Regional Analysis of Ground-Water Recharge

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Abstract

A modeling analysis of runoff and ground-water recharge for the arid and semiarid southwestern United States was performed to investigate the interactions of climate and other controlling factors and to place the eight study-site investigations into a regional context. A distributed-parameter water-balance model (the Basin Characterization Model, or BCM) was used in the analysis. Data requirements of the BCM included digital representations of topography, soils, geology, and vegetation, together with monthly time-series of precipitation and air-temperature data. Time-series of potential evapotranspiration were generated by using a submodel for solar radiation, taking into account topographic shading, cloudiness, and vegetation density. Snowpack accumulation and melting were modeled using precipitation and air-temperature data. Amounts of water available for runoff and ground-water recharge were calculated on the basis of water-budget considerations by using measured- and generated-meteorologic time series together with estimates of soil-water storage and saturated hydraulic conductivity of subsoil geologic units. Calculations were made on a computational grid with a horizontal resolution of about 270 meters for the entire 1,033,840 square-kilometer study area. The modeling analysis was composed of 194 basins, including the eight basins containing ground-water recharge-site investigations. For each grid cell, the BCM computed monthly values of potential evapotranspiration, soil-water storage, in-place ground-water recharge, and runoff (potential stream flow). A fixed percentage of runoff was assumed to become recharge beneath channels operating at a finer resolution than the computational grid of the BCM. Monthly precipitation and temperature data from 1941 to 2004 were used to explore climatic variability in runoff and ground-water recharge.

The selected approach provided a framework for classifying study-site basins with respect to climate and dominant recharge processes. The average climate for all 194 basins ranged from hyperarid to humid, with arid and semiarid basins predominating (fig. 6, chapter A, this volume). Four of the 194 basins had an aridity index of dry subhumid; two of the basins were humid. Of the eight recharge-study sites, six were in semiarid basins, and two were in arid basins. Average-annual potential evapotranspiration showed a regional gradient from less than 1 m/yr in the northeastern part of the study area to more than 2 m/yr in the southwestern part of the study area. Average-annual precipitation was lowest in the two arid-site basins and highest in the two study-site basins in southern Arizona. The relative amount of runoff to in-place recharge varied throughout the study area, reflecting differences primarily in soil water-holding capacity, saturated hydraulic conductivity of subsoil materials, and snowpack dynamics. Climatic forcing expressed in El Niño and Pacific Decadal Oscillation indices strongly influenced the generation of precipitation throughout the study area. Positive values of both indices correlated with the highest amounts of runoff and ground-water recharge.

Introduction

A regional analysis was performed to assess the processes, properties, and climatic factors that affect recharge and runoff variability in the arid and semiarid southwestern United States. The regional analysis was part of a larger study designed to improve understanding of ground-water–surface-water interactions and their effects on the availability and sustainability of ground-water supplies within the study area. The study area includes aquifer systems in Arizona and parts of California, Nevada, New Mexico, and Utah (chapter A, this volume; fig. 1), most of the Basin and Range physiographic province in Arizona, California, Nevada, New Mexico, and Utah, and a large portion of the Colorado Plateau in Arizona, New Mexico, and Utah (Fenneman, 1931). The regional analysis complemented the site-specific ground-water recharge studies, which examined frequency and distribution of streamflow losses and attendant recharge for typical streams and subbasins across the study area. Results from the recharge study-site investigations are described in chapters D–K.

Without a regional framework, results from individual study sites would be difficult to assess given that sites are widely separated, and that climate, soils, and geology differ among the sites. A regional framework increases the extrapolative value of subbasin-scale studies by systematically quantifying the interactions among processes, properties, and climatic factors producing runoff and ground-water recharge. The objective of the analysis was to provide a regionally consistent framework that could be used to characterize basins throughout the entire study area. The distributed-parameter, water-balance model known as the Basin Characterization Model (BCM; Flint and others, 2004; Flint and Flint, 2007) was applied to evaluate regional climatic factors and physical properties that produce runoff and ground-water recharge. The analysis model employs a deterministic mathematical approach that accounts for the temporal and spatial distribu-

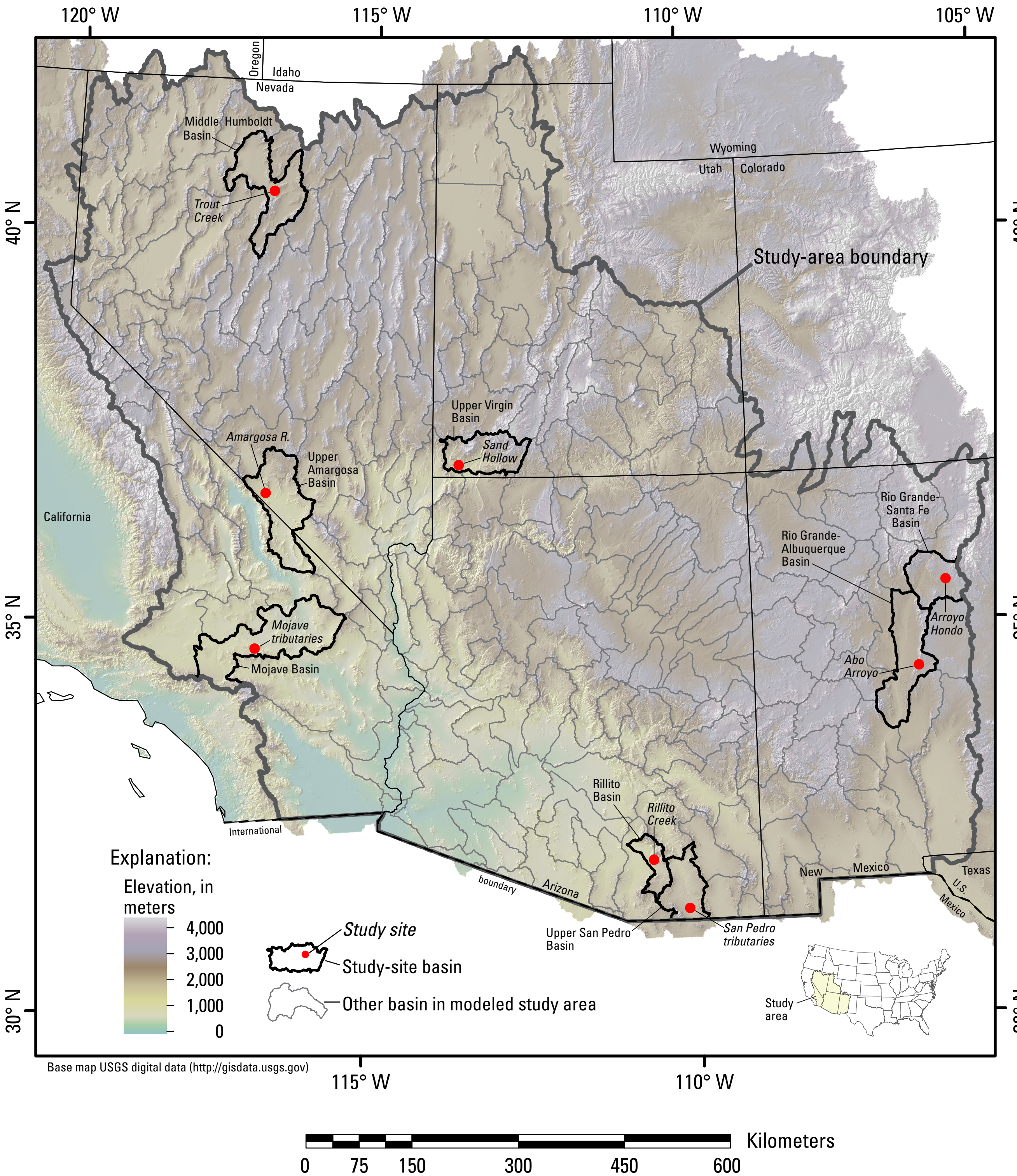

Figure 1. Digital elevation map showing locations of the 194 basins within the modeled arid and semiarid southwestern U.S. study area. Red dots indicate ground-water recharge study sites (chapters D–K, this volume). Basin outlines are drainage areas of USGS 1:250,000 hydrologic accounting units, each of which is identified by an eight-digit hydrologic accounting code (8-digit HUC in table 1) (Seaber and others, 1987).

tion of precipitation (including the accumulation and melting of snow) together with the spatial distribution of soils, vegetation, and hydraulic conductivity of underlying materials; the model also estimates potential evapotranspiration and accounts for changing quantities water stored in the soil (Flint and others, 2004). Available geographic-information-system data (digital GIS coverages), including topography, vegetation, soils, geology, and average monthly precipitation and air temperature were used for the analysis. Estimates of slope and aspect were generated within the model on the basis of digital topographic data.

The BCM was used to estimate quantities of water available for generating runoff (potential streamflow) and in-place (subsoil) recharge within the 194 basins that make up the study area (fig. 1). The 194 basins were defined by using the drainage areas of the U.S. Geological Survey's 1:250,000-scale hydrologic units (Seaber and others, 1987; http://water.usgs.gov/GIS/metadata/usgswrd/XML/huc250k.xml). The analysis allowed the basins containing the eight recharge-study sites to be compared to one another, as well as to other basins in the study area. Figure 1 shows the location of each study site. The eight study sites occupied a relatively small portion of the basins for which in-place recharge and runoff were estimated by using the BCM. Comparison of study-site basins with other basins provides a basis for assessing representativeness within the context of the entire region, and for interpreting differences in precipitation, snowpack dynamics, and in-place recharge or runoff within the context of geologic, vegetational, and soil differences. The analysis included climatic conditions from 1996–2002 for interpretations relevant to the recharge study-site investigations and climatic conditions from 1941–2004 for evaluation of longer-term climate cycles.

Conceptual Framework

A Classification of Basins by Water-Balance Considerations

Basins were classified on the basis of their climate, runoff, and in-place recharge. Spatially distributed estimates of in-place recharge and runoff provided a means to explore fundamental concepts and evaluate mechanisms that control ground-water recharge in all basins of the study area relative to the basins of the eight ground-water recharge-study sites. The effects of precipitation, snowpack accumulation and melting, soil properties including thickness, and hydraulic conductivity of underlying geologic materials were evaluated by using the BCM model. Basins were characterized as being dominated by runoff or by in-place recharge.

The basins of the study area typically consist of three principal geomorphic features—mountains, piedmont slopes consisting of coalescing alluvial fans or a piedmont alluvial plain, and lower valley floors (Thornbury, 1969, p. 271). Piedmont slopes are transition areas between the higher mountains and valley floors. Precipitation generally is higher in the mountains and lower on valley floors, whereas temperature generally is warmer on valley floors and cooler in the mountains (Houghton and others, 1975). Consequently, snow accumulation typically is greater and potential evapotranspiration is less in the mountains than on the piedmont slopes and valley floors.

Ground-water recharge in the mountains occurs from infiltration of precipitation and snowmelt; infiltration of runoff in perennial, intermittent, and ephemeral streams; and from infiltration beneath wetlands and lakes. Direct infiltration into bedrock can occur without runoff in mountainous areas where bedrock is sufficiently permeable, such as areas in eastern Nevada and western Utah underlain by thick sequences of permeable carbonates (Mifflin and Hess, 1979; Harrill and Prudic, 1998; Flint and Flint, 2007). Ground-water recharge on piedmont slopes commonly is limited to infiltration losses along intermittent or ephemeral streams that cross generally coarse-grained basin-fill deposits (chapters D–K). Ground-water recharge on the valley floors can occur from infiltration losses from regional rivers, such as the Colorado, Rio Grande, and Humboldt. Ground-water recharge on valley floors also can occur beneath intermittent and ephemeral streams, playas, lakes, and reservoirs, and—at higher elevations—from direct infiltration during years with extensive snowmelt. Most runoff is generated in the mountains where there is more precipitation and accumulation of winter snow (Eakin and others, 1976; Prudic and others, 1995). A fraction of runoff from the mountains becomes ground-water recharge from infiltration losses along streams that cross piedmont slopes or valley floors.

Conceptually, these processes can be considered "mountain-block recharge" where the water recharges directly into bedrock; "mountain-front recharge" where runoff from the mountain block reaches the piedmont slopes and infiltrates; "diffuse recharge" on the valley floor, and "recharge from stream flow" (Stephens, 1995). The simplified approach used by the BCM calculates mountain-block and diffuse recharge as potential in-place recharge. The recharge is considered potential because the BCM does not keep track of whether or not the water returns to the surface as spring flow from a perched water table before reaching the regional aquifer. Neither runoff nor ground water is routed within the model; rather, the amounts of runoff and in-place recharge are treated as basin characteristics. Some runoff subsequently becomes ground-water recharge. The percentage of runoff that becomes ground-water recharge is variable, depending on the hydraulic properties of soils, geologic units, and streambeds, as well as the hydraulic gradient between ground water and surface water. Estimates of recharge and runoff were made for twelve basins of the Basin and Range carbonate-aquifer system (Flint and Flint, 2007). Results indicated that about 15 percent of runoff typically becomes recharge on the basis of ground-water discharge estimates and estimates of interbasin flow (Laczniak and others, 2007; Lundmark and others, 2007). Stonestrom and others (2004) calculated that 12–15 percent of ephemeral runoff became recharge in the Amargosa River in southern

Nevada. A calibrated model of unsaturated-zone heat and water flow combined with evapotranspiration measurements, chloride-mass balance estimates, and microgravity measurements at the Walnut Gulch watershed in southeastern Arizona indicated that recharge from ephemeral-stream flow constituted 15–40 percent of total flow during a high runoff year (Goodrich and others, 2004). Studies in the southern Mojave Desert indicated that about 10 percent of ephemeral-stream flow became recharge (Izbicki, 2002). A distributed-parameter rainfall-runoff-recharge model, calibrated to (1) stream discharge and (2) a calibrated ground-water model for the Death Valley regional flow system, resulted in approximately 10 percent of runoff becoming recharge (Hevesi and others, 2003). Prudic and others (chapter K, this volume) and Ronan and others (1998) found that as much as 90 percent of runoff became recharge in the Trout Creek area of the Middle Humboldt Basin and in the Carson River drainage near Carson City, Nevada, respectively. These sites are characterized by high precipitation, snowpack, and runoff compared to most other basins in the study area. The resulting unsaturated zone is thin, optimizing the connection between surface water and ground water while enhancing stream flow recharge. The percentage of runoff that becomes recharge is spatially and temporally variable and difficult to quantify. For the purposes of initial comparisons, the present BCM analysis assumed that 15 percent of runoff subsequently became ground-water recharge.

Methods of Estimating Ground-Water Recharge

Flint and others (2002) and Scanlon and others (2002) reviewed methods that have been used to estimate ground-water recharge in the study area. Among methods most commonly used are calculations based on Darcy's law, calculations based on repeated measurements of water-content profiles, inverse calculations based on deviations of measured temperature profiles from heat-conduction-only profiles, chloride-mass balance calculations, calculations based on the decay of atmospherically deposited radionuclides, empirical-transfer methods relating precipitation to ground-water discharge, and distributed-parameter water-balance modeling. Of these methods, only the distributed-parameter water-balance modeling and empirical transfer methods provide spatially distributed estimates throughout a selected region. Maxey and Eakin (1949) developed an empirical method to estimate average annual ground-water recharge in 13 basins in eastern Nevada by using annual precipitation maps delineated by isohyetal contours (Hardman, 1936; 1965). Ground-water recharge was estimated as a percentage of mean-annual precipitation for five distinct ranges of precipitation. Recharge estimates did not address where recharge occurs within a basin. The method was evaluated by Watson and others (1976), who found it useful for providing initial approximations. Estimates of recharge for 12 basins in eastern Nevada produced with the BCM were somewhat higher but relatively close to the estimates of Maxey and Eakin (Flint and Flint, 2007).

Estimating Runoff and In-Place Recharge With a Distributed-Parameter Water-Balance Model

The BCM was used to identify locations and climatic conditions that allow for excess water to become potential runoff or potential in-place recharge, and to estimate the amount of each. Runoff is the volume of water for a given time frame that becomes stream flow and either infiltrates down slope or exits the basin as stream flow. As shown in subsequent chapters, much of the down-slope infiltration exits the basin as evapotranspiration. In-place recharge is calculated as the volume of water for a given time frame that can drain from the soil zone directly into consolidated bedrock or unconsolidated deposits. Ground-water recharge is the combination of in-place recharge and 15 percent of runoff.

A water-balance equation for each 270-meter grid cell was developed by using monthly estimates of precipitation, maximum and minimum air temperature, and potential evapotranspiration. Composite values were used to calculate the monthly volume of runoff and in-place recharge for each basin. The volume of water potentially available for runoff and in-place recharge (*AW*) per unit area of each cell was estimated monthly on the basis of the following equation:

$$AW = P + S_m - PET - S_a + S_s, \qquad (1)$$

where P is the estimated precipitation for the grid cell, S_m is the estimated snowmelt, PET is the potential evapotranspiration, S_a is the estimated snow accumulation, and S_s is the soil-water storage from the previous month. Snow accumulation that does not melt during the month is carried over into the following month. All volumes per grid-cell area are in units of millimeters per month.

Runoff is generated from water in excess of the total soil-water storage capacity (soil porosity multiplied by soil depth). In-place recharge is generated from soil water in excess of the field capacity of the soil (the water content at which drainage becomes negligible), and occurs at a rate determined by the hydraulic conductivity of the underlying materials.

Potential evapotranspiration is modeled on a daily basis from solar radiation that is modeled by using topographic shading and a correction for cloudiness (Flint and Flint, 2008), and is partitioned on the basis of vegetation cover to represent bare-soil evaporation and evapotranspiration due to vegetation. These results are averaged into monthly values for use in equation 1. Depending on the soil-water storage and hydraulic conductivity of the underlying consolidated rocks and basin-fill deposits, excess water is partitioned as either in-place recharge or runoff that potentially can become ground-water recharge from infiltration losses further downstream in the mountains, piedmont slopes or valley floors.

Excess water, calculated as the summed values of average monthly precipitation minus average monthly potential

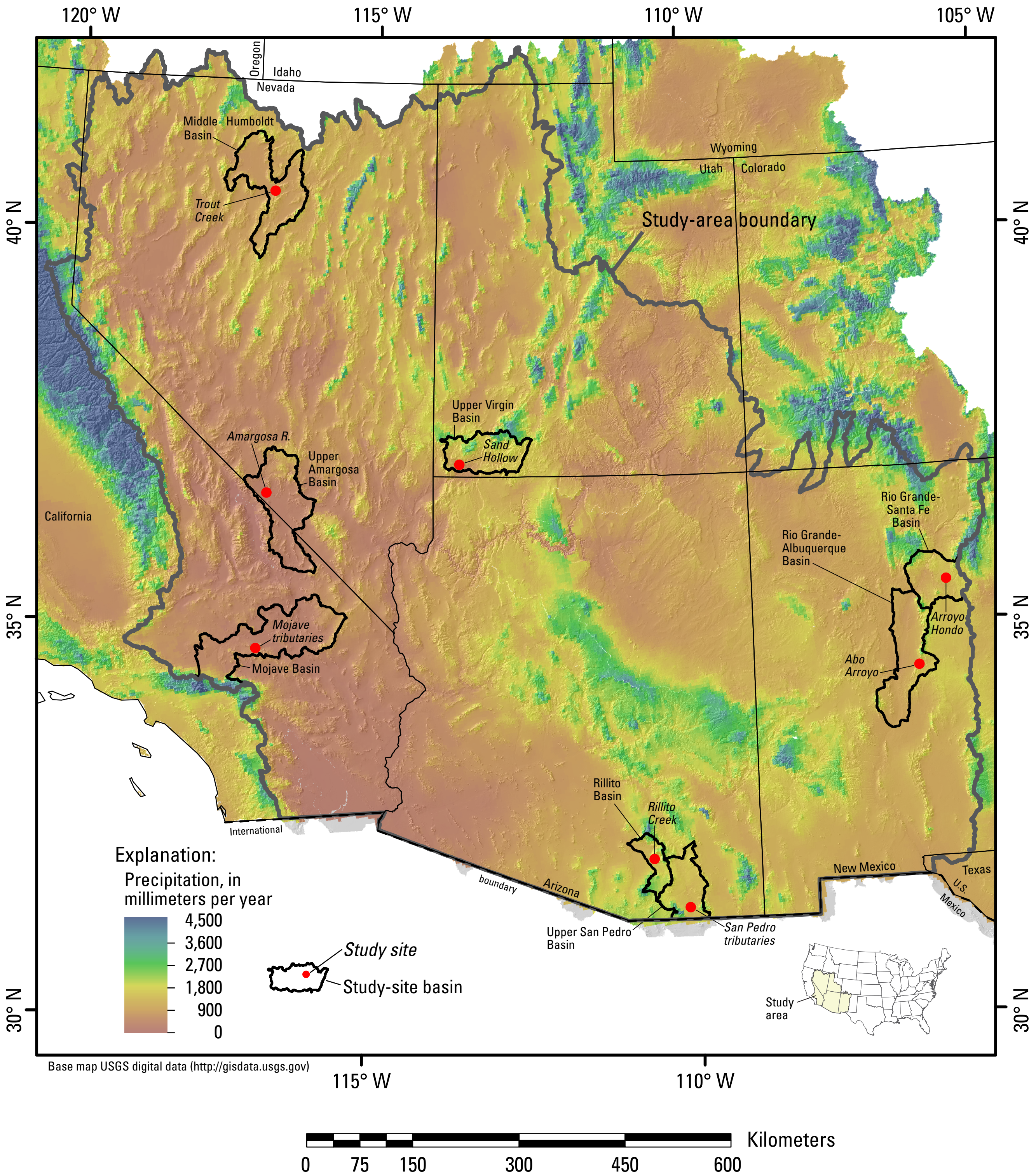

Figure 2. Average annual precipitation for 1971–2000 within the modeled arid and semiarid southwestern U.S. study area, calculated from monthly Precipitation-elevation Regression on Independent Slopes Method (PRISM) data (Daly and others, 2004).

evapotranspiration, is illustrated in figure 3. The excess water is the amount of water that remains in the system, assuming evapotranspiration consumes the maximum possible amount of water. This excess water is the amount available to replenish soil-water storage and generate runoff and in-place recharge. Although recharge can occur in areas with no excess water, the monthly time step limits the ability of the model to resolve short-term dynamics. Figure 3 illustrates this simple water balance concept—no excess water is calculated by using a monthly time step in most of the low-lying desert areas in southern Arizona, southeastern California, southern Nevada, and southern New Mexico. Most of the excess water is in the higher-elevation mountains and plateaus.

Maximum in-place recharge is limited by the assumed hydraulic conductivity of consolidated rocks in the mountains, or basin-fill deposits on the piedmont slopes and valley floors. The volumetric rate is expressed in millimeters per month. When soil-water storage is at total capacity, in-place recharge is set equal to the hydraulic conductivity of the underlying consolidated rocks in the mountains, or basin-fill deposits in the piedmont slopes and valley floors; drainage will continue until the soil-water storage is at field capacity. Any remaining water in the soil zone above field capacity at the end of the month is added to soil-water storage (S_s) at the beginning of the next month. Additionally, any remaining snow accumulation and soil-water storage from the end of a month is added to the beginning of the next month. This becomes important when temperatures are cold enough for precipitation to arrive as snow. Because snow may persist for several months before melting, large volumes of water can be made available for runoff and in-place recharge in a single monthly time step.

The model does not distinguish where runoff may infiltrate through the streambed and become ground-water recharge, nor does it explicitly define the percentage of runoff that becomes ground-water recharge. Because there is insufficient information to partition excess water into runoff and in-place recharge accurately without further refinements to the BCM and additional calibration of parameters, average annual estimates and distribution of runoff, in-place recharge, and ground-water recharge in each basin should be treated as general approximations.

An additional limitation to the BCM is that the calculation of ground-water recharge assumes that water draining past the root zone becomes recharge within that monthly time step, without consideration of the potential for extended periods of ground-water travel time through the unsaturated zone. In the more arid portions of the study area, the unsaturated zone may exceed 100 meters (m) in thickness across broad areas. Calculations of ground-water travel time in the southern Great Basin area have exceeded 10,000 years (Flint and others, 2000) due to variation in net infiltration rates and the thickness of the unsaturated zone, which is commonly 10–100 m thick, but can exceed 2,000 m. However, some locations in mountainous areas have shallow unsaturated zones and may recharge to local ground-water within the monthly time step.

Despite the simplifications of the model, the consistent application of the parameters controlling runoff and in-place recharge provides a means for regional analysis of these mechanisms during the 1996–2002 time frame of the eight ground-water recharge-site investigations. In addition, the BCM allows for the evaluation of runoff and in-place recharge during past wetter and drier climates and the role of decadal-scale climate cycles (El Niño/La Niña and the Pacific Decadal Oscillation).

Precipitation, snowmelt, and overland runoff from upslope areas provide the source of water that infiltrates into the soil zone. Thickness of the soil zone, porosity, and drainage characteristics determine how much water is stored in the soil zone. Rooting depth, type of vegetation, percentage of bare-soil surfaces, and the energy balance control the rate of potential evapotranspiration. Evapotranspiration is highest during the warm summer months, which decreases the amount of water stored in the soil zone, and lowest during the cool winter months, which allows for increased soil-water storage from precipitation, snowmelt, and run-on events. The topography and atmospheric conditions control much of the energy available for potential evapotranspiration. Drainage below the root zone occurs when sufficient water is available to exceed the water-storage capacity of the soil (or rock), only then does “net infiltration” have the potential to become ground-water recharge.

Generally, the hydraulic conductivity of consolidated rocks in the mountains or basin-fill deposits on piedmont slopes and valley floors, soil-water storage capacity, and potential evapotranspiration are the factors that determine the rate of drainage from the soil zone. In locations with thin soils, soil thickness becomes the most important factor affecting soil-water storage capacity. The soil-water storage in thin soils underlain by fractured bedrock will approach capacity (saturation) because the water-entry potential of the fracture network must be exceeded before significant drainage into the underlying bedrock can occur. If the soil is thin and the hydraulic conductivity of the underlying consolidated rocks or basin-fill deposits is low, then evapotranspiration has more time to remove stored water between periods of precipitation, snowmelt, and run-on from upslope areas. If the hydraulic conductivity of the underlying consolidated rock or basin-fill deposits is high, evapotranspiration has less time to remove stored water between infiltration events.

In locations with thick soil, a greater volume of water is needed, compared with thin soil locations, to exceed the soil-water storage capacity of the root zone. If the soil-water storage capacity is high and the hydraulic conductivity of the soil zone is low (for example, fine-grained silt and clay), then drainage through the root zone occurs slowly, and evapotranspiration has more time to remove stored water between periods of precipitation, snowmelt, and run-on from upslope areas. If the soil-water storage capacity is low and the hydraulic conductivity of the soil zone is high (coarse sand and gravel), then drainage through the root zone occurs rapidly, and evapotranspiration has less time to remove stored water.

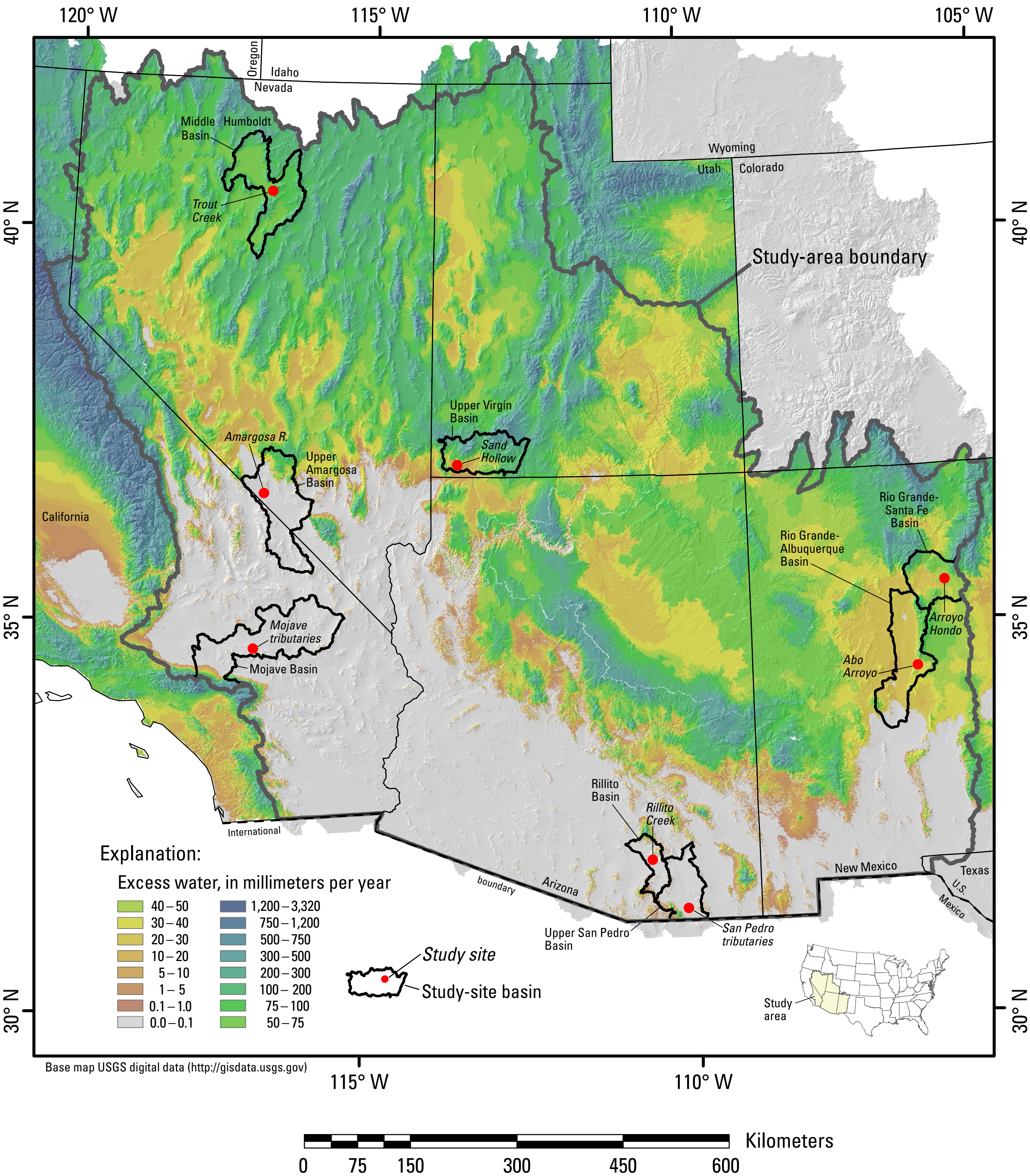

Figure 3. Estimates of annual excess water within the modeled arid and semiarid southwestern United States study area, calculated as the summed values of average monthly precipitation minus average monthly potential evapotranspiration. Texas, Wyoming, and portions of Colorado outside the study area were not included in the analysis.

The mechanisms controlling drainage from the soil zone influence where drainage will occur in a given basin. The location of in-place recharge is important, particularly if one intends to quantify or analyze it by means of field measurements. Limiting measurements to locations where streams cross onto basin fill excludes consideration of in-place recharge higher in the mountains that might contribute sizeable amounts of subsurface flow to aquifers underlying piedmont slopes and valley floors. At the same time, applying simplified distributed-parameter water-balance models without sufficient information about controlling parameters also can result in large errors in estimated recharge and runoff. An advantage of using a distributed-parameter water-balance model to complement site-specific studies is that probable locations for runoff and in-place recharge can be identified reasonably well because the distribution of precipitation, snowmelt, evapotranspiration, soil-water storage capacity, and hydraulic conductivity are mapped at moderately high resolution for the various types of soils, consolidated rocks and basin-fill deposits within the study area.

Input Parameters used in the Water-Balance Model

Spatially Distributed Properties of Soils and Geologic Units

Soil-water storage capacity (fig. 4) was estimated by using soil-texture estimates from STATSGO (State Soil Geographic Database), a geospatial database of soil properties that generally are consistent across state boundaries (USDA-SCS, 1991; http://www.ftw.nrcs.usda.gov/stat_data/html. Uncertainties in soil properties are discussed by Hevesi and others (2003) and Gutmann and Small (2007). Soil thickness was estimated from STATSGO data for all locations, except those where Quaternary basin fill (alluvium) was mapped (fig. 5). In locations with alluvium, a depth of 6 m was chosen on the basis of field observations made in the Mojave Desert of desert plant root penetration into alluvium and bedrock. Thus, the BCM assumes that all processes controlling net infiltration occur within the top 6 m of surface materials. This assumption is supported by data from Yucca Mountain in the southern Great Basin (Flint and Flint, 1995). Relatively large soil-water storage capacities were estimated for the areas of Quaternary basin fill in the Basin and Range Province of Arizona, Nevada, southern California, New Mexico, and western Utah (fig. 4), whereas smaller capacities were estimated for much of the Colorado Plateau in northern and eastern Arizona, southern Utah, and northern and western New Mexico.

The surficial geology was classified broadly for the purpose of assigning saturated hydraulic conductivity values to sub-soil consolidated and unconsolidated materials throughout the region. Geologic units were obtained from geologic maps (Arizona: Hirschberg and Pitts, 2000; California: Jennings, 1977; Colorado: Green, 1992; Idaho: Johnson and Raines, 1996; Nevada: Stewart and others, 2003; Oregon: Walker and McLeod, 1991; Utah: Hintz and others, 2000). The principal geologic units include Quaternary to Tertiary unconsolidated to indurated alluvial, eolian, playa, and lacustrine deposits and volcanic rocks; Mesozoic granitic and other intrusive rocks, sandstone, limestone, and other sedimentary, metavolcanic, and metamorphic rocks; Paleozoic carbonate and clastic rocks (quartzite, argillite, shale); and Precambrian igneous, metamorphic, and clastic sedimentary rocks. The units are mapped on the basis of hydrologic character, rather than geologic age (fig. 5). The saturated hydraulic conductivity (fig. 6) was estimated for each surficial bedrock or unconsolidated surficial unit listed in figure 5. Saturated hydraulic conductivities were estimated from literature values, aquifer-test results, and surface-based infiltration experiments. The hydraulic properties of macropores and fractures are incorporated in the bulk estimates of hydraulic conductivity. Hydraulic conductivity estimates of bedrock are relatively uncertain because of the unknown hydraulic properties and spatial distributions of fractures, faults, fault gouge, and shallow infilling materials associated with different bedrock types.

Quaternary basin-fill deposits have the highest saturated hydraulic conductivity in the study area, particularly the eolian deposits and sand and gravel units, whereas finer-grained flood-plain deposits, clay-rich lacustrine deposits, and playa deposits have the lowest values of the basin-fill deposits (fig. 6). Saturated hydraulic conductivity of surficial bedrock usually differs from underlying transmissivity per unit thickness due to surface weathering and infilling of fractures and faults from soils and calcium-carbonate development. However, relative estimates for various rock types can be derived on the basis of ground-water assessments. Carbonates and sandstones are generally the most permeable of the consolidated rocks (Bedinger and others, 1989). Where fractured and porous, carbonates and sandstones have hydraulic conductivities similar to those of sand and gravel aquifers in the basin fill (Winograd and Thordarson, 1975; Dettinger and others, 2000). Granitic rocks, metamorphic rocks (slates, argillites, marbles, and quartzites), and fine-grained sedimentary rocks (siltstones, and shales) typically have very low saturated hydraulic conductivities and porosities (Davis and DeWiest, 1966; Freeze and Cherry, 1979). Volcanic rocks consist of a variety of rocks associated with volcanic activity. Basalt flows and welded tuffs can be highly permeable and have sufficient porosity to store and transmit large quantities of water (Glancy, 1986; Winograd and Thordarson, 1975). Typically, volcanic rocks in the study area are far less porous and permeable than the sand and gravel of the basin fill or the carbonate rocks (fig. 6).

Temporally and Spatially Distributed Parameters of Climate

Spatially distributed monthly estimates of precipitation, minimum and maximum air temperature, and potential

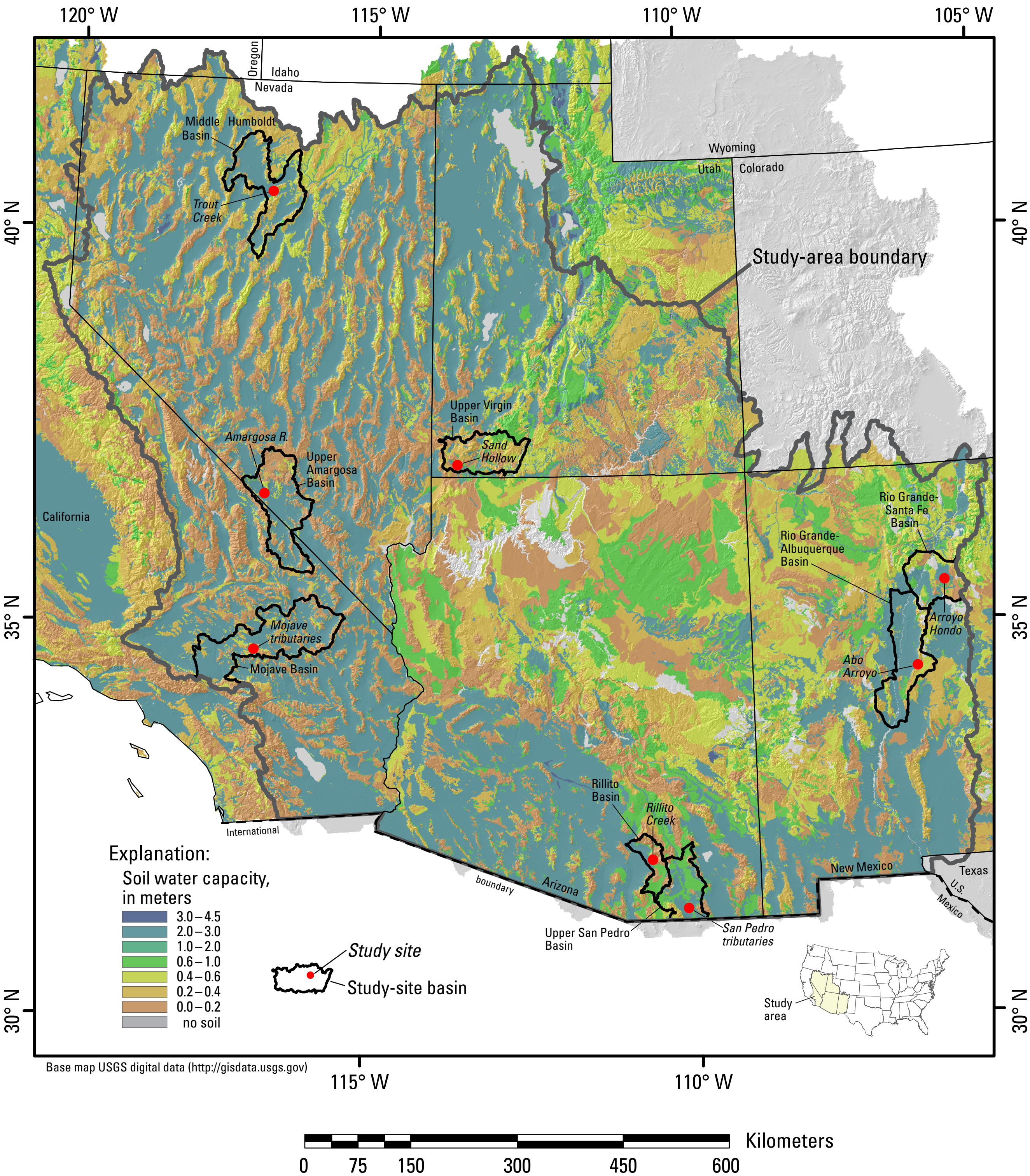

Figure 4. Total soil-water storage capacity for the modeled arid and semiarid southwestern United States study area. Gray areas within the study boundary indicate soil-free bedrock or surface water.

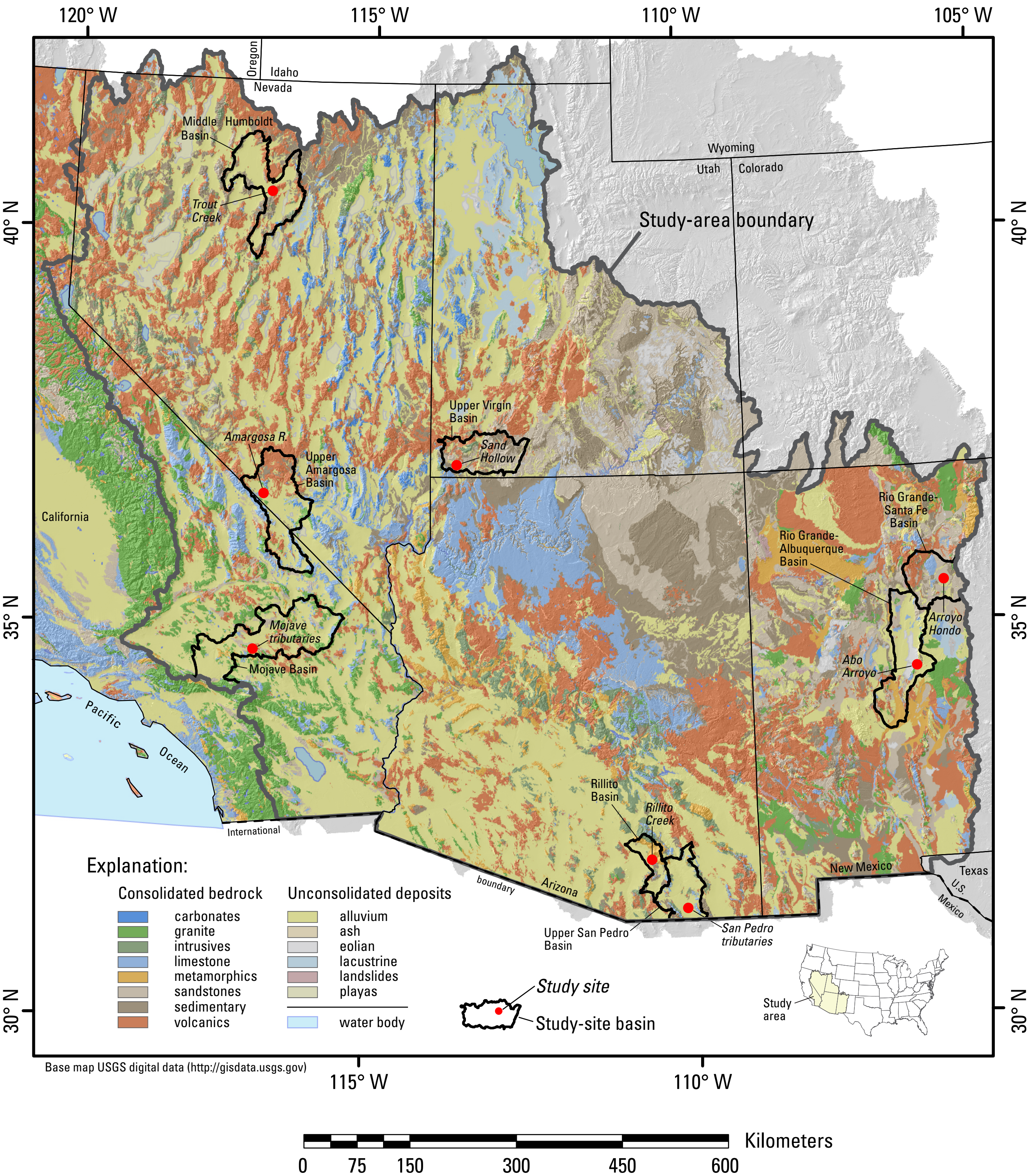

Figure 5. Surficial geology of the modeled arid and semiarid southwestern United States study area. Compiled from: (Arizona) Hirschberg and Pitts, 2000; (California) Jennings, 1977; (Colorado) Green, 1992; (Idaho) Johnson and Raines, 1995; (Nevada) Stewart and others, 2003; and (Utah) Hintz and others, 2000.

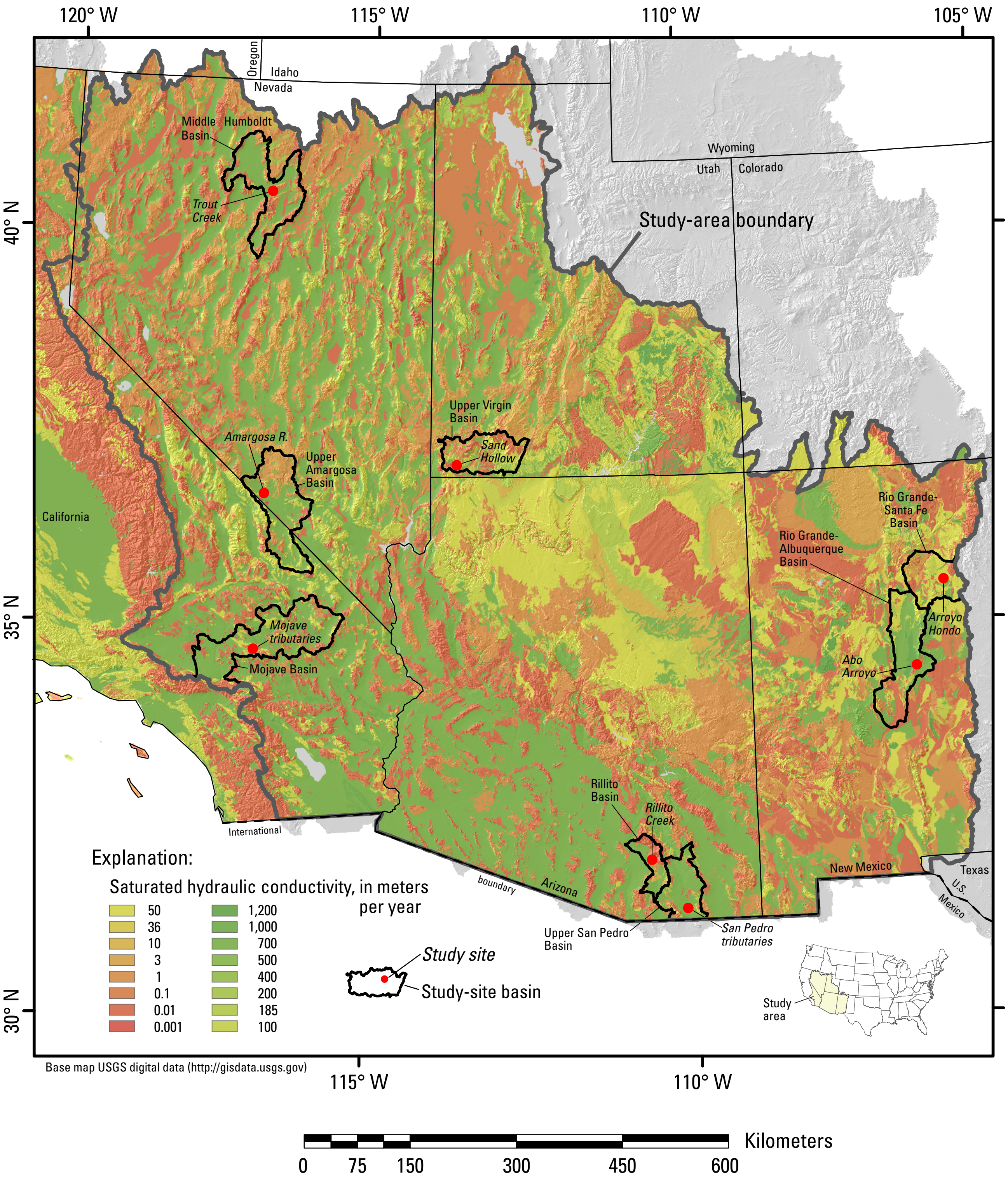

Figure 6. Estimated saturated hydraulic conductivity of surficial geologic units in the modeled arid and semiarid southwestern United States study area. Input to the Basin Characterization Model assumed 16 discrete values of conductivities as shown. Data for water bodies and portions of states outside the study area are not depicted.

evapotranspiration were used to calculate quantities of water available for runoff and in-place recharge by consideration of soil-water storage capacity and hydraulic conductivity of underlying bedrock or unconsolidated materials. Areas of excess water were estimated on a monthly basis.

Precipitation and maximum and minimum air temperatures were derived from a climatic database covering 1941–2004 on a 4,000-m grid (Daly and others, 2004). Centroids of the grid cells were used in downscaling the data to the 270-m BCM grid by applying a multiple-regression method that evaluates spatial gradients by using inverse-distance squared weighting (GIDS) along northing, easting, and elevation dimensions (Nalder and Wein, 1998; Flint and Flint, 2008). The 1941–2004 record was used in a transient analysis to evaluate the effects of antecedent soil-moisture and impacts of recent climatic trends on hydrologic responses, and to provide climatic context for individual study sites. Average monthly values of precipitation and air temperature were also estimated for the period 1971–2000, corresponding to 30-year climatic “normals” (Doggett and others, 2004).

Potential evapotranspiration was estimated by using a computer program modified from Flint and Childs (1987) that calculates solar radiation for the latitude and longitude of each grid cell on the basis of percent of sky viewed due to topographic shading. Computed solar radiation, combined with air temperature, is converted to net radiation and soil-heat flux (Shuttleworth, 1993). The result was used with the Priestley–Taylor equation (Priestley and Taylor, 1972) to estimate potential evapotranspiration (fig. 7), taking into account vegetated and bare-soil areas by using estimates of vegetation cover (fig. 8; National Gap Analysis Program; http://gapanalysis.nbii.gov).

The regional-scale approach of the BCM used computed potential evapotranspiration during monthly time periods in making estimates of ground-water recharge for evaluating mechanisms and differences among basins. Potential evapotranspiration was compared to reference-crop evapotranspiration, ET_o, measured on well-irrigated plots at evapotranspiration stations in Arizona (http://ag.arizona.edu/azmet/) and California (http://www.cimis.water.ca.gov/cimis/). Monthly potential evapotranspiration simulated by the BCM compared well to measured ET_o values, with BCM values overestimated by approximately 10 percent for June, July, and August (fig. 9).

An energy- and mass-balance model for computing snow accumulation and ablation (sublimation plus snowmelt) was adapted from the Snow-17 operational model of the National Weather Service as described by Anderson (1976) and Shamir and Georgakakos (2005). Potential snowmelt was calculated from air temperature and an empirical snowmelt factor that varied by day of year (Lundquist and Flint, 2006). Snow depth was calculated for areas where precipitation occurred with air temperatures at or below 1.5 degrees Celsius. Sublimation was estimated as a percentage of evapotranspiration. Snowmelt was predicted from snowpack energy-balance considerations when air temperatures were above freezing. Empirical snow-accumulation and snowmelt factors were adjusted to match the predicted areal extent of snowpack to satellite data measured with the Moderate-Resolution Imaging Spectroradiometer (MODIS; http://edcdaac.usgs.gov/modis/dataproducts.asp mod43) and fine tuned by varying the temperature threshold at which snowmelt begins (Lundquist and Flint, 2006). Examples of simulated snow cover compared to MODIS-derived snow cover are shown in figure 10 for February 2001, when snowpack was at a maximum, and April 2001, when ablation processes were at a maximum. Although modeled snow distributions differed from observations in detail, the overall snowpack dynamics were represented reasonably well, especially during periods of accumulation and runoff generation.

The results of the BCM were not calibrated to any measured runoff or recharge data. The runoff and recharge estimates produced by the model can thus be viewed as hypothetical values that are perhaps most useful for exploring the relative differences among basins. The BCM did not route water from cell to cell. For simplicity, the percentage of runoff that became recharge was uniformly estimated to be 15 percent. Two submodels of the BCM, one for solar radiation and potential evapotranspiration and one for snow-cover dynamics, were calibrated to measured values. This implies that the water-balance calculations of the BCM have somewhat larger uncertainties in relation to soil properties and precipitation estimates. The partitioning of excess water into runoff and recharge presents the largest uncertainty, as it relies on the estimation of saturated hydraulic conductivity of near-surface materials.

Application to Study-Area Basins

The BCM was applied to the 64-year time series from water year 1941–2004 to evaluate the impact of antecedent hydrologic conditions, and to evaluate recharge mechanisms and amounts under wetter and drier climatic conditions. This period extends through a complete cycle of the negative and positive Pacific Decadal Oscillation. Subsets of this time series were used to provide context for the eight recharge-site investigations. A 30-year record, 1971–2000, was used to compute “normal” monthly conditions for the study area. The 30-year average does not take into account antecedent hydrologic conditions that cause persistence. The nonlinear response of recharge to precipitation tends to underestimate recharge for average monthly conditions because wetter-than-average conditions produce nonlinearly greater amounts of recharge (Flint and others, 2004; Flint and Flint, 2007)

Estimates of annual ground-water recharge for average conditions (calculated as in-place recharge plus 15 percent of runoff) were compiled for all 194 basins in the study area (fig. 11). The results shown indicate that most of the recharge occurs in the mountains of each basin. This was an expected result because the mountains typically have higher precipitation, lower air temperatures, and thinner soils relative to piedmont slopes and valley floors of each basin. Large areas of basin floors with excess water did not produce ground-water recharge because soil-water storage was sufficiently

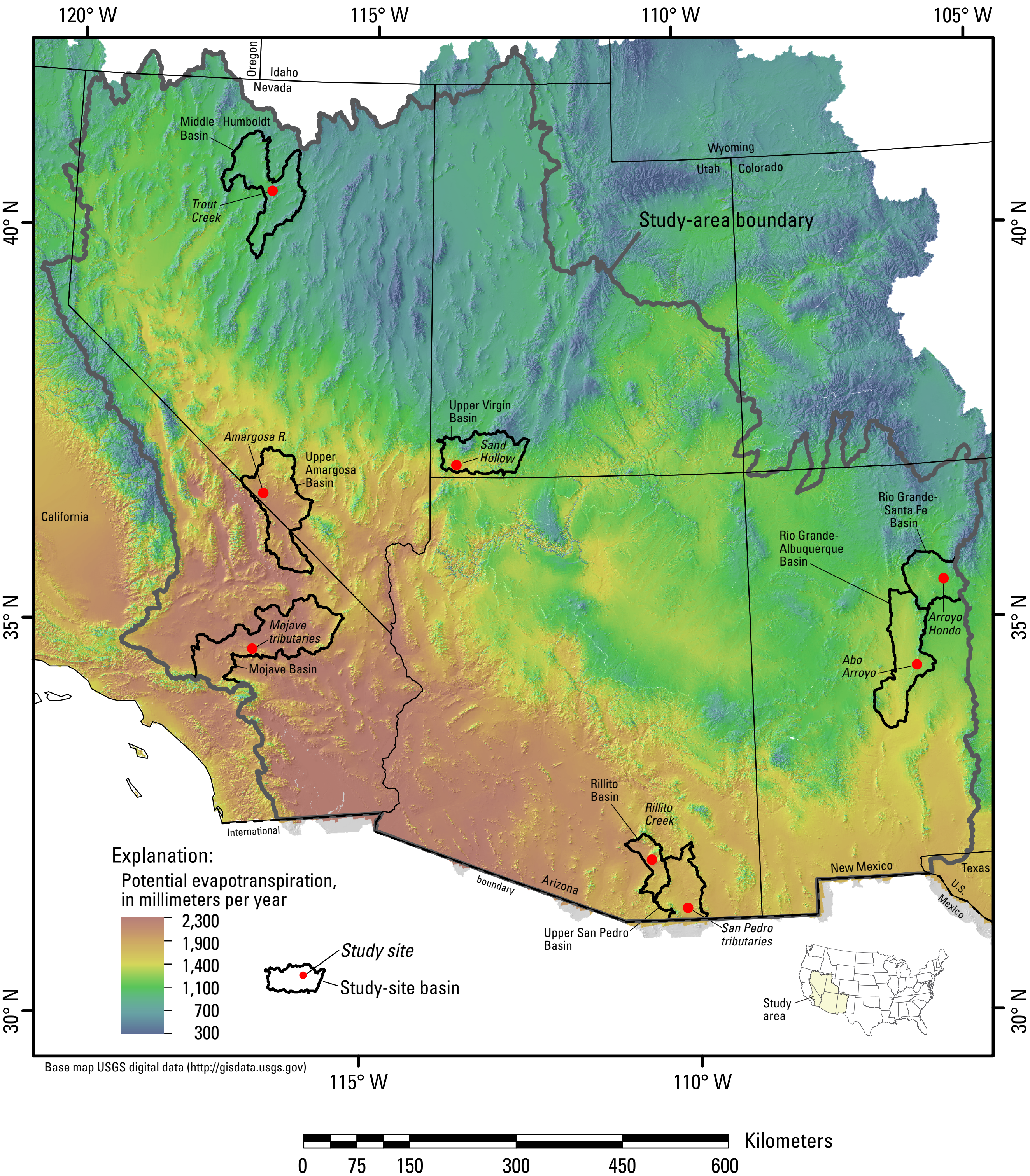

Figure 7. Average annual potential evapotranspiration in the modeled arid and semiarid southwestern United States.

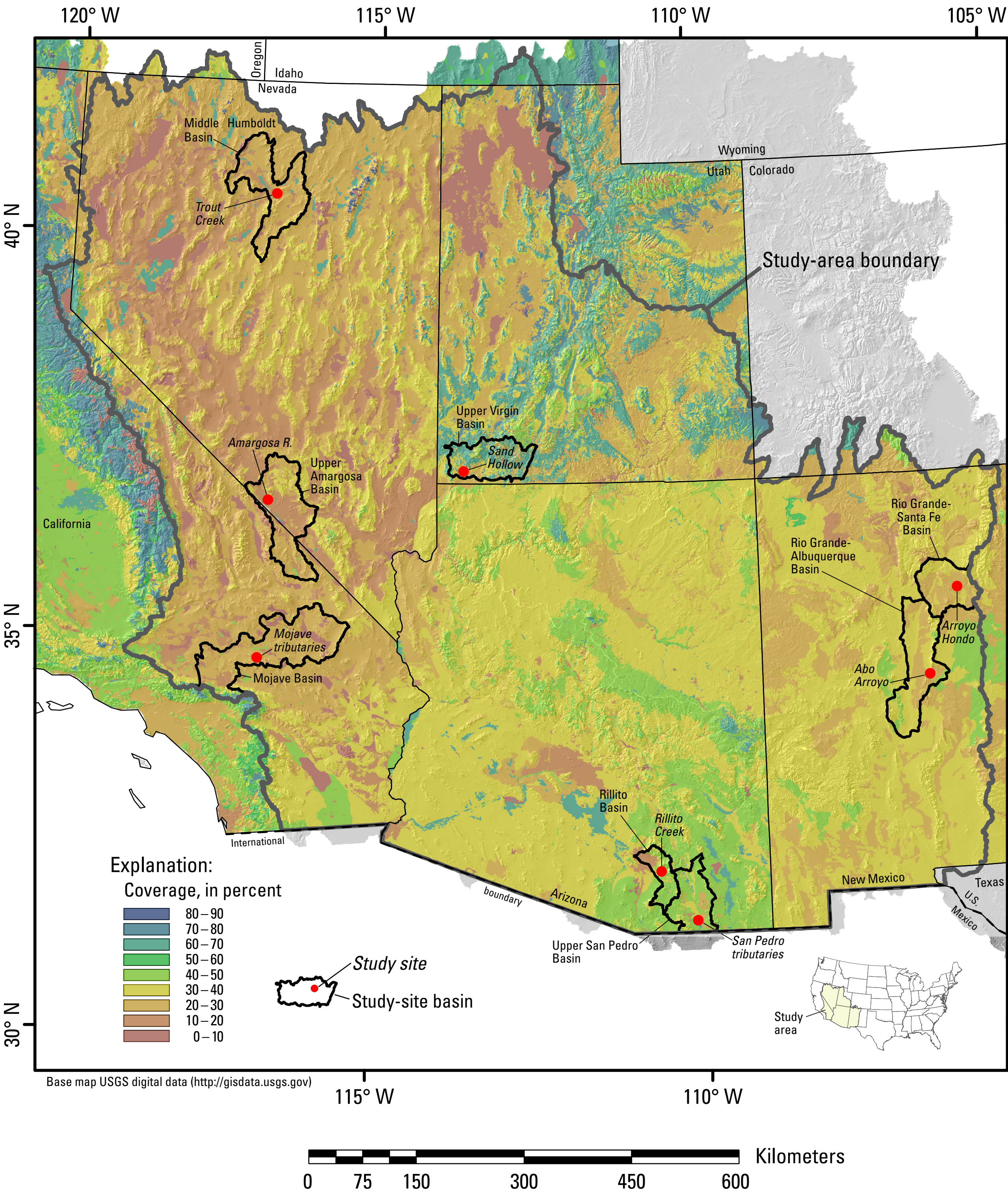

Figure 8. Percentage of area covered by vegetation in the modeled arid and semiarid southwestern United States.

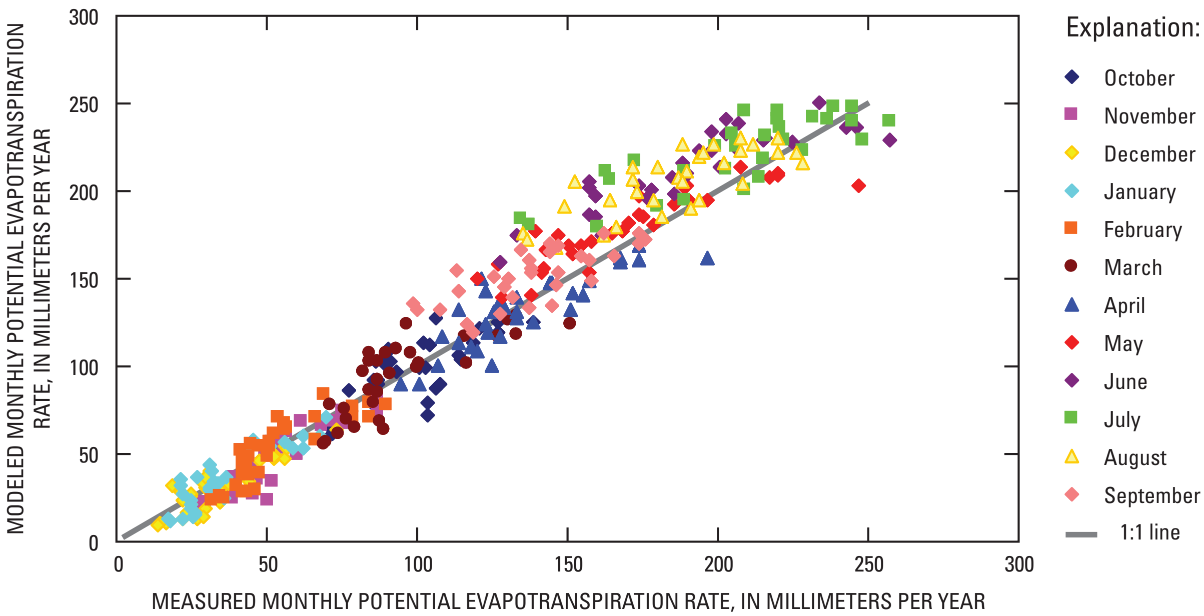

Figure 9. Submodel calibration for potential evapotranspiration (ETo) using values calculated with data from stations in California and Arizona.

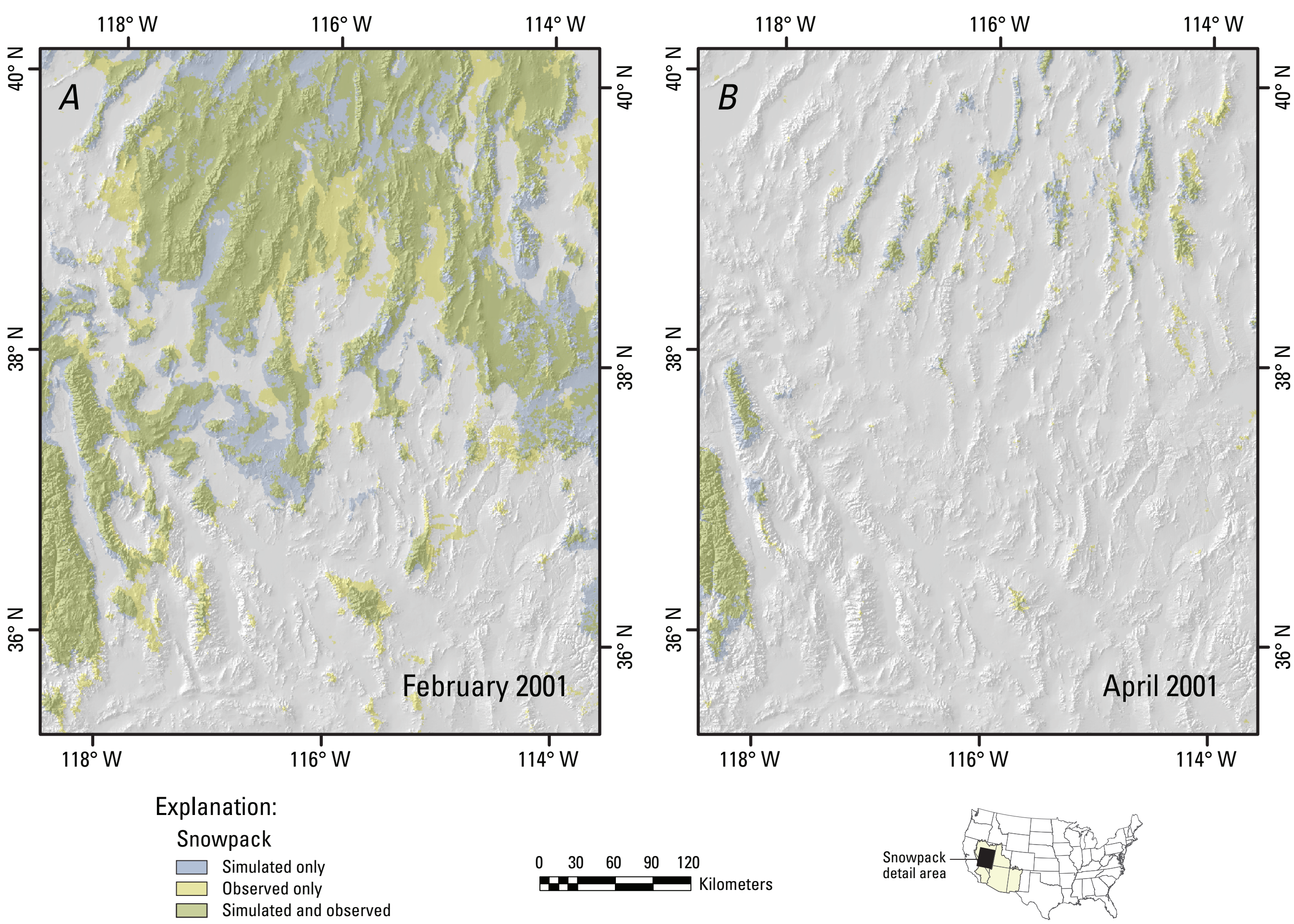

Figure 10. Distribution of model-simulated snowpack compared with measured snowpack in *A*, February 2001, and *B*, April 2001. Blue indicates greater than 30 millimeters of accumulated snowpack calculated by the Basin Characterization Model (BCM). Yellow indicates snowpack measured by MODIS, the Moderate Resolution Imaging Spectroradiometer aboard Terra and Aqua Earth-observing satellites (http://modis.gsfc.nasa.gov/). Where the image appears green, simulated snowpack is co-located with observed snowpack.

high that the excess water generated during winter months was removed by evapotranspiration during spring and summer months. The eight recharge study-site basins generally represented larger and drier basins, with the exception of the Upper Virgin Basin in Utah.

Estimates of ground-water recharge produced by the BCM for basins in Nevada and western Utah were compared by Flint and others (2004) to chloride-mass balance estimates for 14 basins (Dettinger, 1989; Harrill and Prudic, 1998) and to discharge estimates for 15 basins (Nichols, 2000). Flint and others (2004) also compared BCM estimates with estimates from a similar model employing a daily time step (Hevesi and others, 2002; 2003). The version of the BCM used in that analysis used an earlier version of the potential evapotranspiration model. The BCM estimates compared well with recharge estimates from the other approaches (Flint and others, 2004).

Physical characteristics of the basins that include the eight ground-water recharge-study sites are listed in table 1. The northern-most basin is the Middle Humboldt in north central Nevada, the southern-most basin is the Upper San Pedro in southern Arizona, the eastern-most basin is the Rio Grande-Sante Fe in central New Mexico, and the western-most basin is the Mojave in southern California. Drainage areas range from 2,410 km^2 for the Rillito Basin in southern Arizona to 12,084 km^2 for the Mojave Basin in southern California. Average elevations range from 838 m in the Mojave Basin to 1,998 m in the Rio Grande-Santa Fe Basin. The dominant bedrock in the study-sites basins range from relatively impermeable granitic and metamorphic rocks (Rillito Creek) to permeable sandstone (Sand Hollow); however, the dominant geologic rocks in the higher reaches of the basins, where runoff is generated, tend to be less-permeable volcanic, granitic, and metamorphic rocks. The southern-most basin in New Mexico, Rio Grande-Albuquerque, is dominated by relatively permeable Mesozoic sandstone. Total annual soil-water storage ranges from 97 mm for the Upper Amargosa Basin to 421 mm for the Middle Humboldt Basin.

Average annual (1971–2000) climatic conditions, in-place recharge, runoff, and ground-water recharge estimated by the BCM are listed in table 2. Average annual precipitation ranged from a low of 152 mm in the Upper Amargosa Basin to 463 mm for the Rillito Basin. The percentage of precipitation that fell as snow was lowest (2 percent) for the Mojave Basin, 3 and 5 percent for southern Arizona basins (Upper San Pedro and Rillito, respectively), 26 percent for the Middle Humboldt Basin, and highest (32 percent) for the Upper Virgin Basin. Average annual ground-water recharge (calculated as in-place recharge plus 15 percent of runoff) ranged from less than 1 mm for the central New Mexico and Upper San Pedro Basins to 24 mm for the Upper Virgin Basin. Average annual runoff was highest for the Upper Virgin and Mojave Basins relative to the other six study-site basins. The ratio of in-place recharge to runoff indicates which process is dominant in each basin. While all basins corresponding to the eight ground-water recharge-study sites are dominated by runoff, ratios ranged from 0–0.1 for the Rio Grande-Santa Fe, Mojave, and Rillito Basins to 0.8–0.9 for the Rio Grande-Albuquerque and Upper San Pedro Basins.

Effects of Climate Variability

Snow accumulation is the dominant factor in converting excess water into runoff and in-place ground-water recharge. Accumulation of snow delays delivery of liquid water to the land surface, thus increasing the possibility that subsequent combinations of precipitation and snowmelt in ensuing months will exceed soil-water storage capacity and result in drainage past the base of the root zone and, possibly, also in runoff. Therefore, computing ground-water recharge for an *N*-year period by using *N* x 12 monthly calculations results in a more realistic, somewhat higher value of total recharge than would be obtained by using 12 calculations with average monthly values and multiplying the 12-month total by *N* (Flint and others, 2004). BCM results computed by using average monthly values are shown in table 2.

The long-term ocean temperature fluctuation of the Pacific Ocean, called the Pacific Decadal Oscillation (PDO), involves an approximately periodic cycle lasting 50–70 years (Mantua and Hare, 2002) The 64-year time series used in this analysis, 1941–2004, includes one complete PDO cycle. The warm phase, or positive PDO, impacted the study area with below-average rainfall and above-average temperatures. Superimposed on the PDO and acting at shorter time scales of less than 10 years, the El Niño/Southern Oscillation (ENSO) provides an even more important source of climate variability (see chapter A, this volume; Cayan and others, 1998). Negative values of the index represent the cold ENSO phase (La Niña), while positive values represent the warm phase (El Niño). El Niño cycles within positive PDO cycles result in the strongest impacts to the study area, producing above-average rainfall and temperatures (McCabe and Dettinger, 2002).

Annual-precipitation data and ground-water-recharge estimates from 1941 to 2004 for study-site basins are shown in figure 12, along with indications of the PDO climate cycle and the time interval of the investigations. The relation of precipitation to ground-water recharge differs among the eight basins. The Mojave Basin has next to the lowest average-annual precipitation, but has relatively high average annual ground-water recharge, whereas the Rillito and Upper San Pedro Basins have relatively high average-annual precipitation but relatively low-average annual ground-water recharge (table 2, fig. 12). The Rillito and Upper San Pedro Basins have little precipitation that falls as snow, and more rainfall that falls during summer monsoons when evapotranspiration is high. Droughts during the 1950s through 1970s caused a reduction in annual runoff and ground-water recharge in most of the basins, whereas droughts during 1990s and early 2000s were more pronounced in the Mojave Basin in southern California, the Upper Amargosa Basin in southern Nevada, and in the Upper San Pedro and Rillito Basins in southern Arizona.

Annual precipitation and estimated annual ground-water recharge data averaged for different climate patterns are shown in table 3 for each of the basins containing ground-water recharge-study sites. Average-annual precipitation amounts typically were highest in the Rillito and Upper

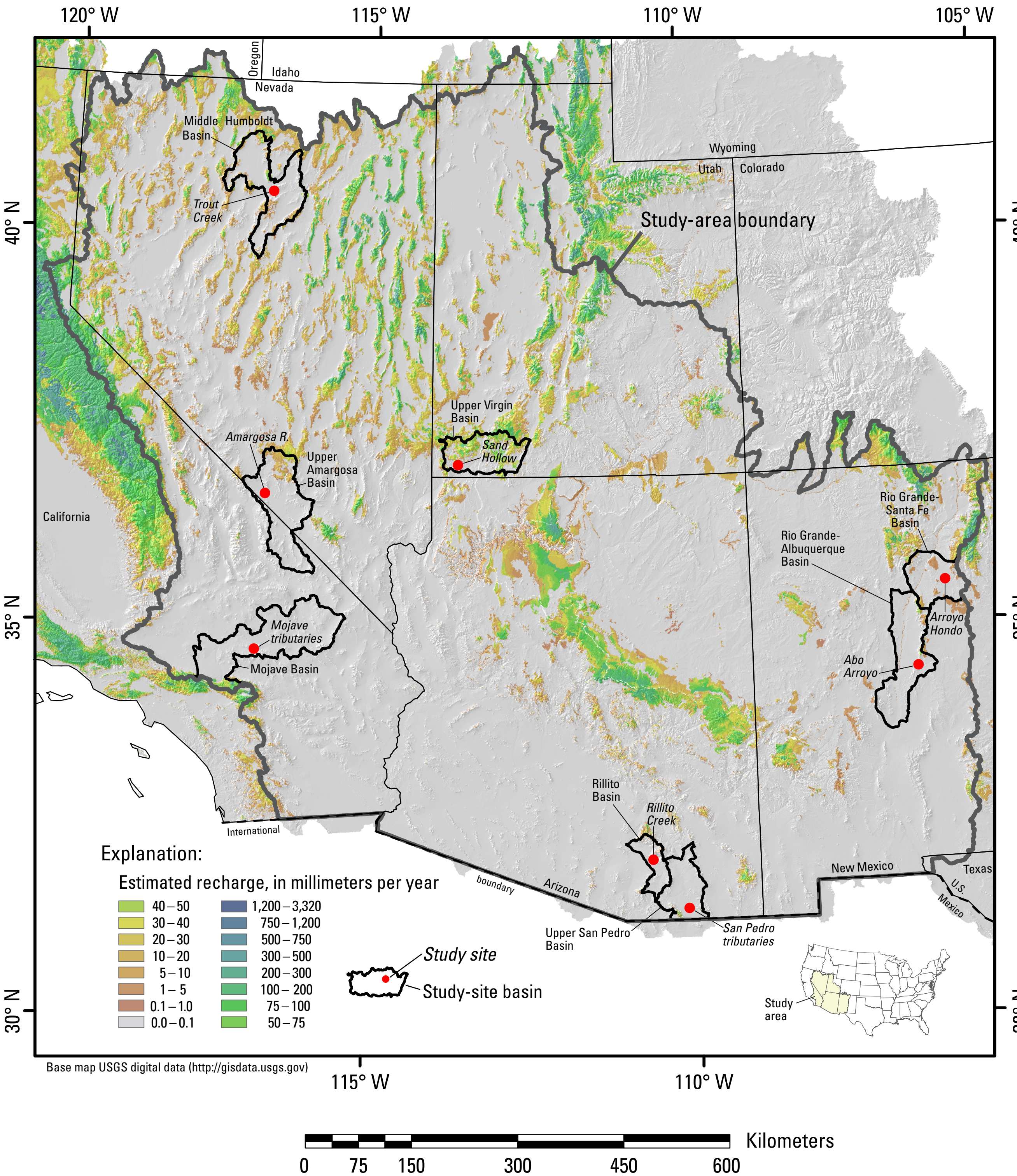

Figure 11. Average annual ground-water recharge within the modeled arid and semiarid southwestern United States study area, calculated with the Basin Characterization Model as in-place recharge plus 15 percent of runoff. Calculations used 30 years of average monthly precipitation and other dynamic input data from 1971–2000. Portions of Colorado outside the study area, Texas, and Wyoming were not modeled.

Table 1. Physical characteristics of the eight recharge study sites, and parameters used in the Basin Characterization Model.

Study site	Basin name	USGS basin identification number (8-digit HUC[1])	Basin area, in square kilometers	Average basin elevation, in meters	Dominant bedrock type	Dominant bedrock type in runoff area	Average bedrock conductivity in runoff area, in meters per year	Average annual soil-water storage in runoff area, in meters
Abo Arroyo	Rio Grande-Albuquerque	13020203	8,169	1,717	Granitic and sedimentary	Sandstone	50.	1.7
Amargosa River	Upper Amargosa	18090202	8,764	1,084	Ash-flow tuffs	Ash-flow and rhyolitic tuffs	2.0	1.3
Arroyo Hondo	Rio Grande-Santa Fe	13020201	4,748	1,998	Granitic and sedimentary	Sandstone	50.	1.1
Mojave tributaries	Mojave	18090208	12,084	838	Granite	Granite	0.01	1.4
Rillito Creek	Rillito	15050302	2,410	1,285	Igneous, metamorphic, and sedimentary	Granite and metamorphics	0.01	0.9
San Pedro tributaries	Upper San Pedro	15050202	4,635	1,419	Igneous, metamorphic, and sedimentary	Granite and volcanics	0.10	1.3
Sand Hollow	Upper Virgin	15010008	5,609	1,735	Navajo sandstone	Granite	0.01	0.7
Trout Creek	Middle Humboldt	16040105	8,318	1,623	Chert and volcanics	Volcanics and sedimentary	1.0	1.6

[1]Hydrologic unit code (HUC).

Table 2. Average annual (1971–2000) conditions determined by using the Basin Characterization Model for the eight ground-water recharge study sites.

[Ground-water recharge is equal to in-place recharge plus 15 percent of runoff]

Study site	Basin name	Precipitation, in millimeters	Potential evapotranspiration, in millimeters	Maximum air temperature, in degrees Celsius	Minimum air temperature, in degrees Celsius	Precipitation that falls as snow, in percent	In-place recharge, in millimeters	Runoff, in millimeters	Ground-water recharge, in millimeters	Ratio of in-place recharge to runoff
Abo Arroyo	Rio Grande-Albuquerque	307	1,163	21.2	2.9	10.3	0.8	0.1	0.9	0.83
Amargosa River	Upper Amargosa	152	1,472	23.5	3.5	16.8	1.2	1.9	1.4	0.57
Arroyo Hondo	Rio Grande-Santa Fe	381	1,075	18.6	4.9	10.5	0.3	1.6	0.5	0.04
Mojave tributaries	Mojave	185	1,664	24.5	7.5	1.9	1.8	12.8	3.7	0.13
Rillito Creek	Rillito	463	1,470	25.2	6.9	4.8	0.3	4.9	1.1	0.07
Sand Hollow	Upper Virgin	418	1,011	18.8	0.0	32.1	19.4	29.3	23.8	0.66
San Pedro tributaries	Upper San Pedro	415	1,462	24.7	7.2	3.4	0.7	0.7	0.8	0.86
Trout Creek	Middle Humboldt	264	990	17.4	1.6	26.5	2.5	5.2	3.3	0.44

Virgin Basins and lowest in the Upper Amargosa and Mojave Basins, whereas average-annual ground-water recharge was highest in the Upper Virgin Basin and lowest in the Rio Grande-Albuquerque and San Pedro Basins—even though annual precipitation levels exceeded those in the Upper Amargosa and Mojave Basins. The difference between high precipitation values and low potential ground-water recharge in the basins in southern Arizona and central New Mexico also is apparent because much of the precipitation falls during the summer months when potential evapotranspiration vales are highest. The Middle Humboldt Basin has the lowest sensitivity to climate cycles, whereas the southern Arizona and Upper Amargosa Basins have the highest sensitivities to climate cycles (table 3).

Annual precipitation during water year 2000 was below average for all basins in the study area, except in the Middle Humboldt Basin (tables 2 and 4). These below-average precipitation values resulted in estimates of potential ground-water recharge in the northern and western basins that were near the 64-year minimums (fig. 12), while the central New Mexico and southern Arizona basins had increased recharge, likely due to the timing of the precipitation. Thus, data collection for the eight site investigations generally did not coincide with average annual conditions.

Areas Dominated by Processes Contributing to In-Place Recharge and Runoff

Estimates of the ratio of in-place recharge to runoff (fig. 13) provide an indication of the mechanisms that likely are dominant in controlling ground-water recharge for a given basin. This analysis provides the distribution of the dominant mechanisms within basins. A ratio of 0.5 or less indicates that more than twice as much water has the potential to become runoff than to become in-place recharge. A ratio of 2.0 or greater indicates that water has at least twice as much potential to become in-place recharge than to become runoff. Little if any recharge or runoff occurs within the areas covered by basin fill or other unconsolidated Quaternary deposits (fig. 11); in most of these locations, neither recharge nor is dominant. In areas of consolidated bedrock, geology—through the associated saturated hydraulic conductivity—largely controls the dominant process (fig. 13). In-place recharge dominates (ratio greater than 2.0) in the mountains of the Great Basin carbonate-rock province, where thick sections of Paleozoic carbonate rock crop out (Mifflin and Hess, 1979; Prudic and others, 1995), and in the upland areas of the Kaibab section of the Colorado Plateau, where thick sections of Mesozoic sandstone crop out (figs. 5 and 6). The importance of geology in determining recharge

Table 3. Average annual precipitation (in millimeters) and ground-water recharge (in millimeters, calculated as in-place recharge plus 15 percent of runoff) for selected climate patterns (1941–2004) in basins conta ining the eight recharge-study sites.

[Pacific Decadal Oscillation (PDO) time periods are identified on figure 12. Positive El Niño-Southern Oscillation (ENSO) conditions correspond to El Niños; negative ENSO conditions correspond to La Niñas]

		Positive PDO, neutral ENSO		Negative PDO, neutral ENSO		All PDO, positive ENSO		All PDO, negative ENSO		Positive PDO, positive ENSO	
Study site	Basin name	Precipitation	Recharge	Precipitation	Recharge	Precipitation	Recharge	Precipitation	Recharge	Precipitation	Recharge
Abo Arroyo	Rio Grande-Albuquerque	318	4	259	2	294	4	254	2	301	5
Amargosa River	Upper Amargosa	400	5	327	3	370	6	326	3	380	7
Arroyo Hondo	Rio Grande-Santa Fe	171	7	125	3	183	9	107	2	196	11
Mojave tributaries	Mojave	207	13	150	8	229	14	125	4	254	18
Rillito Creek	Rillito	513	16	422	7	502	15	387	4	512	19
Sand Hollow	Upper Virgin	458	61	365	34	472	74	335	22	494	83
San Pedro tributaries	Upper San Pedro	424	5	370	2	417	5	347	1	416	6
Trout Creek	Middle Humboldt	279	8	243	6	268	7	263	7	282	8

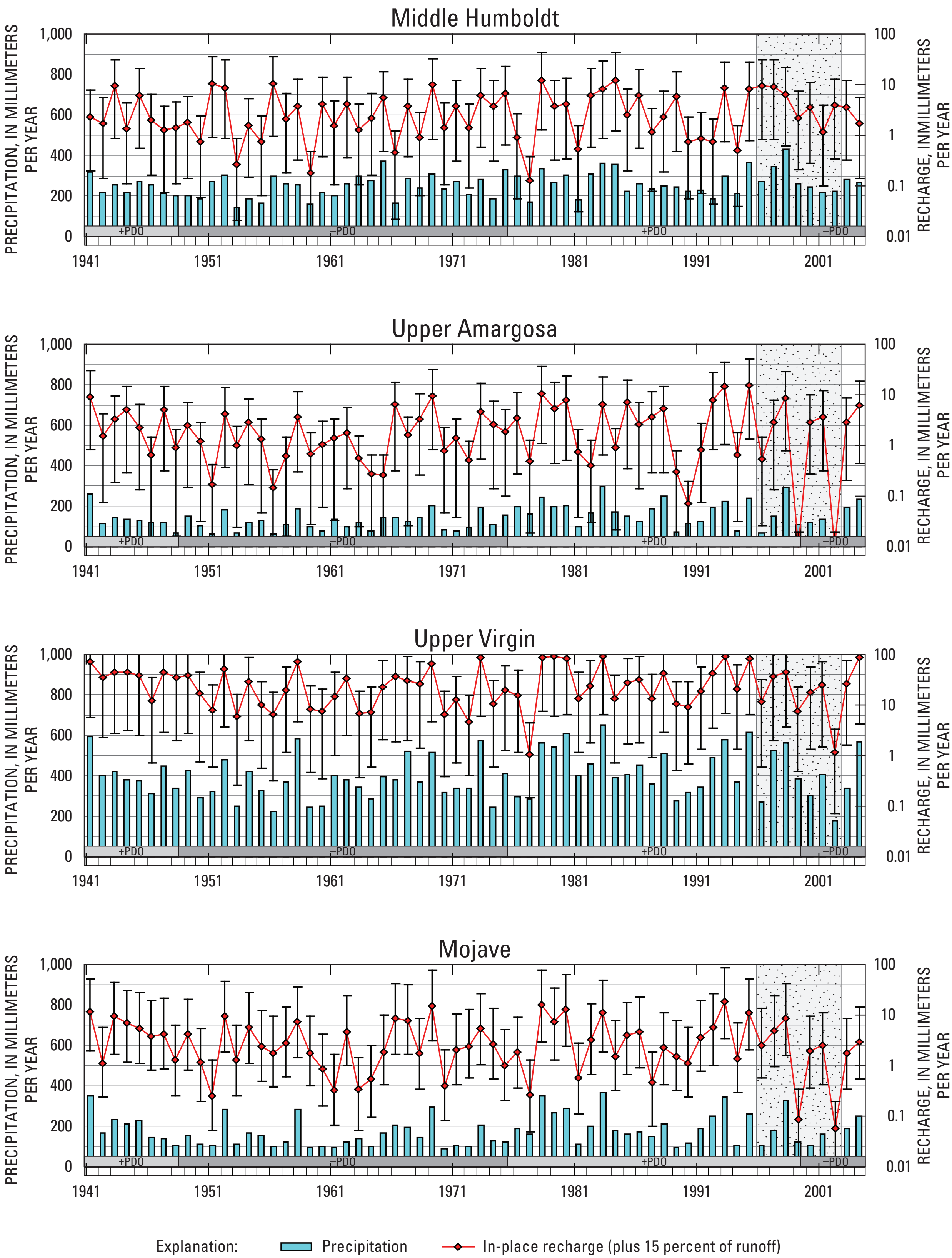

Figure 12. Annual precipitation and ground-water recharge in the basins corresponding to the eight recharge study sites from 1941-2004 in relation to positive and negative Pacific Decadal Oscillations (+PDO and –PDO, respectively). Stippling indicates the nominal period of study-site investigations. Error bars indicate recharge calculated by using 10 and 90 percent of runoff.

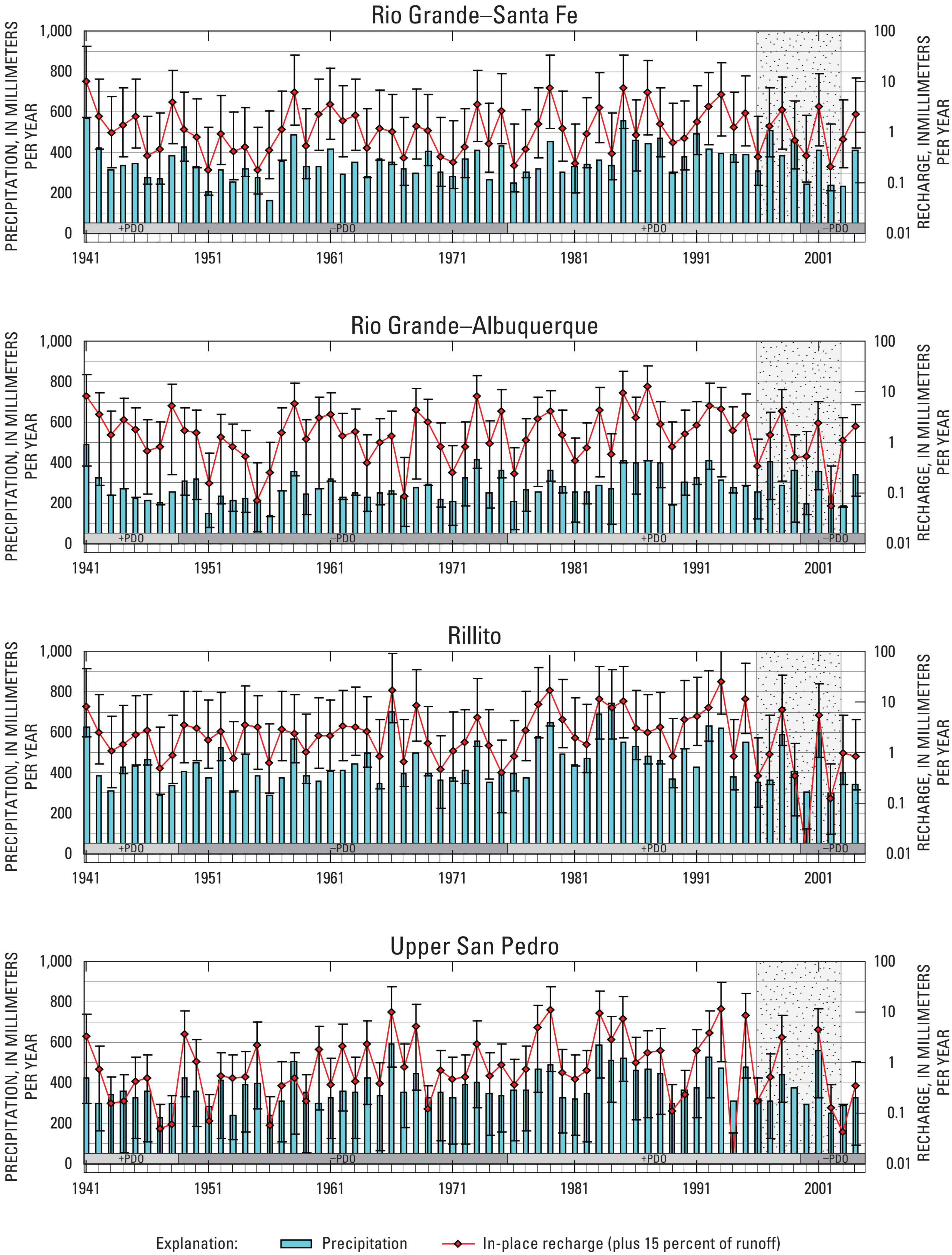

Figure 12.—Continued.

Table 4. Hydrologic conditions for water year 2000 determined by using the Basin Characterization Model for basins corresponding to the eight recharge-study sites.

Study site	Basin name	Water year 2000					
		Precipitation, in millimeters	Potential evapotranspiration, in millimeters	In-place recharge, in millimeters	Runoff, in millimeters	Ground-water recharge, in millimeters	Ratio of in-place recharge to runoff
Abo Arroyo	Rio Grande-Albuquerque	195	1,163	1.7	1.8	2.0	0.95
Amargosa River	Upper Amargosa	121	1,472	0.6	1.9	0.9	0.32
Arroyo Hondo	Rio Grande-Santa Fe	243	1,075	0.6	6.9	1.7	0.09
Mojave tributaries	Mojave	106	1,664	0.9	7.0	1.9	0.12
Rillito Creek	Rillito	303	1,470	2.7	11.2	4.4	0.24
Sand Hollow	Upper Virgin	303	1,011	13.	28.2	17.3	0.46
San Pedro tributaries	Upper San Pedro	294	1,462	3.4	3.2	3.9	1.06
Trout Creek	Middle Humboldt	246	990	2.7	5.6	3.6	0.49

mechanisms was similarly revealed by a detailed water-balance model for the Death Valley region, which indicated higher recharge in mountains dominated by carbonate-rock outcrops and lower recharge in mountains dominated by thick soils and volcanic rock outcrops (Hevesi and others, 2002). Most study-site basins are dominated by runoff in the mountains at their peripheries (fig. 13), as indicated by the basin-wide calculation of the ratio of in-place recharge to runoff (tables 2 and 4). The exception is the Rio Grande-Albuquerque Basin, which has very low ground-water recharge. The ratio of in-place recharge to runoff changed for several of the basins during water year 2000 in response to climatic conditions. The Upper Amargosa, New Mexico, and Upper Virgin Basins all had more runoff in comparison to recharge, whereas the southern Arizona Basins had more recharge in comparison to runoff compared to average annual conditions (tables 2 and 4).

Runoff and In-Place Recharge in Basins Containing the Ground-Water Recharge-Study Sites

With the exception of the Upper Virgin River sandstone basin, the ground-water recharge-study sites were selected in areas where runoff from the mountains routinely discharges onto the piedmont slopes and valley floors due to the importance of estimating the quantity of runoff becoming ground-water recharge in these transitional topographic locations. Runoff and in-place recharge estimates for water year 2000 in the eight basins containing study sites are shown in figure 14. During this relatively dry year, all basins in the study area, with the exception of the Upper San Pedro Basin, were dominated by runoff.

Runoff and in-place recharge for each of the eight basins are different and range from very little recharge and runoff in the Upper Amargosa Basin to large amounts of runoff in the mountain ranges bounding the southwestern edge of the Mojave Basin to diffuse runoff and in-place recharge throughout the Upper Virgin Basin. Most of the estimated runoff and in-place recharge in the Upper Amargosa Basin is in the northwestern part of the basin. The Middle Humboldt Basin, having a large perimeter-to-area ratio due to its compound shape, generates runoff and ground-water recharge in the many mountain ranges defining the basin. Several basins are notable in their spatial variability of runoff or in-place recharge, especially the Mojave Basin, which receives nearly all of its runoff and in-place recharge from the mountains that border its southwestern edge. Similarly, for the Rio Grande Basins, the majority of runoff and in-place recharge is estimated to occur in the highest mountains of each basin.

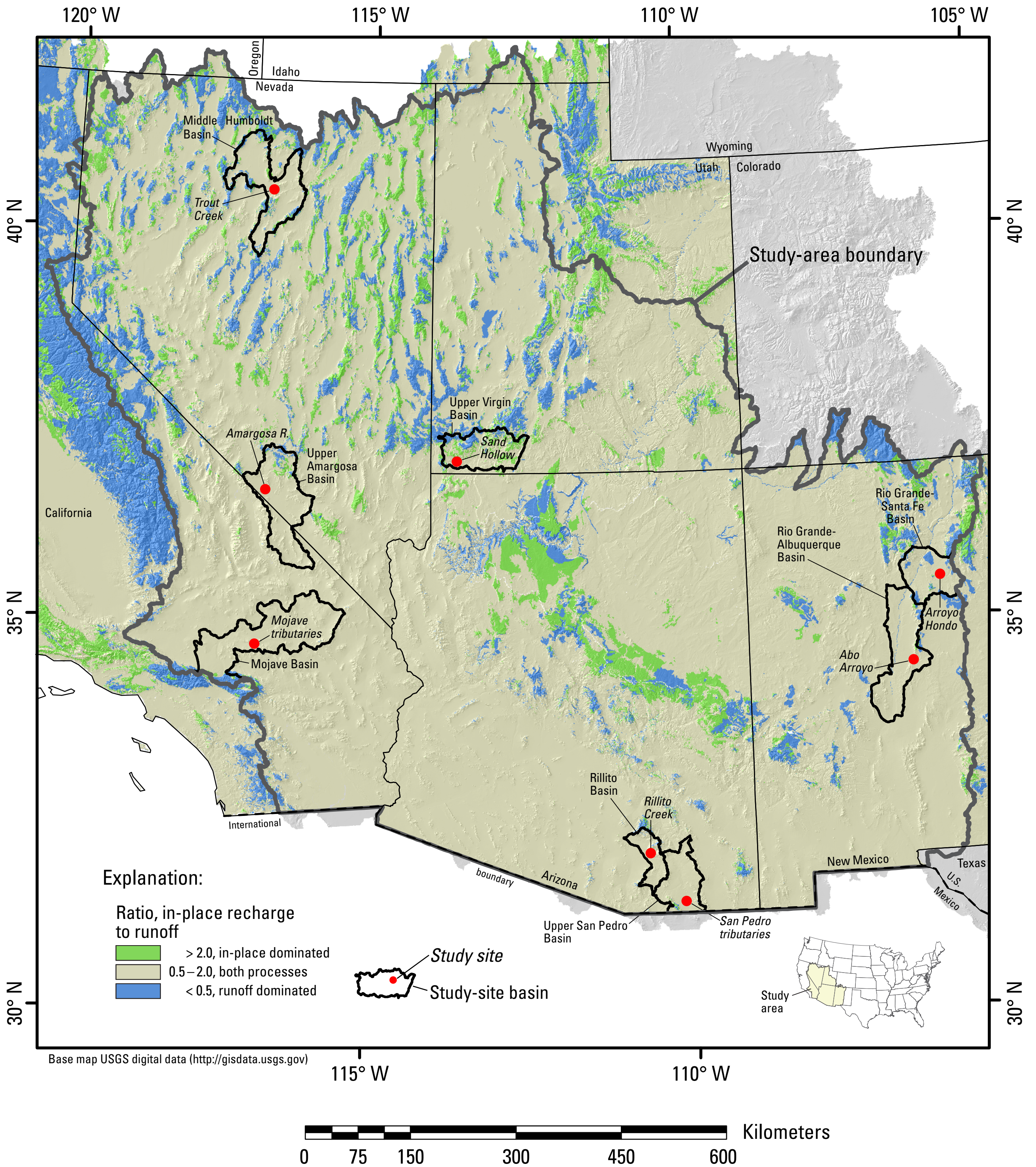

Figure 13. Areas within the modeled arid and semiarid southwestern U.S. study area, where runoff or in-place recharge is dominant, or where runoff and in-place recharge are nearly equal.

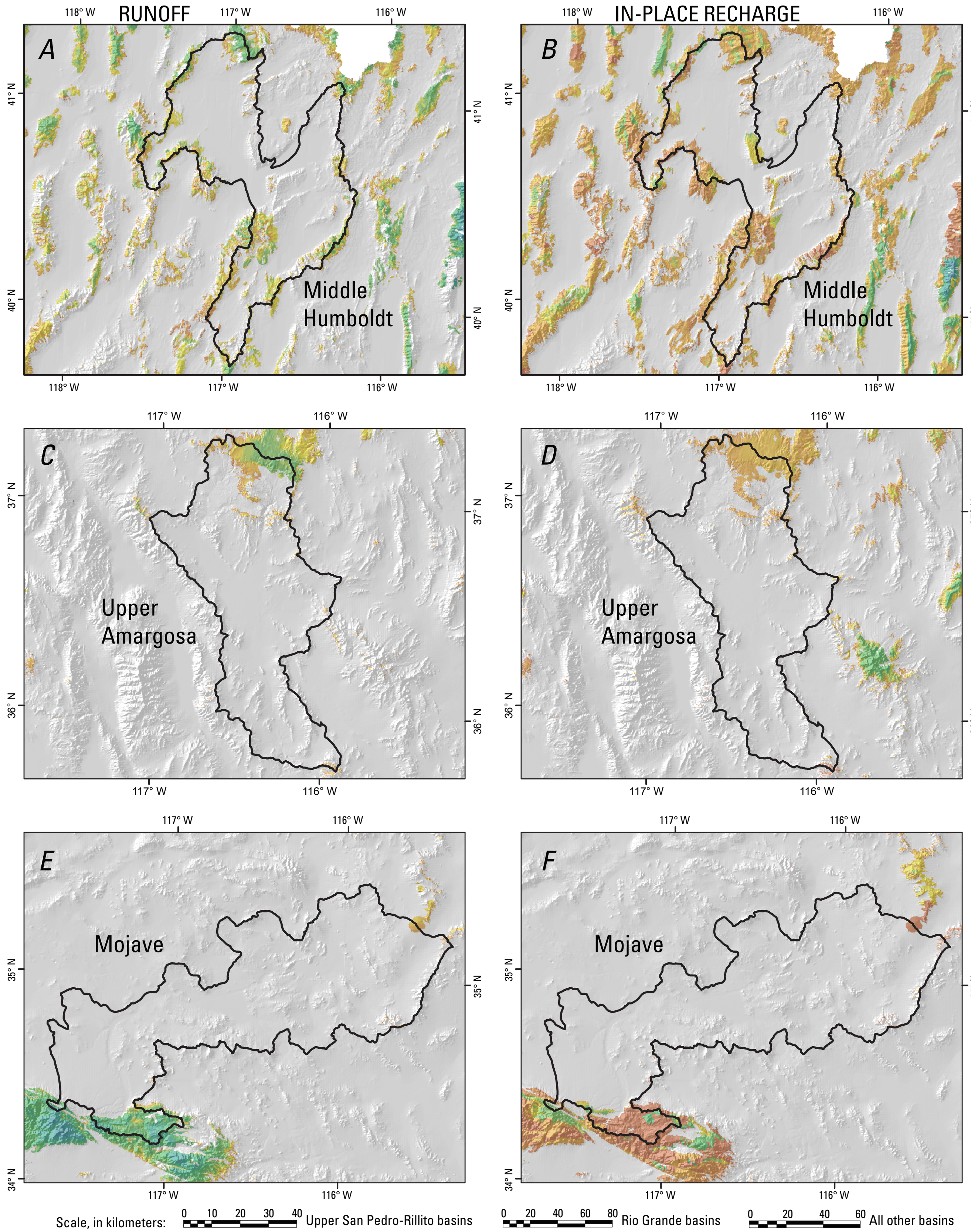

Figure 14. Runoff and in-place recharge for water year 2000 in basins that correspond to the eight study sites. Runoff and in-place recharge in the: *A, B*, Middle Humboldt; *C, D,* Upper Amargosa; *E, F,* Mojave; *G, H,* Upper Virgin; *I, J*, Rio Grande-Santa Fe/Rio Grande-Albuquerque; and *K, L*, Rillito/Upper San Pedro Basins. Scale varies as shown.

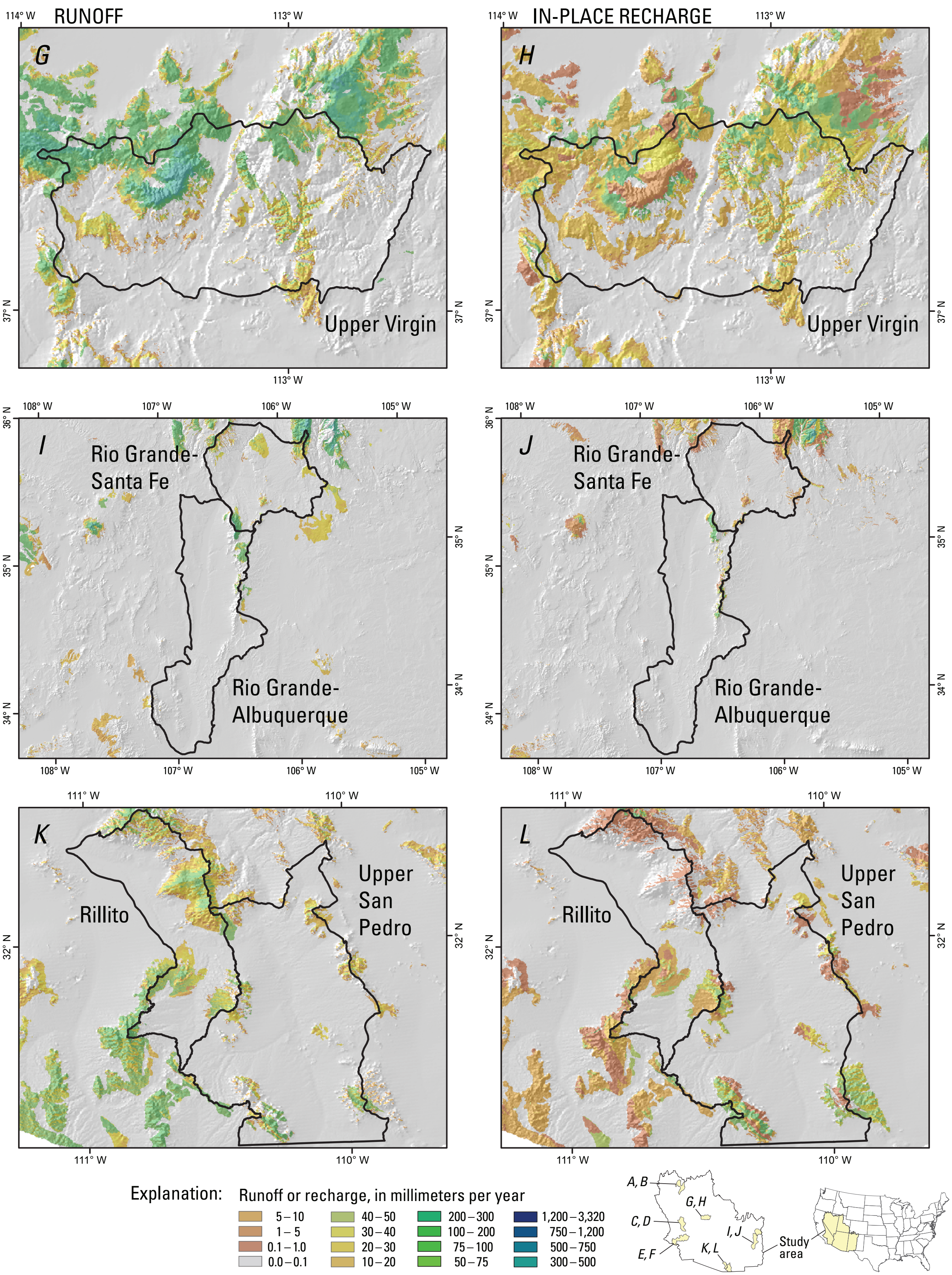

Figure 14. —Continued.

The sensitivity of ground-water recharge to changes in precipitation, for distinct groupings of climatic conditions that occurred during 1941–2004, is shown for the recharge study-site basins (fig. 15). The response generally is nonlinear, such that the change in ground-water recharge is nearly twice the change in precipitation. The nonlinearity reflects the fact that changes in evapotranspiration and soil-water storage are not proportional to changes in precipitation. During years of low precipitation, a greater fraction of precipitation is lost to evapotranspiration and soil-moisture replenishment. During years of high precipitation, a smaller fraction of precipitation is lost to evapotranspiration and soil-moisture replenishment. Soil-water storage typically is not close to capacity and evapotranspiration rates not at potential, except for localized areas at high elevations. An example is Lamoille Canyon in the Ruby Mountains, where runoff is roughly linearly related to precipitation, and about 70 percent of annual precipitation becomes runoff (Prudic and others, 2006). In general, however, evapotranspiration and soil-moisture replenishment account for most incoming water, thus preventing conditions that lead to runoff and ground-water recharge.

General trends in the data indicate that the Rillito and Upper San Pedro Basins have a greater sensitivity of ground-water recharge to changes in precipitation, whereas the Middle Humboldt, Mojave, and Upper Amargosa Basins have a smaller sensitivity. This likely is due to the timing of precipitation in the southern Arizona Basins, which experience monsoonal conditions that often deliver large quantities of precipitation in short periods of time, overwhelming soil-water storage and resulting in increased recharge and runoff, even though on an annual basis the total volume of precipitation does not increase correspondingly.

The ratio of ground-water recharge to precipitation was less than 2 percent for all climatic conditions in the Upper San Pedro Basin in Arizona and the two Rio Grande Basins in New Mexico (fig. 16). However, the ratio increased slightly from years of La Niña and negative PDO to years of El Niño and positive PDO. The highest ratio of ground-water recharge to precipitation was in the Upper Virgin Basin, which also had the largest sensitivity to different climatic conditions. The ratio of ground-water recharge to precipitation increased from about 7 percent for La Niña years to about 17 percent for El Niño years with a positive PDO (fig. 16). The ratio of ground-water recharge to precipitation was least affected by the different climate patterns in the Middle Humboldt Basin.

Relation of Selected Characteristics Among All Basins in the Study Area

Selected characteristics for all basins within the study area are summarized in figure 17. Basins are ranked from low to high for each characteristic. Thus, the order of basins generally changes from plot to plot. For example, the Upper Amargosa Basin ranks 11th with respect to aridity, but ranks 155th with respect to potential evapotranspiration. Aridity indices were determined as the ratio of average annual precipitation divided by potential evapotranspiration (fig. 6, chapter A). Hyperarid conditions denote ratios of 0–0.05, arid conditions denote ratios of 0.05–0.2, semiarid conditions denote ratios of 0.2–0.5, dry subhumid conditions denote ratios of 0.5–0.65, and humid conditions denote ratios of greater than 0.65 (UNESCO, 1979). Basins corresponding to the eight ground-water recharge-study sites are highlighted in each ranking.

Of the basins that correspond to the recharge-study sites, the Upper Amargosa and Mojave Basins are classified as arid, whereas the other six basins are classified as semiarid. The Upper Virgin Basin is the least arid. The Middle Humboldt and Upper Virgin Basins have the lowest values of potential evapotranspiration, whereas the Mojave Basin has the highest value of potential evapotranspiration. The eight recharge study-site basins generally are well distributed among all the basins for precipitation, although about ten percent of the study-area basins have higher average annual precipitation. The eight basins also are generally well distributed with respect to runoff and in-place recharge. All of the eight basins have more estimated runoff than in-place recharge, whereas

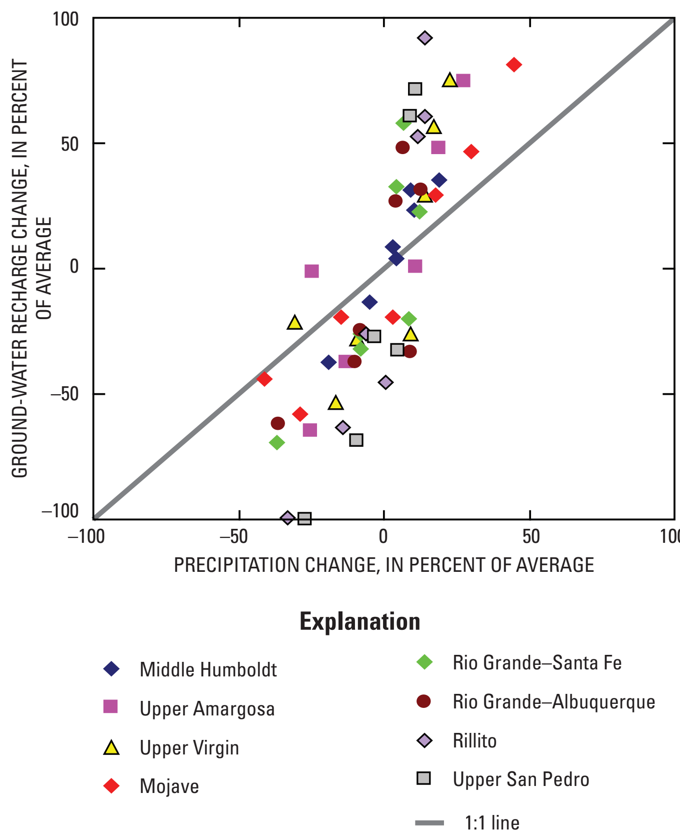

Figure 15. Change in ground-water recharge with change in precipitation, relative to respective 1971–2000 averages, for the eight basins containing recharge study sites. Different points for each basin represent varying combinations of climatic conditions as manifested in the El Niño-Southern Oscillation and Pacific Decadal Oscillation indices during 1941–2004. Ground-water recharge is estimated by using the Basin Characterization Model and assumes in-place recharge plus 15 percent of runoff.

about 30 percent of all basins in the study area have more estimated in-place recharge than runoff. This analysis does not take into account the dominant process contributing to ground-water recharge in a basin—in other words, whether it is a result of in-place recharge or infiltration from runoff—just the physical and hydrologic characteristics of basins that lead to the potential for either runoff or in-place recharge.

The model used to estimate runoff and in-place recharge was not calibrated extensively, and represents basin averages that may not reflect results from the individual study sites. Instead, the model provides general information about the dominant processes within each basin. As previously noted, error produced by assuming a constant percentage of runoff that becomes recharge, here 15 percent throughout the entire study area, may be relatively large in the Middle Humboldt Basin. A further uncertainty lies in the estimates of saturated hydraulic conductivity of subsoil materials. Future studies done by using the BCM will attempt to refine these estimates of runoff and in-place recharge by using measured runoff in basins with predominantly one rock type. Sensitivity analyses indicate that increasing the saturated hydraulic conductivity of the bedrock by one order of magnitude switches the Middle Humboldt from a basin dominated by runoff to a basin dominated by in-place recharge, in agreement with the results of the recharge study-site investigation (Prudic and others, chapter K, this volume). Although it is possible that basins other than the Middle Humboldt have greater runoff than in-place recharge, sufficient data are not available to evaluate this possibility.

The results of the analysis presented herein indicate that the eight ground-water recharge-study sites represent a reasonable distribution of the hydrologic conditions throughout the study area, which includes different timing of precipitation and snowfall, different influences from summer monsoons, and varying bedrock types and soil depths. The main similarity of the eight recharge-study sites is that runoff is an important hydrologic component. On the basis of site-specific analysis alone, however, important mechanisms that contribute to runoff and in-place recharge in a given basin may be overlooked without consideration of the spatially distributed hydrologic-framework analysis.

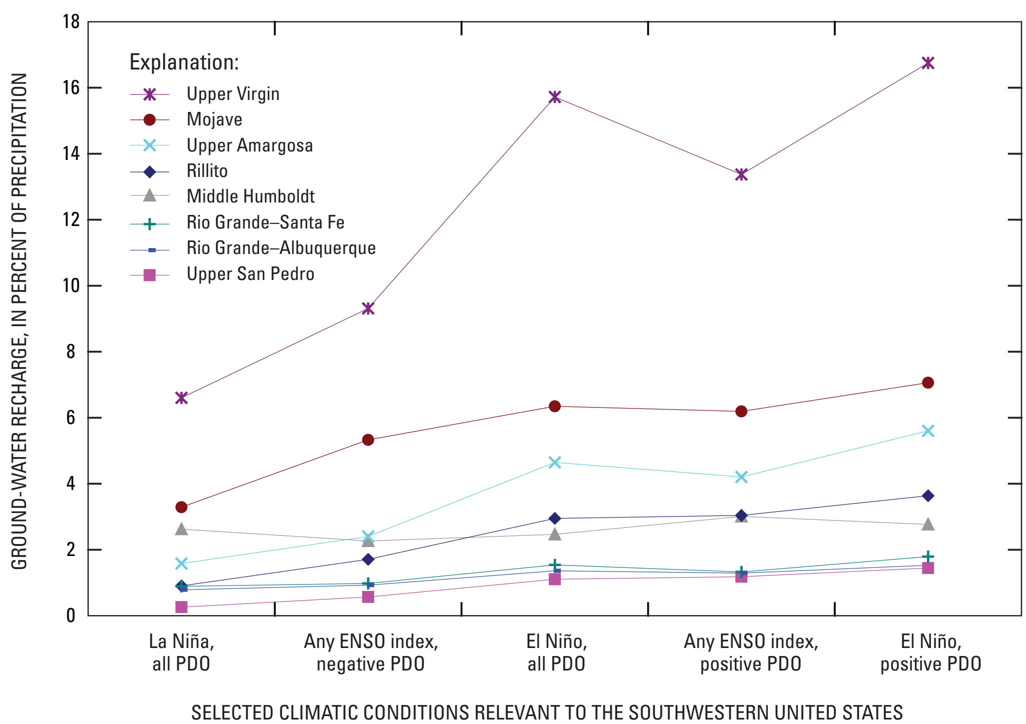

Figure 16. Ground-water recharge as a percentage of precipitation for different climatic conditions 1941–2004 for the eight basins containing the ground-water recharge study sites. The El Niño-Southern Oscillation (ENSO) index indicates shifting of warm Pacific equatorial surface water either toward (positive ENSO index; El Niño conditions) or away from (negative ENSO index; La Niña conditions) the Americas. On a longer (decadal) time scale, the Pacific Decadal Oscillation (PDO) index indicates warm (positive PDO index) or cool (negative PDO index) surface water in the eastern Pacific Ocean north of 20° north latitude. Ground-water recharge as estimated with the Basin Characterization Model assumes in-place recharge plus 15 percent of runoff.

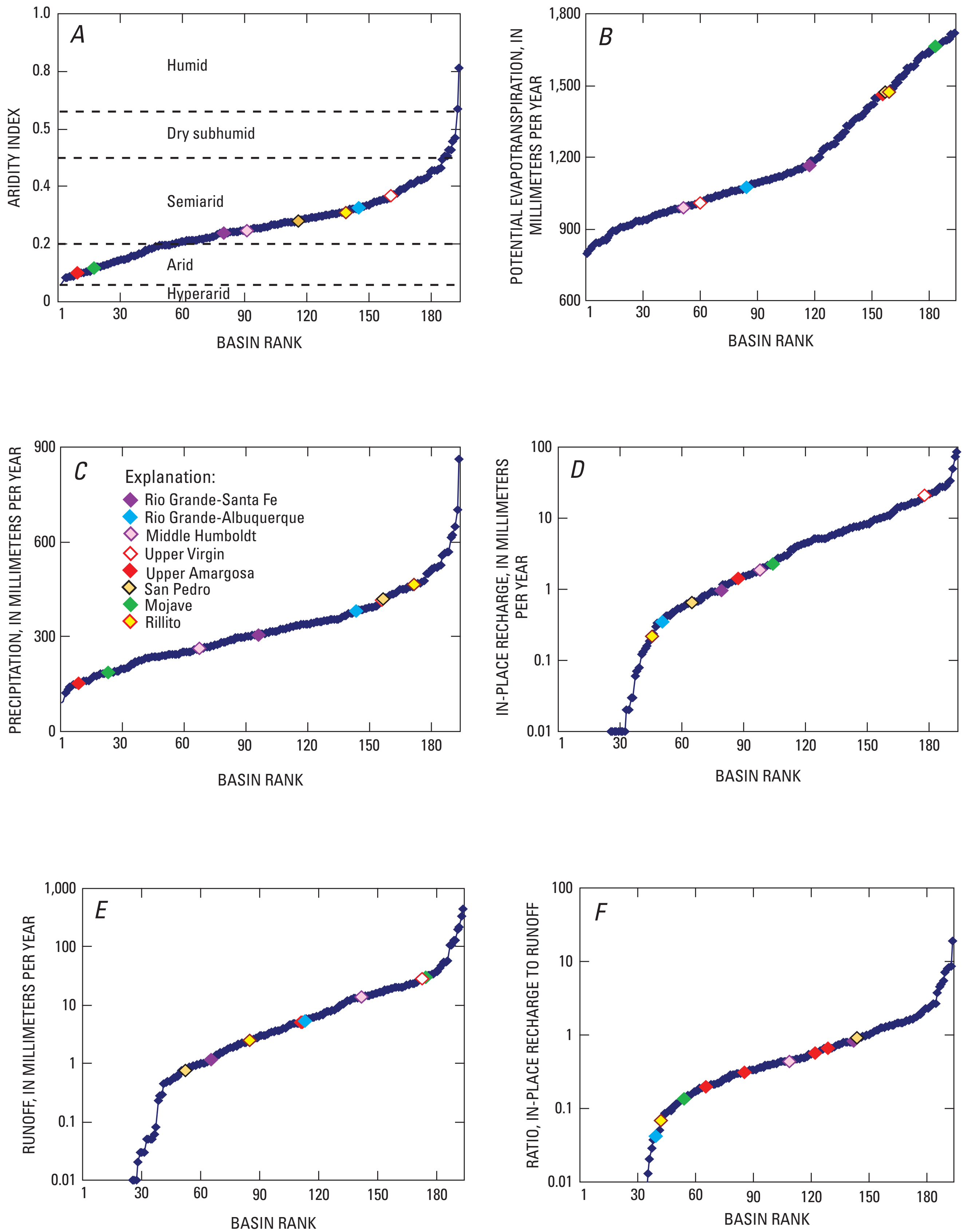

Figure 17. The eight study-site basins ranked among all basins in the study area assuming average annual conditions (1971–2000) for: *A*, aridity; B, potential evapotranspiration; *C*, precipitation; *D*, runoff; *E*, in-place recharge; and *F*, ratio of in-place recharge to runoff.

Summary and Conclusions

Average annual runoff and in-place recharge were estimated by using a spatially distributed water-balance model called the Basin Characterization Model (BCM). Estimates were used to compare similarities and differences among the eight ground-water recharge-study sites and among all basins within the study area. A total of 194 basins were modeled covering 1,033,840 square kilometers. Basins were defined by the drainage areas of the U.S. Geological Survey's 1:250,000-scale hydrologic units. Basin areas ranged from 2,410 to 12,084 km^2. The eight recharge-study sites generally were representative of the basins in the study area. Runoff exceeded in-place recharge in all study-site basins, but runoff exceeded in-place recharge in only three quarters of total basins. Among the basins corresponding to the eight study sites, average annual precipitation ranged from 152 mm for the Upper Amargosa Basin in southern Nevada to 463 mm for the Rillito Basin in southern Arizona. Average annual runoff ranged from 0.1 mm for the Rio Grande-Albuquerque Basin in central New Mexico to 29 mm for the Upper Virgin Basin in southern Utah. Average annual in-place recharge ranged from 0.3 mm in the Rio Grande-Santa Fe Basin in central New Mexico and the Rillito Basin in southern Arizona to about 19 mm for the Upper Virgin Basin. The ratio of average annual ground-water recharge—computed as the sum of in-place recharge plus 15 percent of runoff—to average annual precipitation ranged from less than 0.3 percent in the southern Arizona and central New Mexico Basins to about 6 percent in the Upper Virgin Basin in southern Utah. In-place recharge and runoff in the study area indicated significant sensitivity to variations in climate. The climatic variability was a function of sea-surface temperatures manifested in the Pacific Decadal Oscillation (PDO) and El Niño-La Niña cycles. El Niño years with positive PDO typically produced the largest amounts of precipitation, runoff, and in-place recharge. El Niño years, regardless of whether the PDO was positive (warmer) or negative (cooler), also generally produced greater than average amounts of precipitation, runoff, and in-place recharge. Conversely, La Niña years typically produced below-average precipitation, runoff, and in-place recharge. Basins in the southern part of the study area were more sensitive to the different climate conditions than were basins in the northern part, exemplified by the two basins in southern Arizona compared with the Middle Humboldt Basin in north-central Nevada.

Results from the spatially distributed water-balance model show that runoff is an important component (in addition to in-place recharge) to the available ground-water supply in the basins corresponding to the eight recharge-study sites. The individual site investigations thus provide a detailed understanding of when and where runoff from mountains in the study area becomes ground-water recharge on piedmont slopes and valley floors. The combination of regional modeling and site-specific investigations provides a synergistic understanding of recharge to ground-water systems in the arid and semiarid southwestern United States.

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