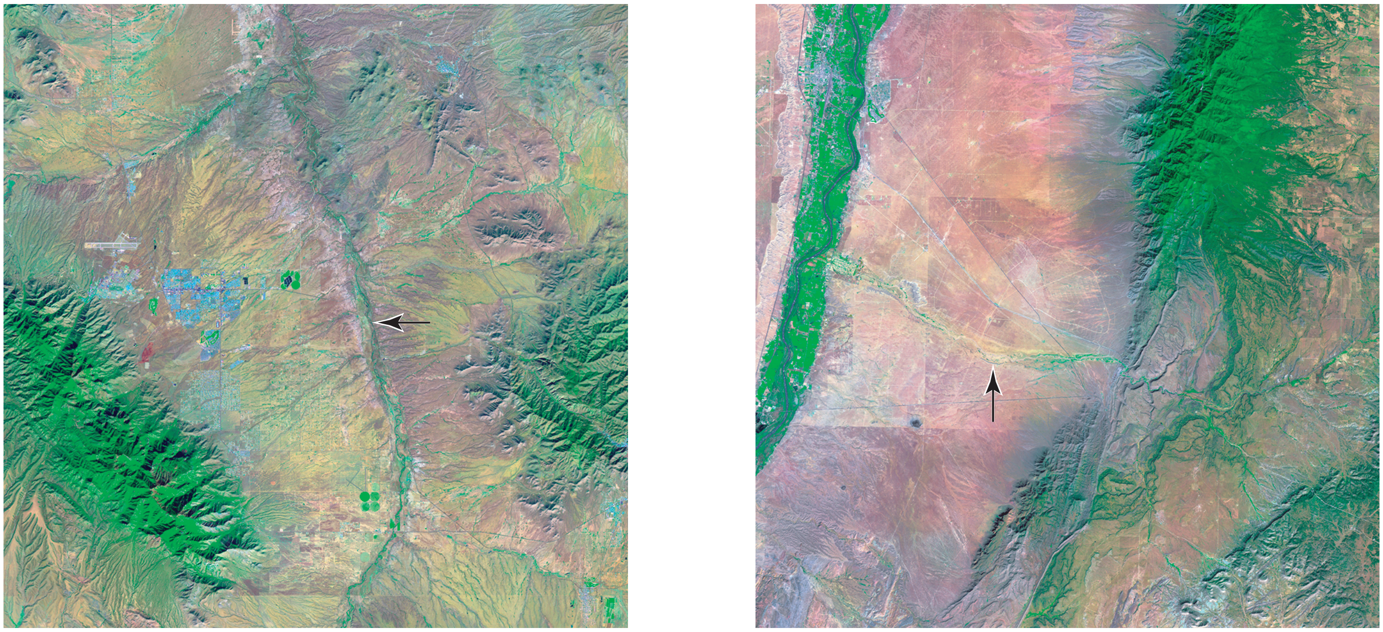
Amargosa River, Nevada

Figure 2. Satellite images of the study sites. The images are 50 kilometers on a side and were acquired by the Landsat 7 Enhanced Thematic Mapper Plus (http://landsat.usgs.gov); spectral bands 7, 4, and 1 are shown as red, green, and blue, respectively. Active vegetation is green; sandstone at Sand Hollow Basin is yellow. In each image, the geographical feature indicated by the arrow and acquisition date are as follows: Abo Arroyo, Sept. 28, 1999; Amargosa River, Sept. 29, 1999 and Oct. 15, 1999 (two images, stitched together); Arroyo Hondo, Oct. 14, 2000; Mojave River, Sept. 9, 2000 and Oct. 4, 2001 (two images, stitched together); Rillito River, Oct. 19, 1999; San Pedro River, Nov. 13, 1999; Sand Hollow, Nov. 2, 1999; and Trout Creek, Sept. 4, 1999. Trout Creek flows north from Battle Mountain (center of image) to the Humboldt River (broad green swath). Arroyo Hondo merges with the Santa Fe River before entering the Middle Rio Grande Basin (at left side of image) through Santa Fe Canyon. See figure 1 for image locations.



Rillito Creek, Arizona

Arroyo Hondo, New Mexico



San Pedro River, Arizona

Abo Arroyo, New Mexico

Figure 2.—Continued.

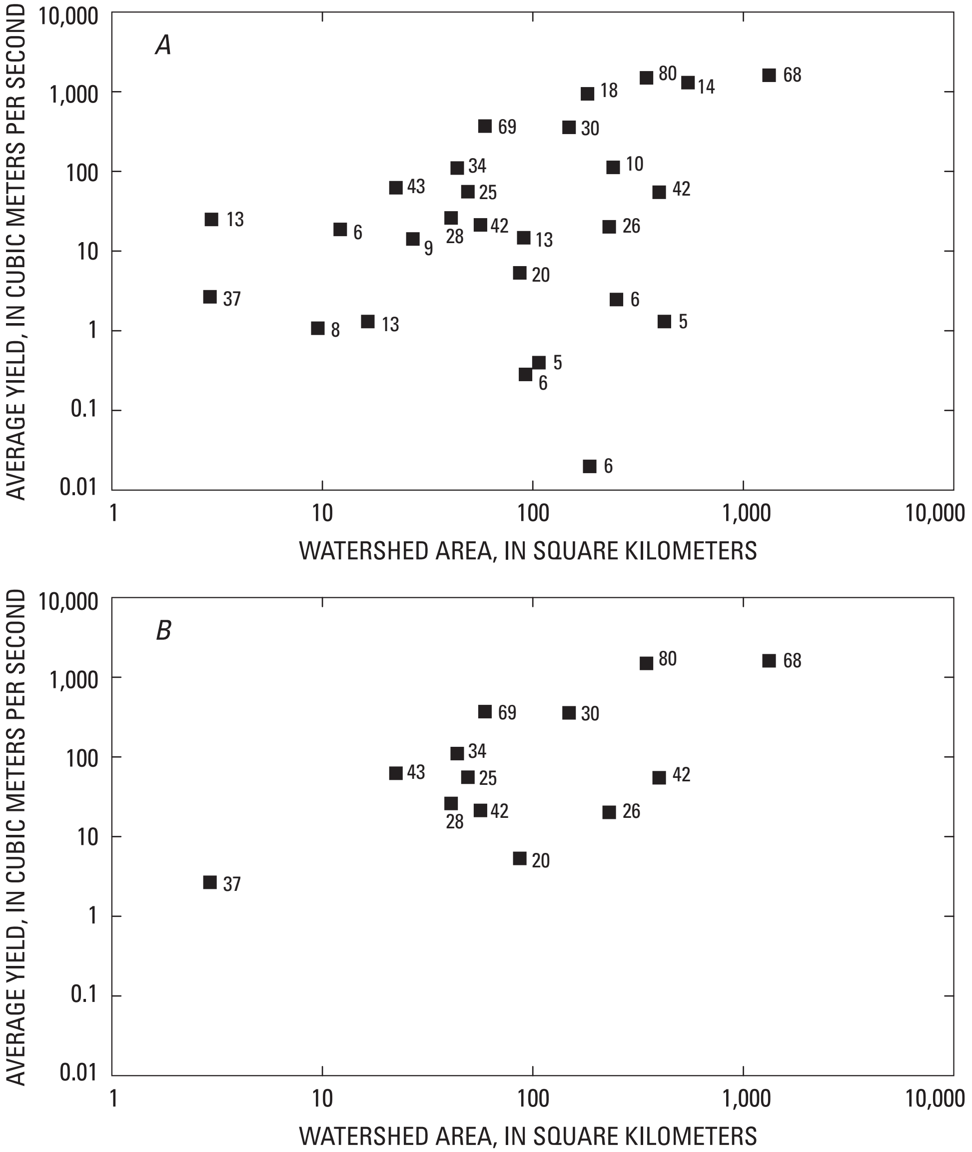


Figure 3. Plot of basin yield (average streamflow exiting watershed) versus watershed area. Numbers to the right of each symbol indicate number of years of record *A*, data for all watersheds; and *B*, data from watersheds that have at least 20 years of record. Data from Lines (1996).

Rio Grande Rift (Sandvig and Phillips, 2006) and juniper associations in westernmost Texas, southeast of the study area (Walvoord and Phillips, 2004). But across vast areas, potential evapotranspiration so greatly exceeds precipitation as to largely prevent direct recharge from rain infiltration in vegetated portions of alluvial basin floors under current climatic conditions (Phillips, 1994).

Site Selection

The approach of the current study was to measure streamflow together with hydrologic, thermal, and chemical parameters at selected sites throughout the Southwest. Seven sites included channels representative of ephemeral flow into either a regional river system (the Rio Grande or Humboldt River, for example) or a regional terminal basin (Death Valley). The eighth site was selected to investigate potential focused recharge on the Colorado Plateau (table 1). All sites are sufficiently isolated from ocean bodies by intervening ranges that their non-mountain portions are arid to semiarid. Sites with ephemeral streamflow relied on streambed temperature analysis to determine infiltration timing and associated percolation.

Sites were selected along transitional reaches of Trout Creek (northern Basin and Range, Nev.), the Amargosa River (southern Basin and Range–Mojave Desert, Nev.), Rillito Creek (Sonoran Desert, south central Ariz.), Abo Arroyo (Rio Grande Rift, central N. Mex.), and Arroyo Hondo (Rio Grande

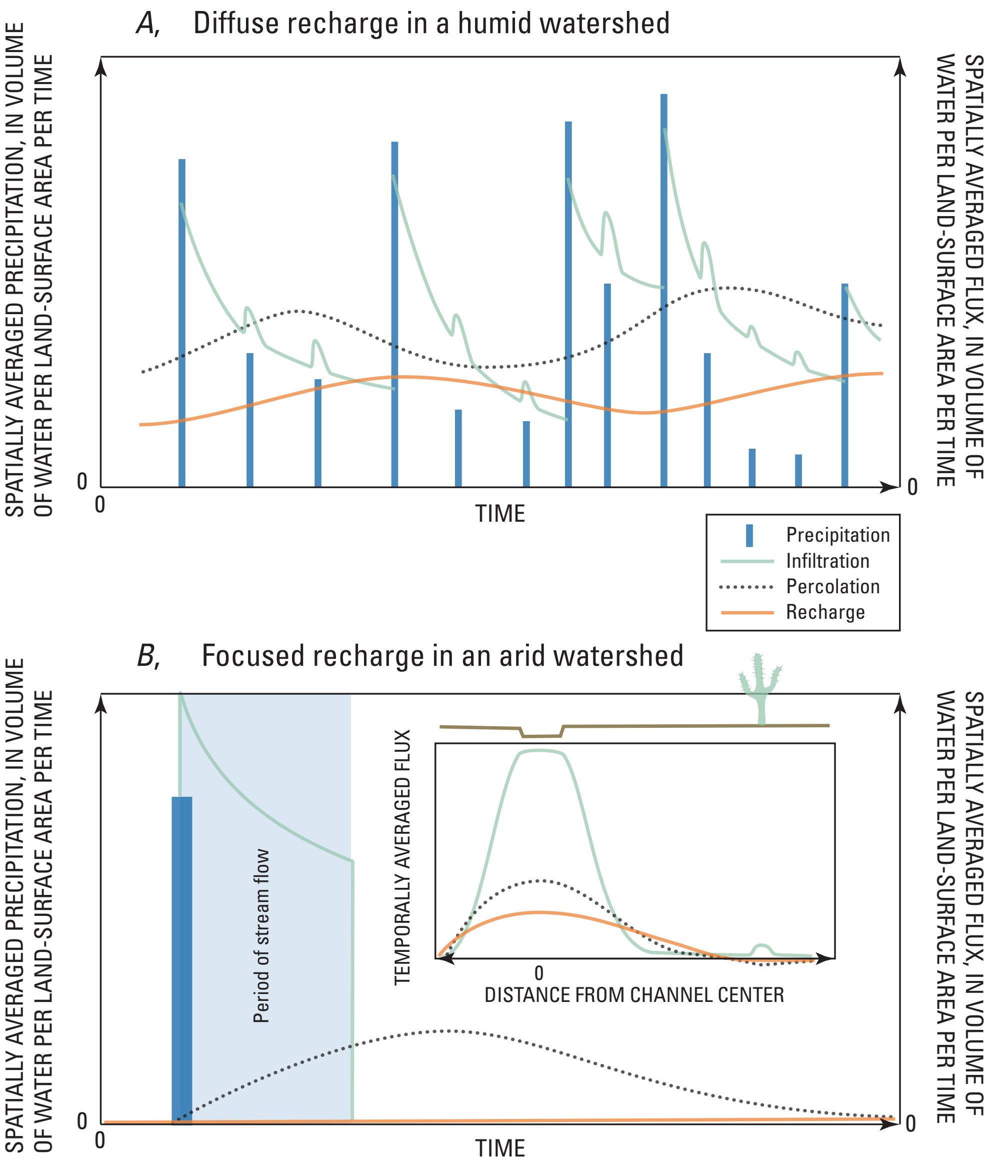


Figure 4. Conceptual diagram of *A*, diffuse ground-water recharge in humid regions—distributed due to diffuse infiltration and percolation—versus *B*, focusedrecharge in arid regions—concentrated due to focused infiltration and percolation. The insert in the lower graphic portrays time-averaged infiltration, percolation, and recharge as a function of distance from the arid channel. Infiltration is downward water flow across the land surface; percolation is flow within the unsaturated zone; and recharge is flow across the water table. Infiltration and subsurface fluxes in *A* and *B* are at different scales, with arid fluxes being relatively small. See text for additional explanation.

Rift, north-central N. Mex.). Transitional reaches included the crossover between streamflow generation in an upland catchment and recharge generation in a downstream alluvial basin. Sites were selected that had an existing or planned streamflow-gaging station (“gage” hereafter) near the crossover point, which typically corresponded to basin-bounding faults. Research followed similar protocols in hydraulic and thermal instrumentation to monitor streamflow and streamflow losses downstream of the gage; however, studies ranged from intensive investigations of limited duration and scope to large multidisciplinary studies that included geophysical, chemical, and modeling components. Spatial scales of contributing catchments varied from several tens of square kilometers to more than two thousand square kilometers (table 1). Temporal scales also varied, although data collection spanned multiple years at most sites (fig. 5). In addition, five tributaries of the Mojave River Basin (Mojave Desert, central southern California) were studied together—Big Rock Creek, Sheep Creek Wash, Oro Grande Wash, Yucca Wash, and Quail Springs Wash. Only Big Rock Creek was instrumented with gages, but data are presented for all tributaries (chapter G, this volume). Similarly, five tributaries of the San Pedro River Basin (Sonoran Desert, southeastern Arizona) were studied, including the gaged channel of Walnut Gulch (chapter J, this volume). Sand Hollow (Colorado Plateau, southwestern Utah), a sandstone basin near the Virgin River, provided information on infiltration in a bedrock basin on the Colorado Plateau (chapter I, this volume).

Physiographic Setting

Brief summaries of the hydrogeologic setting for each site appear below, followed by an overview of climatic

Table 1. Characteristics of focused ground-water recharge study sites, southwestern United States.

[Gage, streamflow-gaging station]

Site (gage identification number)	Regional drain	Average temperature at gage[1], in degrees Celsius	Average annual precipitation at gage[1], in meters	Altitude of gage[2], in meters	Maximum catchment altitude[2], in meters	Contributing area at gage, in square kilometers	Distinguishing characteristics
Abo Arroyo (08331660)	Rio Grande	11.2	0.30	1,667	3,048	650	Moderate monsoon influence; snowmelt affected
Amargosa River (10251217)	Death Valley	14.8	0.15	1,003	2,210	1,200	Strong El Niño influence; arid end member
Arroyo Hondo (08317050)	Rio Grande	9.7	0.36	2,180	2,700	26	Strongly snowmelt affected; some monsoon influence
Mojave River tributaries[3] (10263500)	Mojave River	15.3	0.16	1,234	2,850	75	Strong Pacific Ocean influence; weak snowmelt influence
Rillito Creek (09485700)	Santa Cruz River	19.8	0.32	710	2,780	2,256	Strong monsoon influence; some snowmelt influence
Sand Hollow[4]	Virgin River	16.7	0.21	903	1,300	50	Fractured sandstone basin; strong El Niño influence
San Pedro tributaries[5] (09471200)	San Pedro River	17.8	0.36	1,222	1,540	149	Strong monsoon influence
Trout Creek (3GT[6])	Humboldt River	9.4	0.32	1,600	2,570	48	Strongly snowmelt affected; strong El Niño influence

[1] Interpolated on the basis of elevation from 30-year (1971–2000) normals at nearby climate stations (http://lwf.ncdc.noaa.gov/oa/climate/normals/usnormals.html, accessed March 31, 2007).

[2] National Geodetic Vertical Datum of 1929.

[3] Tabulated values are for Big Rock Creek (downstream portion called Big Rock Wash).

[4] No gage at this site. “Gage” values are for well 27, near the center of catchment (see chapter I, this volume).

[5] Tabulated values are for Walnut Gulch.

[6] Temporary gage for this study (see chapter K, this volume).

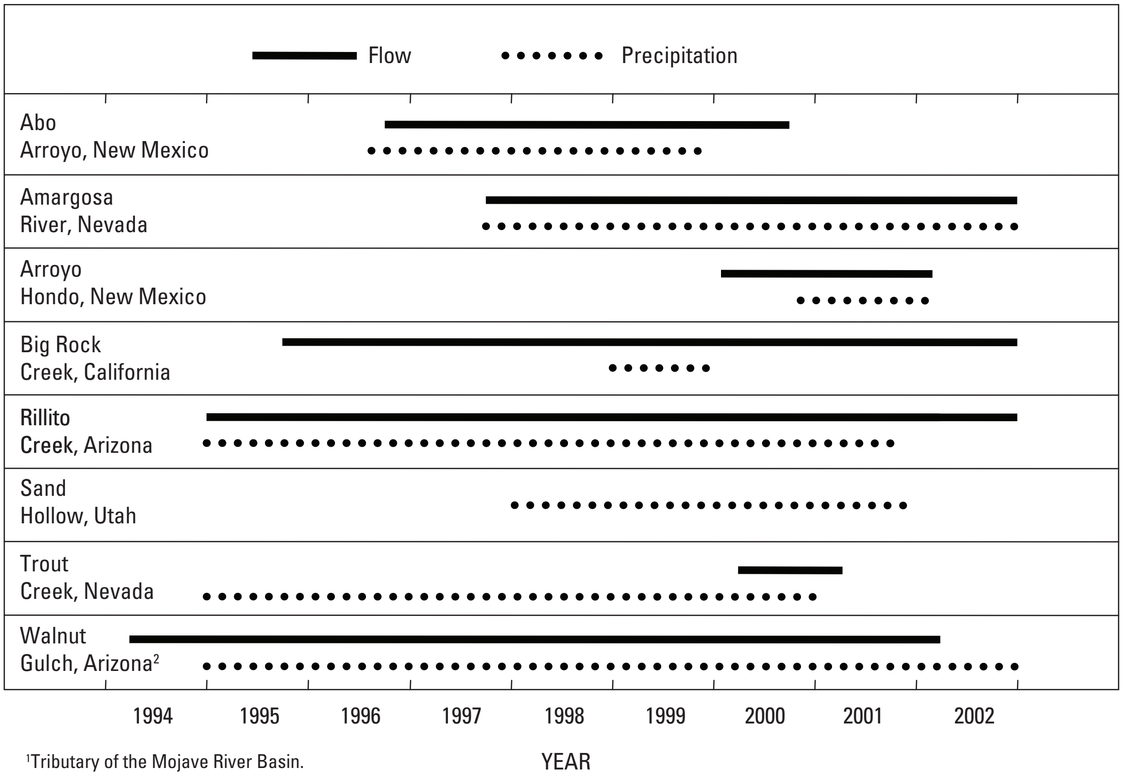
conditions and streamflow during the study period. Detailed descriptions are in individual study-site chapters.

Hydrogeologic Framework

Except for the Colorado Plateau study site, stream channels emerge from mountain-block catchments by crossing a fault (or fault zone) associated with sharp increases in sediment thickness. Often the fault is concealed, but the inflection point where the thickness of alluvial fill increases sharply marks the mountain front and provides hydraulic conditions conducive to recharge. Basin-fill alluvium generally is coarsest near mountain fronts, leading to high hydraulic conductivities and rapid streamflow losses. Sediments fine downstream, leading to lower conductivities and streamflow losses away from the mountain front. This pattern occurs throughout the Southwest, and provides the geologic framework for streambed infiltration and ground-water recharge from ephemeral flow (chapter A, this volume). Sand Hollow is a Colorado Plateau sandstone basin that slopes towards a regional drainage, the Virgin River. The basin has sufficient bedrock permeability (largely through fractures intersecting the surface) and soil-moisture storage that little streamflow is generated.
Table 1 compares precipitation, catchment areas, and other attributes of the eight study areas. Brief descriptions of distinguishing features in each of the study sites follow.

Abo Arroyo Study Site

Abo Arroyo divides the northern tip of the Los Piños Mountains (maximum elevation 2,347 m) from the southern portion of the Manzano Mountains in central New Mexico. The study reach begins near the mountain front, where it has a contributing area of 650 square kilometers (km^2; table 1;



[1]Tributary of the Mojave River Basin.

[2]Tributary of the San Pedro River.

Figure 5. Streamflow and precipitation record for each study site investigated during a multiyear investigation of ground-water recharge, southwestern United States. (Figure by Stanley A. Leake.)

chapter D, this volume). The arroyo enters the Middle Rio Grande Basin, cutting deeply into a bajada (piedmont alluvial plain) formed by the coalescence of many individual alluvial fans. Approximately 12 km from the mountain front, the piedmont terminates, and Abo Arroyo cuts into a stepped sequence of ancestral fluvial terraces of the Rio Grande. The study reach terminates at the confluence of Abo Arroyo and the Rio Grande floodplain (fig. 2). Abo Arroyo is the largest catchment on the eastern side of the Middle Rio Grande Basin.

Amargosa River Study Site

For this study, the selected reach of the Amargosa River is in the Amargosa Desert, a southeast-trending valley where the southern Great Basin overlaps the northern Mojave Desert. The Amargosa River Basin is bounded by block-faulted mountains composed primarily of lower-Paleozoic sedimentary rocks and Tertiary volcanic rocks, and was formed by detachment and normal faulting (chapter E, this volume). The channel enters the Amargosa Desert downstream of Beatty, Nev. The watershed above the entry point has an area of approximately 1,200 km^2 (table 1). Downstream of the entry point, basin-fill alluvium thickens rapidly from less than one meter to several hundred meters. The Amargosa River terminates in Death Valley, Calif. The Amargosa Desert area is among the most arid regions in the United States.

Arroyo Hondo Study Site

Arroyo Hondo is a small mountain-front stream in the southeastern Española Basin, north-central New Mexico (chapter F, this volume). Arroyo Hondo is typical of mountain-front streams draining the western slopes of the Sangre de Cristo Mountains. The mountain front is a sharply defined contact between granitic bedrock and basin-fill alluvium forming the Tesuque aquifer, approximately 2 km below the reach of perennial flow. Arroyo Hondo joins the Santa Fe River before dropping into the Middle Rio Grande Basin (fig. 2). The area of the Arroyo Hondo watershed at the bottom of the instrumented reach is approximately 156 km^2, with 26 km^2 (17 percent) upstream of the mountain front (table 1). The Arroyo Hondo study reach had the highest elevations of the eight research sites.

Tributaries of the Mojave River Basin Study Site

The study area in the western Mojave Desert is northeast of the Los Angeles Basin, along the northern slope of the San Bernardino and San Gabriel mountains (chapter G, this volume). The San Bernardino Mountains are composed largely of granitic rock. The San Gabriel Mountains are composed of granitic and metamorphic rock. Ephemeral flow and associated recharge were examined in five tributaries flowing into the Mojave River Basin. Headwater areas are modified by active tectonism. One of the tributaries, Oro Grande Wash, no longer has contact with the mountain front due to strike-slip movement along the bounding San Andreas Fault.

Rillito Creek Study Site

Rillito Creek is an ephemeral tributary of the Santa Cruz River in south-central Arizona. Surrounding mountains consist of block-faulted granitic, metamorphic, volcanic, and consolidated sedimentary rocks (chapter H, this volume). Basin-fill ranges from gravel to clay-rich and anhydrous playal deposits. Coarse sediments along the basin margins grade to fine-grained and evaporitic sequences in the central parts of the basins. Alluvial thicknesses range from a few meters along mountain fronts to more 3,000 m in the center of the basin. Rillito Creek had the largest contributing area of the study sites (table 1).

Sand Hollow Study Site

Sand Hollow (southwestern Utah) is a bowl-like feature on the Colorado Plateau created by synclinal (concave upward) warpage of Navajo Sandstone, which crops out to form the rim of the basin (fig. 2). The sandstone consists of well-sorted, wind-deposited fine-to-medium sand (primarily quartz) cemented by calcite (chapter I, this volume). The thickness of the sandstone bedrock reaches 350 m. Cross-bedding structures impart small-scale anisotropy to permeability. Fracture zones impart a main control on ground-water recharge. Fractures zones are up to tens of meters wide, separated by wider zones without much fracturing. Lower parts of the basin are covered with up to three meters of soil. Soils range from coarse-grained sand adjacent to bedrock at higher elevations to loamy sands and sandy loams at lower elevations. Evapotranspiration returns most precipitation to the atmosphere (chapter I, this volume). Thin layers of calcrete (less than 1-m thick) commonly form at the contact between soils—particularly fine-grained soils—and underlying sandstone. The sandstone basin lacked a stream connection to the regional drain.

Tributaries of the San Pedro River Study Site

The San Pedro River (southeastern Arizona) runs northward through basin-fill alluvium separating mountain blocks of relatively subdued topography (table 1; fig. 2). A mixture of rock types similar to those in the Rillito Creek study area form the mountain blocks. Basin soils are dominated by lithic, loamy, and fine-grained paleosoils near the mountains, and clayey and calcium-carbonate rich soils along the lower reaches of tributary watersheds (chapter J, this volume). Loamy soils form narrow corridors along the tributary channels, separated by large expanses of less-permeable soils. Calcium-carbonate soils dominate the eastern part of the basin, and the southwestern part of the basin is dominated by sandy soils. The study characterized 27 tributaries on the basis of geomorphology, vegetation, and soils. Ephemeral flow and associated ground-water recharge were detailed for five streams—Banning Creek, Greenbush Draw, Miller Canyon Wash, Willow Creek, and Walnut Gulch.

Trout Creek Study Site

Trout Creek drains a mountain-block watershed in the northern part of the Great Basin, Nevada. A normal fault separates the upper-mountain reach from the middle-mountain reach (chapter K, this volume). The distribution of bedrock influences runoff generation and associated ground-water recharge from rainfall and snowmelt. The highest reaches of the watershed are underlain by folded and faulted Paleozoic sedimentary rocks of low permeability. Downstream of the fault, the channel crosses Tertiary volcanics overlain by poorly sorted Pleistocene alluvium. The channel continues on recent alluvium deposited by streams that began cutting downward into older gravel fans in the late Pleistocene. Once on the Humboldt River plain, the channel continues on Holocene alluvium incised into older alluvium. Trout Creek is a mountain tributary that receives most of its runoff from snowmelt.

Precipitation During the Study Period

Winter rain and spring snowmelt generally are more effective at producing ground-water recharge than is an equal amount of summer precipitation, due to lower evapotranspiration losses associated with lower temperatures and dormant vegetation (chapter B, this volume). Antecedent conditions control the initial water content of channel sediments, which regardless of season can determine whether a given volume of streamflow generates recharge after entering a basin. Because of antecedent conditions, the timing of precipitation can have as much importance as the total amount.

Precipitation during the study period exhibited regionally dependent seasonal and inter-annual patterns. These patterns reflected proximity to moisture sources (primarily the Pacific Ocean and Gulf of California), annual shifts in storm tracks and monsoonal circulation, and global-scale, multiyear fluctuations (chapter A, this volume). Winter and spring precipitation dominated the western and northern sites (Amargosa, Mojave, and Trout Creek; blue sections, fig. 6, and summer and fall precipitation dominated the southern (San Pedro and Rillito) and eastern (Abo Arroyo and Arroyo Hondo) sites (orange and yellow sections, fig. 6). Precipitation at the Sand Hollow site, near the center of the study area, had the most balanced seasonal pattern. While sampling periods varied, observed patterns were consistent with regional expectations (chapter A, this volume). The Amargosa Desert had the lowest daily frequency of precipitation, at eight percent, while Arroyo Hondo had the highest daily frequency of precipitation, at 23 percent.

The climatic pattern during the study period (1997–2002) was one of generally wetter-than-normal conditions near the beginning followed by a shift to gen-

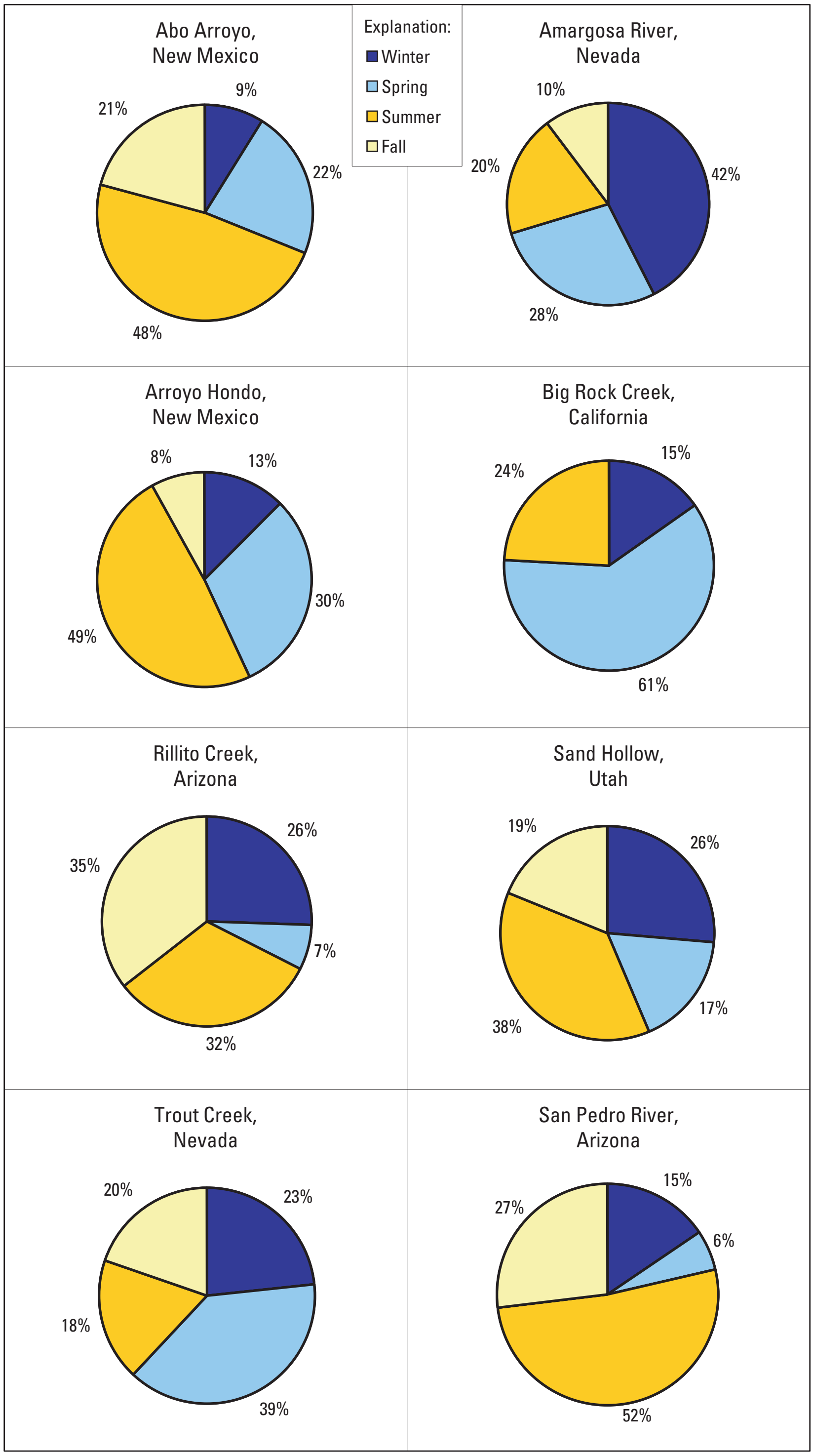


Figure 6. Seasonal distribution of precipitation at the eight study sites during the investigation. Numbers indicate the percentage of annual precipitation during the indicated season. Winter (December, January, and February) is dark blue; spring (March, April, and May) is light blue; summer (June, July, and August) is orange; and fall (Sepember, October, and November) is yellow.

erally drier-than-normal conditions (figs. 7–8). Figure 7 shows regional precipitation and a drought-severity index at two-year intervals. By the end of the study, moderate to severe drought affected nearly all western and midwestern states (fig. 7). Initial wetter-than-normal conditions included development of an El-Niño pattern that brought warm water to the eastern tropical Pacific and shifted North American winter storms southward into the study area (chapter A, this volume). The 1997–98 El Niño was the strongest on record, as determined by satellite-measured sea-surface temperatures (Curtis and Adler, 2000). The subsequent drought was associated with La Niña conditions that included unprecedented warmth in the tropical western Pacific and Indian oceans (Hoerling and Kumar, 2003).

Figure 8 shows trends in annual precipitation for each of the study sites as percentages of mean conditions. The estimates of mean conditions were derived from the global synthesis of meteorologic data archived by the National Oceanic and Atmospheric Administration (Kalnay and others, 1996). Plotted values are estimates for each two-degree by two-degree cell containing a study site (about 220 km north-south by 180 km east-west). These estimates provide an internally consistent comparison of regional variations throughout the study period.

Study sites fall into three groups with respect to regional climatic influences. Sites to the north and west (fig. 8*A*) were more strongly affected by El-Niño conditions than were the sites to the east and south (fig. 8*B*). Sites to the east and south, in turn, were more strongly affected by the weakening of monsoonal conditions. Sand Hollow, near the center of the study area, was affected by both El-Niño and monsoonal conditions, and it showed large relative changes during the study period.

Streamflow During the Study Period

Surface water and ground water are interlinked systems (Alley and others, 2002). Ground-water discharge provides base flow to gaining portions of streams; conversely, enhanced streamflow in response to storms and snowmelt produces ground-water recharge beneath losing portions of streams. Even though lags are introduced by storage changes together with variable-frequency travel times through channel networks, unsaturated zones, and ground-water systems, stream flows are roughly correlated with ground-water recharge. Streamflow records thus provide indirect, but readily accessible information on seasonal and year-to-year trends in ground-water recharge.

The shift to drought conditions during the study period reduced streamflow—and associated ground-water recharge—across the range of drainage-integration areas. To demonstrate these changes at a regional scale, figure 9 compares mean daily streamflows in 1998 and 2002 with long-term average mean daily streamflows for selected regional rivers in the study area—the Rio Grande in central New Mexico (USGS streamflow-gaging station 08330000), the Humboldt River in north-central Nevada (10322500), the Virgin River in northern Arizona (09415000), the Mojave River in central southern California (10261500), and the San Pedro River in southeastern Arizona (09471000). Diamonds in figure 1 show the locations of the gages, which were selected for having continuous records dating back at least to mid century. While all streamflows are impacted by human activities to some degree, rivers and stations were selected for having relatively small anthropogenic effects.

Average mean-daily streamflow for the period 1945–2002 (thick colored lines, fig. 9) show patterns consistent with regional climatic trends. For example, flows in the Humboldt River increase after the arrival of winter storms and peak in early June, due to the dominant influence of spring snowmelt. Flows in the Mojave River peak soon after the arrival of winter storms (January–February), but lack a strong snowmelt signature. The Rio Grande shows a broad peak in flows, from April through June, due to sustained snowmelt from the southern Colorado Rockies. Rio Grande flows rise again to a secondary peak in early November, after the growing season. A similar feature in the Humboldt record (barely apparent at the plotted scale) is explained by the seasonal slowdown of evapotranspiration (Prudic and others, 2006). The July and August peak in San Pedro flows marks the arrival of the summer-monsoon season.

With the exception of the San Pedro River, flow volumes in regional rivers were higher than normal in 1998 (fig. 9). Compared to their respective long-term (1945–2002) averages, annual flow volumes ranged from 101–180 percent of normal in the Rio Grande, Humboldt, Virgin, and Mojave Rivers (table 2). By 2002, annual flow volumes had declined to 10–46 percent of average, revealing the effects of severe drought. In 1998, annual total flow in the San Pedro River was only 31 percent of the 1945–2002 average, and it decreased further to 21 percent by 2002. San Pedro River annual flow volumes, while highly variable, have decreased 66 percent from 1913 to 2002 due to factors other than a shift in climate (Thomas and Pool, 2006).

Discussions of streamflow at individual study sites are presented in subsequent chapters. Streamflow-gaging stations for each site are shown in figure 10. Figure 10 also shows a general view of Sand Hollow, where no stream was present. The bedrock channel at the Big Rock Creek gage (Mojave River Basin) minimized shifts from deposition, scour, and vegetation. The channel at the Walnut Gulch gage (San Pedro River Basin) was a concrete weir designed to accurately measure a wide range of flow rates. The channel at the Abo Arroyo gage was floored by bedrock, but walled by semiconsolidated alluvium, whereas the gage at Rillito Creek was walled by soil cement, but floored by unconsolidated sediment. Statistically fitted curves relating streamflow to stage (water depth) had correlation coefficients whose squares ranged from 0.97 for Big Rock Creek to 0.54 for Arroyo Hondo, which had the smallest catchment (table 1) and largest influences from changing vegetation and shifting sediments.

Figure 11 compares streamflow records for the seven gaged sites, although, records at Arroyo Hondo and Trout Creek were of limited duration. Gages integrated runoff from catchments over a wide range of sizes (table 1) and were sensitively expressive of exact position with respect to the crossover

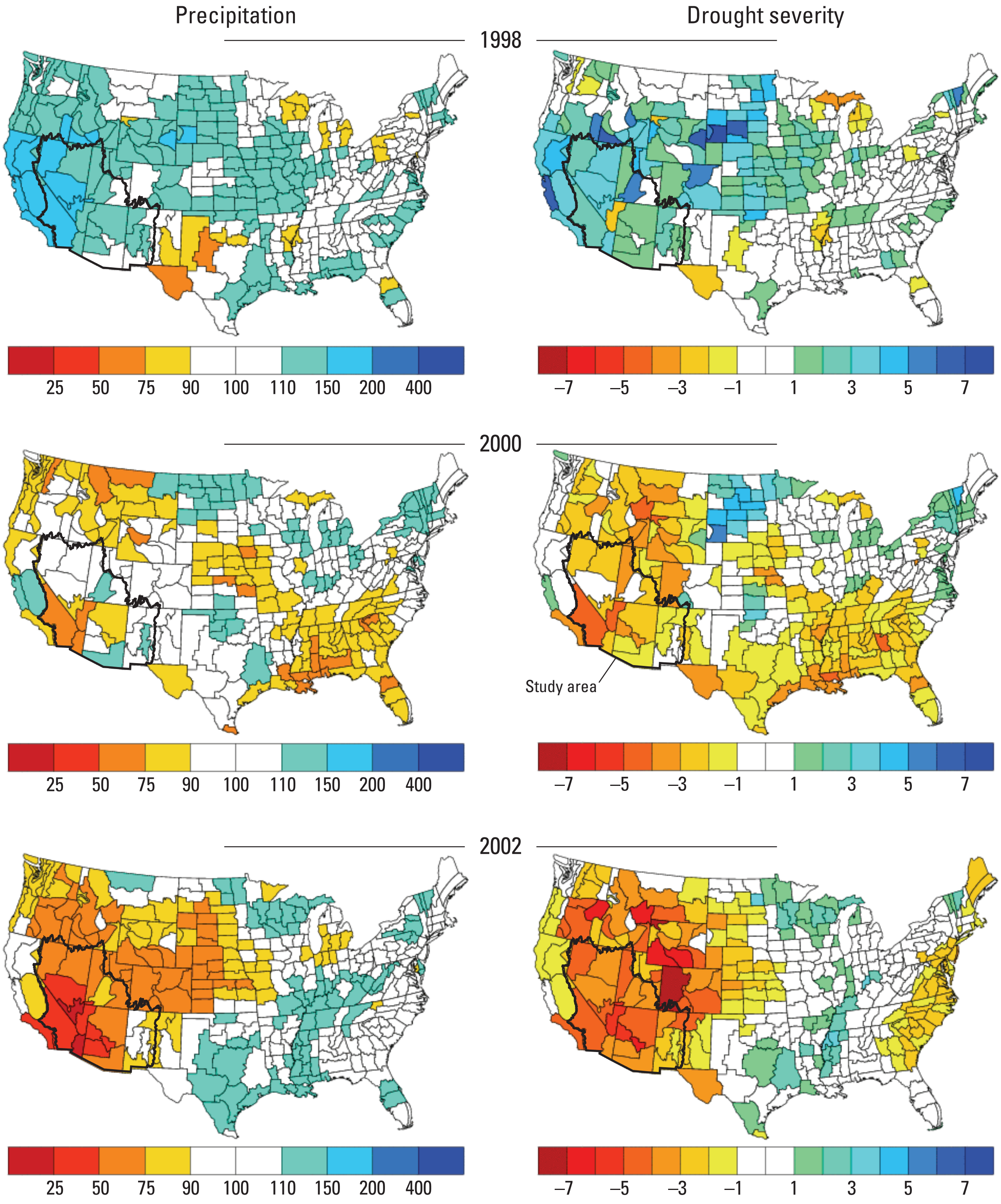


Figure 7. Development of drought conditions in the United States during the study period. Figures at left show annual precipitation in 1998, 2000, and 2002 as a percentage of a long-term (46-year) average (1950–1995). Figures at right show a version of the Palmer drought severity index, which takes into account cumulative soil-moisture deficit and heat stress (Heim, 2002). Negative values indicate drier than normal conditions, with –3 indicating the onset of severe drought. Data by climate division, from the National Oceanic and Atmospheric Administration (http://www.cdc.noaa.gov/USclimate, accessed December 7, 2006).

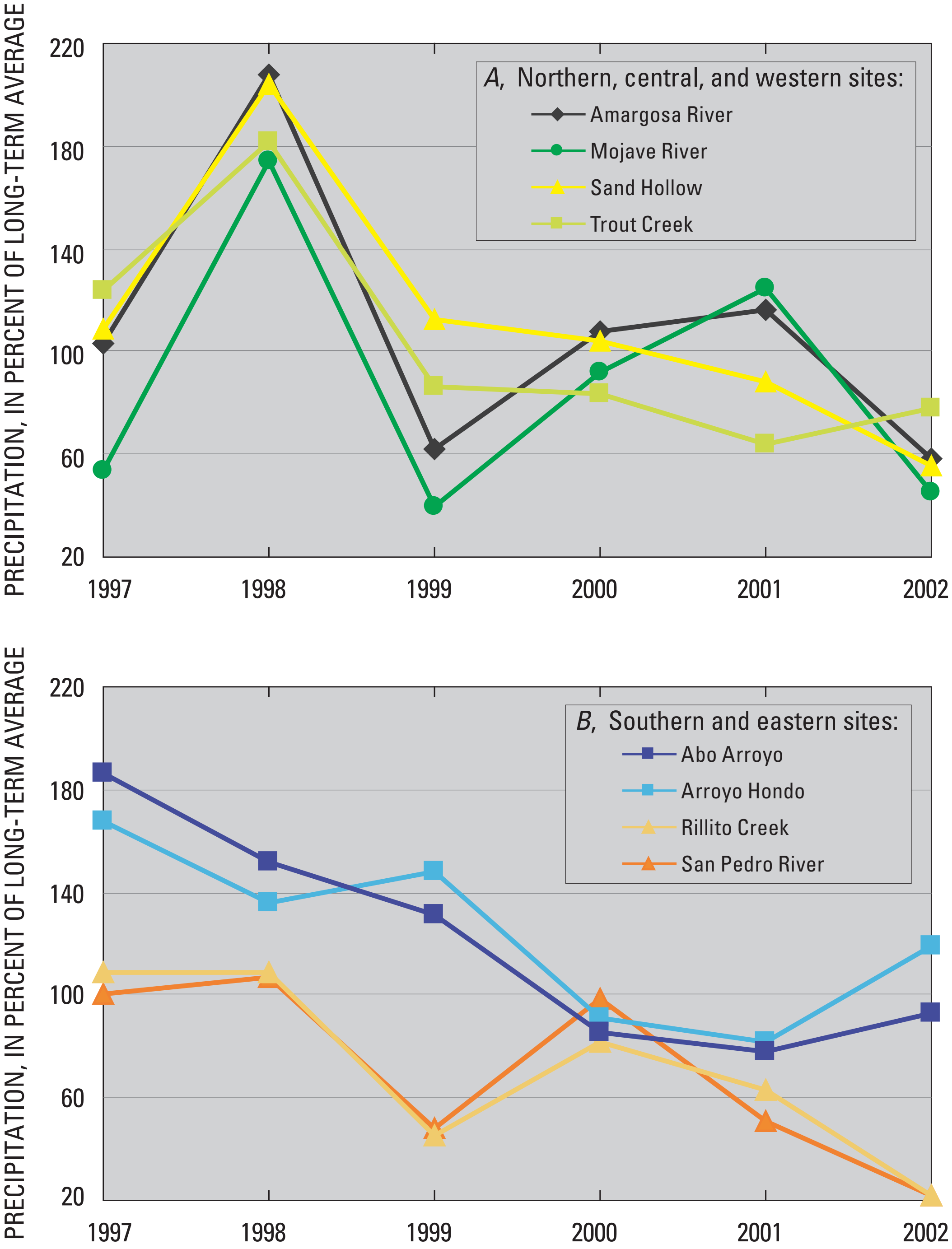
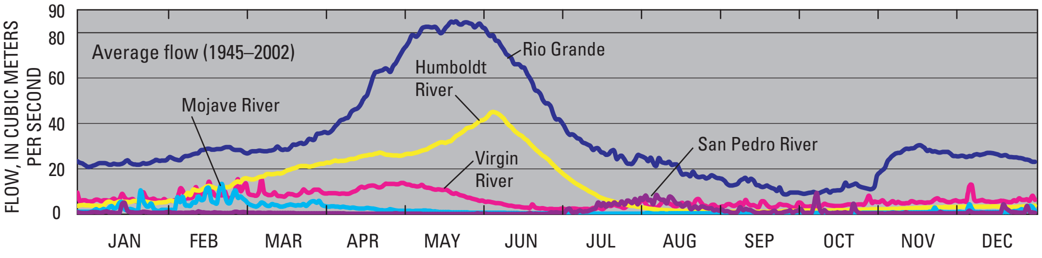


Figure 8. Precipitation as a percentage of long-term (1948–2005) average precipitation for *A*, northern, central, and western study sites and *B*, southern and eastern study sites. Data for each two-degree by two-degree latitude-longitude cell from http://www.cdc.noaa.gov/Timeseries, accessed December 5, 2006.

A, Seasonal distribution of long-term average mean daily flow, 1945–2002



B, Mean daily flow in 1998 and 2002 versus long-term average

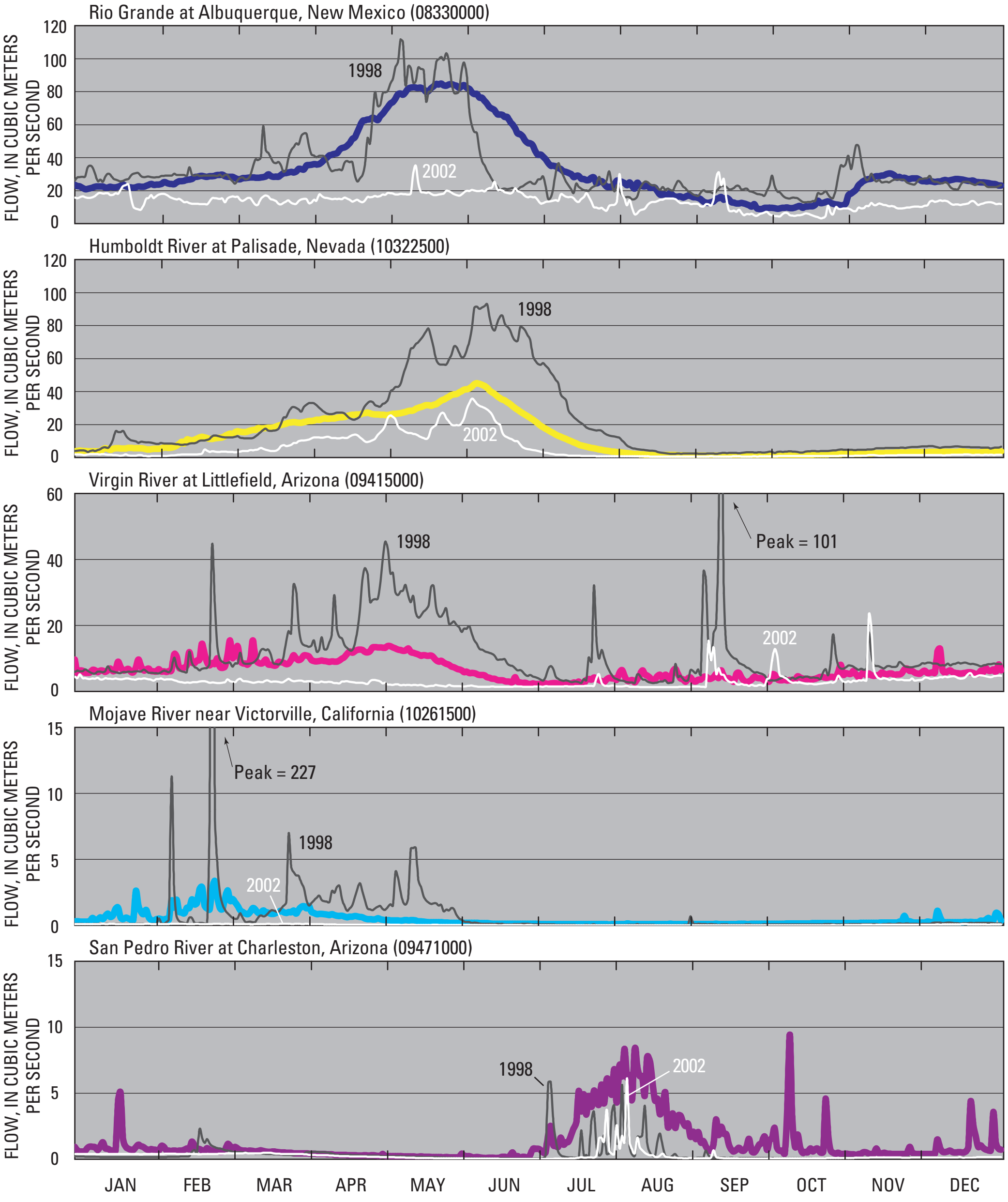


Figure 9. Hydrographs of regional rivers, comparing *A*, long-term average daily mean streamflow (thick colored lines) with *B*, daily mean streamflow for 1998 (black lines) and 2002 (white lines). Values in parentheses are USGS streamflow-gaging station identifiers; figure 1 shows the streamflow-gaging station locations. Data from http://waterdata.usgs.gov/nwis (accessed March 28, 2007).

Table 2. Annual flow volumes in regional rivers, compared to long-term averages, southwestern United States.

[Volumes computed from mean daily flows obtained from http://waterdata.usgs.gov/nwis, accessed April 24, 2007; numbers in parentheses are USGS streamflow-gaging station identifiers. Colors indicate highest—blue and lowest—red annual flow volume for each river]

Period	Rio Grande, New Mexico (08330000)	Humboldt River, Nevada (10322500)	Virgin River, Utah (09415000)	Mojave River, California (10261500)	San Pedro River, Arizona (09471000)
Average annual flow volume, in cubic meters					
1945–2002	1.05 10^9	3.78 10^8	2.05 10^8	5.75 10^7	4.01 10^7
Annual flow volume, in percent of 1945–2002 average					
1997	**141**	168	93	19	40
1998	101	**176**	**172**	**180**	31
1999	113	101	71	18	68
2000	66	55	67	14	**224**
2001	69	**27**	62	11	57
2002	**41**	46	**46**	**10**	**21**

between streamflow generation and streamflow loss. Even so, the effects of climatic variability on streamflow at the ground-water recharge study sites were readily apparent. Summer monsoonal precipitation produced substantial flow at Rillito Creek throughout the developing drought. Gages at Walnut Gulch (a tributary of the San Pedro River) and sites beyond the influence of monsoonal storms (Trout Creek and Big Rock Creek, for example) recorded extended periods of negligible flow (fig. 11). Four of the study sites had extended periods of zero or negligible flow that lasted about 9–15 months. The higher variability of study-site streamflow relative to regional streamflow reflects smaller scales of integration in time and space of the study-site watersheds.

Annual focused infiltration volumes at the study sites ranged from less than 0.1 to about 10 million cubic meters per year (Mm^3/yr) (chapters D–K, this volume). Environmental tracers indicated that Sand Hollow produced recharge directly through the bedrock, controlled largely by fracturing. For the other sites, comparison of estimated average annual infiltration volumes with corresponding catchment areas suggests an upper limit on associated recharge for sites with focused infiltration from streamflow (fig. 12). The low correlation between focused infiltration rates and watershed size is consistent with results shown in figure 3, partly reflecting short records but also indicating differences in orography and other factors. The Amargosa River produced comparatively little focused infiltration for its basin size relative to the Mojave tributaries. Despite having similar precipitation at their respective gages, the Mojave tributaries collect runoff from higher elevations located near the leading edge of Pacific storms (table 1). Trout Creek and Arroyo Hondo were sampled only during drier-than-normal conditions and, therefore, would be expected to have higher average annual focused-infiltration volumes for a longer period of record. Substantial volumes of focused infiltration were estimated for Rillito Creek, Abo Arroyo, and San Pedro tributaries, resulting primarily from summer monsoonal precipitation. In contrast, for Trout Creek, the Amargosa River, and the Mojave River Basin tributaries, focused infiltration was largely from winter precipitation (and subsequent snowmelt at Trout Creek).

Conclusions

Large variations in seasonal patterns of precipitation affected regional streamflows, focused infiltration, and associated ground-water recharge during the study period (1997–2002). The timing of precipitation and snowmelt controlled the timing of streamflow. Strong El Niño conditions in 1997–1998 roughly doubled the annual precipitation (in 1998)

Abo Arroyo (Rio Grande Rift, central New Mexico)

Jim Constantz

Amargosa River (southern Basin and Range, Nevada)

Amy E. Stewart-Deaker

Arroyo Hondo (Rio Grande Rift, north-central New Mexico)

Jim Constantz

Big Rock Creek (Mojave River Basin, California)

USGS file photograph

Rillito Creek (Santa Cruz River Basin, Arizona)

Jim Constantz

Sand Hollow (southwestern Colorado Plateau, Utah)

Victor C. Heilweil

Trout Creek (northern Basin and Range, Nevada)

James L. Wood

Walnut Gulch (San Pedro River Basin, Arizona)

USDA file photograph

Figure 10. Streamflow-gaging stations listed in table 1 for seven of the study sites, plus a general view of Sand Hollow, where no stream was present. Figure 1 shows study-site locations.

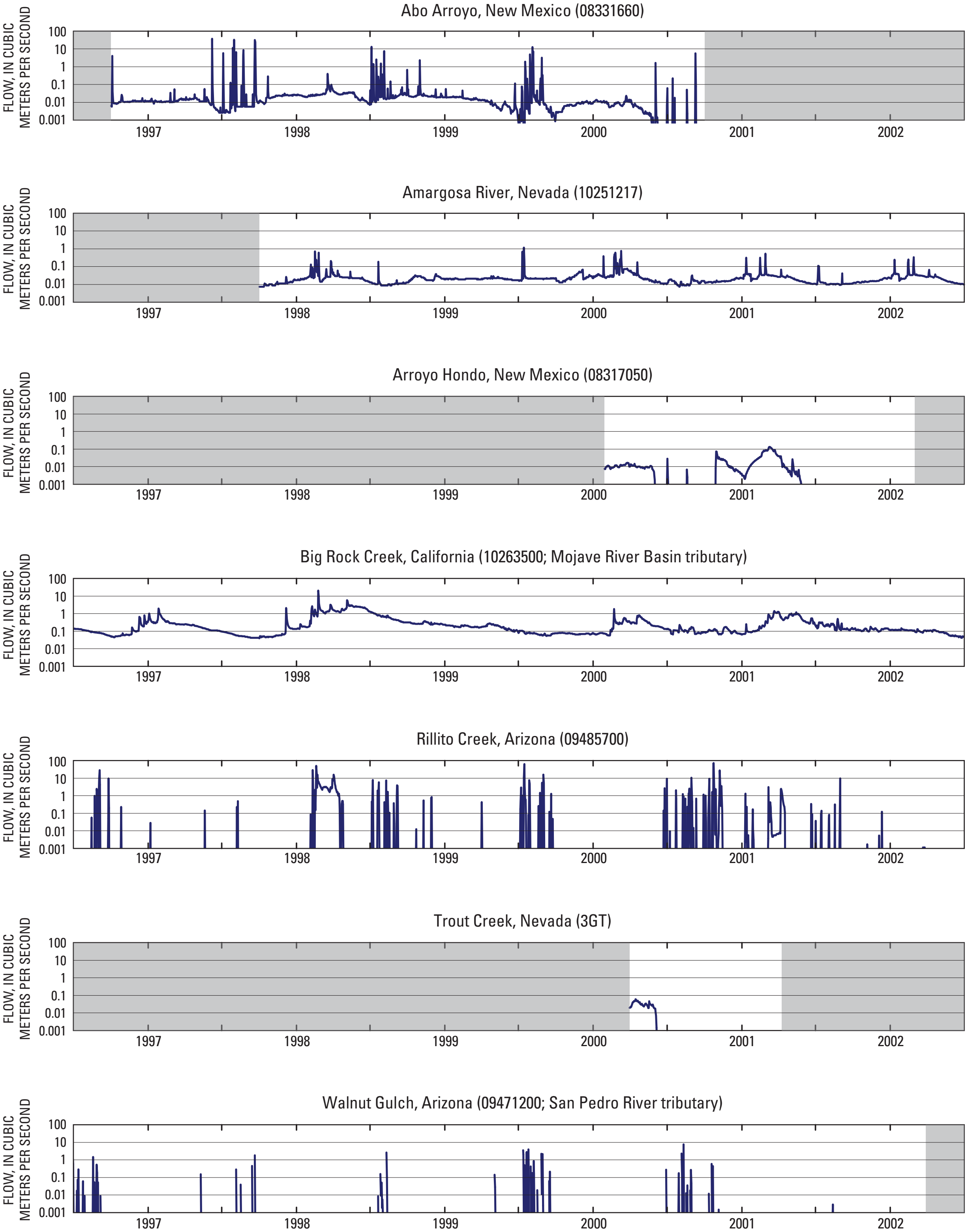


Figure 11. Hydrographs showing streamflow data from July 1, 1996 to July 1, 2002, for the seven study sites with streams, southwestern United States. Gray areas indicate periods without streamflow data. Station identifiers are given in parentheses (see table 1 for explanations).

at the northern, western, and central sites. Subsequent development of severe drought affected streamflow in regional rivers, as well as at the study sites. Overall, summer monsoonal rainfall was the main contributor to runoff and associated recharge at the southern sites, while winter precipitation (and associated snowmelt, where present) was the main contributor at the northern and western sites.

Most of the study sites feature one or more stream channels that originate in contributing upland watersheds dominated by bedrock and cross mountain-front faults into adjoining alluvial basins. Abrupt increases in the thickness of coarse sediments downstream of the mountain front are associated with rapid streamflow losses and focused ground-water recharge. The prolonged drought during the study reduced streamflows crossing the mountain fronts, thereby reducing the potential for focused infiltration and ground-water recharge during this phase of the climatic cycle. Intra- and inter-annual variations in precipitation control streamflow generation and associated ground-water recharge. A main conclusion of the study is the degree to which interpretations of infiltration and ground-water-recharge estimates require knowledge of the meteorologic and climatic conditions to which they correspond.

Ephemeral streamflow produced volumes of focused infiltration in the study area that scaled roughly with catchment area, placing an upper limit on ground-water recharge from transmission losses. The timing of focused infiltration in the Southwest is highly variable and sensitive to climatic fluctuations, such as El Niño cycles and drought. Drought impacted regional flows, as well as focused infiltration volumes throughout the study area, reducing contributions of focused infiltration to basin recharge. Measurements made at the study sites indicate that focused infiltration can become negligible during extended periods of severe drought; however, sites receiving summer monsoonal rains can continue to generate focused recharge even during droughts.

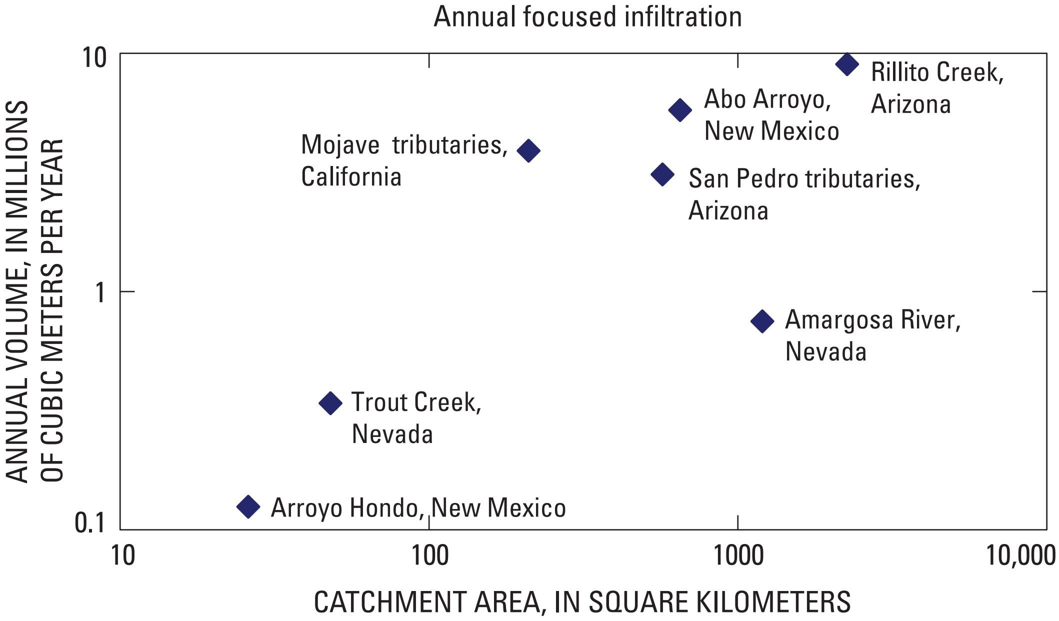


Figure 12. Estimated annual focused-infiltration volumes versus catchment areas (aggregated in the case of the Mojave River Basin tributaries and San Pedro River tributaries).

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