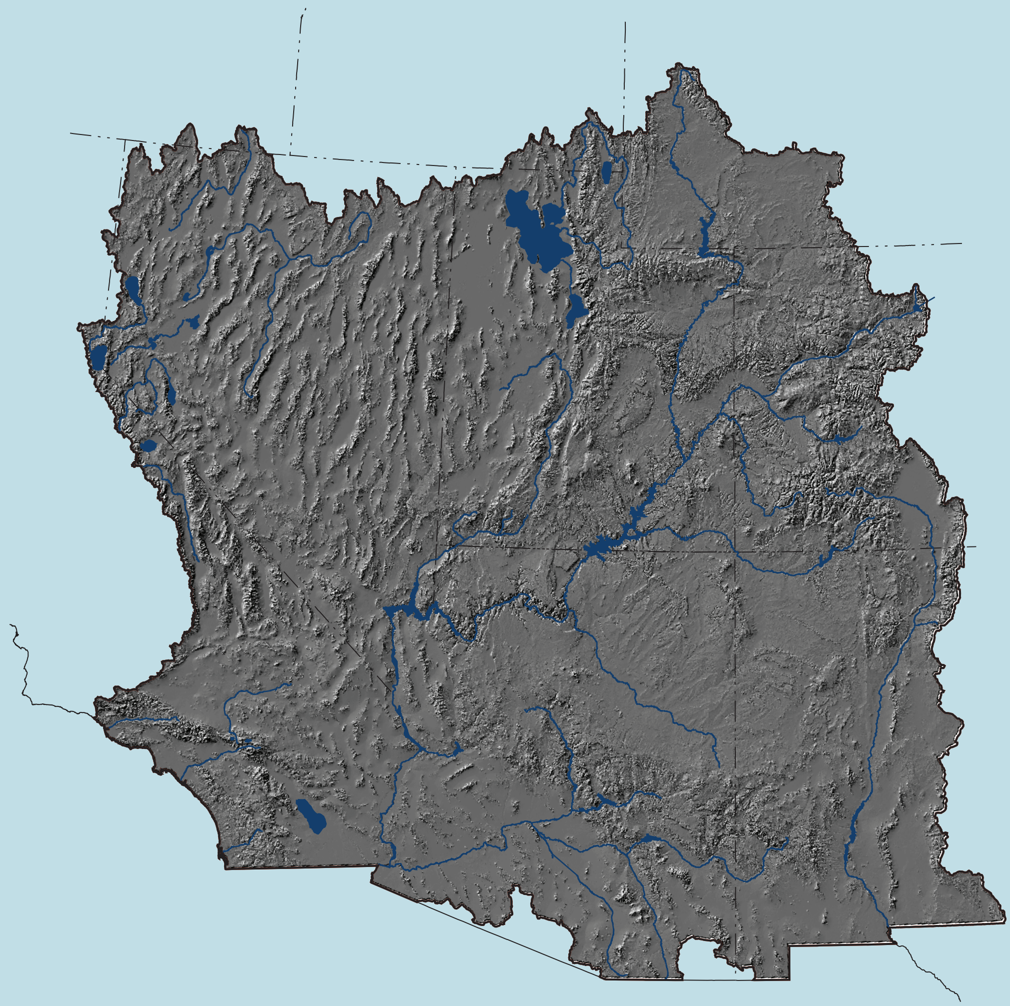
National Water-Quality Assessment Program

Dissolved Solids in Basin-Fill Aquifers and Streams in the Southwestern United States



Scientific Investigations Report 2006–5315, v. 1.1

U.S. Department of the Interior
U.S. Geological Survey

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By David W. Anning, Nancy J. Bauch, Steven J. Gerner, Marilyn E. Flynn, Scott N. Hamlin, Stephanie J. Moore, Donald H. Schaefer, Scott K. Anderholm, and Lawrence E. Spangler

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FOREWORD

The U.S. Geological Survey (USGS) is committed to providing the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the quality of the Nation's water resources is critical to assuring the long-term availability of water that is safe for drinking and recreation and suitable for industry, irrigation, and habitat for fish and wildlife. Population growth and increasing demands for multiple water uses make water availability, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities.

From 1991-2001, the NAWQA Program completed interdisciplinary assessments in 51 of the Nation's major river basins and aquifer systems, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html). Baseline conditions were established for comparison to future assessments, and long-term monitoring was initiated in many of the basins. During the next decade, 42 of the 51 Study Units will be reassessed so that 10 years of comparable monitoring data will be available to determine trends at many of the Nation's streams and aquifers. The next 10 years of study also will fill in critical gaps in characterizing water-quality conditions, enhance understanding of factors that affect water quality, and establish links between sources of contaminants, the transport of those contaminants through the hydrologic system, and the potential effects of contaminants on humans and aquatic ecosystems.

The USGS aims to disseminate credible, timely, and relevant science information to inform practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
Acre	4,047	square meter (m^2)
Acre	0.4047	hectare (ha)
Acre	0.4047	square hectometer (hm^2)
Acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
gallon per minute (gal/min)	3.785	liter per minute (L/min)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton per year (ton/yr)	0.9072	metric ton per year
ton per year per square mile [(ton/yr)/mi^2]	2.35	megagram per year per square kilometer [(Mg/yr)/km^2]
ton per year per square mile [(ton/yr)/mi^2]	2.35	metric ton per year per square kilometer
	Application rate	
pounds per acre per year [(lb/acre)/yr]	1.121	kilograms per hectare per year [(kg/ha)/yr]

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L). Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27). Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms

AADSC	Adjusted annual dissolved-solids concentration
CAZB	Central Arizona Basins
CDS	Calculated dissolved solids
ERF1_2	Enhanced river reach file 2.0
GRSL	Great Salt Lake Basins
LOWESS	Locally-weighted scatterplot smoothing
NAWQA	National Water-Quality Assessment
NLCD	National land-cover data set
NVBR	Nevada Basin and Range
NWIS	National Water Information System
RIOG	Rio Grande Valley
ROE	Residue on evaporation at 180 degrees Celsius
SANA	Santa Ana Basin
SC	Specific conductance
SDWR	Secondary drinking-water regulation
SPARROW	Spatially-referenced regression model of contaminant transport on watershed attributes
SUM	Sum of the dissolved constituents
UCOL	Upper Colorado River Basin
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WWTP	Wastewater-treatment plant

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Abstract

By David W. Anning

The U.S. Geological Survey National Water-Quality Assessment Program performed a regional study in the Southwestern United States (Southwest) to describe the status and trends of dissolved solids in basin-fill aquifers and streams and to determine the natural and human factors that affect dissolved solids. Basin-fill aquifers, which include the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers, are the most extensively used ground-water supplies in the Southwest. Rivers, such as the Colorado, the Rio Grande, and their tributaries, are also important water supplies, as are several smaller river systems that drain internally within the Southwest, or drain externally to the Pacific Ocean in southern California. The study included four components that characterize (1) the spatial distribution of dissolved-solids concentrations in basin-fill aquifers, and dissolved-solids concentrations, loads, and yields in streams; (2) natural and human factors that affect dissolved-solids concentrations; (3) major sources and areas of accumulation of dissolved solids; and (4) trends in dissolved-solids concentrations over time in basin-fill aquifers and streams, and the relation of trends to natural or human factors.

Dissolved-solids concentrations of ground water in the basin-fill aquifers of the Southwest ranged from less than 500 milligrams per liter near basin margins where ground water is recharged from nearby mountains to more than 10,000 milligrams per liter in topographically low areas of some basins or in areas adjacent to specific streams or rivers in the Basin and Range and Rio Grande aquifer systems. The area of the basin-fill aquifer systems with dissolved-solids concentrations less than or equal to 500 milligrams per liter was about 57 percent for the Rio Grande aquifer system, 63 percent for the Basin and Range basin-fill aquifers, and 44 percent for the California Coastal Basin aquifers. At least 70 percent of the area of these three basin-fill aquifer systems had dissolved-solids concentrations less than or equal to 1,000 milligrams per liter.

Dissolved solids in streams were described on the basis of median daily concentration, median annual load, and median annual yield data for 420 surface-water-quality monitoring sites. The time period with dissolved-solids data for individual sites varied but was at least 10 or more years between 1974 and 2003. Median daily dissolved-solids concentrations vary substantially among the sites in the Southwest, ranging between 22 and 13,800 milligrams per liter, and also vary between different sites on the same stream. Median daily concentrations generally increased in a downstream direction for sites on the Rio Grande, Colorado River, Yampa River, White River, Green River, San Juan River, Gila River, Bear River, and Sevier River. Median annual dissolved-solids loads ranged from 60 tons per year for a site on Elk Creek, a headwater tributary to the Colorado River, to 7.86 million tons per year at Colorado River below Hoover Dam, Arizona-Nevada. Typically, streams with the highest flows have the highest dissolved-solids loads. Median annual loads for sites on these rivers generally increased in the downstream direction, except where streamflow decreased substantially due to diversions and (or) streambed infiltration, typically in the downstream part of the river system. Median annual yields ranged from 0.69 to 7,510 tons per year per square mile, and the mean for all 420 sites was 125 tons per year per square mile. Most (104 of 112) sites with median annual yields greater than 100 tons per year per square mile were in the Colorado River basin upstream from Lees Ferry and in the Bear and Great Salt Lake hydrologic subregions.

A conceptual model was developed for the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams. Factors affecting concentrations in streamflow of upland mountain areas include amount of low-concentration runoff in the stream; presence of sedimentary rocks that are less resistant to the solvent action of water, especially evaporite deposits; streamflow storage and mixing processes in reservoirs; evapotranspiration; and transbasin diversions that result in the removal of high-quality water that would otherwise serve to help dilute high-concentration water sources in the originating basin.

Streams eventually flow out of the upland mountain areas and into lowland areas that have flatter terrain and contain large basin-fill aquifers. Ground-water recharge of the basin-fill aquifers along the basin margin by streamflow infiltration, or by subsurface flow from adjacent bedrock highland aquifers, typically has low dissolved-solids concentrations in comparison to ground-water in other parts of the aquifer. Dissolved-solids concentrations in ground-water typically increase along flowpaths through basin-fill aquifers as a result of geochemical reactions with the aquifer matrix, dissolution of disseminated salts and massive evaporite deposits, and evapotranspiration by natural vegetation or by agricultural crops. Dissolved-solids concentrations also can change as a result of mixing two or more subsurface waters; recharge from irrigation seepage, septic tank seepage, and percolation ponds or streambeds that infiltrate imported water or treated municipal wastewater; or seawater intrusion (in coastal areas). Dissolved-solids concentrations in streams also change along their paths through lowland areas due to evapotranspiration or mixing with ground water, irrigation-return flows, or releases from municipal wastewater-treatment plants.

In lowland areas, the enhancement or restriction of surface-water and ground-water outflow affects the accumulation of dissolved solids in water supplies. Natural drainage or artificial drainage by canals or pipelines can enhance the outflow of water containing dissolved solids, thereby diminishing the accumulation of salts. Restriction of outflow through water use, or through natural features like topographic barriers that prevent surface outflow, restricts the outflow of water, thereby promoting the accumulation of salts. The salts generally accumulate in areas with high evapotranspiration, a process that increases dissolved-solids concentrations.

Significant dissolved-solids source and accumulation areas were determined by using a mass-balance analysis of the contributions and losses of dissolved solids for river systems in hydrologic accounting units of the Southwest. Contributions to river systems in each hydrologic accounting unit included inflows, internal deliveries, and imports; and losses included outflows, internal accumulation, and exports. These six terms were quantified by using predictions from a spatially-referenced regression model of contaminant transport on watershed attributes (SPARROW).

The most significant dissolved-solids source areas in the Southwest included the Colorado headwaters, Middle Gila, Lower Bear, and Santa Ana accounting units, where deliveries from internal sources were greater than 150 tons per year per square mile. The most significant dissolved-solids accumulation areas included the Salton Sea, Lower Gila-Agua Fria, Middle Gila, Lower Bear, and Great Salt Lake accounting units, where accumulation rates were greater than 150 tons per year per square mile. The dissolved-solids accumulation rate for the Salton Sea accounting unit, 704 tons per year per square mile, was more than twice as high as the second highest rate, 305 tons per year per square mile for the Lower Gila-Agua Fria accounting unit.

Predictions from the SPARROW model were used to determine the relative significance of the various natural and human internal sources of dissolved solids in Southwest accounting units. Geologic units, which represent natural sources of dissolved solids, contribute 44 percent of the total internal deliveries for all accounting units in the Southwest. Of this percentage for geologic units, about 7 percent is from crystalline and volcanic rocks, 2 percent is from eugeosynclinal rocks, 12 percent is from Tertiary sedimentary rocks, 12 percent is from Mesozoic sedimentary rocks, and 10 percent is from Paleozoic and Precambrian sedimentary rocks. Cultivated lands (44 percent) and pasture lands (12 percent) are anthropogenic sources of dissolved solids and contribute the remaining 56 percent of the total internal deliveries for all Southwest accounting units.

Trends for 1974–88, 1989–2003, and 1974–2003 were determined for concentrations of dissolved solids in basin-fill aquifers and flow-adjusted concentrations in streams. For the basin-fill aquifers, concentrations of dissolved solids did not change over time for most ground-water-quality monitoring wells in the analysis. The portion of wells in basin-fill aquifers with no trend in concentrations was 77 percent for 1974–88, 68 percent for 1989–2003, and 59 percent for 1974–2003. Of the wells that did have a trend in concentrations, increasing trends were more common than decreasing trends for each period. For 1989–2003, the probability of a trend occurring in dissolved-solids concentrations of basin-fill aquifers decreased with the depth to water below the land surface.

In comparison to conditions for ground-water-quality monitoring wells in the basin-fill aquifers, the presence of trends in dissolved-solids concentrations in streams was much more common. The data analyzed included an annual series of concentrations that were adjusted for variation due to variation in discharge and seasonal variability. Of the three time periods, 1974–88 had the greatest percentage of sites with either no change, or an increase in adjusted annual dissolved-solids concentrations. For this time period, no change in adjusted annual dissolved-solids concentrations was noted at 24 percent of sites, and an increase in adjusted annual dissolved-solids concentrations was noted at 34 percent of sites. Decreases in adjusted annual dissolved-solids concentrations were noted at 42 percent of sites. During 1989–2003, adjusted annual dissolved-solids concentrations decreased at more than half (51 percent) of the sites. For the 1989–2003 time period, there were five major river basins where adjusted annual dissolved-solids concentrations decreased at 75 percent or more of the sites. For the 1974–2003 time period, adjusted annual dissolved-solids concentration decreased at about 70 percent of the sites, and the median change in concentration during this period for all sites was about -8 percent. Most of the sites included in the trend analysis for this period are situated on the main stem of major rivers, and as a result, the conclusions that are drawn from this data set relate more specifically to conditions in the major rivers. For several areas in the Colorado River Basin, adjusted annual dissolved-solids concentrations decreased during 1989–2003 at all sites downstream from salinity-control units, whereas increasing and decreasing concentrations trends occurred at sites upstream from the units. Decreases in adjusted annual dissolved-solids concentration occurred at three sites above salinity-control units but were much less than the decreases at sites below those units.

Introduction

By Nancy J. Bauch and David W. Anning

In the Southwestern United States, the location and extent of economic and cultural activities are dependent in part on the availability and quality of water. The Southwest (fig.1) is an arid to semiarid region of the United States, and, as defined in this report, comprises an area of about 503,000 mi^2. In many areas of the Southwest, high concentrations of dissolved solids (also described as total dissolved solids) degrade a water supply's suitability for certain uses. In response to this water-quality issue, the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program began a regional study in 2004 to characterize dissolved-solids conditions in the basin-fill aquifers and streams of the Southwest and to understand how natural and human factors affect the conditions. This report documents the findings of this study.

The NAWQA Program, in partnership with Federal, State, Tribal, and local governments, and research and public interest groups, is designed to assess ground-water- and surface-water-quality conditions across the Nation, how water quality changes over time, and how natural and human factors affect water quality. As part of the NAWQA Program, regional assessments are used to investigate water-quality conditions and trends in 18 principal aquifer systems and in streams draining 8 large geographic areas across the Nation. These assessments add to interdisciplinary (ground water, surface water, and aquatic ecosystems) studies conducted by the NAWQA Program from 1991 to 2001 in 51 river basins throughout the Nation, referred to as "Study Units." The Central Arizona Basins (CAZB), Great Salt Lake Basins (GRSL), Nevada Basin and Range (NVBR), Rio Grande Valley (RIOG), Santa Ana Basin (SANA), and Upper Colorado Basin (UCOL) NAWQA Study Units are within the Southwest (fig. 1). Each regional assessment addresses specific water-quality conditions in a major aquifer system and (or) geographic area, such as the quality of domestic and public ground-water supplies, effects of urban development and agriculture on ground-water quality and aquatic ecosystems, and sources and transport of nitrogen and phosphorus to surface-water bodies, including rivers, lakes, estuaries, and coastal waters. Multiple aquifer systems and (or) geographic areas can be combined into a multiregional assessment. One such assessment is this study of dissolved solids in basin-fill aquifers and streams in the Southwest.

All water naturally contains dissolved solids as a result of the weathering and dissolution of minerals in soils and geologic formations. Major ions, such as bicarbonate, calcium, chloride, magnesium, potassium, silica, sodium, and sulfate, constitute most of the dissolved solids in water and are an indicator of salinity. Some amount of dissolved solids is needed for plant and animal growth and for agricultural, domestic, municipal, and industrial purposes. Many of the major ions are essential to life and have vital nutritional functions. Dissolved solids also are fundamental in numerous products and processes, such as fertilizers, nutritional supplements, water conditioning, food seasoning and production, cleaning products, highway salts, and in the airplane and automobile, building, chemical, electronics, and semiconductor industries.

Dissolved-solids concentrations increase in water primarily through two main processes: salt concentration and salt pickup. Each process can be naturally occurring or human induced. Salt concentration results from the consumptive use of water; diversion of high-quality, low-saline water out of a basin; and evapotranspiration. No dissolved solids are added to the water, or removed with evaporative processes, but dissolved-solids concentrations increase because less river or stream water is available for dilution. Salt pickup primarily occurs when dissolved solids are put into solution by the movement of water through a subsurface flow system or overland flow. In some areas of the Southwest, for example, highly mineralized springs result from the dissolution of geologic source materials containing ancient marine deposits. Municipal and industrial wastes discharge dissolved solids into streams; and irrigation-return flows, primarily from subsurface percolation of water through saline materials rather than surface-water runoff, discharge large amounts of dissolved solids into waters in the Southwest. Surface disturbances from anthropogenic activities, such as off-road vehicle use, grazing, and development, have the potential to increase dissolved solids in water through soil erosion and dissolution of dissolved solids in sediments.

An increase of dissolved solids in water to excessive concentrations affects aquatic ecosystems and agricultural, domestic, municipal, and industrial water users. In aquatic ecosystems, plant and animal species vary in their ability to tolerate dissolved solids, and elevated concentrations can be stressful for some plants and animals because of changing osmotic conditions. Chapman and others (2000), for example, reported that benthic macroinvertebrates were significantly affected when dissolved-solids concentrations in mine effluent were greater than 1,100 mg/L (equivalent to parts per million), whereas trout were tolerant to dissolved-solids concentrations in mine effluent greater than 2,000 mg/L. Synthetic effluents that matched the overall chemical characteristics of dissolved solids in effluents discharged from mines were used in the toxicity tests. Metals were not included because the objective was to characterize the potential effects of dissolved solids. In addition, increased levels of some ions can be more toxic to aquatic organisms than other ions (Chapman and others, 2000; Scannell and Jacobs, 2001). With increased concentrations of dissolved solids or particular ions, less-tolerant plant species may be replaced by more-tolerant species, and animal communities may change as the specific plant community to which they are adapted changes. Overall community structure likely will change with the introduction of salt-tolerant species.

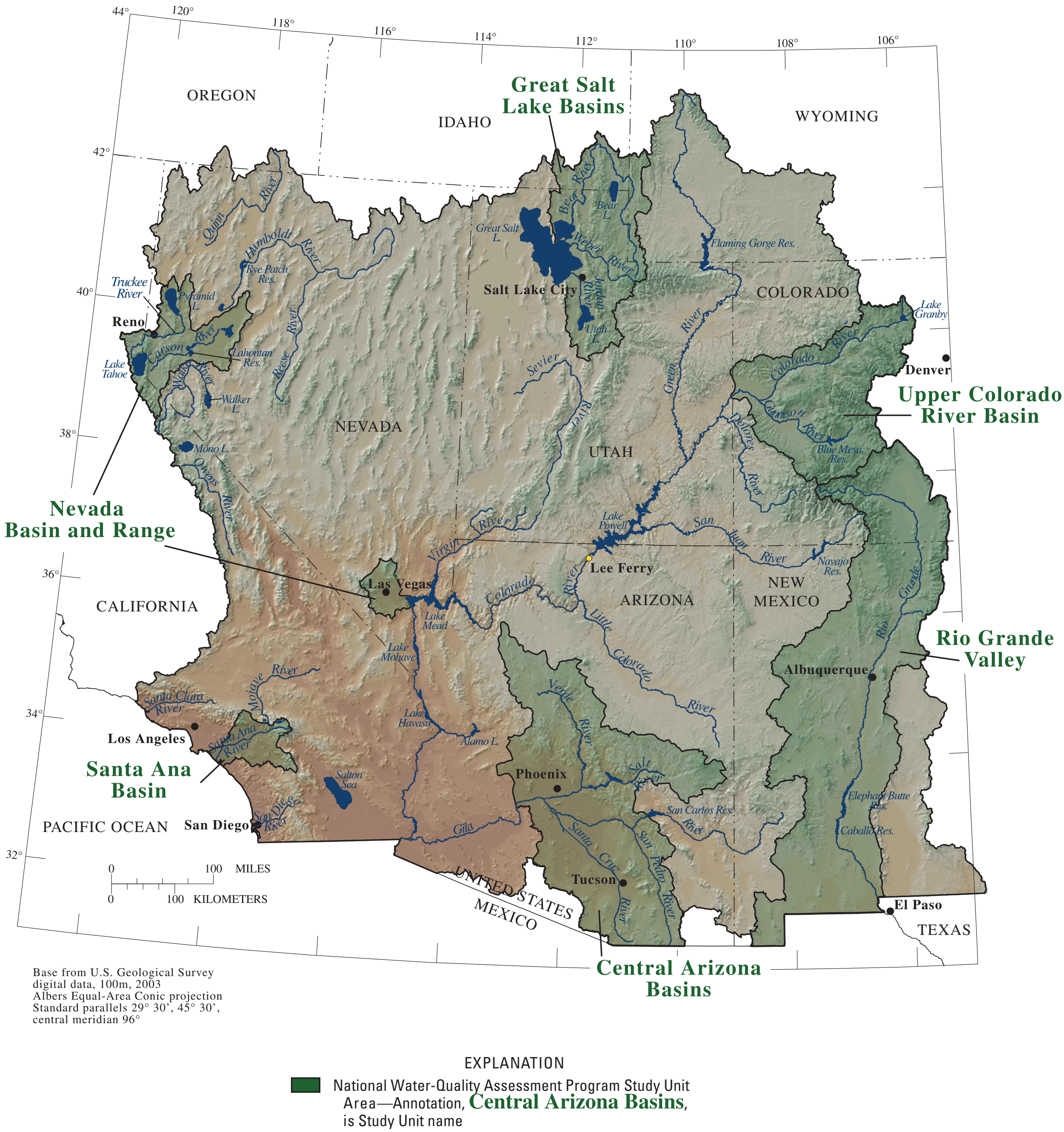


Figure 1. Study area and National Water-Quality Assessment Program Study Units in the Southwestern United States.

Elevated dissolved-solids concentrations in irrigation water and soils can lead to decreased crop production or crop death and, thus, decreases in economic returns, altered crop patterns, greater soil leaching and drainage requirements, degraded soil structure, and higher management costs. In extreme cases, agricultural land may be removed from production. The salinization of soil and water in agricultural areas is not a new concern. Civilizations in ancient Mesopotamia (present-day Iraq) declined in part because food production on agricultural lands in the flood plain of the Tigris and Euphrates Rivers, known as the Fertile Crescent, could not be sustained due to salinization of the land over time.

The Food and Agriculture Organization of the United Nations has reported guidelines for the use of irrigation water regarding dissolved solids. Depending on soil condition and type of vegetation, there is no restriction for irrigation-water use when dissolved-solids concentrations are less than 700 mg/L, slight to moderate restrictions for irrigation-water use when dissolved-solids concentrations are between 700 and 2,000 mg/L, and severe restrictions for irrigation-water use when dissolved-solids concentrations are greater than 2,000 mg/L (Ayers and Westcot, 1994). Several southwestern States have recommended dissolved-solids concentration levels for crop irrigation and agriculture. In Colorado, for example, the maximum allowable dissolved-solids concentration in ground water used for agriculture that has a background dissolved-solids concentration between 0 and 500 mg/L is 400 mg/L or 1.25 times the background concentration, whichever is the higher value (Colorado Department of Public Health and Environment, 2005). With increased dissolved-solids concentrations in irrigation water, crops with low salinity tolerance, such as beans or raspberries, may need to be replaced with crops with moderate or high salinity tolerance, such as corn or peppers and barley or beets, respectively.

For livestock and poultry, high concentrations of dissolved solids and specific ions, particularly magnesium, in drinking water can affect animal health and cause death. The National Academy of Sciences and National Academy of Engineering (1972) reported that a dissolved-solids concentration of 5,000 mg/L or less in drinking water for livestock and poultry was satisfactory. The suitability of any particular water, however, should be evaluated in terms of local conditions and the availability of alternate supplies, water source, seasonal changes in water quality, age and condition of the animal, and animal species (Ayers and Westcot, 1994).

The effects of high concentrations of dissolved-solids in water on domestic, municipal, and industrial users include objectionable taste to drinking water; greater water-treatment costs; increased use of detergents and soaps; encrustment or corrosion of metallic surfaces and reduction in the lifespan of domestic, municipal, and industrial equipment; restricted use for landscape irrigation; and interference with chemical processes. The U.S. Environmental Protection Agency (USEPA) has established nonenforceable secondary drinking water regulation (SDWR) for dissolved solids and selected ions related to esthetic qualities of water, such as taste. For chloride and sulfate, the SDWR is 250 mg/L each, whereas the SDWR for total dissolved solids is 500 mg/L (U.S. Environmental Protection Agency, 2004a). Individual States may have similar regulations or standards. Designated-use limits for some industrial processes include brewing—light beer, 500 mg/L, and dark beer, 1,100 mg/L; pulp and paper—fine paper, 200 mg/L; and canning or freezing, 850 mg/L (Sherrard and others, 1987).

Damages from elevated dissolved-solids concentrations in water can have high economic costs. In the United States portion of the Colorado River Basin, the cost to agricultural, municipal, and industrial users of water high in dissolved-solids concentrations ranges from $500 million to $750 million per year (Bureau of Reclamation, 2005). For coastal southern California, public and private sectors use Colorado River water with dissolved-solids concentrations between 600 and 800 mg/L. The damage estimate for these users is $95 million per year for each 100 mg/L that the dissolved-solids concentrations in water are greater than 500 mg/L (California Energy Commission, 2004). Similarly, the Central Arizona Salinity Study determined that there was $15 million in damages for every 100 mg/L increase in dissolved-solids concentrations in its study areas (Gritzuk, 2004).

Elevated dissolved-solids concentrations in waters of the Southwest have led to the establishment of salinity-control projects and processes throughout the area, a few of which are described in this report. In the Colorado River Basin, public laws enacted in 1974 and 1984 authorized the planning and construction of numerous salinity-control projects to improve or prevent further degradation in the quality of Colorado River water for use by the United States and Mexico (Bureau of Reclamation, 2005). These salinity-control projects have included canal lining, lateral piping, on-farm irrigation control, irrigation drainage, pumping of ground water, well plugging, vegetation management, and land retirement. As of 2004, it is estimated that the projects in operation reduced salt loading to the Colorado River by about 980,000 tons of salt per year (Colorado River Basin Salinity Control Forum, 2005). In municipal areas where salinity-control projects for source control cannot be done, concentrations in brackish water supplies are reduced through water-treatment processes, such as reverse osmosis.

Purpose and Scope

This report is a regional water-quality assessment that documents the spatial and temporal patterns in dissolved-solids concentrations in basin-fill aquifers and streams in the Southwest and identifies the factors and processes that influence those patterns and concentrations. The analyses relied entirely on existing data, and no new data were collected as part of the effort. This report addresses four objectives that are oriented to provide water-resource managers with information that is useful in decision making regarding water-resources development, protection, and improvement. The report is organized into sections that focus on each objective.

- The first objective is to describe the spatial distribution of dissolved-solids concentrations in basin-fill aquifers, and dissolved-solids concentrations, loads, and yields of major rivers and their tributaries. Information about the spatial distribution of dissolved-solids in aquifers and streams is fundamental for water providers who are evaluating their current supplies or seeking new water supplies.

- The second objective is to describe the natural and human factors that affect dissolved solids along selected ground-water and surface-water flow paths in the Southwest. An understanding of the effects of natural and human factors on dissolved-solids concentrations allows for informed decision making in developing strategic water-quality protection and improvement policies or programs.

- The third objective is to describe the major sources and areas of accumulation of dissolved solids in the Southwest. An understanding of the major sources and areas of accumulation allows for strategic placement of water-quality-protection policies and programs that can mitigate source contributions of dissolved solids in water resources and minimize the effects of accumulation of dissolved solids in specific areas.

- The fourth objective is to describe the trends of dissolved-solids concentrations in basin-fill aquifers and streams over time, and to relate the trends to causes, such as water-resources development, protection, or improvement projects. An understanding of the trends and their causes allows for informed decision making in water-quality protection and improvement issues.

The Southwest contains several principal aquifers composed of basin-fill, sandstones, carbonate, and volcanic-rock aquifers (Miller, 2000). Principal aquifers composed of basin-fill deposits in the Southwest (fig. 2) include the Rio Grande aquifer system, Basin and Range basin-fill aquifers, California Coastal Basin aquifers, and Pacific Northwest basin-fill aquifers. Only minor parts of the Pacific Northwest basin-fill aquifers are in the Southwest. For simplicity these aquifers are included in Basin and Range basin-fill aquifers in this report. Colorado Plateau aquifers are primarily composed of sandstones and occur in a significant portion of Southwest. Other principal aquifers in the Southwest (not shown in fig. 2) include Basin and Range carbonate-rock aquifers and southern Nevada volcanic-rock aquifers. This report focuses on the basin-fill aquifers because, as a group, they are extensive and the most utilized aquifers in the Southwest.

The Southwest contains two of the largest river systems in the country, the Colorado and Rio Grande, as well as several smaller river systems that drain internally or drain to the Pacific Ocean in southern California. The Southwest was divided into 12 major river basins to facilitate reporting results (fig. 3, table 1). The Colorado River Basin is made up of seven of the major river basins: the Upper Colorado River Basin, Green River Basin, San Juan River Basin, Little Colorado River Basin, Middle Colorado River Basin, Gila River Basin, and Lower Colorado River Basin. In contrast to these seven major river basins and also the Upper Rio Grande Basin, the remaining four major river basins each typically contain several smaller river systems (the Central Lahontan Basins, Southern California Coastal Basins, Central Nevada and Eastern California Desert Basins, and Great Salt Lake and Sevier River Basins).

The major river basin boundaries were delineated on the basis of the boundaries for hydrologic subregions (table 1; fig. 4), which are a set of basins established as part of the USGS hydrologic unit system (Seaber and others, 1987). The hydrologic unit system subdivides the United States into nested basins at four different spatial levels: regions, which are the largest basins and contain subregions, which in turn contain accounting units, which in turn contain cataloging units. The hydrologic unit system uses a number system with a 2-digit code for regions, a 4-digit code for subregions, a 6-digit code for accounting units, and an 8-digit code for cataloging units. The codes indicate the nesting of regions, subregions, accounting units, and cataloging units. For example, the Big Sandy cataloging unit (15030201) is in the Bill Williams accounting unit (150302), which in turn is in the Lower Colorado subregion (1503), which in turn is in the Lower Colorado Region (15). In the Southwest, there are 5 regions, 28 subregions, 47 accounting units, and 266 cataloging units.

Results for each of the four main study objectives related to surface-water conditions are summarized by major river basin, subregion, and (or) accounting unit (figs. 3 and 4). In a few cases, results were reported specifically for the surface-water-quality monitoring site Colorado River above Lees Ferry (site 09380000). The significance of this site lies in its location, which is about a mile upstream from Lee Ferry, the divide for the legally defined Upper Colorado River Basin and Lower Colorado River Basin, and about 16 miles downstream from Lake Powell (fig. 1). The drainage to the Colorado River upstream from Lee Ferry is in the Upper Colorado River Basin, and the drainage to the Colorado River downstream from Lee Ferry is in the Lower Colorado River Basin.
The major river basins defined in this report as the “Upper Colorado River Basin” and the “Lower Colorado River Basin” drain different, much smaller areas than the legally defined basins. Results for each of the four main study objectives related to ground-water conditions are summarized by basin-fill aquifer, subregion, and (or) accounting unit.

Several of the river systems, including the Colorado River and the Rio Grande, underwent considerable reservoir development during the early and middle parts of the 20th century. To avoid potential errors and misinterpretations associated with combining data from both pre- and post-reservoir development, the temporal scope of data for streams is restricted to water years 1974–2003. By 1974, many of the larger reservoirs within the Southwest had been completed and filled. The temporal scope of data for basin-fill aquifers was generally restricted to the same time period, water years 1974–2003.

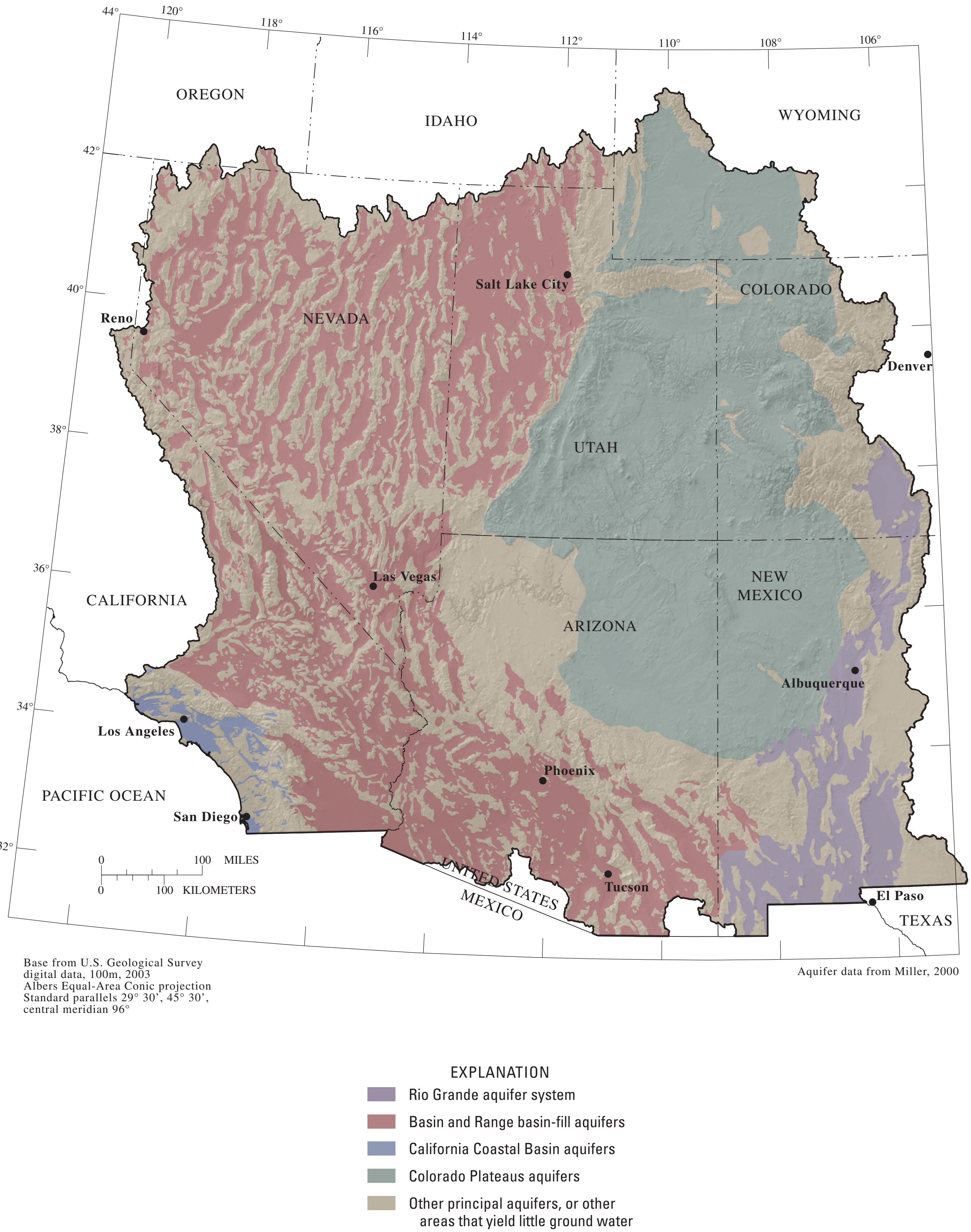


Figure 2. Selected principal aquifers in the Southwestern United States.

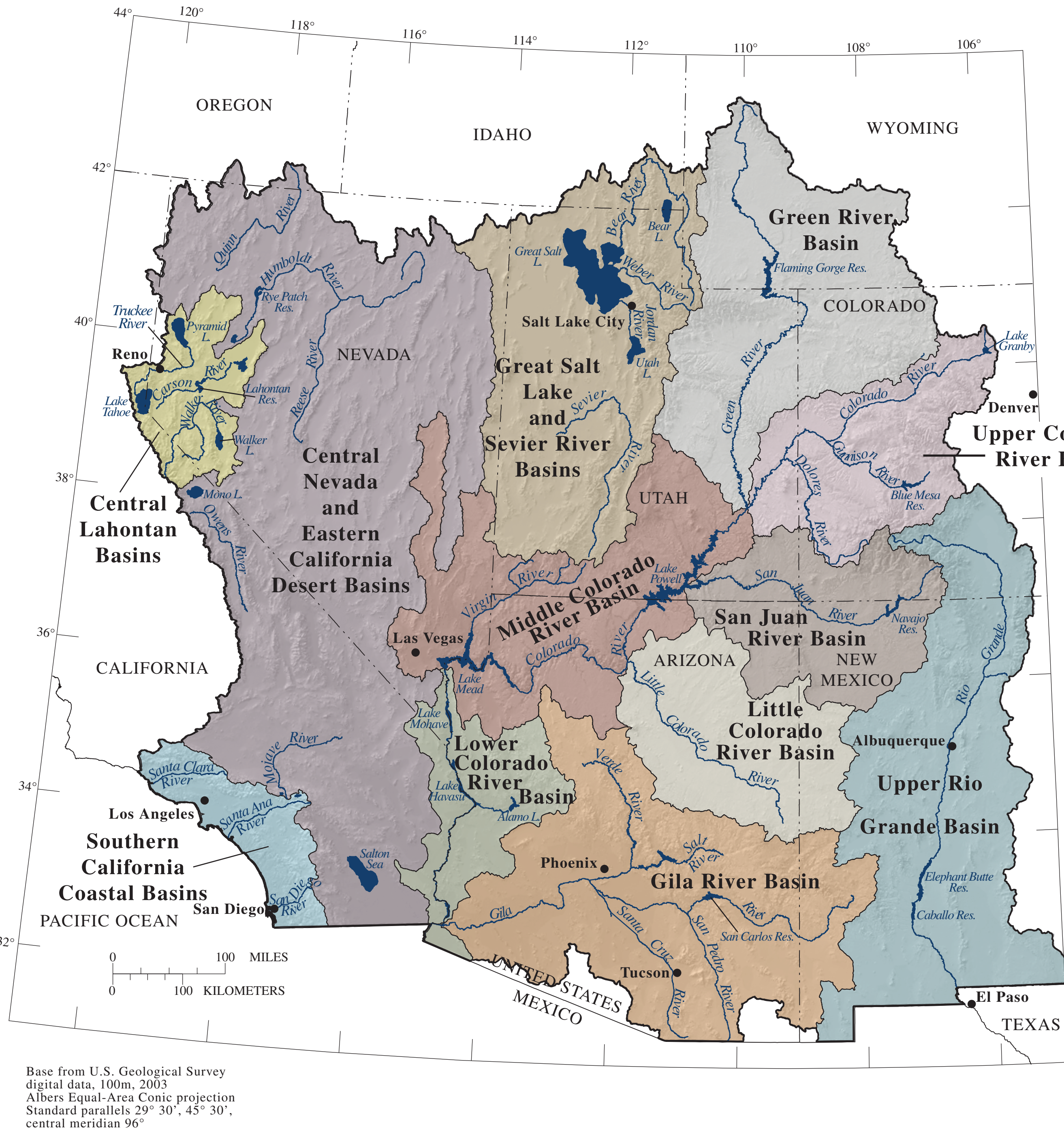


Figure 3. Major river basins in the Southwestern United States.

Table 1. Spatial correspondence of hydrologic subregions and accounting units for basin-fill aquifers and major river basins in the Southwestern United States.

[Hydrologic subregions and accounting units from Seaber and others, 1987]

Hydrologic subregion		Hydrologic accounting unit			Major river basin	Principal basin-fill aquifer system
Code	Name	Code	Name	Main stem river(s)		
1301	Rio Grande headwaters	130100	Rio Grande headwaters	Rio Grande	Upper Rio Grande Basin	Rio Grande aquifer system
1302	Rio Grande-Elephant Butte	130201	Upper Rio Grande	Rio Grande		
		130202	Rio Grande-Elephant Butte			
1303	Rio Grande-Mimbres	130301	Rio Grande-Caballo	Rio Grande		
		130302	Mimbres	Mimbres		
1305	Rio Grande closed basins	130500	Rio Grande closed basins	Three topographically closed basins with minor rivers		
1401	Colorado headwaters	140100	Colorado headwaters	Colorado River	Upper Colorado River Basin	There are no major basin-fill aquifers in these subregions, except for Basin and Range basin-fill aquifers which occur in the western part of subregion 1501 (Lower Colorado–Lake Mead)
1402	Gunnison	140200	Gunnison	Gunnison River		
1403	Upper Colorado-Dolores	140300	Upper Colorado-Dolores	Colorado and Dolores Rivers		
1404	Great Divide–Upper Green	140401	Upper Green	Green River	Green River Basin	
		140402	Great Divide closed basin	A closed basin with minor rivers		
1405	White-Yampa	140500	White-Yampa	White and Yampa Rivers		
1406	Lower Green	140600	Lower Green	Green River		
1407	Upper Colorado-Dirty Devil	140700	Upper Colorado-Dirty Devil	Colorado River	Middle Colorado River Basin	
1501	Lower Colorado-Lake Mead	150100	Lower Colorado-Lake Mead	Colorado and Virgin Rivers		
1408	San Juan	140801	Upper San Juan	San Juan River	San Juan River Basin	
		140802	Lower San Juan	San Juan River		
1502	Little Colorado	150200	Little Colorado	Little Colorado River	Little Colorado River Basin	
1503	Lower Colorado	150301	Lower Colorado	Colorado River	Lower Colorado River Basin	Basin and Range basin-fill aquifers
		150302	Bill Williams	Bill Williams River		
1504	Upper Gila	150400	Upper Gila	Gila River	Gila River Basin	
1505	Middle Gila	150501	Middle Gila	Gila River		
		150502	San Pedro–Willcox	San Pedro River		
		150503	Santa Cruz	Santa Cruz River		
1506	Salt	150601	Salt	Salt River		
		150602	Verde	Verde River		
1507	Lower Gila	150701	Lower Gila–Agua Fria	Gila River		
		150702	Lower Gila	Gila River		
1601	Bear	160101	Upper Bear	Bear River	Great Salt Lake and Sevier River Basins	
		160102	Lower Bear	Bear River		
1602	Great Salt Lake	160201	Weber	Weber River		
		160202	Jordan	Jordan River		
		160203	Great Salt Lake	Contains several topographically closed basins with minor rivers		
1603	Escalante Desert-Sevier Lake	160300	Escalante Desert–Sevier Lake	Sevier River		

Table 1. Spatial correspondence of hydrologic subregions and accounting units for basin-fill aquifers and major river basins in the Southwestern United States—Continued.

Hydrologic subregion		Hydrologic accounting unit			Major river basin	Principal basin-fill aquifer system
Code	Name	Code	Name	Main stem river(s)		
1605	Central Lahontan	160501	Truckee	Truckee River	Central Lahontan Basins	Basin and Range basin-fill aquifers—cont.
		160502	Carson	Carson River		
		160503	Walker	Walker River		
1604	Black Rock Desert-Humboldt	160401	Humboldt	Humboldt River	Central Nevada and Eastern California Desert Basins	
		160402	Black Rock Desert	Quinn River		
1606	Central Nevada Desert Basins	160600	Central Nevada Desert Basins	Contains several topographically closed basins with minor rivers		
1809	Northern Mojave-Mono Lake	180901	Mono–Owens Lakes	Owens River		
		180902	Northern Mojave	Mojave, Armagosa, and several minor rivers in topographically closed basins		
1810	Southern Mojave-Salton Sea	181001	Southern Mojave	Contains several topographically closed basins with minor rivers		
		181002	Salton Sea	A single topographically closed basin with minor rivers		
1807	Southern California Coastal	180701	Ventura–San Gabriel Coastal	Santa Clara River	Southern California Coastal Basins	California Coastal Basin aquifers
		180702	Santa Ana	Santa Ana River		
		180703	Laguna–San Diego Coastal	San Diego River		

Base from U.S. Geological Survey
digital data, 100m, 2003
Albers Equal-Area Conic projection
Standard parallels 29° 30', 45° 30',
central meridian 96°

Hydrologic subregion and accounting
unit data from Seaber and others, 1987

EXPLANATION

Hydrologic subregion boundary—Annotation, **Upper Gila**, is hydrologic subregion name

Hydrologic accounting unit boundary—Number, ***150400***, is accounting unit codes

Figure 4. Hydrologic subregions and accounting units in the Southwestern United States.

Acknowledgments

The success of this study rests with the many hydrologic data-collection programs that were intellectually, physically, and financially supported by numerous Federal, State, and local cooperating agencies. A special “thank you” goes to these agencies and to the many field scientists for their years of dedicated service collecting hydrologic data.

Environmental Setting of the Southwest

By David W. Anning and Lawrence E. Spangler

The environmental setting of the Southwest, as characterized by its physiography, geology, climate, land cover, population patterns, and water-resources availability, usage, and protection, distinguishes this part of the country from other regions of the United States. Variation in these environmental characteristics generates variability in hydrologic characteristics of basin-fill aquifers and streams, which in turn causes variations in dissolved-solids concentrations in water supplies. A description of the fundamental hydrologic characteristics for basin-fill aquifers and streams and a summary of environmental conditions for the Southwest are presented in this section of the report.

Basin-Fill Aquifers

The principal basin-fill aquifers in the Southwest include the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and the California Coastal Basin aquifers (fig. 2, table 1). Brief descriptions of these aquifers are provided here, mostly on the basis of summaries provided by Planert and Williams (1995) and in Robson and Banta (1995).

Rio Grande Aquifer System

The Rio Grande aquifer system includes over about 55,000 mi^2 of the Southwest (fig. 2). The principal geologic feature in the area is the Rio Grande Rift, a northward-trending series of interconnected, downfaulted and rotated blocks between uplifted blocks to the east and west. This tectonics feature created about 20 alluvial basins, and the sediments and water that filled them form the Rio Grande aquifer system. Mountains made of bedrock that surround the basins are relatively impermeable and are considered barriers to ground-water flow. Gaps in the mountains and subsurface bedrock between the basins, however, allow for surface and subsurface flow. Basins along the Rio Grande are topographically open and have surface drainage to the river, whereas several of the adjacent basins are topographically closed. In most cases the basin-fill aquifers of adjacent basins are hydraulically connected with subsurface interbasin flow.

The basin fill thickness ranges from a veneer along the mountain fronts to several thousand ft in the basin center and as much as 30,000 ft in the San Luis Valley of south-central Colorado. The principal water-yielding materials in the Rio Grande aquifer system can be divided into the older basin fill and the younger basin fill. Older basin fill consists of moderately consolidated lenticular deposits of gravel, sand, and clay interbedded in some areas with andesitic and rhyolitic lava flows, tuffs, and breccias. Younger basin fill consists of unconsolidated poorly to well-sorted interbedded Quaternary gravel, sand, silt, and clay in alluvial fan, pediment-cover, and flood-plain terrace deposits. In some basins, clay and silt lenses form laterally continuous confining units, particularly in the central or downgradient areas of the basin.

The Rio Grande aquifer system is the primary ground-water supply for the basins along and adjacent to the Rio Grande. Ground water from the aquifers is primarily used for crop irrigation, except in the vicinity of Albuquerque where it is used for both municipal and crop irrigation purposes. The primary porosity and permeability of the aquifers are typically high, particularly in younger basin fill, and well yields can exceed 1,000 gal/min.

Recharge to the aquifer system is generally from precipitation and from underflow from upgradient areas. Recharge from precipitation generally occurs along the mountain fronts from infiltration of runoff along stream channels. Most precipitation that falls on the basin floors evaporates and little of it becomes recharge. Discharge from the aquifer system is generally from evapotranspiration of shallow ground water, withdrawal from wells, seepage to streams, and underflow to downgradient areas. The aquifers are hydraulically connected to the Rio Grande along much of its length, and discharge to the river is a significant component of total ground-water discharge. Ground-water withdrawals near the Rio Grande can reduce ground-water discharge to the river and (or) induce recharge through streamflow infiltration.

Basin and Range Basin-Fill Aquifers

Basin and Range basin-fill aquifers include over about 200,000 mi^2 of the Southwest and occur in about 330 intermountain basins (Anning and Konieczki, 2005). The general composition and structure of basin fill of the Basin and Range basin-fill aquifers is comparable to that described above for the Rio Grande aquifer system.

Basins along the Colorado River and its tributaries in the Lower Colorado, Lower Gila, Middle Gila, and Upper Gila subregions are topographically open. In these basins, ground water typically is discharged from the aquifers by evapotranspiration of shallow ground water, withdrawal from wells, seepage to streambeds, and underflow to downgradient areas. Many of the basins are topographically closed in the Great Salt Lake, Escalante Desert-Sevier Lake, Black Rock Desert-Humboldt, Central Lahontan, Central Nevada Desert Basins, Northern Mojave-Mono Lake, and Southern Mojave-Salton Sea hydrologic subregions. Of these basins, some are partially drained by ground-water flow through basin-fill deposits or permeable bedrock, and others are hydraulically closed by low-permeability bedrock (Planert and Williams, 1995; Robson and Banta, 1995; Anning and Konieczki, 2005). Where topographically closed and hydraulically closed in the subsurface, ground-water discharge is primarily through evapotranspiration and withdrawal by wells. Contaminants reaching these aquifers are more likely to be retained and concentrated owing to the lack of ground-water outflow to other areas. Recharge primarily occurs along the mountain fronts or along stream channels in the central parts of basins.

The basin-fill aquifers are the principal source of ground water for domestic and municipal supply and for irrigated agriculture in the Basin and Range Physiographic Province. These uses of water account for most of the total water use in this region. Water-supply development and use has significantly altered storage and flow of ground-water in some parts of the basin-fill aquifers. Ground-water withdrawals have lowered the aquifer more than 200 ft in several large agricultural and urban areas (Anderson, 1995). The lowered water levels have resulted in land subsidence in parts of several basins, more than 7 ft in a 120 mi^2 area between Phoenix and Tucson in south central Arizona (Laney and others, 1978). Water use also has increased annual recharge in some areas. Water returned to streams from municipal wastewater-treatment plants infiltrates streambeds in losing reaches, and recharges aquifers. Another substantial source of recharge is excess agricultural or urban irrigation water that percolates through the basin-fill sediments and recharges the aquifers. In some basins infiltration of treated municipal wastewater and excess irrigation water are greater than natural sources of recharge.

California Coastal Basin Aquifers

The California Coastal Basin aquifers include about 11,000 mi^2 of the Southwest and occur in structural depressions that are the result of folding and faulting. In the coastal areas, the basin fill consists of (1) unconsolidated and semiconsolidated marine sediments that were deposited during periodic encroachment of the sea and (2) unconsolidated continental deposits that consist of weathered igneous and sedimentary rock material that was transported into the basins by mountain streams (Planert and Williams, 1995). Basin-fill sediments in the inland areas are generally eroded from the surrounding mountains (Hamlin and others, 2002). In the basin fill of the coastal plain near Los Angeles, several sand and gravel units are separated by intervening and confining silt and clay units.

The California Coastal Basin aquifers are used primarily for public supply and secondarily for crop irrigation. Before major development, ground-water flow generally was from inland mountains toward the sea, and ground water discharged directly to the ocean. Development of the aquifers, however, has altered the flow systems and most discharge is now by ground-water withdrawals from wells in the basins. Along some parts of the coast, ground-water gradients reversed, and flow was redirected inland, causing saltwater intrusion. Coordinated management of ground-water pumping began in the 1950s to mitigate the water-quality problems associated with saltwater intrusion (Planert and Williams, 1995). Natural recharge to the aquifers generally occurs along the mountain fronts from streamflow infiltration. In several basins, however, natural recharge is augmented with engineered recharge of mountain runoff, imported water, and (or) treated municipal wastewater through either streambeds or infiltration ponds.

Streams

The Southwest contains several river systems that provide important water supplies to municipal and agricultural users, and also provide drinking water and habitat for terrestrial and aquatic life. An overview of these river systems is presented here, and their stream permanence, sources of flow, significant reservoirs and transbasin diversions, and major offstream water uses are summarized in table 2.

The Colorado River and the Rio Grande are the largest river systems in the Southwest and are among the larger river systems in the continental United States. The Colorado River drains about 247,000 mi^2 of the Southwest (fig. 3; site 09522000, appendix 1), and the Rio Grande drains about 32,000 mi^2 of the Southwest (fig. 3; site 08364000, appendix 1). These two rivers, and several smaller rivers that drain about 11,000 mi^2 of land (Seaber and others, 1987) in the coastal region of Southern California, drain to the ocean. The remaining part of the Southwest, about 213,000 mi^2, is internally drained by several smaller river systems such as the Bear, Sevier, Truckee, Carson, Walker, and Humboldt Rivers in Nevada and Utah, and the Owens and Mojave Rivers in the desert region of southern California (fig. 3). These rivers drain topographically closed areas and terminate in playas or terminal lakes, such as the Great Salt Lake, Mono Lake, Pyramid Lake, Walker Lake, and the Salton Sea (fig. 3).

The main stems of many river systems in the Southwest have perennial streamflow (table 2); however, some, particularly in low altitude reaches, have intermittent or ephemeral streamflow as a result of climate, hydrogeology, stream regulation, and (or) water diversions. Main-stem tributaries with perennial flow tend to occur in intermediate to high altitude reaches where the climate is wetter and cooler than at low altitudes. Many main-stem tributaries at low altitudes have ephemeral or intermittent flow, particularly in the Basin and Range Physiographic Province.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States.

[1301 - Rio Grande headwaters, number is hydrologic subregion code followed by hydrologic subregion name]

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
Upper Rio Grande Basin		
1301 - Rio Grande headwaters		
Streamflow in the Rio Grande Headwaters is perennial and highly regulated. Major tributaries to the Rio Grande include Willow Creek, Goose Creek, South Fork Rio Grande, and the Conejos River; these perennial tributaries are snowmelt-dominated.	Streamflow is stored in Platoro Reservoir on the Conejos River, and other small reservoirs. Streamflow may be diverted into the Rio Grande Basin from the San Juan Basin or the Gunnison River Basin; transmountain diversions vary from year to year.	Streamflow is diverted for irrigation throughout the San Luis Valley; streamflow is diverted from the Rio Grande and its major tributaries.
1302 - Rio Grande-Elephant Butte		
Streamflow in the Rio Grande-Elephant Butte Basin is perennial and highly regulated. Major tributaries include Red River, Rio Pueblo de Taos, Embudo Creek, and Rio Chama. Several wastewater treatment plants discharge effluent to the Rio Grande and its tributaries; Albuquerque and Rio Rancho are the largest wastewater-treatment plants in this reach of the Rio Grande Basin.	Streamflow is stored in Heron, El Vado, and Abiquiu Reservoirs on the Rio Chama, Jemez Canyon Reservoir on the Jemez River, Elephant Butte Reservoir on the Rio Grande, and other small reservoirs throughout the basin. Streamflow is diverted from the San Juan Basin via Azotea tunnel into the Rio Chama Basin; these are the largest transmountain diversions in the entire Rio Grande Basin.	Streamflow is diverted for irrigation throughout the Middle Rio Grande Basin, and, to a lesser extent, in the agricultural areas near the confluence of the Rio Grande and Rio Chama.
1303 - Rio Grande-Mimbres		
Streamflow is ephemeral and highly regulated in the Rio Grande-Mimbres Basin. Streamflow is maintained by releases for irrigation diversions, ground-water inflow, and wastewater-treatment plant effluent. Tributaries, which are ephemeral and flow only in response to summer thunderstorms, do not contribute significant streamflow to the Rio Grande in this reach.	Streamflow is stored in Caballo Reservoir.	Streamflow is used for irrigation in Rincon and Mesilla Valleys. Some streamflow is diverted for municipal use.
1305 - Rio Grande closed basins		
Streamflow in the Rio Grande Closed Basins is ephemeral and highly variable. The largest of the Rio Grande Closed Basins are Estancia and Tularosa Basins.	None	None
Upper Colorado River Basin		
1401 - Colorado headwaters, Southern Rocky Mountains Physiographic Province		
Streamflow is perennial and maintained by snowmelt runoff, ground-water discharge, and reservoir releases.	Streamflow is stored in 12 or more reservoirs for transbasin diversions and to meet downstream flow needs. Between 450,000 to 600,000 acre-ft per year are removed from streams and reservoirs and diverted through 12 major transmountain diversions for use in eastern Colorado.	Within-basin water uses include municipal, domestic, and livestock. Water removed through transbasin diversions is used for municipal purposes and agricultural irrigation throughout the Front Range of Colorado, from Fort Collins, the Denver and Colorado Springs metropolitan areas, to Pueblo. In some areas water is also used for snow making.
1401 - Colorado headwaters, Colorado Plateau Physiographic Province		
Almost all streamflow is perennial and maintained by snowmelt runoff, ground-water discharge, reservoir releases, and irrigation return flows. Some small tributaries are ephemeral.	Streamflow is stored in small reservoirs. Within-basin diversions of water occur through canals and ditches in the Grand Valley/Grand Junction area.	Irrigation in the Grand Junction/ Grand Valley area.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
	Upper Colorado River Basin—Cont.	
	1402 - Gunnison	
Streamflow is perennial and maintained by snowmelt runoff, ground-water discharge, reservoir releases, and irrigation return flows.	Streamflow is stored in Taylor Park Reservoir, the Aspinall Unit (Blue Mesa, Morrow Point, and Crystal Reservoirs), Ridgway Reservoir, and small reservoirs. Within-basin diversions of water occur through the Gunnison Tunnel and in ditches in the Uncompahgre River Valley.	Water uses include municipal, domestic, livestock, and irrigation in the Uncompahgre River Valley (Delta/Montrose area).
	1403 - Upper Colorado-Dolores	
Most streamflow is perennial and maintained by snowmelt runoff, ground-water discharge, reservoir releases, and irrigation return flows. Some small tributaries are ephemeral.	Streamflow is stored in McPhee Reservoir is diverted for irrigation in areas of the upper San Juan Basin. Several small reservoirs are also in the basin.	Water uses include municipal, domestic, and livestock.
	Green River Basin	
	1404 - Great Divide-Upper Green	
Streamflow is perennial and originates from alpine snowmelt (Wind River Range) and ground-water inflow. Flow in Utah part of basin controlled by Flaming Gorge Reservoir. Yampa River (from Colorado) is major tributary to Green.	Flaming Gorge Reservoir is principal reservoir on the Green River; Fontanelle Reservoir is upstream. No major transbasin diversions occur from this basin.	Irrigation
	1405 - White-Yampa	
Most streamflow is perennial and maintained by snowmelt runoff, ground-water discharge, reservoir releases, and irrigation return flows. Some small tributaries are ephemeral.	Streamflow is stored in Stagecoach and Elkhead Reservoirs, and also in several small reservoirs.	Water uses include domestic, municipal, and livestock.
	1406 - Lower Green	
Streamflow is perennial along the river's entire reach. Flow originates from snowmelt (Uinta Mountains and Wasatch Plateau) and thunderstorms, in addition to ground-water inflow. Duchesne River is major tributary to Green River.	Principal reservoirs are Strawberry and Starvation, both located on Strawberry River, a tributary to the Duchesne River; no reservoirs are located along the main stem. Central Utah Water Conservancy diverts water to west slope of Wasatch Range.	Major uses are thermoelectric, public supply and irrigation.
	Middle Colorado River Basin	
	1407 - Upper Colorado-Dirty Devil	
Streamflow is generally from the Upper Colorado River basin, the Green River Basin, the San Juan River basin, and the Little Colorado River basin. Streamflow is perennial along major drainages even through desert region. Flow originating within the basin comes from snowmelt on high plateaus (Dirty Devil basin), thunderstorms, and ground-water inflow. Lake Powell contains a significant length of Colorado River.	Streamflow is stored in Lake Powell, one of the largest reservoirs in the Southwest and in the United States. There are no transbasin diversions from Lake Powell.	Major uses are public supply and irrigation.
	1501 - Lower Colorado-Lake Mead	
The lower Colorado River is highly regulated. Streamflow is perennial and maintained by releases from Lake Powell, and also by tributary inflow.	Streamflow is stored in Lake Mead, one of the largest reservoirs in the Southwest and in the United States.	Storage in Lake Meade is withdrawn for municipal uses in the Las Vegas metropolitan area.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
San Juan River Basin		
1408 - San Juan		
The San Juan River is perennial. Major tributaries include the La Plata and the Animas, which are also perennial. The largest source of streamflow is snowmelt; however, summer and fall thunderstorms may also contribute to streamflow. There are numerous ephemeral tributaries in the southern part of the San Juan Basin. The lowermost reach of the river is impounded by Lake Powell at its confluence with the Colorado River.	Streamflow is stored in Navajo Reservoir in New Mexico. Streamflow is diverted out of the San Juan Basin into the Rio Grande Basin at seven locations in Colorado and New Mexico; the largest diversions occur at Azotea tunnel in New Mexico.	Major uses are for irrigation and industrial purposes.
Little Colorado River Basin		
1502 - Little Colorado		
Reaches of the Little Colorado River are mostly perennial (1) above Lyman Lake, (2) near Woodruff and Holbrook, and (3) from Blue spring to the mouth. Perennial flow is maintained by snowmelt above Lyman Lake, and by ground-water discharge for all three of these reaches. For the reach extending about 20 miles downstream from Lyman Lake, streamflow is partly regulated and maintained by reservoir releases. Elsewhere, streamflow is ephemeral occurs primarily in response to summer runoff.	Streamflow is stored in Lyman Lake and many smaller reservoirs.	Streamflow is used for irrigation in the Springerville and St. Johns areas.
Lower Colorado River Basin		
1503 - Lower Colorado		
The lower Colorado River is highly regulated; streamflow is perennial and maintained by releases from Lake Mead, Lake Mohave, and Lake Havasu.	Streamflow is stored in Lake Mohave, Lake Havasu, and also a few smaller reservoirs. In 2003, 1.49 million acre-ft were diverted for use in central Arizona through the Central Arizona Project Canal, 0.77 million acre-ft were diverted for use in southern California through the Colorado River Aqueduct, and 3.26 million acre-ft were diverted for use in the Imperial Valley of southern California through the All-American Canal.	Streamflow diversions along the main stem of the lower Colorado River primarily are used for agricultural irrigation. Transbasin diversions to central Arizona are used for municipal purposes in the Phoenix and Tucson metropolitan areas, and for agricultural irrigation in surrounding areas. Transbasin diversions to southern California through the Colorado River aqueduct are primarily used for municipal purposes in the Los Angeles metropolitan area. Transbasin diversions to Imperial Valley are primarily for agricultural irrigation.
Gila River Basin		
1504 - Upper Gila		
The upper Gila River is perennial in most reaches. Snowmelt, summer thunderstorm runoff, and ground-water discharge maintain streamflow.	Streamflow is stored in San Carlos Reservoir.	Streamflow is diverted for agricultural irrigation in the Duncan and Safford areas of the upper Gila River basin, and for agricultural irrigation downstream in the middle Gila River basin.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
Gila River Basin—Cont.		
1505 - Middle Gila		
The middle Gila River is perennial above the Ashurst-Hayden diversion dam. Streamflow in this reach is sustained by releases from San Carlos Reservoir in the upper Gila River basin, and from ground-water discharge. Nearly all streamflow is diverted at the dam; however, summer and winter rainfall runoff generate ephemeral streamflow.	None	Streamflow diverted at Ashurst-Hayden Dam is used for agricultural irrigation in the areas of the eastern part of the middle Gila River basin.
1506 - Salt		
Snowmelt, winter rainfall runoff, and ground-water discharge maintain perennial streamflow upstream from the reservoir systems on the Salt and Verde Rivers. Downstream from the reservoirs, streamflow primarily is maintained by reservoir releases. Below the reservoirs and the confluence of the Salt and Verde Rivers, nearly all of the streamflow is diverted at Granite Reef dam. Summer and winter rainfall runoff generate ephemeral streamflow downstream from this diversion. The reach extending about 4 miles above the mouth of the Salt River is maintained by return flows from the 91st Avenue Wastewater Treatment Plant, and by ground-water discharge.	Streamflow of the upper Salt River and Tonto Creek is stored in a system of four reservoirs: Theodore Roosevelt, Apache, Canyon, and Saguaro Lakes. Streamflow of the Verde River is stored in Horseshoe and Bartlett Reservoirs.	Streamflow diverted at Granite Reef diversion dam is used for municipal purposes in the Phoenix metropolitan area, and for agricultural irrigation in surrounding areas.
1507 - Lower Gila		
Streamflow in the Lower Gila River, from the mouth of the Salt River to Gillespie Dam, is perennial and maintained primarily by return flows from municipal wastewater-treatment plants and from agricultural irrigation, as well as by ground-water discharge. Below Gillespie Dam, the lower Gila River is mostly ephemeral, and streamflow occurs only in response to summer or winter rainfall runoff.	Infrequently, water spilled from the reservoir systems upstream on the Gila, Salt, and (or) Verde Rivers is retained in Painted Rock Reservoir. At most times, however, storage in this reservoir is minimal.	Streamflow in the reach above Gillespie Dam is diverted for agricultural irrigation near Buckeye and Gila Bend.
Great Salt Lake and Sevier River Basins		
1601 - Bear		
Streamflow in Bear River is perennial and fed by snowmelt and ground-water inflow; flow is also regulated out of Bear Lake. Primary source of Bear River is Bear River Range and Uinta Mountains. Major tributaries to Bear River include the Little Bear, Logan and Cub Rivers.	Bear Lake is principal reservoir on Bear River; Cutler, Soda Point, and Oneida Reservoirs control flow on river downstream from Bear Lake. There are no transbasin diversions from the Lake.	Streamflow is diverted principally for irrigation.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
Great Salt Lake and Sevier River Basins—Cont.		
1602 - Great Salt Lake		
Streamflow in Jordan and Weber Rivers is perennial but all inflow to Great Salt Lake is terminal (no outflow). Primary source of Jordan River is Utah Lake, which receives snowmelt from Wasatch and Uinta Mountains via Provo River and also receives flow from lake-margin springs. Jordan River also gains from ground-water inflow and from treatment-plant effluent. Source of Weber River is snowmelt from Wasatch and Uinta Mountains and from ground-water inflow. Ogden River is principal tributary to Weber River. Most flow in western part of basin (Basin and Range) is ephemeral.	Streamflow for Provo River is stored in Deer Creek and Jordanelle Reservoirs. Weber River flow is stored in Rockport and Echo Reservoirs and in Willard Bay of Great Salt Lake. Ogden River flow is stored in Pineview Reservoir. Central Utah Water Conservancy District has transbasin diversions from south slope of the Uinta Mountains into valleys along the Wasatch Front.	Streamflow is diverted for public supply and irrigation.
1603 - Escalante Desert-Sevier Lake		
All surface flow in Escalante Desert is ephemeral. Sevier River is perennial except in lowest reaches near where it terminates in Sevier Lake (no outflow), which is also ephemeral. Source of water to Sevier River is from snowmelt and springs on high plateaus.	Yuba Lake is the principal storage reservoir for Sevier River; Piute Reservoir stores upstream flow.	Water is used for irrigation.
Central Lahontan Basins		
1605 - Central Lahontan		
The Carson, Truckee, and Walker are the three major rivers and are perennial. Streamflow in these streams and their tributaries is derived from snow pack in Sierra Nevada Mountains.	All river systems are impounded by dams. A major dam on the Carson River creates Lake Lahontan. The Truckee River flows out of Lake Tahoe. All rivers flow into or previously flowed into terminal lakes.	All rivers are used for irrigation, public supply, and recreational purposes. Historic mining and milling operations used water along Carson and Walker Rivers.
Central Nevada and Eastern California Desert Basins		
1604 - Black Rock Desert-Humboldt		
Streamflow in the Humboldt River is perennial. The Black Rock Desert has no perennial streams. The source of flow in most streams is snowmelt.	Humboldt River impounded by Rye Patch Reservoir.	Humboldt used for irrigation along entire course. Considerable mining in both the Black Rock and Humboldt River areas.
1606 - Central Nevada Desert Basins		
There are no major perennial streams. Streamflow is mostly generated by runoff from summer thunderstorms.	There are no significant reservoirs. Small wildlife refuges exist because of regional spring flow in several areas.	Irrigation and stock use. Isolated areas of mining.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
Central Nevada and Eastern California Desert Basins—Cont.		
1809 - Northern Mojave-Mono Lake		
The Mono Basin is a closed drainage system with no outlet; all surface water and ground water naturally drains toward Mono Lake. Most of the water feeding the five principal streams in the basin is derived primarily from spring and summer snowmelt in the Sierra Nevada Mountains. Streamflow is exported from the Mono Basin into the Owens River for irrigation, industrial, and recreational purposes. The Owens Valley is also a closed drainage system. Most streamflow in the Owens River is runoff from precipitation and snowmelt in the Sierra Nevada Mountains. Flow in the Owens River is controlled by releases from reservoirs and diversion to the Los Angeles aqueduct.The Mojave River is ephemeral, except for a small stretch that has perennial flow.	Streamflow in the Mono Basin is exported to the Owens River via the Mono Craters Tunnel. In the Owens Valley above the intake for the Los Angeles aqueduct, flow in the Owens River is regulated by releases from Lake Crowley and Tinemaha Reservoir. Below the aqueduct intake, Grant Lake, Pleasant Valley Reservoir, and Haiwee Reservoir are used primarily to regulate flow and store water. Mojave River Dam is an ungated flood-control structure. Nearby are Cedar Springs Dam and associated Silverwood Lake, which are part of the California aqueduct system.	In the Mono Basin, nearly the entire flow in streams is diverted: Rush and Lee Vining Creeks are exported for use in Los Angeles; Walker and Parker Creeks for in-basin irrigation and transbasin export; Mill Creek for hydropower production and in-basin irrigation. A large portion of the surface water in the Owens Valley is exported for municipal use in Los Angeles. In-valley uses include irrigation and stock watering. Water use along the Mojave River is primarily for ground-water recharge. Water imported from the California aqueduct is also used for recharge in engineered facilities along the Mojave.
1810 - Southern Mojave-Salton Sea		
At the northern part of the basin, recharge basins in Coachella Valley with a capacity of 300,000 acre-ft/yr receive water from the Whitewater River and the Colorado River aqueduct. The Salton Sea to the south receives water from the Whitewater River (ephemeral), New and Alamo Rivers (perennial and originates in Mexico), and agricultural drainage. The Salton Sea is California's largest lake and was once famous for its sport fishery and recreational uses. Currently, the Salton Sea serves as a sump for agricultural wastewater from the Imperial and Coachella Valleys. About 75 percent of the freshwater inflow to the Sea is agricultural drain water from the Imperial Valley. Because the Sea has no outlets, salts concentrate in it and nutrient levels produce eutrophic conditions. Salinity in the Sea is about 25 percent greater than in the ocean and increases about 1 percent each year.	The Colorado River Aqueduct is 242 miles long and supplies Los Angeles and much of southern California with water. In 1992, the aqueduct was recognized by the American Society of Civil Engineers as one of the seven "wonders" of the American engineering world. The All-American Canal to the south also diverts water from the Colorado River, entering California near the international border and delivers water to the Imperial and Coachella Valleys.	Imported water is used in-basin primarily for agricultural irrigation and is exported for municipal use in the California Coastal Basins. The Salton Sea National Wildlife Refuge is a critical stop on the Pacific Flyway for migrating birds, including several endangered and threatened species. However, catastrophic die-offs of birds and fish between 1992 and 1997 indicate that the Salton Sea may not be able to support these beneficial uses in the future.

Table 2. Selected characteristics of streams in major river basins and hydrologic subregions in the Southwestern United States—Continued.

Perennial status and primary sources of flow for principal stream(s) and their tributaries	Significant reservoirs and transbasin diversions	Major offstream water uses
Southern California Coastal Basins		
1807 - Southern California Coastal		
The upper Santa Ana River above Seven Oaks Dam is mostly perennial, maintained by ground-water discharges, discharge from Bear Creek and, at times, snowmelt from the San Bernardino Mountains. Little water is impounded by the Seven Oaks Dam. However, diversions downstream of the dam limit discharge to ephemeral flows between these diversions and wastewater treatment plant outfalls in the Riverside area. Effluent from these outfalls provides nearly all of the discharge in the lower Santa Ana River. The San Jacinto River is the major stream in the San Jacinto Basin, which is upgradient of the Inland and Coastal basins and is essentially a hydrologically closed system. Flow is maintained by runoff from the San Jacinto Mountains that has low dissolved-solids concentrations. Flow rarely reaches the terminus of the river, Lake Elsinore, except in extreme storm events.	Storm water in the Santa Ana River and its tributaries is periodically retained behind Prado Dam for flood control and to prevent flow from exceeding the infiltration capacity of ground-water recharge facilities located approximately 12 miles downstream of the dam. Water is also imported for recharge and municipal use in the Santa Ana Basin via the California and Colorado River aqueducts; Lake Perris and Lake Matthews receive water from both aqueducts.	Much of the streamflow in the lower Santa Ana River is diverted to engineered facilities which have a capacity of about 300,000 acre-ft/yr and are used to recharge an aquifer system in the Coastal Basin that is used for public supply. Imported water is used for recharge and for public supply, amounting to about about 30 percent of the consumptive demand in the Santa Ana Basin. Average diversion of water from the San Jacinto River for municipal use has been about 6,000 acre-ft/yr; river water is also used for ground-water recharge, averaging about 50,000 acre-ft/yr.

Water-supply development has significantly altered streamflow in many of the river systems. Many of the major rivers have one or more reservoirs that provide (1) storage for a water supply to downstream users, (2) storage for hydroelectric-power generation, (3) flood control, and (4) recreational areas (table 2). Larger reservoirs typically alter the seasonal pattern in flow by storing water from winter and spring runoff, which constitutes most of the annual flow, and then releasing that water at lower magnitude discharges for longer durations during the summer months and remainder of the year. Most major river systems have significant diversions for municipal and (or) agricultural purposes, particularly in their lower reaches. Several streams tributary to the upper Colorado River also have transbasin diversions to the Front Range cities in Colorado, such as Denver. As a result of these diversions, and in some cases with the additional factor of lowered ground-water levels due to ground-water pumpage, some of the low-altitude reaches have become intermittent or ephemeral. In some of these low-altitude river reaches, such as the lower Gila River, perennial flow has been restored or is augmented by treated municipal wastewater and (or) irrigation-return flows.

Physiography and Geology

The Southwest contains eight physiographic provinces (Fenneman, 1931), that represent a variety of physiographic features that are largely influenced by geology (table 3). These features include mountain ranges, desert valleys, desert plains, alluvial fans, uplands, high plateaus, and deep canyons. Provinces differ from each other in the assemblage of these features found in each province. Certain physical, chemical, and biological processes tend to be associated with these features, and as a result, the provinces also are different with respect to hydrology and water chemistry. For this reason, some of the results of this study are presented by physiographic province.

Most of the Southwest is contained in the Colorado Plateaus and Basin and Range Physiographic Provinces (fig. 5). The Colorado Plateaus Province is characterized by dissected plateaus and canyons of moderate depth. The Basin and Range province is characterized by north-south trending block-faulted mountain ranges and intervening flat-floored desert valleys that are bounded by extensive alluvial fans or pediments. Some of the highest mountains in the United States are in the Southern Rocky Mountains and Cascade-Sierra Mountains provinces. Drainages in some of the higher-altitude mountains show evidence of glaciation.

Table 3. Distinctive features of physiographic provinces and sections in the Southwestern United States.

[Data from Fenneman and Johnson, 1946]

Physiographic province	Physiographic section	Distinctive physiographic features
Basin and Range	Great Basin	Isolated north-south mountain ranges separated by desert valleys
	Sonoran Desert	Widely separated short mountain ranges within desert plains
	Salton Trough	Desert alluvial fans and delta plain; Gulf of California
	Mexican Highland	Isolated ranges separated by aggraded desert valleys
	Sacramento section	Mature block mountains with gently tilted strata; block plateaus
Colorado Plateaus	High Plateaus of Utah	High block plateaus that are locally lava-capped or terraced
	Uinta Basin	Dissected high-relief plateau
	Canyon Lands	Young to mature canyon-carved plateaus with high relief
	Navajo section	Young plateaus with moderate relief
	Grand Canyon section	High block plateaus cut by Grand Canyon
	Datil section	Lava flows and volcanic necks
Wyoming Basin	(Not divided into sections)	Elevated dissected plains with isolated low mountains
Southern Rocky Mountains	(Not divided into sections)	Complex granitic and sedimentary mountains with intermountain basins; Continental Divide
Middle Rocky Mountains	(Not divided into sections)	Complex anticlinal mountains with intermontane basins
Cascade-Sierra Mountains	Sierra Nevada	Block mountain ranges tilted west with alpine peaks on east flank; granitic and glaciated
Pacific Border	Los Angeles Ranges	Narrow ranges and broad fault blocks; alluviated lowlands
Lower Californian	(Not divided into sections)	Dissected westward-sloping granitic upland

Figure 5. Physiographic provinces and sections in the Southwestern United States.

Relief ranges from sea level or below along the Pacific Coast, the Salton Trough, and Death Valley, to more than 14,000 ft in the southern Rocky Mountains in Colorado and the Sierra Nevada in California (U.S. Geological Survey, 2003).

Bedrock geology is variable throughout the Southwest and consists of plutonic, volcanic, metamorphic, and sedimentary rocks of various ages (fig. 6; King and Beikman, 1974). The distinctive features of the physiographic provinces that distinguish them are largely the result of differences in the geology of each province. In the Basin and Range province, high-angle normal faulting has uplifted the mountain ranges and downdropped the basins. Bedrock in the mountains generally varies by physiographic section and consists primarily of Paleozoic sedimentary rocks and volcanic rocks in the eastern part of the Great Basin, volcanic and crystalline rocks in the western part of the Great Basin, crystalline and volcanic rocks in the Sonoran Desert, volcanic rocks in the Mexican Highlands, and Paleozoic sedimentary rocks in the Sacramento section (fig. 6; King and Beikman, 1974). The basin-fill aquifers consist of unconsolidated and semi-consolidated clay, silt, sand, and gravel that were derived from the bedrock of adjacent mountain ranges. Sediment grain size generally decreases away from the mountains, and the central parts of the basin often have thick sequences of clay (Anderson and others, 1992; Plume, 1996). Many of the basins that are presently hydraulically closed, or were hydraulically closed in the geologic past, contain thick sequences of gypsum, anhydrite, halite, and (or) other evaporites in the central parts of the basin (Anderson and others, 1992; Plume, 1996). The high solubility of evaporites results in high dissolved-solids concentrations in ground water, and in some cases, the concentrations are too high for most uses (Thomas and others, 1996).

The plateaus, canyons, buttes, mesas, and other landforms that distinguish the Colorado Plateaus province from surrounding provinces result from its laterally extensive layers of Paleozoic, Mesozoic, and Cenozoic (Tertiary in fig. 6) sedimentary rocks that have undergone deformation and erosion. Cap rocks form the top of the sequences of geologic units and are generally Paleozoic sedimentary rocks and volcanic rocks in the Grand Canyon physiographic section, Mesozoic and Cenozoic sedimentary rocks in the Navajo physiographic section, volcanic rocks and Cenozoic sedimentary rocks in the High Plateaus of Utah physiographic section, Mesozoic and Paleozoic sedimentary rocks in the Canyon Lands physiographic section, and Cenozoic sedimentary rocks in the Uinta Basin (figs. 5 and 6). In contrast to these physiographic sections, the Datil section is capped primarily by volcanic rocks. While the cap rocks have a direct effect on the surface-water hydrology and chemistry, the underlying sequences of rocks affect the ground-water hydrology and chemistry. Ground water that discharges to springs and streams mixes with surface water and, therefore, affects streamflow and stream chemistry.

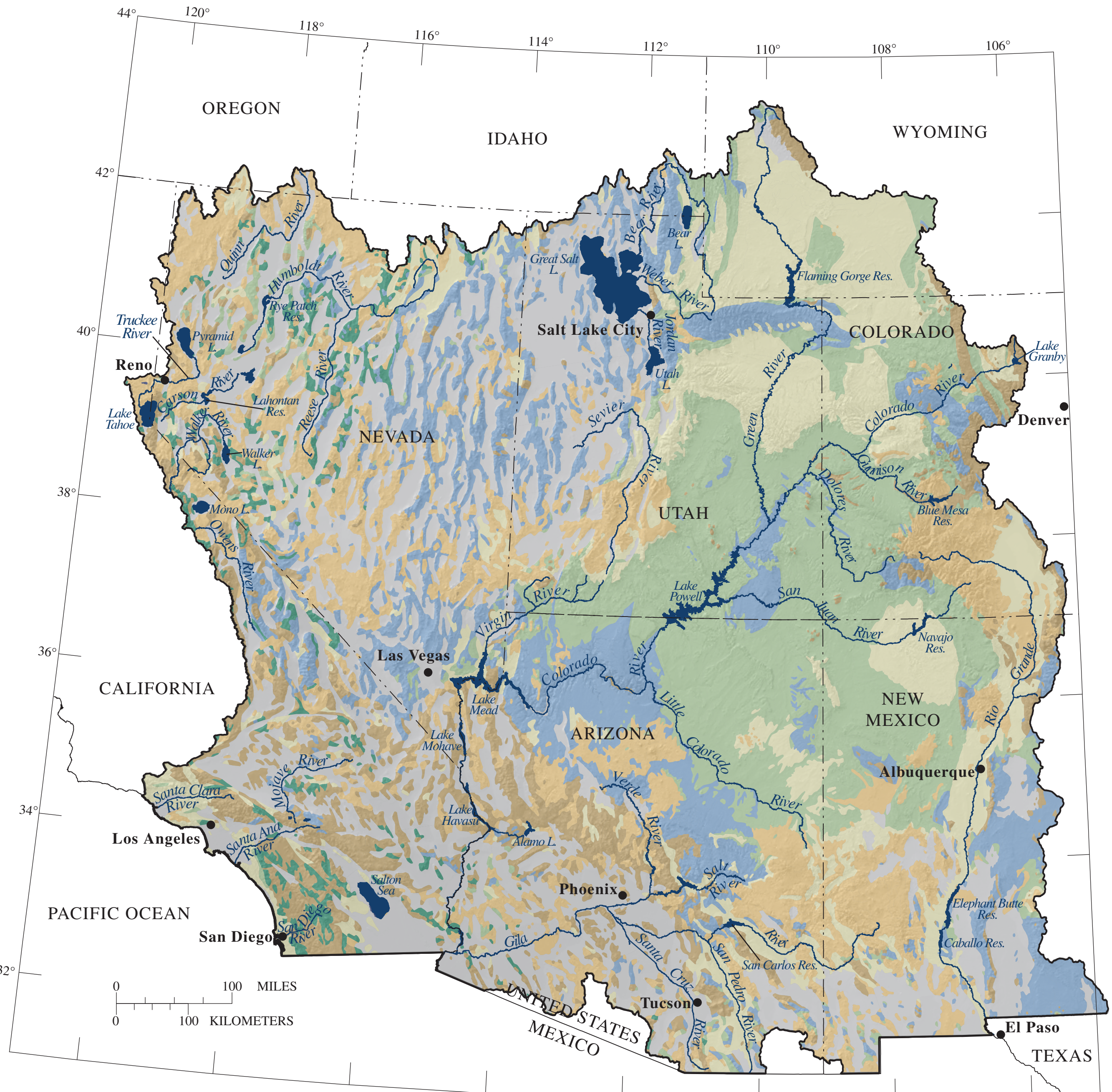
The lithology and corresponding hydraulic properties of geologic units that make up the Colorado Plateaus often change vertically from one geologic unit to the next and, consequently, the sedimentary rock units form alternating series of aquifers and confining units (Robson and Banta, 1995). Several factors complicate the hydrogeology, including the lateral gradation of lithology within a given geologic unit, discontinuities in the lateral extent of geologic units, and presence of geologic structures such as folds and faults (Freethey and others, 1988; Lindner-Lundsford and others, 1989).

In the Colorado Plateaus province, many of the Paleozoic sedimentary geologic units are composed primarily of limestones or dolomite; however, geologic units composed of sandstones, siltstones, and shale also are present (Lindner-Lundsford and others, 1989). Paleozoic sedimentary rocks include the Eagle Valley Formation and the Paradox member of the Hermosa Formation, which contain evaporite beds. Ground-water discharge from these two units to streams can increase the dissolved-solids load considerably (Lindner-Lundsford and others, 1989).

Most of the Mesozoic sedimentary geologic units in the Colorado Plateaus province are composed of sandstones that are interbedded with siltstones and shales (Freethey and others, 1988). One notable unit is the Mancos Shale, which is generally considered a confining unit. In outcrop, the Mancos Shale is highly erodable, and surface runoff from the Mancos Shale is usually moderately saline (Warner and others, 1985). In areas where irrigation water is applied to soils derived from the Mancos Shale, irrigation-return flow can significantly add to the load of dissolved solids in streams (Warner and others, 1985).

In the Colorado Plateaus province, most of the Cenozoic sedimentary geologic units are composed of shale, siltstones, and sandstones. The Wasatch and Green River Formations consist of Tertiary fine-grained deposits and contain soluble minerals that contribute significant loads of dissolved solids to streams (Warner and others, 1985). Lowlands of the Uinta Basin in the Colorado Plateaus province and of the Wyoming Basin province contain Cenozoic sedimentary rocks (figs. 5 and 6).

The parts of the Cascade-Sierra Mountains, Pacific Border and Lower Californian Physiographic Provinces that are within the Southwest are mountainous. For the most part, mountains of these provinces consist of crystalline rock, and to a lesser extent in the Pacific Border province, Tertiary sedimentary rocks (figs. 5 and 6). Bedrock in the Middle Rocky Mountain province generally are crystalline and volcanic (figs. 5 and 6).



Base from U.S. Geological Survey digital data, 100m, 2003
Albers Equal-Area Conic projection
Standard parallels 29° 30', 45° 30', central meridian 96°

Geologic units modified from King and Beikman, 1974

EXPLANATION

- Undifferentiated crystalline rocks
- Undifferentiated volcanic rocks
- Undifferentiated eugeosynclinal rocks
- Quaternary basin fill
- Tertiary sedimentary rocks
- Mesozoic sedimentary rocks
- Paleozoic and Precambrian sedimentary rocks

Figure 6. Bedrock geology in the Southwestern United States.

Climate

The Southwest generally has abundant sunshine, moderate to high wind, low relative humidity, a large range in daily temperature, and a semiarid climate. Winter precipitation is derived from eastward-tracking Pacific storms and generally is greater than summer precipitation, especially in mountainous areas. Winter precipitation generally falls from widespread storms, whereas summer precipitation falls from spatially scattered thunderstorms. Variations in climate across the Southwest (figs. 7 and 8; Daymet, 2006) are largely affected by altitude, proximity to the coast, and physiographic features such as mountains.

In southern California, mountain ranges that parallel the coast affect precipitation and temperature distribution (Planert and Williams, 1995). The quantity of precipitation generally is much greater in the coastal areas than in the inland areas, and is greater on the western slopes of mountains than on the eastern slopes because of a rain-shadow effect. Seaward of the mountains, temperature is moderated by the ocean, and the range between daily high and low temperatures usually is less than 20°F. In contrast, the valleys east of the coastal mountains experience much greater temperature extremes. In these valleys, summer daytime temperatures can be greater than 90°F and fall to 55°F or less at night. In addition, temperature extremes are greater in the desert than in other lowland areas. Temperature ranges in the mountains also can vary widely.

In the Basin and Range and Colorado Plateaus Physiographic Provinces, areas have different climatic conditions primarily because of differences in altitude (Robson and Banta, 1995). Temperature generally decreases and precipitation generally increases with increased altitude. These physiographic provinces are characterized by a large daily range in temperature and low precipitation. Average annual precipitation in the valleys ranges from less than 4 inches in southwestern Arizona to about 16 inches in north-central Utah (fig. 7). Most of the annual rainfall for a given area may fall during one or two storms. Prominent mountain ranges in eastern California and western Nevada have an important influence on moisture distribution in the region. Precipitation amounts generally are much greater on the windward (western) side of the north-south-trending mountain ranges, whereas semiarid to arid conditions prevail on the leeward (eastern) side of the mountains. In the Colorado Plateaus province, alpine climatic conditions may occur at higher altitudes. Less precipitation and higher temperatures prevail at lower altitudes, where semiarid, desert-like conditions may be present. Average annual precipitation ranges from about 8 to 16 in. in the plateau areas (4,000–9,000 ft altitude) to more than 30 in. at higher altitudes (fig. 7).

The climate of the Southern Rocky Mountains Physiographic Province is greatly affected by differences in altitude (Robson and Banta, 1995). Rain-shadow effects tend to decrease precipitation on leeward slopes of mountain ranges and to increase precipitation on windward slopes. Most precipitation occurs as snowfall during the winter months. Average annual snowfall ranges from about 5 ft at low altitudes or on the leeward slopes to more than 35 ft at high altitudes or on the windward slopes.

Much of the precipitation that falls in the Southwest is lost to evapotranspiration or sublimation; the remainder becomes runoff in streams or recharge to aquifers. Dissolved-solids concentrations in runoff or in infiltrating storm water are low because of the low concentrations in precipitation. Dissolved-solids concentrations observed in precipitation samples from National Atmospheric Deposition Program monitoring sites (National Atmospheric Deposition Program, 2004) within and adjacent to the Southwest are generally less than 2.0 mg/L (fig. 9).

Land Cover, Population, and Water Use

The arid to semiarid climate of the Southwest affects the land cover. Dry climatic conditions are conducive to the development of shrubland, grassland, and barren land, which account for 59.7, 11.4, and 5.5 percent, respectively, of the land cover in the Southwest (table 4, fig. 10; U.S. Geological Survey, 2005a and 2005b). Most of the shrubland occurs in intermountain valleys within the Basin and Range province and the plateaus of the Colorado Plateaus province and is used for cattle grazing. Forested lands account for 18.7 percent of the land in the Southwest (U.S. Geological Survey, 2005a and 2005b) and occur at the higher altitudes where the climate is wetter than at low altitudes (table 4, fig. 10). Much of the shrubland, grassland, barren land, and forested land are Federal or Tribal lands and are used for recreation, livestock grazing, mineral extraction, or timber production.

Urban land makes up only 1.0 percent of the total land in the Southwest (table 4; U.S. Geological Survey, 2005a and 2005b). Cultivated and pasture lands (fig. 10) are more extensive than urban lands and make up 2.5 percent of the total land area in the Southwest (table 4; U.S. Geological Survey, 2005a and 2005b). These lands generally are confined to relatively flat intermountain basins or valleys where unconsolidated sands, silts, and clays provide optimum growing conditions: soils have high water-retention properties, temperatures are warm, and a supply of ground water or surface water is readily available for irrigation (Cordy and others, 1998; Levings and others, 1998). Although urban, cultivated, and pasture lands make up only a small percentage of the land cover in the Southwest, they are hydrologically significant because most of the water is consumed in these areas. For example, only 4 percent of the land in the Rio Grande Valley is cultivated or pasture land, but water use on these lands consumes 89 percent of total withdrawals (Levings and others, 1998).

Most of the cultivated and pasture land in the Southwest is irrigated and is in the Basin and Range Physiographic Province (figs. 6 and 10). From 1985 to 2000, about one-third of the irrigated land in the Basin and Range Physiographic Province was in Imperial County, California and in Maricopa and Yuma Counties, Arizona (Konieczki and Heilman, 2004).

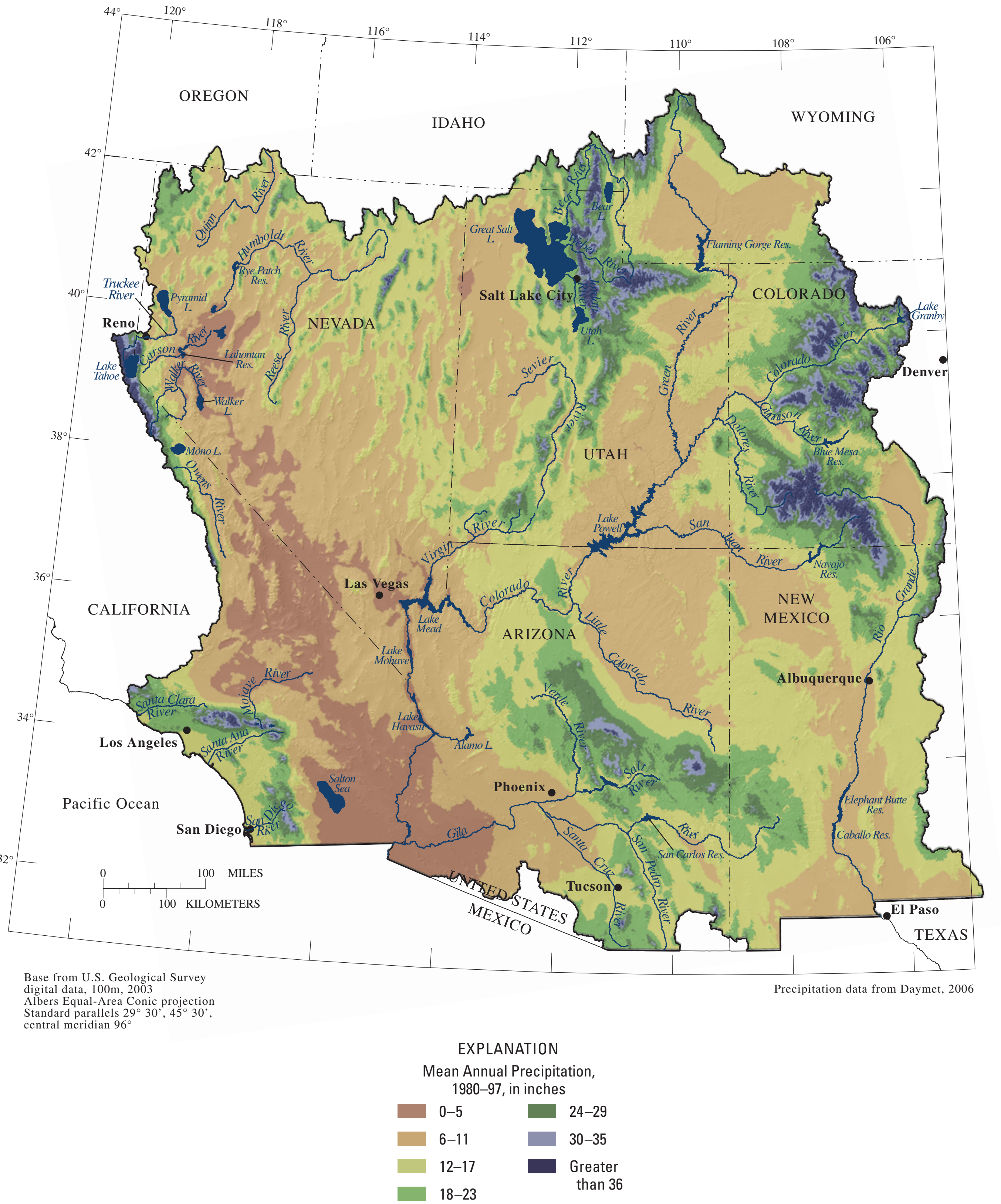


Figure 7. Mean annual precipitation in the Southwestern United States, 1980–97.

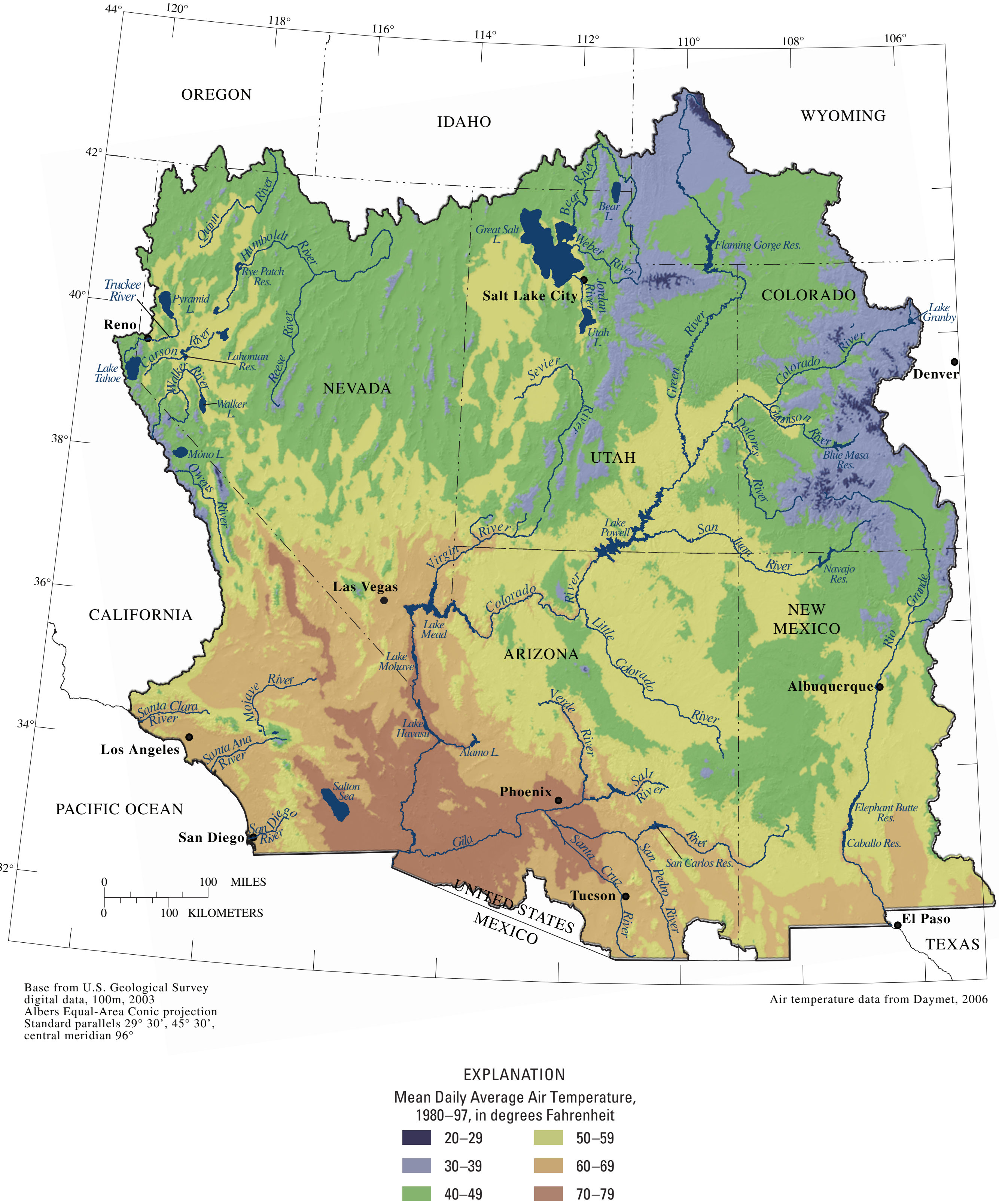


Figure 8. Mean daily average air temperature in the Southwestern United States, 1980–97.

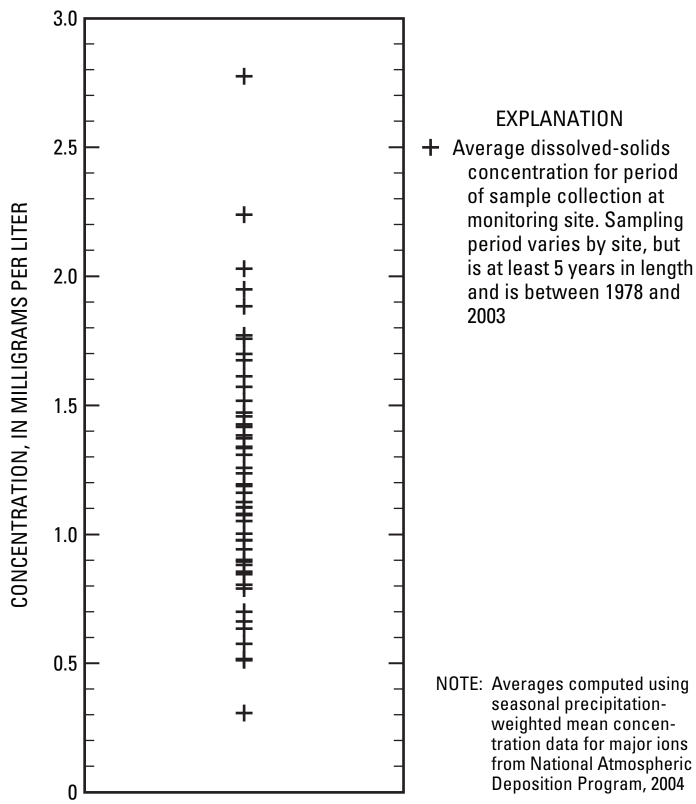


Figure 9. Average dissolved-solids concentration for precipitation samples collected at 53 atmospheric-deposition monitoring sites within and adjacent to the Southwestern United States.

Table 4. Land cover for hydrologic subregions in the Southwestern United States.

[Tabulated from reach level data for the enhanced river reach file, version 1.2 (ERF1_2) stream network that was provided by Greg Schwarz, USGS economist, and determined from the 1990's National Land Cover Data Set (Vogelmann and others, 2001). About 41,000 square miles in the Southwest are not represented in this table because it does not contribute drainage to reaches in the ERF1_2 network. Most of the unreported area is in the Rio Grande-Mimbres, Rio Grande closed basins, Central Nevada Desert Basins, Northern Mojave-Mono Lake, and Southern Mojave-Salton Sea subregions]

Hydrologic subregion	Land cover, in square miles								
	Urban land	Cultivated land	Pasture land	Barren land	Forested land	Grass land	Shrub land	Other lands	Total land area
Rio Grande headwaters	10	130	310	130	2,310	2,140	1,390	70	6,490
Rio Grande-Elephant Butte	200	70	120	640	7,270	8,530	10,270	130	27,230
Rio Grande-Mimbres	50	100	30	110	610	1,470	4,730	20	7,130
Rio Grande closed basins	10	30	10	180	560	2,700	990	0	4,480
Colorado headwaters	60	60	250	210	5,580	1,300	2,260	140	9,860
Gunnison	20	130	320	210	4,190	1,640	1,470	50	8,020
Upper Colorado-Dolores	20	20	70	160	3,250	660	4,000	20	8,190
Great Divide–Upper Green	30	40	330	300	1,990	2,340	15,160	370	20,560
White-Yampa	20	130	210	130	4,570	1,930	6,310	60	13,370
Lower Green	30	40	250	1,250	3,490	1,210	7,990	70	14,330
Upper Colorado-Dirty Devil	10	0	30	1,810	1,420	2,260	8,060	150	13,750
Lower Colorado-Lake Mead	210	10	100	1,280	5,680	2,800	20,400	240	30,720
San Juan	40	180	400	630	5,380	5,510	12,900	80	25,130
Little Colorado	60	10	30	340	6,770	3,370	15,960	50	26,600
Lower Colorado	90	220	310	1,530	1,340	540	12,970	130	17,120
Upper Gila	20	130	30	140	3,880	1,610	9,380	30	15,220
Middle Gila	370	790	130	110	690	500	13,330	50	15,980
Salt	290	70	20	90	6,560	590	6,080	80	13,770
Lower Gila	170	570	170	1,430	510	640	11,400	30	14,920
Bear	30	650	640	20	1,060	1,070	3,050	180	6,690
Great Salt Lake	360	300	610	5,850	4,320	2,600	12,070	2,670	28,780
Escalante Desert-Sevier Lake	40	20	460	940	4,590	1,200	7,780	80	15,110
Central Lahontan	100	0	260	430	1,510	620	8,850	130	11,900
Black Rock Desert-Humboldt	40	60	750	1,360	880	2,050	22,270	110	27,520
Central Nevada Desert Basins	30	0	100	1,250	4,560	610	23,300	70	29,920
Northern Mojave-Mono Lake	140	90	290	2,590	950	880	19,530	90	24,570
Southern Mojave-Salton Sea	120	350	510	1,860	220	350	6,640	10	10,070
Southern California Coastal	2,030	530	210	200	1,610	1,160	5,070	200	11,020
All subregions in the Southwestern United States (percentage of total area)	4,600 (1.0)	4,730 (1.0)	6,950 (1.5)	25,180 (5.5)	85,750 (18.7)	52,280 (11.4)	273,610 (59.7)	5,310 (1.2)	458,450 (100)

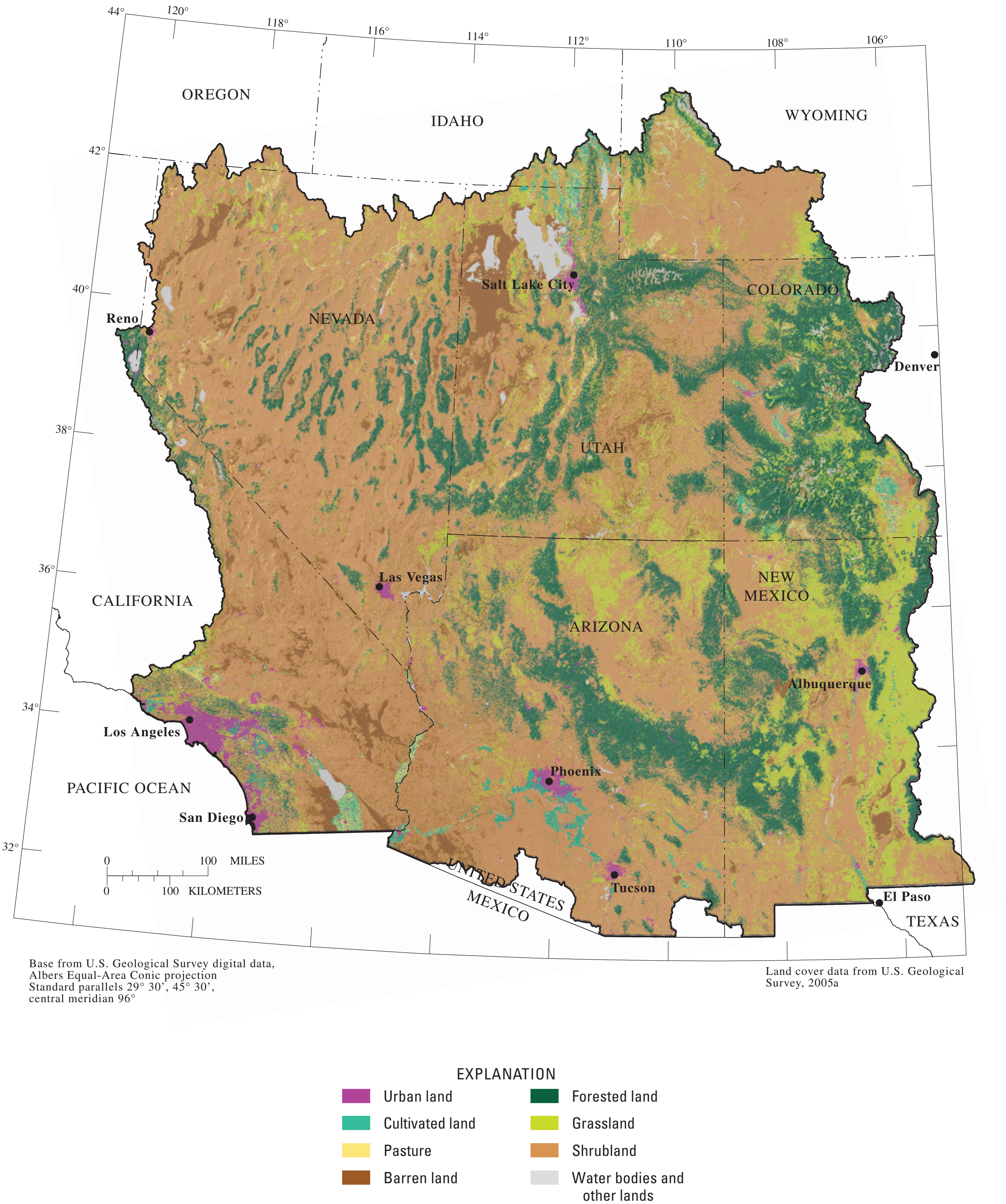


Figure 10. Land cover in the Southwestern United States.

Irrigated acreage in California, Nevada, Utah, New Mexico, and Arizona increased or remained the same from 1965 to 1980, declined from 1980 to 1995, and increased again from 1995 to 2000 (Konieczki and Heilman, 2004). The net increase in irrigated acreage for these five States from 1965 to 2000 was about 12 percent (Konieczki and Heilman, 2004). Decreases in irrigated acreage have been noted in some areas, however, and are largely attributed to encroachment of urban development (Cordy and others, 1998; Covay and others, 1996).

In 1995, the population of the Southwest was about 28.2 million (table 5; U.S. Geological Survey, 2004b). About 60 percent of this population resides in metropolitan areas of the Southern California Coastal basins. Much of the remaining population of the Southwest live in the metropolitan areas of Phoenix, Tucson, Las Vegas, Reno, Salt Lake City, and Albuquerque. While most of the population lives in urban areas, the portion of the Southwest covered by urban land is small—only about 1 percent of the total land area (table 4). In Utah, about 85 percent of the State population resides along the western margin of the Wasatch Mountains, a narrow corridor about 75 mi long (Baskin and others, 2002). While the urban areas have high population densities, large parts of the Southwest are rural with low population densities (fig. 11). These rural areas are characterized by small farming and ranching communities that are surrounded by Federal or Tribal lands.

The population in the Southwest is among the fastest growing in the country, particularly in the Basin and Range Physiographic Province. The population in Nevada has been increasing faster than that of any other state in the Southwest—1,150 percent between 1950 and 2000 (Konieczki and Heilman, 2004)—with most of the growth taking place in the Las Vegas area. The populations in Riverside County and San Bernardino County in southern California are among the fastest growing in the Southwest counties (Konieczki and Heilman, 2004). Although the population of California is larger than the combined population of Arizona, New Mexico, Nevada, and Utah, the combined population of these States grew faster than the population of California (Konieczki and Heilman, 2004). From 1950 to 2000, the California population increased 220 percent, but the combined population of the four other States increased 390 percent.

Major metropolitan areas can be potential sources of dissolved solids in surface water and in shallow ground water. Industrial and wastewater effluents may contain high concentrations of major ions, such as sulfate or chloride, that can increase dissolved-solids concentrations and thus affect the receiving water (Paulson and others, 1993). Use of salt, primarily sodium chloride, in urban areas for de-icing roads also may result in local increases in dissolved solids and degradation of water quality.

In the Southwest, the demand for good quality water and the limited availability of renewable water supplies makes water a precious commodity. Surface-water supplies often are used in areas adjacent to rivers, but in other areas water is diverted to distant locations through extensive conveyance networks. Where surface-water supplies are unavailable, ground water is used. The Colorado River is the single largest renewable water supply in the Southwest. This supply is conveyed to areas that lack sufficient local water supplies in southern Nevada, central Arizona, and southern California through extensive networks of canals, tunnels, pipelines, pumping plants, and reservoirs. Water from the Colorado River is used for municipal purposes in the Las Vegas, Phoenix, Tucson, Los Angeles, and San Diego metropolitan areas. Colorado River water also is used to irrigate expansive areas of farmland (1) along the lower Colorado River, (2) in several central Arizona basins, and (3) near the Salton Sea.

In 1995, about 36.7 million acre-ft of fresh water was used in the Southwest (table 5; U.S. Geological Survey, 2004b). About 25 percent of this freshwater was from ground-water supplies, and the remaining 75 percent was from surface-water supplies. About 44 percent of the ground water used in the Southwest was in the Southern California Coastal, the Middle Gila, and the Lower Gila hydrologic subregions (table 5 and fig. 4). About 96 percent of the ground water used in the Southwest was from subregions where basin-fill aquifers (Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers, fig. 2) were the primary ground-water supply. The remaining 4 percent of ground-water use was in subregions where sandstones aquifers (Colorado Plateau aquifers, fig. 2) were the primary ground-water supply. With the exception of the Little Colorado subregion, surface-water use exceeded ground-water use in the subregions that primarily use sandstones aquifers (table 5). About 49 percent of the surface-water use in the Southwest occurs in 6 of the 28 subregions: the Southern Mojave-Salton Sea, Southern California Coastal, Colorado headwaters, Lower Colorado, Gunnison, and Rio Grande headwaters.

Of the total freshwater use in the Southwest, about 79 percent was for irrigation and 16 percent was for public supply (water provided to municipal users by water utilities). The remaining 5 percent was for commercial, domestic, industrial, livestock, mining, and thermoelectric power production purposes by entities providing their own water supply. Most of the water used for irrigation occurs in the Southern Mojave-Salton Sea, Lower Colorado, Rio Grande headwaters, Colorado headwaters, Gunnison, Lower Gila, and Middle Gila subregions (table 5).

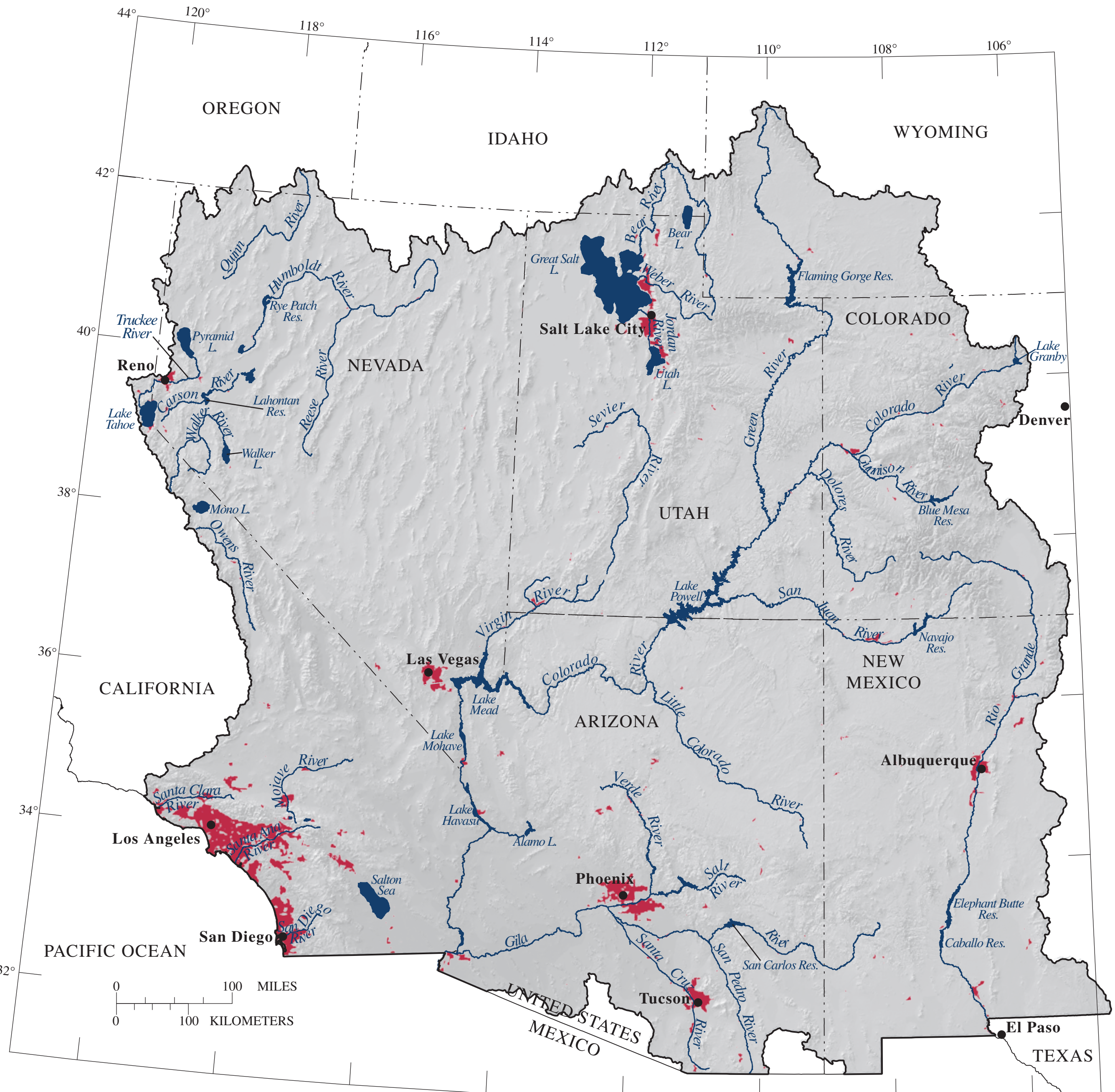
Water use in Southwestern States has increased substantially from 1950 to 2000. Konieczki and Heilman (2004) found that water used for domestic, agricultural, and industrial purposes in California, Nevada, Utah, Arizona, and New Mexico, increased 59 percent, from 39.6 million to 62.8 million acre-ft/yr, during this period. Public supply and self-supplied domestic use increased 410 percent, from 2.0 million to 10.2 million acre-ft/yr, although the population only increased 250 percent. From 1965 to 2000, water used for irrigation and livestock purposes increased 14 percent, from 44.0 to 50.2 million acre-ft/yr. Statewide average crop application rates (water withdrawn for crops divided by the irrigated crop acreage) for 1965–2000 ranged from 3.1 acre-ft/yr per acre for Utah to 5.5 acre-ft/yr per acre for Arizona. The higher rate for Arizona is likely a result of the high evapotranspiration rates, low precipitation rates, long growing seasons, and multiple crop production.

Table 5. Population and use of freshwater supplies in hydrologic subregions of the Southwestern United States, 1995.

[Data from U.S. Geological Survey, 2004b]

Hydrologic subregion	Predominant ground-water supply in subregion	Population, in thousands	Freshwater use, in thousands of acre feet				
			Water supply			Use[1]	
			Ground water	Surface water	Total	Public supply	Irrigation
Rio Grande headwaters	Basin-fill aquifers	40	460	1,820	2,280	10	2,270
Rio Grande-Elephant Butte	Basin-fill aquifers	880	290	730	1,020	180	790
Rio Grande-Mimbres	Basin-fill aquifers	280	300	450	750	60	650
Rio Grande closed basins	Basin-fill aquifers	100	290	10	300	20	270
Colorado headwaters	Sandstone aquifers	210	30	2,100	2,130	60	2,050
Gunnison	Sandstone aquifers	70	20	1,970	1,990	20	1,960
Upper Colorado-Dolores	Sandstone aquifers	20	10	220	230	10	220
Great Divide-Upper Green	Sandstone aquifers	60	10	1,080	1,090	10	1,040
White-Yampa	Sandstone aquifers	40	10	830	840	10	810
Lower Green	Sandstone aquifers	70	20	610	630	10	580
Upper Colorado-Dirty Devil	Sandstone aquifers	10	10	110	120	0	80
Lower Colorado-Lake Mead	Sandstone aquifers	1,090	130	430	560	400	130
San Juan	Sandstone aquifers	230	20	1,240	1,260	40	1,150
Little Colorado	Sandstone aquifers	240	120	20	140	30	50
Lower Colorado	Basin-fill aquifers	270	480	2,070	2,550	50	2,420
Upper Gila	Basin-fill aquifers	50	200	190	390	10	350
Middle Gila	Basin-fill aquifers	1,380	1,180	1,100	2,280	220	1,900
Salt	Basin-fill aquifers	1,810	300	600	900	530	360
Lower Gila	Basin-fill aquifers	400	880	1,140	2,020	80	1,920
Bear	Basin-fill aquifers	160	170	1,340	1,510	60	1,400
Great Salt Lake	Basin-fill aquifers	1,580	440	1,490	1,930	440	1,400
Escalante Desert-Sevier Lake	Basin-fill aquifers	90	310	900	1,210	30	1,110
Central Lahontan	Basin-fill aquifers	460	200	710	910	130	750
Black Rock Desert-Humbolt	Basin-fill aquifers	60	400	420	820	20	750
Central Nevada Desert Basins	Basin-fill aquifers	60	290	80	370	10	330
Northern Mojave-Mono Lake	Basin-fill aquifers	790	390	220	610	110	320
Southern Mojave-Salton Sea	Basin-fill aquifers	490	320	3,160	3,480	170	3,250
Southern California Coastal	Basin-fill aquifers	17,230	2,080	2,320	4,400	3,270	800
All subregions in the Southwestern United States		28,170	9,340	27,390	36,730	5,990	29,110

[1] Public supply and irrigation are the main uses; other uses include commercial, domestic self-supply, industrial, livestock, mining, and thermoelectric power production.



Base from U.S. Geological Survey digital data, 100m, 2003
Albers Equal-Area Conic projection
Standard parallels 29° 30', 45° 30', central meridian 96°

Population data from GeoLytics, Inc., 2001

EXPLANATION

2000 population density by census block group

More than 500 people per square mile

Figure 11. Population density in the Southwestern United States.

Salinity-Control Programs and Desalinization Plants

The objective of salinity-control projects is to abate or prevent salt loading of important water supplies, such as the Colorado River. Most of the salinity-control projects in the Southwest are in the Colorado River Basin and aim to reduce dissolved-solids concentrations in its lower reaches. The Colorado River and its tributaries provide municipal and industrial water for more than 27 million people in the seven basin States (Colorado, New Mexico, Utah, Wyoming, Nevada, Arizona, and California) and irrigation water to nearly 4 million acres of land (U.S. Department of the Interior, 2003). The Colorado River also serves about 2.3 million people and 500,000 acres in Mexico. Water-quality problems in the Colorado River were recognized as early as 1903 and have been a major concern in both the United States and Mexico. Damages to municipal and agricultural water users in the United States from elevated dissolved-solids concentrations in the Colorado River are estimated to cost from $500 to $750 million per year (Bureau of Reclamation, 2005).

The Colorado River Basin Salinity Control Act of 1974 (Public Law 93–320) authorized the construction, operation, and maintenance of desalting works in the Colorado River Basin to control the dissolved-solids concentration of water delivered to Mexico. Title I of the Salinity Control Act directed the United States to deliver water to Mexico having an average concentration that does not exceed more than 115 mg/L (plus or minus 30 mg/L) greater than the annual average concentration of the Colorado River at Imperial Dam (U.S. Department of the Interior, 2003). Salinity-control programs authorized under Title I of the 1974 Salinity Control Act are implemented by the Bureau of Reclamation and include the Yuma Desalting Plant, Coachella Canal Lining, the Protective and Regulatory Pumping Unit, and the Welltons-Mohawk Irrigation and Drainage District. These programs in southern Arizona and southern California (fig. 12) were implemented to reduce the dissolved-solids concentrations of Lower Colorado River water and are summarized in table 6.

Title II of the Salinity Control Act authorized several specific salinity-control units upstream from Imperial Dam to meet the objectives and standards set by the 1972 Clean Water Act. Major structural features of these units involved construction of facilities, such as wells, dikes, pipelines, pumps, desalinization plants, and evaporation ponds, to collect and dispose of saline water. Title II projects that were implemented are shown on figure 12 and summarized in table 7.

Salt removal by the Colorado River Basin Salinity Control Program has grown from less than 100,000 ton/yr in 1983 to more than 980,000 ton/yr in 2004 (Colorado River Basin Salinity Control Forum, 2005). To meet the target of 1.8 million ton/yr of salinity control through 2020 (U.S. Department of the Interior, 2003) and minimize additional impacts, however, it will be necessary to fund and implement potential new measures that ensure the removal of an additional 820,000 ton/yr.

Whereas salinity-control projects typically mitigate salt loading at or near the source, high dissolved-solids concentrations are addressed in some instances through water treatment near the location of use. In some areas where freshwater supplies are unavailable, concentrations of dissolved solids in brackish-water supplies are reduced by water-treatment plants that use microfiltration, nanofiltration, ultrafiltration, or most commonly, brackish reverse osmosis. A survey conducted in 1999 indicated that at least 14 such desalinization plants were in the Southwest and had capacities to treat more that 50,000 gal/day (Mickley and associates, 2001). Of the 14 plants, 2 are in Nevada near Lake Mead, 3 are in central Arizona, and the remaining 9 are in the coastal parts of southern California.

Approach, Data Compilation, and Analysis Methods

By David W. Anning

This report presents a retrospective analysis of existing dissolved-solids concentration data and ancillary information for the Southwest used to accomplish the four major report objectives. The approach, data, and methods used in this analysis are presented in this section in the same order that results for each objective are presented in the remainder of the report.

Compilation of Concentration Data for Basin-Fill Aquifers

The spatial distribution of dissolved-solids concentrations in basin-fill aquifers was compiled from previously published maps (table 8). The maps illustrate areas where concentrations in ground water are within a specified range, for example, 0 to 500 mg/L, 501 to 1,000 mg/L, and so forth. Most of the maps were published in the mid-1980s and are based on data available through their time of publication.

For some areas of the basin-fill aquifers, concentration-range data from previously published maps were unavailable. For these areas, concentration ranges were manually delineated as part of this study on the basis of concentration and well-location data in the National Water-Information System (NWIS) database, which is available on the Web (U.S. Geological Survey, 2004a). The most significant areas that required delineation were in the Rio Grande headwaters accounting unit in south central Colorado and in the Ventura-San Gabriel Coastal, Santa Ana, and Laguna-San Diego Coastal accounting units in southern California. In a few areas, available ground-water concentration data were not adequate to fill in the gaps. There were sufficient previously published maps and concentration data in NWIS to compile dissolved-solids concentration distribution maps for the Rio Grande aquifer system, the Basin and Range basin-fill aquifers, and the California Coastal Basin aquifers.

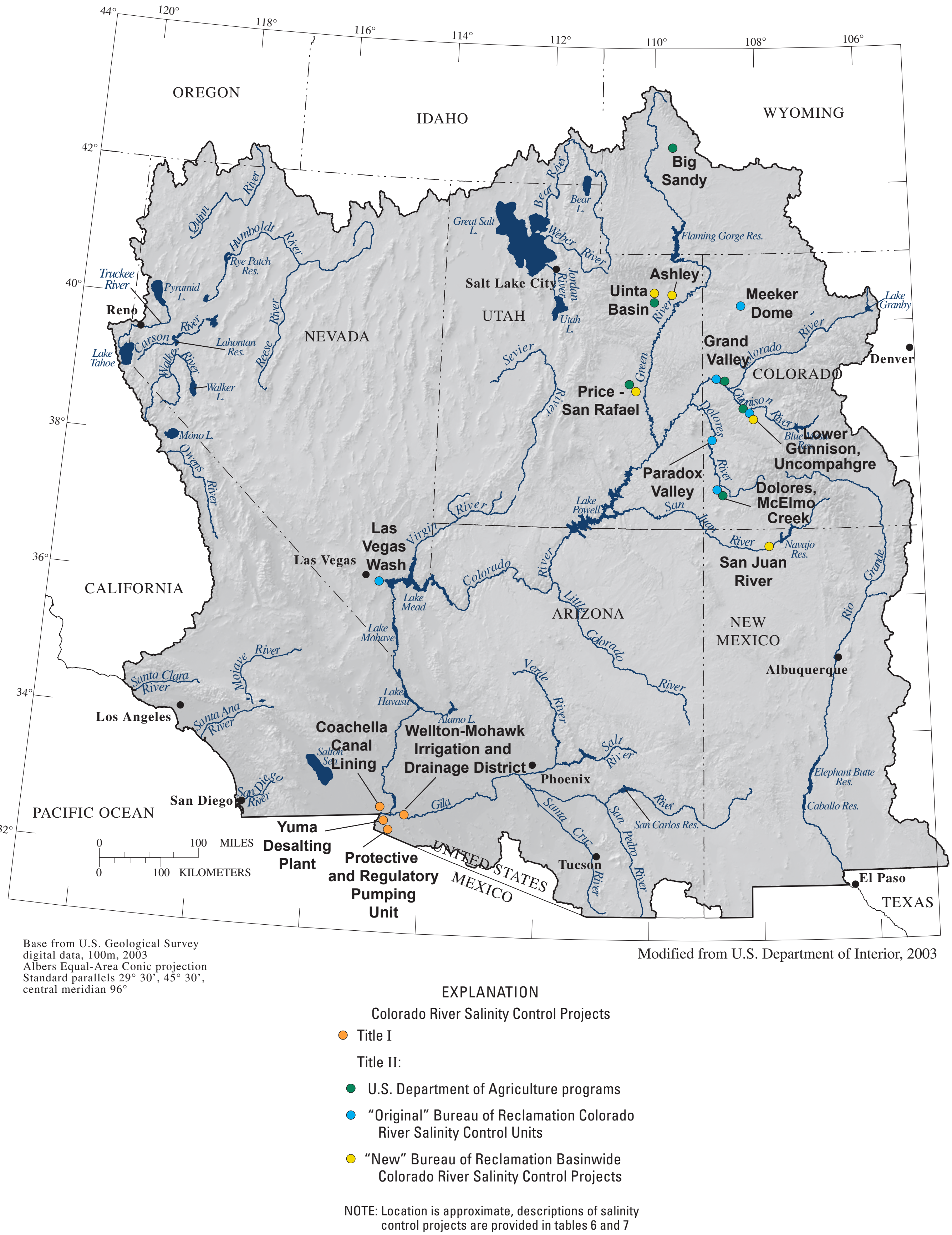


Figure 12. Title I and Title II salinity-control projects for the Colorado River.

Table 6. Title I salinity-control projects for the Colorado River.

[Data from U.S. Department of the Interior, 2003. See figure 12 for project locations]

Project	Description
Wellton-Mohawk Irrigation and Drainage District	Crop damage from shallow ground water is mitigated by the Welton-Mohawk Irrigation and Drainage District through ground-water pumpage. This ground-water discharge has high dissolved-solids concentrations and has created water-quality problems in the Colorado River below Imperial Dam. Pumpage of high dissolved-solids concentration ground water for drainage purposes was reduced by (1) removing some lands requiring high water use from irrigation and (2) increasing irrigation efficiencies.
Yuma Desalting Plant	The Yuma Desalting Plant was built to improve the quality of Colorado River that is delivered to Mexico in partial satisfaction of the Mexican Water Treaty of 1944. The Yuma Desalting Plant is a membrane-process desalting plant designed to lower the dissolved solids in irrigation-drainage water from the Welton-Mohawk Irrigation and Drainage District (described above). Water-quality requirements of water delivered to Mexico have been met through alternative means and the plant has not been in operation since 1993.
Coachella Canal Lining	The Coachella Canal carries Colorado River water from the All-American Canal to the Coachella Valley. The project entailed replacing the 49 miles of earthen-lined canal with a new concrete-lined canal, and has reduced seepage losses by 132,000 acre-feet per year. The water saved are to be used to substitute for the bypassed Welton-Mohawk Irrigation and Drainage District irrigation drainage waters and for the reject stream from the Yuma Desalting Plant.
Protective and Regulatory Pumping Unit	This program provided for construction of a well field located on a 5-mile-wide strip of land along the boundary between Arizona and Sonora, Mexico. Pumped water, as much as 125,000 acre-feet per year are used to help satisfy Mexico's entitlement of 1.5 million acre-feet per year of water with dissolved-solids concentrations that are no more than 115 mg/L greater than the average annual concentration of the Colorado River water at Imperial Dam.

Table 7. Title II salinity-control projects for the Colorado River.

[Data from U.S. Department of the Interior, 2003. See figure 12 for project locations]

Project	Description	Year first implemented	Salt removal rate, ton per year
	U.S. Bureau of Land Management		
Various locations in the Colorado River drainage	Detention or retention of runoff in areas with saline soil conditions	1997	10,100
	U.S. Department of Agriculture Programs		
McElmo Creek Unit, Colorado	Installation of more water-efficient irrigation systems that reduce (1) percolation of excess irrigation water through saline soils and subsequent ground-water seepage to streams, and (2) surface runoff from irrigation	1990	18,800
Lower Gunnison Basin Unit, Colorado		1988	62,500
Grand Valley Unit, Colorado		1987	87,100
Uinta Basin Unit, Utah		1987	121,000
Big Sandy River Unit, Wyoming		1988	40,400
Price-San Rafael Unit, Utah		1988	27,400
		Total	357,200
	"Original" Bureau of Reclamation Colorado River Salinity-Control Units		
Meeker Dome Unit, Colorado	Several flowing wells were plugged to stop discharge of saline ground water to tributaries of the White River. Wells were abondoned from oil exploration efforts conducted in the 1920s.	1980	48,000
Las Vegas Wash Unit, Nevada	Pipelines were built to convey industrial wastewater returns delivered to Las Vegas Wash. These discharges originally flowed through ditches in saline soils and dissolved soluble minerals during transport.	1978	3,800
Grand Valley Unit, Colorado	Installation of more water-efficient irrigation systems that reduce (1) percolation of excess irrigation water through saline soils and subsequent ground-water seepage to the Colorado River, and (2) surface runoff from irrigation	1980	127,500
Paradox Valley Unit, Colorado	Ground water that has been in contact with a salt dome and is nearly saturated with sodium chloride discharges to the Dolores River in Paradox Valley. This discharge is intercepted by wells and disposed of in deep injection wells	1988	109,000
Dolores Project, Colorado	Irrigation canals were lined to reduce percolation through saline soils and subsequent ground-water seepage to McElmo Creek	1990	23,000
Lower Gunnison Unit, Colorado	A canal system that conveyed water through saline soils and supplied livestock during the winter was replaced by upgrading an existing pipeline system that was used for other purposes	1991	41,380
		Total	352,680
	"New" Bureau of Reclamation Basinwide Colorado River Salinity-Control Projects		
San Juan River Unit, New Mexico	Installation of more water-efficient irrigation systems in the Hammond Project that reduce (1) percolation of excess irrigation water through saline soils and subsequent ground-water seepage to the San Juan River, and (2) surface runoff from irrigation	1996	48,100
Uncompahgre, Colorado	Replace unlined earthen irrigation system with buried pipe in the Uncompahgre Project's South Canal System	1998	2,300
Ashley, Utah	Replace leaking Ashley Valley Sewer Lagoons near Vernal, Utah	1999	9,000
Price-San Rafael Unit, Utah	Installation of more water-efficient irrigation systems that reduce (1) percolation of excess irrigation water through saline soils and subsequent ground-water seepage to the Price and San Rafael Rivers, and (2) surface runoff from irrigation	1998	115,700
Uinta Basin Unit, Utah	Installation of more water-efficient irrigation systems that reduce (1) percolation of excess irrigation water through saline soils and subsequent ground-water seepage to the tributaries of the Colorado River in the Uinta Basin, and (2) surface runoff from irrigation	2000	230,700
		Total	405,800

Table 8. Sources of information used to compile the spatial distribution of dissolved-solids concentrations in basin-fill aquifers in the Southwestern United States

Principal basin-fill aquifer	General spatial extent of information	Source
Rio Grande aquifer system	San Luis Valley, Colorado, south to Santa Fe, New Mexico	Emery and others, 1973, supplemented with data from the National Water Information System
	Santa Fe, New Mexico, south to the New Mexico-Texas border	Thompson, Chappell, and Hart, 1984
Basin and Range basin-fill aquifers	Arizona	Thompson, Nuter, and Anderson, 1984
	Southeastern California	Thompson, Nuter, Moyle, and Wollfenden, 1984
	Idaho	Thompson and Chappell, 1984a
	Nevada	Thompson and Chappell, 1984b
	Utah	Thompson and Nuter, 1984
California Coastal Basin aquifers	Southwestern California	Data from National Water Information System

Determination of Concentration, Load, and Yield Data for Surface-Water-Quality Monitoring Sites

The spatial distribution of dissolved-solids in major river systems was characterized on the basis of median values of daily-concentration, annual-load, and annual-yield data for surface-water-quality monitoring sites. Surface-water-quality sample data and streamflow data were compiled from the NWIS database for use in the determination of daily concentration, annual load, and annual yield of dissolved solids. Sites that had at least 40 samples and 10 years of approximately quarterly or more frequent sample collection between water years 1974 and 2003 were selected for use in this study. This number of samples and years of data were assumed to be about the minimum needed to account for climate variations and other factors that need to be considered for accurate characterization of dissolved-solids conditions in streams for the stated period. An additional criterion was that daily discharge data be available for the period of water-quality record. A few exceptions were made to these criteria to reduce large spatial gaps between sites along streams. Because the study objectives focus on major rivers and their tributaries, sites that monitor stream diversions and return flows were generally excluded in this study. A few sites that monitor major diversions, such as the Central Arizona Project Canal, were included in this study because they are important water supplies for the Southwest.

Altogether, 420 surface-water-quality monitoring sites were selected for use in this study (appendix 1). Drainage areas for the sites varied from 3 mi^2 to 246,700 mi^2 (fig. 13*A*; appendix 1). The number of samples used for analysis varied by site; the number was often more than 50 samples and less than 200 samples (fig. 13*B*; appendix 2). The number of sites with daily concentration data for a given water year increases from 1974 through 1984, and then decreases from 1984 through 2003 (fig. 14). The large increase in the number of stations with daily concentration data from 1983 to 1984 resulted from the onset of data collection at several sites in Colorado. The large decrease in the number of sites with daily concentration data from 1991 to 1992 resulted from discontinuing data collection at several sites in Utah. Most sites have more than 10 years of data; however, few sites have data for all 30 years between 1974 and 2003 (fig. 13*C*). Many of the sites with 18 years of data (fig. 13*C*) are in Utah with data collected from 1974 through 1991, and many of the sites with 20 years of data are in Colorado with data collected from 1984 through 2003.

Data retrieved from NWIS for the samples at each site include the date, time, discharge, specific conductance (SC), concentrations of residue on evaporation at 180°C (ROE), sum of the dissolved constituents (SUM), and dissolved concentrations of calcium, magnesium, potassium, sodium, alkalinity, bicarbonate, carbonate, chloride, sulfate, and silica. Four separate estimates of dissolved-solids concentrations can be determined from these data, including three estimates that are described in Liebermann and others (1987). The preferred choice of the four estimates is the calculated dissolved-solids estimate (CDS), which is determined as the sum of the concentrations of dissolved silica, calcium, magnesium, potassium, sodium, chloride, sulfate, and carbon expressed as the carbonate equivalent (Liebermann and others, 1987). These are the major cations and anions that are normally present in streams. Concentrations for individual ions may be stored in more than one database field because different laboratory or field methods were used in the determination. The algorithm listed by Liebermann and others (1987) was adapted to prioritize selection of the data-base fields used in the computation of CDS. The second preference of the four methods is SUM, which like CDS, is a calculated value. The SUM estimate, however, includes concentrations of certain minor ions if they were analyzed for the sample. The minor ions analyzed and included in the SUM estimate vary by sample, so SUM is a less consistent estimate than CDS. In addition, SUM is reported only to two significant figures. The third preference of the four methods is ROE. In this method, dissolved-solids concentrations are determined by evaporating a known volume of the sample in the laboratory and then weighing the residual salt.

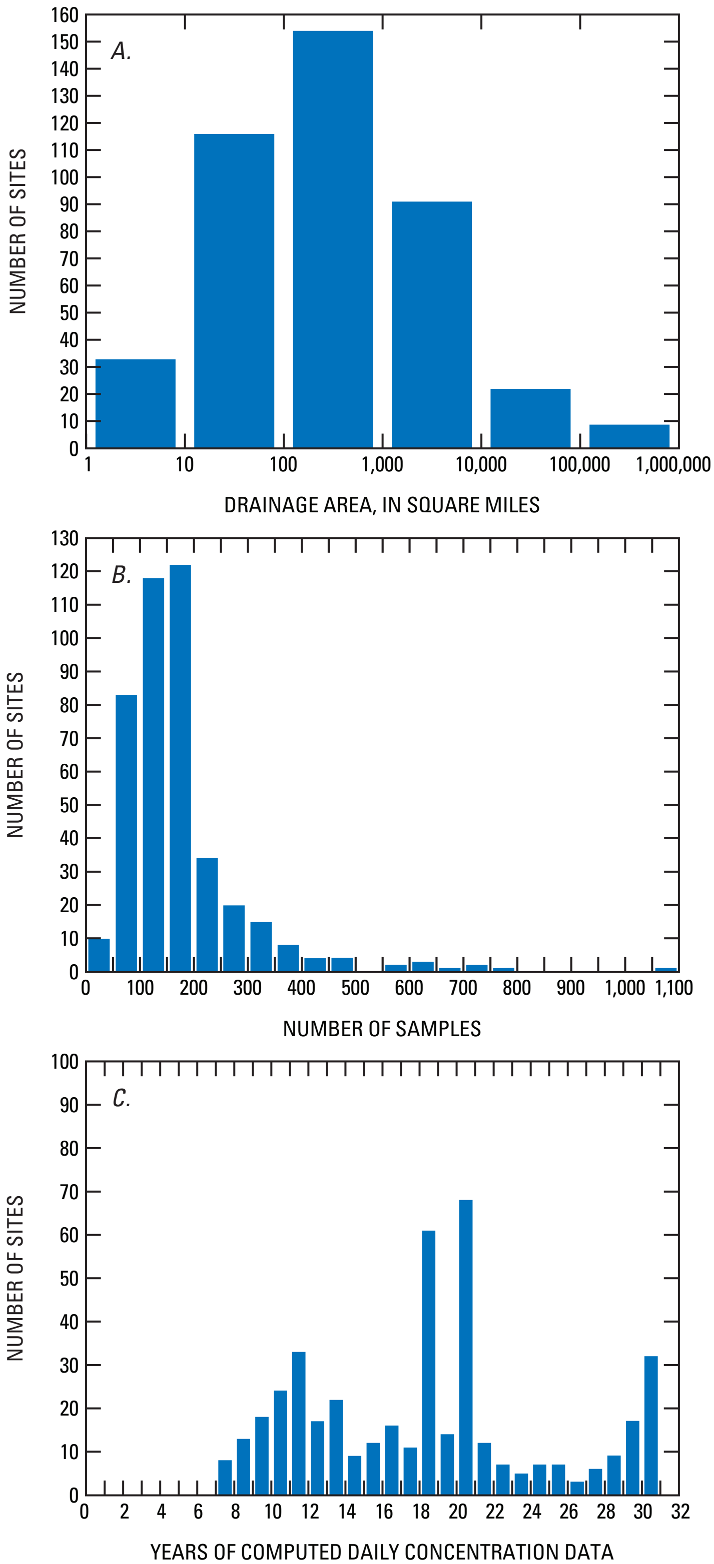


Figure 13. Distribution of 420 surface-water-quality monitoring sites in the Southwestern United States by *A*, drainage area; *B*, number of samples used to compute daily dissolved-solids concentration data; *C*, number of years with computed daily dissolved-solids concentration data.

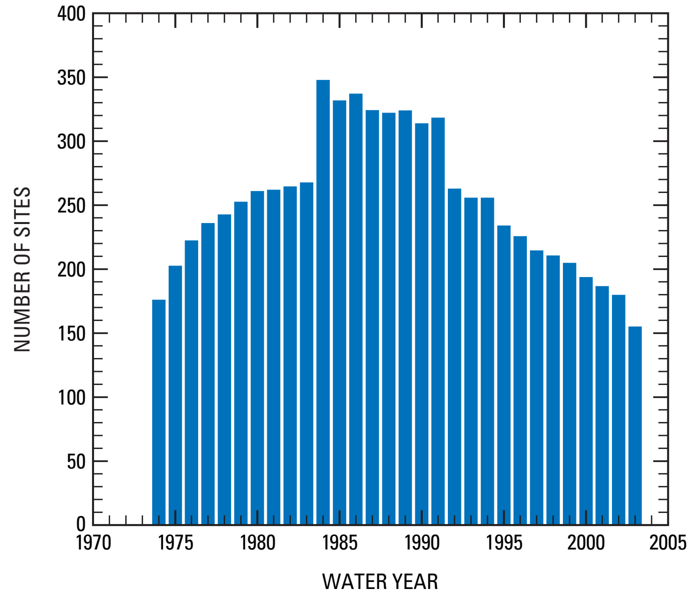


Figure 14. Number of surface-water-quality monitoring sites in the Southwestern United States with computed daily dissolved-solids concentration data, water years 1974–2003.

During the data compilation it was recognized that, for several sites, there were many samples with SC data available, but few CDS, SUM, and ROE data were available. In fact, SC data were the only data available for some sites. To utilize the SC data, an average value of the ratio between dissolved-solids concentrations (CDS, SUM, or ROE, in that preference) and SC for the samples was determined for each site. Then for a given site, the dissolved-solids concentrations were determined for samples without CDS, SUM, or ROE data by multiplying the SC by the site-specific average value of the ratio. It was qualitatively determined by using graphical methods that the estimate for the average value of this ratio was more stable and less variable when about eight or more samples were used to compute this average.

For some sites there were fewer than eight samples with SC and CDS, SUM, or ROE data available to compute a site-specific ratio. For these sites, a regional value for the ratio was used. The regional value was computed as the average of the site-specific average values of the ratio for all sites within a hydrologic unit (areas defined by Seaber and others, 1987). Where there were no other sites within the hydrologic unit, the average of the site-specific average values of the ratio for sites within an accounting unit (areas defined by Seaber and others, 1987) was used. Dissolved-solids concentrations computed on the basis of the SC and a site-specific value or regional value for the ratio are referred to as SCDS in this report and are the fourth priority estimate for dissolved-solids concentrations. The ratio used for each site is listed in appendix 2 along with data-source information that lists whether the ratio value was determined from site-specific data or was determined as an average value for several sites within the same hydrologic unit or accounting unit.

Daily dissolved-solids concentrations for each site were determined for the continuous period during which samples were routinely collected and daily discharge data were available. For many sites, this period was shorter than the complete period with available sample and discharge data because (1) some routine sample collection occurred before water year 1974, and (2) infrequent, miscellaneous samples were sporadically present in the record before and (or) after the routine period, with large time gaps occurring between the routine and miscellaneous sampling efforts.

Dissolved-solids concentration and discharge data for the routine samples were used to develop an equation for determining daily concentrations at each site. At most sites, concentrations typically have a predictable inverse relation to discharge that varies seasonally and interannually (year to year). The equation describing this relation at each site was determined by using stepwise regression; more information and details of the regression procedures and model diagnostics that are briefly described here can be found in Helsel and Hirsch (1992). The full regression equation with all considered explanatory variables is:

$$\log_{10} C = b_0 + b_1 \log_{10} Q + b_2 \log_{10} Q^2 + b_3 T + b_4 T^2 + b_5 \cos(2\pi T) + b_6 \sin(2\pi T) + e, \tag{1}$$

where

C	is	dissolved-solids concentration, in mg/L;
$b_0 \ldots b_6$	are	regression coefficients;
Q	is	discharge, in ft^3/s;
T	is	calendar year, in decimal form; and
e	is	the residual error.

On the right side of the equation, the second and third terms account for variability in concentration due to stream discharge; generally these account for more variation than the remaining terms combined. The fourth and fifth terms account for variations in the relation between concentration and discharge over time, and the sixth and seventh terms account for seasonal variation between concentration and discharge. The stepwise-regression procedures simplify equation 1 by removing explanatory variables that have coefficients that are not statistically different from zero ($p>0.05$) and determine the regression coefficients. As a result, the explanatory variables of the equation vary for each site.

Various diagnostics for the stepwise-regression results were used to identify outliers and verify model adequacy. Cook's D (Belsley and others, 1980) is a measure of the influence that individual sample data have on the regression coefficients and was used to identify potential outliers. At several sites one or more outliers identified on the basis of the Cook's D statistic and hydrologic judgment were removed from the data set used to calibrate the regression equation. Model adequacy for the equations was determined on the basis of regression summary statistics and diagnostic plots. The overall F-test was used to determine if the regression relation was statistically significant—that is, the apparent relation of the explanatory variables and concentrations was not likely to arise by chance alone. The p-value for the F-test of the regression equations was less than 0.01 for all but two sites (appendix 2). Whereas the F-test is a measure of the validity of explanatory variables in the regression equation, the multiple-R^2 value is a measure of the reduction in the uncertainty of concentration estimates that occurs by accounting for variation due to the explanatory variables. The multiple-R^2 values for the regressions ranged from 0.05 to 0.98 (fig. 15, appendix 2). Although high R^2 values are desirable, low R^2 values do not necessarily indicate an inadequate model. For example, R^2 values were less than 0.50 for several sites; however, the residual error of the regression equations for many of these sites was less than 20 percent of the median concentration (fig. 15). Residual error is a measure of the variation in concentrations that is not explained by the regression equation, and was generally less than 30 percent of the median concentration at most sites (fig. 15; appendix 2). In addition to these regression summary statistics, model adequacy was determined by using visual inspection of graphs that plot (1) fitted concentrations against measured concentrations, (2) residual concentrations against fitted concentrations, and (3) residuals against standard quantiles of standard normal.

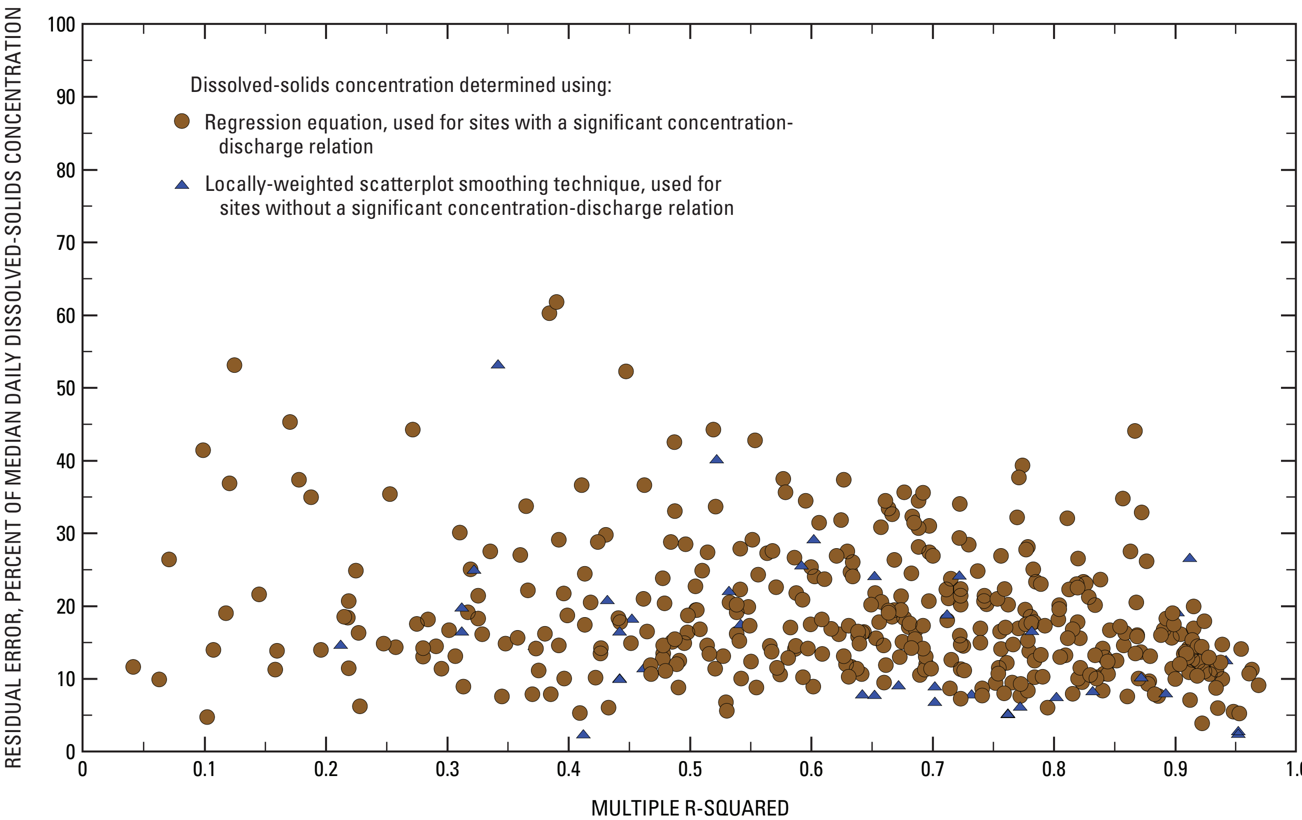


Figure 15. Summary statistics for statistical models used to determine daily dissolved-solids concentrations at 420 surface-water-quality monitoring sites in the Southwestern United States.

Daily dissolved-solids concentrations for each site were determined for the period of routine sampling on the basis of equation 1 with the calibrated regression coefficients and daily mean discharges. Use of daily mean discharges in equation 1 implicitly assumes that the relation between instantaneous concentrations and discharges holds true for daily concentrations and discharges. Equation 1 underestimates predicted concentrations because the dependent variable concentration is log-transformed (Ferguson, 1986). To correct for this bias, daily concentrations were predicted by using the following equation (Ferguson, 1986):

$$C_d = 10^{(C_{d'})} \times \exp(2.65\sigma^2) \tag{2}$$

where

- C_d is the unbiased estimate of a daily concentration, in mg/L;
- $C_{d'}$ is is the biased estimate of a daily concentration determined from equation 1, in log base-10 units of mg/L;
- exp is the base of natural logarithms and approximately equal to 2.7183; and
- σ is the residual error from equation 1, in log base-10 units of mg/L.

The first term on the right-hand side of equation 2 is the retransformed estimate for concentration, in mg/L, and the second term on the right is the bias correction factor. Note that the bias correction factor is always equal to or greater than one because σ^2 is always equal to or greater than zero.

Daily loads, in ton/day, were determined for the period of routine sampling by multiplying the daily concentration C_d, in mg/L, by the daily mean discharge, in ft^3/s, and a unit conversion factor of 0.0026969. Annual load (ton/yr), the mass of dissolved solids transported past a site on a stream in a given year, was compiled for each water year from the daily load data. Annual yield [(ton/yr)/mi^2], computed as the annual load at a site for a given water year divided by the drainage area, facilitate comparison of annual loads because the data are standardized to account for differences in drainage area among sites.

For 44 sites directly below large reservoirs, the dissolved-solids concentration is independent of discharge and does not fluctuate much from sample to sample. For these sites, daily concentrations were determined by using locally weighted scatterplot smoothing (LOWESS; Cleveland, 1979). LOWESS curves were fit to the time series of sample-concentration data, and values for the curve were used as estimates for the daily concentrations. The smoothness of a LOWESS curve is controlled by the smoothness factor, *f*, which can be assigned values between 0 and 1. For larger values of *f*, a wider window of points is used to estimate the LOWESS curve value (concentration) at a given point (time), and results in a smoother curve, providing a more regional fit of the data. In contrast, for smaller values of *f*, a narrower window of points is used to estimate the LOWESS curve value at a given point, and results in a more undulating curve, providing a more local fit of the data. If the value of *f* chosen is too small, then gaps occur in the LOWESS curve for periods during which samples are spaced infrequently.

For the purpose of smoothing the sample concentration data, the smallest value of *f* was used that allowed for estimation of concentration on all days of the routine sampling period. Values used for *f* were typically between 0.05 and 0.20. Plots of the sample points and LOWESS curves were visually inspected to validate model adequacy. In general, values of R^2 for the LOWESS curves were comparable or higher and residual error was comparable or lower than those statistics for sites where stepwise regression was used (fig. 15).

The spatial distribution of dissolved solids in streams in the Southwest was characterized on the basis of the median daily concentration, median annual load, and median annual yield for the 420 surface-water-quality monitoring sites. These three summary statistics were computed on the basis of the daily concentration, annual-load, and annual-yield data that were determined by using equation 1 or the LOWESS curves method. Median daily concentration (mg/L) is a central value for the statistical distribution of all daily concentrations for a given site. Half of the daily concentrations are smaller than the median daily concentration, and half of the daily concentrations are larger than the median. Median values were selected rather than mean values in this analysis because the population of daily or annual values that they describe typically has a few days (or years) with very high flows. As a result, mean values are greatly influenced by a few high values and appear much higher than the typical conditions of the stream. Median values, however, are not strongly influenced by such high values and, therefore, are more representative of typical conditions in the stream.

Development of a Conceptual Model for Effects of Natural and Human Factors

A conceptual model of the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams was developed through an analysis of dissolved-solids concentrations and environmental conditions along ground-water and surface-water flow paths in 12 areas. Each area is in one of the six NAWQA Study Units (fig. 1) in the Southwest and has a large amount of dissolved-solids concentration and environmental-condition information available. The areas were selected to represent diverse hydrologic, geologic, climatic, land-use, and water-use conditions. As a result of this environmental diversity, a wide variety of natural and human factors were found to affect dissolved-solids concentrations.

Data and information about concentration conditions and environmental conditions of a particular stream reach or part of an aquifer came from previously published studies or from the "Environmental Setting of the Southwest" and "Spatial Distribution of Dissolved Solids" sections in this report. These data and information from individual sources were used collectively to describe (1) concentrations, (2) changes in concentrations, and (3) natural or human factors that cause concentration conditions or changes in concentrations along the ground-water and surface-water flow paths in each area. The conceptual model for the natural and human factors that affect dissolved-solids concentrations in the Southwest was developed through a synthesis of all the natural and human factors causing concentration conditions or changes in concentrations along the flow paths in the 12 areas.

Determination of Sources and Accumulation of Dissolved Solids

Source areas were characterized by the amount of dissolved solids originating from the area and transported out of the area, and conversely, areas of accumulation were characterized by the amount of dissolved solids received from other areas and retained in that area. Significant source areas and accumulation areas were evaluated by determining the contributions and losses of dissolved solids to and from river systems in hydrologic accounting units (Seaber and others, 1987). Contributions of dissolved solids to accounting unit river systems include:

- Inflows, L_{in}, the annual loads delivered to streams from upstream hydrologic accounting units;
- Internal deliveries, I_{del}, the annual loads delivered to accounting unit streams from internal sources; and
- Imports, T_{imp}, the annual loads conveyed into accounting unit streams or water-supply systems from transbasin imported water.

Losses of dissolved solids from the accounting unit surface waters include:

- Outflows, L_{out}, which are the annual load that flows out of accounting unit streams to downstream accounting units;
- Internal accumulation, I_{acc}, the annual load removed from accounting unit streams that are retained and accumulate internally; and
- Exports, T_{exp}, the annual load conveyed out of accounting unit streams or water-supply systems through transbasin exported water.

The following equation shows the mass balance for contributions and losses of dissolved-solids mass for a hydrologic accounting unit's river systems:

$$\Delta S = \left[L_{in} + I_{del} + T_{imp} \right] - \left[L_{out} + I_{acc} + T_{\exp} \right] , \quad (3)$$

where

ΔS is the annual change in mass for the hydrologic accounting unit's river systems.

Studies of mass transport often focus on stream yields, which are computed as outflow, L_{out}, divided by the drainage area. Note that by moving L_{out} to the left side of equation 3 and assuming ΔS equals zero, it can be shown that, for an accounting unit, yield is a function of inflows, internal deliveries, imports, internal accumulation, and exports. To determine significant source areas and accumulation areas of dissolved solids, however, the focus is not on yields but rather on internal deliveries and internal accumulation.

Accounting units with the largest annual internal deliveries represent significant sources of dissolved solids in the Southwest, and similarly, accounting units with the largest annual internal accumulation represent significant areas accumulating dissolved solids. Accounting units in the Southwest vary in size; to allow for fair comparison among accounting units, the annual internal delivery was divided by the accounting unit area and are referred to as annual "delivery rates." Similarly, annual internal accumulation divided by the accounting unit area is referred to as annual "accumulation rates." It should be recognized that delivery and accumulation rates represent an average value for all parts of the accounting unit; some parts of each accounting unit have higher rates, while other parts have lower rates.

A spatially referenced regression model of contaminant transport on watershed attributes (SPARROW model; Smith and others, 1997) was used to determine delivery and accumulation rates of dissolved solids for accounting units in the Southwest. The SPARROW model estimates the release of dissolved solids from sources to the land surface, land to water delivery of dissolved solids, transport of instream loads of dissolved solids, and stream losses of dissolved solids. More detail about the model is discussed below. Inflow and outflow values for equation 3 were taken from stream-load predictions of dissolved solids from the SPARROW model at the inlet(s) and outlet(s) of each accounting unit. Imports and exports in equation 3 were determined as part of this study and aggregated for each accounting unit. Internal deliveries were determined as the sum of the predicted deliveries to streams from the SPARROW model for all sources within all catchments that comprise the accounting unit. The SPARROW model has terms that reflect internal accumulation processes and exports; however, output from the model did not allow for direct separation of these two terms in equation 3. For this reason internal accumulation for accounting units was determined as the residual of the sum of contributions of dissolved solids minus the outflow and exports of dissolved solids. Use of this calculation has the benefit of a zero-value residual for the balance; however, the errors for each term in the calculation are accumulated in the estimate for internal losses.

Calibration of the SPARROW Model for Dissolved-Solids Transport

An overview of the SPARROW model and details of the calibration of the SPARROW model for dissolved-solids transport in the Southwest is presented in this section. More information about the SPARROW model is described in detail in Smith and others (1997) and Schwarz and others (2006) along with examples of total nitrogen and total phosphorus transport in the United States. Examples of other SPARROW models can be obtained on-line at http://water.usgs.gov/nawqa/sparrow/intro/pubs.html.

The SPARROW model for dissolved-solids transport in the Southwest is founded on the enhanced river-reach file 2.0 (ERF1_2; Nolan and others, 2002), an enhancement of the U.S. Environmental Protection Agency's original river-reach file (DeWald and others, 1985, U.S. Environmental Protection Agency, 1996). The ERF1_2 provides the spatial framework used by the SPARROW model for tracking downstream transport of dissolved-solids loads from stream headwaters to stream mouths. It consists of a digital network of 5,214 stream-reach segments (reaches) in the Southwest and contains catchment-boundary information as well as flow-path information for each reach (fig. 16).

The SPARROW model relates the dependent variable, the annual dissolved-solids load transported out of a given stream reach of the network, to several explanatory variables that reflect upstream environmental conditions: (1) nonpoint and point sources of dissolved solids in the reach catchment, (2) environmental conditions that affect land-to-water delivery of dissolved solids from sources to the reach, and (3) environmental conditions that affect losses of dissolved-solids loads during in-stream transport through the reach. The mathematical form of the SPARROW model is a nonlinear regression model with explanatory variables that represent sources, land-to-water delivery processes, and reach losses:

$$L_i = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} S_{n,j} \beta_n e^{(\alpha' Z_j)} \right] (1 - \delta' T_{i,j}) \right\} e^{\varepsilon_i} \quad (4)$$

	Load	Source	Land-to-water delivery	Reach loses	Error
Term	L_i	$S_{n,j}\beta_n$	$e^{(\alpha' Z_j)}$	$1 - \delta' T_{i,j}$	ε_i

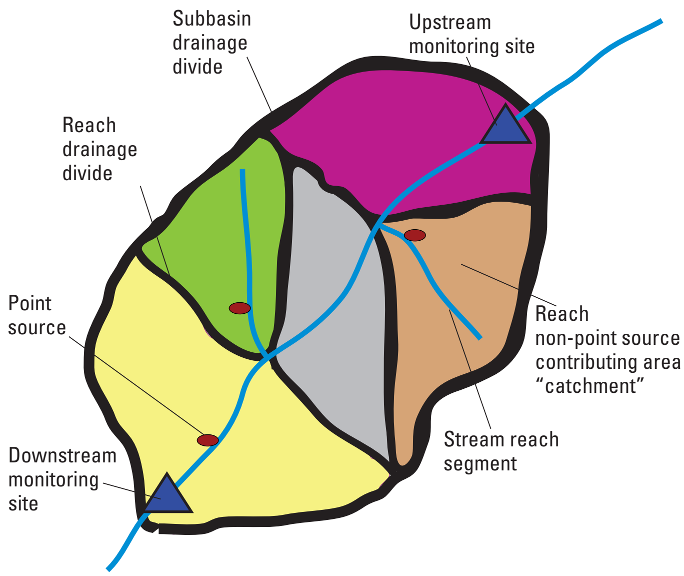


Figure 16. Features of the SPARROW model network for a generalized subbasin.

where

L_i is the dissolved-solids load in reach i, in ton/yr;

i is the index for reaches of the ERF1_2 network in the Southwest;

$J(i)$ is the set of all reaches j that includes reach i and all upstream reaches except those that contain or are upstream of monitoring stations upstream from i;

n is the index for dissolved-solids sources;

N is the total number of individual dissolved-solids sources;

$S_{n,j}$ is a mass, area, or other property for dissolved-solids source n in reach j;

β_n is the estimated source coefficient for dissolved-solids source n;

α is the estimated vector of land-to-water delivery coefficients;

Z_j is the vector of environmental variables associated with land transport of dissolved solids to reach j;

δ is the estimated vector of reach-loss coefficients;

$T_{i,j}$ is the vector of environmental variables associated with losses of dissolved solids in reach j;

ε is the error; and

e is the base for the natural logarithm (equal to about 2.7183).

Given the mathematical structure of the model, source terms ($S_{n,j}\beta_n$) reflect the annual mass of dissolved solids released from point and nonpoint sources, which is attenuated or amplified by land-to-water delivery terms ($e^{(\alpha' Z_j)}$). The product of these terms reflects the annual dissolved-solids mass that is released from these sources and delivered to the streams. Reach loss terms ($1-\delta' T_{i,j}$) are applied to the annual dissolved solids delivered to the streams from the reach catchment and from upstream reaches, and as applied in this study, they reduce the instream load of dissolved solids.

For model calibration, the reach catchments between monitoring sites along the ERF1_2 network are lumped together to form subbasins ($J(i)$; fig. 16). For a given subbasin, the load at the downstream monitoring site is the model's dependent variable, whereas the load(s) at the upstream monitoring site(s) is treated as a point source of dissolved solids. This effectively separates common drainage areas of nested basins in the ERF1_2 network and, therefore, allows for the monitored loads to serve as independent observations. The model coefficients (β_n, α', and δ') are calibrated on the basis of load data at monitoring sites (L_i) and environmental data ($S_{n,j}$, Z_j, and $T_{i,j}$) for the subbasins.

Median annual loads at sites for 1974–2003 were used as the monitored reach load (L_i). Although median annual-load data were available for 420 sites, only 315 sites were used for model calibration because 105 sites were either (1) located on a tributary to a reach rather than a reach in the ERF1_2 network or (2) were duplicate sites on a single reach. Sites used in the SPARROW model calibration are listed in appendix 1.

Nonpoint sources of dissolved solids ($S_{n,j}$) include the area of geologic units, the area of agricultural land, human populations, and transbasin imported water delivered to offstream locations (table 9). Point sources include dissolved solids carried in transbasin imported water (table 9). Calibrated source coefficients (β_n) are dimensionless for sources with units of ton/yr; however, for sources with other units the coefficients have units such that the product of the coefficient and the source data has units of ton/yr. As an example, for a source with units of mi^2, the coefficient has units of $(ton/yr)/mi^2$.

A digital map containing bedrock geology of the conterminous United States (Schruben and others, 1997; King and Beikman, 1974) and reach-catchment boundaries from the ERF1_2 were used to determine outcrop areas for geologic units in each reach. Altogether, there were 70 different geologic units in the Southwest. Theoretically, each geologic unit could be considered as an individual source in the model, each having different values for the source coefficients and delivering different amounts of dissolved solids. Groups of geologic units, however, were aggregated to simplify the model. Geologic units were first split into groups on the basis of general lithology and age: crystalline (plutonic and metamorphic) rocks, felsic volcanic rocks, mafic volcanic rocks, eugeosynclinal rocks, Quaternary basin fill (generally unconsolidated deposits), Tertiary sedimentary rocks, Mesozoic sedimentary rocks, and Paleozoic and Precambrian sedimentary rocks. Tertiary, Mesozoic, and Paleozoic and Precambrian rocks were further divided into low-, medium-, or high-yield groups of geologic units. This subsequent division of geologic units was accomplished by transferring each unit from the low-yield group to the high-yield group, one at a time, and then rerunning the model and comparing model diagnostics. Geologic units were reassigned to the high-yield group if as a result of the transfer (1) the source coefficient, β, for the low-yield group decreased and the source coefficient for the high-yield group increased; (2) the probability value of the source coefficients remained about the same or decreased; and (3) the R^2 of the model remained about the same or increased as a result of moving a unit from the low-yield group to the high-yield group. If these three conditions were not met, then the geologic unit was kept in the low-yield group.

Areas of agricultural lands tested as sources of dissolved solids include cropland and pasture land. Areas of these two types of agricultural lands for each river reach were provided by Greg Schwarz (U.S. Geological Survey economist, written commun., November 29, 2004) and were determined from the National Land Cover Data set (NLCD; Vogelmann and others, 2001). Cropland includes (1) row crops, such as corn, soybeans, vegetables, and cottons, (2) small grains, such as wheat, barley, oats, and rice, and (3) fallow areas. In contrast, pasture includes areas of grasses and (or) legumes planted for livestock grazing or for production of seed or hay crops. Human populations were also considered diffuse (nonpoint) sources of dissolved solids. Population data for each reach were provided by Greg Schwarz (U.S. Geological Survey economist, written commun., November 29, 2004) and were determined from the 1990 census data.

There are numerous surface-water diversions in the Southwest, which, inherently, are also diversions of dissolved solids. Diversions are not included in the topology of the ERF1_2 network, and, therefore, transport of dissolved solids in diverted water was accounted for by using source variables and reach-loss variables in the SPARROW model. Diversions from a given reach can result in deliveries of dissolved solids to (1) the same reach catchment, (2) the next downstream reach catchment, or (3) a reach catchment in another river basin (a transbasin diversion). Removal of dissolved solids from streams in a given reach by any of these three types of diversions is accounted for in the SPARROW model through the reach-loss variable “change in reach discharge,” which is discussed later in this section. Some deliveries to reaches from surface-water diversions were accounted for by including transbasin imported water deliveries of dissolved solids (ton/yr) as a source variable. These data were compiled as part of this project for transfers between hydrologic accounting units (table 10). The compilation generally included only large deliveries (greater than 1,000 ton/yr) that originated from reaches in a different hydrologic accounting unit. In most cases, the annual load of dissolved solids for a given diversion/delivery was determined by multiplying an annual flow volume representative of recent years by a representative concentration, often a mean value determined from samples collected at nearby surface-water-quality monitoring sites. For reaches where diversions were delivered to the same reach or to downstream reaches, the delivered dissolved-solids load was not included as a source variable. As a result, the dissolved-solids load removed from the streams of these reaches is accounted for by the model as a reach loss where the diversion occurred. This represents an error in the reach location where the diverted dissolved solids are retained, and it is, in part, for this reason that the mass-balance results are computed for hydrologic accounting units rather than for each reach catchment.

The annual mass of dissolved solids delivered from a given source to each reach varies spatially because (1) the value for the source variable varies by reach; for example, areas of crystalline rocks vary from reach to reach, and (2) the mass delivered from a source is adjusted (multiplied) by a land-to-water delivery term (equation 4). Land-to-water delivery variables reflect environmental conditions of the land surface that affect release of dissolved solids from sources and delivery to streams. Land-to-water delivery variables tested during model development include runoff depth, precipitation depth, air temperature, drainage density, soil permeability, and percentage of selected land covers, including forested, shrubland, grassland, barren, transitional, urban, cultivated, and pasture. Values of these variables for each ERF1_2 reach were provided by Greg Schwarz (U.S. Geological Survey economist, written commun., November 29, 2004). Runoff depth is the volume of runoff divided by the drainage area, and therefore, has unit dimensions of depth like precipitation does. For a given catchment, runoff depth is smaller than precipitation depth owing to the fact that of precipitation that falls onto the land surface, only a portion of it becomes runoff, and the remainder infiltrates the soil or evaporates. With the exceptions of cropland, pasture, and transbasin imported-water deliveries of dissolved solids, land-to-water delivery terms were applied to each source. For these three sources, the value of the land-to-water delivery term was set to equal 1 because these sources are not considered to be affected by any of the land-to-water delivery variables.

While runoff depth, precipitation depth, air temperature, drainage density, and soil permeability represent single physical properties of the land, the percentage of areas covered by selected land covers are surrogate variables representative of several properties. For example, forested lands (1) are located in areas of the Southwest with cooler and wetter climates, (2) have vegetation with leaves that intercept precipitation before striking the land surface, (3) have ground cover that slows and captures overland runoff, and (4) have vegetation to capture and transpire precipitation infiltration. The sign of a land-to-water delivery coefficient indicates whether the land-to-water variable attenuates or amplifies the amount from the sources—positive coefficients amplify source loads whereas negative coefficients attenuate source loads.

Reach-loss variables ($T_{i,j}$) reflect environmental conditions of the channel characteristics of the reach that affect losses of dissolved-solids loads. Reach-loss variables include change in reach discharge, percent Quaternary basin fill, reservoir presence, and reservoir area. The first two variables were applied to all reaches whereas the last two were only applied to those reaches containing reservoirs. Change in reach discharge, ΔQ, was determined on the basis of reach discharge data that are included in the ERF1_2 file, and was calculated as follows:

$$\Delta Q = 0, \text{ if } Q_{us} = 0 \text{ or } Q_{us} < Q_r, \qquad \text{or}$$

$$\Delta Q = \frac{Q_{us} - Q_r}{Q_{us}} \quad \text{otherwise,} \tag{5}$$

where

Q_{us} is the sum of stream discharge entering the reach of interest from all adjacent upstream reaches, and

Q_r is stream discharge in the reach of interest.

For gaining reaches, ΔQ is assigned a value of zero, and for losing reaches ΔQ is assigned a value between zero and one. For reaches with no outflow, Q_r equals zero and ΔQ equals one. A loss in stream discharge in a reach can occur due to streamflow diversions or due to streamflow infiltration. An implied assumption of ΔQ is that changes in dissolved-solids loads across the reach are correlated to changes in streamflow volume across the reach. The reach-loss coefficient (δ) for ΔQ is expected to be near one; however, coefficient values larger or smaller than one can result because the coefficient does not account for change in dissolved-solids concentrations across the reach due to discharge loss by evaporation or discharge gain by stream inflow.

The percent of Quaternary basin fill was computed by dividing the area of Quaternary unconsolidated sediments in the reach catchment by the area of the reach catchment. This term reflects additional loss processes that specifically occur in Quaternary basin fill and are not captured by the change in reach discharge term. The larger percentage of Quaternary basin fill, the smaller the reach-loss term (equation 4).

Two variables were used to account for retention of dissolved solids in reservoirs, reservoir presence and reservoir area. Reservoir presence indicates that a large reservoir is present on the reach and accounts for processes in reservoirs. Reservoir presence date are available in the ERF1_2 files, and the value for T_i is one if a reservoir is present and zero if it is absent. Dissolved solids generally are considered to behave conservatively in streams and, therefore, the coefficient for reservoir presence (δ) is expected to be small. Reservoir area was the other variable tested. For this variable, the reach-loss term took an alternate form than that listed in equation 5, ($e^{-T_i\delta}$), where T_i was the surface area of the reservoir in reach *i*. The value for (δ) was restricted to be greater than zero so that the term (- T_iδ) would be negative. The larger the reservoir area, therefore, the smaller the reach-loss term, indicating loss of dissolved solids within the reservoir. Only reservoirs attached to the ERF1_2 network are included in the analysis; processes in reservoirs not on the network are not accounted for.

Table 9. Sources and determination methods for data used in the SPARROW model of dissolved-solids transport in the Southwestern United States.

[In most cases the data provider determined data values for each reach on the basis of previously published data that is listed in the “Original data source and method of determination” column. USGS, U.S. Geological Survey; m^2, square mile; SPARROW, Spatially referenced regression model of contaminant transportation on watershed attributes]

Data type category	Data type determined for each reach	Data provider	Original data source and method of determination	Units
LOADS	Median annual load of dissolved solids for period with data between 1974 and 2003 (315 alibration reaches)	Determined as part of this study	Calculated on the basis of daily streamflow data and periodic water-quality samples	Ton per year
STREAM NETWORK	River reaches	Nolan and others, 2002	Enhanced original river reach network (U.S. Environmental Protection Agency, 1996 and DeWald and others, 1985)	Unitless (data are non-numeric)
	Reach catchment boundaries	Ditto	A 1-kilometer raster grid of reaches was merged with a flow direction data set to generate a digital elevation model (DEM) based watershed grid.	Unitless (data are non-numeric)
	Mean annual streamflows	Ditto	Provided in original river reach file (U.S. Environmental Protection Agency, 1996 and DeWald and others, 1985); these data determined on the basis of interpolation of data from USGS streamflow-gaging stations	Cubic feet per second
	Surface area of lakes and reservoirs	Ditto	Provided in original river reach network (U.S. Environmental Protection Agency, 1996 and DeWald and others, 1985)	$Mile^2$
TESTED SOURCES OF DISSOLVED SOLIDS	Geologic unit outcrop area	Determined as part of this study	Reach-level data compiled from geospatial analysis of digital geologic map (Schruben and others, 1997). Original map (King and Beikman, 1974) compiled data from geologic maps for each state in the Southwest	$Mile^2$
	Land use (cropland, pasture, and urban land)	Greg Schwarz (USGS Economist, written commun., November 29, 2004)	Reach-level data obtained using geospatial techniques and digital information from the National Land Cover Data set, which was determined from satellite images (Vogelmann and others, 2001)	$Mile^2$
	Human population	Greg Schwarz (USGS Economist, written commun., November 29, 2004)	Reach-level data obtained using geospatial techniques and population data from U.S. Bureau of Census data for 1990	Persons
	Transbasin imports	Determined as part of this study	Determined loads based on compiled flow volume and dissolved-solids concentration data that were available from many agencies	Ton per year
TESTED LAND-TO-WATER DELIVERY VARIABLES	Runoff depth	Greg Schwarz (USGS Economist, written commun., November 29, 2004)	Reach-level data obtained using geospatial techniques and runoff-depth information for the United States (Gerber and others, 1987)	Inches per year
	Precipitation depth	Ditto	Reach-level data obtained using geospatial techniques and Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Spatial Climate Analysis Service, 1995)	Inches per year
	Air temperature	Ditto	Reach-level data obtained using geospatial techniques and PRISM data (Spatial Climate Analysis Service, 1995)	Degrees Celsius
	Drainage density	Ditto	Ditto	Mile per $mile^2$

Table 9. Sources and determination methods for data used in the SPARROW model of dissolved-solids transport in the Southwestern United States—Continued.

Data type category	Data type determined for each reach	Data provider	Original data source and method of determination	Units
TESTED LAND-TO-WATER DELIVERY VARIABLES—Continued	Soil permeability	Ditto	Average permeability data for each reach obtained using geospatial techniques and digital State Soil Geographic Data Base (STATSGO; U.S. Department of Agriculture, National Resource Conservation Service, National Soil Survey Center, 1994,) that was compiled by Schwarz and Alexander (1995)	Inches per hour
	Percentage of selected land covers (forested, shrubland, grassland, barren, transitional, urban, cultivated, and pasture)	Ditto	Reach-level data obtained using geospatial techniques and digital information from the National Land Cover Data set, which was determined from satellite images (Vogelmann and others, 2001)	$Mile^2$ per $mile^2$
TESTED REACH-LOSS VARIABLES	Change in reach discharge	Determined as part of this study	Determined on the basis of the gain or loss of discharge through the reach; discharge data from the ERF1_2 file	Unitless
	Percentage of reach catchment covered by Quaternary basin fill	Ditto	Reach-level data compiled from geospatial analysis of digital map (Schruben and others, 1997). Original map (King and Beikman, 1974) compiled data from geologic maps for each state in the Southwest	$Mile^2$ per $mile^2$
	Reservoir presence	Nolan and others, 2002	Provided in original river reach network (U.S. Environmental Protection Agency, 1996 and DeWald and others, 1985)	Unitless
	Reservoir area	Ditto	Ditto	Ditto

Table 10. Summary of major interbasin transfers of dissolved solids by hydrologic accounting units in the Southwestern United States.

[---, no number because area is outside the boundary of the Southwest; n/a, not available. In most cases, total transfer represents the sum of transfers from several reaches in each accounting unit]

Hydrologic accounting unit export is from		Hydrologic accounting unit import is to		Interbasin transfer, ton per year
Code	Name	Code	Name	
140100	Colorado headwaters	---	Front Range	32,160
140500	White-Yampa	---	Ditto	1,860
140300	Upper Colorado-Dolores	140802	Lower San Juan	23,100
140500	White-Yampa	140100	Colorado headwaters	360
140600	Lower Green	160202	Jordan	18,790
140600	Lower Green	160300	Escalante Desert-Sevier Lake	1,090
140801	Upper San Juan	130201	Upper Rio Grande	15,700
150100	Lower Colorado-Lake Mead[1]	150100	Lower Colorado-Lake Mead[1]	375,000
150200	Little Colorado River	150601	Salt	410
150200	Little Colorado River	150602	Verde	1,090
150301	Lower Colorado (Lake Havasu)	150501	Middle Gila	192,000
Ditto	Ditto	150503	Santa Cruz	203,550
Ditto	Ditto	150601	Salt	212,000
Ditto	Ditto	150602	Verde	1,340
Ditto	Ditto	150701	Lower Gila-Agua Fria	170,080
Ditto	Ditto	180701	Ventura-San Gabriel Coast	655,400
Ditto	Ditto	180702	Santa Ana	200,470
Ditto	Ditto	180703	Laguna-San Diego Coastal	173,380
150301	Lower Colorado (Imperial Reservoir)	150702	Lower Gila	417,000
Ditto	Ditto	181002	Salton Sea	3,360,000
150601	Salt	150400	Upper Gila	1,030
150702	Lower Gila	---	Mexico through Lower Colorado River	524,000
160300	Escalante Desert-Sevier Lake	140700	Upper Colorado-Dirty Devil	1,360
160501	Truckee	160502	Carson	36,500
180701	Ventura-San Gabriel Coastal	---	Pacific Ocean	n/a[2]
180702	Santa Ana	---	Ditto	n/a[2]
180703	Laguna-San Diego Coastal	---	Ditto	n/a[2]
180901	Mono-Owens Lakes	180701	Ventura-San Gabriel Coastal	99,590
---	Northern California	180701	Ventura-San Gabriel Coastal	95,580
---	Ditto	180702	Santa Ana	29,040
---	Ditto	180703	Laguna-San Diego Coastal	22,530
---	Ditto	180902	Northern Mohave	36,920
---	Ditto	181001	Southern Mojave	840
---	Ditto	181002	Salton Sea	19,200

[1]Diversion from Colorado River and delivery to Las Vegas are within same accounting unit; however, diversion is substantial and therefore included.

[2]Export is through municipal wastewater-treatment plants and brine pipelines.

Model diagnostics allowed for selection of source terms, land-to-water delivery terms, and reach-loss terms. In particular, t-test statistics for model coefficients (β_n, α', and δ') were used to determine the probability of the coefficient being different than zero; those with less than a 0.10 chance were retained in the model, while those greater than 0.10 generally were not included.

Computer software (Schwarz and others, 2006) was used to calibrate and apply the model. The model was calibrated by using nonlinear least squares to determine parametric values of the model coefficients. A bootstrap analysis was conducted to assess errors associated with model predictions and to confirm calibration results. For the bootstrap analysis, observations of monitored stream load data are subsampled, then the model is recalibrated by using nonlinear least squares, and model coefficients are recorded; this process is repeated for several iterations, and the resulting set of recorded model coefficients are used to describe the empirical distribution of the model coefficients. At least 200 iterations are needed for 90-percent confidence interval estimates for the model coefficients (Schwarz and others, 2006). Parametric values for the model coefficients were verified by comparing them to the mean value of the coefficients from 200 bootstrap iterations.

In the model application, the parametric calibration coefficients were used to predict catchment source loads, reach stream loads, and catchment losses of dissolved solids. Predicted values for these variables are computed in downstream order as the stream load for a given reach is determined as the sum of the stream load generated internally from catchment sources plus the stream load entering from upstream reaches, minus any reach losses. Predicted reach loads at hydrologic accounting unit boundaries were used to estimate inflows and outflows of dissolved solids in the mass balance equation 3. Where monitored loads were available near the boundary, the model residual for the monitored load was added to the predicted load at the boundary. This adjustment made the mass-balance inflow and outflow estimates reflect monitored loads more closely.

Determination of Trends in Concentration Data for Ground-Water-Quality Monitoring Wells

An analysis of trends in concentrations of dissolved solids in basin-fill aquifers was performed to determine whether dissolved solids have been increasing or decreasing in recent years and whether there are any patterns in the trends related to natural and human factors. The analysis was performed for three periods: (1) water years 1974–2003, (2) water years 1974–88, and (3) water years 1989–2003. Determining trends for the latter two short periods allowed for inclusion of more sites in the trend analysis and more detail of trends than an analysis of a single long period.

Trends in basin-fill aquifers were determined on the basis of ground-water-quality monitoring-well samples collected between 1974 and 2003 that were available in the NWIS database. Trends were analyzed on the basis of specific-conductance data because these data were more common than dissolved-solids concentration data. Specific-conductance data for the ground-water samples were multiplied by a conversion factor of 0.65 to approximate dissolved-solids concentrations to allow for reporting the trends in units of mg/L. Only data for wells with several samples were used in the analysis; details of the selection criteria are described here. Most wells with multiple samples had an annual sampling frequency. To make the data set uniform, an initial step for selecting wells was to remove samples less than one-half year apart for a given well so that the sample frequency did not exceed one sample per year. The next step was to exclude wells from each analysis period that had more than a 5-year gap between samples. Of the remaining wells, those with eight or more samples for 1974–88 or for 1989–2003 were included in the analysis for these periods. Wells that were included in both of these periods were included in the 1974–2003 analysis. The final set of wells used in the trend analysis generally had samples collected between 0.5 and 1.5 years apart.

The Kendall's tau test (Kendall, 1938; Helsel and Hirsh, 1992, p. 212) was used to detect the occurrence of significant positive or negative monotonic trends in the time series of computed dissolved-solids concentrations for each well. The magnitude of the trend for each well was characterized by the "period change" in concentration for each well, by using the following procedure: for wells without a significant trend, the period change was zero. For wells with significant trends the Sen slope (Sen, 1968; Theil, 1950; Helsel and Hirsh, 1992, p. 266) was computed. The Sen slope is the median of all possible slopes of lines connecting pairwise sample date and concentration data points. A linear model of the trend for each well was made by using the Sen slope, the median time for the period, and the median sample concentration. By using predicted concentrations from the linear model, the period change for an individual well was computed as the change in concentrations for the beginning of the analysis period to the end of the analysis period, divided by the concentration for the beginning of the analysis period. This number was then multiplied by 100 to express the period change as a percent. Thus, the period change for a well represents the change in dissolved-solids concentrations that occurred during 15 years for 1974–88 and for 1989–2003, and change in concentration during 30 years for 1974–2003. Trend-occurrence and period-change data for wells were summarized for each time period and basin-fill aquifer.

The relations of trend occurrence (positive or negative) to selected natural and human factors were explored through statistical modeling. Eight explanatory variables were used in the model to represent natural and human factors: depth to water below the land surface, well depth, and six variables representing land use around the well. Depth to water below the land surface and well-depth data were available in NWIS for most wells. Depth to water below the land surface for each well was taken as the average of several depths measured during 1974–2003. Water-level data collected under pumping or recent-pumping conditions were omitted from the analysis. In a few cases where water-level data for 1974–2003 were not available, water-level data collected before 1974 were used.

The land-use variables include the percentage of (1) agricultural land, (2) urban land, (3) nonagricultural and nonurban land in a 1,640 ft (500 m) radius area around the well, and the percentage of (4) agricultural land, (5) urban land, and (6) nonagricultural and nonurban land in a 16,400 ft (5 km) radius area around the well. Land-use data for the areas were determined by using geospatial techniques and 98-ft (30-m) resolution land-use data from the National Land Cover Database (U.S. Geological Survey, 2005a).

The eight variables were selected on the basis of their plausible relevance to trends and on their ability to be represented with existing data. Other factors may also be relevant to trends; however, data to represent them were not readily available for testing.

The relation of trend occurrence to natural and human factors was determined by using logistic regression. Logistic regression relates the probability for one value of a binary variable occurring to one or more explanatory variables (Helsel and Hirsch, 1992). The regression equation uses the logit transformation and has the form:

$$p = \frac{\exp(b_0 + b_1 x_1 + b_2 x_2 + \ldots.. b_n x_n)}{1 + \exp(b_0 + b_1 x_1 + b_2 x_2 + \ldots.. b_n x_n)} \quad , \qquad (6)$$

where p is the probability of a trend occurring, b_0, b_1, … b_n are regression coefficients, and x_1, x_2, …x_n, are explanatory variables such as depth to water below the land surface, well depth, or percentage of a specific land use in a specified area around the well. Polynomial and step functions, as well as log and power transformations for each explanatory variable were tested in the development of the model. The final model was arrived at by constructing many different models with the various possible combinations of the eight explanatory variables representing natural and human factors and then evaluating the significance of each variable and overall significance of the model.

Determination of Trends in Concentration Data for Surface-Water-Quality Monitoring Sites

An analysis of trends in a time series of annual dissolved-solids concentrations at water-quality monitoring sites in major river basins was performed to determine whether dissolved solids have been increasing or decreasing in recent years, and whether or not there are any spatial patterns in these trends. The three periods of interest were water years 1974–2003, water years 1974–88, and water years 1989–2003. Determining trends for the latter two short periods allowed for inclusion of more sites in the trend analysis and more detail of trends than an analysis of a single long period. To maximize the number of stations in the analysis and ensure adequate representation of data for the period analyzed, trends for 1974–2003 were determined only for sites with 25 or more years of dissolved-solids concentration and discharge data. Similarly, trends for 1974–88 and 1989–2003 were determined only for sites with 13 or more years of dissolved-solids concentration and discharge data during those respective periods. Sites meeting these requirements are noted in appendix 1.

For sites with daily concentrations determined by using equation 1, trends in dissolved-solids concentrations were determined by using parametric methods (Helsel and Hirsch, 1992) on the basis of this equation. The trend terms ($b_3T+b_4T^2$) are additive in this equation, and in effect, adjust the predicted concentration by a positive or negative amount to account for changes in the concentration-discharge relation that occur during the period of sampling due to natural and human factors. The variation in concentration at a site over time only due to trends and not due to variation in discharge or seasonal effects was determined by creating an annual series of predicted concentrations from equation 1. The series was generated by using one data point per year for the period of sampling, and the discharge associated with each point was held constant and equal to the median daily discharge. Holding discharge constant removed variation in the predicted concentration due to variation in discharge, which was important because it comprises a large component of the total variation in concentration and confounds observation of the true trends. The day of the year associated with each point was also held constant and equal to January 1. This removed variation in the predicted concentration due to seasonal effects by keeping the result of the terms $b_5\cos(2\pi T)$ and $b_6\sin(2\pi T)$ a constant value. With the discharge and seasonal terms held constant in equation 1, the annual series predicted concentrations vary only as a result of nonzero values for b_3 and b_4 and the changing value of T. Note that where b_3 and b_4 in equation 1 were not significantly different from 0, and therefore dropped from the equation, the predicted concentrations had a constant value and, therefore, no trend. The resulting predicted series of concentrations is referred to as “adjusted annual dissolved-solids concentrations (AADSC)” in this report.

The trend analysis was performed on the adjusted concentrations so that (1) trends could be compared among sites without the confounding effects of different climatic trends among the sites, and (2) the trend identified could be attributed to nonclimatic factors, such as salinity-control projects, water-quality protection measures, or land- and water-use policy. Although variation in concentrations due to discharge is accounted for by holding discharge constant in equation 1, not all of the effects of climate are accounted for. The climatic factors affecting discharge in a given year may also affect concentrations of dissolved solids in subsequent years. Consider for example, a wet year with above average precipitation followed by several average years of precipitation. Variation in concentration in the first, wet year due to a high discharge will be accounted for. During the wet year, however, there may be a flushing of salts (1) that are on the land surface and soils that are washed into channels during precipitation runoff and (2) that are in contact with ground water that is discharged to streams. Such a flushing and diminishment of available salts could result in lower concentrations for a given discharge in subsequent years, which would be observed as a decrease in the adjusted concentrations. Thus, while variation in concentration due to variation in discharge is accounted for, climate can still cause trends in the adjusted concentration data.

For the 44 sites below reservoirs where concentrations were not correlated to discharge and daily concentrations were estimated by using the LOWESS-curve technique, the trends in concentration were determined as follows. First, the following equation was fit by using stepwise regression and the sample concentration data:

$$C = b_0 + b_1 T + b_2 T^2 + b_3 \cos(2\pi T) + b_4 \sin(2\pi T) + e, \tag{7}$$

This is similar to equation 1; however, concentrations were not log-transformed because the variation in concentration for a given site was usually small. Also, discharge was not an explanatory variable—decimal time is the only explanatory variable. Next, concentrations were predicted for January 1 of each year. The resultant annual series of concentrations is also referred to as “adjusted annual dissolved-solids concentrations (AADSC)” in this report, and represent the trend in concentration.

The series of AADSC for 1974–88, 1989–2003, and 1974–2003 were used to identify the type of trend and the net change from the beginning of the period to the end of the period. Equations 1 and 7 allow for trends to be absent, linear, or parabolic, and therefore, were classified as (1) absent with no increases or decreases, (2) a steady (monotonic) decrease, (3) an overall decrease containing an increase followed by a larger decrease, (4) an overall decrease, containing a decrease followed by a smaller increase, (5) a steady (monotonic) increase, (6) an overall increase, containing an increase followed by a smaller decrease, (7) an overall increase, containing a decrease followed by a larger increase, or (8) absent with no net change but containing an intervening increase or decrease.

The net change in AADSC was determined by first subtracting the earliest value in the annual time series from the latest value in the annual time series. The range of AADSC among these sites extends over many orders of magnitude and, as a result, comparison of the net change in AADSC amongst sites is not very meaningful. Consequently, the change in AADSC from the first year to the last year of a given period was expressed as a percentage of the first year value. This allowed for a standardized measure of change for comparison of results amongst multiple sites and is referred to as the “period change” in this report. Period changes of one percent or less over the entire period being analyzed were not considered environmentally significant. Therefore, sites with period changes of one percent or less were considered to have no change.

Spatial Distribution of Dissolved Solids

By Nancy J. Bauch

The spatial distribution of dissolved-solids concentrations in basin-fill aquifers and dissolved-solids concentrations, loads, and yields in streams in the Southwest are discussed in this section. Spatial variation of dissolved-solids concentrations in basin-fill aquifers is described by principal aquifer and hydrologic accounting units and also by physiographic province. Spatial variation of dissolved-solids concentrations, loads, and yields in streams are described by major river basin and also by physiographic province. Additional detailed descriptions of dissolved solids in ground and surface water in selected areas of the six NAWQA Study Units in the Southwest are in the section “Effects of Natural and Human Factors on Dissolved-Solids Concentrations.”

Basin-Fill Aquifers

Dissolved-solids concentrations of ground water in the Basin and Range basin-fill aquifers, the Rio Grande aquifer system, and the California Coastal Basin aquifers are affected by the type and solubility of minerals in recharge areas and basin fill, quality of water entering or recharging the aquifer through ground-water flow or surface-water infiltration, evapotranspiration, water use and reuse, and type of hydrogeologic flow system in a basin. For the Rio Grande aquifer system and Basin and Range basin-fill aquifers, three hydrogeologic flow systems have been delineated by Anning and Konieczki (2005): (1) single area; (2) terminally closed, multiple area; and (3) terminally open, multiple area. Single-area systems are isolated and have no interbasin flows. All recharge water stays within the hydrogeologic basin and most or all of it is evaporated, leaving brackish or saline lakes and dry lake beds (playas). In terminally closed, multiple-area systems, hydrogeologic basins are hydraulically connected by interbasin flow until a terminal discharge basin or area of dissolved solids accumulation is reached. Recharge water is removed only by evapotranspiration. In terminally open, multiple-area systems, some water in a hydrogeologic basin is lost by evapotranspiration, and the remaining water flows into the next downgradient system through underflow, ground-water discharge to streams, and surface-water flow. With sufficient flow, dissolved solids are continually removed from the basin. Anning and Konieczki (2005) have delineated flow systems for 344 individual basins in the Basin and Range Physiographic Province. Ground-water flow in the California Coastal Basin aquifers primarily is from recharge areas to withdrawal centers (Planert and Williams, 1995).

Dissolved-solids concentration of ground water in the basin-fill aquifers in the Southwest ranged from less than 500 mg/L near basin margins where ground water is recharged from nearby mountains to more than 10,000 mg/L in topographically low areas of some basins or in areas adjacent to specific streams or rivers in the Basin and Range and Rio Grande aquifer systems (pl. 1). For reference, the USEPA SDWR for dissolved solids is 500 mg/L. In most basin-fill aquifers of the Southwest, dissolved-solids concentrations in ground water primarily are less than or equal to 1,000 mg/L (pl. 1). Concentrations less than 1,000 mg/L are suitable for most uses.

Dissolved-solids concentrations greater than 3,000 mg/L occur in topographically low areas with brackish or saline lakes, playas and terminal basins (pl. 1). The most prominent of these areas are the Great Salt Lake and Desert in Utah; the Mojave Desert with its many playas, Death Valley, and the Salton Sea area in California; the Black Rock Desert and Carson and Humboldt Sinks in Nevada; and the Tularosa Basin in New Mexico. Most of these examples represent a terminally closed, multiple-area system. In these basins, dissolved-solids concentrations in basin-fill aquifers can exceed 35,000 mg/L; some concentrations in the Great Salt Lake and Mojave Deserts and Salton Sea area are greater than 300,000 mg/L (Thompson and Nuter, 1984; Thompson, Nuter, Moyle, and Wollfenden, 1984). Other areas with dissolved-solids concentrations greater than 3,000 mg/L include the San Luis Valley of Colorado, the northern part of the Jornada del Muerto Basin in New Mexico, the Willcox Basin in Arizona, the Searles Valley in California, and the Columbus Salt Marsh and Claytons Valleys in Nevada (pl. 1). The Willcox Basin and the Searles Valley are single, isolated hydrogeologic basins. In the topographically low areas, ground-water loss by evapotranspiration has a substantial effect on the quality of the ground water. With evapotranspiration, some water is removed from the aquifer or soil and the dissolved solids remain behind to become more concentrated in the remaining water. In basins with little or no ground-water discharge as underflow to other basins and streamflow, salts accumulate in the ground water and the water becomes more brackish or saline.

The area of the Salton Sea in southern California receives recharge from the Colorado River that is diverted through the All-American Canal. The quality of the recharge water is largely determined by the salinity of the Colorado River above Imperial Dam (site 09429490 in pl. 1), the location of the diversion to the All-American Canal. For water years 1977–2003, the median daily dissolved-solids concentration at the site above Imperial Dam ranged between 586 and 902 mg/L (appendix 3). According to the Imperial Irrigation District, the Colorado River in the All-American Canal carries about one tons of salt per acre-foot of water applied to cropland (Imperial Irrigation District, 2006). As irrigation water is applied to fields, there is an increase in dissolved-solids concentrations in the seepage water, and eventually the ground water, because of evaporation and the consumption of water by plants. The effect of irrigated agriculture on seepage water and ground water is magnified when irrigation water with higher dissolved-solids concentrations is applied. The Salton Sea primarily is replenished by irrigation runoff and drainage and also by industrial and domestic waste water, runoff, and seepage (Colorado River Board of California, 1992).

Dissolved-solids concentrations greater than 3,000 mg/L also occur in ground water in the Basin and Range basin-fill aquifers and Rio Grande aquifer system near or along drainages of the Virgin and Gila Rivers, and the Jemez River and Rio Puerco, respectively (pl. 1). These examples represent terminally open, multiple-area hydrogeologic flow systems. High dissolved-solids concentrations in ground water in the lower Virgin River Valley northeast of Las Vegas primarily are due to irrigation-return flows from agricultural activities (Clark County Department of Air Quality and Environmental Management, 2000). In the area west of Phoenix along the Gila River, high dissolved-solids concentrations in ground water may result from evapotranspiration, evaporite deposits, long ground-water flow paths, and ground-water contributions from deep percolation of irrigation water. In the area along the lower Gila River upstream from Yuma, the highest dissolved-solids concentrations in ground water are related to irrigated lands adjacent to the river. For the aquifers near or along the Jemez River and Rio Puerco in the Rio Grande Valley, high dissolved-solids concentrations possibly result from recharge by ground-water inflow from Mesozoic and (or) Paleozoic rocks along the western margin of the aquifers. High concentrations in the Rio Puerco aquifer also may be the result of infiltration from the Rio Puerco (Plummer and others, 2004).

In the California Coastal Basin aquifers, the highest dissolved-solids concentrations were found in the Irvine area and the area northwest of the mouth of the Santa Ana River. High concentrations in the Irvine area are due to the movement of recharge water through marine sediments in the Santa Ana Mountains (Singer, 1973) and agricultural activities. Seawater intrusion has affected dissolved-solids concentrations in the area northwest of the Santa Ana River mouth.

Concentration Variation by Principal Aquifer and Hydrologic Accounting Unit

The distribution of dissolved-solids concentrations in basin-fill aquifers varies by principal aquifer and hydrologic accounting unit (pl. 1; table 11). Thirty-five of the hydrologic accounting units contain a basin-fill aquifer. Basin-fill aquifers in the Rio Grande aquifer system occur in 6 hydrologic accounting units and occupy about 43 percent of the area (pl. 1; table 11). Similarly, Basin and Range basin-fill aquifers occur in 26 accounting units and occupy about 55 percent of the area, and California Coastal Basin aquifers occur in 3 accounting units and occupy about 28 percent of the area. Within a hydrologic accounting unit, the percent area occupied by basin-fill aquifers varies from less than 1 percent in the Upper Bear to almost 100 percent in the Rio Grande closed basins (pl. 1; table 11).

In the three principal aquifers, ground water is suitable for most uses. The percent area of basin-fill aquifers with dissolved-solids concentrations less than or equal to 500 mg/L was found to be about 57 percent for the Rio Grande aquifer system, 62 percent for the Basin and Range basin-fill aquifers, and 44 percent for the California Coastal Basin aquifers (pl. 1; table 11). At least 70 percent of the area of the basin-fill aquifers had dissolved-solids concentrations less than or equal to 1,000 mg/L (pl. 1; table 11). The maximum was 87 percent in the California Coastal Basin aquifers. Excluding the Upper Bear accounting unit because of the small area occupied by basin-fill aquifers, the Bill Williams and Verde accounting units had the lowest dissolved-solids concentrations. In these two accounting units, more than 99 percent of the basin-fill areas had dissolved-solids concentrations less than or equal to 1,000 mg/L (pl. 1; table 11). In contrast, only 26 percent of the area of the basin-fill aquifers in the Rio Grande closed basins accounting unit had dissolved-solids concentrations less than or equal to 1,000 mg/L (pl. 1; table 11).

Almost 7 percent of the area of the Basin and Range basin-fill aquifers had dissolved-solids concentrations greater than 10,000 mg/L, the highest percentage of the three principal aquifers (pl. 1; table 11). Much of this percentage is due to areas with high dissolved-solids concentrations in the Great Salt Lake and Salton Sea hydrologic accounting units. Both accounting units lack ground-water or surface-water outflow and, therefore, accumulate dissolved solids. Fifteen additional accounting units throughout the Southwest had part of their basin-fill area with dissolved-solids concentrations greater than 10,000 mg/L (pl. 1; table 11). For most (11 of 15) of these accounting units, the percentage of area with concentrations greater than 10,000 mg/L was less than 1 percent.

Concentration Variation by Physiographic Province

The basin-fill aquifers in the Southwest are in three physiographic provinces: Southern Rocky Mountains, Pacific Border (Los Angeles Ranges section only), and Basin and Range (pl. 1; table 3). The Southern Rocky Mountains and Pacific Border provinces cover only small areas within the boundaries of the basin-fill aquifers. Dissolved-solids concentrations in ground water in the basin-fill aquifers of these two provinces primarily were less than 1,000 mg/L. Except for the terminally closed portion of the San Luis Valley in Colorado, the Southern Rocky Mountains and the Pacific Border represent terminally open, multiple-area hydrogeologic flow systems. The Basin and Range Physiographic Province covers most of the area encompassing basin-fill aquifers, and dissolved-solids concentrations in ground water within this province range from less than 500 mg/L to greater than 10,000 mg/L. Concentrations can exceed 300,000 mg/L in some areas in the Basin and Range province. Many of the basins in this province represent terminally closed, multiple-area hydrogeologic flow systems.

The Basin and Range Physiographic Province is divided into five physiographic sections: Salton Trough, Sacramento, Sonoran Desert, Mexican Highland, and Great Basin (pl. 1; table 3). The Salton Trough and Sacramento sections cover the smallest areas within the boundaries of the basin-fill aquifers and the Great Basin the largest area. In the Salton Trough section, most dissolved-solids concentrations in ground water in the basin-fill aquifers are greater than 3,000 mg/L. Concentrations near the Salton Sea can exceed 300,000 mg/L (Thompson, Nuter, Moyle, and Wollfenden, 1984). Topographically, the Salton Trough section is a closed basin, and much of the section is at or near sea level.

Table 11. Percent area with basin-fill aquifer and with basin-fill aquifer containing dissolved solids in specific concentration ranges for hydrologic accounting units encompassing the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwestern United States.

[mg/L, milligrams per liter; >, greater than; <, less than. Percent values have been rounded, and sum may not equal 100]

Hydrologic accounting unit		Percent area of accounting unit with basin-fill aquifer	Dissolved-solids concentration range (mg/L)				
			0-500	501-1,000	1,001-3000	3,001-10,000	> 10,000
Code	Name		Percent area of basin-fill aquifer				
Rio Grande aquifer system							
130100	Rio Grande headwaters	40	80	16	4	< 1	< 1
130201	Upper Rio Grande	25	100	0	0	0	0
130202	Rio Grande-Elephant Butte	36	56	11	25	7	< 1
130301	Rio Grande-Caballo	67	55	28	17	< 1	0
130302	Mimbres	69	81	15	3	< 1	0
130500	Rio Grande closed basins	100	15	11	37	32	5
Area encompassing all 6 accounting units		43	57	14	19	9	1
Basin and Range basin-fill aquifers							
150301	Lower Colorado	63	62	25	12	< 1	0
150302	Bill Williams	31	93	7	< 1	0	0
150400	Upper Gila	46	84	13	2	< 1	0
150501	Middle Gila	64	61	19	20	< 1	0
150502	San Pedro-Willcox	67	90	7	2	< 1	1
150503	Santa Cruz	72	89	9	1	< 1	< 1
150601	Salt	17	63	23	15	< 1	0
150602	Verde	23	86	13	< 1	< 1	0
150701	Lower Gila-Agua Fria	57	70	19	9	2	< 1
150702	Lower Gila	70	77	12	7	5	< 1
160101	Upper Bear	< 1	99	1	0	0	0
160102	Lower Bear	45	66	16	12	4	1
160201	Weber	15	48	37	10	5	< 1
160202	Jordan	38	45	29	21	5	< 1
160203	Great Salt Lake	75	35	12	13	13	27
160300	Escalante Desert-Sevier Lake	43	37	40	20	1	0
160501	Truckee	43	56	20	18	6	< 1
160502	Carson	59	34	13	24	29	0
160503	Walker	42	52	35	12	< 1	0
160401	Humboldt	53	79	16	5	1	0
160402	Black Rock Desert	46	54	25	16	5	0
160600	Central Nevada Desert Basins	57	78	15	5	< 1	< 1
180901	Mono-Owens Lakes	40	85	5	8	2	0
180902	Northern Mojave	56	62	21	13	3	< 1
181001	Southern Mojave	63	69	17	8	3	2
181002	Salton Sea	67	29	15	24	18	14
Area encompassing all 26 accounting units		55	62	17	10	4	7

Table 11. Percent area with basin-fill aquifer and with basin-fill aquifer containing dissolved solids in specific concentration ranges for hydrologic accounting units encompassing the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwestern United States—Continued.

Hydrologic accounting unit		Percent area of accounting unit with basin-fill aquifer	Dissolved-solids concentration range (mg/L)				
			0-500	501-1,000	1,001-3000	3,001-10,000	> 10,000
Code	Name		Percent area of basin-fill aquifer				
California Coastal Basin aquifers							
180701	Ventura-San Gabriel Coastal	38	40	49	11	0	0
180702	Santa Ana	44	50	36	7	7	0
180703	Laguna-San Diego Coastal	17	41	38	18	2	< 1
Area encompassing all 3 accounting units		28	44	43	10	3	< 1

Evaporation is the only outlet for ground and surface water in the section. In the Sacramento section, the basin-fill aquifers primarily have dissolved-solids concentrations greater than 500 mg/L. Concentrations greater than 10,000 mg/L can be found in playas in the Estancia Basin southeast of Albuquerque. Dissolved-solids concentrations in ground water in basin-fill aquifers in the Sonoran Desert section generally are less than 3,000 mg/L. Concentrations greater than 3,000 mg/L in the Sonoran Desert section primarily are in basin-fill aquifers in the Mojave Desert and along or near the Gila River. Concentrations can exceed 300,000 mg/L in areas of the terminally closed Mojave Desert (Thompson, Nuter, Moyle, and Wollfenden, 1984). In the Mexican Highlands section, dissolved-solids concentrations in ground water primarily were found to be less than 1,000 mg/L, excluding portions of the Rio Grande Valley and adjacent closed valleys. These concentrations typically were lower than those in the Sonoran Desert section, most likely because of greater precipitation and lower evaporation rates in the higher altitude Mexican Highlands section (pl. 1). In the Great Basin section, dissolved-solids concentrations in ground water in basin-fill aquifers range from less than 500 mg/L to greater than 10,000 mg/L. In this section, dissolved-solids concentrations in ground water in the basin-fill aquifers of the terminally closed Great Salt Lake and Desert, Death Valley, Black Rock Desert, and Carson and Humboldt Sinks can exceed 35,000 mg/L. Concentrations can exceed 300,000 mg/L in the Great Salt Lake Desert (Thompson and Nuter, 1984).

Streams

Throughout the Southwest, the principal natural factors that affect the chemical composition and dissolved-solids concentration in streams include geology and residual materials (soils and alluvium) in a watershed, precipitation, runoff and erosion, evapotranspiration, ground-water discharge, and mineral springs. Typically, sedimentary rocks are more soluble than igneous and metamorphic rocks, and streams underlain by sedimentary rocks have higher dissolved-solids concentrations. Soils derived from sedimentary rocks contribute significantly to dissolved-solids loads when irrigated (Enburg, 1999; Enburg and Sylvester, 1993). Precipitation can be a source of dissolved solids from the atmosphere, but more importantly, it directly affects runoff, streamflow amounts, and dilution of dissolved solids in streams. Sediment yields that are associated with surface runoff and soil erosion have corresponding salt yields. When annual precipitation increases from zero to about 12 in., sediment yields increase as more runoff is available to transport sediment (Langbein and Schumm, 1958). Annual precipitation rates greater than 12 in. promote vegetation growth and reduce sediment yields. Evapotranspiration concentrates dissolved solids in streams and reservoirs. In some desert areas, potential evaporation rates can be as much as 140 in/yr (Robson and Banta, 1995). Ground-water discharge and springs and seeps in many areas of the Southwest add dissolved solids to surface water and can affect downstream water quality. Pah Tempe Springs in the Lower Colorado-Lake Mead subregion along the Virgin River, for example, have a dissolved-solids concentration of 9,650 mg/L (Blinn and Poff, 2005).

Streamflow characteristics and land-use practices vary throughout the Southwest and affect dissolved-solids concentrations in water at a site. Streamflow at a site can be free flowing and unregulated, regulated (dependent in part or whole on upstream reservoir releases), or effluent dependent. Most or all water in effluent-dependent streams comes from municipal wastewater-treatment plants, irrigation-return flows, or both. The duration of streamflow at sites can be perennial, intermittent, or ephemeral. The volume of streamflow depends on water diversions (either removal or delivery), reservoir and effluent releases, and water management. In many areas of the Southwest, hydrologic systems have undergone extensive anthropogenic modification, including dams and reservoirs and diversion systems. In this study, no attempt has been made to analyze dissolved solids based on stream regulation and stream permanence. Finally, watersheds for sites included in this analysis are minimally developed or have agricultural, urban, or a mixture of land uses.

Data for the characterization of the spatial distribution of dissolved solids in the surface waters of the Southwest include 71,809 water-quality samples collected between 1974 and 2003 at 420 sites in the 12 major river basins in the region and in 8 physiographic provinces (pl. 1; table 12; appendix 1). Not all sites have the same period of record for surface water dissolved-solids data. One site, for example, may have data for 1974–89, and another site may have dissolved-solids data for 1974–2003. Computation of dissolved-solids statistics is based on all available data for a site within the overall time period of 1974–2003, recognizing that for some sites data also may only be available for certain times of the year because of intermittent or ephemeral streamflow.

Variation of Concentration, Load, and Yield by Major River Basin

Dissolved-solids data are available for a large part of the Southwest, but large spatial gaps in the distribution of data are present in some of the major river basins. Data were sparse for rivers and streams in desert areas and closed drainages due to the small number of surface-water-quality monitoring sites (pl. 1; table 12). In contrast, the headwater areas of the main-stem Colorado River, Gunnison River, White River, Yampa River, and lower Green River have an extensive spatial distribution of dissolved-solids data due to a large number of monitoring sites. Data discussed in this section include median daily dissolved-solids concentration and load, median annual dissolved-solids load and yield, and median daily and annual streamflow discharge at 420 surface-water-quality monitoring sites in the Southwest (pl. 1; appendices 3 and 4). Median daily concentrations can be used as a measure of the suitability of water at a site for a particular beneficial use, such as water supply or habitat conditions for aquatic life. Median annual loads measure the amount of dissolved solids being transported past a site and are the basis for comparing sources and fates of dissolved solids. Median annual yields are used to compare the amount of dissolved solids produced in one watershed to amounts produced in other watersheds. Detailed descriptions of dissolved solids in selected areas of the six NAWQA Study Units in the Southwest are presented in the section “Conceptual Model for Effects of Natural and Human Factors on Dissolved-Solids Concentrations.”

Median daily dissolved-solids concentrations vary greatly among the 420 sites in the Southwest, ranging between 22 and 13,800 mg/L, and also vary between different sites on the same stream (pl. 1; appendix 3). Median daily dissolved-solids concentrations less than 100 mg/L predominately are found at sites in the headwaters of the Colorado, Green, San Juan, Truckee, Carson, and Rio Grande Rivers (pl. 1). These areas are underlain by igneous and metamorphic rocks that are relatively resistant to the solvent action of water, and there is little irrigated agriculture. Streamflow is perennial with higher flows during snowmelt runoff in the spring. Streams with the lowest (less than 60 mg/L) median daily dissolved-solids concentrations are found near the Continental Divide and in the higher parts of the San Juan, Uinta, and Sierra Nevada Mountains.

Median daily dissolved-solids concentrations greater than 500 mg/L are predominately found in streams in contact with more soluble sedimentary rocks and streams affected by particular natural and anthropogenic factors. For example, in the Colorado River Basins upstream from Lees Ferry, Ariz., dissolved-solids concentrations are elevated in watersheds draining mostly Mesozoic age sedimentary rocks, in particular the marine Mancos Shale, the Mesa Verde Group, and formations related to each (fig. 6). Many broad valleys underlain with Mancos Shale have been developed and contain extensive agricultural areas. Irrigation-return flows (deep percolation, tailwater, and runoff) from these areas add substantial amounts of dissolved solids to streams and rivers. The greatest median daily concentration among all sites of 13,800 mg/L was found in Bitter Creek at the mouth, near Bonanza, Utah (site 09306850, appendix 3). This site, in the White-Yampa subregion of the Green River Basin, is an intermittent stream and is in an area of high salinity rocks and low precipitation.

In the Gila River subregions in Arizona, median daily dissolved-solids concentrations greater than 500 mg/L reflect both natural and anthropogenic influences. Concentrations in some streams in the upper Gila River subregion are affected by discharge from saline springs (Feth and Hem, 1963). Use of effluent from municipal wastewater-treatment plants, importation of surface water having greater salinity, irrigation-return flows, ground-water inflow, and evapotranspiration contribute to the elevated dissolved-solids concentrations in the middle and lower Gila River subregions.

Municipal and industrial effluent and importation of surface water having greater salinity also affect dissolved-solids concentrations in the southern California Coastal subregion, along with engineered recharge, urban runoff, agricultural activities, ground-water inflows, and evaporite deposits. In the lower Colorado-Lake Mead subregion, dissolved-solids concentrations greater than 500 mg/L are due to discharge from natural saline springs, irrigation-return flows, and evapotranspiration. Concentrations in the Las Vegas area also are affected by municipal and industrial effluent and inflow of ground water from Basin and Range carbonate aquifers (U.S. Department of the Interior, 2003). In the Upper, Middle, and lower Colorado River Basins, salinity-control projects have been enacted in many areas with elevated dissolved-solids concentrations, especially in areas upstream from Lees Ferry, Ariz. (table 7; U.S. Department of the Interior, 2003).

Table 12. Number of surface-water-quality monitoring sites in major river basins and hydrologic subregions in the Southwestern United States.

Major river basin	Number of surface-water-quality monitoring sites by major river basin	Hydrologic subregion		
		Code	Name	Number of surface-water-quality monitoring sites by subregion
Upper Rio Grande Basin	27	1301	Rio Grande headwaters	2
		1302	Rio Grande-Elephant Butte	22
		1303	Rio Grande-Mimbres	2
		1305	Rio Grande closed basins	1
Upper Colorado River Basin	119	1401	Colorado headwaters	82
		1402	Gunnison	26
		1403	Upper Colorado-Dolores	11
Green River Basin	95	1404	Great Divide-Upper Green	12
		1405	White-Yampa	40
		1406	Lower Green	43
San Juan River Basin	27	1408	San Juan	27
Little Colorado River Basin	3	1502	Little Colorado	3
Middle Colorado River Basin	18	1407	Upper Colorado-Dirty Devil	9
		1501	Lower Colorado-Lake Mead	9
Gila River Basin	22	1504	Upper Gila	6
		1505	Middle Gila	2
		1506	Salt	11
		1507	Lower Gila	3
Lower Colorado River Basin	7	1503	Lower Colorado	7
Great Salt Lake and Sevier River Basin	62	1601	Bear	23
		1602	Great Salt Lake	25
		1603	Escalante Desert-Sevier Lake	14
Central Lahontan Basins	21	1605	Central Lahontan	21
Central Nevada and Eastern California Desert Basins	14	1604	Black Rock Desert-Humboldt	5
		1606	Central Nevada Desert Basins	3
		1809	Northern Mojave-Mono Lake	3
		1810	Southern Mojave-Salton Sea	3
Southern California Coastal Basins	5	1807	Southern California Coastal	5

Dissolved-solids load data at different locations along a stream can be important for identifying the sources and fate of the dissolved solids in the stream. Transport of dissolved solids in streams within and out of a basin largely depends on the amount of streamflow, including the amount of precipitation that runs off as streamflow, water diversions, and reservoir impoundments. Typically, streams with the highest flows have the highest dissolved-solids loads. In hydrologic systems unaffected by anthropogenic factors, dissolved-solids loads increase in a downstream direction. In streams affected by dams and diversions there may be a decrease in loads from an upstream site to the next downstream site. For many lower elevation sites in the Southwest, streamflow is ephemeral and much of the dissolved-solids load may be the result of a few localized intense summer thunderstorms.

Annual dissolved-solids loads were estimated for each of the 420 sites; median annual dissolved-solids loads for each site are shown in pl. 1 and appendix 4. Median annual dissolved-solids loads ranged from 60 ton/yr at Elk Creek near Fraser, CO (site 09025400, appendix 4) in the Colorado headwaters hydrologic subregion to more than 7.86 million ton/yr at Colorado River below Hoover Dam, AZ-NV (site 09421500, appendix 4), the downstream site of the Lower Colorado-Lake Mead subregion. Most subregions (22 of 28) of the major river basins had one or more sites with median annual loads greater than or equal to 100,000 ton/yr (pl. 1). Sites with these large dissolved-solids loads were on the main stem of the major rivers—Rio Grande, Colorado, Gunnison, Green, White, Yampa, San Juan, Gila, Bear, Weber, Jordan, Salt, Verde, Sevier, Owens, and Santa Ana. Median annual loads greater than or equal to 100,000 ton/yr also were found at downstream sites of primary tributaries to the major rivers, and at a few smaller tributaries that were in areas with soluble sedimentary rocks. Median annual streamflow for all sites with median annual loads greater than or equal to 100,000 ton/yr was 698 ft^3/s. Most of these sites (78 of 101) had median annual streamflow greater than 287 ft^3/s, the 75th percentile for median annual streamflow.

Most subregions (18 of 28) had sites with median annual dissolved-solids loads that were less than 3,000 ton/yr (a value slightly less than the 25th percentile load of 3,069 ton/yr; pl. 1). Sites with loads less than 3,000 mg/L typically were in headwater areas and (or) desert or drier areas of the major river basins, and had relatively small median annual streamflow. Median annual streamflow for these sites was 10 ft^3/s, and most sites (76 percent) had median annual streamflow less than 21 ft^3/s, the 25th percentile value of median annual streamflow. A few sites in areas of the White-Yampa subregion with soluble sedimentary rocks had some of the greatest median daily dissolved-solids concentrations, but loads were low because of small streamflows. For Foidel Creek near Oak Creek, CO (site 09243800), for example, the median daily dissolved-solids concentration was saline at 2,080 mg/L, but the median annual load was low at 2,530 ton/yr. Median annual streamflow at this site was 1,130 acre-ft/yr (appendices 3 and 4).

For the Colorado River Basin upstream from Lees Ferry, Ariz., and the Great Salt Lake Basin, median annual dissolved-solids loads at the furthest downstream sites on the major tributaries were used to estimate the load contribution from the tributaries. Load contributions for other major river basins were not tabulated. In the Colorado River Basin upstream from Lees Ferry, Ariz., the largest median annual dissolved-solids loads contribution was from the Upper Colorado River Basin upstream from the Colorado River at CO-UT State Line (site 09163500), followed by the Green River Basin upstream from the Green River at Green River, UT (site 09315000), and the San Juan River Basin (table 13). The largest contributor of dissolved-solids loads to the Great Salt Lake was the Bear River Basin, followed by the Jordan River Basin (table 13). Load data for the site Jordan River at 1700 South at Salt Lake City, UT (site 10171000, table 13) represents only a portion of the load contributed from the basin because of nearby upstream diversions. The Jordan River Basin contributes closer to 500,000 tons of dissolved solids per year to the Great Salt Lake (Steve Gerner, hydrologic technician, U.S. Geological Survey, personal commun., 2005). Sulphur Creek (site 101261180, table 13), another major load contributor to Great Salt Lake, drains a very small area (15.5 mi^2) but had a high median-daily dissolved-solids concentration (1,825 mg/L; appendix 3). Dissolved solids in Sulphur Creek likely originate from irrigation-return flows and small springs (Utah Department of Environmental Quality, 2000).

In most major river basins in the western half of the study area (Great Salt Lake and Sevier River, Central Lahontan, and Central Nevada and Eastern California Desert Basins), rivers and streams terminate in areas or lakes that are sinks where dissolved solids accumulate (pl. 1). Prominent sinks include the Great Salt Lake, the Salton Sea, Carson Sink (terminus of the Carson River), Sevier Lake (terminus of the Sevier River), and the Humboldt Sink. Prior to European settlement, the Humboldt River terminated in the Humboldt Sink. Except in climatologically wet years with high flows, the Humboldt River currently does not reach the sink because of water diversions (Shiozawa and Rader, 2005).

Table 13. Median annual dissolved-solids loads in selected tributaries to the Colorado River basin upstream from Lees Ferry, Arizona, and in selected tributaries to Great Salt Lake.

[USGS, U.S. Geological Survey. Gunnison River near Grand Junction, CO, is a tributary to the Colorado River near Colorado-Utah State Line; Green River near Jensen, UT, Ashley Creek near Jensen, UT, White River at mouth, near Ouray, UT, Duschesne River near Randlett, UT, Pariette Draw at mouth, near Ouray, UT, and Willow Creek near Ouray, UT, are tributaries to the Green River at Green River, UT]

USGS site identifier	Site name	Median annual dissolved-solids load, ton per year
	Tributaries to the Colorado River basin upstream from Lees Ferry, Arizona	
09163500	Colorado River near Colorado-Utah State Line	3,170,000
09152500	Gunnison River near Grand Junction, CO	1,170,000
09180000	Dolores River near Cisco, UT	383,000
09315000	Green River at Green River, UT	2,370,000
09261000	Green River near Jensen, UT	1,410,000
09271500	Ashley Creek near Jensen, UT	44,900
09306900	White River at mouth, near Ouray, UT	321,000
09302000	Duchesne River near Randlett, UT	235,000
09307300	Pariette Draw at mouth, near Ouray, UT	50,100
09308000	Willow Creek near Ouray, UT	20,500
09328500	San Rafael River near Green River, UT	130,000
09333500	Dirty Devil River above Poison Spring Wash, near Hanksville, UT	119,000
09379500	San Juan River near Bluff, UT	742,000
	Tributaries to the Great Salt Lake	
10126180	Sulphur Creek near Corinne, UT	116,000
10126000	Bear River near Corinne, UT	900,000
10141000	Weber River near Plain City, UT	139,000
10171000	Jordan River at 1700 South at Salt Lake City, UT[1]	127,000

[1]Load data represents only a portion of the load contributed from the Jordan River basin because this site is downstream from the Surplus Canal diversion. The Jordan River basin contributes closer to 500,000 tons of dissolved solids per year to the Great Salt Lake.

The change in concentrations and loads of dissolved solids in a downstream direction along a stream can be seen by examining median daily concentrations and median annual loads and streamflow for the nine major rivers (Rio Grande, Colorado, Yampa, White, Green, San Juan, Gila, Bear, and Sevier) with six or more sites on the main stem of each river (figs. 17–25). Some major rivers, including the Gunnison, Humboldt, and Santa Ana, had less than six main-stem sites and are not illustrated. Median daily concentrations generally increased in a downstream direction for sites on the nine major rivers. Median annual loads generally increased in the downstream direction, except where streamflow decreased substantially due to diversions and (or) streambed infiltration, typically in the downstream part of the river system. The Bear River and Colorado River downstream from the Colorado-Utah State line are used to illustrate in further detail changes in concentrations and loads and discharge that can occur in rivers in the Southwest and primary factors that affect dissolved solids and discharge. Additional discussion of changes in discharge and concentrations and loads of dissolved solids in the Rio Grande; Colorado River upstream from the Colorado-Utah State line; Gila, Carson, Jordan, and Santa Ana Rivers; Las Vegas Wash; and tributaries are found in the section “Effects of Natural and Human Factors on Dissolved-Solids Concentrations.”

The Bear River, in northeastern Utah, southeastern Idaho, and southwestern Wyoming, flows about 500 mi from its headwaters in the Uinta Mountains to its outflow to the Great Salt Lake. Throughout the length of the river, streamflow and dissolved solids are affected by tributary inflows, agricultural return flows, irrigation diversions, and storage reservoirs (fig. 24). Between the initial main-stem site Bear River near Utah-Wyoming state line (site 10011500) and Bear River above reservoir near Woodruff, UT (site 10020100), the median daily dissolved-solids concentration almost doubled, from 135 to 268 mg/L (fig. 24; appendix 3), because of agricultural return flows. There was only a slight increase in streamflow, from 65 to 84 ft^3/s (appendix 3), with small tributaries flowing into the river and diversions removing water. The storage of water in Woodruff Narrows Reservoir reduced the median daily discharge by about one-half between sites above and below the reservoir, from 84 to 40 ft^3/s (appendix 3). Downstream from the reservoir, the tributary Saleratus Creek has been assessed as not meeting all beneficial uses, in part because of dissolved solids from natural and agricultural sources (Utah Department of Environmental Quality, 2000). Between the sites Bear River near Randolph, UT (site 10026500) and Bear River below Smiths Fork, near Cokeville, WY (site 10038000), dissolved solids and streamflow are affected by the inflow of lower dissolved-solids concentration water from Smiths Fork, diversion of water through Pixley Dam and other structures, and agricultural return flows. A median annual discharge of 142,000 acre-ft/yr from the Smiths Fork tributary to the Bear River almost doubles the discharge of the Bear River below the tributary (appendix 4). Between the sites Bear River at Border, WY (site 10039500) and Bear River at Pescadero, ID (site 10068500), most of the streamflow in the Bear River is diverted to and released from Bear Lake, a natural lake. The primary use of Bear Lake is storage of water for irrigation use and power generation. Inflow of tributaries into Bear River and Bear Lake substantially increased discharge at Bear River at Pescadero, ID (site210068500). Median daily dissolved-solids concentrations changed little between Border, Wyo., and Pescadero, Idaho, ranging between 344 and 346 mg/L, respectively (appendix 3). Downstream from Pescadero, Idaho, to the site Bear River at the Idaho-Utah state line (site 10092700), dissolved-solids concentration and streamflow are affected by tributaries such as Soda, Cottonwood, and Weston Creeks, agricultural return flows, diversions, and reservoir storage. Prior to the Bear River site at the Idaho-Utah State Line, median daily dissolved-solids concentrations at upstream sites on the Bear River had been less than 500 mg/L, the USEPA SDWR for dissolved solids (appendix 3). The median daily concentration at the State Line site was 519 mg/L (appendix 3). Downstream from this site, the median concentration decreased to 438 mg/L at Bear River near Collinston, UT (site 10118000, appendix 3). Major tributaries that drain into the Bear River between the State Line and Collinston include the Cub, Little Bear, and Logan Rivers and Blacksmith Fork. Median daily dissolved-solids concentrations in these tributaries ranged between 157 and 261 mg/L (appendix 3), diluting the concentration in the Bear River near Collinston. The highest median daily dissolved-solids concentration on the Bear River of 715 mg/L was found at the most downstream site, Bear River near Corrine, UT (site 10126000; appendix 3). The major tributary to the Bear River downstream from Collinston, Utah, is the Malad River. This tributary, with a median daily dissolved-solids concentration of 2,500 mg/L near Plymouth, UT (site 10125600, appendix 3), delivers high dissolved-solids concentration water to the Bear River from thermal springs and agricultural return flows. Along the entire length of the Bear River, the only decrease in median annual discharge occurred between the Collinston and Corinne sites, from 1.06 million acre-ft/yr to 0.96 million acre-ft/yr, respectively (appendix 3). In this reach of the river, about 191,000 acre-ft of water per year are diverted to the West Side Canal for irrigation use (Utah State University, 2006).

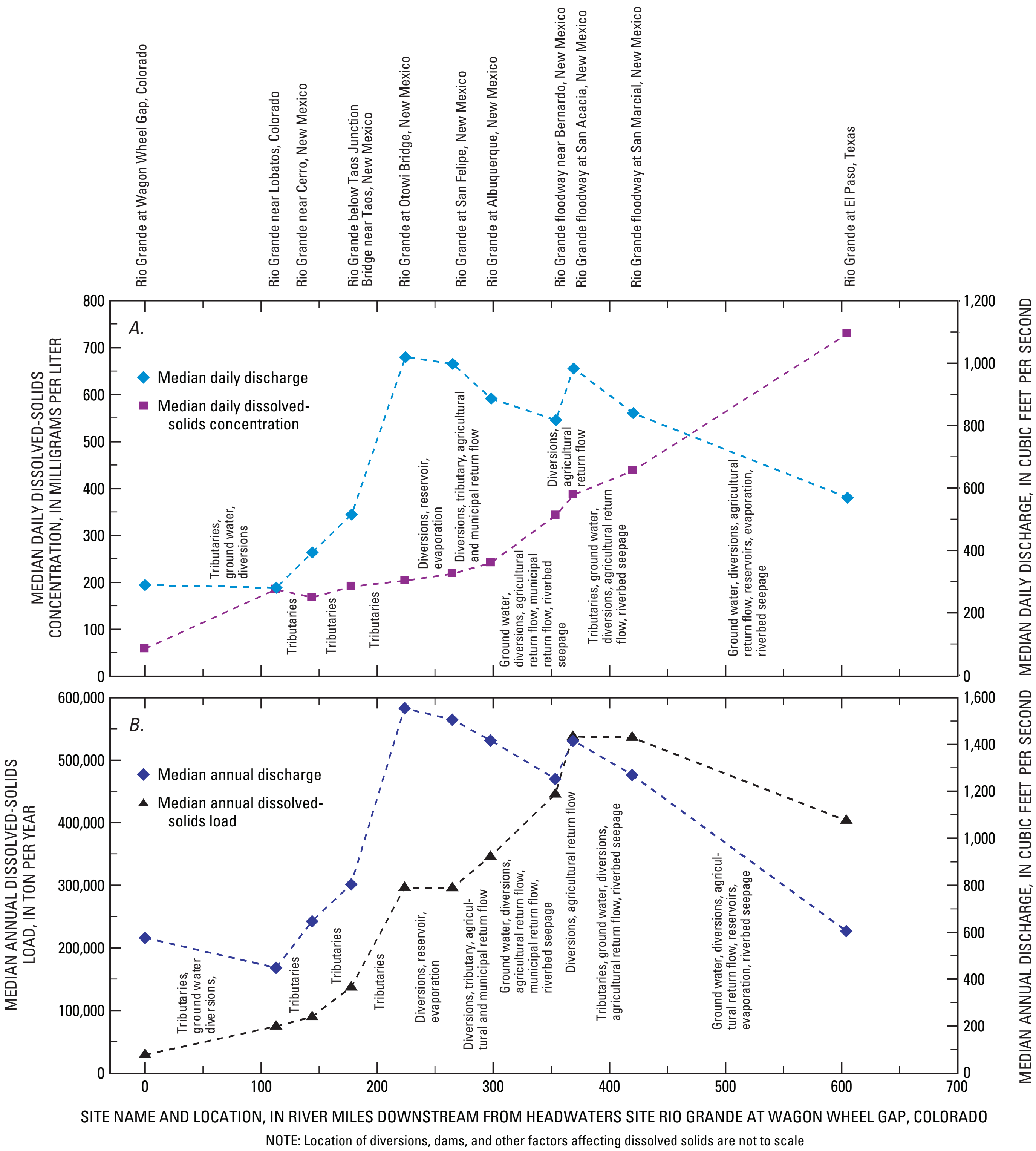


Figure 17. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Rio Grande.

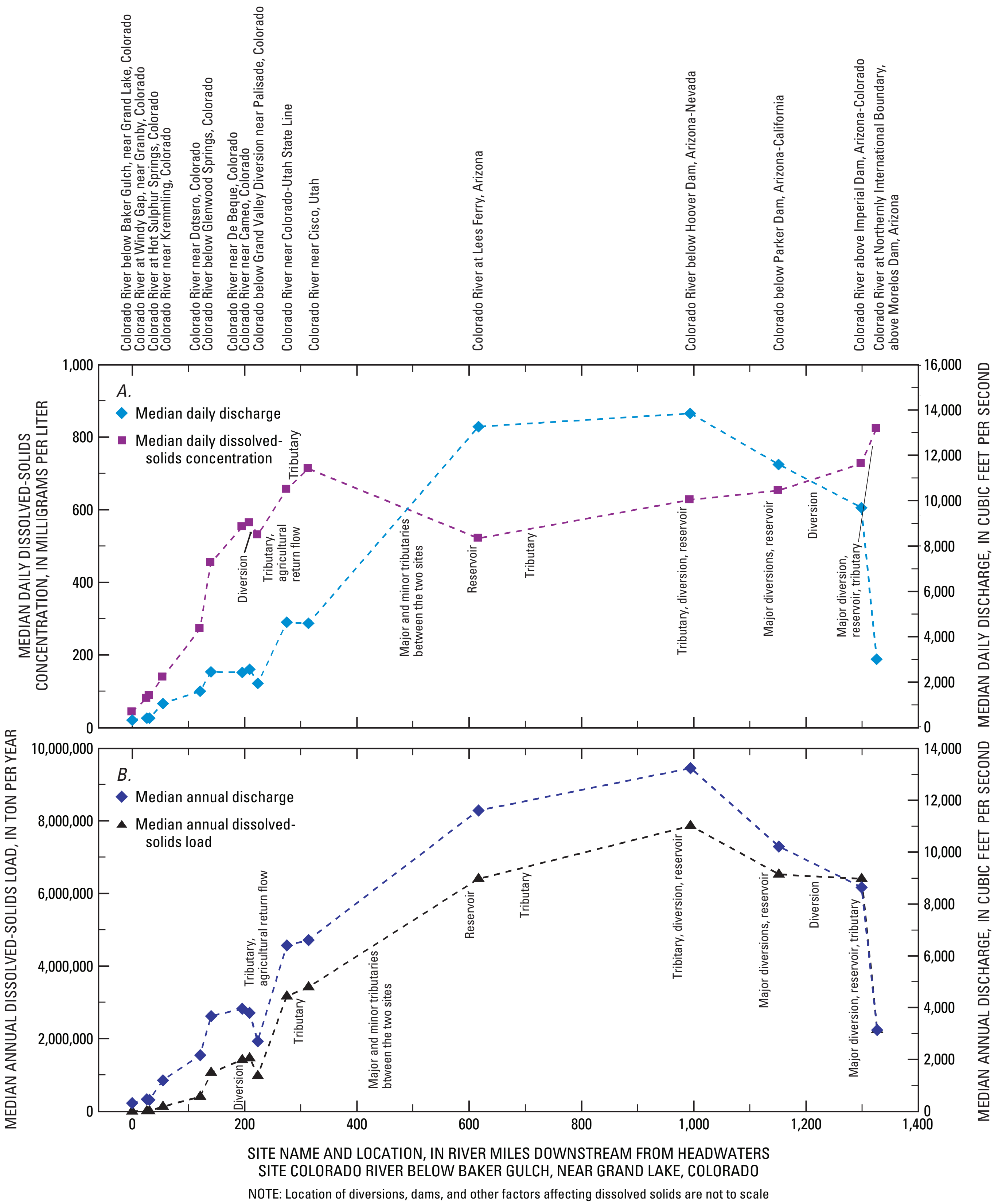


Figure 18. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Colorado River.

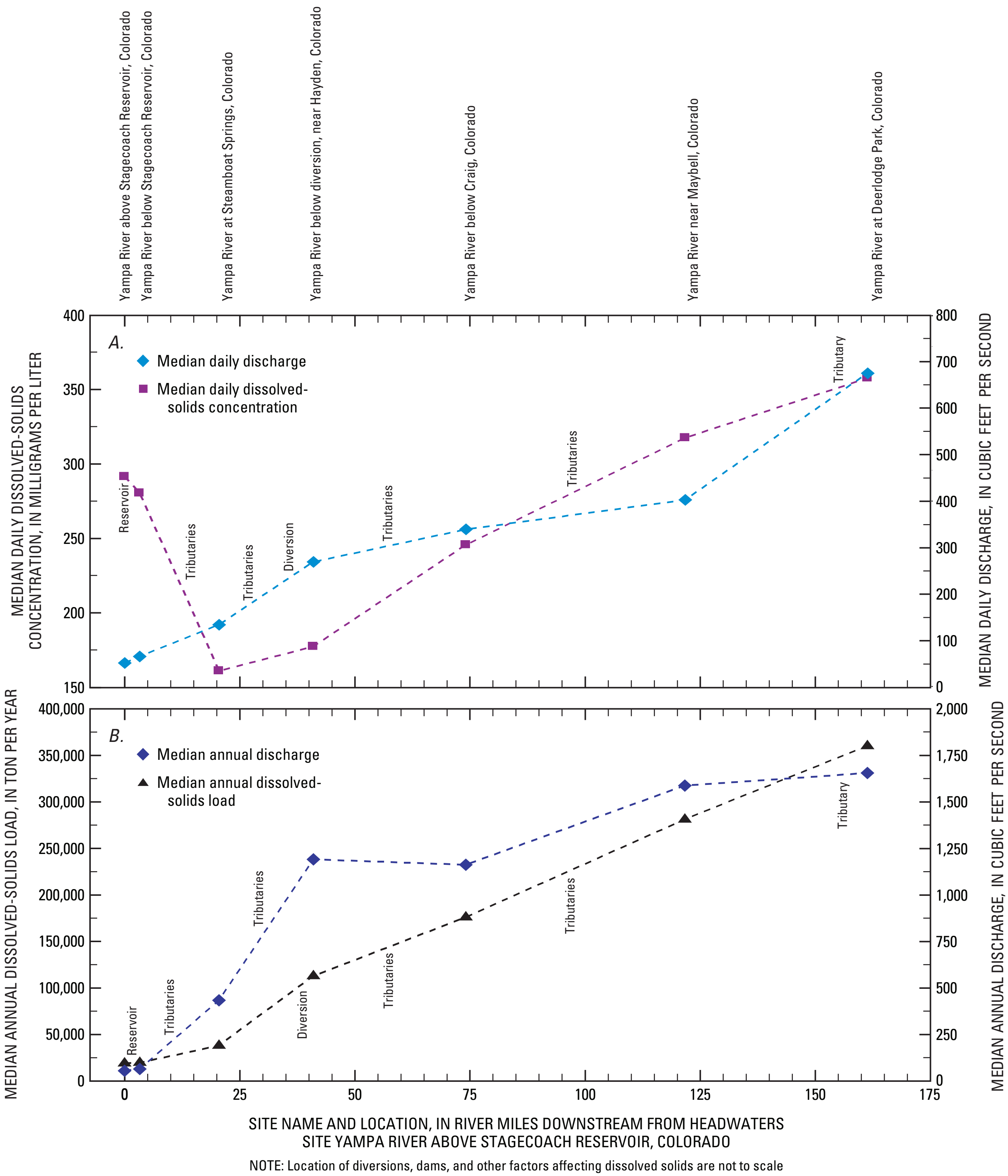


Figure 19. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Yampa River.

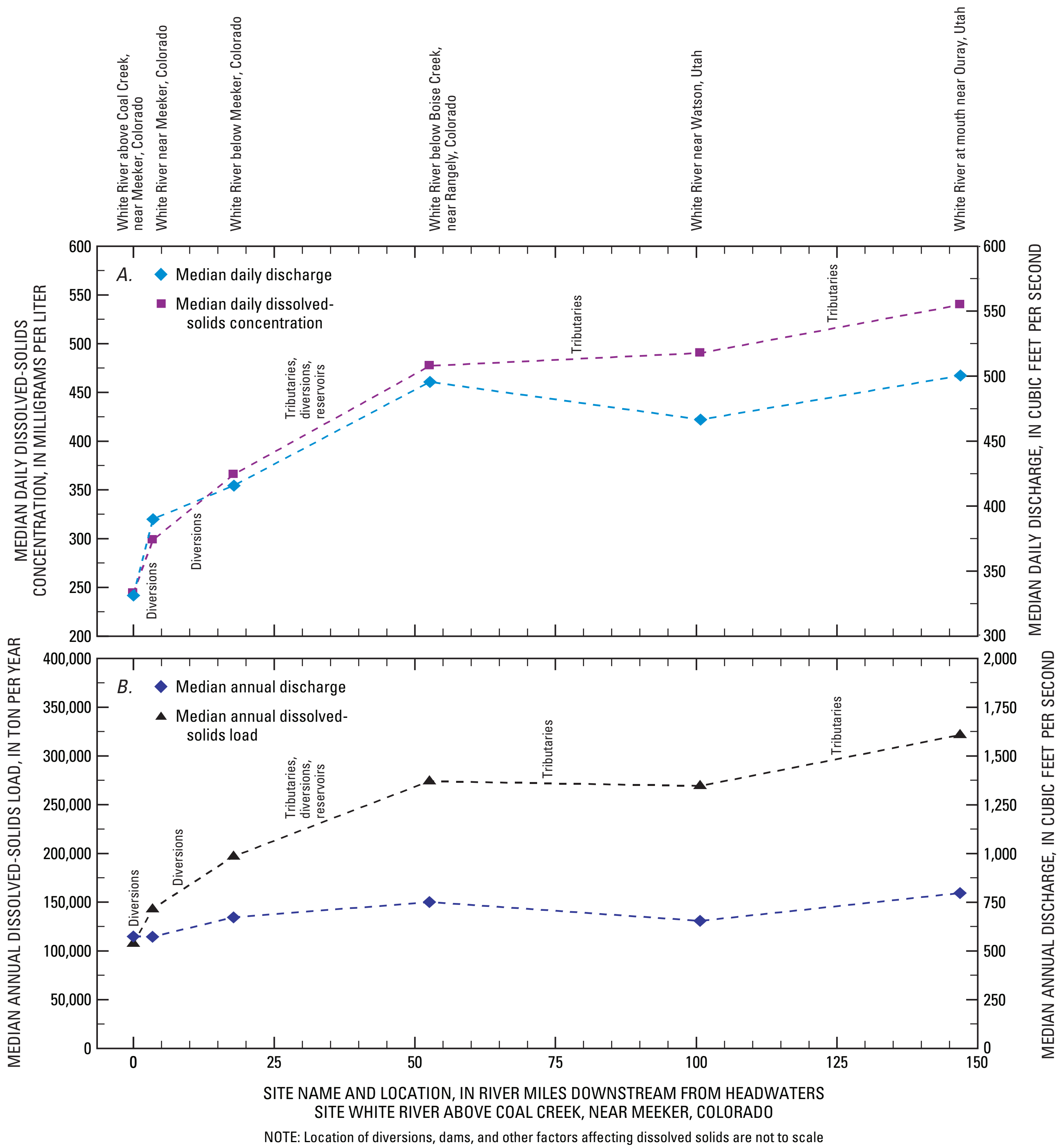


Figure 20. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the White River.

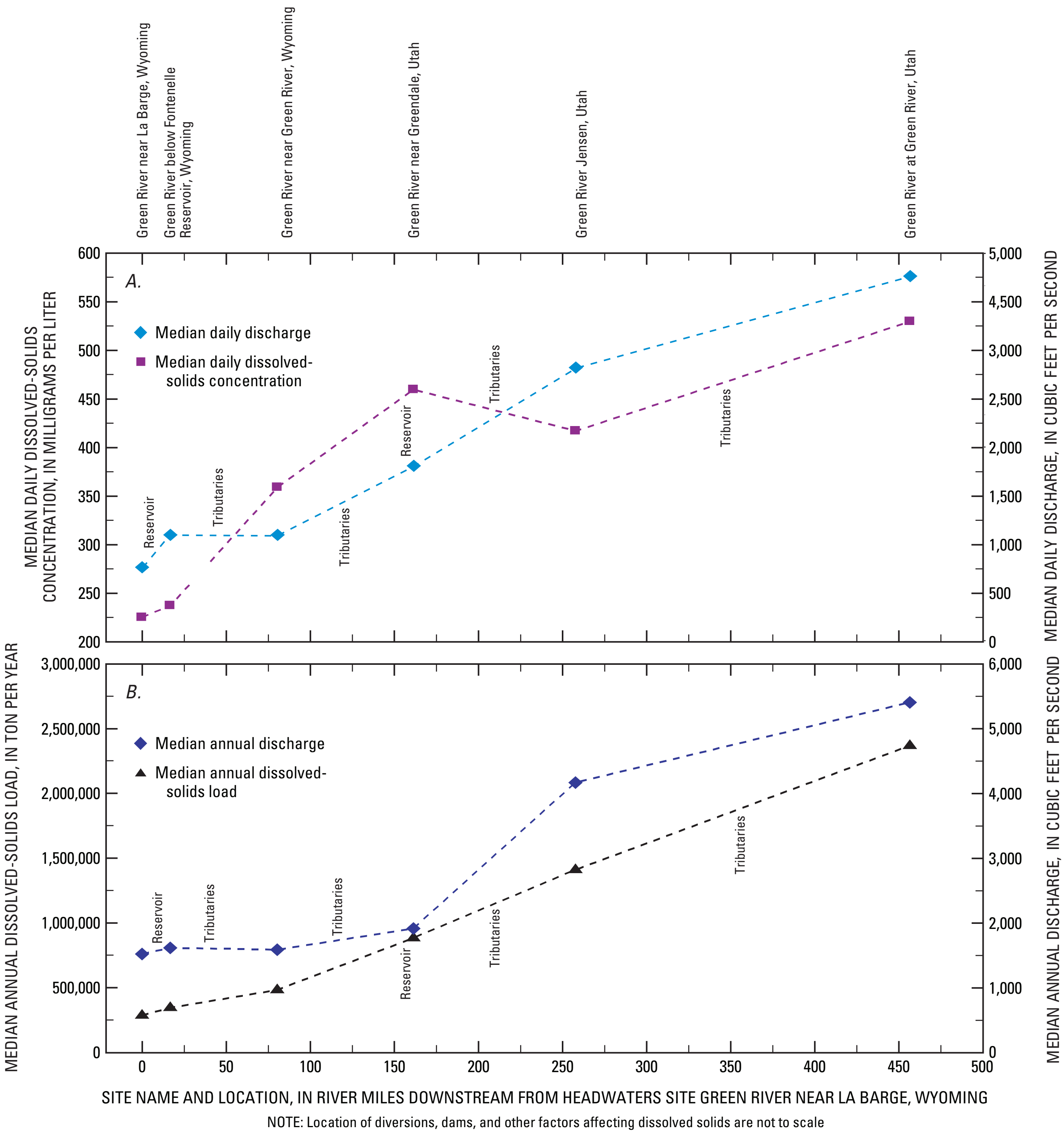


Figure 21. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Green River.

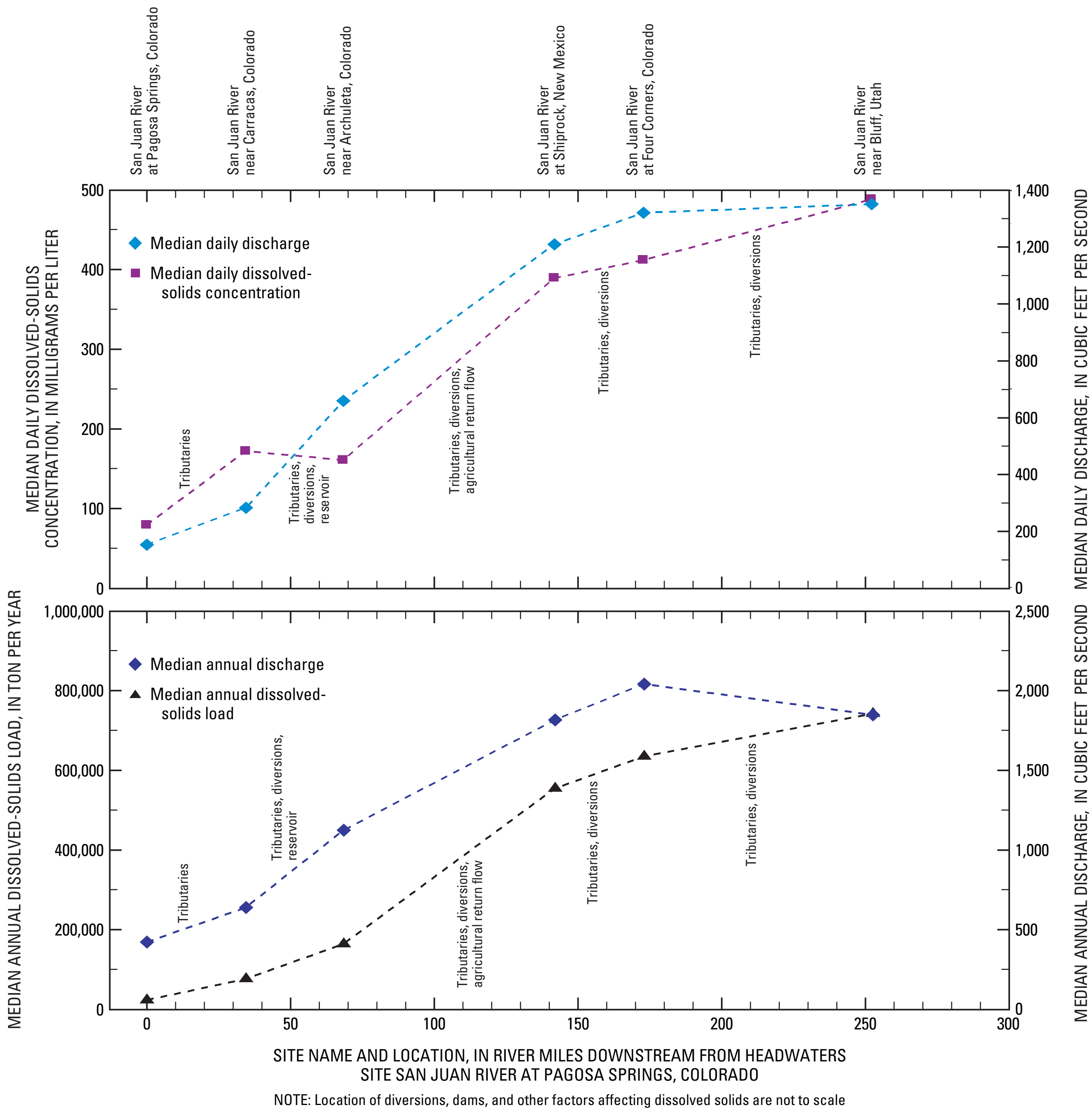


Figure 22. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the San Juan River.

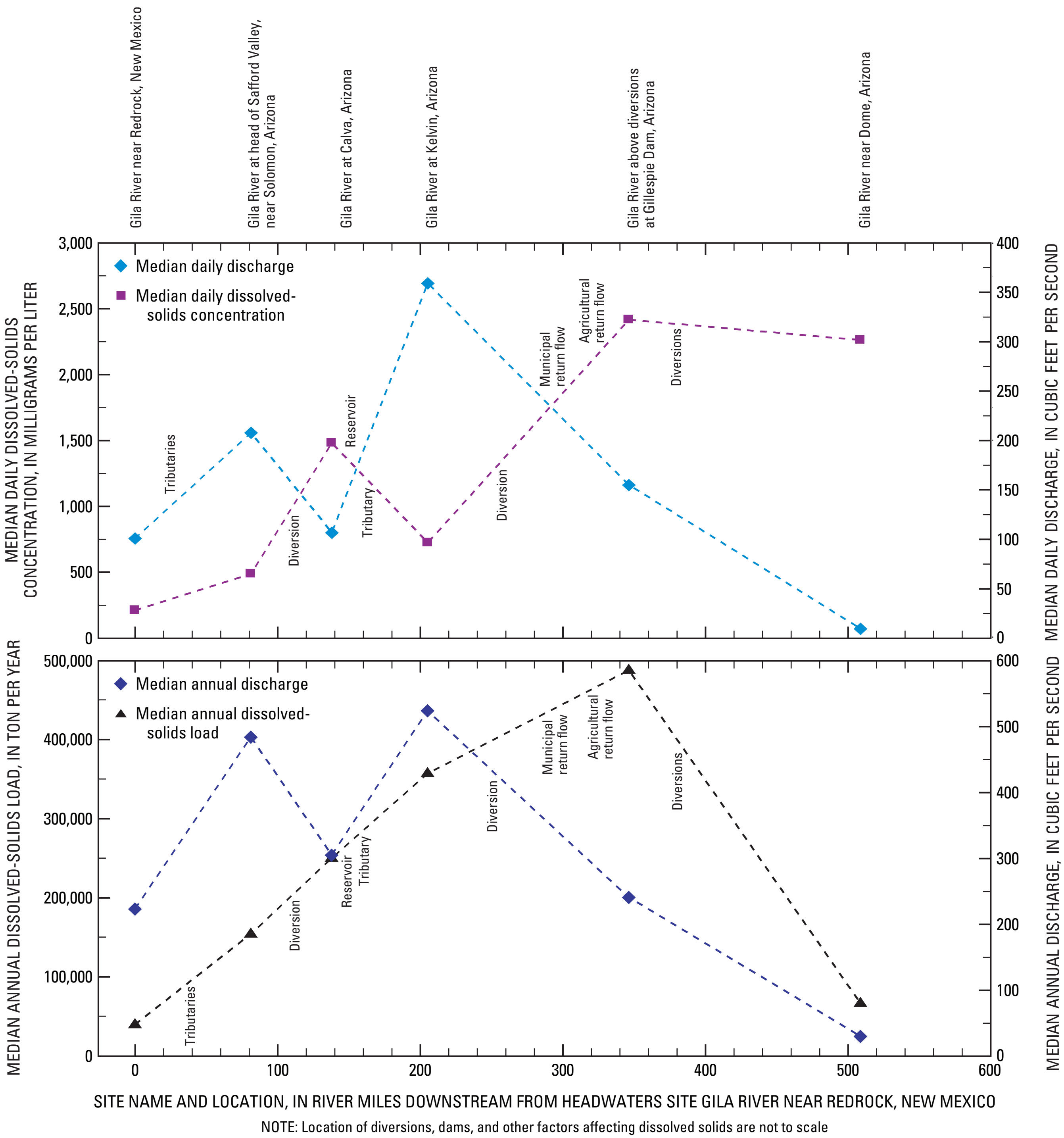


Figure 23. Graph showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Gila River.

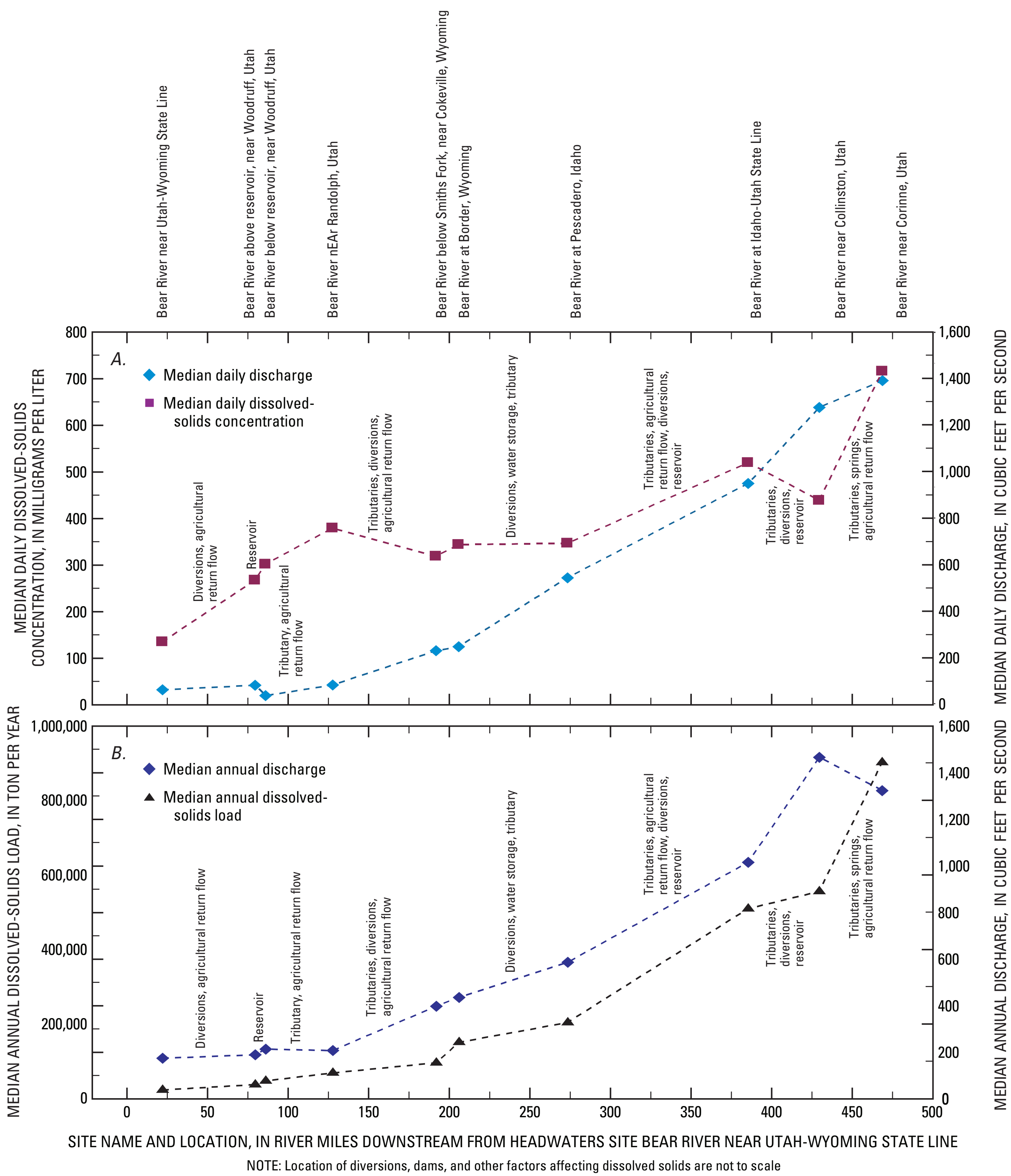


Figure 24. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Bear River.

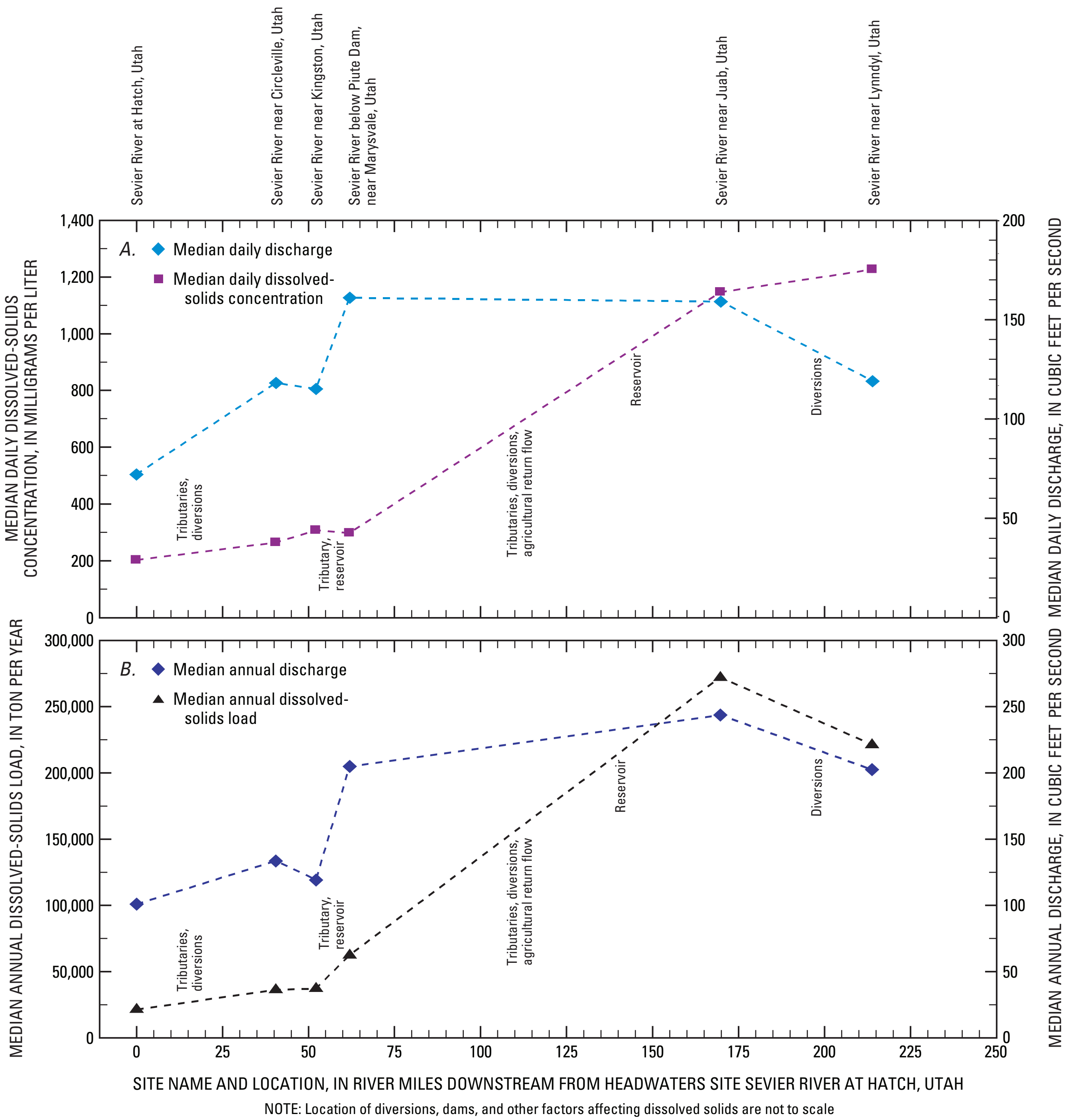


Figure 25. Graphs showing *A*, median daily dissolved-solids concentrations and discharge; *B*, median annual dissolved-solids loads and discharge, and factors that can affect concentrations of dissolved solids and loads for surface-water-quality monitoring sites on the main stem of the Sevier River.

In the Colorado River basin, the median daily dissolved-solid concentration increased between the sites Colorado River near CO-UT State Line (site 09163500) and the Colorado River near Cisco, UT (site 09180000; fig. 18) with the inflow of higher dissolved-solids concentration water from the Dolores River near Cisco, UT (site 09180000, appendix 3). The median concentration decreased from 704 mg/L at the Colorado River near Cisco, UT (site 09180000) to 521 mg/L at Colorado River at Lees Ferry, AZ (site 0938000), whereas the median daily discharge more than tripled between the two sites (fig. 24; appendix 3). The primary tributaries to the Colorado River between these two sites are the Green and San Juan Rivers. The sites Green River at Green River, UT (site 09315000) and San Juan River near Bluff, UT (site 09379500) each had lower dissolved-solids concentration water (appendix 3). Median daily discharge at this Green River site of 3,760 ft^3/s almost equaled the median discharge of 4,360 ft^3/s at Colorado River at Cisco, UT (site 09180000; appendix 3). Median daily and annual discharge and median annual dissolved-solids load decreased between the sites Colorado River below Hoover Dam, AZ-NV (site 09421500) and Colorado River below Parker Dam, AZ-CA (site 09427520) with the diversion of water to Colorado River Aqueduct, CA (site 09424150) and the Central Arizona Project Canal, AZ (site 09426650; fig. 24; appendices 3 and 4). Water also is diverted from the Colorado River to the Palo Verde Diversion between the Parker Dam site (site 09427520) and the Colorado River above Imperial Dam, AZ-CA (site 09429490). Median daily and annual discharge and median annual dissolved-solids load decreased substantially between the Imperial Dam site and the Colorado River at Northerly International Boundary, AZ (site 09522000) with the diversion of water to the All-American Canal, CA (site 09527500; fig. 18; appendices 3 and 4). The median annual load and discharge diverted at the Northerly International Boundary site was more than one-half the median annual load (54 percent) and discharge (52 percent) at the Colorado River above Imperial Dam site (site 09429490, appendix 4). Similarly, 50 percent of the median daily discharge was diverted to the All-American Canal (appendix 3). Unlike the median daily discharge and median annual load and discharge, there was a continual increase in the median daily dissolved-solids concentration between the sites Colorado River at Lees Ferry, AZ (site 09380000) and Colorado River at Northerly International Boundary, AZ (site 09522000), with water use and evaporation. Many of the tributaries that flowed into the Colorado River between these two sites had high median dissolved-solids concentrations but low median daily discharge. At the site Virgin River at Littlefield, AZ (site 09415000), for example, the median daily concentration and discharge were 1,940 mg/L and 152 ft^3/s, respectively (appendix 3).

While median annual dissolved-solids loads are useful for comparing the amount of dissolved solids transported past various sites, it does not provide information on the production of dissolved solids within the various watersheds based on drainage basin sizes. Median annual dissolved-solids yields (median annual dissolved-solids load divided by drainage basin size) were computed to compare among sites the amount of dissolved solids produced per unit area of drainage basin (pl. 1; appendix 4). For example, Mud Creek at State Highway 32, near Cortez, CO (site 09371492), and Salt Creek at Nephi, UT (site 10146000), both had median annual loads of about 12,000 ton/yr. Drainage basin size and, therefore, yields were different. Mud Creek has a drainage basin size of 34 mi^2 and a median annual yield of 356 (ton/yr)/mi^2. Salt Creek has a drainage basin size of 96 mi^2 and a median annual yield of 126 (ton/yr)/mi^2 (appendix 4). Production of dissolved solids per unit area, as yield, was much higher in Mud Creek Basin even though the drainage size was much smaller. Mud Creek drains irrigated areas of Mancos Shale in the Montezuma Valley southwest of Cortez, Colo., which is an important source of dissolved-solids loads to the stream.

Median annual yields ranged from 0.69 to 7,510 (ton/yr)/mi^2, and the mean for all 420 sites was 125 (ton/yr)/mi^2 (pl. 1; appendix 4). Most sites (104 of 112) with median annual yields greater than or equal to 100 (ton/yr)/mi^2 (a value slightly less than the 75th percentile yield of 105 (ton/yr)/mi^2) were in the Colorado River basin upstream from Lees Ferry, Ariz., and in the Bear and Great Salt Lake subregions (pl. 1; appendix 4). High yield sites in the Colorado River Basin upstream from Lees Ferry, Ariz., typically were in watersheds draining mostly Mesozoic age sedimentary rocks (pl. 1; fig. 6). Many of these sites are in agricultural areas with salinity-control projects (table 7). High yields in the Bear subregion can be attributed to dissolution of salts from geologic sources in the upper basin and concentration of salts due to water use (primarily irrigation), as well as inflow of saline ground water in the lower basin (Waddell and Price, 1972). In the Great Salt Lake subregion, geologic sources of dissolved solids contribute to dissolved-solids yields in the upper basins of the Weber and Provo Rivers. However, the storage of water in Utah Lake, the processes that contribute to high dissolved-solids concentration in the lake (mainly evaporation), and the subsequent release of that water probably are the major underlying causes of high dissolved-solids yield from this subregion. Dissolved solids in the three streams (Sulphur and Sowers Creek in Utah and Reed Wash in Colo.) with the greatest median annual yields are affected by irrigation-return flows and (or) saline geologic formations and soils (pl. 1; appendix 4). The Reed Wash Basin, for example, is a small (16 mi^2) farmed and ranched area in the Grand Valley area of western Colorado (Spahr and others, 2000). Irrigation occurs on heavy clay soils derived from the saline Mancos Shale. Deep percolation of irrigation water comes in contact with the soils and underlying shale. Salts are leached from the saline materials and subsequently loaded to Reed Wash and eventually to the Colorado River.

Sites with median annual yields less than 25 (ton/yr)/mi^2 were in all subregions except for the Rio Grande closed basins, Salt, and Northern Mojave-Mono Lake subregions (pl. 1; appendix 4). These sites with relatively small yields tended to have similar relations between median annual dissolved-solids loads and drainage basin size; sites with larger loads tended to have larger drainage basins, and sites with smaller loads tended to have smaller drainage basins. Dissolved-solids yields were not determined for five sites. Three sites are aqueducts or canals, one site is on the New River that flows through and carries drainage from Mexico, and one site is on the Alamo River. The New and Alamo Rivers carry discharge from agricultural activities in the Imperial Valley to the Salton Sea (appendix 4).

Concentration Variation by Physiographic Province

The eight physiographic provinces included within the boundaries of the Southwest (as defined in this report; pl. 1; table 3) include the Basin and Range, Cascade-Sierra Mountains, Colorado Plateaus, Lower Californian, Middle Rocky Mountains, Pacific Border, Southern Rocky Mountains, and Wyoming Basin. Natural sources of dissolved solids in rivers and streams in the physiographic provinces are derived from some of the physical characteristics of the provinces, such as average annual evaporation rates greater than 100 inches in the Sonoran Desert, for example, and also are affected by the human activities that occur within the provinces. Knowledge of the physiographic province where a site is located can be an additional tool for understanding dissolved-solids conditions at a site and why dissolved solids vary between sites.

Four of the eight physiographic provinces, Basin and Range, Colorado Plateaus, Cascade-Sierra Mountains, and Pacific Border, are divided into sections (table 3). Only the Basin and Range and Colorado Plateaus provinces have more than one section each; dissolved-solids data for these sections will be described separately. For the Cascade-Sierra Mountains and Pacific Border provinces, only one section for each province is within the Southwest. These sections will not be discussed.

The division of a site within a physiographic province/section is defined in two ways. The first is the physiographic province/section where a site is physically located, and the second is whether or not the drainage basin area of a site is primarily located in the site's physiographic province/section (pl. 1; table 14; appendix 5). The physical location of a site may be in one physiographic province/section, but most of the drainage basin area may be in another province/section. For example, the site West Walker River at Hoye Bridge near Wellingtons, NV (site 10297500) is physically located in the Great Basin physiographic section but primarily drains the Sierra Nevada section (pl. 1). For the purposes of this report, this West Walker River site will be included in computations and discussion of physiographic section site location in the Great Basin, but will be excluded from the compilation of sites whose drainage basin area is primarily within the Great Basin section. Some sites, such as those on main-stem rivers, drain multiple provinces/sections and are considered as "mixed" sites and also will be excluded from statistical computations of dissolved solids by drainage basin. Computations made by using site location within a physiographic province/section are useful for describing water quality within a physiographic province/section. Some longer streams may originate outside of the physiographic province/section but are still important water sources within the province/section. Computations made by using sites whose drainage basin is primarily within the physiographic province/section are useful for describing the quality of water that is produced in the province/section.

Data for the characterization of the spatial distribution of median daily dissolved-solids concentrations in surface waters of the Southwest based on location in a physiographic province include 420 sites in 8 provinces (pl. 1; table 14; appendix 5). Characterization of median daily dissolved solids-concentrations for sites with their drainage basin area almost entirely within the physiographic province of site location includes 351 sites in 8 provinces (pl. 1; table 14; appendix 5). For three provinces (Cascade-Sierra Mountains, Lower Californian, and Pacific Border), all sites had drainage basins within the physiographic province of the site location.

As with the spatial distribution of dissolved solids in the major river basins, the spatial distribution of dissolved solids in physiographic provinces varies from sparse coverage in the Basin and Range to extensive coverage in the Middle and Southern Rocky Mountains (pl. 1). Median daily dissolved-solids concentrations were at a minimum in the Cascade-Sierra Mountains, and there was little variability, reflecting the consistent source of low dissolved-solids concentrations from the granitic composition of the Sierra Nevada mountains (fig. 26; table 14; appendix 5).

Median daily dissolved-solids concentrations in the Southern and Middle Rocky Mountains primarily were less than 500 mg/L (fig. 26; table 14; appendix 5). For the two sites in each province with concentrations greater than 500 mg/L, dissolved solids were affected by irrigation-return flows and (or) sedimentary formations containing marine shales and evaporite beds. Median daily dissolved-solids concentrations at most sites (23 of 30) in the Wyoming Basin were less than 500 mg/L (fig. 26; table 14; appendix 5). Concentrations at seven sites that ranged between 512 and 2,543 mg/L were affected by geologic formations and mineral seeps, irrigation-return flows, and at some sites, possibly by coal mining.

Table 14. Statistical summary of median daily dissolved-solids concentrations for surface-water-quality monitoring site locations and site drainage basin locations in physiographic provinces and sections of the Southwestern United States.

[mg/L, milligrams per liter; N, number of sites; NA, not applicable]

		Median daily dissolved-solids concentration (mg/L)						Median daily dissolved-solids concentration (mg/L)			
		Minimum	Median	Maximum	Standard deviation			Minimum	Median	Maximum	Standard deviation
Physiographic province	N	Site location within physiographic province				Section	N	Site location within the section of the physiographic province			
Basin and Range	93	45	387	3,891	839	Great Basin	46	45	297	2,504	616
						Mexican Highland	31	75	356	3,583	799
						Salton Trough	4	729	1,606	3,891	1,497
						Sonoran Desert	12	278	640	3,102	1,003
Colorado Plateaus	130	39	461	13,819	1,491	Canyon Lands	47	96	595	3,550	901
						Datil	2	66	180	293	160
						High Plateaus of Utah	25	73	290	884	192
						Navajo	17	39	322	6,344	1,494
						Uinta Basin	39	84	577	13,819	2,268
Cascade-Sierra Mountains	15	25	57	142	30	Sierra Nevada	15	25	57	142	30
Lower Californian	1	1,341	1,341	1,341	NA	(not divided into sections)	NA	NA	NA	NA	NA
Middle Rocky Mountains	43	44	213	615	134	(not divided into sections)	NA	NA	NA	NA	NA
Pacific Border	5	81	580	994	328	Los Angeles Ranges	5	81	580	994	328
Southern Rocky Mountains	103	22	93	612	111	(not divided into sections)	NA	NA	NA	NA	NA
Wyoming Basin	30	26	245	2,543	654	(not divided into sections)	NA	NA	NA	NA	NA
		Drainage area almost entirely within physiographic province of site location						Drainage area almost entirely within the section of site location			
Basin and Range	64	45	362	3,891	898	Great Basin	35	45	304	2,504	646
						Mexican Highland	21	75	362	2,669	685
						Salton Trough	2	2,390	3,140	3,891	1,061
						Sonoran Desert	3	278	2,463	3,102	1,481
Colorado Plateaus	103	66	488	13,819	1,644	Canyon Lands	30	164	1,338	3,550	961
						Datil	2	66	180	293	160
						High Plateaus of Utah	22	73	267	884	177
						Navajo	14	127	353	6,344	1,633
						Uinta Basin	32	84	760	13,819	2,461
Cascade-Sierra Mountains	15	25	57	142	30	Sierra Nevada	15	25	57	142	30
Lower Californian	1	1,341	1,341	1,341	NA	(not divided into sections)	NA	NA	NA	NA	NA
Middle Rocky Mountains	40	44	213	615	131	(not divided into sections)	NA	NA	NA	NA	NA
Pacific Border	5	81	580	994	328	Los Angeles Ranges	5	81	580	994	328
Southern Rocky Mountains	100	22	91	612	110	(not divided into sections)	NA	NA	NA	NA	NA
Wyoming Basin	23	79	291	2,543	712	(not divided into sections)	NA	NA	NA	NA	NA

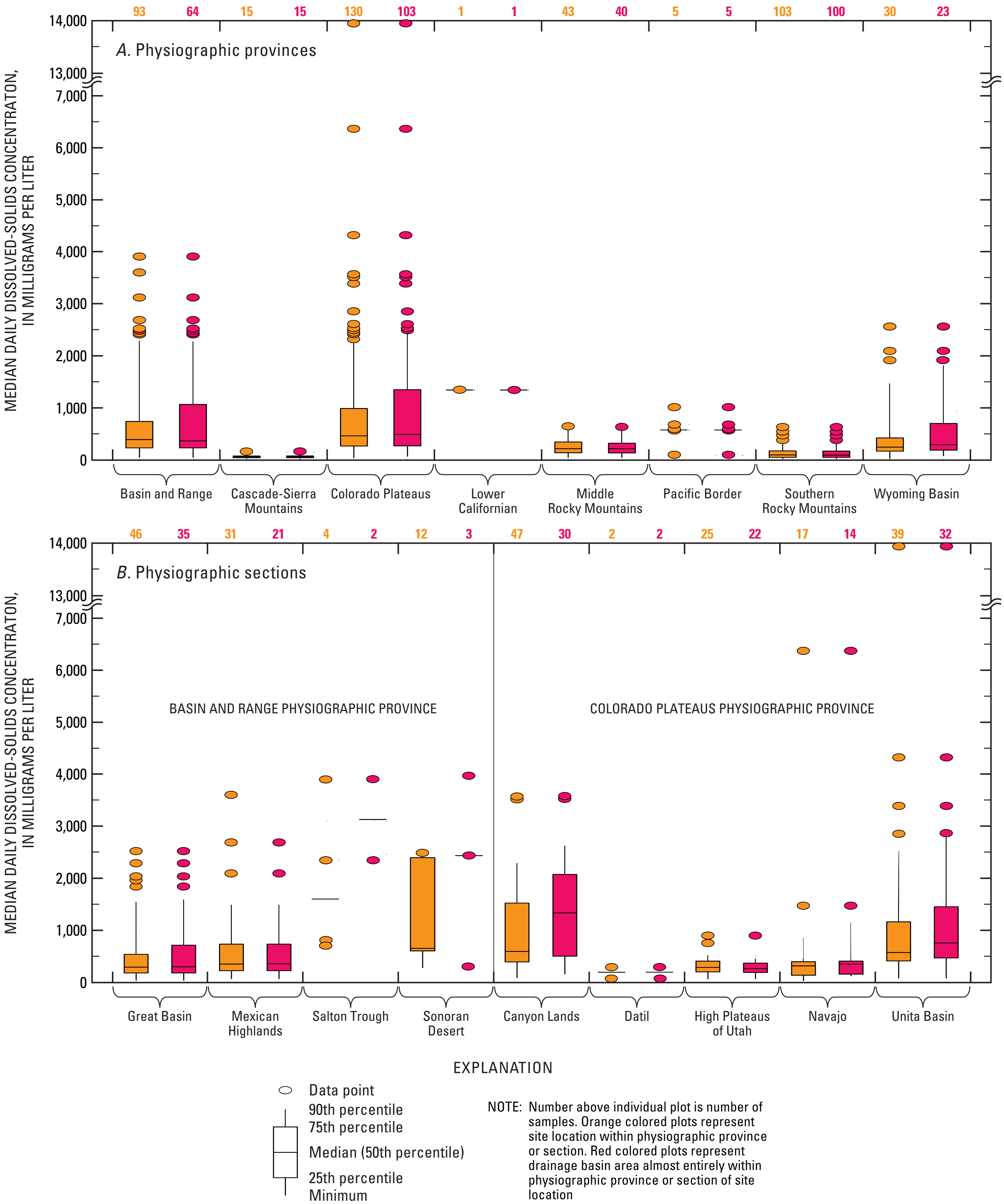


Figure 26. Box plots showing median daily dissolved-solids concentrations for surface-water-quality monitoring site locations and site drainage basin locations in *A*, physiographic provinces and *B*, physiographic sections of the Southwestern United States.

Almost 45 percent (58 of 130) of the Colorado Plateaus sites had median daily dissolved-solids concentrations greater than 500 mg/L (appendix 5). Streamflow at many sites in this province is intermittent or ephemeral. Among all physiographic provinces, median daily dissolved-solids concentrations were highest and had the largest variability in the Colorado Plateaus (fig. 26; table 14; appendix 5). The Colorado Plateaus is characterized by extensive areas of sedimentary formations, including the salt rich, marine Mancos Shale and the Carmel Formation, and volcanic structures, such as cinder cones and extensive lava-capped plateaus and mesas (Hunt, 1974). Dissolved-solids concentrations in streams in the Colorado Plateaus are affected by the natural dissolution of soluble salts in soil and substrata, ground-water inflow, mineral springs and seeps, irrigation-return flows, and evapotranspiration. For many of the streams, irrigation of alluvial soils derived from marine shales has increased the amount of dissolved solids in the streams over what would occur from natural dissolution.

In the Basin and Range Physiographic Province, almost 42 percent (39 of 93) of the sites had median daily dissolved-solids concentrations greater than 500 mg/L (fig. 26; table 14). This province consists of parallel mountains separated by lower elevation basins. Many of the basins are closed drainages and are areas that accumulate dissolved solids, including the Carson Sink and the Great Salt Lake. Many streams in the province are intermittent or ephemeral. With large population centers, such as the Rio Grande Valley between Santa Fe and El Paso, Tucson-Phoenix, Las Vegas, Reno/Carson City, and Salt Lake City, municipal activities in the Basin and Range province have a greater affect on dissolved solids than in other provinces except for the Pacific Border.

Median daily dissolved-solids concentrations in the Pacific Border Physiographic Province were greater than 500 mg/L at four of five sites. Dissolved solids in the province are affected by urbanization, water use and reuse (including effluent and recharged water), agricultural activities, ground-water inflows, imported surface water, and evaporite deposits.

In addition to categorizing and describing dissolved solids based on the physiographic province or section where a site is located, dissolved solids also can be discussed based on the physiographic province/section that contains most of a site's drainage basin. As stated previously in this section of the report, these two categories define the quality of water that is available or produced, respectively, within a physiographic province/section. For the Middle and Southern Rocky Mountains Physiographic Provinces there was little difference in dissolved-solids concentrations between sites that were located within the provinces, including sites with drainage basins primarily outside of the province boundaries (available water), and sites with drainage basins primarily within the provinces (produced water; fig. 26; table 14; appendix 5). About 58 and 55 percent of the sites in the Basin and Range and Colorado Plateaus, respectively, that represent the quality of water available within the provinces had median daily dissolved-solids concentrations less than 500 mg/L. For sites representing the quality of water produced within the provinces, about 58 percent of the sites in the Basin and Range and 51 percent of the sites in the Colorado Plateaus had median daily dissolved-solids concentrations of less than 500 mg/L.

The Basin and Range Physiographic Province contains five sections (table 3). The Sacramento section, with no sites, will not be discussed. In the Great Basin section, which covers about one-half the area of the Basin and Range Physiographic Province, median daily dissolved-solids concentrations at 33 of 46 sites were less than 500 mg/L (fig. 26, table 14, appendix 5). Sites with dissolved-solids concentrations greater than 500 mg/L primarily were in the Salt Lake City area, the lower reaches of the Sevier River, and in or near the Virgin River north of Las Vegas. In the Mexican Highland section, median daily dissolved-solids concentrations greater than 500 mg/L were concentrated in the Rio Grande Valley near Bernardo, N. Mex., and at El Paso, Tex., and in the upper Gila River and Salt Creek drainage basins in Arizona. These elevated concentrations in the Rio Grande Valley were due to urban and agricultural activities, ground-water inflow, and evapotranspiration. The elevated concentrations in the Gila River and Salt Creek drainages primarily were due to agricultural activities, water use and reuse, springs and seeps, other ground-water inflow, and evapotranspiration. All four sites in the Salton Trough section and 11 of 12 sites in the Sonoran Desert section had median daily dissolved-solids concentrations greater than 500 mg/L. In both sections, dissolved-solids concentrations were affected by agricultural activities, ground-water inflow, imported surface water, and evapotranspiration. Concentrations in the Sonoran Desert section also were affected by urban activities in and around Phoenix, Tucson, and Las Vegas and by site locations at the downstream portions of the Colorado and Gila Rivers that reflect all upstream processes.

Six physiographic sections are in the Colorado Plateaus Physiographic Province (table 3). No sites are in the Grand Canyon section. Many sites in the remaining five sections of the Colorado Plateaus have intermittent or ephemeral streamflow. Median daily dissolved-solids concentrations greater than 500 mg/L were found at more than one-half of the sites in the Canyon Lands (70 percent) and Uinta Basin (62 percent) sections. Dissolved solids in both sections were affected by sedimentary geologic formations, ground-water inflow, and irrigation-return flows. Median daily dissolved-solids concentrations at the two sites in the Datil section were less than 300 mg/L and possibly were a result of the thick, less soluble lavas that make up the surface geology of the section. In the High Plateaus of Utah section, all median daily dissolved-solids concentrations were less than 900 mg/L. Most sites (15 of 17) in the Navajo section had median daily dissolved-solids concentrations less than

500 mg/L. Dissolved solids at the two sites (Chaco River and Shumway Arroyo, both near Waterflow, N. Mex.) with concentrations greater than 6,000 mg/L may have been the result of localized industrial wastes.

The primary differences in summary statistics for water available and produced within the different sections were higher median daily dissolved-solids concentrations for water produced within the Salton Trough and Sonoran Desert sections of the Basin and Range province and the Canyon Lands section of the Colorado Plateaus province (fig. 26; table 14). Many of the sites with drainage areas primarily outside of the site-location section had lower dissolved-solids concentrations than sites whose drainage basins primarily were within the section (fig. 26; appendix 5). The lower dissolved-solids concentrations occurred because the sites were large rivers or smaller streams with dilution effects on water quality from increased streamflow or snowmelt runoff from higher elevations, respectively, or were aqueducts or canals that carried imported water. The calculated median dissolved-solids concentrations for water produced within the sections were higher with the exclusion of the lower-concentration sites from the calculation.

Effects of Natural and Human Factors on Dissolved-Solids Concentrations

By David W. Anning

A conceptual model of the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams was developed through an analysis of dissolved-solids concentrations and environmental conditions along ground-water and surface-water flow paths in 12 areas. A flow path is the generalized route water follows from areas of recharge to areas of discharge in a hydrologic-flow system. For subsurface water, the paths are through soils and aquifers and for surface water, the paths are across the land surface and through streams, reservoirs, and lakes. Along a flow path, various natural or human factors drive processes that either add or remove salts or water from the flow system, resulting in increases or decreases in dissolved-solids concentrations.

The 12 selected areas are within the six NAWQA Study Units in the Southwest (fig. 27) and were chosen on the basis of four factors:

1. The uniqueness of the area's environmental conditions as compared to those of the other selected areas, to minimize redundancy of descriptions;
2. The similarity and representativeness of the areas in comparison to other areas in the Southwest, to facilitate information transfer;
3. The availability of information on the effects of natural and human factors on dissolved solids in that area; and
4. The importance of the basin-fill aquifers and streams in the area as water supplies in the Southwest.

The areas include the San Luis Valley (RIOG) in Colorado; the Middle Rio Grande Basin and Mesilla Valley (RIOG) in New Mexico; the upper Colorado River Basin (UCOL) in Colorado; the East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin (CAZB) in Arizona; the Carson River Basin (NVBR) in California and Nevada; the Las Vegas Valley (NVBR) in Nevada; the Utah, Goshen, and Salt Lake Valleys (GRSL) in Utah; and the San Jacinto, Inland, and Coastal Basins (SANA) in Southern California. These 12 areas represent the wide variety of physiographical, geological, hydrological, climatalogical, and cultural conditions that occur across the Southwest that were characterized in the "Environmental Setting of the Southwest" section in this report. This diversity of environmental conditions results in a wide variety of natural and human factors that affect dissolved-solids concentrations along flow paths in the basin-fill aquifers and streams at site, basin, and regional scales. Physiographic, climate, and cultural conditions of each area are summarized in table 15, and the diverse hydrologic conditions are summarized in table 16.

As a result of this environmental diversity, a wide variety of natural and human factors were found to affect dissolved-solids concentrations. Data and information about concentrations and environmental conditions of a particular stream reach or part of an aquifer came from previously published studies or from the "Environmental Setting" and "Spatial Distribution" sections in this report. These data and information from individual sources were used collectively to describe (1) the status and changes in dissolved-solids concentrations, and (2) the natural or human factors that affect concentration conditions or changes in concentrations along the ground-water and surface-water flow paths in each area. The descriptions of the natural and human factors affecting dissolved-solids concentrations along flow paths for each area follow this introduction.

The conceptual model for the natural and human factors that affect dissolved-solids concentrations in the Southwest is described at the end of this section and was developed through a synthesis of all the natural and human factors affecting concentration conditions or changes in concentrations along the flow paths in the 12 areas. While the descriptions for each area are informative for local and State water management and policy to the area, they also provide insight into water management in other areas in the Southwest where natural and human environmental conditions affecting dissolved-solids concentrations are similar. The conceptual model for the natural and human factors affecting dissolved-solids concentrations in the Southwest provides a comprehensive understanding and is useful for regional-scale management of the water resources in the Southwest.

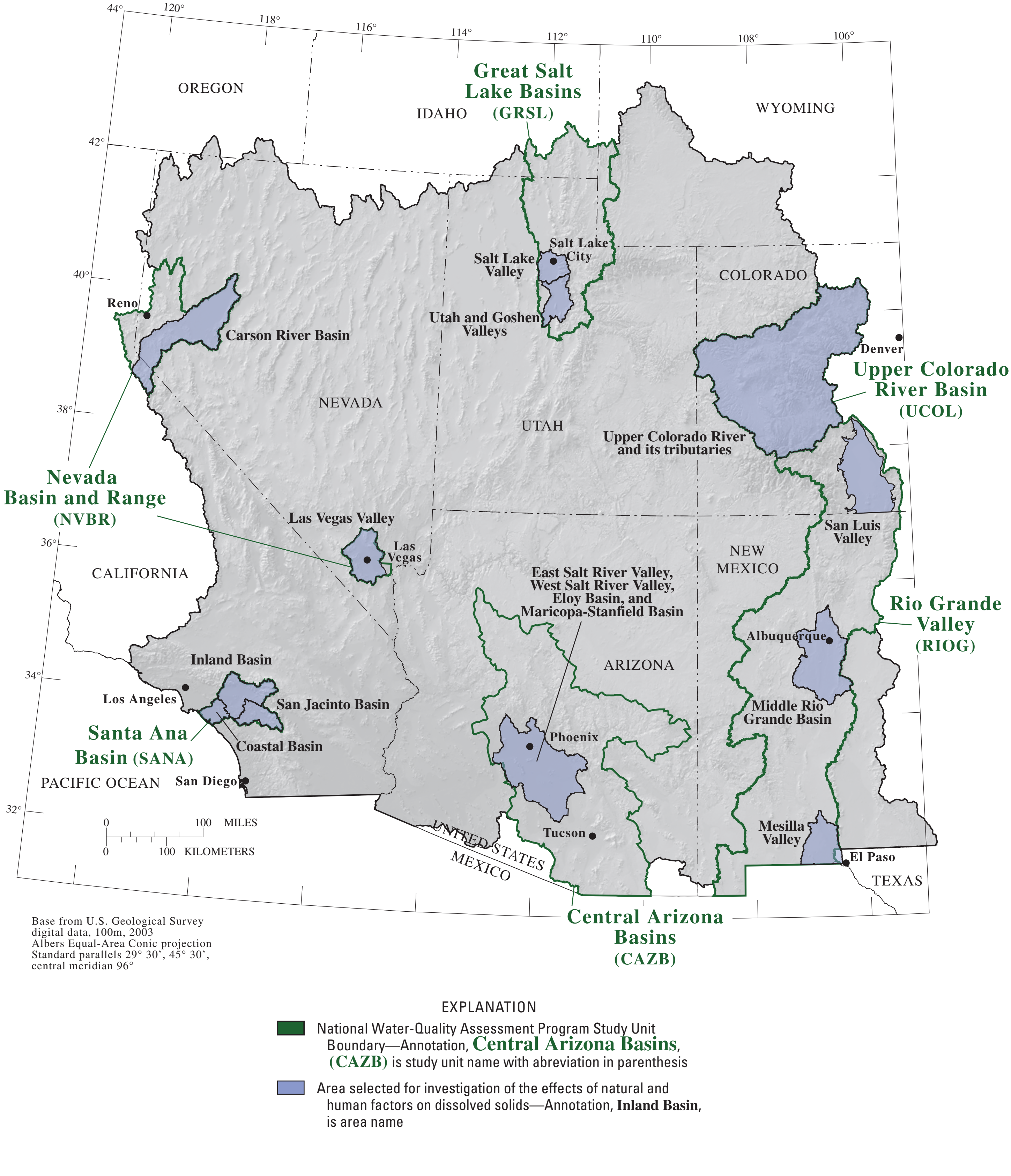


Figure 27. National Water-Quality Assessment Program Study Units and 12 selected areas for the investigation of the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams of the Southwestern United States.

Table 15. Physiographic, climatic, and cultural conditions in selected areas of the Southwestern United States.
[mi², square mile; min, minimum; max, maximum]

Selected area[1]	Area extent, mi²	Range of physiographic and climatic conditions within area: Land surface altitude, feet above sea level — Min	Land surface altitude — Max	Average air temperature, 1980-1997, degrees Fahrenheit — Min	Average air temperature — Max	Average annual precipitation, 1980-1997, inches — Min	Average annual precipitation — Max	Cultural conditions: Population year 2000, total	Land use: Urban mi²	Urban Percent	Agricultrual mi²	Agricultrual Percent	Other mi²	Other Percent
Rio Grande Valley, New Mexico and Colorado														
San Luis Valley	3,212	7,392	10,692	34	44	7	26	38,784	16	0	753	23	2,443	76
Middle Rio Grande Basin	3,611	4,665	10,656	39	58	8	28	687,585	165	4	59	2	3,386	94
Mesilla Valley	1,572	3,724	8,963	51	64	4	7	259,146	50	3	93	6	1,429	91
Upper Colorado River Basin, Colorado														
Upper Colorado River Basin	17,884	4,318	14,262	23	54	11	56	327,437	113	1	758	4	17,013	95
Central Arizona Basins, Arizona														
East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin	5,433	771	5,571	59	73	8	27	4,066,772	572	11	1,103	20	3,758	69
Nevada Basin and Range, California and Nevada														
Carson River Basin	3,967	3,031	11,374	32	53	4	56	124,745	32	1	138	3	3,796	96
Las Vegas Valley	1,568	1,398	11,506	34	69	5	17	1,323,131	173	11	2	0	1,393	89
Great Salt Lake Basins, Utah														
Utah and Goshen Valleys	1,033	4,442	11,644	32	52	16	61	364,266	73	7	145	14	815	79
Salt Lake Valley	814	4,199	11,407	32	54	18	62	927,683	185	23	52	6	577	71
Santa Ana Basin, California														
San Jacinto Basin	788	1,234	10,754	36	66	13	37	420,215	90	11	133	17	565	72
Inland Basin	1,473	486	11,319	34	67	13	51	2,007,202	368	25	124	8	981	67
Coastal Basin	484	0	5,672	53	66	13	33	1,846,323	233	48	14	3	238	49

[1]See figure 27 for location and extent of area

Data Sources:

Elevation: bilinear resample of National Elevation Data (NED) from 30 meter to 100 meter; U.S. Geological Survey, 2003

Air temperature and precipitation: Thornton and others, 1997, and Daymet, 2006

Population: Geolytics, Inc., 2001

Land use: U.S. Geological Survey, 2005a

Table 16. Hydrologic conditions in selected areas of the Southwestern United States.

[n/a, not applicable. See figure 27 for location and extent of area]

		Principal aquifer			Principal river(s)			
Selected area	**Interbasin flows**	**Name**	**Primary sources of ground-water recharge**	**Primary ground-water-discharge processes**	**Name(s)**	**Primary streamflow sources**	**Appreciable diversions**	**Hydraulic connection between principal aquifers and principal rivers**
				Rio Grande Valley, Colorado and New Mexico				
San Luis Valley	Northern part has no ground-water or surface-water inflows or outflows. Southern part has ground-water and surface-water outflow	Rio Grande aquifer system	Mountain-front recharge and streamflow infiltration; incidental recharge from irrigation	Ground-water pumpage for irrigation and also for drainage purposes; evapotranspiration of shallow ground water in the central parts of the basin	Rio Grande	Snowmelt from surrounding mountain ranges	Several diversions from the Rio Grande for irrigation	Depth to ground water is shallow across much of the area and Rio Grande and many other rivers are well connected to the aquifer
Middle Rio Grande Basin	Ground-water and surface-water inflow and outflow	Rio Grande aquifer system	Ditto.	Ground-water pumpage for municipal and irrigation purposes; discharge to the Rio Grande; evapotranspiration of shallow ground water along the flood plain	Rio Grande	Inflow to the basin from the Rio Grande and principal tributaries including the Rio Chama; runoff from surrounding mountains; agricultural- and municipal-return flows	The Rio Grande is diverted for irrigation	The Rio Grande is hydraulically connected to the principal aquifer primarily in the flood plain
Mesilla Valley	Ground-water and surface-water inflow and outflow	Rio Grande aquifer system	Ditto.	Ground-water pumpage for irrigation and municipal purposes; discharge to the Rio Grande; evapotranspiration of shallow ground water along the flood plain	Rio Grande	Inflow to the basin from the Rio Grande; runoff from surrounding mountains; agricultural-return flows	Ditto.	Ditto.

Table 16. Hydrologic conditions in selected areas of the Southwestern United States—Continued.

Selected area	Interbasin flows	Principal aquifer: Name	Principal aquifer: Primary sources of ground-water recharge	Principal aquifer: Primary ground-water discharge processes	Principal river(s): Name(s)	Principal river(s): Primary streamflow sources	Principal river(s): Appreciable diversions	Principal river(s): Hydraulic connection between principal aquifers and principal rivers
Upper Colorado River Basin, Colorado								
Upper Colorado River Basin	No inflows; outflow is through the Colorado River and exported water to the Front Range of Colorado	None	n/a	n/a	Colorado River, Gunnison River	Snowmelt from surrounding mountain ranges	Several diversions from the Colorado River and its tributaries; much of which is exported to the Front Range of Colorado	n/a
Central Arizona Basins, Arizona								
East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin	Imported Colorado River water, ground-water and surface-water inflow and outflow	Basin and Range basin-fill aquifers	Infiltration of urban runoff, irrigation seepage, canal seepage, and infiltration of streamflow during years of higher than normal rainfall	Ground-water pumpage for municipal and irrigation purposes, evapotranspiration and seepage along the lower Salt and Gila Rivers	The middle and lower Gila River, and the lower Salt River	Reservoir releases, precipitation runoff, treated municipal effluent, irrigation-return flows, and ground-water seepage	Nearly all of the streamflow entering the basins is diverted for agricultural and municipal uses. Municipal and irrigation-return flows to streams are subsequently diverted for additional reuse	Principal rivers are hydraulically connected to major aquifers above major diversion points, disconnected below diversion points for several miles, and then connected again where major return flows occur.
Nevada Basin and Range, Nevada								
Carson River Basin	Imported Truckee River water; otherwise no inflows nor outflows.	Basin and Range basin-fill aquifers	Mountain-front recharge and streamflow infiltration; incidental recharge from irrigation	Ground-water pumpage, evapotranspiration, and seepage along the Carson River and in the Carson Sink	Carson River	Snowmelt from surrounding mountain ranges; imported Truckee River water in lower reach	Several diversions along the Carson River for irrigation purposes	The Carson River is hydraulically connected to the principal aquifer for most of its length

Table 16. Hydrologic conditions in selected areas of the Southwestern United States—Continued.

		Principal aquifer			Principal river(s)			
Selected area	**Interbasin flows**	**Name**	**Primary sources of ground-water recharge**	**Primary ground-water discharge processes**	**Name(s)**	**Primary streamflow sources**	**Appreciable diversions**	**Hydraulic connection between principal aquifers and principal rivers**
				Nevada Basin and Range, Nevada—Continued				
Las Vegas Valley	Imported Colorado River water, no appreciable natural inflows; ground-water and surface-water outflows	Basin and Range basin-fill aquifers	Mountain front recharge, infiltration of urban runoff, artificial recharge of Colorado River water	Ground-water pumpage, evapotranspiration and seepage along the Las Vegas Wash	Las Vegas Wash	Treated municipal-wastewater releases, urban runoff, ground-water seepage	None	The upper reaches and many of the tributaries to Las Vegas Wash are disconnected; the lower reaches of Las Vegas Wash are hydraulically connected to the principal aquifer
				Great Salt Lake Basins, Utah				
Utah and Goshen Valleys	Imported water from Colorado River basin, inflows from Currant Creek, the Provo River, and other streams; ground water and surface water outflow to Salt Lake Valley	Basin and Range basin-fill aquifers	Infiltration of precipitation, streamflow, urban runoff, underflow from consolidated rock, irrigation seepage, and canal seepage	Ground-water pumpage, and seepage to Utah Lake and springs, and evapotranspiration of shallow ground water	Provo River, American Fork, and Spanish Fork rivers	Reservoir releases, precipitation runoff, irrigation-return flows, and ground-water discharge	Nearly all of the streamflow entering the basins is diverted for agricultural and municipal uses. Municipal and irrigation-return flows to streams are subsequently diverted for additional reuse	Principal rivers are hydraulically connected where they recharge the principal (deep) aquifer near canyon mouths and then again where major ground-water return flows occur
Salt Lake Valley	Imported water from the Colorado River Basin and inflows from adjacent basins; ground-water and surface-water outflows are to Great Salt Lake, a closed water body	Basin and Range basin-fill aquifers	Ditto.	Ground-water pumpage, evapotranspiration of shallow ground water, and seepage to Jordan River and Great Salt Lake	Jordan River	Ditto.	Ditto.	The Jordan River is hydraulically connected to the principal aquifer, receiving ground-water discharge through most of its Salt Lake Valley traverse

Table 16. Hydrologic conditions in selected areas of the Southwestern United States—Continued.

Selected area	Interbasin flows	Principal aquifer: Name	Principal aquifer: Primary sources of ground-water recharge	Principal aquifer: Primary ground-water discharge processes	Principal river(s): Name(s)	Principal river(s): Primary streamflow sources	Principal river(s): Appreciable diversions	Principal river(s): Hydraulic connection between principal aquifers and principal rivers
Santa Ana Basin, California								
San Jacinto Basin	Imported water from the Colorado River, Owens Valley, and northern California; no natural inflows. Surface-water outflow to the Inland Basin	California Coastal Basin aquifers	Artificial recharge of Colorado River water, streamflow from surrounding mountians, and treated municipal wastewater	Ground-water pumpage	San Jacinto River	Runoff from surrounding mountains, urban runoff, treated municipal wastewater	Streamlfow at mountain front is diverted for artificial recharge	The hydraulic connection between streams and principal aquifer is spatially and seasonally variable
Inland Basin	Imported water from the Colorado River, Owens Valley, and northern California; surface-water inflow from San Jacinto basin. Surface-water outflow to Coastal basin	California Coastal Basin aquifers	Ditto.	Ditto.	Santa Ana River	Ditto.	Ditto.	Ditto.
Coastal Basin	Imported water from the Colorado River, Owens Valley, and northern California; seawater intrusion in some areas; minimal surface-water inflow from the Inland Basin	California Coastal Basin aquifers	Ditto.	Ditto.	Santa Ana River	Ditto.	Streamflow in the Santa Ana River, which is mostly treated municipal wastewater, is diverted to recharge basins	Ditto.

Rio Grande Valley

By Stephanie J. Moore and Scott K. Anderholm

In this section, the status of dissolved-solids concentrations and changes in dissolved-solids concentrations along flow paths due to natural and human factors are described in general for the RIOG Study Unit, and in more detail for the San Luis, Middle Rio Grande, and Mesilla Valleys. The entire Rio Grande watershed upstream from the streamflow-gaging station Rio Grande at El Paso, TX, as well as the closed-basin part of the San Luis Valley in Colorado (fig. 28), are included in the Study Unit.

The RIOG Study Unit consists of a series of alluvial basins that are surrounded by mountainous bedrock areas. Environmental conditions vary throughout the RIOG Study Unit and are described in detail by Ellis and others (1993). Climatic variations are extreme and vary from alpine tundra to Sonoran desert (Ellis and others, 1993). Albuquerque is the largest city with approximately 450,000 residents, followed by Las Cruces, Santa Fe, and Rio Rancho, all in New Mexico (U.S. Census Bureau, 2004). Land cover and use is predominantly rangeland and forest, with a small percentage of agricultural use along the river. Although agricultural and urban land uses make up only 5 percent of the RIOG Study Unit, they account for almost all (98 percent) water use in the Study Unit (Levings and others, 1998). Ground water is the principal source for domestic, industrial, and municipal supply; surface water is the principal source for agricultural supply.

The Rio Grande is a shallow, wide river flanked by dense riparian vegetation. Agricultural areas generally are confined to the flood plain (or inner valley) of the Rio Grande. Throughout most of New Mexico, the Rio Grande flood plain is entrenched 200 to 500 ft below a piedmont surface that extends from the basin margins (Anderholm, 1987). Stream-aquifer interactions have significant effects on streamflow in the Rio Grande.

Most streamflow in the Rio Grande originates as runoff from the surrounding mountain ranges in the northern part of the watershed. Streamflow is generally largest during spring snowmelt; however, late summer and early fall thunderstorms also contribute to increased streamflow. Streamflow decreases in the downstream direction because outflows, such as diversions for agricultural use, instream transit losses to ground water, and evapotranspiration, are greater than inflows, such as tributary flow, return flows from agricultural drains, ground-water discharge, and inflow from wastewater-treatment plants (Moore and Anderholm, 2002; Moore and others, 2003).

Many anthropogenic structures affect streamflow in the RIOG Study Unit. Several major reservoirs regulate streamflow on the Rio Grande and its largest tributary, the Rio Chama (fig. 28). A complex system of canals and drains deliver water to and from the irrigated areas in the Rio Grande flood plain. The drains were constructed to (1) intercept shallow ground water and convey it to the Rio Grande and (2) return any unused portion of diverted water to the Rio Grande. Several wastewater-treatment plants discharge to the Rio Grande—the largest one is in Albuquerque.

Median sample dissolved-solids concentrations in the Rio Grande for 1993–95 increase from 73 mg/L near the headwaters to 652 mg/L at El Paso, Tex., which is an increase by a factor of about 9 (fig. 28; Moore and Anderholm, 2002). Evapotranspiration, wastewater-treatment-plant releases, irrigation-return flows, and ground-water discharge to the Rio Grande contribute to increases in dissolved-solids concentrations throughout the watershed.

The Rio Grande aquifer system includes a series of hydraulically connected aquifers. The principal aquifers of the system are composed of basin-fill deposits. Basin-fill aquifers of the Rio Grande system generally are recharged by one of the following mechanisms: (1) mountain-front recharge, which includes subsurface inflow from adjacent mountain-block aquifers and streambed infiltration of runoff derived from mountainous areas, (2) inflow from adjacent aquifers, (3) infiltration of perennial and ephemeral surface water, and (4) infiltration of irrigation water in agricultural areas. Additionally, direct infiltration of precipitation may provide some recharge; however, direct infiltration contributes only a small percentage of total recharge. Ground-water movement is generally from the basin margins to the basin center (Ellis and others, 1993). Discharge from the aquifers is by flow to rivers or lakes, evapotranspiration, flow to adjacent aquifers, and ground-water pumpage.

Prior to the development of ground-water resources, the aquifers were in a steady state, where recharge (typically occurring near the basin margins) equaled discharge (typically occurring in the flood plain). In many areas where ground-water resources have been developed, discharge is now greater than recharge, and pumping has resulted in large drawdowns and the reversal of hydraulic gradients (and, therefore, of flow paths).

Dissolved-solids concentrations in the Rio Grande aquifer system vary spatially and are affected by many natural and anthropogenic factors. The chemical composition of recharge is an important factor. Mountain-front recharge generally has small dissolved-solids concentrations. Inflow from adjacent aquifers can have a wide range of dissolved-solids concentrations. The dissolved-solids concentrations in infiltrating surface water may vary from year to year, depending on the quantity of annual precipitation and other factors. Because of the effects of evapotranspiration, shallow ground water and irrigation-return flows generally have larger dissolved-solids concentrations than does the Rio Grande. In areas where ground-water development has diminished discharge to the Rio Grande, dissolved-solids concentrations in ground water adjacent to the river can increase because of evapotranspiration by crops and riparian vegetation. Ground-water flow paths may influence dissolved-solids concentrations if the ground water comes in contact with soluble or reactive aquifer materials. The effect of geochemical reactions, such as ion-exchange, depends on the residence time and rate of ground-water flow.

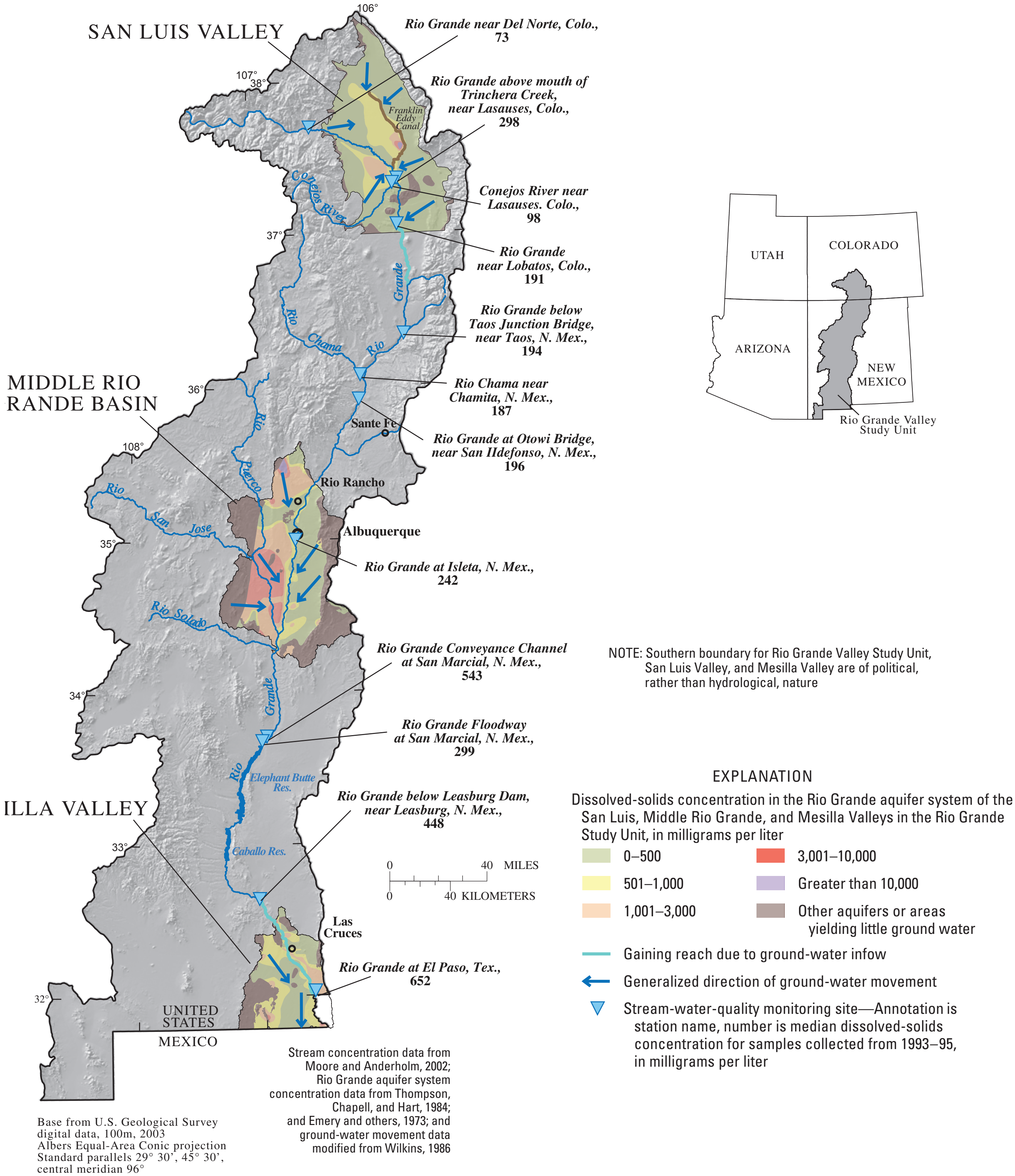


Figure 28. Dissolved-solids concentrations in the Rio Grande aquifer system, the Rio Grande, and its tributaries in the San Luis Valley, Middle Rio Grande Basin, and Mesilla Valley of the Rio Grande Valley Study Unit.

A detailed description of each aquifer in the Rio Grande aquifer system is beyond the scope of this report; however, discussion of three principal aquifers of the Rio Grande Valley (San Luis Valley, Middle Rio Grande Basin, and Mesilla Valley; fig. 28) provide examples of the most important processes controlling dissolved-solids concentrations. The San Luis and Mesilla Valleys are the largest agricultural areas within the Rio Grande Valley. The largest population centers in the Rio Grande Valley are in the Middle Rio Grande Basin and the Mesilla Valley. These three basins represent the full range of physiographic conditions within the Rio Grande Valley (fig. 28).

San Luis Valley

The San Luis Valley is bordered by the San Juan and Sangre de Cristo Mountains of south-central Colorado. The northern part of the San Luis Valley is a closed basin with no substantial amount of natural surface or subsurface outflow, while the southern part of the valley is an open basin that is drained by the Rio Grande (fig. 28). The Closed Basin Division Project, however, was constructed to salvage unconfined ground water from the closed basin that would otherwise be lost to evapotranspiration. The salvage water is conveyed to the Rio Grande through the Franklin Eddy Canal. Although the Closed Basin Division Project was designed to reduce the amount of natural evapotranspiration and water-logging problems, it also reduces accumulation of dissolved solids in the shallow aquifer.

Agriculture is the primary use of land and water in the San Luis Valley. Both surface- and ground-water supplies are used for irrigation purposes. The basin-fill aquifer of the San Luis Valley includes a confined aquifer and an unconfined aquifer; however, this discussion will focus on the unconfined aquifer because it is the principal source of irrigation water (Emery and others, 1973). The unconfined aquifer underlies the entire San Luis Valley, and water levels are historically less than 12 ft below land surface (Edelmann and Buckles, 1984). Ground-water flow is from the basin margins to the basin center in the northern part of the San Luis Valley and toward the Rio Grande in Southern San Luis Valley. Surface-water diversions from the Rio Grande are used to maintain a shallow water table in the unconfined aquifer. To facilitate drainage in the unconfined aquifer, shallow ground water is pumped into the Franklin Eddy Canal, which discharges to the Rio Grande. This drainage addresses not only water-logging problems, but also reduces accumulation of dissolved solids in the shallow aquifer.

Near the basin-fill aquifer boundaries, dissolved-solids concentrations are generally less than 170 mg/L (Edelmann and Buckles, 1984). Dissolved-solids concentrations increase as water moves downgradient toward the center of the San Luis Valley. The primary factors affecting dissolved-solids concentrations in the San Luis Valley are (1) the composition of recharge, (2) dissolution and ion-exchange reactions occurring along the ground-water flow paths, (3) evapotranspiration from the shallow water table, and (4) the recirculation of water due to agricultural use (Edelmann and Buckles, 1984). Dissolution increases dissolved-solids concentrations, and ion-exchange reactions decrease the calcium-sodium ratio. Evapotranspiration removes water and increases dissolved-solids concentrations, particularly near the valley center where water levels less than 6 ft below land surface facilitate large evapotranspiration rates. The reuse of ground water for irrigation recirculates shallow ground water and allows for increased evapotranspiration and leaching of salts from fields, which result in additional increases in dissolved-solids concentrations as ground water moves from the valley margins towards the valley center. The combined effect of these factors is dissolved-solids concentrations that exceed 500 mg/L near the valley center and, in some areas, concentrations greater than 1,500 mg/L (Edelmann and Buckles, 1984).

Dissolved solids are transported out of the San Luis Valley unconfined aquifer primarily by ground-water pumpage to the Franklin Eddy Canal and ground-water discharge to the Rio Grande and its tributaries, including agricultural drainage canals. The median dissolved-solids concentration of the Rio Grande for 1993–95 increases from 73 to 298 mg/L in the San Luis Valley between Del Norte, Colo., and the mouth of Trinchera Creek (fig. 28; Moore and Anderholm, 2002). The addition of ground water with concentrations greater than 300 mg/L from the San Luis Valley is the primary cause of increases in the dissolved-solids concentration and load in this reach of the Rio Grande (Moore and Anderholm, 2002).

Middle Rio Grande Basin

The Middle Rio Grande Basin is also known as the Albuquerque Basin. The city of Albuquerque and surrounding metropolitan areas constitute the largest urban area of the RIOG Study Unit. Land use in the Middle Rio Grande Basin, however, is predominantly rangeland. Ground water is the principal source for municipal water use. Agricultural areas are generally confined to the inner valley of the Rio Grande where surface water is the primary source for irrigation of agricultural areas. The basin-fill aquifer of the Middle Rio Grande Basin is composed of unconsolidated to moderately consolidated sediments. Depth to water is generally less than 30 ft below land surface in the inner valley and 300–400 ft below land surface in the surrounding areas; however, depth to water can exceed 900 ft in the western part of the basin. Ground-water movement is predominantly from north to south with a component of east-west flow from the basin margins (Plummer and others, 2004).

Dissolved-solids concentrations in the Middle Rio Grande Basin are affected primarily by the composition of recharge water. Geochemical reactions along ground-water flow paths have little, if any, effect on dissolved-solids concentrations because sediments of the basin-fill deposits are relatively unreactive (Plummer and others, 2004). Dissolved-solids concentrations in ground water range from 80 to 29,000 mg/L throughout the basin; however, dissolved-solids concentrations for most of the basin are generally less than 400 mg/L. These concentrations can be attributed to the relatively low dissolved-solids concentrations of the two major recharge sources: mountain-front recharge and infiltration from the Rio Grande (Plummer and others, 2004). In the Albuquerque area, however, ground-water pumpage has increased recharge in agricultural areas of the Rio Grande flood plain (McAda and Barrol, 2002, p. 63), and as a result, recently recharged water has higher dissolved-solids concentrations than recharge that occurred during pre-development conditions. The largest dissolved-solids concentrations in the basin are the result of inflow of saline ground waters from adjacent basins, especially on the western margin where inflow is from sedimentary-rock aquifers.

Dissolved-solids are transported out of the Middle Rio Grande Basin by one of the following mechanisms: (1) discharge to the Rio Grande, (2) ground-water withdrawals and subsequent storage in the unsaturated zone, and (3) subsurface flow out of the basin. Upstream from the Middle Rio Grande Basin, the median dissolved-solids concentration from samples collected from 1993–95 at Rio Grande at Otowi Bridge, NM, is 196 mg/L; for the same period, the median sample concentration increases to 299 mg/L below the Middle Rio Grande Basin (Rio Grande Floodway at San Marcial, NM, fig. 28). Increases in dissolved-solids concentrations in this reach of the Rio Grande can be attributed to irrigation-return flows, municipal wastewater-treatment plant releases, tributary inflow, and ground-water discharge to the Rio Grande (Moore and Anderholm, 2002).

Mesilla Valley

The Mesilla Valley is in the southern part of the Rio Grande Valley, and land use is primarily rangeland, agriculture, and urban (Levings and others, 1998). Both surface and ground water are used for agriculture; however, ground water is the principal source for municipal use (Ellis and others, 1993). Depth to water is about 10–25 ft below land surface in the inner valley, and ground-water flow is generally from north to south (Wilson and others, 1981).

Dissolved-solids concentrations are less than 500 mg/L in much of the northeastern part of the Mesilla Valley (fig. 28; Wilson and others, 1981; Thompson, Chapell, and Hart, 1984). Concentrations in the northern half of the valley are affected by the chemical composition of irrigation water, which is similar to Rio Grande water, the principal source of recharge to the shallow alluvial aquifer. Dissolved-solids concentrations are generally higher south of Las Cruces than in other parts of the basin and often exceed 500 mg/L. The higher dissolved-solids concentrations can be attributed to (1) evapotranspiration from the shallow water table, (2) the recirculation of water due to agricultural use, and (3) deep ground-water inflow (Mills, 2003). In the Las Cruces area, reversed gradients caused by ground-water development may result in greater recharge from the agricultural areas near the Rio Grande flood plain (Wilson and others, 1981) and, therefore, increased dissolved-solids concentrations.

Dissolved solids are transported out of the basin when shallow ground water is intercepted by drains and conveyed to the Rio Grande, or by ground-water discharge directly to the Rio Grande. The addition of high-salinity ground water from the Mesilla Valley increases the dissolved-solids concentration and load of the Rio Grande (Moore and Anderholm, 2002).

Upper Colorado River Basin

By Nancy J. Bauch

The status of dissolved-solids concentrations and changes in dissolved-solids concentrations due to natural and human factors along the Colorado River and its tributaries are described in this section. This discussion is limited to stream water because it is the primary water resource used in the Study Unit. Dissolved-solids concentrations that are described for water years 1996–98 are the result of sampling activities in the Upper Colorado River Basin Study Unit as part of the NAWQA Program.

The UCOL Study Unit incorporates the 17,800 mi^2 drainage basin of the Colorado River upstream from the Colorado-Utah State line (figs. 1 and 29). The UCOL Study Unit is almost equally divided between the Southern Rocky Mountain and Colorado Plateaus Physiographic Provinces (fig. 29). The topography varies from rugged mountains in the east and south to high plateaus and mesas and broad valleys in the west. The climate varies with altitude from alpine conditions and 40 in. or more of precipitation per year in the mountains to arid conditions and less than 10 in. of precipitation per year in the western valleys. The Colorado River originates in the central mountains of Colorado and flows about 230 mi southwest into Utah. About 327,000 people reside in the basin (table 15), which is primarily rural with small towns. The largest municipality, Grand Junction, Colo., had a population of almost 42,000 in 2000 (Colorado Department of Local Affairs, 2004). There are large seasonal fluctuations in nonresident population throughout the basin due to recreational activities.

Most (99 percent) of the water used in the UCOL Study Unit is surface water, of which 97 percent is used for irrigated agriculture. Most irrigated agriculture occurs in the Grand Valley around Grand Junction and in the Uncompahgre River Valley around Montrose, Colo. (fig. 29). Ground water from alluvial aquifers is an important resource in mountain and rural areas and is used primarily for domestic and municipal purposes. Many mountain towns rely on this ground water for their municipal water supply. In some areas, there may be individual domestic use of ground water from deeper consolidated-rock aquifers.

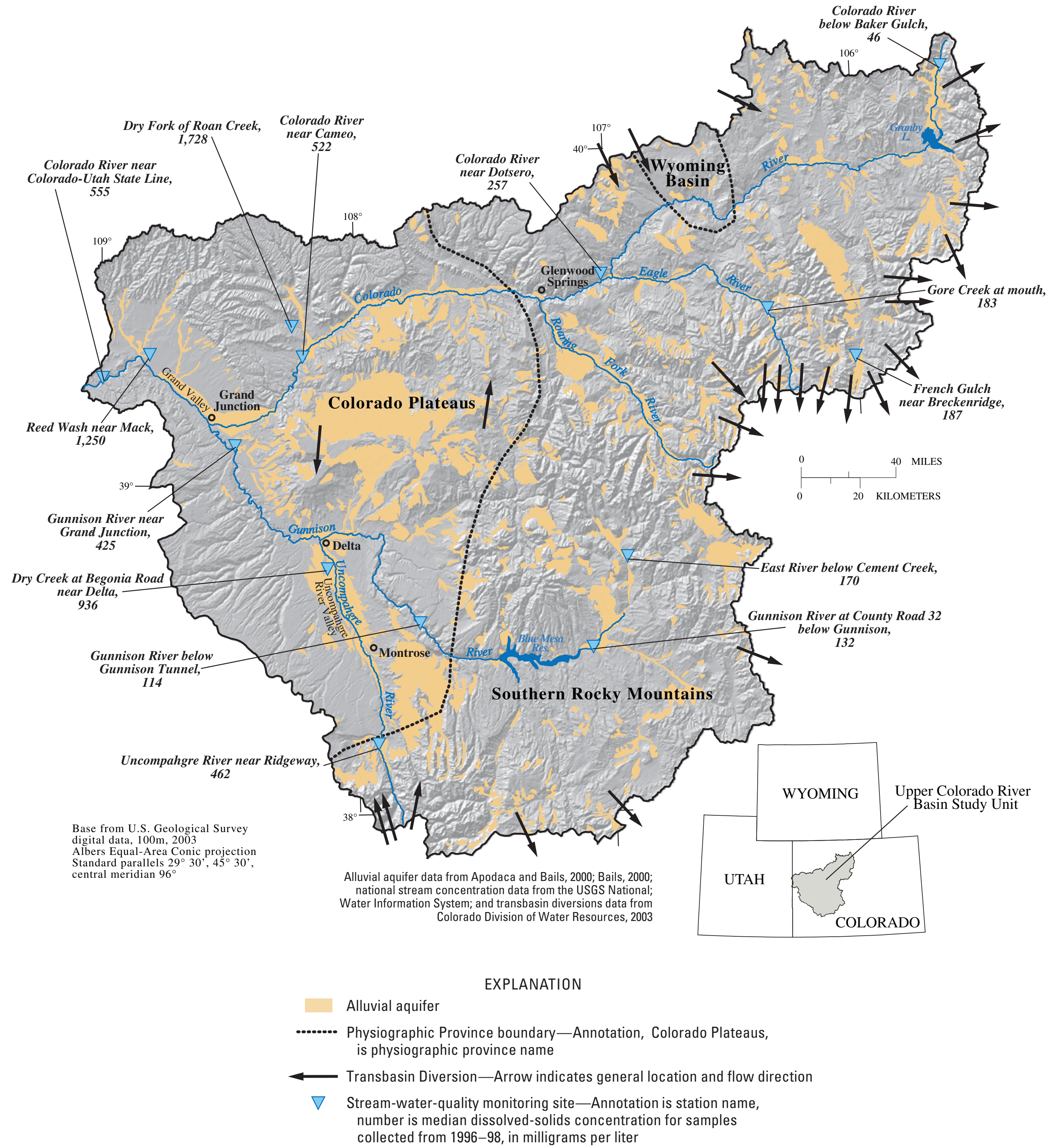


Figure 29. Dissolved-solids concentrations in the Colorado River and its tributaries in the Upper Colorado River Basin Study Unit.

Most streamflow in the Colorado River and its tributaries originates as snow in the mountainous areas of the basin. Streamflow peaks with snowmelt in the spring and early summer and decreases as the supply of snow is fully melted. Localized summer thunderstorms can cause rapid increases in streamflow over short periods of time for some streams, especially those in the western parts of the basin. In winter, most streamflow is base flow from ground water. Throughout the year, reservoir releases add stored water to streams. Streamflow generally increases in a downstream direction in the basin but may decrease in areas with diversions for water supply, power generation, and reservoir impoundments. Twelve major transbasin diversions in the headwater areas remove between 450,000 to 600,000 acre-ft of water per year from the basin and transport it east to the Front Range of Colorado (Colorado River Water Conservation District, 2004a, 2004b). The diversions make up more than 25 percent of Colorado's total use of the Colorado River (Colorado River Water Conservation District, 2000b).

In the Uncompahgre River and Grand Valleys, a complex system of canals, ditches, and drains divert stream water to and from irrigated-agricultural areas. In the central part of the basin, the combined annual discharge of the thermal mineral springs near Dotsero and Glenwood Springs to the Colorado River is 25,000 acre-ft (U.S. Department of the Interior, 2003).

The alluvial aquifers in the UCOL Study Unit are unconsolidated valley-fill deposits of moderately sorted boulders, cobbles, gravel, sand, and silt along principal streams (fig. 29; Apodaca and Bails, 2000). The extent of these deposits is small and discontinuous. In headwater areas, the alluvial material is derived from igneous and metamorphic rocks that are resistant to the solvent action of water. In downstream areas, shales and silts that contain soluble salts are the principal components of the alluvium. In the Grand and Uncompahgre River Valleys, much of the alluvial material is reworked Mancos Shale, a saline marine deposit. Recharge of the alluvial aquifers occurs through the percolation of precipitation or irrigation water, by infiltration of water from streams, and by inflow from adjacent bedrock aquifers (Apodaca and others, 2002). Ground water is discharged from the alluvial aquifers as base flow to streams, through withdrawal from wells for individual and municipal use, and by evapotranspiration from vegetation. The only principal aquifer system that is present in the UCOL Study Unit is the Colorado Plateaus aquifers in western Colorado (fig. 2). Because this principal aquifer is not commonly used as a source of water in the UCOL Study Unit, it is not discussed in this section.

Upper Colorado River and its Tributaries

The major natural factors affecting dissolved-solids concentrations in the stream and ground water of the UCOL Study Unit are the different types of rocks and soils in the basin and the solubility of materials in the rocks and soils. The many thermal mineral springs in the central portion of the basin near Dotsero and Glenwood Springs, Colo., and downstream from Carbondale, Colo., on the Roaring Fork River also affect stream-water quality (fig. 29). The principal anthropogenic factors affecting dissolved solids are irrigated agriculture and transbasin diversions.

In headwater areas of the UCOL Study Unit, streams that are underlain by relatively insoluble igneous and metamorphic rocks typically have low dissolved-solids concentrations that are less than 100 mg/L (fig. 6; pl. 1). Other streams overlie volcanics and sedimentary rocks that are primarily derived from the igneous and metamorphic rocks, and dissolved-solids concentrations in these streams are slightly higher. Median dissolved-solids concentrations at surface-water-quality monitoring sites in the Southern Rocky Mountains Physiographic Province typically were less than 200 mg/L for water years 1996–98 (Spahr and others, 2000). With the low solubility of rocks in the mountainous areas, there is little appreciative effect of geology on dissolved-solids concentrations in ground water. The median dissolved-solids concentration in water from alluvial aquifers in the Southern Rocky Mountains Physiographic Province was 176 mg/L during 1997 (Apodaca and Bails, 2000).

Sedimentary rocks that contain soluble, saline marine deposits and a veneer of alluvium derived from the sedimentary rocks underlie streams in the central and western parts of the UCOL Study Unit. Because of this geology, and as a result of irrigation practices in the agricultural areas of western Colorado and the reuse of water throughout the basin, the concentration of dissolved solids increases progressively downstream. On the main stem of the Colorado River, median dissolved-solids concentrations increased from a low of 46 mg/L in the headwaters to 555 mg/L at the Colorado-Utah State line for water years 1996–98 (fig. 29). Small tributaries in the Colorado Plateaus and agricultural areas had dissolved-solids concentrations in the thousands of milligrams per liter for the same time period (Spahr and others, 2000).

In the west-central part of the UCOL Study Unit, evaporite beds of the Eagle Valley Evaporite Formation contribute an estimated 880,000 tons of dissolved solids per year to the Colorado River (Chafin and Butler, 2002). The total salt load consists of contributions from the Eagle River Basin; the Roaring Fork River Basin; the Colorado River Basin upstream from the mouth of the Eagle River; saline springs and ground water along the Colorado River between the sites Colorado River near Dotsero and Colorado River near Glenwood Springs, and in the vicinity of Glenwood Springs; and three small, southward-flowing creeks downstream from Glenwood Springs. Of the total salt load, the springs and seeps along the Colorado River near Dotsero and Glenwood Springs alone contribute about 50 percent (440,000 tons of dissolved solids) to the river annually (U.S. Department of the Interior, 2003). Eisenhauer (1983) measured an average dissolved-solids concentration of 9,954 mg/L for 11 springs in the Dotsero area and 18,780 mg/L for 14 springs in the Glenwood Springs area. Median dissolved-solids concentrations in the Colorado River increased from 257 mg/L at a site near Dotsero upstream from the springs to 522 mg/L at a site about 90 mi downstream near Cameo, Colo., for water years 1996–98 (fig. 29).

In the agricultural areas around Grand Junction and Montrose, Colo., most of the soil is derived from Mancos Shale. Deep percolation of irrigation water and seepage losses from irrigation-canal systems leach salt from the soil and shale, increasing the dissolved-solids concentrations in the ground water and subsequent irrigation-return flows. The effect of the Mancos Shale on concentrations is apparent in an intensively farmed and ranched area in the Grand Valley where the median dissolved-solids concentrations in a stream were about 4,200 mg/L in base flow during winter and 920 mg/L in high flow during spring runoff for water years 1996–98. An estimated 940,000 tons of dissolved solids per year are added to the Colorado River from the agricultural areas in the Grand and Uncompahgre River Valleys (U.S. Department of the Interior, 2003). Because ground-water recharge from irrigation practices is the major source of this dissolved-solids loading (Bureau of Reclamation, 1978), salinity-control projects have been developed in the agricultural areas to limit the amount of recharge (fig. 12). These projects include the lining of the conveyance systems, underground piping, upgrading irrigation systems, and improving irrigation management.

Transbasin diversions in headwater areas of the UCOL Study Unit transport high-quality water with low dissolved-solids concentrations out of the basin and east to the Front Range of Colorado. Water in one major diversion, for example, had a mean dissolved-solids concentration of 29 mg/L in the 1980s and early 1990s (Bauch and Spahr, 1998). This removal of water having low dissolved-solids concentrations from the UCOL Study Unit has the effect of increasing dissolved-solids concentrations downstream in the basin. Iorns and others (1965) estimated that for one site on the Colorado River near its headwaters, the weighted average dissolved-solids concentration increased from 60 to 74 mg/L (about a 23 percent increase) during the 7 years before and after water diversions and water storage began.

The Colorado River and its tributaries in Colorado are a major source of dissolved solids for the Colorado River Basin below the Colorado-Utah State line. About 50 percent of the median annual dissolved-solids load at Lees Ferry, Ariz., is contributed by the Colorado River Basin upstream from the Colorado-Utah State line (appendix 4; pl. 1). There are no appreciable areas of accumulation for dissolved solids in the UCOL Study Unit.

Central Arizona Basins

By David W. Anning

The status of dissolved-solids concentrations and changes in dissolved-solids concentrations due to natural and human factors along flow paths for four basins in the CAZB Study Unit are described in this section. These basins straddle the Gila River near the Phoenix metropolitan area and include the East Salt River Valley, the West Salt River Valley, the Eloy Basin, and the Maricopa-Stanfield Basin (fig. 30). Concentrations in the ground water in parts of these basins and concentrations in the Gila River and some of its tributaries often exceed the USEPA SDWR of 500 mg/L for dissolved solids in drinking water (fig. 30), and therefore, it is important to understand sources, transport processes, and areas of accumulation of dissolved solids in these basins. Environmental conditions are similar among the basins, and the hydrologic boundaries separating them (ground-water subbasin boundaries shown in fig. 30) are not as easily distinguished as for other basins in the Southwest. For this reason, the basins are discussed in a single section below rather than on an individual basis.

In comparison to the other areas discussed in this report, these basins are generally hotter and dryer. The climate of these basins is arid with hot summers, mild winters, and large daily temperature variations. Average annual rainfall is 8–12 in. (Spatial Climate Analysis Service, 2000), and free-water-surface evaporation rates can exceed 5 ft/yr (Farnsworth and others, 1982).

The basins were selected for discussion primarily because they contain most of the population, irrigated cropland, and, therefore, water-use of the CAZB Study Unit. More than 65 percent of Arizona's population is concentrated in these basins with the majority in Phoenix and the surrounding cities that are in the East and West Salt River Valleys (U.S. Census Bureau, 2004). Although rangeland and agriculture are the predominant land uses by acreage in these basins, they are rapidly being overtaken by urban development (Cordy and others, 1998; fig. 10). Despite a 30-percent decline in irrigated acreage in Arizona from 1975 to 2000 and conversion of agricultural water use to municipal and industrial uses, agriculture remains the largest water user in Arizona, consuming about 80 percent of the water used in 2000 (Konieczki and Heilman, 2004).

The water withdrawals for 2000 were evenly split between surface water and ground water (based on data for Maricopa County in Konieczki and Heilman, 2004). Over time, ground-water withdrawals have not been replenished by natural recharge, and thus, these basins are in a state of ground-water overdraft. In an effort to address extensive overdraft and sustain agriculture, water supplies have been supplemented by a transbasin diversion of Colorado River water that has been delivered to these basins as part of the Central Arizona Project since the mid- to late 1980s. The Colorado River water represents a substantial source of dissolved solids being imported to the basins (Anning, 2003) as discussed below.

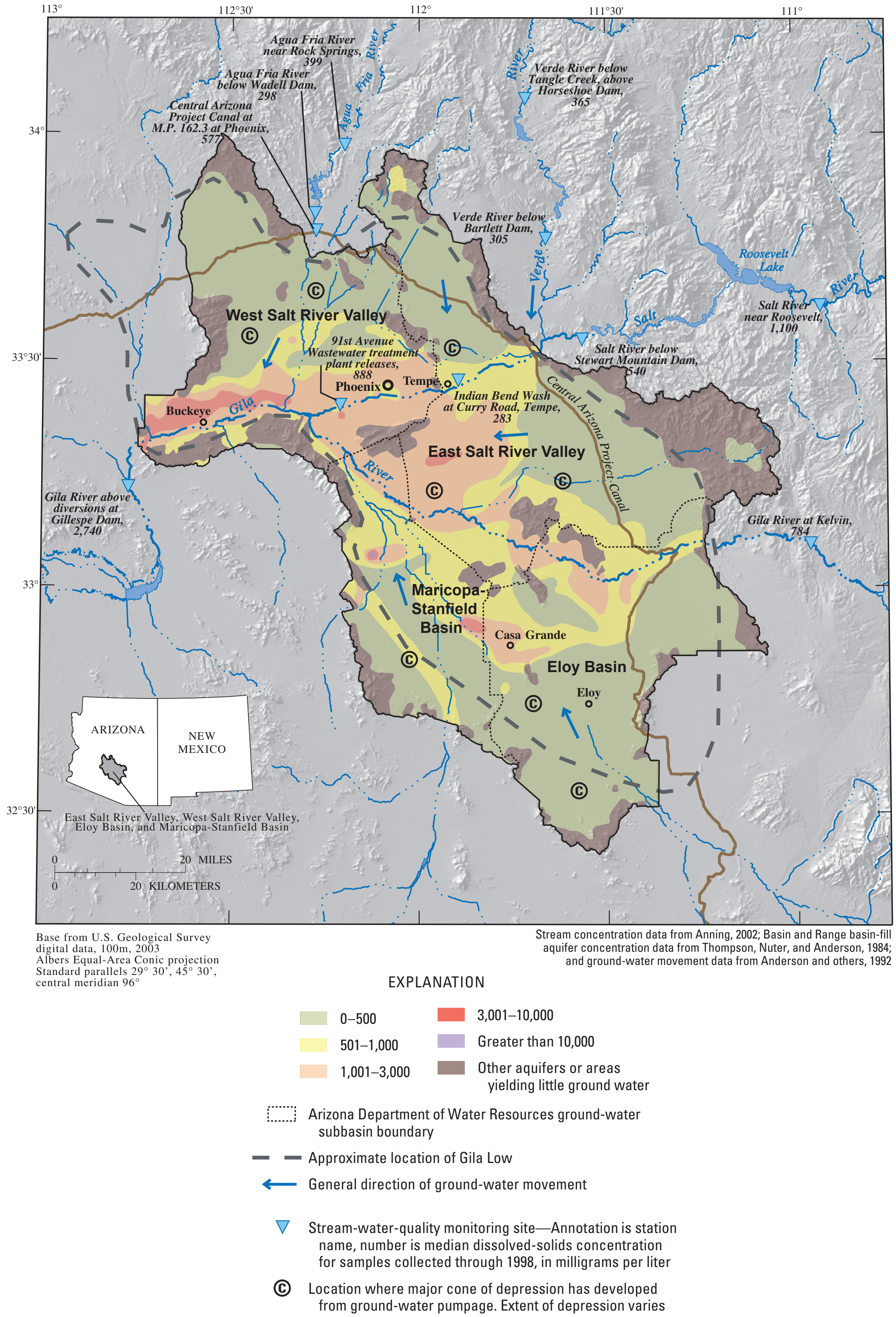


Figure 30. Dissolved-solids concentrations in the Basin and Range basin-fill aquifers, the Gila River, and its tributaries in the East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin of the Central Arizona Basins Study Unit.

The basins are contiguous and hydraulically interconnected by streamflow in the Gila River, its tributaries, and diversion canals and also by subsurface flow through Basin and Range basin-fill aquifers (fig. 30). Ground water in these basins is generally unconfined. Recharge takes place along the mountain fronts and along the axis of each basin where permeable alluvium in stream channels accepts infiltration of surface runoff (Anderson and others, 1992). Excess irrigation water and seepage from canals also provide recharge in these basins (Brown and Pool, 1989). Ground-water flow in the basin-fill aquifers is generally parallel to surface flow and is toward and along the Salt and Gila Rivers, except where substantial ground-water withdrawals have created ground-water overdraft and large cones of depression that divert water from normal flow paths (fig. 30; Anderson and others, 1992). Many of the basin-fill aquifers are hydraulically disconnected from the rivers, and as a result, natural discharge of ground water to land surface is limited. Most of the ground-water discharge from basin-fill aquifers in these basins is by pumping for agricultural and municipal use, evapotranspiration, discharge to streams as base flow, and underflow to downgradient basins (Anderson and others, 1992).

East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin

The Gila River and its major tributaries, the Agua Fria, Salt, and Verde Rivers, drain the Mogollon Rim (outside of fig. 30) and are impounded to provide steady, reliable surface-water supplies to users in the East Salt River Valley, West Salt River Valley, Eloy Basin, and Maricopa-Stanfield Basin (fig. 30). In reaches of the Agua Fria, middle Gila, Salt, and Verde Rivers upstream from reservoirs, dissolved-solids concentrations can be less than 100 mg/L during periods of runoff; however, they are much higher when streamflow is sustained solely by spring flow and ground water discharged through the streambed. During periods of low flows in these reaches, concentrations vary by discharge, but typically are between 200 and 700 mg/L (Anning, 2003). For the Salt River near Roosevelt (fig. 30), however, concentrations frequently are more than 500 mg/L and have been as high as 3,110 mg/L (Anning, 2003). The high concentrations result from discharge of upstream saline springs that issue from Precambrian quartzite near the junction of the White and Black Rivers and near Salt Banks (upstream from Roosevelt Lake and outside of fig. 30; Feth and Hem, 1963).

Large reservoirs on the Agua Fria, middle Gila, Salt, and Verde Rivers reduce the dissolved-solids concentrations and their variability. Median sample concentrations of dissolved solids, which represent a time-weighted central value for concentrations in the stream, are lower in reaches downstream from large reservoirs than in reaches upstream of the reservoirs (fig. 30). For example, the median sample concentration for the Salt River near Roosevelt, 1,100 mg/L, is about twice as large as that for the Salt River below Stewart Mountain Dam, 540 mg/L (fig. 30). This decrease results from dilution of relatively high-concentration base flows by low-concentration runoff from winter frontal storms or summer thunderstorms. Mixing and storage of reservoir inflows also reduces the variability of dissolved-solids concentrations in reservoir releases. For example, the standard deviation of samples from the Salt River near Roosevelt, 663 mg/L, is nearly four times greater than that for the Salt River below Stewart Mountain Dam, 176 mg/L. The reduced concentration and variability represents improved water quality and a more consistent supply for water users.

Downstream from the reservoirs on the Agua Fria, middle Gila, Salt, and Verde Rivers, all water is diverted out of the rivers and used for agricultural irrigation or municipal supply. The diversions result in dry channels except during periods of rainfall runoff or infrequent occasions when the reservoirs spill. Storm runoff from Indian Bend Wash, an urban dry wash near Phoenix, had a median sample concentration of 283 mg/L (fig. 30; Anning, 2003, appendix 1). Runoff in these ephemeral channels also is a source of ground-water recharge. Some stream reaches in urban areas that would otherwise be dry, have perennial flow where wastewater is returned to the major rivers after municipal or irrigation use.

The Central Arizona Project Canal carries water into the area from the Colorado River to supplement surface-water supplies and thereby mitigate ground-water overdraft that can lead to land subsidence and other problems. The median sample concentration of dissolved solids in Central Arizona Project water is 577 mg/L, which is 77 mg/L above the USEPA SDWR (fig. 30).

Ground water from basin-fill aquifers is used when and where surface-water supplies are unavailable. Ground-water quality varies along flow paths. Dissolved-solids concentrations for water from basin-fill aquifers near recharge areas are typically about 400 mg/L, and may decrease to less than 200 mg/L downgradient, as a result of precipitation reactions, or may increase to several thousand milligrams per liter as a result of dissolution reactions (Robertson, 1991). For the West Salt River Valley and the northern part of the East Salt River Valley, concentrations are lowest (less than 500 mg/L) in the northern parts of these areas along basin margins near bedrock mountains at the upgradient end of flow paths (fig. 30). Concentrations increase to the south along the flow paths and are highest (up to 10,000 mg/L) along the lower Salt and Gila Rivers where ground water discharges. For the Maricopa-Stanfield and Eloy Basins and the southwestern part of the East Salt River Valley, concentrations are lowest in the southern parts of these areas and increase to the north and west along the flow paths toward the Gila River.

High dissolved-solids concentrations in ground water near the lower Salt and Gila Rivers may be attributed to at least three factors: evapotranspiration, the presence of massive basin-fill evaporite deposits, and long flow paths. Dissolved solids in shallow ground water along and directly adjacent to the lower Salt and Gila Rivers may be concentrated by evapotranspiration of ground water by phreatophytes—relatively pure water is transpired to the atmosphere and the residual salt remains in the ground water and soils. High dissolved-solids concentrations in ground water in the vicinity of the lower Salt and Gila Rivers (Gellenbeck and Coes, 1999) also can be attributed to occurrence of massive evaporite deposits that occur in an area described by Peirce (1974) as the "Gila Low" (fig. 30). The Gila Low is interpreted to have been a late Cenozoic terminal "sink" (area of accumulation) for dissolved materials transported from adjacent basins of a regionally closed drainage system (Scarborough and Peirce, 1978). Minerals that make up the evaporite deposits include gypsum, anhydrite, and halite. These deposits provide a rich, soluble source for dissolution, and could thereby increase dissolved-solids concentrations in ground water. For selected wells in the Eloy Basin, Kister and Hardt (1966) found a correlation between specific conductance and vertical proximity to evaporite deposits. The correlation indicated that evaporites were dissolving and increasing dissolved-solids concentrations in ground water. High concentrations near the lower Salt and Gila Rivers can also be attributed to the long distances traveled by water moving along flow paths at slow velocities. The associated long distances, and therefore long travel times, allow for dissolution of evaporites and for aquifer matrix-water interactions to occur and increase concentrations as water flows through the alluvial deposits.

In some areas, irrigation causes increased dissolved-solids concentrations in ground water. Kister and Hardt (1966) point out that irrigation concentrates the mineral content in water through evapotranspiration and that this water will seep down toward the aquifer, and thereby increase dissolved-solids concentrations. Kister and Hardt (1966) note that this may not be the case for some areas near Eloy and Casa Grande where, as a result of ground-water pumpage, water levels are probably declining faster than the rate of downward movement of percolating excess irrigation water. Kister and Hardt (1966) hypothesize that in these areas, percolating excess irrigation water may not affect water quality. These findings would also apply for urban irrigation, although this type of water use was not prevalent at the time of their study.

In the West Salt River Valley, concentrations of dissolved solids in ground water and surface water are affected by use and reuse of water. Median sample concentrations are larger in the effluent from the 91st Avenue Wastewater-Treatment Plant (WWTP) that is returned to the lower Salt River than are concentrations in water diverted upstream from the WWTP below the dams (fig. 30). The median dissolved-solids concentrations in the effluent from the WWTP is 888 mg/L, which is 348 mg/L and 583 mg/L greater than median concentrations for reaches below reservoirs on the Salt River and Verde River, respectively (fig. 30). This difference in concentration can be attributed to salts added to the water during use, as well as the fact that other sources of water with higher dissolved-solids concentrations, such as ground-water and Central Arizona Project water (fig. 30), also are used for municipal purposes and then treated at the 91st Avenue WWTP.

Downstream from the 91st Avenue WWTP, effluent flows down the lower Salt River and into the Gila River. Downstream from the mouth of the Agua Fria River, effluent in the Gila River is diverted and reused for irrigation, and excess irrigation water is returned back to the Gila River. Dissolved-solids concentrations increase in this reach down to Gillespie Dam, where the median concentration is 2,740 mg/L (fig. 30). This increase of 1,852 mg/L, is the result of evapotranspiration and soil-water interactions that occur during irrigation and also from saline ground-water discharges to the Gila River (Anning, 2003).

Edmonds and Gellenbeck (2002) found evidence for concentration of dissolved solids in ground water by irrigation seepage in their study of the West Salt River Valley. For an irrigated area in the southwestern part of the West Salt River Valley, dissolved-solids concentrations were about 2,500 mg/L higher in wells that had perforations above a fine-grained confining bed than in wells that had perforations entirely below the confining beds. The high dissolved-solids concentrations in ground water above the confining bed in the southwestern, downgradient end of the West Salt River Valley was attributed to the seepage of irrigation water and its entrapment above the confining beds, as well as reuse of water as it moves through the West Salt River Valley.

Despite the fact that the closed-drainage system contributing to the Gila Low has opened since Late Cenozoic times and now drains to the Colorado River, the four basins currently are areas of accumulation for dissolved solids. In 1997, about 1.8 million tons of dissolved solids entered the basins adjacent to the Gila River through the Agua Fria, middle Gila, Salt, and Verde Rivers, as well as through the Central Arizona Project Canal (Anning, 2003). Due to diversions for municipal and agricultural use from streams and the Central Arizona Project Canal, only about 0.5 million tons of dissolved solids annually are transported out of the basins through the Gila River above diversions at Gillespie Dam, which is at the surface and subsurface outlet for the four basins (fig. 30). The difference, 1.3 million tons of dissolved solids per year, remains in the basins and is most likely stored in soils, the unsaturated zones, and aquifers in agricultural and urban areas as a result of diverting the streams and irrigating crops and urban vegetation.

Nevada Basin and Range

By Donald H. Schaefer

The status of dissolved-solids concentrations and changes in dissolved-solids concentrations due to natural and human factors along flow paths are described in this section for several basins within the Carson River Basin and the Las Vegas Valley. The Truckee River Basin, which is also in the NVBR Study Unit (fig. 27), is not included in this discussion because of its hydrologic similarity to the Carson River Basin, and because it is intermediate between the Carson River Basin and the Las Vegas Valley in the amount of agricultural and urban development.

Nevada is the driest State in the Nation (Bevans and others, 1998) with annual precipitation ranging from 30 in. in the Sierra Nevada to less than 5 in. in the Carson Desert and the Las Vegas Valley. For the most part, ground water from the deeper, principal aquifers is the focus of this water-quality discussion. Ground water from shallow aquifers in the basins described here is generally not used because these aquifers contain water of much poorer quality than that of the principal aquifers.

In 2000, the Carson River Basin contained a population of about 124,000 people. In the same year, the Las Vegas Valley had about 1.6 million people and the fastest population growth in the West, with an annual growth rate up to 34 percent/yr in some parts of the valley. Population density is highest in the Las Vegas Valley, exceeding 20,000 people per mi^2 in the city of Las Vegas. In both basins, urban development has replaced agricultural and rangeland areas. Surface water is the major source of water supply and provides about 80 percent of the total water demand. Water is exchanged between the Truckee River Basin and the Carson River Basin through the Truckee Canal. Municipal water use accounts for about 90 percent of the total water use in the Las Vegas Valley, but only about 20 percent in the Carson River Basin. In contrast, agricultural and other water uses are only 10 percent of the total water use in the Las Vegas Valley, but 80 percent in the Carson River Basin. As a consequence of the arid climate and the demands of the urban population, the hydrologic cycle is affected by human activities: ground-water pumping, engineered recharge operations, and use of treated wastewater for irrigation.

Carson River Basin

Streamflow in the Carson River (fig. 31) originates as snowmelt in the Sierra Nevada. The upper and middle reaches of the Carson River are minimally regulated, and base flows within these reaches are maintained largely by ground-water discharge and irrigation-return flows. The lower reaches of the Carson River, including discharges to the Carson Desert, are regulated by water releases from Lahontan Reservoir. The Carson River is a terminal system, and both surface water and ground water ultimately discharge into the Carson Sink. The Carson Sink is typically closed; however, during periods of extremely high flow it can be hydraulically connected to the terminus of the Humboldt River (Humboldt Sink, Paul and Thodal, 2003; fig. 27).

The Carson River Basin contains several ground-water basins with basin-fill aquifers (fig. 31). In most cases, the ground-water basins are hydraulically connected to each other and to the river systems that flow through them. Information about dissolved-solids concentrations in the principal aquifers of these ground-water basins is presented in this section on the basis of samples collected as part of the NVBR NAWQA program, as well as other studies that have shown dissolved-solids concentrations to be related to natural and human factors.

The Carson Valley is the most upgradient ground-water basin in the Carson River Basin that has dissolved-solids concentration data available. The Carson Valley is primarily an agricultural area, but urban areas are rapidly increasing. In 2000, about 37 percent of ground water pumped was used for irrigation and stock watering (Lopes and Evetts, 2004, p. 21). Many of the houses in the valley are on septic systems. Widespread use of septic tanks within urban areas has caused elevated nitrate concentrations in shallow aquifers. The septic systems also have caused an overall increase in dissolved-solids concentrations in shallow ground water. A study to examine the effects of septic systems in the Carson Valley indicates that nitrate concentrations increased in 56 percent of shallow wells monitored from 1985 to 2001. Dissolved-solids concentrations increased in 52 percent of the wells monitored during the same time period (Rosen, 2003). Treated municipal effluent from the adjacent Lake Tahoe basin is piped to the Carson Valley and used for irrigation during the summer and stored in constructed wetlands during the winter (Lico, 1998). This interbasin transfer adds dissolved solids to the Carson Valley and increases concentrations because the dissolved-solids concentration of the effluent is higher than that of the native water. Welch and others (1989) found that active geothermal systems also have an effect on ground-water quality in the Carson River Basin, where concentrations of fluoride and sulfate are elevated compared to surrounding areas. Dissolved-solids concentrations in ground-water samples collected in the Carson Valley in 1988 and 1995 range from less than 100 mg/L to greater than 500 mg/L, and average about 450 mg/L. These data indicate that dissolved-solids concentrations generally increase downgradient in the direction of ground-water flow.

Eagle Valley, the next ground-water basin downgradient along the Carson River, includes Carson City and the State Capitol, and is primarily urban with a few remaining agricultural areas. The principal aquifer in Eagle Valley was sampled in 1988 and most recently in 2002 with two different networks that sampled both public-supply wells and deeper domestic and observation wells. Dissolved-solids concentrations for these samples range from about 100 mg/L to more than 500 mg/L, and average about 270 mg/L. Eagle Valley also includes several geothermal areas (fig. 31) that may affect water quality in the northern part of the valley. A golf course in the northeastern part of the valley has been irrigated with treated sewage effluent for many years, and higher concentrations of dissolved solids were measured in ground water here than elsewhere in Eagle Valley. Maurer and Thodal (2000, p. 42), found that sewage effluent used as recharge was one of the most likely sources of ground-water contamination among all sources of recharge in Carson City. Dissolved-solids concentrations in treated sewage effluent were about five times higher than finished drinking water served to the city.

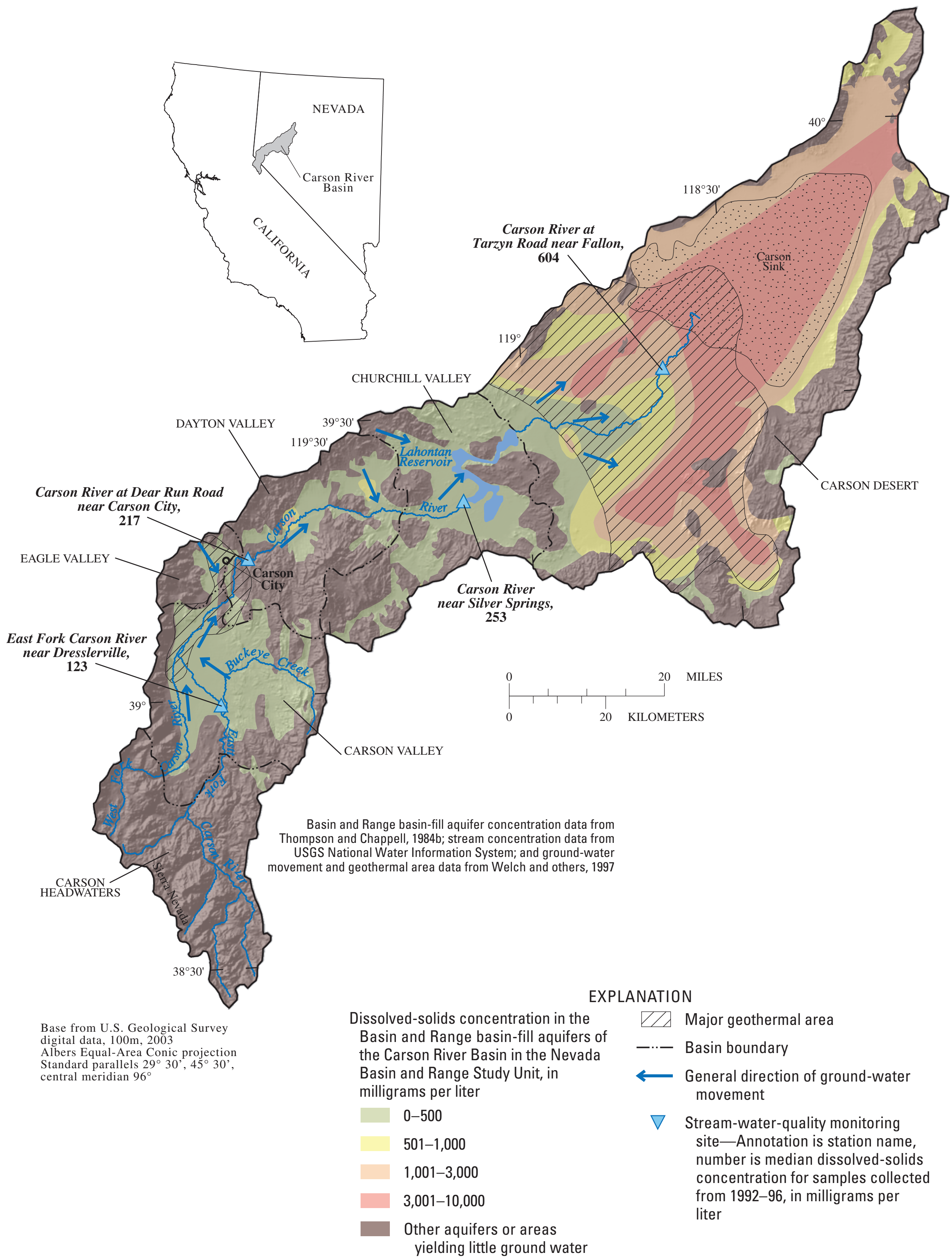


Figure 31. Dissolved-solids concentrations in the Basin and Range basin-fill aquifers, the Carson River, and its tributaries in the Carson River Basin of the Nevada Basin and Range Study Unit.

Dayton Valley, the next ground-water basin downgradient along the Carson River, contains some rapidly urbanizing areas; however, the valley is primarily agricultural. Most of the residences in the basin are on septic systems. A considerable amount of mining activity has occurred in the basin since the 1870s. The famous Comstock Lode of Virginia City is in this area, as well as several mills that processed the ore by using mercury. High sulfate concentrations in ground water in the western part of Dayton Valley are the result of gypsum deposits. Dissolved-solids concentrations in ground-water samples collected in this basin in 1988 and 1989 range from 200 mg/L to almost 500 mg/L, and average 325 mg/L.

Moving eastward and downgradient in the Carson River Basin, the average altitude of land surface decreases and average air temperature increases. Loss of ground water through evapotranspiration increases in the downstream basins. When shallow ground water is transpired through plants or evaporated directly from the ground, dissolved solids are left behind and the overall dissolved-solids concentration increases as in Churchill Valley, the next basin downgradient. Churchill Valley has some isolated agricultural areas, as well as some isolated urban areas. Most houses in this basin are on septic systems. Dissolved-solids concentrations in ground-water samples collected in this basin in 1988 and 1989 range from 300 mg/L to more than 1,500 mg/L, and average 450 mg/L.

The Carson Desert is the next ground-water basin downgradient, and it is a closed basin that has no surface or subsurface outflow. The Lahontan Reservoir bounds the upstream part of the Carson Desert and serves to store water that is later released for agricultural use and for maintaining wetlands around the valley. Dissolved-solids concentrations in ground-water samples collected in this basin in 1988–89, 1994, and 2001 ranged from less than 200 mg/L to greater than 8,000 mg/L, and averaged about 800 mg/L. Owing to the closed nature of the hydrologic system of the Carson Desert, surface and subsurface water flow to the Carson Sink, a playa at the downgradient end of the basin. Surface water and shallow ground water is removed from the basin by evaporation, and as a result, the highest concentrations of dissolved solids generally occur in the vicinity of the Carson Sink.

Another factor that contributes to high dissolved-solids concentrations in the ground water of the Carson Desert is the cultivation and irrigation of about 56,000 acres of land. During irrigation, relatively good quality water is evaporated and transpired, and poorer quality water is returned to the ground water. The high water table that has resulted from irrigating lands since 1915 has mobilized arsenic compounds, as well as other constituents that become concentrated over time due to evaporation (Welch and others, 1997).

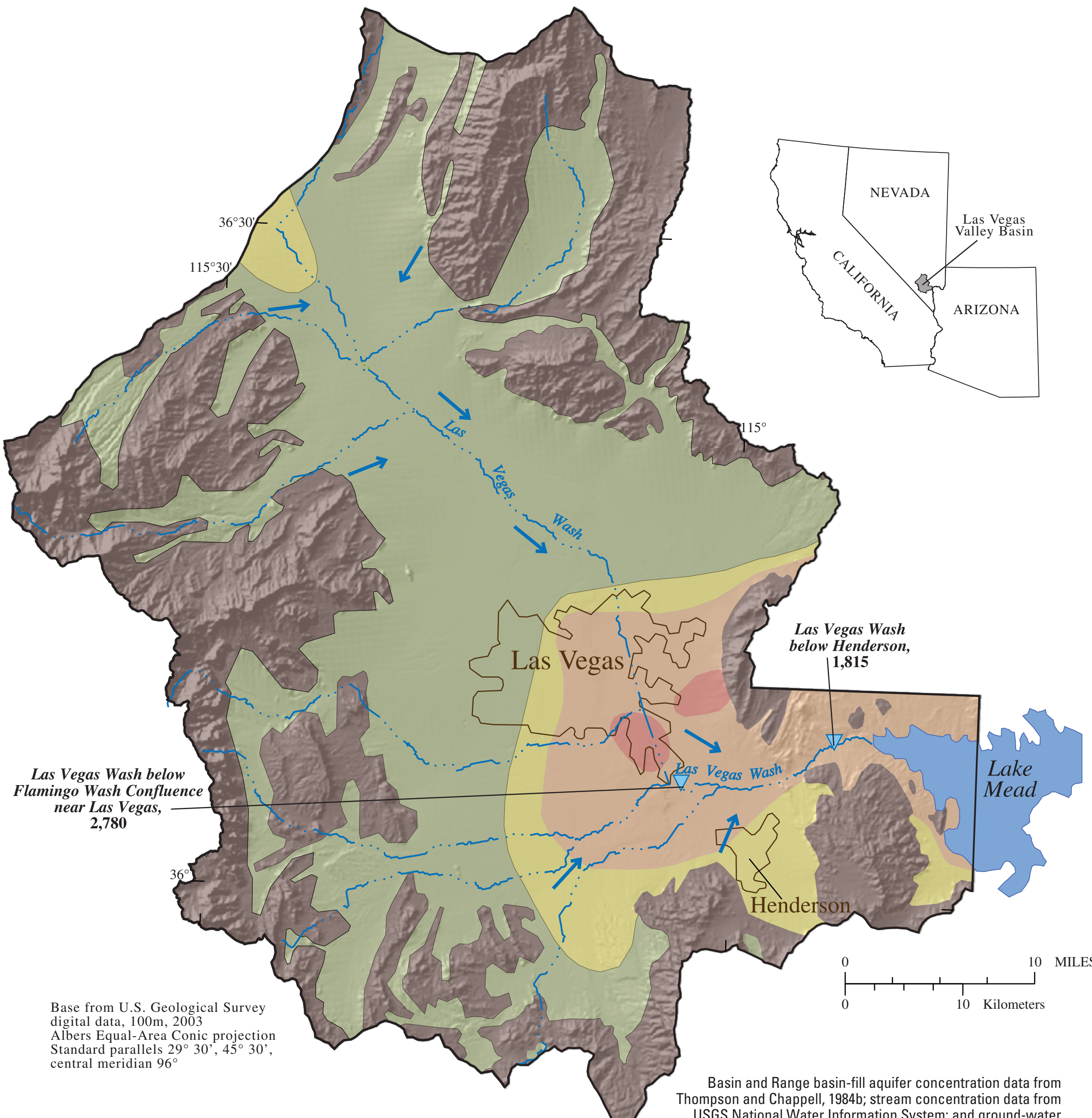
Dissolved-solids concentrations in the Carson River and its tributaries were characterized for 1992–96 as part of a NAWQA surface-water-quality sampling program (Bevans and others, 1998). Dissolved-solids concentrations generally increase downstream in the Carson River. Median dissolved-solids concentrations in the headwaters of the Carson River were 123 mg/L (fig. 31). Near the terminus of the river system, samples from the Carson River near Fallon had a median dissolved-solids concentration of 604 mg/L (fig. 31). The increase in concentration in a downstream direction through the river system is the result of several processes. In the stream headwaters, contact time between water and rock is short, and therefore, dissolved-solids concentrations resulting from dissolution and from geochemical reactions are small. Stream velocities and sediment grain size decrease downstream, thereby increasing the reaction time and reaction surface area between the water and sediment (Bevans and others, 1998). The lower reaches of the Carson River contain evaporite minerals which, when exposed to water, can become a source of sodium, calcium, bicarbonate, and sulfate (Bevans and others, 1998), and the lower reaches are influenced by irrigation drainage (Kilroy and others, 1997). Evapotranspiration processes can also play a key role in concentrating dissolved solids in these streams (Bevans and others, 1998, p. 11).

Las Vegas Valley

The Las Vegas Wash is the major drainage in the Las Vegas Valley (fig. 32). Flow within the wash is perennial, largely due to urban runoff and, within the lower reaches, the inflow of tertiary-treated municipal effluent, industrial effluent, and saline ground water (Covay and others, 1996; Bevans and others, 1998). Flow in Las Vegas Wash increased approximately fourfold from 1964 to 1995 as a result of increases in urban drainage and treated municipal effluent (Bevans and others, 1998). In 1990, it was estimated that 86 percent of the flow in the lower Las Vegas Wash near Henderson was treated municipal effluent (Kilroy and others, 1997). Las Vegas Wash and its tributaries also receive runoff from occasional thunderstorms (Bevans and others, 1998). Surface water and ground water are discharged out of Las Vegas Valley through Las Vegas Wash and into Lake Mead on the Colorado River.

The Las Vegas Valley contains Basin and Range basin-fill aquifers that are underlain by a carbonate-rock aquifer. This discussion will focus on dissolved-solids concentrations in the principal aquifer of the basin-fill deposits. Mountain-front recharge and artificial recharge of Colorado River water are important sources of ground-water recharge. Ground-water discharge is primarily by ground-water pumpage, but also occurs through evapotranspiration where depths to ground water are shallow, and through ground-water seepage to Las Vegas Wash. Use of ground water in 2000 for the Las Vegas Valley was almost 74,000 acre-ft with 99 percent of that amount used for public supply (Lopes and Evetts, 2004).

During periods of low water demand, Colorado River water is used to recharge the deep aquifer in Las Vegas Valley through injection wells. The injected water has considerably higher dissolved-solids concentrations than the existing water in the aquifer and, therefore, this type of recharge diminishes the water quality in the aquifer. In 2000, almost 30,000 acre-ft of water were injected into the principal aquifer in the Las Vegas Valley (Lopes and Evetts, 2004, p. 28).



EXPLANATION

Dissolved-solids concentration in the Basin and Range basin-fill aquifers in the Las Vegas Valley basin of the Nevada Basin and Range Study Unit, in milligrams per liter

- 0–500
- 501–1,000
- 1,001–3,000
- 3,001–10,000
- Other aquifers or areas yielding little ground water

General direction of ground-water movement

Stream-water-quality monitoring site—Annotation is station name, number is median dissolved-solids concentration for samples collected from 1992–96, in milligrams per liter

Figure 32. Dissolved-solids concentrations in the Basin and Range basin-fill aquifers, the Las Vegas Wash, and its tributaries in the Las Vegas Valley of the Nevada Basin and Range Study Unit.

The dissolved-solids concentration of ground water in the Las Vegas Valley varies from less than 500 mg/L near the center of the basin to more than 3,000 mg/L in the southeastern parts of the basin (fig. 32). The highest dissolved-solids concentrations in ground water are in the southeastern part of the Las Vegas Valley near Henderson. This area has been the site of an industrial complex built during World War II and has dissolved-solids concentrations that exceed 15,000 mg/L (Carlsen and others, 1991).

Dissolved-solids concentrations in Las Vegas Wash and its tributaries were characterized for 1992–96 as part of a NAWQA surface-water-quality sampling program (Bevans and others, 1998). The median dissolved-solids concentration for samples from Las Vegas Wash below the confluence with Flamingo Wash was 2,780 mg/L (fig. 32). The high concentrations result, in part, from discharge of ground water to Las Vegas Wash that has been in contact with evaporite minerals, as well as irrigation-return flows. The median concentrations for samples collected downstream from Henderson was lower, 1,815 mg/L, as a result of mixing with lower-concentration treated municipal wastewater (Kilroy and others, 1997).

Great Salt Lake Basins

By Steven J. Gerner

The status of dissolved-solids concentrations and changes in dissolved-solids concentrations due to natural and human factors along flow paths are described in this section for three basins in Utah: (1) Goshen Valley, (2) Utah Valley, and (3) Salt Lake Valley. These basins are described here as the "Great Salt Lake Basins" (fig. 33). The southeastern margin of the Great Salt Lake and its adjacent shore land also is discussed and is included as part of the Salt Lake Valley for the purpose of this report. These three basins were selected for discussion primarily because they represent most of the sources and processes contributing to increased dissolved solids in waters of the GRSL Study Unit.

The climate in the Great Salt Lake Basins is typical of mountainous areas in the western United States. There are wide fluctuations in temperature from winter to summer and from day to night. These basins receive most of their precipitation as snow in winter. Average annual precipitation ranges from 16 in. in the valleys to 70 in. in the surrounding high mountains (Baskin and others, 2002). Most of the annual runoff is in spring from snowmelt, which recharges the principal aquifers along the mountain fronts (Baskin and others, 2002).

More than 76 percent of Utah's population, about 1.7 million people, lives in the cities along the western flank of the Wasatch Range, where the State's largest cities are located. Metropolitan Salt Lake City and Provo are in the Salt Lake and Utah Valleys, respectively. As with many of the areas described in this report, agriculture uses more than 70 percent of the water resources in the Great Salt Lake Basins. Utah, however, has extensive surface-water resources such that 85 percent of the water supplied for all uses is surface water, and 15 percent is ground water (Baskin and others, 2002).

Extensive development and management of the water resources in these basins has prompted numerous basin studies and ongoing data-collection efforts so that much is known about water quality in the streams and underlying aquifers. These basins continue to undergo a transition from largely agricultural to predominantly urban land use, accompanied by changes in patterns of water use. The matrix of climate, land use, water use, population, and hydrologic characteristics found in the Great Salt Lake Basins is unique in the region; however, some of these elements are similar to those of other areas discussed in this report (table 15).

The alluvial basins in the Great Salt Lake Basins study area (fig. 33) are hydraulically interconnected by streamflow and by subsurface flow through Basin and Range basin-fill aquifers. Basin-fill aquifers in Goshen, Utah, and Salt Lake Valleys are categorized as either shallow unconfined aquifers or principal aquifers. Shallow unconfined aquifers overlie the principal aquifers and consist of basin-fill deposits that do not contain fine-grained material that form confining layers. The principal aquifers in these valleys include a confined aquifer system that consists of saturated sand and (or) gravel layers with an overlying, less permeable layer of silt and (or) clay; an unconfined aquifer along the mountain front; and consolidated-rock formations that are in direct contact with and hydraulically connected to the basin-fill deposits (Anderson and others, 1994). The primary recharge areas are along the mountain fronts, where runoff from snow melt can enter the basin-fill aquifers because sediments are permeable and confining layers are absent. Recharge to consolidated-rock formations of the mountains also can flow into adjacent basin-fill aquifers (Baskin and others, 2002). Ground water moves from the recharge areas toward the axes of the basins where it may discharge to streams or to the Great Salt Lake or Utah Lake. Ground water also is discharged by evapotranspiration in areas where the ground water is near the land surface.

The ground-water data discussed in the following sections is for wells finished in the principal aquifers in the three basins. Data were collected as part of the NAWQA program from 1998–2001 (Baskin and others, 2002).

Utah and Goshen Valleys

Ground water and surface water in Utah and Goshen Valleys generally flow into Utah Lake, a remnant of Lake Bonneville, and then flow out of the lake through the Jordan River (fig. 33). Utah Lake provides water to irrigate agricultural and urban land in Salt Lake Valley and provides the exchange water that allows municipalities to use higher-quality water from the Wasatch Range for municipal purposes. The surface area of the lake is about 150 mi^2, and it has an average depth of only about 10 ft; however, the size of the lake is regulated, in part, by a pumping station at the outlet to the Jordan River. The volume of the lake, when full, is about 870,000 acre-ft (Utah Board of Water Resources, 1997).

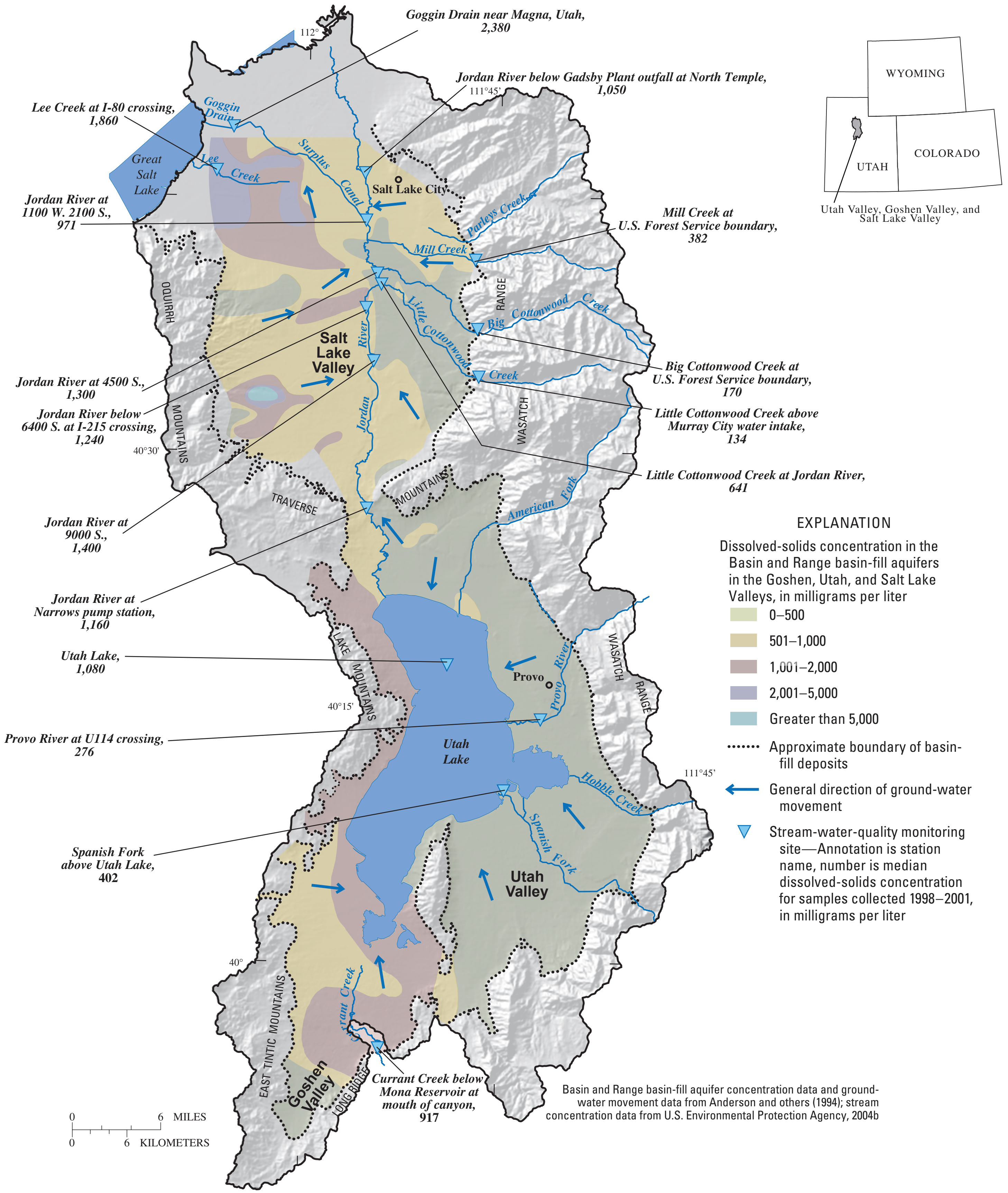


Figure 33. Dissolved-solids concentrations in Basin and Range basin-fill aquifers, the Jordan River, Utah Lake, and their tributaries in the Utah Valley, Goshen Valley, and Salt Lake Valley of the Great Salt Lake Basins Study Unit.

The median dissolved-solids concentration of Utah Lake is about 1,100 mg/L, but this varies with climatic change. Concentrations are relatively high during times of drought, warm temperatures, and when the volume of the lake is small. Concentrations are relatively low during wetter, cooler periods. The primary factors controlling the dissolved-solids concentration of Utah Lake are (1) evaporation, which averages more than 340,000 acre-ft per year (Hyatt and others, 1969, fig. 59) and (2) springs which discharge about 97,000 acre-ft of water directly to the lake. These springs are of two types. The first are cold springs, such as those along the eastern and northern shores, which have characteristics similar to water in the principal aquifer with water temperatures generally less than 68°F and dissolved-solids concentrations that range from 300 to 1,100 mg/L, (Fuhriman and others, 1975; Veirs, 1964). On the western and southern shores of Utah Lake are warm springs, such as those near Lincoln Point, which have water temperatures as high as 97°F and dissolved-solids concentrations that range from 2,700 to 7,930 mg/L (Baskin and others, 1994). These springs are further characterized by travertine and tufa deposits and appear to discharge from a geologic fault extending across the lake in a north-south direction (Fuhriman and others, 1975; Veirs, 1964) and are likely hydraulically connected to fractured consolidated rock.

The principal tributaries to Utah Lake are Provo River, which has headwaters in the Uinta Mountains (not shown in fig. 33) and flows west through a reservoir system in high mountain valleys; and Hobble Creek, American Fork, and Spanish Fork, which drain the Wasatch Range and are diverted for irrigation. Dissolved-solids concentrations in these streams are generally less than 500 mg/L, but can vary from less than 100 mg/L during snowmelt runoff to more than 900 mg/L when most of the flow is diverted for municipal and agricultural use and replaced by urban and agricultural runoff, wastewater, and ground water discharged through seeps, springs, and bed material.

Surface water from the Colorado River Basin is imported to Utah and Salt Lake Valleys through tunnels and aqueducts developed as part of the Central Utah Project. This imported water, which has a dissolved-solids concentration generally less than 250 mg/L, seldom reaches Utah Lake; however, it does recharge ground-water aquifers through canal leakage and deep percolation of unconsumed irrigation applications. Dissolved solids are transported out of Utah Valley to Salt Lake Valley primarily in Jordan River outflow.

Ground-water quality in Utah Valley is similar to the water quality of streams that enter the valley because recharge occurs primarily from surface water and subsurface inflow (Brooks and Stolp, 1995). Dissolved-solids concentrations in Utah Valley ground water are generally less than 500 mg/L east and southeast of Utah Lake and between 500 and 2,000 mg/L west of Utah Lake and the Jordan River (fig. 33).

Ground-water quality in Goshen Valley is variable, with dissolved-solids concentrations ranging from 200 to 2,600 mg/L (Stolp and others, 1993, table 5). Concentrations generally increase from south to north in the direction of flow. The quality of the ground water is more similar to that found in surrounding consolidated rock than to surface water entering the valley, indicating that subsurface inflow is probably the largest contributor to dissolved solids in the Goshen Valley basin-fill aquifer. No perennial streams originate in the mountains adjacent to Goshen Valley; however, Currant Creek flows from Juab Valley (not shown in fig. 33) into the southern end of Goshen Valley. This stream had a median dissolved-solids concentration of 917 mg/L and transports salts that originate from shale deposits in Juab Valley. Currant Creek is almost entirely diverted for agricultural use in Goshen Valley prior to discharging to Utah Lake. As a result, salts transported into the basin by Currant Creek reach Utah Lake through agricultural runoff and ground-water discharge.

Salt Lake Valley

The principal aquifer in Salt Lake Valley is composed of coarse-grained basin-fill sediments that were eroded from the surrounding Wasatch and Oquirrh Mountains. The principal aquifer is generally unconfined near the mountain fronts but becomes confined towards the middle of the basin (Anderson and others, 1994). In general, ground water in the Salt Lake Valley flows from the mountain fronts toward the Jordan River, and then toward Great Salt Lake. Basin-fill material in the southeastern part of Salt Lake Valley consists mainly of resistant quartzite and quartz monzonite that are relatively insoluble, and, as a result, dissolved-solids concentrations in ground water are generally less than 500 mg/L (fig. 33). In the northern part of the valley, where the basin-fill material is derived from less resistant shale and limestone strata that occur in the Wasatch Range. Dissolution of minerals in this aquifer material results in dissolved-solids concentrations in ground water that are greater than 500 mg/L (Thiros, 1995).

Basin-fill material in the southwestern part of Salt Lake Valley includes carbonate rocks that have undergone sulfide mineralization. Geochemical reactions between these rocks and water recharged from a variety of sources has resulted in ground water that is high in chloride and sulfate with a wide range of dissolved-solids concentrations ranging from less than 500 mg/L to more than 5,000 mg/L. Mining processes have resulted in high dissolved-solids concentrations in localized areas, whereas canal seepage and infiltration of unconsumed irrigation water have contributed to higher overall dissolved-solids concentrations in this part of the valley.

In the northwestern part of the valley, sulfate reduction, the presence of calcite, and sodium and chloride ions in pore water left from Lake Bonneville contribute to chemical processes that result in a sodium-chloride-type ground water. Dissolved-solids concentrations typically are greater than 1,000 mg/L in this area.

The Jordan River, which originates at Utah Lake and flows north to Great Salt Lake, varies in dissolved-solids concentration due to the influences of ground-water and tributary inflow, irrigation diversion, wastewater inflow, urban and agricultural runoff, and evapotranspiration. The median dissolved-solids concentration for water samples collected at the Jordan River Narrows is 1,160 mg/L (fig. 33). Most of the flow of the Jordan River can be diverted into irrigation canals at or prior to the Narrows; thus, the principal sources of streamflow downstream from this point may be ground water, irrigation-return flow, and urban runoff (Hely and others, 1971). Near the diversions, dissolved-solids concentrations in ground water that discharges to the river can exceed 2,000 mg/L (Anderson and others, 1994), which results in a median dissolved-solids concentration in the Jordan River at 9000 South Street of 1,400 mg/L. Dissolved-solids concentration in the river downstream of 9000 South Street is diluted by ground water discharged to the river from the eastern side of Salt Lake Valley, inflow from tributary streams, and inflow of municipal wastewater from two treatment plants. Consequently, the median dissolved-solids concentration of water samples from two sites in the central part of the Salt Lake Valley are 1,240 and 1,300 mg/L. Further downstream near the northern end of Salt Lake Valley, the median dissolved-solids concentration of water samples from two sites are 971 and 1,050 mg/L. The Surplus Canal in northern Salt Lake Valley diverts a substantial part of the Jordan River flow for irrigation and flood control. The median dissolved-solids concentrations in the Goggin Drain/Surplus Canal and nearby Lee Creek are 2,380 mg/L and 1,860 mg/L, respectively, near their outflows to Great Salt Lake. Dissolved-solid concentrations in surface water increase near Great Salt Lake owing to evapotranspiration and to salt contributions from irrigation-return flows and saline ground-water discharges.

Most tributaries of the Jordan River originate in the Wasatch Range; consequently, the major flow component is snowmelt runoff. The dissolved-solids concentrations in these streams vary according to the geology of their drainage area in the Wasatch Mountains. For example, the median concentration in Big Cottonwood Creek at the mouth of Big Cottonwood Canyon is 170 mg/L. The geology of Big Cottonwood Canyon is dominated by quartzite with interbedded shales. The median dissolved-solids concentration near the mouth of Mill Creek is 382 mg/L. Mill Creek Canyon is north of Big Cottonwood and is dominantly clastic sedimentary rocks and carbonates. Much of the water in these streams is diverted for municipal supply and irrigation at the mountain front. Within the urban area, dissolved-solids concentrations increase due to inflow from urban runoff, irrigation-return flows, and tailwater from canals transporting water from Utah Lake. For example, Little Cottonwood Creek has a median dissolved-solids concentration of 134 mg/L near the mountain front and 641 mg/L near the confluence with the Jordan River. Seasonal applications of sodium-chloride de-icers to the Salt Lake Valley road network are a substantial source of dissolved solids in the basin. Road salt is transported to the Jordan River and its tributaries in storm runoff from roadways and parking areas. Consequently, the concentration of dissolved chloride in some Jordan River tributaries may exceed recommended criteria for the protection of aquatic organisms when discharge is low and urban runoff containing road salt is a substantial flow component (Gerner and Waddell, 2003).

Ground and surface water, and the dissolved solids they transport, eventually discharge to Great Salt Lake. On an annual basis, the dissolved solids in freshwater inflow to Great Salt Lake contribute a relatively insignificant part of the total mass of salt contained in the lake; however, the dissolved-solids concentration of the lake is primarily dependent on tributary inflows as well as the amount of evaporation. Consequently, the lake elevation increases and the salinity of the water decreases during cooler, wetter periods. In contrast, the lake elevation decreases and the salinity of the water increases during warmer, drier periods. Dissolved-solid concentrations in the southern arm of Great Salt Lake, which receives most of the tributary inflow, varied between about 60,000 and 340,000 mg/L during 1959–98 (Loving and others, 2000).

Santa Ana Basin

By Scott N. Hamlin

The status of dissolved-solids concentrations and changes in dissolved-solids concentrations due to natural and human factors along flow paths in the Santa Ana Basin are described in this section. The SANA Study Unit encompasses the Santa Ana Basin (figs. 27 and 34). The California Coastal Basins aquifer system is the primary aquifer system in the Santa Ana Basin and consists of aquifers in three basins—the San Jacinto Basin, the Inland Basin, and the Coastal Basin—that contain water-bearing alluvium and are hydraulically disconnected from each other by relatively impervious hills and mountains (fig. 34).

The climate of the Santa Ana Basin is Mediterranean, with hot, dry summers and cool, wet winters. This area generally has more precipitation and milder temperature ranges than the other areas discussed in this report. Average annual precipitation ranges from 10 to 24 in. in the coastal plain and inland valleys and from 24 to 48 in. in the surrounding mountains.

The Santa Ana Basin is the most populous of the 12 areas discussed in this report—more than 4 million people reside in the basin, and this population is expected to grow to about 7 million people by 2025. Population density is highest in the Coastal Basin, with more than 20,000 people per mi^2 in the city of Santa Ana.

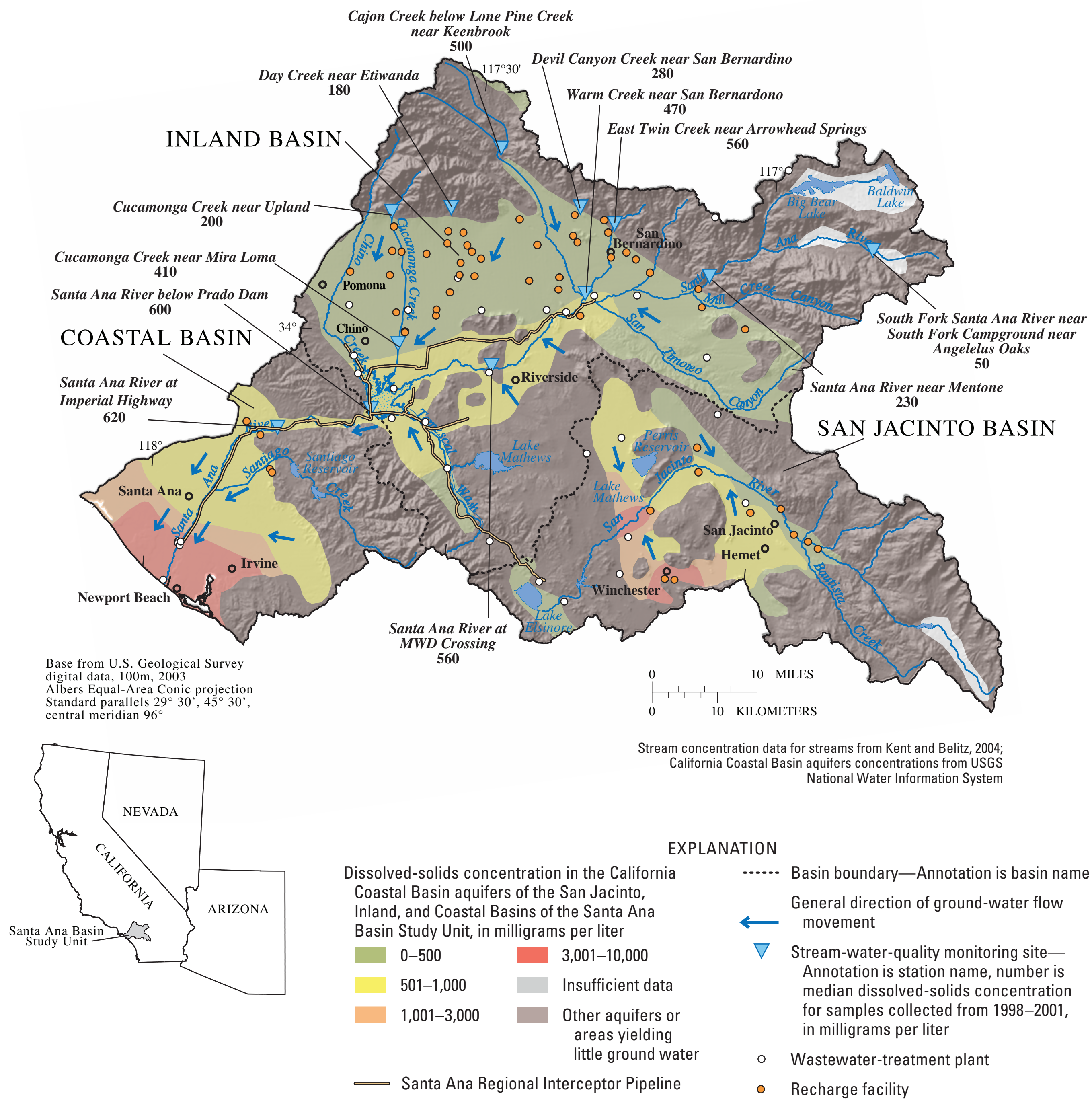


Figure 34. Dissolved-solids concentrations in the California Costal Basin aquifers, the Santa Ana River, and its tributaries in the San Jacinto Basin, Inland Basin, and Coastal Basin of the Santa Ana Basin Study Unit.

Urban and agricultural land uses occur primarily in the alluvium-filled valleys and the coastal plain. Land use in the Santa Ana Basin is about 35 percent urban, 10 percent agricultural, and 55 percent open space, which primarily is on steep mountain slopes (Belitz and others, 2004).

Ground water is the major water supply in the Santa Ana Basin, providing about two-thirds of the total water used. Water imported from northern California and the Colorado River accounts for about one-quarter of the total used. Urban water use is about 75 percent of the total demand, and the remaining 25 percent of the total demand is mostly from agriculture.

As a result of the semiarid climate and the water demands of the urban population, the hydrologic cycle is greatly affected by human activities: ground-water pumping, engineered-recharge operations, and discharge of treated wastewater to local streams (Belitz and others, 2004). Streams and rivers draining the mountains are diverted to ground-water-recharge facilities. Most ground-water recharge occurs artificially at facilities that use stream flow, imported surface water, or treated wastewater.

The Santa Ana Basin is drained by the Santa Ana River, the largest river system in southern California. All of the base flow and most of the storm flow in the Santa Ana River is diverted for recharge at localized facilities designed to replenish aquifers in the Coastal Basin. During the dry season, streamflow in the Santa Ana River is maintained by discharge from wastewater-treatment plants. Under normal conditions, there is minimal discharge from the river to the Pacific Ocean. Recharge facilities in the Inland and San Jacinto basins are more widely distributed than those in the Coastal Basin and generally utilize streamflow, imported water, and reclaimed water.

Ground-water discharge is primarily by ground-water pumping, but also occurs as base flow to the Santa Ana River in some areas of the Inland Basin. Ground-water flow generally follows topography and surface flow. Exceptions include areas where ground-water pumping has produced depressions in the water table, such as in the Hemet area of the San Jacinto Basin, and areas where faults act as barriers to flow. Ground-water flow in the Coastal Basin is generally characterized by a radial wedge with focused recharge and distributed pumpage. In the San Bernardino area of the Inland Basin, flow is characterized by radially convergent flow paths and focused discharge. In this area, the San Jacinto Fault acts as a barrier to ground-water flow (Dawson and others, 2003).

Ground-water pumpage and artificial recharge have accelerated the flow of water and the transport of dissolved constituents through the California Coastal Basins aquifer system of the Santa Ana Basin. To a large extent, native ground water has been replaced by water recharged since the 1950s. The quality of younger ground water is often different than that of older, native water. Dissolved-solids concentrations are generally higher in younger ground water, except in areas where geologic materials have released salts to older ground water.

Much of the streamflow in the Santa Ana Basin is utilized for ground-water recharge operations. In the San Jacinto Basin, treated municipal wastewater is recharged in percolation ponds. Most treated municipal wastewater in the Inland Basin is discharged to the Santa Ana River and diverted downstream in the Coastal Basin for ground-water recharge. Dissolved-solids concentrations have increased over time in the Santa Ana River, which reflects the increased amount of urban development and higher discharges of treated wastewater to the river. As a consequence, dissolved-solids concentrations of ground water in the Coastal Basin that is recharged by flow from the Santa Ana River also reflect this trend.

In response to concerns about increasing salinity in ground water throughout Southern California, the Metropolitan Water District and the Bureau of Reclamation initiated a regional study in 1996 to evaluate sources of dissolved solids and existing management practices (Santa Ana Watershed Project Authority, 1998). At that time, 627,000 tons of dissolved solids were being added to ground water each year. The sources of dissolved solids include Colorado River water imported for use in the ground-water basins, urban activities, agricultural practices, and in a few areas, geologic materials such as marine shales.

Dissolved-solids concentrations in the California Coastal Basins aquifer system of the Santa Ana Basin are lowest (about 150 to 250 mg/L) in areas recharged by runoff from the surrounding mountains and by artificial-recharge facilities in the San Jacinto and Inland Basins. As ground water moves away from the mountains, dissolved-solids concentrations increase (fig. 34) as a result of urban and agricultural activities, alteration of the hydrologic cycle, and natural sources of dissolved solids. Dissolved-solids concentrations are highest in wells distant from mountain-front and engineered recharge (about 800 to 1,500 mg/L). Sample data from a NAWQA sampling program designed to assess overall aquifer conditions indicate that the USEPA SDWR for dissolved solids (500 mg/L) was exceeded in 39 percent of the wells sampled in the San Jacinto Basin; 10 percent of the wells sampled in the Inland Basin; and in 45 percent of the well samples in the Coastal Basin (Hamlin and others, 2002).

Dissolved-solids concentrations in the Santa Ana River and its tributaries were characterized by a NAWQA sampling program that collected base-flow and storm-runoff samples during 1998–2001 (Kent and Belitz, 2004). The lowest dissolved-solids concentrations were found in mountain streams and storm runoff, typically ranging from 100 to 300 mg/L. The median dissolved-solids concentration in base-flow samples from mountain sites was 200 mg/L. Rainfall runoff usually dilutes stream dissolved-solids concentrations. The median dissolved-solids concentration in all discrete storm samples throughout the Santa Ana Study Unit was 260 mg/L (Kent and Belitz, 2004). The median flow-weighted average dissolved-solids concentration for stormflow, based on continuous measurement of specific conductance and hydrograph separation of the continuous discharge record, was 190 mg/L. Dissolved-solids concentrations in stormflow, however, were variable and depended on whether the storm was associated with a relatively small or large rainfall event. Dissolved-solids concentrations in stormflow associated with relatively small events ranged from about 50 to 600 mg/L with a median of 220 mg/L, whereas concentrations in stormflow associated with relatively large events ranged from about 40 to 300 mg/L with a median of 100 mg/L.

San Jacinto Basin

The San Jacinto Basin has the most agricultural land use and is the least urbanized of the three SANA Study Unit ground-water basins. Aquifers in the San Jacinto Basin are mostly unconfined. The basin has the lowest ground-water use among the three basins that comprise the California Coastal Basins aquifer system and, consequently, the lowest transport rates for dissolved constituents. Dissolved-solids concentrations commonly exceeded the USEPA SDWR for dissolved solids (500 mg/L) in parts of the basin (fig. 34; California Department of Water Resources, 2003). The highest dissolved-solids concentrations were found in the southwestern part of the basin up to 12,000 mg/L (California Department of Water Resources, 2003).

Dissolved-solids concentrations have changed as the San Jacinto Basin has been developed, lowering the water table and altering ground-water-flow directions. Before significant ground-water use in the basin, water levels in some areas of the basin were near or at the ground surface, resulting in evapotranspiration and high concentrations of dissolved solids. Infiltration of water from agricultural irrigation has also elevated dissolved-solids concentrations in many parts of the basin. The quality of water delivered for public supply in an area of saline ground water is improved by reverse osmosis treatment at the Menifee desalter. A 23-mile pipeline conveys the brine produced during the treatment process to the ocean via the Santa Ana Regional Interceptor pipeline (fig. 34) in the Inland Basin.

In the Hemet area of the San Jacinto Basin, dissolved-solids concentrations in public-supply wells sampled for the NAWQA regional study reflect proximity to natural and engineered recharge from the San Jacinto River. Runoff from the San Jacinto Mountains has dissolved-solids concentrations of about 100 mg/L. Dissolved-solids concentrations in wells near the river and associated engineered-recharge facilities ranged from about 160 to 260 mg/L. Dissolved-solids concentrations in supply wells distant from the river and engineered-recharge facilities ranged from about 250 to 720 mg/L. Sources of dissolved solids in the Hemet area include dissolution of the aquifer matrix, evaporative concentration, and agricultural practices (Kaehler and others, 1998).

Inland Basin

The Inland Basin has an intermediate amount of agricultural and urban development when compared to the San Jacinto and Coastal Basins. Aquifers in the Inland Basin are mostly unconfined, and ground-water use is substantially higher than in the San Jacinto Basin. Dissolved-solids concentrations exceed the USEPA SDWR (500 mg/L) in parts of the basin (California Department of Water Resources, 2003). The highest dissolved-solids concentrations were in samples collected in the Chino area and ranged from about 150 to 1,700 mg/L. Dissolved-solids concentrations in samples collected from public-supply wells in the Inland Basin as part of the NAWQA program reflect proximity to natural recharge and artificial-recharge facilities. A large number of spatially-distributed recharge facilities use low-dissolved solids runoff from the San Gabriel and San Bernardino Mountains as a recharge source (fig. 34). Dissolved-solids concentrations in wells near the recharge facilities ranged from about 180 to 250 mg/L. Dissolved-solids concentrations in wells distant from recharge facilities ranged from about 270 to 820 mg/L. Similarly, dissolved-solids concentrations in streams were higher in the downstream reaches of the Santa Ana River and its tributaries, which generally have more urban development and associated discharges (fig. 34).

Desalting plants operate in the Inland Basin to produce potable water. The brine produced as a byproduct of this process is exported from the basin through the Santa Ana Regional Interceptor pipeline. This pipeline was designed to convey 33,600 acre-ft/yr (30 million gallons per day) of nonreclaimable wastewater from the Inland Basin to the ocean for disposal after treatment. The nonreclaimable wastewater consists of desalter concentrate and industrial wastewater.

One desalting facility extracts and treats impaired ground water from the southwestern part of the City of Riverside (Santa Ana Watershed Project Authority, 1998). This desalter uses reverse osmosis to produce up to 6,700 acre-ft/yr of blended desalinized water. About 1,100 acre-ft/yr of concentrated brine generated by this plant is discharged to the Santa Ana Regional Interceptor pipeline. Near the Chino Dairy Preserve, southeast of Chino, high dissolved-solids concentrations result from infiltration of discharges from dairies in the area. A desalter project in this area also utilizes reverse osmosis and has the capacity to remove 10,000 tons of salts annually from the basin through discharge to the Santa Ana Regional Interceptor pipeline.

Dissolved-solids concentrations of streams in the lowlands of the Inland Basin are affected by urban runoff, discharge of treated wastewater, dairy operations in the Chino Dairy Preserve, landscape irrigation, and the use of water imported from the Colorado River. Dissolved-solids concentrations often exceeded the USEPA SDWR (500 mg/L) in the Santa Ana River and many of its tributaries. The highest dissolved-solids concentrations were found in the Santa Ana River and valley-floor tributaries during low-flow conditions, and ranged from about 400 to 600 mg/L. Low flow in most stream reaches is sustained predominantly by treated wastewater, with minor contributions from ground-water discharge and urban runoff. The limited available data suggest that dissolved-solids concentrations in urban runoff are about 300 mg/L. The Santa Ana River carries all surface outflow from the Inland Basin; most of this flow is utilized for ground-water recharge in the Coastal Basin.

Dissolved-solids concentrations in the Santa Ana River generally increase as water moves downstream through the Inland Basin (fig. 34; Kent and Belitz, 2004). Constructed wetlands above Prado Dam in the Inland Basin were designed primarily to lower nitrate concentrations in the Santa Ana River. Dissolved-solids compositions at two sites on the Santa Ana River downstream from Prado Dam in the Coastal Basin appear to reflect a mixture of water from three upstream sites: Santa Ana River at Metropolitan Water District Crossing, Cucamonga Creek, and Warm Creek. Downstream from the dam, nearly all of the streamflow is diverted and used for ground-water recharge in the Coastal Basin. Below the recharge facilities, the Santa Ana River has been channelized and lined with concrete.

Coastal Basin

The Coastal Basin has the highest percentage of urbanized land and the lowest percentage of agricultural land of the three ground-water basins in the California Coastal Basins aquifer system. Ground-water use is highest in the Coastal Basin, and in contrast to the other basins, most of the basin's aquifers used for public supply are confined and insulated from overlying land use.

The highest concentrations of dissolved solids in ground water are found along the coast and in the Irvine area (fig. 34). Seawater intrusion had occurred historically along the western margin of the basin due to ground-water overdraft. The Orange County Water District has constructed recharge projects and has installed injection well networks in the gaps to prevent seawater intrusion into the aquifer used for public supply. The dissolved-solids concentration of mountain-front recharge in the Irvine area exceeds 1,000 mg/L due to leaching of salts from marine sediments in the Santa Ana Mountains (Singer, 1973). High dissolved-solids concentrations in the Irvine area also result from past and current agricultural practices. A desalter project in the Irvine area is planned to provide 3,900 acre-ft of water annually for landscaping and other nondrinking-water uses. The project will also provide 4,000 acre-ft of drinking water per year by removing volatile organic compounds from areas of contaminated ground water.

Within the Coastal Basin, the ground-water-flow system is dominated by high rates of recharge from engineered facilities along the Santa Ana River. Water-quality data show that recharge water extends more than 12 mi from the recharge facilities into the aquifer system, reflecting a relatively long history of intense, focused recharge.

In the Coastal Basin, Orange County Water District began large-scale recharge of water imported from the Colorado River in the early 1950s. The imported water historically had higher concentrations of dissolved solids (about 700 mg/L) than the native ground water (Herndon and others, 1997). As a consequence, dissolved-solids concentrations in ground water began to rise to unacceptable levels (Herndon and others, 1997). Subsequently, alternate water supplies with lower dissolved-solids concentrations were developed to minimize the use of Colorado River water for ground-water recharge.

During 1995–96, Orange County Water District purchased and recharged water imported from northern California with an average dissolved-solids concentration of 321 mg/L. Concentrations of dissolved solids increased to about 400 mg/L due to evaporation and leaching of salts during conveyance to the recharge facilities (Herndon and others, 1997). Although imported water from northern California is lower in dissolved solids than Colorado River water, it contains higher concentrations of organic compounds that may produce trihalomethanes when the water is disinfected by chlorination.

Conceptual Model

By David W. Anning

A conceptual model of the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams in the Southwest was developed through a synthesis and analysis of specific examples from 12 selected areas in the six NAWQA Study Units (fig. 27) in the Southwest. The description of the conceptual model is presented here in the general order that water would encounter various natural and human factors along a flow path for surface and ground water through the Southwest, from upstream and upgradient areas to downstream and downgradient areas.

Much of the surface water and ground water in the Southwest originate from precipitation in bedrock-dominated mountain areas. In these higher altitude and cooler areas, precipitation falls as snow, and snowmelt runoff is a major source of water in streams. Dissolved-solids concentrations in precipitation are low, and consequently, the dissolved-solids concentration of runoff into mountain streams is also low, as described for mountain streams in the headwater areas and mountain streams in the areas described for the UCOL, CAZB, GRSL, and SANA Study Units. Some precipitation infiltrates the soils and recharges bedrock aquifers, dissolving minerals from the rocks along this path. In cases where the ground-water flow path is through sedimentary rocks or evaporite deposits, such as the Eagle Valley Evaporite Formation in the headwaters area of the UCOL Study Unit, springs that discharge such ground water can have high dissolved-solids concentrations. Saline springs that discharge to the Colorado River near Glenwood, Colo., in the UCOL

Study Unit and saline springs that discharge to the Salt River in the CAZB Study Unit are good examples of this process. Streamflow in mountain streams is typically a mixture of surface runoff and ground-water discharge from springs or gaining reaches. Dissolved-solids concentrations are generally low in streams draining metamorphic and igneous rocks, as described for headwater areas in the UCOL Study Unit and the headwater areas of the Carson River Basin in the NVBR Study Unit. In comparison, dissolved-solids concentrations are generally higher in streams draining sedimentary rocks, as described for areas of the Colorado Plateaus in the UCOL Study Unit and streams draining into the Salt Lake Valley in the GRSL Study Unit.

Streamflow in the upland and mountainous areas of the Southwest is often stored in one or more reservoirs. In many of these areas, a large portion of the annual runoff occurs in the spring and early summer as the result of snowmelt. The water stored in the reservoirs is used at a later time instream for power generation or is diverted offstream for municipal or agricultural uses. Concentrations of reservoir inflow are typically variable over time; however, the inflows mix in the reservoir and as a result, dissolved-solids concentrations of reservoir outflow are typically less variable. This effect is well demonstrated by concentrations in streamflow above and below the reservoir system on the Salt River in the CAZB Study Unit. Evaporation from reservoirs has the effect of increasing dissolved-solids concentrations. Streamflow in the upland and mountainous areas, especially in the headwater areas of the UCOL Study Unit, is also diverted out of the basin for use in other areas that may be many miles away. While these transbasin diversions may not transport a large mass of dissolved solids to other areas, they result in the removal of water with a low dissolved-solids concentration that would otherwise serve to help dilute water with a high dissolved-solids concentration that discharges to the streams in downstream reaches.

Surface water and ground water eventually flow out of the bedrock-dominated upland and mountainous areas into lowland alluvial basin areas, which typically have flatter terrain and are underlain by large basin-fill aquifers. Along the basin margins, streamflow is often diminished due to infiltration or due to diversion for offstream uses. In many areas described for the RIOG, CAZB, NVBR, GRSL, and SANA Study Units, recharge to the basin-fill aquifers along the basin margin by streamflow infiltration or by subsurface inflow from adjacent bedrock aquifers in upland or mountain areas has low dissolved-solids concentrations in comparison to ground water in other parts of the basin-fill aquifer. In the SANA Study Unit, areas with artificial recharge of mountain stream runoff in infiltration basins also have relatively low dissolved-solids concentrations in ground water as compared to other parts of the aquifer. Dissolved-solids concentrations in ground water are not always low along the basin margins, however, as was shown for the western margin of the Middle Rio Grande Basin in the RIOG Study Unit. Ground water along this margin has high dissolved-solids concentrations due to ground-water inflow from bedrock aquifers to the west.

Ground-water concentrations typically increase along flowpaths through basin-fill or alluvial deposits as a result of geochemical reactions with the aquifer matrix. In some parts of the aquifer, as described for areas in the RIOG and CAZB Study Units, sediments that make up the aquifer matrix react with the ground water through processes such as cation exchange, and dissolved ions are released into solution. In comparison, such geochemical reactions generally are slow in comparison to the dissolution of salts from soils or the aquifer matrix. In areas such as those with soils and alluvium derived from the Mancos Shale around Grand Junction and Montrose, Colo., in the UCOL Study Unit, disseminated salts in the aquifer matrix are leached into the ground water. In parts of the Gila Low in the CAZB Study Unit, dissolution of evaporite deposits in the basin-fill aquifer increase dissolved-solids concentrations. In the Carson River Basin of the NVBR Study Unit, dissolved-solids concentrations in the basin-fill aquifer are higher in some areas as a result of geothermal activity.

Dissolved-solids concentrations in basin-fill aquifers may also increase as a result of evapotranspiration directly from the ground-water system or evapotranspiration of water applied to crops which subsequently infiltrates and recharges the aquifer. Increases in dissolved-solids concentrations in shallow ground water were described as a result of evapotranspiration directly from the ground-water system by natural vegetation or by agricultural crops in the San Luis and Mesilla Basins in the RIOG Study Unit, areas adjacent to the lower Salt and Gila Rivers in the CAZB Study Unit, along the Carson River in the NVBR Study Unit, and in areas of shallow ground water in the Salt Lake Valley of the GRSL Study Unit. During evapotranspiration, the shallow water is absorbed by plant roots and is released (transpired) as pure water to the atmosphere through the cells of the leaves. As a result of this process, dissolved solids remain in the ground water and increase in concentration due to the water removal. In agricultural areas, water diverted from streams or pumped from the aquifer is applied to crops. The excess irrigation water not consumed by crops, which has a higher dissolved-solids concentration as the result of evapotranspiration, can seep back to the aquifer and carry with it dissolved solids from the irrigation water and any additional salts leached from the soils. Where ground water is shallow and the amount of time for excess irrigation water to percolate back to the water table is short, recirculation of ground water to fields and back to the aquifer results in significant increases in dissolved-solids concentrations in the aquifer over time. Where ground water is deep, the recirculation cycle will take longer due to a longer distance for percolating irrigation seepage to travel. In the CAZB Study Unit, depths to water is sufficiently large enough in some areas that recirculation may not occur because the ground-water table elevation has been lowered by pumpage at a faster rate than the percolation of the excess irrigation water.

Dissolved-solids concentrations also increase as a result of mixing two or more subsurface waters. In the Mesilla Valley of the RIOG Study Unit, dissolved-solids concentrations in shallow ground water increase as a result of mixing with deeper, higher dissolved-solids concentration ground water that moves upward in the southern (downgradient) part of the basin. In the Coastal Basin of the SANA Study Unit, dissolved-solids concentrations in ground water near the coast have increased as a result of seawater intrusion. In a different part of the Coastal Basin, artificial recharge of Colorado River water also increased dissolved-solids concentrations because concentrations in the native ground water were lower. In the Carson Valley of the NVBR Study Unit, dissolved-solids concentrations in ground water increased because concentrations in recharge from irrigation, septic systems, and treated municipal wastewater were higher than the native ground water.

Dissolved-solids concentrations in streams also change downstream in lowland areas due to evaporation and inflow of ground water and surface water. Dissolved-solids concentrations in streams, reservoirs, and lakes increase as a result of evaporation, which was illustrated for the Carson River in the NVBR Study Unit and Utah Lake in the GRSL Study Unit. Dissolved-solids concentrations increase in the lower Salt and Gila River of the CAZB Study Unit, and the Jordan River and Utah Lake in the GRSL Study Unit where ground water discharges to the streams. Concentrations also change in streams that receive irrigation-return flows or releases from municipal wastewater-treatment plants. Irrigation-return flows have increased dissolved-solids concentrations because of evapotranspiration of the irrigation water. Instream mixing of streamflow and irrigation-return flow result in increases in dissolved-solids concentrations. Municipal wastewater-treatment plant effluent typically has increased dissolved-solids concentrations relative to the supply water. In most cases, mixing of wastewater-treatment plant effluent and streamflow results in increases in dissolved-solids concentrations. In the case of Las Vegas Wash in the NVBR Study Unit, dissolved-solids concentrations that were high as a result of saline ground-water discharge decreased as a result of inflows of comparatively low dissolved-solids concentration treated municipal wastewater to the stream. In areas with cold climates and significant urban development and road systems, such as those discussed in the GRSL Study Unit, use of road de-icers may also increase dissolved-solids concentrations in streams.

Accumulation of dissolved solids in water supplies is affected by natural and artificial drainage and restriction of surface-water and ground-water outflow. In the closed part of the San Luis Basin in the RIOG Study Unit, pumpage of shallow ground water into the Franklin Eddy Canal facilitates drainage of shallow ground-water into the Rio Grande. This helps prevent the accumulation of dissolved solids and an associated increase in dissolved-solids concentrations in ground water over time due to agricultural recirculation and evapotranspiration of shallow ground water. In the SANA Study Unit, the Santa Ana Regional Interceptor pipeline facilitates drainage of high concentration wastewaters directly to the ocean, which prevents them from mixing with and deteriorating good-quality water supplies. In the CAZB Study Unit, much of the dissolved solids carried into the Gila Low from local surface supplies of the Agua Fria, Gila, Salt, and Verde Rivers, as well as imported water from the Colorado River through the Central Arizona Project, are retained within that area as a result of the water being used for urban and agricultural irrigation. The difference in mass between inflow and outflow of dissolved solids, about 1.3 million ton/yr, accumulates in the soils, vadose zone, and ground water of the area. Whereas the Gila Low is drained by the Gila River, which allows for some outflow of water and transport of dissolved solids, other areas, such as the Carson Sink in the NVBR Study Unit and the Great Salt Lake in the GRSL Study Unit, are closed to surface and subsurface outflow. As a result of being closed systems, all water that enters these areas is ultimately removed through evaporation, leaving dissolved solids behind to accumulate. Where accumulation is accompanied by evapotranspiration, dissolved-solids concentrations increase in the water supply, and ultimately, may render the supply useless or in need of treatment methods, such as reverse osmosis. In the Santa Ana Study Unit, ground-water supplies with high dissolved-solids concentrations were treated by using reverse-osmosis technology.

Sources and Accumulation of Dissolved Solids

By David W. Anning

Significant source and accumulation areas of dissolved solids were determined by using a mass-balance analysis of the contributions and losses of dissolved solids for river systems in hydrologic accounting units of the Southwest. Contributions to river systems in each hydrologic accounting unit included inflows, internal deliveries, and imports, and losses included outflows, internal accumulation, and exports (equation 3 in the "Approach, Data Compilation, and Analysis Methods—Determination of Sources and Accumulation of Dissolved Solids" section of this report). These six terms were quantified by using predictions from the SPARROW model for dissolved-solids transport in the Southwest.

In this section, a description of the calibrated SPARROW model is presented along with a discussion of physical interpretations for the model coefficients, and a discussion of the model assumptions, strengths, and limitations. This is followed by a discussion of the significant source and accumulation areas in the Southwest that were determined on the basis of hydrologic accounting unit internal deliveries and internal accumulation terms from the mass-balance analysis. Source areas are further characterized through a description of the relative contribution of dissolved solids delivered from individual natural and human sources to river systems in each hydrologic accounting unit, which were determined from the SPARROW model. In the final part of this section, sources, transport, and accumulation of dissolved solids are summarized for each major river basin in the Southwest. An understanding of the sources, transport, and accumulation of dissolved solids can be used to build spatially targeted strategies and measures that mitigate source deliveries of dissolved solids to streams and intercept transport of dissolved solids to important water resources. In addition, areas of accumulation of dissolved solids can be targeted for monitoring programs to assess changes in dissolved-solids concentrations over time.

SPARROW Model of Dissolved-Solids Transport

A SPARROW model (equation 4) was developed to estimate values for the terms in the mass-balance analysis (equation 3) and to provide more information about the relative importance of individual natural or human sources of dissolved solids in hydrologic accounting units. The SPARROW model methodology is summarized here but is described in much more detail in the “Approach, Data Compilation, and Analysis Methods—Calibration of the SPARROW Model of Dissolved Solids Transport” section of this report. The SPARROW model relates annual dissolved-solids loads in the ERF1_2 stream-reach network to the reach-catchment characteristics. Dissolved-solids loads in each stream reach originate from (1) deliveries from catchment sources and, if present, (2) inflow from upstream reaches. Dissolved-solids deliveries from catchment sources to each reach are based on catchment characteristics that reflect the sources, such as the outcrop area of geologic units in the reach catchment. Delivery rates from each source are adjusted by land-to-water delivery variables that reflect surface transport of dissolved solids with reach characteristics, such as annual precipitation depth. Instream dissolved-solids loads delivered to each reach from upstream reaches and from catchment sources are transferred to downstream reaches, minus any losses to sinks along each reach. Reach losses of dissolved-solids loads occur as a result of streamflow infiltration or diversions and also are determined on the basis of reach characteristics.

Monitored stream-load data and associated catchment characteristics for 315 reaches were used to calibrate the model. Results from the nonlinear least squares calibration are summarized in table 17. Catchment sources of dissolved solids include 12 geologic units, cultivated and pasture land, and imported water. Two of the geologic units, eugeosynclinal rocks and low-yield Paleozoic and Precambrian sedimentary rocks, were significant at levels less than the 0.10 level (table 17). While the delivery rates of dissolved-solids are less certain for these units than for other units with more significance, they were retained so that the effect of geology for all areas of the Southwest was represented by the model. Significant factors affecting land-to-water delivery include runoff depth, drainage density, and percent barren land. Significant factors related to instream losses included change in reach discharge and percent Quaternary basin fill. Neither of the two tested reservoir retention variables was found significant.

The R^2 value indicates that the model accounts for about 89 percent of the variability observed in the annual stream-load data (table 17). The values of R^2 for load models generally are high simply because there is typically a significant relation between annual discharge, a component factor of annual load, and drainage area. The yield R^2 value is 0.63, and reflects the percent variability accounted for in the observed stream loads by the SPARROW model after the variability in the observed data resulting from drainage area is removed (Schwarz and others, 2006). Standard errors of prediction determined from the 200 calibration iterations of the bootstrap analysis varied by reach; the average standard error for the 5,214 reaches was 59 percent of the predicted load.

Physical Interpretations of Model Coefficients

The SPARROW model coefficients (table 17) have physical interpretations that provide insight to (1) the delivery of dissolved solids to streams from specific sources, (2) the effects of specific environmental conditions on the delivery from sources to streams, and (3) the effects of specific environmental conditions that affect instream losses of dissolved solids.

The source coefficients for each rock type indicate the average annual load of dissolved solids [(ton/yr)/mi^2] delivered to streams for a given area of that rock type under average conditions for the land-to-water delivery variables. Many of the bootstrap confidence intervals for the source coefficients of different rock types do not overlap, which indicates that the delivery rates of dissolved solids to reaches varies significantly by rock type, given all other conditions are equal. Dissolved-solids deliveries associated with each rock type can result from surface processes that deliver dissolved solids through precipitation runoff, or the deliveries can result from subsurface processes which deliver dissolved solids to the stream through ground-water discharge. The delivery coefficients for the geologic units represent deliveries that result from both surface and subsurface processes.

Crystalline rocks, which are primarily granitic, and metamorphic rocks, deliver 6.52 (ton/yr)/mi^2 (table 17). With the exception of low-yield Paleozoic and Precambrian sedimentary rocks, this is the lowest rate amongst the rock types. The source coefficient for mafic volcanic rocks is 10.66 (ton/yr)/mi^2, which is less than that for felsic volcanic rocks, 16.20 (ton/yr)/mi^2. Several sedimentary rocks types deliver more dissolved solids than crystalline or volcanic rocks; their source coefficients range from 3.39 (ton/yr)/mi^2 for low-yield Paleozoic and Precambrian sedimentary rocks to 131.58 (ton/yr)/mi^2 for high-yield Paleozoic and Precambrian sedimentary rocks. Sedimentary rocks deposited in a given geologic era have varying source coefficients of dissolved solids. For example, geologic units grouped in the “high-yield Tertiary sedimentary rocks” deliver about 70 percent more than “low-yield Tertiary sedimentary rocks”.

Table 17. Results of nonlinear least squares calibration and bootstrap analysis for the SPARROW model of dissolved-solids transport in the Southwestern United States.

[Bootstrap analysis consisted of 200 calibration iterations. yr, year; /, per; mi, mile; mi^2, square mile; ac, acre]

		Nonlinear least squares calibration			Bootstrap analysis			
Model parameters[1]	Coefficient units[2]	Coefficient	Standard error	*p*-value	Lower 90 percent confidence interval	Mean coefficient[3]	Upper 90 percent confidence interval	*p*-value
Dissolved-solids sources								
Crystalline rocks	(ton/yr)/mi^2	6.52	1.89	0.001	0.68	6.27	9.62	0.035
Mafic volcanic rocks	(ton/yr)/mi^2	10.66	3.04	.001	1.11	9.35	14.89	.020
Felsic volcanic rocks	(ton/yr)/mi^2	16.20	7.06	.022	-6.19	14.61	25.33	.060
Eugeosynclinal rocks	(ton/yr)/mi^2	61.58	45.12	.173	-79.54	49.80	129.71	.165
Sedimentary Rocks	(ton/yr)/mi^2							
High-yield Tertiary	(ton/yr)/mi^2	49.68	12.38	<.001	28.87	48.74	64.31	<.005
Low-yield Tertiary	(ton/yr)/mi^2	29.28	6.18	<.001	14.51	29.55	39.94	<.005
High-yield Mesozoic	(ton/yr)/mi^2	46.01	14.81	.002	-16.09	41.57	72.85	.070
Medium-yield Mesozoic	(ton/yr)/mi^2	31.15	15.35	.043	-7.07	27.89	48.36	.065
Low-yield Mesozoic	(ton/yr)/mi^2	8.64	4.48	.055	-17.35	5.58	15.14	.130
High-yield Paleozoic and Precambrian	(ton/yr)/mi^2	131.58	54.64	.017	26.76	125.37	200.35	.025
Medium-yield Paleozoic and Precambrian	(ton/yr)/mi^2	47.05	12.67	<.001	5.26	45.90	75.92	.030
Low-yield Paleozoic and Precambrian	(ton/yr)/mi^2	3.39	2.73	.216	-6.15	1.99	5.90	.130
Cultivated land	(ton/yr)/ac	2.54	.68	<.001	.99	2.64	4.04	.010
Pasture land	(ton/yr)/ac	.49	.15	.002	.05	.49	.84	.025
Imported water	dimensionless	.58	.29	.043	.2595	.5482	.8031	<.005
Land-to-water delivery variables								
Runoff depth	$(inches/yr)^{-1}$	.5671	.0726	<.001	.3849	.5705	.7883	<.005
Drainage density	$(mi)^{-1}$	.3581	.1032	<.001	.1007	.3230	.5416	<.005
Percent barren land	dimensionless	.1106	.0351	.002	.0257	.1127	.1912	.015
Instream-loss variables								
Change in reach discharge	dimensionless	.3184	.1601	.048	.0738	.3250	.6247	.025
Percent Quaternary basin fill	dimensionless	.0900	.0488	.066	.0112	.0824	.1386	.035
R^2	.89							
[(4)]Yield R^2	.63							
Mean square error	.50							
Root mean square error	.71							
Number of observations	315							

[1] No reservoir retention variables were not found significant in the model.

[2] Dependent variable in tons per year.

[3] Also called the bootstrap estimate.

[4] Indicates variability removed from observed data after removing variability resulting from drainage area.

The geologic units depicted by King and Beikman (1974) and their area in the Southwest are tabulated and described by each group of rock types used in the SPARROW model in table 18. This table is intended to provide a coarse summary of the rock types used in the SPARROW model by providing a brief description of the rock type and a noninclusive list of the names of geologic groups and formations that correspond to geologic units depicted in King and Beikman (1974). For example, the Mancos Shale has been identified by previous studies as a significant source of dissolved solids, and is included in the Austin and Eagle Ford Groups, uK_2, in King and Biekman (1974) and falls under the high-yield Mesozoic sedimentary rocks category used in the SPARROW model. The source coefficient for the high-yield Mesozoic sedimentary rocks from the nonlinear least squares calibration is 46.01 (ton/yr)/mi^2. Results from the bootstrap analysis verify the value of this coefficient. The bias adjusted estimate of mean coefficient from the bootstrap analysis is 41.57 (ton/yr)/mi^2, which is comparable to that determined in the least squares. The 90 percent bootstrap confidence interval for this coefficient spans from -16.09 (ton/yr)/mi^2 to 72.85 (ton/yr)/mi^2, and indicates the amount of uncertainty in the estimate for the coefficient. For the geologic-source coefficients, some of this uncertainty arises from the fact that each rock type in the model contains several different geologic units (table 18). These units likely deliver various amounts of dissolved solids amongst themselves, and each unit likely has variation within itself. The high p-values (table 17) for the source coefficients for eugeosynclinal rocks and low-yield Paleozoic and Precambrian rocks indicate that, as compared to other units, there is less certainty that these two coefficients are significantly different than zero. This is likely a result of, in part, the fact that the outcrop area for these two units occurs in areas of the Southwest with few surface-water-quality monitoring stations that can be used for model calibration (pl. 1).

In the exploratory models calibrated during the development of the final selected model, the sign of source coefficients for Quaternary basin fill were negative, indicating a loss in dissolved solids occurs in basins with Quaternary basin fill. Use of a source variable with a negative coefficient can lead to reaches that have negative stream loads, particularly where loads from the remaining source variables are small. For this reason, the percentage of Quaternary basin fill in a reach catchment was explored as a reach-loss variable.

The source coefficients indicate that the yield of dissolved solids for cultivated land, 2.54 (ton/yr)/acre [1,630 (ton/yr)/mi^2], is more than five times greater than that for pasture land, 0.49 (ton/yr)/acre [314 (ton/yr)/mi^2]. These coefficients are much greater than those for the geologic units (table 17). The difference in the source coefficients implies that the type and intensity of farming has an effect on the dissolved solids yielded from agricultural lands. In comparison to pasture land, cultivated land is likely to be irrigated more frequently, have higher water application rates, and be harvested rather than grazed. The cultivated land and pasture source coefficients determined in this study are in good agreement with results found by Iorns and others (1965, tables 12 and 13 on pp. 33 and 34) for irrigated lands in the Upper Colorado River Basin (above Lee's Ferry). They determined yields for 1957 conditions from 21 areas that make up 41 percent of the irrigated lands in the Upper Colorado River Basin and found that they range from 0.1 (ton/yr)/acre to 5.5 (ton/yr)/acre. Basin wide, Iorns and others (1965) determined that the area-weighted average yield was 2.5 (ton/yr)/acre.

The SPARROW model was constructed to not adjust source loadings from cultivated land, pasture land, and imported water on the basis of the three land-to-water delivery variables. Conceptually, these three source variables should not be affected by the land-to-water delivery variables. The source coefficient for imported water was 0.58, which indicates that about 58 percent of the annual dissolved-solids mass imported to a reach catchment are delivered to the stream and about 42 percent remains in the catchment, most likely as a result of water uses that do not return the used imported water to the stream. Imported water is used, in part, for municipal purposes in several of the major population centers, such as the Los Angeles, Las Vegas, Phoenix, and Tucson metropolitan areas. Loads contributed by municipal water use are, therefore, partially accounted for by the imported water source variable where imported water is used for municipal supply. In areas where imported water is not used, dissolved-solids contributions from municipal water use are not accounted for. While population was tried as a source variable to represent municipal water use, its coefficient was found insignificant, and therefore, not included in the model.

Source loadings from geologic sources were adjusted by three land-to-water delivery variables—runoff depth, drainage density, and percent barren land (table 17). The positive sign for the runoff-depth coefficient (table 17) indicates that source loads of dissolved solids from a given geologic unit increase for areas with an increase in runoff depth. This makes physical sense because where runoff depth is greater, there is more precipitation to chemically weather and transport geologic materials to streams. For the final SPARROW model selected, as well as for all of the various exploratory models developed before arriving at the final model, runoff depth or precipitation depth were always the most significant variable in the model; p-values for this variable were often smaller than 10^{-10}. Their high level of significance originates from the fact that the SPARROW model is predicting load, a product of streamflow and concentration. While both variables were tested in exploratory versions of the model, runoff depth was selected over precipitation depth because mean square errors from the model were slightly smaller when this variable was used.

The positive sign for the drainage-density coefficient (table 17) indicates that source loads of dissolved solids from a given geologic unit increase for areas with an increase in drainage density. This makes physical sense because a denser stream-drainage network would expedite transport to the streams.

Table 18. Groups of geologic units used in the SPARROW model of dissolved-solids transport in the Southwestern United States.

[Geologic units are from King and Beikman (1974); mi, mile; AZ, Arizona; CA, California; CO, Colorado; NM, New Mexico; NV, Nevada; UT, Utah; WY, Wyoming; Gp, Group; Fm, Formation]

King and Beikman (1974) geologic units			
Geologic unit	Area, mi^2	Name	Noninclusive summary of rocks and geologic units depicted in state geologic maps that generally correspond to the King and Beikman (1974) map[1]
		Crystalline rocks—43,670 mi^2 total area	
Ti	2,450	Tertiary intrusive rocks	Intrusive rocks ranging in composition from granite to diorite in AZ, CA, CO, NM, NV, and UT
Kg	11,000	Cretaceous granitic rocks	Mostly granite, quartz monzonite, and granodiorite in AZ, CA, and NV
Kg_3	990	Latest Cretaceous granitic	Mostly granite, quartz monzonite, and granodiorite in AZ
Kg_2	2,020	Upper Cretaceous granitic	Granite, quartz monzonite, granodiorite, quartz diorite in CA and NV
Kg_1	70	Lower Cretaceous granitic rocks	Granite, quartz monzonite, granodiorite, quartz diorite in CA
T_Rg	850	Triassic granitic group	Granite, quartz monzonite, granodiorite, quartz diorite in CA and NV
Jg	2,270	Jurassic granitic rocks	Granite, quartz monzonite, granodiorite, quartz diorite in CA and NV
Jmi	120	Jurassic mafic intrusives	Intrusive rocks ranging in composition from diorite to gabbro in NV
Pzg_2, Pzg_3	170	Upper Paleozoic granitic rocks	Granites in CA
Cg	20	Cambrian granitic rocks	Granites in CO
Yg_2,Yg_3	90	Younger Y granitic rocks	Granites in AZ and NM
Yg_1	3,220	Older Y granitic rocks	Granites and quartz monzonites in AZ, CO, and NM
Ya	110	Anorthosite	Anorthositic rocks in CA
Xg	5,980	X granitic rocks	Granites, quartz monzonite, and granodiorites in AZ, CA, CO, and NM
Xm	10,670	X orthogneiss and paragneiss	Gniess and schist in AZ, CA, CO, NV, and UT
X	2,420	X metasedimentary rocks	Metasedimentary rocks including quartzite in AZ and NM
Wg	240	W granitic rocks	Granite and granodiorite in WY
Wgn	970	W orthogneiss and paragneiss	Schist, gniess, and quartzite in UT and WY
W	10	W metasedimentary rocks	Schist, metagreywacke, and metaconglomerate in WY
		Mafic volcanic rocks—56,620 mi^2 total area	
Qv	8,040	Quaternary volcanic rocks	Basaltic to andesitic lava flows and associated volcaniclastic sedimentary rocks in AZ, CA, NM, and UT
Tpv	24,030	Pliocene volcanic rocks	Basaltic to andesitic lava flows and associated volcaniclastic sedimentary rocks in AZ, CA, CO, NM, NV, and UT
Tmv	10,040	Miocene volcanic rocks	Basaltic to andesitic flows and associated volcaniclastic sedimentary rocks in AZ, CA, CO, NM, NV, and UT
lTv	14,010	Lower Tertiary volcanic rocks	Basaltic to andesitic flows and associated volcaniclastic sedimentary rocks in AZ, CA, CO, NM, NV, and UT
Kv	260	Cretaceous volcanic rocks	Basaltic to andesitic flows and associated volcaniclastic sedimentary rocks in AZ and NM
lMzv	240	Lower Mesozoic volcanic rocks	Various composition flows and tuffs in NV
		Felsic volcanic rocks—23,940 mi^2 total area	
Qf	1,430	Quaternary felsic volcanic rocks	Rhyolitic to andesitic flows and tuffs in CA and NM
Tpf	8,000	Pliocene felsic volcanic rocks	Rhyolitic to andesitic flows and tuffs in AZ, NV, and UT
Tmf	11,530	Miocene felsic volcanic rocks	Rhyolitic to andesitic flows and tuffs in AZ, NM, and NV

See footnote at end of table.

Table 18. Groups of geologic units used in the SPARROW model of dissolved-solids transport in the Southwestern United States—Continued.

King and Beikman (1974) geologic units			
Geologic unit	Area, mi^2	Name	Noninclusive summary of rocks and geologic units depicted in state geologic maps that generally correspond to the King and Beikman (1974) Map[1]
Eugeosynclinal rocks—10,320 mi^2 total area			
lTf	2,980	Lower Tertiary felsic volcanic rocks	Rhyolitic to andesitic flows and tuffs in CO and NM
uMze	430	Upper Mesozoic eugeosynclinal	Volcaniclastic sedimentary rocks and metavolcanic rocks in AZ, CA, and NV
lMze	4,700	Lower Mesozoic eugeosynclinal	Volcaniclastic sedimentary rocks and metavolcanic rocks in AZ, CA, and NV
TRPe	940	Triassic and Permian eugeosynclinal	Volcaniclastic sedimentary rocks and metavolcanic rocks in NV
uPze	1,320	Upper Paleozoic eugeosynclinal	Volcaniclastic sedimentary rocks and metavolcanic rocks in CA, and NV
lPze	2,930	Lower Paleozoic eugeosynclinal	Volcaniclastic sedimentary rocks and metavolcanic rocks in CA, and NV
Quaternary basin fill—121,180 mi^2 total area			
Q	121,180	Quaternary	Alluvium, colluvium, lake, playa, terrrace deposits; in some areas young basalt flows (all States). Mostly unconsolidated or semiconsolidated
Low-yield Tertiary sedimentary rocks—62,910 mi^2 total area			
Tp	590	Pliocene	Various marine units in CA mostly consisting of moderately consolidated sandstone, siltstone, shale, and conglomerate
Tpc	29,680	Pliocene continental	Alamosa Fm (CO), Bidahochi Fm (AZ and NM), Chuska Sandstone (NM), Gila Gp (AZ and NM), Las Feveras Fm (NM), Santa Fe Gp (NM), Sevier River Fm (UT), Salt Lake Fm (UT), and various sedimentary rock units in CA and NV
Tm	940	Miocene	Various marine units in CA mostly consisting of moderately consolidated sandstone, shale, siltstone, conglomerate, and breccia
Tmc	4,800	Miocene continental	Browns Park Fm (CO and UT), Fence Lake Fm (NM), Los Pinos Fm (NM), Quemado Fm (NM), and other continental sedimentary rock units (all States)
Toc	1,800	Oligocene continental	Bishop Conglomerate and Duchesne River Fm (UT), and various continental units in CA mostly consisting of well consolidated sandstone, shale, and conglomerate
Te	730	Eocene	Various marine units in CA mostly consisting of well consolidated shale, sandstone, conglomerate, and limestone
Tec	24,300	Eocene continental	Baca Fm (NM), Blanco Basin Fm (NM), Bridger Fm (CO and UT), Cub Mountain Fm (NM), El Rito Fm (NM), Fowkes Fm (UT), Galisteo Fm (NM), Hart Mine Fm (NM), Lobo Fm (NM), Love Ranch Fm (NM), San Jose Fm (CO), Sanders Canyon Fm (NM), Skunk Ranch Fm (NM), Timberlake Fm (NM), San Juan Fm (NM), Uinta Fm (UT), Wasatch Fm (CO, UT and WY), Washakie Fm (WY)
Tx	70	Paleocene	Various marine units in CA mostly consisting of well consolidated sandstone, shale, and conglomerate
High-yield Tertiary sedimentary rocks—16,500 mi^2 total area			
Tel	9,890	Eocene lacustrine	Green River Fm (CO, UT, and WY)
Txc	6,610	Paleocene continental	Clarion Fm (UT), Flagstaff Limestone (UT), Fort Union Fm (CO and WY), Middle Park Fm (CO), and Nacimiento Fm (CO and NM)
Low-yield Mesozoic sedimentary rocks—36,820 mi^2 total area			
uK	1,410	Upper Cretaceous	Beartooth Fm (NM), Iron Springs Fm (UT), Hilliard Shale (WY), Pinkard Fm (AZ), Sarten Fm (NM), and various units in CA mostly consisting of sandstone, shale, and conglomerate

See footnote at end of table.

Table 18. Groups of geologic units used in the SPARROW model of dissolved-solids transport in the Southwestern United States—Continued.

King and Beikman (1974) geologic units			
Geologic unit	**Area, mi²**	**Name**	**Noninclusive summary of rocks and geologic units depicted in state geologic maps that generally correspond to the King and Beikman (1974) Map[1]**
Low-yield Mesozoic sedimentary rocks—36,820 mi² total area—Continued			
uK_4	2,340	Navarro Group	Fruitland Fm (CO and NM), Lance Formation (CO and WY), Lewis Shale (CO and WY), Kirtland Shale (CO and NM), and Pictured Cliffs Sandstone (CO and NM)
uK_1	7,980	Woodbine and Tuscaloosa groups	Dakota Sandstone (AZ, CO, NM, and UT), Cedar Mountain Fm (UT), and Kelvin Fm (UT)
J	14,050	Jurassic	Morrison Fm and San Rafael Gp (AZ, CO, NM, and UT)
JT_R	11,040	Lower Jurassic and upper Triassic	Glenn Canyon Gp (AZ, CO, NM, and UT)
Medium-yield Mesozoic sedimentary rocks—29,810 mi² total area			
uK_3,uK_3a	11,360	Taylor Group	Mesa Verde Gp (CO, NM, UT and WY), Lewis Shale (NM), and Williams Fork Fm (CO)
lK,lK_1,lK_2	2,140	Lower Cretaceous	Blind Bull Fm (WY), Frontier Fm (WY), Gannet Gp (WY), Hell-to-Finish Fm (NM), Mojado Fm (NM), and select units in AZ
T_R	16,310	Triassic	Chinle Fm (AZ, CO, NM, and UT), Moenkopi Fm (AZ, CO, NM, and UT)
High-yield Mesozoic sedimentary rocks—24,820 mi² total area			
uK_2	18,790	Austin and Eagle Ford Groups	Baxter Shale (WY), Cravasse Canyon Fm (NM), Mancos Shale (AZ, CO, NM, UT), Point Lookout Sandstone (NM), and Tres Hermonos Fm (NM), Mesa Verde Gp (AZ)
Kc	1,390	Cretaceous continental	Continental sedimentary rocks mostly in NV and AZ and includes units such as the Baseline Sandstone (NV), King Lear Fm (NV), Newark Canyon Fm (NV), and Willow Tank Fm (NV).
lMz	4,640	Lower Mesozoic	Several units from Nevada including the Auld Lang Syncline and Star Peak Gps; the Augusta Mountain, Cane Spring, Dixie Valley, Gabbs, Luning, Sunrise, and Tobin Favret Fms; and the Aztec Sandstone. Also includes the Stump Fm and Nugget Sandstone (WY)
Low-yield Paleozoic and Precambrian sedimentary rocks—44,260 mi² total area			
P_3b	100	Upper part of Guadalupian Series	Artesia Gp (NM)
P_3	100	Guadalupian Series	Queen and Grayburg Fms (NM)
P_2b	12,230	Upper part of Leonardian Series	Coconino Sandstone (AZ and UT), Glorieta Sandstone (AZ and NM), Kaibab Limestone (AZ and UT), San Andreas Fm (AZ and NM), and Toroweap Fm (AZ)
P_1	330	Wolfcampian Series	Hueco Fm (NM)
P_1c	1,080	Wolfcampian Series continental	Abo Fm (NM)
P	6,400	Permian	Arcturus Fm (NV and UT), Coconino Sandstone (NV); Cutler Gp (UT), Diamond Creek Sandstone (UT), Gerster Limestone (UT), Hermit Shale (NV), Kaibab Limestone (NV), Kirkman Limestone (UT), Oquirrh Group (UT), Park City Gp (NV and UT), Pequop Fm (NV), Phosphoria Fm (UT), Plympton Fm (UT), Queantoweap Sandstone (NV), Rib Hill Sandstone (NV), and Toroweap Fm (NV); several units in CA mostly consisting of shale, conglomerate, limestone and dolomite, sandstone, slate, hornfels, quartzite, and minor pyroclastic rocks
uPzc	650	Upper Paleozoic clastic wedge facies	Chainman Shale, Diamond Peak Fm, Eleana Fm, Joana Limstone, Mercury Limestone, Narrow Canyon Limestone, and Pilot Shale in NV

See footnote at end of table.

Table 18. Groups of geologic units used in the SPARROW model of dissolved-solids transport in the Southwestern United States—Continued.

King and Beikman (1974) geologic units			
Geologic unit	**Area, mi^2**	**Name**	**Noninclusive summary of rocks and geologic units depicted in state geologic maps that generally correspond to the King and Beikman (1974) Map[1]**
Low-yield Paleozoic and Precambrian sedimentary rocks—44,260 mi^2 total area—Continued			
C	9,910	Cambrian	Abrigo Fm (AZ), Bloomington Fm (UT), Blacksmith Fm (UT), Bolsa Quartzite (AZ), Bonanza King Fm (NV), Dunderberg Shale (NV), El Dorado Dolomite (NV), Geddes Limestone (NV), Gold Hill Fm (NV), Geertsen Canyon Quartzite (UT), Hamburg Dolomite (NV), Harmony Fm (NV), Langston Fm (UT), Nopah Fm (NV), Nounan Dolomite (UT), Osgood Mountain Quartzite (NV), Pioche Shale (NV), Prospect Mountain Quartzite (NV), Secret Canyon Shale (NV), St. Charles Fm (UT), Stirling Quartzite (NV), Tapeats Sandstone (NV), Tonto Gp (AZ), Ute Fm (UT), Windfall Fm (NV), Wood Canyon Fm (NV), Worm Creek Quartzite (UT), and Zabriskie Quartzite (NV); several units in CA mostly consiting of sandstone, shale, limestone, dolomite, chert, quartzite and phyllite
lPz	9,100	Lower Paleozoic	Caballero Fm (NM), Contadero Fm (NM), Devils Gate Limestone (NV), Dotsero Fm (CO), Dyer Dolomite (CO), Ely Springs Dolomite (NV and UT), Escabrosa Gp (NM), Eureka Quartzite (NV and UT), Gilman Sandstone (CO), Guilmett Fm (NV and UT), Helms Fm (NM), Lone Mountain Dolomite (NV); Las Cruces Fm (NM), Laketown Dolomite (NV and UT), Lake Valley Fm (NM), Leadville Limestone (CO), Madison Limestone (CO), Nevada Fm (NV), Onate Fm (NM), Parting Fm (CO), Peerless Fm (CO), Percha Shale (NM), Pilot Shale (UT), Pogonip Gp (NV and UT), Rancheria Fm (NM), Sawatch Fm (CO), Sevy Dolomite (NV and UT), Simonson Dolomite (NV and UT), Sly Gap Fm (NM), Watson Ranch Quartzite (UT); several units in CA and WY mostly consisting of limestone, dolomite, sandstone, and shale
Y	4,360	Y sedimentary rocks	Apache Gp (AZ), Grand Canyon Super Gp (AZ), Troy Quartzite (AZ), Uinta Mountain Gp (UT); several units in CA consisting of conglomerate, sandstone, shale, limestone, dolomite, marble, and gniess
Medium-yield Paleozoic and Precambrian sedimentary rocks—18,710 mi^2 total area			
uPz	18,710	Upper Paleozoic	Alamitos Fm (NM), Amsden Fm (WY), Bird Spring Fm (NV), Callville Limestone (NV), Chainman Shale (UT), Colina Fm (NM), Concha Fm (NM), Cutler Fm (CO), Deseret Limestone (UT), Earp Fm (NM), Ely Limestone (NV), Epitaph Fm (NM), Escabrosa Limestone (AZ), El Paso Limestone (AZ), Flechado Fm (NM), Great Blue Limestone (UT), Hermosa Fm (CO), Humbug Fm (UT), Joana Limestone (UT), La Pasada Fm (NM), Lodgepole Limestone (UT), Madera Fm (NM), Martin Fm (AZ), Minturn Fm (CO), Morgan Formation (CO), Ochre Mountain Limestone (UT), Percha Shale (AZ), Phosphoria Fm (WY), Redwall Limestone (AZ), Rico Fm (CO), Riepe Spring Limestone (NV), Round Valley Fm (CO), Sandia Fm (NM), Temple Butte Limestone (AZ), Weber Sandstone (CO), Woodman Fm (UT); several units in CA mostly consisting of shale, sandstone, conglomerate, limestone, dolomite, chert, hornfels, marble and quartzite
High-yield Paleozoic and Precambrian sedimentary rocks—8,990 mi^2 total area			
P_2a	7,380	Lower part of Leonardian Series	Callville Limestone (AZ), Cutler Gp (AZ), Hermit Shale (AZ), Naco Gp (AZ), Queantoweap Sandstone (AZ), Supai Gp (AZ), and Yeso Fm (NM)
Z	1,610	Z sedimentary rocks	Black Canyon Fm (UT), Browns Hole Fm (UT), Caddy Canyon Quartzite (UT), Inkom Fm (UT), Kelley Canyon Fm (UT), Maple Canyon Fm (UT), McCoy Creek Gp (NV), Mineral Fork Fm (UT), Mutual Fm (UT), Papoose Creek Fm (UT), Wyman Fm (NV)

[1]Data were compiled by comparison of outcrop location of King and Beikman (1974) units to outcrop locations shown in State geologic maps compiled by: Hintze (1980), Love and Christiansen (1985), Jennings and others (1977), Richard and others (2000), Stewart and others (1978), Scholle (2003), and Tweto (1979). In some cases only some of the geologic units that comprise a given formation or group actually outcrop in the listed states. Not all units, formations, or groups depicted in the state maps as occuring within the outcrop area of geologic units depicted by King and Beikman (1974) are listed here.

The percentage of barren land reflects vegetation density and soil exposure, and conceptually, a decrease in vegetation density and an increase in soil exposure would expedite dissolution of salts from geologic materials. Model results reflect this as for a given catchment, a larger percentage of barren lands results in a higher delivery of dissolved solids from geologic sources because the coefficient is positive. The percentage of barren land may also serve to provide fine adjustments to the runoff depth because more vegetation would impede runoff, and less vegetation would expedite runoff.

Instream transport of dissolved solids through each reach was reduced by two reach-loss variables—change in reach discharge and percentage Quaternary basin fill. The change in reach-discharge variable was constructed such that instream loads are reduced only when a streamflow loss across the reach occurs. Where there is a gain in streamflow, instream loads are not affected by the change in reach discharge variable (equation 5). Given the value of 0.3184 for the change in reach discharge coefficient and, as an example, a reduction in discharge of 10 percent, the instream load would be multiplied by about 0.97 (computed as 1.00-0.10 x 0.3184), which represents a 3-percent reduction in stream load. Similarly, for a 90-percent reduction in discharge across the reach, the instream load would be multiplied by about 0.71 (computed as 1.00-0.91 x 0.3184), which represents a 29-percent reduction in stream load. Therefore, as a result of the value for the change in reach-discharge coefficient of 0.3184, reductions in stream loads are only about one-third the reductions in stream discharge. The smaller reduction in stream load likely results from increases in dissolved-solids concentrations across the reach, which was demonstrated in the section “Spatial Distribution of Dissolved Solids—Streams” of this report. Such increases could result from evapotranspiration of water by irrigated crops or by riparian vegetation, or from high concentration ground-water seepage to streams.

The sign of the percentage of Quaternary basin fill instream-loss coefficient indicates that there are larger instream losses of dissolved-solids loads in reach catchments with large portions of Quaternary basin fill than in reach catchments with little Quaternary basin fill. Given a coefficient of 0.0900 (table 17) and a catchment of 100-percent Quaternary basin fill, the stream load would be multiplied by about 0.91 (computed as 1.00-1.00 x 0.0900), which represents a 9-percent reduction in stream load. The reduction of stream loads in reach catchments with Quaternary basin fill is likely a result of streamflow infiltration of (1) the reach delineated in the ERF1_2 network and (2) all the tributaries to the reach within the reach catchment. Given the latter of the two reasons for the reduction, the percentage of Quaternary basin fill variable also performs the function of a land-to-water delivery variable.

Neither of the reservoir retention variables was found significant in developing the SPARROW model and, therefore, they are not included in the final model (table 17). The lack of significance of either tested reservoir retention variable has the physical interpretation that dissolved solids behave conservatively in the reservoirs.

Model Assumptions, Strengths, and Limitations

As with any model constructed to mathematically represent a natural system, there are certain assumptions and limitations to the SPARROW model. The primary assumptions of the model are those for a multiple-regression model. These assumptions include (1) that the variables included and their functional form in the model are correct with respect to the physical processes affecting transport, and (2) that model residuals are independently distributed across observations, and are homoscedastic. The variables included and their functional form in the model were generally discussed in the previous section and justified as reasonable with respect to physical processes affecting transport.

Model diagnostic statistics and plots indicate that residuals generally are normally distributed, independent across observations, and homoscedastic. Output from the model includes the Shapiro-Wilks test (Shapiro and others, 1968), which indicated that the model residuals were normal. A uniform distribution of residuals with respect to observed values and with respect to physical location indicates lack of a bias in the model. Figure 35 shows that there is an absence of a spatial pattern to the residual values. Figure 35, however, also shows that there is a lack of data in the Little Colorado River Basin in northeastern Arizona, the western part of the Great Salt Lake and Sevier River Basins in western Utah, and most of the Central Nevada and Eastern California desert basins. As a result, model coefficients and predictions are likely to be less accurate for these areas and more accurate for areas well represented with monitoring sites used to calibrate the model. Serial correlation of residuals along streams is largely avoided because of the way the model treats nested basins. When one monitored basin contains another monitored basin, the model uses the monitored transport from the upstream basin (rather than the model-estimated transport) to represent contaminant sources entering the lower basin, and as a result, errors should not cascade down a river basin (Smith and others, 1997). Deviations from a 1:1 line for a plot of the predicted stream loads against observed stream loads indicate the sign and magnitude of residuals. The predicted against observed plot for the SPARROW model shows that residuals are evenly distributed with respect to observed values—residuals are not biased for certain ranges of observed values, nor does the variance of residuals change across the range of observed values (fig. 36).

There are many strengths and limitations to the SPARROW model of dissolved-solids transport in the Southwest. A significant strength of the model is its ability to provide a regionally consistent characterization of the natural and human factors and processes that affect dissolved-solids transport at a regional scale. Additionally, the model was constructed by using existing water-quality-monitoring network data and geospatial data, which was cost-effective as compared to collecting new data. The information and insight gained about dissolved-solids transport through the model coefficients and predictions can be used to help strategically direct future data collection, scientific research, and water-resources management activities.

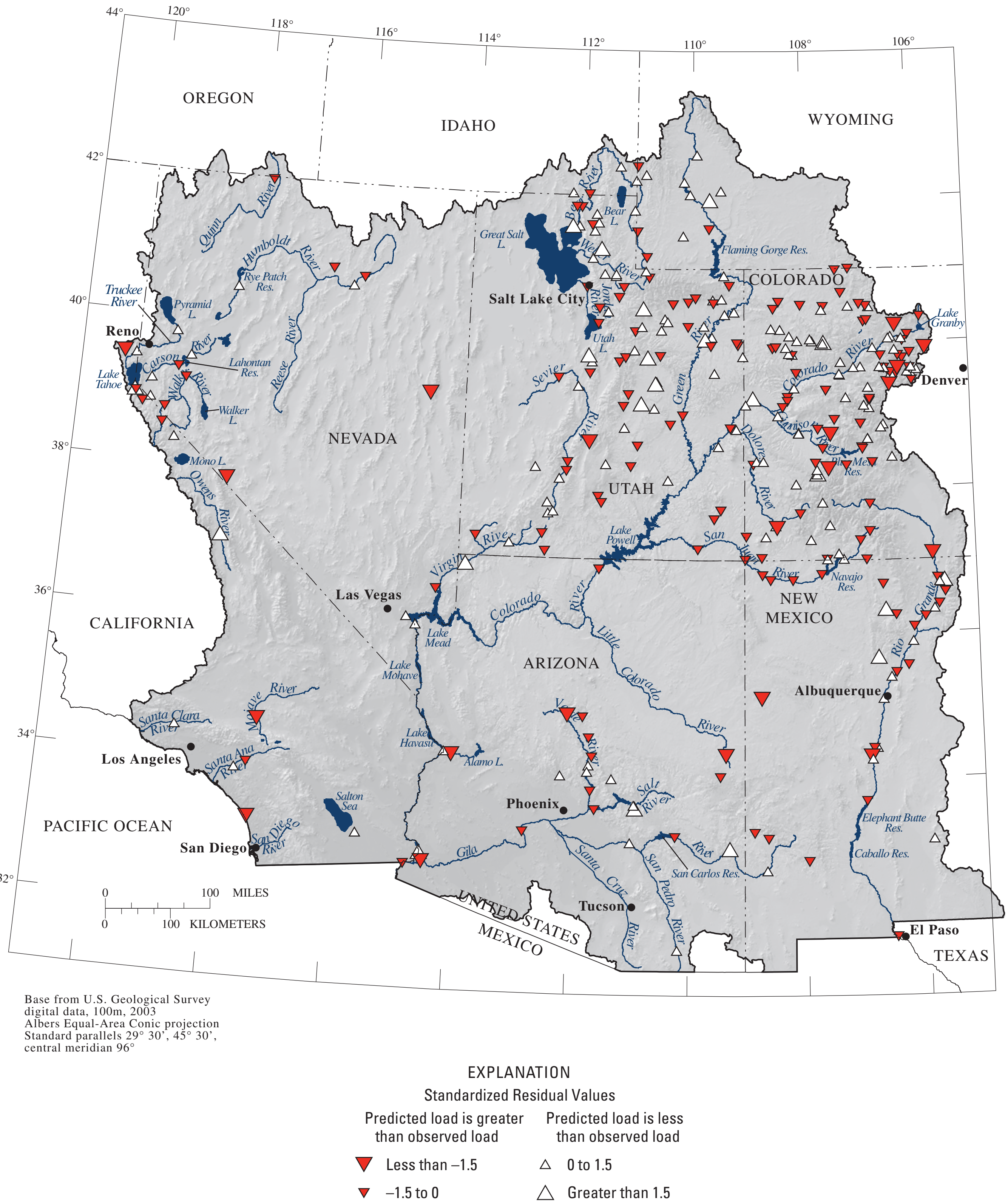


Figure 35. Standardized residual values for 315 surface-water-quality monitoring sites used to calibrate the SPARROW model of dissolved-solids transport in the Southwestern United States.

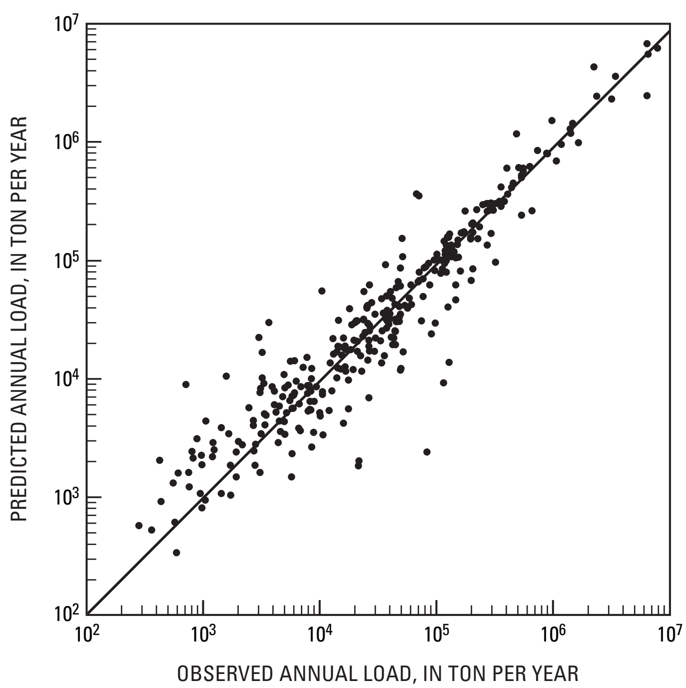


Figure 36. Relation between predicted and observed annual loads for 315 surface-water-quality monitoring sites used to calibrate the SPARROW model of dissolved-solids transport in the Southwestern United States.

Model limitations are generally related to the model structure and data used to calibrate the model. The number of sources and processes affecting dissolved-solids transport in nature are numerous and cannot all be captured and simulated by the simplistic mathematical structure and available data sources for the model. The root mean square error, being greater than zero, indicates this is true; however, the R^2 value of about 0.89 indicates the model does regionally capture the most important sources and processes. Data used to calibrate the model are temporally representative of recent years (1974–2003) and spatially representative for the Southwest. Model predictions are best suited for this time and space boundary, and are uncertain outside these limits.

Significant Source and Accumulation Areas

Significant source areas are those where dissolved solids are released from internal sources and delivered to streams at high delivery rates [(ton/yr)/mi^2]. In contrast, significant accumulation areas are those where dissolved solids transported in streams are retained internally at high accumulation rates [(ton/yr)/mi^2]. Significant source and accumulation areas were determined on the basis of delivery and accumulation rates assessed from predictions of the SPARROW model of dissolved-solids transport in the Southwest. Knowledge of significant source and accumulation areas can be used to target and strategically allocate financial resources towards salinity-control projects, desalinization projects, and other water-quality protection or improvement programs.

Delivery rates from internal sources of dissolved solids in the hydrologic accounting units have considerable variability within the Southwest and ranged from 9 (ton/yr)/mi^2 for the Central Nevada desert basins to 432 (ton/yr)/mi^2 for the Lower Bear (table 19; figs. 37 and 38). The median delivery rate was 48 (ton/yr)/mi^2. The histogram of delivery rates (fig. 37) indicates a main group of accounting units with annual yields less than 150 (ton/yr)/mi^2, and a smaller group of accounting units with rates greater than that value. Delivery rates were greater than 150 (ton/yr)/mi^2 in the Colorado headwaters, Middle Gila, Lower Bear, and Santa Ana accounting units (table 19; fig. 38). These four accounting units are among the most significant source areas of dissolved solids in the Southwest. Delivery rates were less than 15 (ton/yr)/mi^2 in the Mimbres, Great Divide closed basin, Bill Williams, Central Nevada desert basins, and Southern Mojave accounting units (table 19; fig. 38).

Delivery rates tend to be greater in accounting units with (1) wetter climates, such as the Colorado headwaters, Rio Grande headwaters, and upper Bear accounting units, and (2) intensive cultivation of crops and pasture, such as the Salton Sea, Middle Gila, and Lower Bear accounting units (table 19; fig. 38). Delivery rates tend to be low in accounting units with drier climates and minimal cultivation of crops and pasture, such as the Central Nevada Desert Basins, Little Colorado, and Mimbres accounting units (table 19; fig. 38).

Accumulation rates from internal sources of dissolved solids in the accounting units also have considerable variability within the Southwest and ranged from less than 1 (ton/yr)/mi^2 for the Colorado headwaters, Gunnison, and Lower Green accounting units to 704 (ton/yr)/mi^2 for the Salton Sea accounting unit (table 19; figs. 37 and 39). The accumulation rate for the Salton Sea accounting unit was more than twice as large as the second highest rate, 305 (ton/yr)/mi^2 for the Lower Gila-Agua Fria accounting unit. The median accumulation rate was 26 (ton/yr)/mi^2. Accumulation rates were greater than 150 (ton/yr)/mi^2 for the Middle Gila, Lower Gila-Agua Fria, Lower Bear, Great Salt Lake, and Salton Sea accounting units (table 19; fig. 39). These five accounting units are amongst the most significant accumulation areas in the Southwest. Accumulation rates were low—less than 15 (ton/yr)/mi^2 —in about 36 percent (17 of the 47) of the accounting units (table 19; fig. 39).

Accumulation rates tend to be greater in accounting units with (1) closed-surface drainage with significant inflow, such as the Great Salt Lake, (2) significant diversions for irrigation of cultivated and pasture lands, such as the Gila and Lower Bear, or (3) both of the above, as is the case for the Salton Sea. Accumulation rates are smallest in accounting units without significant inflow or diversions for irrigation of cultivated and pasture lands, such as the Central Nevada Desert Basins.

The Ventura-San Gabriel Coast, Santa Ana, and Laguna-San Diego Coastal accounting units are different from the other accounting units in the Southwest in that they each have numerous exports of dissolved solids to the Pacific Ocean through releases of wastewater-treatment-plant effluent. In the other accounting units, such releases occur within the accounting unit and may leave the accounting unit through outflow. Where the effluent releases occur outside of the accounting unit of origin, estimates of the dissolved-solids load exported through the effluent are needed. For the three accounting units on the coast, such exports were not computed because of the numerous treatment plants. Additionally, the treatment-plant loads are likely to vary with the quality and quantity entering the municipal system from different water supplies, which makes obtaining a representative annual export through wastewater-treatment plants a complex task. Consequently, accumulation rates were not computed for the Ventura-San Gabriel Coast, Santa Ana, and Laguna-San Diego Coastal accounting units because the quantity of dissolved solids exported to the Pacific Ocean through wastewater-treatment plants was not quantified.

Areas with high accumulation rates are likely accumulating dissolved solids in the subsurface where flow infiltrates the stream bed in rivers or where agricultural or urban irrigation water is applied and infiltrates. Accumulation can occur as precipitated salts in the soil or underlying sediments, and (or) dissolved salts in soil- or sediment-pore water, or ground water. This accumulation represents a water-quality concern with respect to dissolved-solids concentration in ground water in areas where concentrations of the streamflow-infiltration or irrigation-seepage water are higher than the concentration of the receiving ground water.

In areas where concentrations of the streamflow infiltration or irrigation seepage water are lower than the concentration of the receiving ground water, the infiltrating water would serve to dilute the receiving ground water.

For most accounting units, more dissolved solids are delivered to surface waters than are accumulating from retained surface waters (table 19). For these accounting units, excess dissolved solids not accumulated were transported to other accounting units as outflow or exports. However, for eight accounting units—the Rio Grande-Caballo, Upper Colorado-Dirty Devil, Lower Gila-Agua Fria, Lower Gila, Great Salt Lake, Carson, and Salton Sea—the accumulation rates were much greater than the delivery rates (table 19). These seven accounting units accumulated the dissolved-solids mass generated internally as well as that transported in from other accounting units. For eight accounting units, delivery and accumulation rates were equal because the accounting units were closed basins and had neither outflow nor exports.

With the exception of the Lower Gila, Ventura-San Gabriel Coast, and Salton Sea accounting units, dissolved solids contributed from internal sources within accounting units are greater than dissolved solids contributed from imports from other accounting units (table 19). Imports to the Salton Sea are about 3.75 times as large as dissolved solids delivered from internal sources. In several accounting units, however, imports are greater than 10 percent of the dissolved solids generated internally. These include the Lower Colorado-Lake Mead, Middle Gila, Santa Cruz, Salt, Lower Gila-Agua Fria, Carson, Santa Ana, and Laguna-San Diego Coastal accounting units.

Significant Sources

Predictions from the SPARROW model were used to determine the relative significance of the various natural and human internal sources of dissolved solids that are delivered to river systems in hydrologic accounting units of the Southwest. Significant internal sources of dissolved solids vary by accounting unit as a result of variation across the Southwest in (1) the area of each geologic unit, cultivated land, and pasture land, (2) the source coefficients, (3) the value for each of the land-to-water delivery variables, and (4) the land-to-water delivery variable coefficients. Geologic units, which represent natural sources of dissolved solids, contribute 44 percent of the total internal deliveries for all accounting units in the Southwest (table 20). Cultivated and pasture lands are anthropogenically induced sources of dissolved solids, and contribute the remaining 56 percent of the total internal deliveries for all accounting units in the Southwest.

For the purpose of this discussion, the three sources contributing the largest percentage of internal deliveries of dissolved solids for a given accounting unit are considered “significant sources”. In addition, the discussion points out where sources contribute more than one-third of the total delivery for an accounting unit and where sources contribute more than two-thirds of the total delivery for an accounting unit. While the above criteria for determining the significance of sources are subjective, data in table 20 can be reinterpreted by others with different criteria to determine the significance of each source.

Crystalline rocks contribute 2 percent of the internal deliveries in the Southwest, and are significant sources for four accounting units in the Southwest (table 20). Crystalline rocks contribute more than one-third of the internal deliveries for the Southern Mojave accounting unit.

Volcanic rocks contribute 5 percent of the internal deliveries in the Southwest. While mafic volcanic rocks contribute only 3 percent of the internal deliveries in the Southwest, they are significant sources in 10 accounting units (table 20). Mafic volcanic rocks contribute more than one-third of the internal deliveries for the Truckee accounting unit. Felsic volcanic rocks contribute 2 percent of the internal deliveries in the Southwest and are significant sources in three accounting units. Eugeosynclinal rocks contribute 2 percent of the internal deliveries in the Southwest, and are significant sources in 11 accounting units. Eugeosynclinal rocks contribute more than one-third of the internal deliveries for the Walker and Mono-Owens Lake accounting units.

Table 19. Contributions and losses of dissolved solids to and from river systems in hydrologic accounting units of the Southwestern United States.

[Data determined on the basis of predictions from the SPARROW model of dissolved-solids transport in the Southwest. <, less than]

Hydrologic accounting unit			Contributions of dissolved solids to hydrologic accounting unit surface waters, ton per year			Losses of dissolved solids from hydrologic accounting unit surface waters, ton per year			Area-normalized internal source load and loss rates, ton per year per square mile	
Name	Code	Area, square miles[a]	Inflow	Imports	Internal source loads	Outflow	Exports	Internal losses	Delivery rates	Accumulation rates
Upper Rio Grande Basin										
Rio Grande headwaters	130100	6,490	0	0	712,000	71,000	0	641,000	110	99
Upper Rio Grande	130201	6,270	71,000	16,000	303,000	257,000	0	133,000	48	21
Rio Grande-Elephant Butte	130202	20,960	257,000	0	475,000	545,000	0	187,000	23	9
Rio Grande-Caballo	130301	5,180	545,000	0	287,000	402,000	0	430,000	55	83
Mimbres	130302	2,010	0	0	23,000	0	0	23,000	11	11
Rio Grande closed basins	130500	4,490	0	0	223,000	0	0	223,000	50	50
Upper Colorado River Basin										
Colorado headwaters	140100	9,860	1,173,000	0	[b]2,028,000	3,170,000	32,000	0	206	<1
Gunnison	140200	8,020	0	0	[b]1,173,000	1,173,000	0	0	146	<1
Upper Colorado-Dolores	140300	8,190	3,170,000	0	315,000	3,421,000	23,000	40,000	38	5
Green River Basin										
Upper Green	140401	16,850	0	0	1,062,000	931,000	0	130,000	63	8
Great Divide closed basin	140402	3,680	0	0	53,000	0	0	53,000	14	14
White-Yampa	140500	13,350	0	0	976,000	685,000	2,000	289,000	73	22
Lower Green	140600	14,320	1,616,000	0	[b]882,000	2,478,000	20,000	0	62	<1
Middle Colorado River Basin										
Upper Colorado-Dirty Devil	140700	13,740	6,644,000	1,000	345,000	6,393,000	0	597,000	25	43
Lower Colorado-Lake Mead	150100	30,710	6,900,000	375,000	[c]1,113,000	7,856,000	375,000	[c]158,000	36	5
San Juan River Basin										
Upper San Juan	140801	14,650	0	0	957,000	574,000	16,000	367,000	65	25
Lower San Juan	140802	10,470	574,000	23,000	420,000	744,000	0	274,000	40	26
Little Colorado River Basin										
Little Colorado	150200	26,600	0	0	594,000	508,000	1,000	85,000	22	3
Lower Colorado River Basin										
Lower Colorado	150301	11,840	7,948,000	17,000	684,000	2,482,000	5,603,000	564,000	58	48
Bill Williams	150302	5,390	0	0	63,000	5,000	0	59,000	12	11
Gila River Basin										
Upper Gila	150400	15,260	0	1,000	422,000	254,000	0	169,000	28	11
Middle Gila	150501	3,470	855,000	192,000	1,009,000	1,372,000	0	683,000	290	197
San Pedro-Willcox	150502	4,920	0	0	92,000	58,000	0	34,000	19	7
Santa Cruz	150503	8,670	0	203,000	860,000	543,000	0	520,000	99	60
Salt	150601	7,110	111,000	212,000	488,000	625,000	1,000	186,000	69	26
Verde	150602	6,660	0	2,000	214,000	111,000	0	105,000	32	16
Lower Gila-Agua Fria	150701	7,970	1,997,000	170,000	1,122,000	856,000	0	2,434,000	141	305
Lower Gila	150702	6,960	856,000	417,000	332,000	88,000	524,000	992,000	48	143

See footnotes at end of table.

Table 19. Contributions and losses of dissolved solids to and from river systems in hydrologic accounting units of the Southwestern United States—Continued.

Hydrologic accounting unit			Contributions of dissolved solids to hydrologic accounting unit surface waters, ton per year			Losses of dissolved solids from hydrologic accounting unit surface waters, ton per year			Area-normalized internal source load and loss rates, ton per year per square mile	
Name	Code	Area, square miles[a]	Inflow	Imports	Internal source loads	Outflow	Exports	Internal losses	Delivery rates	Accum-ulation rates
Great Salt Lake and Sevier River Basins										
Upper Bear	160101	2,910	0	0	321,000	197,000	0	123,000	110	42
Lower Bear	160102	3,780	197,000	0	1,632,000	900,000	0	929,000	432	246
Weber	160201	2,390	0	0	323,000	297,000	0	26,000	135	11
Jordan	160202	14,170	0	19,000	370,000	127,000	0	261,000	26	18
Great Salt Lake	160203	12,190	1,324,000	0	663,000	0	0	1,987,000	54	163
Escalante Desert-Sevier Lake	160300	15,100	0	1,000	537,000	0	1,000	537,000	36	36
Central Lahontan Basins										
Truckee	160501	3,690	0	0	84,000	0	36,000	48,000	23	13
Carson	160502	3,690	0	36,000	98,000	0	0	135,000	27	37
Walker	160503	4,510	0	0	155,000	0	0	155,000	34	34
Central Nevada and Eastern California Desert Basins										
Humboldt	160401	16,600	0	0	427,000	0	0	427,000	26	26
Black Rock Desert	160402	10,890	0	0	373,000	0	0	373,000	34	34
Central Nevada Desert Basins	160600	29,890	0	0	272,000	0	0	272,000	9	9
Mono-Owens Lakes	180901	3,630	0	0	223,000	0	100,000	123,000	61	34
Northern Mojave	180902	20,930	0	37,000	488,000	0	0	525,000	23	25
Southern Mojave	181001	4,620	0	1,000	53,000	0	0	54,000	11	12
Salton Sea	181002	6,500	0	[d]3,612,000	963,000	0	0	4,574,000	148	704
Southern California Coastal Basins										
Ventura-San Gabriel Coastal	180701	4,420	0	851,000	515,000	296,000	(e)	(e)	116	(e)
Santa Ana	180702	2,570	0	230,000	505,000	69,000	(e)	(e)	197	(e)
Laguna-San Diego Coastal	180703	5,280	0	196,000	646,000	90,000	(e)	(e)	122	(e)

[a]Only includes contributing drainage area in ERF1_2 network.

[b]Mass balance computation results in negative losses, suggesting underestimated internal source loads; losses therefore reported as zero and catchment source loads augmented by 1,059,000 ton/year in 140100; 267,000 ton/year 140200; and 77,000 ton/year in 140600 so that contributions equal losses.

[c]Export from Colorado River to Las Vegas area occurs within accounting unit. Internal loss determined on the basis of import to Las Vegas area and source coefficient of 0.58 for imports in SPARROW model of dissolved-solids transport in the Southwest. Source loads increased by 519,300 ton/year so that contributions equal losses.

[d]Includes 222,000 ton/year inflow through New River and 10,000 ton/year inflow from Alamo River, which originate in Mexico.

[e]Retention not computed because dissolved-solids loads removed from accounting units and delivered to the Pacific Ocean through municipal wastewater-treatment systems is unaccounted for.

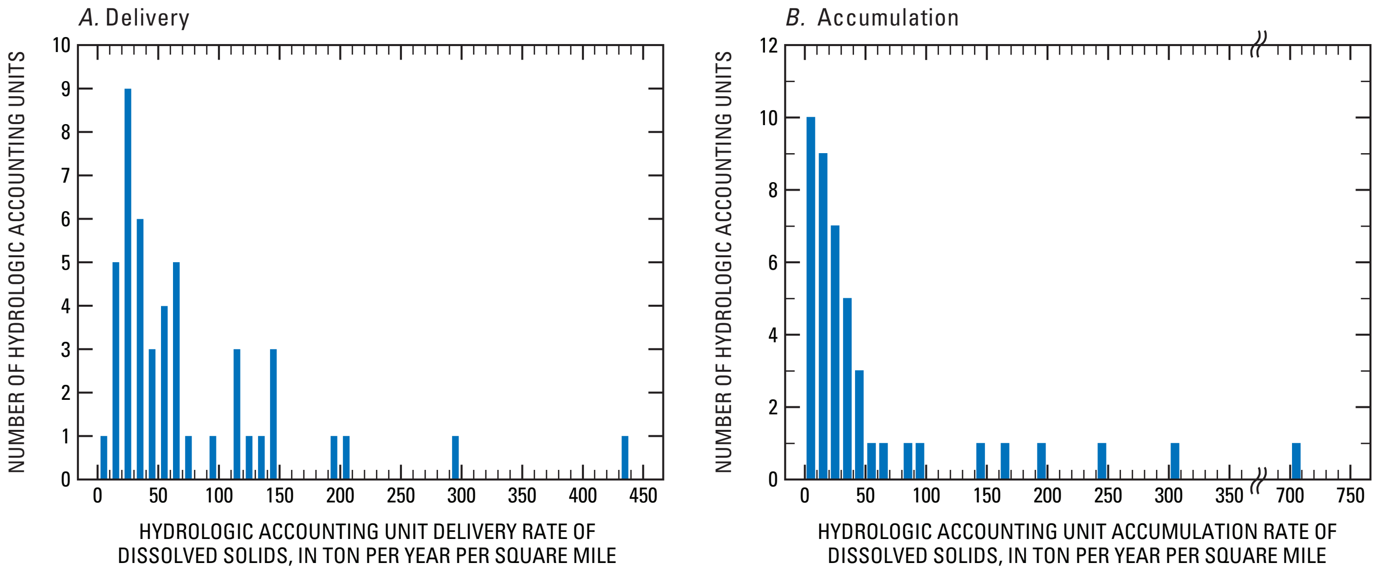


Figure 37. Histograms of *A*, Delivery; and *B*, Accumulation rates of dissolved solids for hydrologic accounting units in the Southwestern United States.

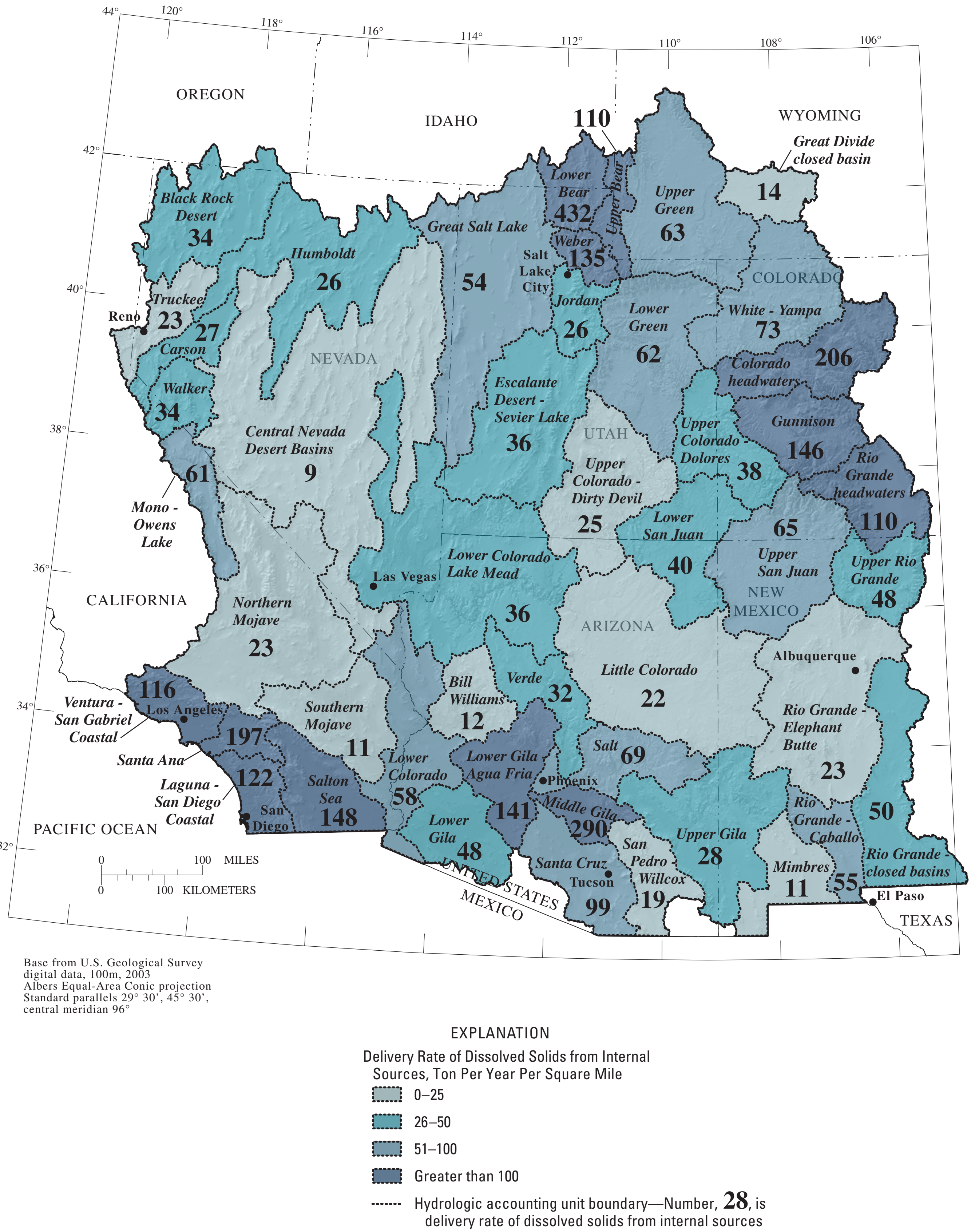


Figure 38. Delivery rates of dissolved solids from internal sources in hydrologic accounting units of the Southwestern United States.

Figure 39. Accumulation rates of dissolved solids in hydrologic accounting units of the Southwestern United States.

Table 20. Relative contribution of dissolved solids delivered to river systems from internal sources in hydrologic accounting units of the Southwestern United States.

[Data are expressed as a percentage of the total catchment sources in each hydrologic accounting unit. Values highlighted in white indicate the three largest sources for each hydrologic accounting unit. In some cases contributions from all sources total to less than 99 percent due to rounding errors]

Hydrologic accounting unit			Volcanic rocks			Sedimentary rocks								Agricultural lands	
						Tertiary		Mesozoic			Paleozoic and Precambrian				
Name	Code	Crystalline rocks	Mafic	Felsic	Eugeosynclinal rocks	High-yield	Low-yield	High-yield	Medium-yield	Low-yield	High-yield	Medium-yield	Low-yield	Cultivated	Pasture
Upper Rio Grande Basin															
Rio Grande headwaters	130100	1	8	14	0	0	14	0	0	0	0	2	0	42	19
Upper Rio Grande	130201	4	8	1	0	0	21	13	3	1	0	23	0	18	8
Rio Grande-Elephant Butte	130202	1	5	2	0	1	19	15	11	2	13	4	1	22	5
Rio Grande-Caballo	130301	0	3	0	0	0	8	0	0	0	2	3	0	80	4
Mimbres	130302	2	13	6	0	0	24	0	4	3	0	13	0	26	9
Rio Grande closed basins	130500	0	1	0	0	1	0	0	2	1	44	5	2	39	4
Upper Colorado River Basin															
Colorado headwaters	140100	5	2	0	0	11	12	9	4	3	0	28	1	14	11
Gunnison	140200	3	5	7	0	1	4	20	9	4	0	3	0	31	14
Upper Colorado-Dolores	140300	1	1	0	0	1	1	30	17	18	0	7	0	15	9
Green River Basin															
Upper Green	140401	2	0	0	0	22	34	10	4	0	0	5	1	7	14
Great Divide closed basin	140402	0	0	0	0	42	45	4	4	1	0	0	0	4	0
White-Yampa	140500	2	1	0	0	11	19	11	9	2	0	6	0	30	9
Lower Green	140600	0	0	0	0	24	17	17	9	4	0	6	2	10	13
Middle Colorado River Basin															
Upper Colorado-Dirty Devil	140700	0	3	0	0	5	1	41	17	23	0	2	1	3	4
Lower Colorado-Lake Mead	150100	1	4	4	0	1	10	9	12	3	26	18	4	3	7
San Juan River Basin															
Upper San Juan	140801	2	3	4	0	8	8	12	16	4	0	10	0	19	14
Lower San Juan	140802	0	0	0	0	0	1	3	12	12	5	1	1	56	8
Little Colorado River Basin															
Little Colorado	150200	0	5	0	0	0	13	20	27	4	24	0	2	4	3
Lower Colorado River Basin															
Lower Colorado	150301	2	3	0	2	0	1	1	0	0	0	1	0	70	19
Bill Williams	150302	25	24	2	0	0	6	0	0	0	2	16	0	20	5

Table 20. Relative contribution of dissolved solids delivered to river systems from internal sources in hydrologic accounting units of the Southwestern United States—Continued.

Hydrologic accounting unit			Volcanic rocks			Sedimentary rocks								Agricultural lands	
						Tertiary		Mesozoic			Paleozoic and Precambrian				
Name	Code	Crystalline rocks	Mafic	Felsic	Eugeosynclinal rocks	High-yield	Low-yield	High-yield	Medium-yield	Low-yield	High-yield	Medium-yield	Low-yield	Cultivated	Pasture
Gila River Basin															
Upper Gila	150400	1	9	3	0	0	14	0	0	0	0	1	0	68	3
Middle Gila	150501	0	0	0	0	0	0	0	0	0	0	0	0	96	2
San Pedro-Willcox	150502	2	2	3	0	0	29	0	3	0	0	6	0	43	11
Santa Cruz	150503	1	1	0	0	0	1	0	0	0	0	1	0	93	3
Salt	150601	2	8	1	0	0	7	0	0	1	50	2	1	28	1
Verde	150602	3	16	0	0	0	2	0	0	0	58	8	1	9	3
Lower Gila-Agua Fria	150701	1	1	0	0	0	1	0	0	0	0	0	0	94	3
Lower Gila	150702	2	5	0	2	0	1	1	0	0	0	0	0	77	12
Great Salt Lake and Sevier River Basins															
Upper Bear	160101	0	0	0	0	7	22	15	6	0	0	4	1	26	20
Lower Bear	160102	0	0	0	0	0	2	1	0	0	1	2	1	81	12
Weber	160201	0	1	0	0	0	17	6	1	0	18	7	1	35	12
Jordan	160202	0	2	0	0	9	2	4	2	0	2	22	1	20	36
Great Salt Lake	160203	0	1	0	0	0	4	0	0	0	2	9	1	72	10
Escalante Desert-Sevier Lake	160300	0	10	1	0	29	4	7	0	0	4	1	0	7	36
Central Lahonton Basins															
Truckee	160501	9	51	3	13	0	6	5	0	0	0	0	0	0	13
Carson	160502	11	16	1	18	0	5	4	0	0	0	0	0	0	46
Walker	160503	8	10	3	42	0	2	1	0	0	0	0	0	0	34
Central Nevada and Eastern California Desert Basins															
Humboldt	160401	0	2	7	19	0	13	5	0	0	0	3	1	10	40
Black Rock Desert	160402	2	6	9	5	0	3	8	0	0	0	0	0	26	42
Central Nevada Desert Basins	160600	1	8	18	18	0	4	6	0	0	7	17	4	1	16
Mono-Owens Lakes	180901	10	1	17	56	0	0	0	0	0	5	1	1	0	9
Northern Mojave	180902	7	3	3	8	0	4	0	0	0	7	4	1	42	21
Southern Mojave	181001	41	11	0	19	0	2	0	0	0	0	3	0	18	5
Salton Sea	181002	1	0	0	3	0	2	0	0	0	0	0	0	73	21

Table 20. Relative contribution of dissolved solids delivered to river systems from internal sources in hydrologic accounting units of the Southwestern United States—Continued.

Hydrologic accounting unit			Volcanic rocks			Sedimentary rocks								Agricultural lands	
						Tertiary		Mesozoic			Paleozoic and Precambrian				
Name	Code	Crystalline rocks	Mafic	Felsic	Eugeosynclinal rocks	High-yield	Low-yield	High-yield	Medium-yield	Low-yield	High-yield	Medium-yield	Low-yield	Cultivated	Pasture
Southern California Coastal Basins															
Ventura-San Gabriel Coastal	180701	4	1	0	4	0	25	0	0	0	0	0	0	59	7
Santa Ana	180702	4	0	0	5	0	3	0	0	0	0	1	0	83	4
Laguna-San Diego Coastal	180703	4	0	0	11	0	4	0	0	0	0	0	0	75	6
Southwestern United States															
All hydrologic accounting units		2	3	2	2	4	8	6	4	2	4	5	1	44	12

Sedimentary rocks contribute 34 percent of the internal deliveries in the Southwest, which is much greater than the percentage contributed from crystalline, volcanic, and eugeosynclinal rocks combined (9 percent). Tertiary sedimentary rocks contribute 12 percent of the internal deliveries in the Southwest. High-yield Tertiary sedimentary rocks contribute 4 percent of the internal deliveries in the Southwest, and are significant sources in four accounting units—the Upper Green, Great Divide closed basin, Lower Green, and Escalante Desert-Sevier Lake accounting units (table 20). High-yield Tertiary rocks contribute more than one-third of the internal source loads in the Great Divide closed basin accounting unit. Low-yield Tertiary sedimentary rocks contribute 8 percent of the internal deliveries in the Southwest, and are significant sources in 19 accounting units. Low-yield Tertiary rocks contribute more than one-third of the internal deliveries in the Upper Green and Great Divide closed basin accounting units.

Mesozoic sedimentary rocks contribute 12 percent of the internal deliveries in the Southwest. High-yield Mesozoic sedimentary rocks contribute 6 percent of the internal deliveries in the Southwest, and are significant sources in seven accounting units (table 20). High-yield Mesozoic sedimentary rocks contribute more than one-third of the internal deliveries in the Upper Colorado-Dirty Devil accounting unit. Medium-yield Mesozoic sedimentary rocks contribute 4 percent of the internal deliveries in the Southwest, and are significant sources in six accounting units. Low-yield Mesozoic sedimentary rocks contribute 2 percent of the internal deliveries in the Southwest, and are significant sources in the Upper Colorado-Dolores and Upper Colorado-Dirty Devil accounting units. Medium-yield and low-yield Mesozoic sedimentary rocks, individually, did not contribute more than one-third of the internal deliveries in any accounting unit.

Paleozoic and Precambrian sedimentary rocks contribute 10 percent of the internal deliveries in the Southwest. High-yield Paleozoic and Precambrian sedimentary rocks contribute 4 percent of the internal deliveries in the Southwest, and were significant sources in six accounting units (table 20). High-yield Paleozoic and Precambrian sedimentary rocks contribute more than one-third of the internal deliveries in the Rio Grande closed basins, Salt, and Verde accounting units. Medium-yield Paleozoic and Precambrian sedimentary rocks contribute 5 percent of the internal deliveries in the Southwest, and were significant sources in eight accounting units. Low-yield Paleozoic and Precambrian sedimentary rocks contribute only 1 percent of the internal deliveries in the Southwest, and were not significant sources in any accounting unit.

Cultivated lands and pasture lands represent human sources of dissolved solids and contribute 56 percent of the internal deliveries of dissolved solids in the Southwest (table 20). Of the 14 internal sources included in the SPARROW model, cultivated lands contribute the highest percentage of internal deliveries of dissolved solids in the Southwest, 44 percent. In addition, cultivated lands are significant sources in 34 of the 47 accounting units, making it the most commonly occurring significant source for accounting units of the Southwest. Further, cultivated lands contribute more than one-third of the internal deliveries in 19 accounting units, and contribute more than two-thirds of the internal deliveries in 12 accounting units. Pasture lands are also a regionally significant source of dissolved solids. Pasture lands contribute 12 percent of the internal deliveries in the Southwest, and are a significant source in 26 accounting units. Pasture lands contribute more than one-third of the internal source deliveries in the Jordan, Escalante Desert-Sevier Lake, Carson, Walker, Humboldt and Black Rock Desert accounting units. The importance of cultivated lands and pasture lands as sources of dissolved solids has been recognized by several scientific investigations, and many of the salinity-control projects in the Colorado River Basin listed in tables 6 and 7 are designed to mitigate deliveries from these sources.

Sources, Transport, and Accumulation in Major River Basins

The sources, transport, and accumulation of dissolved solids vary by major river basin and are described in this section on the basis of information in tables 19 and 20, and figures 38 and 39. Major river basin boundaries are shown in figure 3. In the upper Rio Grande major river basin, delivery rates in accounting units decrease in the downstream direction until the Rio Grande-Caballo accounting unit, where delivery rates are greater and cultivated lands contribute 80 percent of the internal deliveries. Significant internal sources for the major river basin include low-yield Tertiary sedimentary rocks, high-yield Mesozoic sedimentary rocks, high-yield and medium yield Paleozoic and Precambrian sedimentary rocks, cultivated lands, and pasture lands. Accumulation is high in the Rio Grande headwaters accounting unit [99 (ton/yr)/mi^2] because of internal losses that occur within the San Luis Valley area in this accounting unit. This area is partly topographically closed, and therefore, retains dissolved solids because they cannot flow to downstream areas. In addition, the area contains significant diversions for agriculture, which removes water from streams, and only part of the dissolved solids load diverted flows back to the streams in irrigation-return flows. Accumulation also is high in the Rio Grande-Caballo accounting unit due to diversions for agriculture. Accumulation in the Mimbres and Rio Grande closed basins accounting units is not high despite the fact that they are closed to surface drainage; for these accounting units the accumulation rate equals the delivery rate.

Accounting units in the Upper Colorado River Basin have some of the highest delivery rates for internal deliveries of dissolved solids in the Southwest, and some of the lowest accumulation rates. Consequently, nearly all of the dissolved solids delivered to streams in this major river basin flow downstream to the Middle Colorado River Basin. Significant internal sources in the major river basin include low-yield Tertiary sedimentary rocks; high-, medium-, and low-yield Mesozoic sedimentary rocks; medium yield Paleozoic and Precambrian sedimentary rocks, cultivated lands, and pasture lands.

In the Green River Basin, delivery rates are moderately high, 62 to 73 (ton/yr)/mi^2, for accounting units contributing loads to the Green River. The delivery rate for the Great Divide closed basin, however, is much lower at 14 (ton/yr)/mi^2. Significant internal deliveries in the major river basin include high-yield and low-yield Tertiary sedimentary rocks, high-yield Mesozoic sedimentary rocks, cultivated lands, and pasture lands. Accumulation rates for accounting units are moderately low and range from less than 1 to 22 (ton/yr)/mi^2. Most of the dissolved solids delivered in this major river basin flow out downstream to the Middle Colorado River Basin.

In the San Juan River Basin, delivery rates for accounting units are moderate, 65 and 40 (ton/yr)/mi^2 for the Upper San Juan accounting unit and the Lower San Juan accounting unit, respectively. Accumulation rates for these two accounting units are 25 and 26 (ton/yr)/mi^2, respectively. Significant internal sources in the major river basin are medium-yield Mesozoic sedimentary rocks, cultivated lands, and pasture lands. Most of the dissolved solids delivered to streams in this major river basin are transported out through outflow to the Middle Colorado River Basin.

In the Little Colorado River Basin, both delivery and accumulation rates for accounting units are low at 22 and 3 (ton/yr)/mi^2, respectively. Significant internal sources include high-yield and medium-yield Mesozoic sedimentary rocks, and high-yield Paleozoic and Precambrian sedimentary rocks. Most of the dissolved solids delivered to streams in this major river basin are transported out through outflow to the Middle Colorado River Basin.

The largest contribution of dissolved solids to the Middle Colorado River basin by far is from inflow from the Upper Colorado, Green River, San Juan, and Little Colorado River basins. Delivery rates for the Upper Colorado-Dirty Devil and Lower Colorado-Lake Mead accounting units are moderately low at 25 and 36 (ton/yr)/mi^2, respectively. Significant internal deliveries in the major river basin include high-, medium-, and low-yield Mesozoic sedimentary rocks; high- and medium-yield Paleozoic and Precambrian sedimentary rocks. Accumulation rates for the Upper Colorado-Dirty Devil and Lower Colorado-Lake Mead accounting units are 43 and 5 (ton/yr)/mi^2, respectively.

Similar to the Middle Colorado River Basin, the largest contribution of dissolved solids to the Lower Colorado River Basin is from inflow. Delivery and accumulation rates are moderately high for the Lower Colorado accounting unit [58 and 48 (ton/yr)/mi^2, respectively] but are low for the Bill Williams accounting unit [12 and 11 (ton/yr)/mi^2, respectively]. Significant sources include crystalline rocks, mafic volcanic rocks, cultivated lands, and pasture lands. Exports of dissolved solids from the Lower Colorado River Basin to Gila River Basin accounting units, Southern California Coastal Basin accounting units, and the Salton Sea accounting unit are more than twice the outflow into Mexico.

In the Gila River Basin, delivery rates are low for the Upper Gila, San Pedro-Willcox, and Verde accounting units. Delivery rates, however, are moderate or high for the Middle Gila, Santa Cruz, Lower Gila-Agua Fria, and Lower Gila accounting units, where cultivated lands contribute more than 70 percent of the internal deliveries of dissolved solids. In the Salt accounting unit, delivery rates also are high, however the predominant source of dissolved solids is high-yield Paleozoic and Precambrian sedimentary rocks (50 percent). Other significant internal sources for accounting units in the Gila River Basin include mafic volcanic rocks, low-yield Tertiary sedimentary rocks, cultivated lands, and pasture lands. The Middle Gila, Santa Cruz, Salt, Lower Gila-Agua Fria, and Lower Gila accounting units also receive substantial contributions of dissolved solids from imported water from the Lower Colorado River. Accumulation rates for the Middle Gila, Lower Gila-Agua Fria, and Lower Gila accounting units are amongst the highest in the Southwest, and result from streamflow losses due to diversions for municipal and agricultural use, as well as streamflow infiltration in reaches within the Quaternary basin fill.

In the Great Salt Lake and Sevier River Basins, delivery rates are moderate to high. The delivery rate for the Lower Bear is the highest of all accounting units, 432 (ton/yr)/mi^2, where cultivated lands contribute 81 percent of the internal deliveries of dissolved solids (fig. 38). Significant internal sources of dissolved solids in this major river basin include mafic volcanic rocks, high-yield and low-yield Tertiary sedimentary rocks, high-yield and medium-yield Paleozoic and Precambrian sedimentary rocks, cultivated land, and pasture lands. Accumulation rates are variable, however, those for the Lower Bear and Great Salt Lake at 246 and 163 (ton/yr)/mi^2, respectively, are amongst the highest for accounting units in the Southwest. The Great Salt Lake accounting unit receives outflow from the Lower Bear, Weber, and Jordan accounting units. The Great Salt Lake and Escalante Desert-Sevier Lake accounting units are closed, with no outflow.

The Central Lahontan Basins have moderately low delivery rates [23 to 34 (ton/yr)/mi^2] and accumulation rates [13 to 37 (ton/yr)/mi^2]. While the three accounting units in this major river basin are closed, the Carson accounting unit receives substantial imports of water from the Truckee accounting unit. Significant internal sources of dissolved solids include mafic volcanic rocks, eugeosynclinal rocks, and pasture lands.

Accounting units in the Central Nevada and Eastern California Desert Basins generally have moderate or low delivery and accumulation rates. Accounting units are closed in this major river basin, and consequently, most contributions are derived from internal sources, and most losses occur internally rather than from export or outflow. Significant internal sources include crystalline rocks, felsic volcanic rocks, eugeosynclinal rocks, low-yield Tertiary sedimentary rocks, medium-yield Paleozoic and Precambrian sedimentary rocks, cultivated lands, and pasture lands. A significant exception to these observations for accounting units in this major river basin is the Salton Sea. In contrast to the other accounting units, the Salton Sea receives more contributions of dissolved solids from imports than from internal sources. The imported water is used primarily to irrigate cultivated and pasture lands, which in turn are sources of dissolved solids and account for 94 percent of the internal deliveries of dissolved solids to streams in the accounting unit (table 20). As a result of the large contribution from imports, the high delivery rate from internal sources [148 (ton/yr)/mi^2], and the fact that there is no outflow, the accumulation rate for the Salton Sea is by far the highest rate amongst all accounting units at 704 (ton/yr)/mi^2.

Delivery rates are high for accounting units in the Southern California Coastal Basins, ranging from 116 to 197 (ton/yr)/mi^2. Like the Salton Sea accounting unit and several accounting units in the Gila River Basin, imports from the Lower Colorado River basin are a significant portion of the total contributions of dissolved solids to the accounting units in the Southern California Coastal Basins. In fact, contributions are larger from imports than from internal sources in the Ventura-San Gabriel Coast accounting unit. Significant internal sources include crystalline rocks, eugeosynclinal rocks, low-yield Tertiary sedimentary rocks, cultivated lands, and pasture lands. Outflow is though streams and exports are through sewer systems, both transporting dissolved solids to the Pacific Ocean. Estimates of exports to the ocean through sewer systems, however, were not determined, and as a result, accumulation rates were not computed.

Trends of Dissolved Solids

An analysis of trends in concentrations of dissolved solids in basin-fill aquifers and streams was performed to determine whether dissolved-solids concentrations have been generally increasing or decreasing in recent years, and whether there are any patterns in the trends related to natural and human factors. The temporal scope of the trend analysis like other analyses in this report is restricted to water years 1974–2003 to avoid potential errors and misinterpretations associated with combining data from both pre- and post-reservoir development on major streams. By 1974, many of the larger reservoirs within the Southwest had been completed and filled. The temporal scope of data for basin-fill aquifers was also restricted to the same time period. The analyses were performed for three periods: water years 1974–2003, water years 1974–88, and water years 1989–2003. Determining trends for the latter two, short periods allowed for inclusion of more sites in the trend analysis and more detail of trends than an analysis of a single long period. Results from the trend analysis of dissolved solids in basin-fill aquifers and streams of the Southwest are described in the following sections.

Basin-Fill Aquifers

By David W. Anning

The type of trend—increasing, decreasing, or no trend—and the period change for trends in dissolved-solids concentrations were determined for ground-water-quality monitoring wells completed in basin-fill aquifers of the Southwest for 1974–88, 1989–2003, and 1974–2003. The trend data were computed according to the methods described in the "Approach, Data Compilation, and Analysis Methods" section of this report. Information on the type and magnitude of trends in concentrations for these periods can be used to assess whether water quality conditions have generally improved, remained static, or degraded over time in the basin-fill aquifers. The relation of presence and magnitude of trends to selected natural and human factors also is presented, and is useful for identifying the conditions under which trends are likely to occur. The trend results, location information, and natural- and human-factor data that were used for each well in this analysis are listed in appendix 6.

The majority of the ground-water-quality monitoring wells used in this analysis are part of independent State, county, or local ground-water quality networks that monitor changes in concentrations of dissolved solids and other constituents over time. The assemblage of ground-water-quality monitoring wells from these individual networks form a substantial set of wells for monitoring trends in dissolved-solids concentrations in basin-fill aquifers across the Southwest. The number of wells with dissolved-solids trend data varies by analysis period, basin-fill aquifer, and accounting unit (table 21). For the basin-fill aquifers in the Southwest, there were more wells with trend data available for 1989–2003 (182 wells) than for 1974–88 (110 wells) or for 1974–2003 (51 wells). The spatial distribution of wells with trend data for each analysis period is shown in figure 40.

For each of the three periods, there were many more ground-water-quality monitoring wells with dissolved-solids trend data available for the Basin and Range basin-fill aquifers than for the Rio Grande aquifer system or the California Coastal Basin aquifers (table 21). The differences in trend-data availability are partly because the Basin and Range basin-fill aquifers are spatially the most extensive of the three aquifers. There are, however, large spatial gaps of available trend data for the Basin and Range basin-fill aquifers (fig. 40 A, B, and C) in most all of Nevada (all periods), east-central Utah (all periods), southeastern California and southwestern Arizona (all periods), all of New Mexico (all periods), and all of Arizona (1974–88 and 1974–2003 only). Much of the area represented by these spatial gaps of data do not have significant ground-water development; however, there are some areas, such as the Las Vegas Valley that have significant ground-water development but are not represented by any wells with trend data.

Table 21. Number of ground-water-quality monitoring wells with dissolved-solids concentration trend data for 1974–88, 1989–2003, and 1974–2003 in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers by hydrologic accounting units of the Southwestern United States.

Hydrologic accounting unit		Number of ground-water quality monitoring wells with dissolved-solids concentration trend data		
		Analysis period		
Name	Code	1974–1988	1989–2003	1974–2003
Rio Grande aquifer system				
Rio Grande-Elephant Butte	130202	0	1	0
Rio Grande closed basins	130500	19	0	0
Total for principal aquifer		19	1	0
Basin and Range basin-fill aquifers				
Lower Colorado-Lake Mead	150100	0	6	0
Lower Colorado	150301	0	6	0
Bill Williams	150302	0	1	0
Upper Gila	150400	0	5	0
Middle Gila	150501	0	2	0
San Pedro-Willcox	150502	0	5	0
Santa Cruz	150503	0	10	0
Verde	150602	0	3	0
Lower Gila-Agua Fria	150701	0	12	0
Lower Gila	150702	0	2	0
Lower Bear	160102	5	2	2
Weber	160201	5	4	4
Jordan	160202	14	16	9
Great Salt Lake	160203	12	8	5
Escalante Desert-Sevier Lake	160300	21	34	15
Truckee	160501	0	11	0
Carson	160502	0	10	0
Walker	160503	0	1	0
Northern Mojave	180902	16	27	9
Southern Mojave	181001	1	2	0
Salton Sea	181002	9	9	5
Total for principal aquifer		83	176	49
California Coastal Basin aquifers				
Ventura - San Gabriel Coastal	180701	1	0	0
Santa Ana	180702	0	2	0
Laguna-San Diego Coastal	180703	7	3	2
Total for principal aquifer		8	5	2
Total for basin-fill aquifers in the Southwestern United States		110	182	51

A.

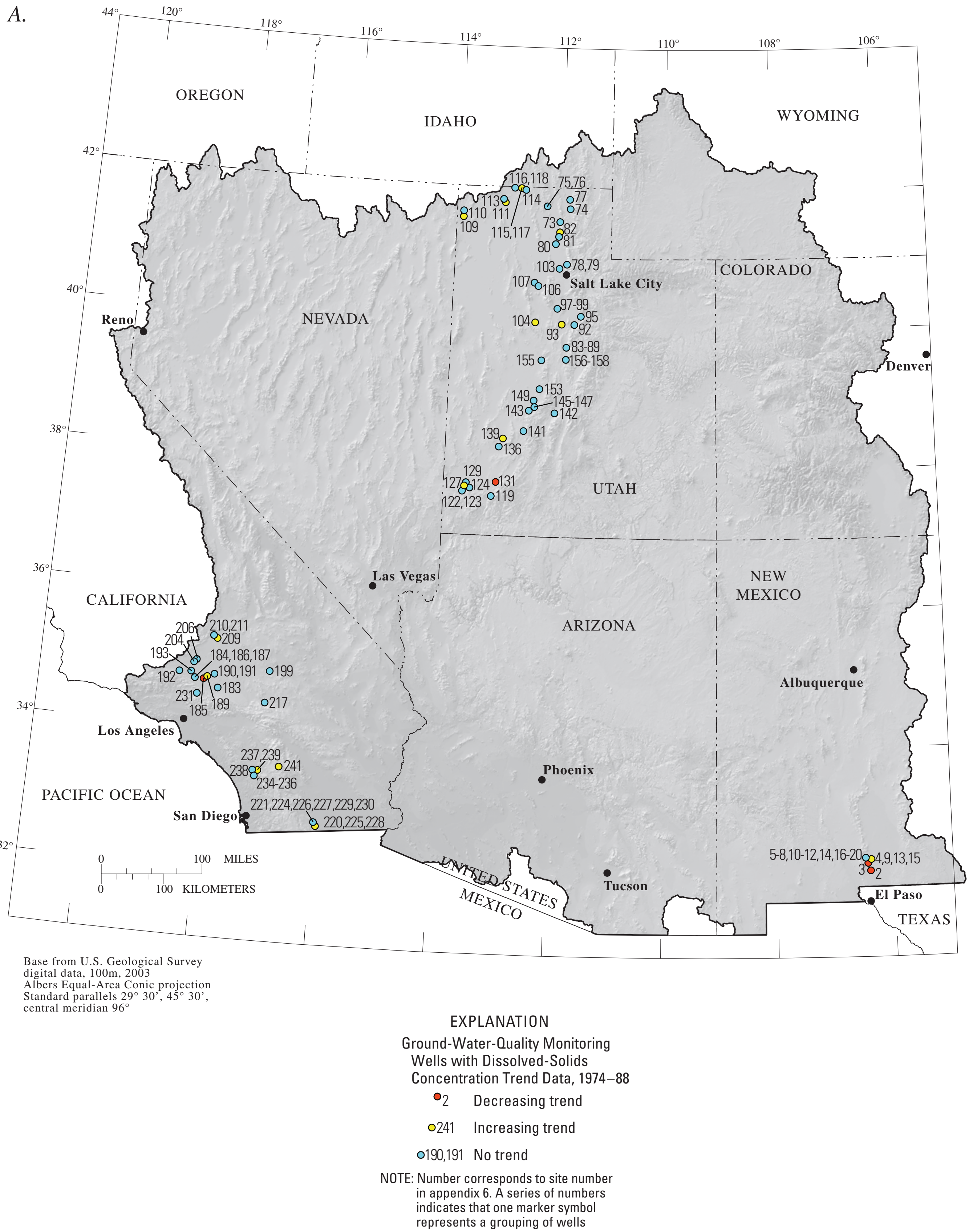
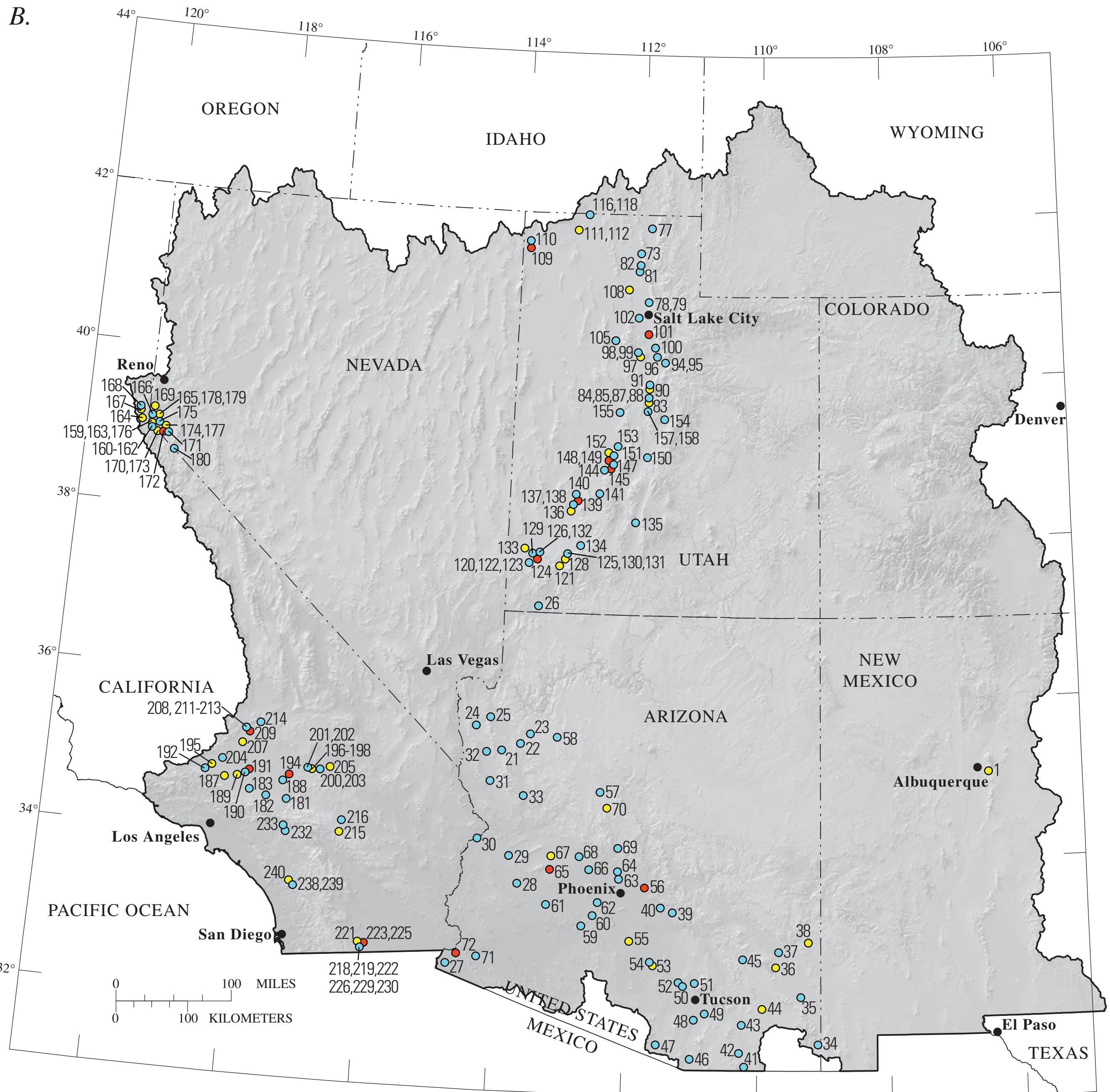


Figure 40. Location of and trend in dissolved-solids concentrations for ground-water-quality monitoring wells in basin-fill aquifers of the Southwestern United States. *A*, 1974–88; *B*, 1989–2003; and *C*, 1974–2003.

B.



Base from U.S. Geological Survey
digital data, 100m, 2003
Albers Equal-Area Conic projection
Standard parallels 29° 30’, 45° 30’,
central meridian 96°

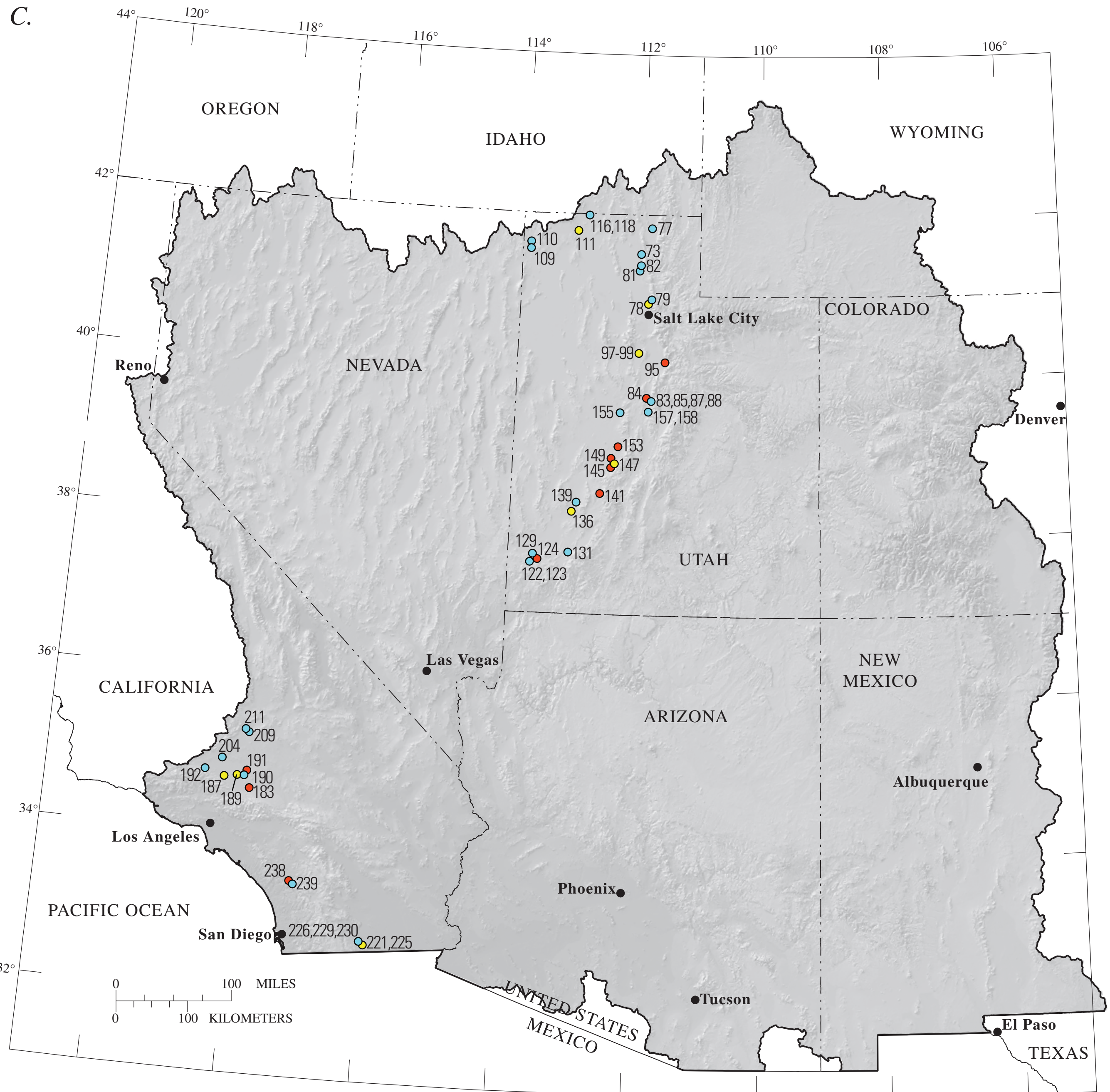
EXPLANATION

Ground-Water-Quality Monitoring Wells with Dissolved-Solids Concentration Trend Data, 1989–2003

- 56 Decreasing trend
- 215 Increasing trend
- 238,239 No trend

NOTE: Number corresponds to site number in appendix 6. A series of numbers indicates that one marker symbol represents a grouping of wells

Figure 40. Continued.



Base from U.S. Geological Survey digital data, 100m, 2003
Albers Equal-Area Conic projection
Standard parallels 29° 30', 45° 30', central meridian 96°

EXPLANATION

Ground-Water-Quality Monitoring Wells with Dissolved-Solids Concentration Trend Data, 1974–2003

- 153 Decreasing trend
- 221,225 Increasing trend
- 131 No trend

NOTE: Number corresponds to site number in appendix 6. A series of numbers indicates that one marker symbol represents a grouping of wells

Figure 40. Continued.

For the Rio Grande aquifer system, trend data were available for 1 ground-water-quality monitoring well in the Rio Grande-Elephant Butte accounting unit for 1989–2003 and 19 wells in the Rio Grande closed basins accounting unit for 1974–88. For the Basin and Range basin-fill aquifers, trend data were available for at least one of the three periods for all accounting units except the Salt, Humboldt, Black Rock Desert, Central Nevada Desert Basins, and Mono-Owens Lake accounting units. For several accounting units, the number of wells in the Basin and Range basin-fill aquifers with trend data available varies greatly by analysis period. For 1974–88 and 1974–2003, there are several accounting units without any trend data for wells in the Basin and Range basin-fill aquifers. For all three periods, the Jordan, Escalante Desert-Sevier Lake, and Northern Mojave accounting units have a much larger number of wells with trend data available for Basin and Range basin-fill aquifers than other accounting units. Although trend data for wells are available for each accounting unit in the California Coastal Basin aquifers, the number of wells with trend data is small for each analysis period.

Caution must be used when interpreting the dissolved-solids concentration trend data. Ground water in the basin-fill aquifers generally moves slowly, and, as a result, trends in dissolved-solids concentrations observed for a given ground-water-quality monitoring well generally represent conditions for a small area near the well rather than for a large portion of the ground-water basin's aquifer. Given (1) the limited number of wells with trend data available, (2) the localized area represented by a single well, and (3) the large areas of the aquifers without trend data available, the trend data was not used to spatially map areas having increasing, decreasing, or no trends in dissolved-solids concentrations. Rather, the trend data for a given period from all ground-water-quality monitoring wells in the three aquifers were used collectively to represent a sample population for conditions in basin-fill aquifers in specific areas of the Southwest. The sample population, represented by the available trend data, was used in an exploratory analysis to understand trends generally occurring in basin-fill aquifers of the Southwest and to gain insight into the factors associated with the trends.

There is considerable variation in the hydrologic and land-use conditions for the ground-water-quality monitoring wells in each basin-fill aquifer and analysis period (table 22). This variation in hydrologic and land-use conditions was used to relate trend data to various hydrologic and land-use conditions found in the basin-fill aquifers of the Southwest. For the three principle basin-fill aquifers, the depth to water for wells with trend data range from 40 ft above the land surface, representing artesian conditions, to 1,013 ft below the land surface. The depth of the wells with trend data also demonstrate considerable variability and range from 23 ft deep to 1,750 ft deep. The agricultural land use in a 1,640 ft (500 m) radius area around each well varies from 0 percent to 100 percent, and the percentage of urban land use in the same area ranged from 0 percent to 98 percent. The percentage of land use other than agricultural or urban ranged from 0 percent to 100 percent. Land use for a larger area around each well, 16,400 ft (5 km) radius, also was variable. For this larger area, the agricultural land use ranged from 0 percent to 78 percent, and the urban land use ranged from 0 to 68 percent. Land use other than agricultural or urban for the larger area ranged from 14 percent to 100 percent.

Changes and Trends: 1974–88

Of the 110 ground-water-quality monitoring wells in the basin-fill aquifers of the Southwest with dissolved-solids concentration-trend data for 1974–88, 85 wells (77 percent) did not have a trend, 21 wells (19 percent) had an increasing trend, and 4 wells (4 percent) had a decreasing trend (table 23). The pattern of most wells not having a trend, a small portion of wells having an increasing trend, and a smaller portion of wells having a decreasing trend is repeated for each of the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers individually (table 23). Geographically, there are no spatial patterns or clusters in the occurrence of wells with no trend, an increasing trend, or a decreasing trend; that is, wells with an increasing trend or decreasing trend are generally dispersed (fig. 40*A*).

The period change for an individual well is computed as the change in modeled concentration for the beginning of the analysis period (1974) to the end of the analysis period (1988), divided by the modeled concentration for the beginning of the analysis period. This number is then multiplied by 100 to express the period change as a percent. Thus, period changes represent the change in dissolved-solids concentrations that occurs over 15 years for 1974–88 and 1989–2003, and over 30 years for 1974–2003. For 1974–88, the four wells that have a decreasing trend in concentration, the average period change was -32 percent (table 24). For the 21 wells that have an increasing trend in concentrations, the average period change was +59 percent.

Changes and Trends: 1989–2003

Of the 182 ground-water-quality monitoring wells in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwest with dissolved-solids concentration-trend data for 1989–2003, 123 wells (68 percent) did not have a trend, 43 wells (24 percent) had an increasing trend, and 16 wells (9 percent) had a decreasing trend (table 23). The pattern of most wells not having a trend, a small portion of wells having an increasing trend, and a smaller portion of wells having a decreasing trend is repeated for the Basin and Range basin-fill aquifers, and California Coastal Basin aquifers individually (table 23). Trend data was only available for one well in the Rio Grande aquifer system, and it indicated an increase in concentration. Geographically, there are no spatial patterns or clusters in the occurrence of wells with no trend, an increasing trend, or a decreasing trend (fig. 40*B*).

Table 22. Summary statistics for hydrologic and land-use characteristics for ground-water-quality monitoring wells in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwestern United States with dissolved-solids concentration trend data for 1974–88, 1989–2003, and 1974–2003.

[Negative values for depth below land surface indicate artesian conditions]

Principal aquifer	Analysis period	Count	Minimum	Mean	Maximum
Depth to water below land surface, feet					
Rio Grande aquifer system	1974–88	12	188	367	570
	1989–2003	1	68	68	68
Basin and Range basin-fill aquifers	1974–88	69	-40	85	258
	1989–2003	154	-40	142	1,013
	1974–2003	39	-40	88	248
California Coastal Basin aquifers	1974–88	7	8	45	106
	1989–2003	5	1	92	263
	1974–2003	2	36	71	106
Well depth, feet					
Rio Grande aquifer system	1974–88	12	351	692	1,060
	1989–2003	1	120	120	120
Basin and Range basin-fill aquifers	1974–88	79	60	365	930
	1989–2003	168	23	389	1,750
	1974–2003	47	84	379	930
California Coastal Basin aquifers	1974–88	8	50	265	1,000
	1989–2003	5	96	624	1,000
	1974–2003	2	96	548	1,000
Agricultural area in 1,640 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	0	0	0
	1989–2003	1	0	0	0
Basin and Range basin-fill aquifers	1974–88	83	0	41	100
	1989–2003	175	0	28	99
	1974–2003	49	0	39	99
California Coastal Basin aquifers	1974–88	8	0	25	74
	1989–2003	5	0	16	62
	1974–2003	2	1	1	1
Urban area in 1,640 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	0	10	53
	1989–2003	1	44	44	44
Basin and Range basin-fill aquifers	1974–88	83	0	12	96
	1989–2003	175	0	13	98
	1974–2003	49	0	15	96
California Coastal Basin aquifers	1974–88	8	0	7	48
	1989–2003	5	3	27	82
	1974–2003	2	3	4	4

Table 22. Summary statistics for hydrologic and land-use characteristics for ground-water-quality monitoring wells in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwestern United States with dissolved-solids concentration trend data for 1974–88, 1989–2003, and 1974–2003 —Continued.

Principal aquifer	Analysis period	Count	Minimum	Mean	Maximum
Nonagricultural and nonurban area in 1,640 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	47	90	100
	1989–2003	1	56	56	56
Basin and Range basin-fill aquifers	1974–88	83	0	47	100
	1989–2003	175	1	59	100
	1974–2003	49	1	46	100
California Coastal Basin aquifers	1974–88	8	26	68	100
	1989–2003	5	18	58	96
	1974–2003	2	96	96	96
Agricultural area in 16,400 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	0	0	0
	1989–2003	1	0	0	0
Basin and Range basin-fill aquifers	1974–88	83	0	25	78
	1989–2003	175	0	16	76
	1974–2003	49	0	23	73
California Coastal Basin aquifers	1974–88	8	2	12	22
	1989–2003	5	2	10	20
	1974–2003	2	8	8	8
Urban area in 16,400 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	1	3	5
	1989–2003	1	7	7	7
Basin and Range basin-fill aquifers	1974–88	83	0	4	43
	1989–2003	175	0	5	40
	1974–2003	49	0	4	43
California Coastal Basin aquifers	1974–88	8	1	4	6
	1989–2003	5	6	28	68
	1974–2003	2	6	6	6
Nonagricultural and nonurban area in 16,400 foot radius of well, percent					
Rio Grande aquifer system	1974–88	19	95	97	99
	1989–2003	1	93	93	93
Basin and Range basin-fill aquifers	1974–88	83	14	71	99
	1989–2003	175	20	79	100
	1974–2003	49	20	72	99
California Coastal Basin aquifers	1974–88	8	74	84	93
	1989–2003	5	28	62	86
	1974–2003	2	85	85	86

Table 23. Dissolved-solids concentration-trend types for 1974–88, 1989–2003, and 1974–2003, for ground-water-quality monitoring wells in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers of the Southwestern United States.

Principal aquifer	Dissolved-solids concentration trend type			
	Decrease	Increase	No trend	Total
Number of ground-water-quality monitoring wells, count				
1974–88				
Rio Grande aquifer system	2	4	13	19
Basin and Range basin-fill aquifers	2	14	67	83
California Coastal Basin aquifers	0	3	5	8
All three basin-fill aquifers in the Southwestern United States	4	21	85	110
1989–2003				
Rio Grande aquifer system	0	1	0	1
Basin and Range basin-fill aquifers	16	41	119	176
California Coastal Basin aquifers	0	1	4	5
All three basin-fill aquifers in the Southwestern United States	16	43	123	182
1974–2003				
Rio Grande aquifer system	0	0	0	0
Basin and Range basin-fill aquifers	9	11	29	49
California Coastal Basin aquifers	1	0	1	2
All three basin-fill aquifers in the Southwestern United States	10	11	30	51
Number of ground-water-quality monitoring wells, percent				
1974–88				
Rio Grande aquifer system	11	21	68	100
Basin and Range basin-fill aquifers	2	17	81	100
California Coastal Basin aquifers	0	38	63	100
All three basin-fill aquifers in the Southwestern United States	4	19	77	100
1989–2003				
Rio Grande aquifer system	0	100	0	100
Basin and Range basin-fill aquifers	9	23	68	100
California Coastal Basin aquifers	0	20	80	100
All three basin-fill aquifers in the Southwestern United States	9	24	68	100
1974–2003				
Rio Grande aquifer system	0	0	0	100
Basin and Range basin-fill aquifers	18	22	59	100
California Coastal Basin aquifers	50	0	50	100
All three basin-fill aquifers in the Southwestern United States	20	22	59	100

Table 24. Average period change in dissolved-solids concentrations for 1974–88, 1989–2003, and 1974–2003, for ground-water-quality monitoring wells with increasing or decreasing trend types in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers of the Southwestern United States.

[---, no wells with this trend type]

Principal aquifer	Average period change, percent[1] — Dissolved-solids concentration-trend type: Decrease	Increase
1974–88		
Rio Grande aquifer system	-34	23
Basin and Range basin-fill aquifers	-30	73
California Coastal Basin aquifers	---	48
All three basin-fill aquifers in the Southwestern United States	-32	59
1989–2003		
Rio Grande aquifer system	---	95
Basin and Range basin-fill aquifers	-24	30
California Coastal Basin aquifers	---	8
All three basin-fill aquifers in the Southwestern United States	-24	31
1974–2003		
Rio Grande aquifer system	---	---
Basin and Range basin-fill aquifers	-20	37
California Coastal Basin aquifers	-7	---
All three basin-fill aquifers in the Southwestern United States	-18	37

[1]Period change for an individual well is computed as the change in the modeled concentration from the beginning of the period to the end of the period, divided by the modeled concentration for the beginnning of the period, and is expressed as a percent. Tabulated data represent the average period change for wells with the same trend type for each principal aquifer and analysis period.

For the 16 wells that have a decreasing trend in concentrations, all of which were in Basin and Range basin-fill aquifers, the average period change was -24 percent (table 24). For the 43 wells in the 3 basin-fill aquifers that have an increasing trend in dissolved-solids concentration, the average period change was +31 percent.

Changes and Trends: 1974–2003

Of the 51 ground-water-quality monitoring wells in the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers in the Southwest with dissolved-solids concentration-trend data for 1974–2003, 30 wells (59 percent) did not have a trend, 11 wells (22 percent) had an increasing trend, and 10 wells (20 percent) had a decreasing trend (table 23). There were only two wells in the California Coastal Basin aquifers with trend data available, and there were no wells in the Rio Grande aquifer system with trend data available. Geographically, there are no spatial patterns or clusters in the occurrence of wells with no trend, an increasing trend, or a decreasing trend (fig. 40*C*). For the 10 wells that have a decreasing trend in concentrations, the average period change is -18 percent (table 24). For the 11 wells that have an increasing trend in concentrations, the average period change is +37 percent.

Trend Summary and Comparison of Trends Between Periods at Common Sites

For all three periods, the majority of wells had no trend in dissolved-solids concentrations (table 23). The smaller portion of all wells that had either an increasing trend or decreasing trend generally were dispersed evenly across the Southwest. The mixture of trends spatially and the lack of clusters of wells all having the same trend in a particular area suggests that trends in dissolved-solids concentrations tend to occur in localized areas and not across large regions.

Trend data for 51 ground-water-quality monitoring wells that had data available for both 1974–88 and 1989–2003 generally were consistent between these two periods. Trend types were the same for both periods for 35 of the 51 wells (2 increasing, 33 no trend). Trend types for the remaining 16 wells were mixed between periods. Trend types for 1974–88 and 1989–2003 were no trend, then decreasing, respectively, for 4 wells; no trend, then increasing, respectively, for 5 wells; decrease, then no trend, respectively, for 1 well; and increase, then no trend, respectively, for 2 wells. Trends were opposite for only 4 of the 51 wells, which had increasing trends for 1974–88 and decreasing trends for 1989–2003.

Factors Affecting Trends

An understanding of the relation of trends to natural and human factors provides useful information for making land- and water-policy decisions. In this section, the relation of trend occurrence to selected natural and human factors—depth to water, well depth, and land use around the well—is explored through logistic regression modeling. Ground-water-quality monitoring wells with trend data for the period 1989–2003 were used in this analysis because there are more wells with trend data available for this period than for 1974–88 or 1974–2003, and because the available land-use data are more representative for this period than for the other two periods. Of the 182 wells with trend data for 1989–2003, land-use data were available for all 182 wells, well-depth data were available for 174 wells, and depth-to-water data were available for 160 wells (table 22).

In the logistic regression model, the relation of trend occurrence to eight explanatory variables representing natural and human factors was tested: depth to water below the land surface, well depth, and six variables representing land use around the well. The land use variables include the percent of (1) agricultural land, (2) urban land, (3) nonagricultural and nonurban land in a 1,640 ft (500 m) radius area around the well, and also the percentage of (4) agricultural land, (5) urban land, (6) nonagricultural and nonurban land in a 16,400 ft (5 km) radius area around the well. Step functions, log transformations, and power transformations for each of the eight explanatory variables were tested in the development of the model. The final model was arrived at by constructing many different models with the various possible combinations of the eight explanatory variables representing natural and human factors and evaluating the significance of each explanatory variable and overall significance of the model.

Trend occurrence was found to be significantly related to depth to water below the land surface. The likelihood ratio test for the logistic regression model indicated that it was better than an intercept-only model ($p = 0.01$). The model is nonlinear and contains a step function (fig. 41). Wells having negative depths to water below the land surface are under artesian conditions, and have an 8 percent probability of having a trend. For wells with water levels below the land surface, indicated by positive depths to water below the land surface, the probability of having a trend decreases with depth to water below the land surface (fig. 41). The probability is largest for wells with shallow depths to water, 42 percent where water is just below the land surface.

The logistic regression model for trend occurrence has important physical interpretations. Wells under artesian conditions must have a low-permeability confining unit that (1) prevents movement of ground water from a saturated unit to the land surface, and (2) also prevents infiltrating water and solutes that are transported downward from the land surface from reaching the saturated zone.

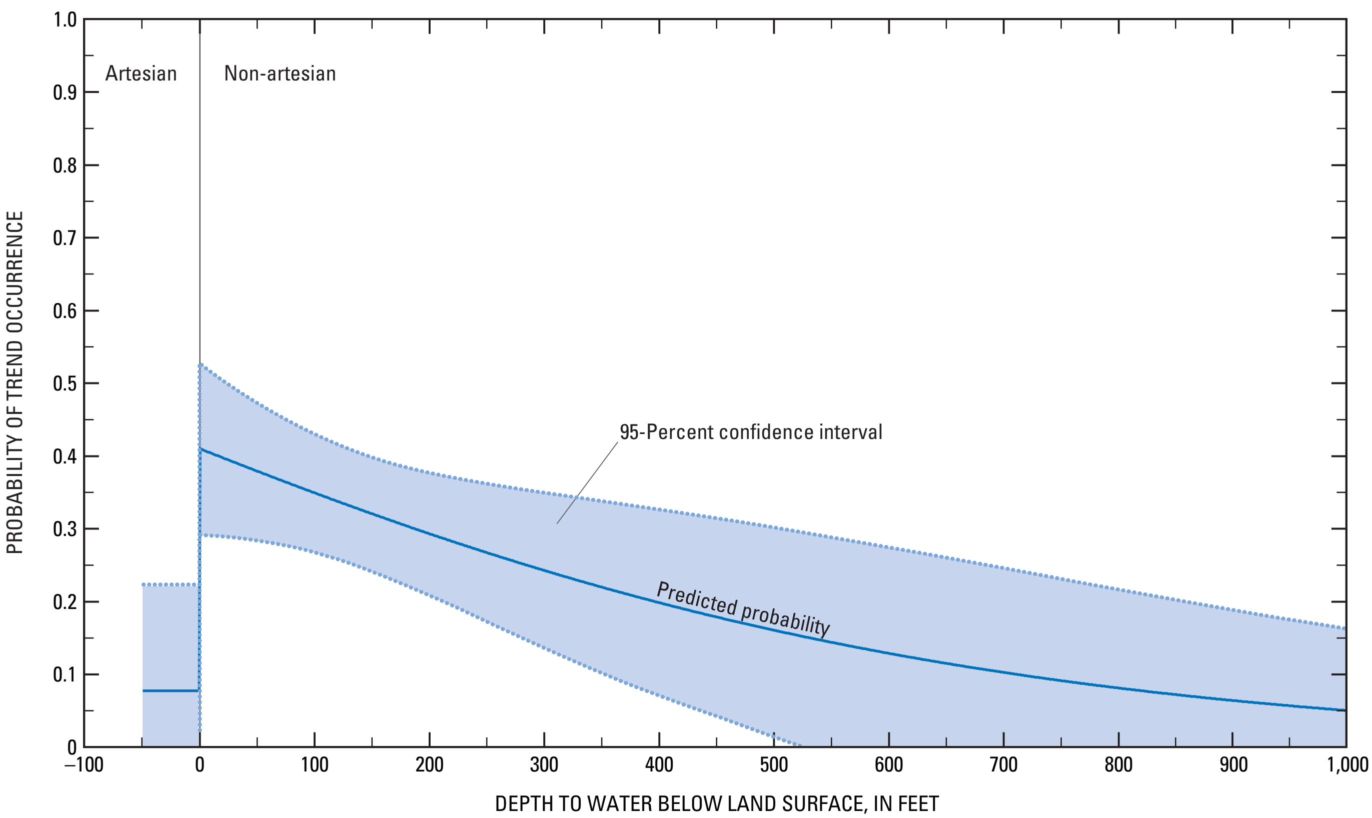


Figure 41. Logistic regression model for probability of dissolved-solids concentration trend occurrence for ground-water-quality monitoring wells in basin-fill aquifers of the Southwestern United States, 1989–2003, as a function of depth to water below land surface.

The confining, unit therefore, serves as a protective layer that prevents the aquifer from mixing with higher or lower dissolved-solids concentration infiltrating water, and in turn, prevents the generation of a trend in concentrations over time due to mixing. The model also indicates that for nonartesian conditions, the probability of a trend occurring decreases with an increase in depth to water. This decreasing probability likely results from a larger travel distance and travel time for infiltrating water, and also increased possibility for occurrence of and larger thickness of confining units between the land surface and the aquifer that would retard infiltration.

The lack of significance of land-use variables in the logistic-regression model for trend occurrence may be a matter of the scale rather than a true reflection of cause and effect. During model development, models tested with land-use percentages for the smaller 1,640 ft radius area generally were more significant than comparable models tested with land-use percentages for the 16,400 ft radius area. Given this trend, it would make sense to test significance of land use variables for an area with a radius even smaller than 1,640 ft. For a smaller radius area, 164 ft for example, field-acquired land-use data would be much preferable to satellite-based land-use data owing to uncertainties in the well-location accuracy and of the land-use data resolution (98.4 ft). Consequently land-use variables for smaller areas were not tested.

Streams

By Steven J. Gerner

The amount of change in dissolved-solids concentration in a river during recent periods can be used to guide resource-management decisions. For example, the effect that land-use change or salinity-control projects in the Upper Colorado River Basin have on dissolved solids in the Colorado River can be evaluated by analyzing trends or change at various sites on the Colorado River. Trends in dissolved-solids concentrations of streams in the southwestern United States have been previously studied on a local or regional level, and results have been presented in numerous reports. For example, Liebermann and others (1989) described trends in dissolved solids for select sites in the Upper Colorado River Basin and present a list of studies completed before 1989 in that region. Vaill and Butler (1999) also described trends in dissolved solids for select sites in the Upper Colorado River Basin, extending the period of analysis through 1996. Baldys (1990) investigated dissolved-solids trends in the Verde River Basin of Arizona, and Baldys and others (1995) investigated dissolved-solids trends in the Gila River Basin of Arizona. Smith and others (1987) included trends in chloride and sulfate concentrations at many sites in the Southwest in their investigation of water-quality trends in major U.S. rivers. The examination of trends in dissolved-solids concentration in the Southwest in this report expands this body of knowledge both spatially and temporally.

The types of trend and period changes in adjusted[1] annual dissolved-solids concentration (AADSC) for surface-water-quality monitoring sites in major river basins of the Southwest are summarized here for 1974–88, 1989–2003, and 1974–2003. The trends in AADSC that occurred at sites in the Southwest include linear and nonlinear variations of no trend, decreasing trend, and increasing trend (fig. 42; table 25). Period changes in AADSC represent the net change from the beginning to the end of one of the time periods mentioned above and are expressed as a percentage of the value for the initial year of the time period being considered. Although summaries of the type of trend and period change are presented for major river basins, many readers may find that their interest is restricted to particular sites or rivers that are not discussed in these summaries. Results of AADSC trend analyses, including site location and summary statistics for individual sites, are found on plate 1 and in appendices 7, 8, and 9.

A total of 157 sites had sufficient AADSC data (13 or more years) during 1974–88 to be included in the trend analysis for this period. A total of 168 sites met the same criteria for 1989–2003, allowing them to be included in the trend analysis for this period. Seventy-four sites had a sufficient amount of annual data (25 or more years) to determine trends for 1974–2003.

The spatial distribution of sites is somewhat uniform for 1974–2003 (pl. 1). The spatial distribution of water-quality monitoring sites with dissolved-solids data for the 1974–88 and 1989–2003 periods is less uniform, as there are some hydrologic subregions within the study area that have substantially more sites than others. For example, the Great Salt Lake and Sevier River Basin and the Green River Basin have the largest number of sites during 1974–88 (table 26). These basins are represented by substantially more sites during 1974–88 than 1989–2003. The Upper Colorado River Basin has the most sites analyzed for dissolved-solids trends during 1989–2003. Several hydrologic subregions in the Great Salt Lake and Sevier River, Central Nevada and Eastern California Desert, and Southern California Coastal major river basins are sparsely represented or have no sites on which to determine trends for one or more of the periods of interest. Direct comparisons of changes in AADSCs in major river basins between the periods of interest is difficult because the number and location of sites used for trend analysis in each major river basin is substantially different for each analytical period. There is sufficient data for 58 sites from all three periods (1974–88, 1989–2003, and 1974–2003) so that trends can be determined and compared between these periods by using this subset of sites (table 26).

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[1]The annual dissolved-solids concentrations upon which these time series were built were adjusted for seasonal and some climatic variation by controlling the date and discharge from which they were determined. See a detailed explanation of "adjusted annual dissolved-solids concentrations" in the "Approach, Data Compilation, and Analysis Methods—Determination of Trends in Concentration Data for Surface-Water-Quality Monitoring Sites" section of this report.

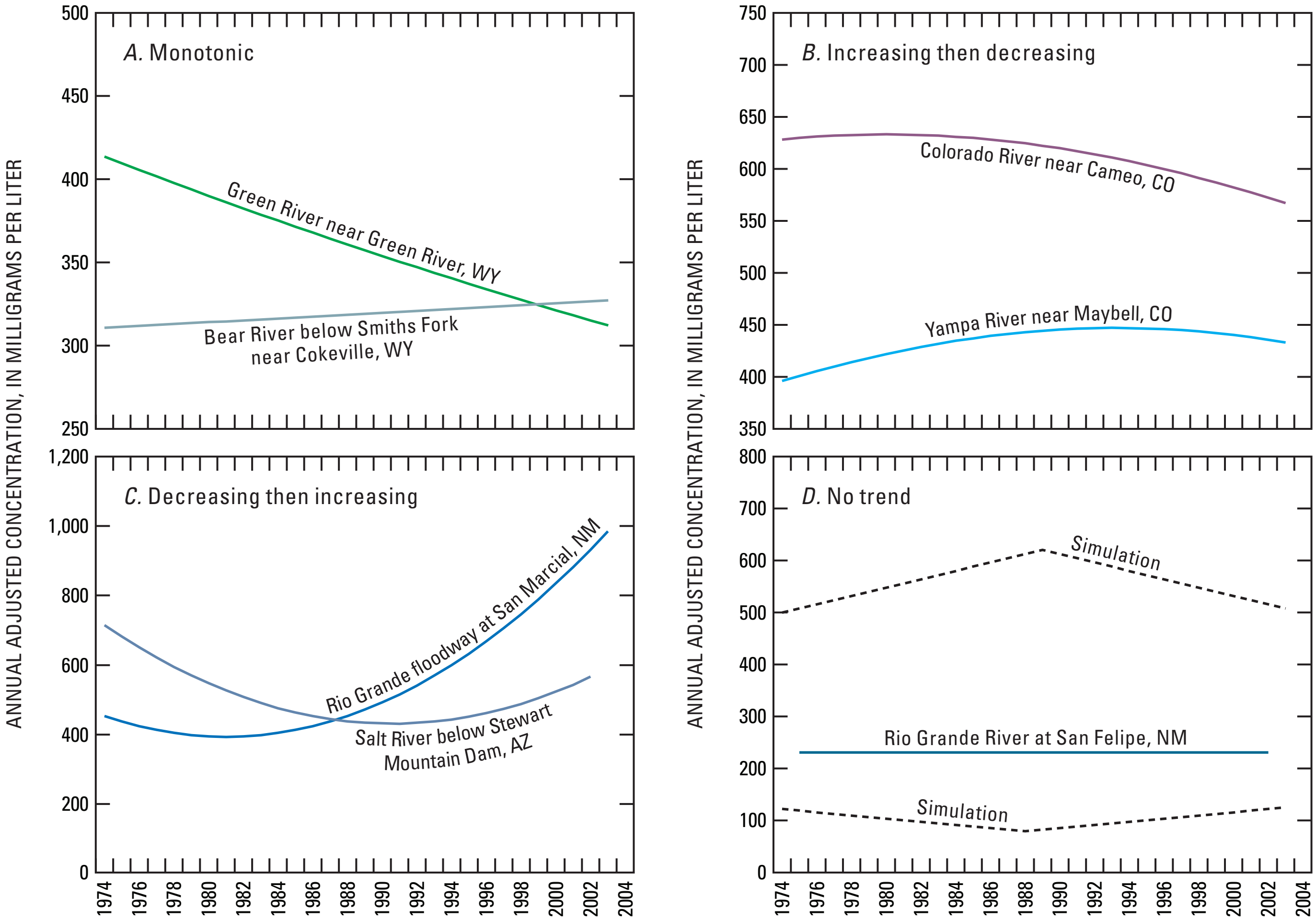

Figure 42. Typical trends in annual adjusted dissolved-solids concentration at select surface-water-quality monitoring sites in the Southwestern United States. *A*, Monotonic; *B*, Increasing then decreasing; *C*, Decreasing then increasing; and *D*, No trend.

Table 25. Number and percent of surface-water-quality monitoring sites in the Southwestern United States with various trends in adjusted annual dissolved-solids concentration for analysis periods 1974–88, 1989–2003, and 1974–2003.

Trend type		1974–88						1989–2003						1974–2003					
		All sites		Main-stem sites		Tributary sites		All sites		Main-stem sites		Tributary sites		All sites		Main-stem sites		Tributary sites	
Designation	Description	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Percent
No trends																			
1	No trend	31	19.7	11	15.3	20	23.5	24	14.3	7	10.8	17	16.5	8	10.8	6	11.8	2	8.7
8	No trend, adjusted annual dissolved-solids concentration of base year and ending year are within one percent but some variation in values occurred in intervening years.	7	4.5	5	6.9	2	2.4	5	3.0	3	4.6	2	1.9	0	0	0	0	0	0
Subtotal of sites with no trend		38	24.2	16	22.2	22	25.9	29	17.3	10	15.4	19	18.4	8	10.8	6	11.8	2	8.7
Decreasing trends																			
2	Monotonic decrease	42	26.8	21	29.2	21	24.7	57	33.9	32	49.2	25	24.3	23	31.1	12	23.5	11	47.8
3	General decrease (initial increase followed by a decrease)	10	6.4	8	11.1	2	2.4	14	8.3	5	7.7	9	8.7	15	20.3	12	23.5	3	13
4	General decrease (initial decrease followed by an increase)	14	8.9	6	8.3	8	9.4	15	8.9	4	6.2	11	10.7	14	18.9	9	17.6	5	21.7
Subtotal of sites with decreasing trend		66	42	35	48.6	31	36.5	86	51.1	41	63.1	45	43.7	52	70.3	33	64.7	19	82.6
Increasing trends																			
5	Monotonic increase	22	14.0	12	16.7	10	11.8	29	17.3	7	10.8	22	21.4	4	5.4	4	7.8	0	0
6	General increase (initial increase followed by a decrease)	29	18.5	7	9.7	22	25.9	5	3.0	0	0	5	4.9	6	8.1	4	7.8	2	8.7
7	General increase (initial decrease followed by an increase)	2	1.3	2	2.8	0	0	19	11.3	7	10.8	12	11.7	4	5.4	4	7.8	0	0
Subtotal of sites with increasing trend		53	33.8	21	29.2	32	37.6	53	31.5	14	21.5	39	37.9	14	18.9	12	23.5	2	8.7

Table 26. Number of surface-water-quality monitoring sites in the Southwestern United States used in the analysis of trends in adjusted annual dissolved-solids concentration, by major river basin, hydrologic subregion and analysis period.

Major river basin	Hydrologic sub-region code	Hydrologic subregion	Number of Sites			
			1974–88	1989–2003	1974–2003	All periods[1]
Upper Rio Grande Basin	1301	Rio Grande headwaters	1	1	1	1
	1302	Rio Grande-Elephant Butte	10	12	8	8
	1303	Rio Grande-Mimbres	1	1	1	1
	1305	Rio Grande closed basins	1	0	0	0
Upper Colorado River Basin	1401	Colorado headwaters	6	55	5	4
	1402	Gunnison	2	19	3	2
	1403	Upper Colorado-Dolores	5	5	2	2
Green River Basin	1404	Great Divide-Upper Green	7	4	5	4
	1405	White-Yampa	12	21	10	7
	1406	Lower Green	24	4	4	4
San Juan River Basin	1408	San Juan	6	13	9	5
Little Colorado River Basin	1502	Little Colorado	0	0	0	0
Middle Colorado River Basin	1407	Upper Colorado-Dirty Devil	6	1	1	1
	1501	Lower Colorado-Lake Mead	4	3	0	2
Lower Colorado River Basin	1503	Lower Colorado	3	6	4	2
Gila River Basin	1504	Upper Gila	6	4	4	4
	1505	Middle Gila	1	2	2	1
	1506	Salt	6	6	4	4
	1507	Lower Gila	1	0	1	0
Great Salt Lake and Sevier River Basins	1601	Bear	16	1	2	1
	1602	Great Salt Lake	20	2	4	2
	1603	Escalante Desert-Sevier Lake	10	0	0	0
Central Lahontan Basins	1605	Central Lahontan	3	4	1	0
Central Nevada and Eastern California Desert Basins	1604	Black Rock Desert-Humboldt	0	0	0	0
	1606	Central Nevada Desert Basins	2	0	0	0
	1809	Northern Mojave-Mono Lake	0	1	0	0
	1810	Southern Mojave-Salton Sea	1	1	1	1
Southern California Coastal Basins	1807	Southern California Coastal	3	2	2	2

[1]Number of sites that were used to compare trends among time periods.

Table 27. Percentage of surface-water-quality monitoring sites in each major river basin in the Southwestern United States with a particular type of trend in adjusted annual dissolved-solids concentration during 1974–88.

	Percentage of sites in major river basin with a particular type of trend								
	Trend type[1]								
	1	2	3	4	5	6	7	8	Count of sites within major river basin
Major river basin	No trend	Decreasing trends			Increasing trends			No trend	
Upper Rio Grande Basin	30.8	46.2	0	7.7	15.4	0	0	0	13
Upper Colorado River Basin	7.7	23.1	23.1	15.4	15.4	7.7	0	7.7	13
Green River Basin	20.9	32.6	4.7	0	11.6	23.3	0	7.0	43
San Juan River Basin	33.3	33.3	16.7	0	16.7	0	0	0	6
Middle Colorado River Basin	0	30.0	10.0	20.0	0	40.0	0	0	10
Gila River Basin	21.4	14.3	7.1	21.4	7.1	21.4	0	7.1	14
Lower Colorado River Basin	0	100.0	0	0	0	0	0	0	3
Great Salt Lake and Sevier River Basins	23.9	15.2	2.2	13.0	17.4	19.6	4.3	4.3	46
Central Lahontan Basins	0	33.3	0	0	33.3	33.3	0	0	3
Central Nevada and Eastern California Desert Basins	33.3	33.3	0	0	33.3	0	0	0	3
Southern California Coastal Basins	0	0	33.3	0	33.3	33.3	0	0	3
All major river basins	19.7	26.8	6.4	8.9	14.0	18.5	1.3	4.5	157

[1]Categories of trend types including (1) no trend, (2) monotonic decrease, (3) general decrease, initial increase followed by a decrease, (4) general decrease, initial decrease followed by an increase, (5) monotonic increase, (6) general increase, initial increase followed by a decrease, (7) general increase, initial decrease followed by an increase, (8) no trend, base year and ending year are within one percent but some variation in values occurred in intervening years.

Changes and Trends: 1974–88

Changes in AADSC for 1974–88 were mixed throughout the Southwest with most major river basins having surface-water-quality monitoring sites in both the increasing and decreasing categories. There were, however, more sites with an overall decline in AADSCs (42 percent of sites) than there were sites with an overall increase (33.8 percent of sites; table 25). The most prevalent trend category during this period was a monotonic decrease, which occurred at 26.8 percent of the sites (table 27). Of the three time periods, 1974–88 had the largest percentage of sites with no change or an increase in AADSCs (table 25). No change in AADSCs occurred at 24.2 percent of the sites for the period 1974–88.

The AADSCs more often increased during 1974–88 at sites on tributary streams (37.6 percent of tributary sites) than at sites on major rivers (29.2 percent of main-stem sites; table 25). For example, AADSCs decreased at most main-stem sites on the Green River but increased at many tributary sites, particularly those streams draining the southern slope of the Uinta Mountains (pl. 1).

Sites in the Upper Rio Grande Basin generally had a decrease in AADSCs (tables 27 and 28). In fact, a monotonic decrease in AADSCs occurred at 46.2 percent of the sites in this basin. The largest period decrease in AADSCs, (39 percent) among all sites in the Southwest for the period 1974–88 occurred in the Rio Grande floodway at San Marcial, NM (site 08358400) in the Rio Grande-Elephant Butte hydrologic subregion (pl. 1; appendix 7). There were no trends in AADSCs at 30.8 percent of the sites in the Upper Rio Grande Basin.

Within the Upper Colorado River Basin, more than 50 percent of the sites on tributaries and 75 percent of the sites on major rivers had an overall decrease in AADSCs during 1974–88. For 1974–88, sites within the Green River Basin were split almost equally among those having an increase in AADSCs and those having a decrease in AADSCs. Period changes in AADSCs in this major river basin included the largest increase among all sites in the Southwest—53 percent in Corral Gulch below Water Gulch, near Rangely, CO (site 09306235), in the White-Yampa subregion, and the second largest decrease in AADSCs—38 percent in the Whiterocks River near Whiterocks, UT (site 09299500) in the Lower Green subregion (pl. 1; appendix 7). Changes in AADSCs for 1974–88 at sites on tributary streams in the Green River Basin were mixed; however, more than half of the sites on main-stem rivers had a decrease in AADSCs (table 28). Within the San Juan River Basin, AADSCs generally decreased during 1974–88, mainly because the three water-quality-monitoring sites on the San Juan River had either no change or a decrease. In the Middle Colorado River Basin, AADSCs were declining at a majority of the sites on the main-stem and tributary rivers. In addition, sites with an overall increase in dissolved-solids concentration during this period exhibited a type 6 trend, meaning that dissolved-solids concentrations were declining during the latter part of 1974–88 (tables 25 and 27). The AADSC declined at least 9 percent at all three sites in the Lower Colorado River Basin.

There were more sites in the Gila River Basin where adjusted annual dissolved-solids concentration decreased during 1974–88 than increased (42.8 percent and 28.5 percent, respectively; tables 27 and 28). Only one site in each of the Upper Gila and Salt hydrologic subregions had an increasing AADSC and the increase for those sites was less than 3 percent.

Within the Great Salt Lake and Sevier River Basins there were 46 surface-water-quality monitoring sites with sufficient data to analyze trends in AADSC; this is the largest number of sites among major river basins for this period. More of these sites had increasing AADSCs than decreasing AADSCs (41.3 percent and 30.4 percent, respectively). Additionally, a larger percentage of sites on tributary streams had increasing AADSCs than on main-stem rivers. The largest increase in AADSCs was a 41 percent period change at Trout Creek near Callao, UT (site 10172870) in the Great Salt Lake subregion (pl. 1; appendix 7). Many of the sites, 28.2 percent, had no substantial change in AADSCs during this period.

There were few sites (nine total) in the Central Lahontan, Central Nevada and Eastern California Desert, and Southern California Coastal Basins with enough dissolved-solids data to determine trends for this period. At these few sites within this group of major river basins, however, AADSCs increased, more than decreased, specifically in the Central Lahontan and Southern California Coastal Basins where 4 of 6 sites had increased AADSCs. Sites on the Santa Clara and Walker Rivers, however, had decreases in AADSCs of 18 and 19 percent, respectively.

Changes and Trends: 1989–2003

During 1989–2003, water quality relative to dissolved solids generally improved at surface-water-quality monitoring sites in the southwestern United States. AADSCs decreased at 51.1 percent of the sites included in the 1989–2003 trend analysis (table 25). Nearly 34 percent of sites had monotonic decreases in AADSCs. Furthermore, there were four major river basins where AADSCs decreased at 75 percent or more of the sites (table 29). The fact that there was a decrease in AADSCs at all of the sites on the main stem of the Colorado and Green Rivers, except for the most upstream and downstream sites on the Colorado River, is an example of how widespread these reductions in dissolved solids were. Above average amounts of precipitation occurred throughout the southwestern United States during several years in the mid-to-late 1990s, followed by a drier-than-normal period during 1999–2003 (fig. 43). This may have resulted in higher concentrations of dissolved solids being flushed through some major river basins during the early part of this period followed by a diminishment of available salts, leading to an observed decrease in the AADSCs.

In the Upper Rio Grande Basin the AADSCs most often did not change, or increased at surface-water-quality monitoring sites from the beginning to the end of the period. There were more sites with no trend in AADSCs (42.7 percent of sites) than sites with either an increasing (36.1 percent) or decreasing (21.3 percent) trend in AADSCs. The period change in AADSCs, ranged from a decrease of 22 percent to an increase of 30 percent at sites in the Upper Rio Grande Basin with no apparent spatial pattern (table 30; pl. 1; appendix 8).

Table 28. Statistical summary of the period change in adjusted annual dissolved-solids concentration at surface-water-quality monitoring sites in major river basins in the Southwestern United States, 1974–88.

[Site types: (1) ALL, both main-stem and tributary sites; (2) MS, main-stem sites; (3) T, tributary sites. Shaded area identifies values which represent declining dissolved-solids concentration; NA, not applicable]

Major river basin	Site type	Minimum	25th percentile	Mean	Median	75th percentile	Maximum	Standard deviation	Number of sites
		Change in adjusted annual dissolved-solids concentration, in percent							
Upper Rio Grande Basin	ALL	-39	-21	-8	-13	0	27	20	13
Upper Rio Grande Basin	MS	-39	-22	-6	-6	6	27	24	8
Upper Rio Grande Basin	T	-23	-21	-12	-14	0	0	11	5
Upper Colorado River Basin	ALL	-24	-5	-1	-2	0	30	12	13
Upper Colorado River Basin	MS	-11	-3	-2	-2	-1	5	5	7
Upper Colorado River Basin	T	-24	-7	0.3	-2	6	30	18	6
Green River Basin	ALL	-38	-6	1	0	9	53	16	43
Green River Basin	MS	-13	-6	-1	-1	-0.2	12	7	10
Green River Basin	T	-38	-5	2	0	10	53	18	33
San Juan River Basin	ALL	-10	-5	-0.1	-3	-0.3	21	11	6
San Juan River Basin	MS	-10	-8	-5	-5	-3	0	5	3
San Juan River Basin	T	-5	-3	5	-1	10	21	14	3
Middle Colorado River Basin	ALL	-16	-7	-0.2	-4	5	19	11	10
Middle Colorado River Basin	MS	-16	-10	-3	-8	-2	19	15	3
Middle Colorado River Basin	T	-6	-4	2	-1	5	19	9	7
Gila River Basin	ALL	-11	-7	-2	-0.1	1	11	6	14
Gila River Basin	MS	-11	-7	-2	-0.1	1	11	7	9
Gila River Basin	T	-10	-8	-3	0	0	3	6	5
Lower Colorado River Basin	ALL	-14	-12	-11	-10	-10	-9	3	3
Lower Colorado River Basin	MS	-10	-10	-10	-10	-9	-9	1	2
Lower Colorado River Basin	T	-14	-14	-14	-14	-14	-14	NA	1
Great Salt Lake and Sevier River Basins	ALL	-19	-4	2	0	5	41	11	46
Great Salt Lake and Sevier River Basins	MS	-19	-6	-1	0	3	9	7	23
Great Salt Lake and Sevier River Basins	T	-10	0	6	1	9	41	13	23
Central Lahontan Basins	ALL	-19	-7	-2	5	7	10	16	3
Central Lahontan Basins	MS	-19	-7	-2	5	7	10	16	3
Central Nevada and Eastern California Desert Basins	ALL	-5	-3	1	-1	3	8	6	3
Central Nevada and Eastern California Desert Basins	T	-5	-3	1	-1	3	8	6	3
Southern California Coastal Basins	ALL	-18	-6	2	6	11	17	18	3
Southern California Coastal Basins	MS	-18	-6	2	6	11	17	18	3
All major river basins	ALL	-39	-7	0	0	4.9	53	13	157
All major river basins	MS	-39	-8	-2	-1	2	27	11	72
All major river basins	T	-38	-6	1	0	8	53	15	85

Table 29. Percentage of surface-water-quality monitoring sites in each major river basin in the Southwestern United States with a particular type of trend in adjusted annual dissolved-solids concentration during 1989–2003.

Major river basin	Percentage of sites in major river basin with a particular type of trend — Trend type[1]								Count of sites within major river basin
	1	2	3	4	5	6	7	8	
	No trend	Decreasing trends			Increasing trends			No trend	
Upper Rio Grande Basin	35.7	14.3	7.0	0	7.1	0	29.0	7.0	14
Upper Colorado River Basin	15.2	26.6	3.8	7.6	26.6	5.1	13.0	2.5	79
Green River Basin	6.9	44.8	24.1	13.8	6.9	0	0	3.4	29
San Juan River Basin	15.4	61.5	15.4	8.0	0	0	0	0	13
Middle Colorado River Basin	25.0	50.0	0	25.0	0	0	0	0	4
Gila River Basin	8.3	41.7	0	8.3	25.0	0	17.0	0	12
Lower Colorado River Basin	0	50.0	17.0	17.0	0	0	17.0	0	6
Great Salt Lake and Sevier River Basins	0	33.3	0	0	33.3	0	33.3	0	3
Central Lahontan Basins	25.0	0	0	25.0	25.0	25.0	0	0	4
Central Nevada and Eastern California Desert Basins	0	50.0	0	0	0	0	50.0	0	2
Southern California Coastal Basins	0	50.0	0	0	0	0	0	50.0	2
All major river basins	14.3	33.9	8.3	8.9	17.3	3.0	11.3	3.0	168

[1]Categories of trend types including (1) no trend, (2) monotonic decrease, (3) general decrease, initial increase followed by a decrease, (4) general decrease, initial decrease followed by an increase, (5) monotonic increase, (6) general increase, initial increase followed by a decrease, (7) general increase, initial decrease followed by an increase, (8) no trend, base year and ending year are within one percent but some variation in values occurred in intervening years.

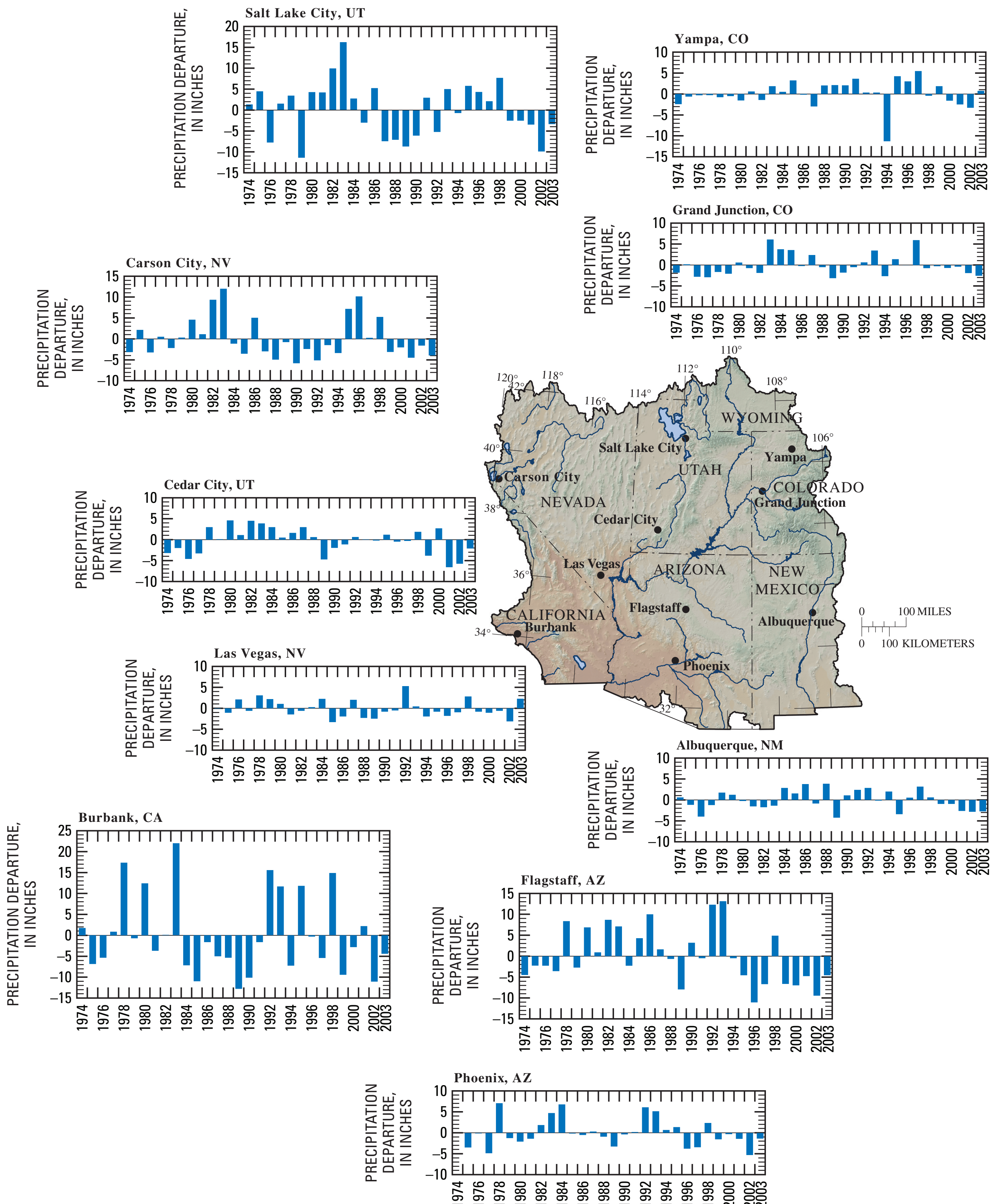

Figure 43. Annual precipitation departure from the 1974–2003 average at selected sites in the Southwestern United States.

In the Upper Colorado River Basin, increases in AADSCs occurred more often (44.7 percent of sites) than decreases (38 percent of sites). The AADSCs, however, generally decreased at sites on main-stem rivers; the 75th percentile of the period change being a decline of about 4 percent. In contrast, the median period change at sites on tributary streams in the Upper Colorado River Basin was an increase of about 2 percent. The largest period change, an increase of 105 percent, occurred at Black Gore Creek near Minturn, CO (site 09066000), in the Colorado headwaters hydrologic subregion (pl. 1; appendix 8).

Reductions in AADSCs during 1989–2003 were widespread in the Green River basin where 82.7 percent of the sites had decreases (table 29). In fact, AADSCs decreased at all of the sites on tributary streams in the Green River Basin.

All but two sites in the San Juan River Basin had a substantial decrease in AADSCs during this period, and those two sites had no change (table 30). The median period change in AADSCs at sites in this basin was -9 percent (table 30).

Similar to sites in upstream major river basins, sites in the Middle and Lower Colorado River Basins generally had decreased AADSCs during 1989–2003. In fact, the AADSCs decreased at all sites except for a 2 percent increase at the Colorado River above Imperial Dam, AZ-CA (site 09429490; pl. 1; appendix 8).

In the Gila River Basin there was no apparent spatial pattern relative to trends in AADSCs. The largest range in period change in AADSCs among sites within a major river basin was in the Gila River Basin—period changes in AADSCs ranged from a decrease of 54 percent at Pinal Creek at Inspiration Dam, near Globe, AZ (site 09498400), to an increase of 109 percent at Salt River below Stewart Mountain Dam, AZ (site 09502000; pl. 1; appendix 8). Both of these sites are in the Salt subregion. These were the largest period changes in AADSCs among sites in the Southwest for 1989–2003.

There were far fewer sites in the Great Salt Lake and Sevier River Basins with adequate amounts of data to interpret period changes during 1989–2003 (3 sites) compared to 1974–88 (46 sites). Period changes in AADSCs were small, ranging from a decrease of 4 percent to an increase of about 3 percent.

There were also few surface-water-quality monitoring sites in the Central Lahontan (4 sites), Central Nevada and Eastern California Desert (2 sites), and Southern California Coastal Basins (2 sites) with adequate amounts of data to interpret period changes during 1989–2003. Period changes during 1989–2003 at sites that had enough data were mixed with nearly an equal number having an increase, a decrease, or no change in AADSCs.

Changes and Trends: 1974–2003

Most of the sites included in trend analysis for this period are situated on the main stem of major rivers (table 25), as a result, the conclusions that are drawn from this data set relate more specifically to conditions in the major rivers. AADSCs decreased at 70.3 percent of the sites from 1974 to 2003 (tables 25 and 31) with the median period change in adjusted annual concentration for all sites being -9 percent (table 32).

AADSCs decreased during 1974–2003 at 60 percent of the sites in the Upper Rio Grande River Basin. The median period change at 10 sites, mostly on the main stem of the Rio Grande, was an 8 percent decrease (table 32). AADSC increased 17 percent at Rio Grande below Taos Junction Bridge near Taos, NM (site 08276500; pl. 1; appendix 9) the only increase in AADSC in this major river basin.

There were substantial reductions in AADSCs during 1974–2003 in the Upper Colorado, Green, San Juan, Middle Colorado, and Lower Colorado River Basins, where the median period changes in AADSCs among all sites in each major river basin were declines of 12, 9, 16, 17, and 17 percent respectively. Reductions in AADSCs occurred at all seven sites in the Middle Colorado and Lower Colorado River Basins. The White-Yampa hydrologic subregion of the Green River Basin, however, had an equal number of sites with increasing AADSCs and decreasing AADSCs: the median period change among these sites was an increase of about 2 percent. An earlier investigation by Vaill and Butler (1999) found significant increasing trends in dissolved-solids concentration at several sites within this hydrologic subregion during portions of this time period.

During 1974–2003, changes in AADSCs at sites in the Gila River Basin were variable. AADSCs decreased during 1974–2003 at sites on the upper and middle Gila River and San Pedro River; however, changes in AADSCs increased at sites on the Verde and Salt Rivers, as much as 117 percent (pl. 1; appendix 9). AADSCs in the lower Gila River increased, probably due in part to the influence of higher dissolved-solids concentrations in inflow from the Salt and Verde Rivers.

For this period there were relatively few sites with adequate data to assess trends in the Great Salt Lake and Sevier River Basins (6 sites), and even fewer in the Central Lahontan (1 site), Central Nevada and Eastern California Desert (1 site), and Southern California Coastal Basins (2 sites). There were more sites in these major river basins with declines in AADSCs during 1974–2003 (6 sites) than there were sites with increases in AADSCs (3 sites).

Comparison of Changes among Periods at Common Sites

Of the 74 sites included in the 1974–2003 trend analysis, 58 had at least 13 years of data in each of two other periods, 1974–88 and 1989–2003. These sites were used to compare changes in adjusted annual dissolved-solids concentration between the two periods. The distribution of change in AADSCs was nearly the same for 1974–88 and 1989–2003: 75 percent of the sites had either no trend or downward trends and the median period change was a decrease of about 4.5 percent (fig. 44). Ten sites had decreases in AADSCs during 1974–88 then increases during 1989–2003.

Conversely, 11 sites had increases in AADSCs during 1974–88 and then decreases during 1989–2003. Most of the remaining sites had decreasing AADSCs during both periods.

Table 30. Statistical summary of the period change in adjusted annual dissolved-solids concentration at surface-water-quality monitoring sites in major river basins in the Southwestern United States, 1989–2003.

[Site types: ALL, both main-stem and tributary sites; MS, main-stem sites; T, tributary sites. Shaded area identifies values which represent declining dissolved-solids concentration; NA, not applicable]

Major river basin	Site type	Minimum	25th percentile	Mean	Median	75th percentile	Maximum	Standard deviation	Number of sites
		Change in adjusted annual dissolved-solids concentration, in percent							
Upper Rio Grande Basin	ALL	-22	0	1	0	7	30	13	14
Upper Rio Grande Basin	MS	-22	-8	0	0	4	30	16	9
Upper Rio Grande Basin	T	0	0	4	0	8	11	5	5
Upper Colorado River Basin	ALL	-38	-5	4	0	7	105	19	79
Upper Colorado River Basin	MS	-38	-17	-12	-9	-4	5	12	15
Upper Colorado River Basin	T	-18	-3	7	2	8	105	19	64
Green River Basin	ALL	-22	-13	-7	-6	-3	4	7	29
Green River Basin	MS	-22	-12	-6	-6	0	4	7	16
Green River Basin	T	-20	-13	-8	-6	-5	-1	6	13
San Juan River Basin	ALL	-28	-17	-11	-9	-4	0	9	13
San Juan River Basin	MS	-21	-18	-12	-13	-7	0	9	4
San Juan River Basin	T	-28	-17	-11	-8	-4	0	9	9
Middle Colorado River Basin	ALL	-12	-10	-6	-6	-2	0	6	4
Middle Colorado River Basin	MS	-9	-7	-6	-6	-4	-2	5	2
Middle Colorado River Basin	T	-12	-9	-6	-6	-3	0	8	2
Gila River Basin	ALL	-54	-8	4	-2	9	109	39	12
Gila River Basin	MS	-32	-6	10	-2	16	109	38	10
Gila River Basin	T	-54	-39	-24	-24	-9	6	42	2
Lower Colorado River Basin	ALL	-10	-10	-6	-7	-2	2	5	6
Lower Colorado River Basin	MS	-10	-10	-5	-5	0	2	6	4
Lower Colorado River Basin	T	-10	-9	-7	-7	-6	-4	4	2
Great Salt Lake and Sevier River Basins	ALL	-4	-1	1	3	3	3	4	3
Great Salt Lake and Sevier River Basins	MS	3	3	3	3	3	3	1	2
Great Salt Lake and Sevier River Basins	T	-4	-4	-4	-4	-4	-4	NA	1
Central Lahontan Basins	ALL	-1	0	2	1	4	8	4	4
Central Lahontan Basins	MS	0	0	0	0	0	0	NA	1
Central Lahontan Basins	T	-1	1	3	3	5	8	5	3
Central Nevada and Eastern California Desert Basins	ALL	-5	-3	-1	-1	0	2	5	2
Central Nevada and Eastern California Desert Basins	T	-5	-3	-1	-1	0	2	5	2
Southern California Coastal Basins	ALL	-20	-15	-10	-10	-5	0	14	2
Southern California Coastal Basins	MS	-20	-15	-10	-10	-5	0	14	2
All major river basins	ALL	-54	-8	0	-1	4	109	18	168
All major river basins	MS	-38	-11	-4	-5	2	109	19	65
All major river basins	T	-54	-6	2	0	7	105	18	103

Table 31. Percentage of surface-water-quality monitoring sites in each major river basin in the Southwestern United States with a particular type of trend in adjusted annual dissolved-solids concentration during 1974–2003.

Major river basin	Percentage of sites in major river basin with a particular type of trend								Count of sites within major river basin
	Trend type[1]								
	1	2	3	4	5	6	7	8	
	No trend	Decreasing trends			Increasing trends			No trend	
Upper Rio Grande Basin	30.0	10.0	10.0	40.0	0	10.0	0	0	10
Upper Colorado River Basin	0	30.0	50.0	0	0	20.0	0	0	10
Green River Basin	10.5	47.4	10.5	10.5	5.3	10.5	5.0	0	19
San Juan River Basin	14.3	42.9	28.6	14.0	0	0	0	0	7
Middle Colorado River Basin	0	33.3	33.3	33.3	0	0	0	0	3
Gila River Basin	9.1	9.1	18.2	27.3	0	9.1	27.0	0	11
Lower Colorado River Basin	0	50.0	0	50.0	0	0	0	0	4
Great Salt Lake and Sevier River Basins	0	33.3	16.7	16.7	33.3	0	0	0	6
Central Lahontan Basins	100.0	0	0	0	0	0	0	0	1
Central Nevada and Eastern California Desert Basins	0	100.0	0	0	0	0	0	0	1
Southern California Coastal Basins	0	0	50.0	0	50.0	0	0	0	2
All major river basins	10.8	31.1	20.3	18.9	5.4	8.1	5.4	0	74

[1]Categories of trend types including (1) no trend, (2) monotonic decrease, (3) general decrease, initial increase followed by a decrease, (4) general decrease, initial decrease followed by an increase, (5) monotonic increase, (6) general increase, initial increase followed by a decrease, (7) general increase, initial decrease followed by an increase, (8) no trend, base year and ending year are within one percent but some variation in values occurred in intervening years.

Table 32. Statistical summary of the period change in adjusted annual dissolved-solids concentration at surface-water-quality monitoring sites in major river basins in the Southwestern United States, 1974–2003.

[Site types: ALL, both main-stem and tributary sites; MS, main-stem sites; T, tributary sites. Shaded area identifies values which represent declining dissolved-solids concentration; NA, not applicable]

Major river basin	Site type	Minimum	25th percentile	Mean	Median	75th percentile	Maximum	Standard deviation	Number of sites
		Change in adjusted annual dissolved-solids concentration, in percent							
Upper Rio Grande Basin	ALL	-33	-19	-9	-8	0	17	15	10
Upper Rio Grande Basin	MS	-33	-22	-10	-8	0	17	16	8
Upper Rio Grande Basin	T	-15	-11	-8	-8	-4	0	11	2
Upper Colorado River Basin	ALL	-46	-18	-11	-12	-5	24	18	10
Upper Colorado River Basin	MS	-46	-19	-16	-17	-6	1	16	7
Upper Colorado River Basin	T	-15	-12	-.2	-10	7	24	21	3
Green River Basin	ALL	-28	-14	-9	-9	0	9	11	19
Green River Basin	MS	-25	-16	-8	-11	3	9	12	10
Green River Basin	T	-28	-13	-9	-9	-7	7	10	9
San Juan River Basin	ALL	-28	-23	-15	-16	-9	0	10	7
San Juan River Basin	MS	-26	-23	-15	-19	-9	0	13	3
San Juan River Basin	T	-28	-19	-16	-13	-9	-9	9	4
Middle Colorado River Basin	ALL	-18	-18	-14	-17	-12	-7	6	3
Middle Colorado River Basin	MS	-18	-18	-18	-18	-18	-17	1	2
Middle Colorado River Basin	T	-7	-7	-7	-7	-7	-7	NA	1
Gila River Basin	ALL	-31	-13	6	-2	10	117	40	11
Gila River Basin	MS	-31	-17	7	-1	12	117	42	10
Gila River Basin	T	-5	-5	-5	-5	-5	-5	NA	1
Lower Colorado River Basin	ALL	-18	-18	-16	-17	-15	-14	2	4
Lower Colorado River Basin	MS	-18	-17	-16	-15	-15	-14	2	3
Lower Colorado River Basin	T	-18	-18	-18	-18	-18	-18	NA	1
Great Salt Lake and Sevier River Basins	ALL	-18	-5	-2	-2	3	13	10	6
Great Salt Lake and Sevier River Basins	MS	-18	-6	-2	-3	5	13	12	5
Great Salt Lake and Sevier River Basins	T	-2	-2	-2	-2	-2	-2	NA	1
Central Lahontan Basins	ALL	0	0	0	0	0	0	NA	1
Central Lahontan Basins	MS	0	0	0	0	0	0	NA	1
Central Nevada and Eastern California Desert Basins	ALL	-10	-10	-10	-10	-10	-10	NA	1
Central Nevada and Eastern California Desert Basins	T	-10	-10	-10	-10	-10	-10	NA	1
Southern California Coastal Basins	ALL	-15	-7	1	1	9	18	23	2
Southern California Coastal Basins	MS	-15	-7	1	1	9	18	23	2
All major river basins	ALL	-46	-17	-6	-9	0	117	20	74
All major river basins	MS	-46	-18	-6	-8	0	117	23	51
All major river basins	T	-28	-15	-8	-9	-6	24	11	23

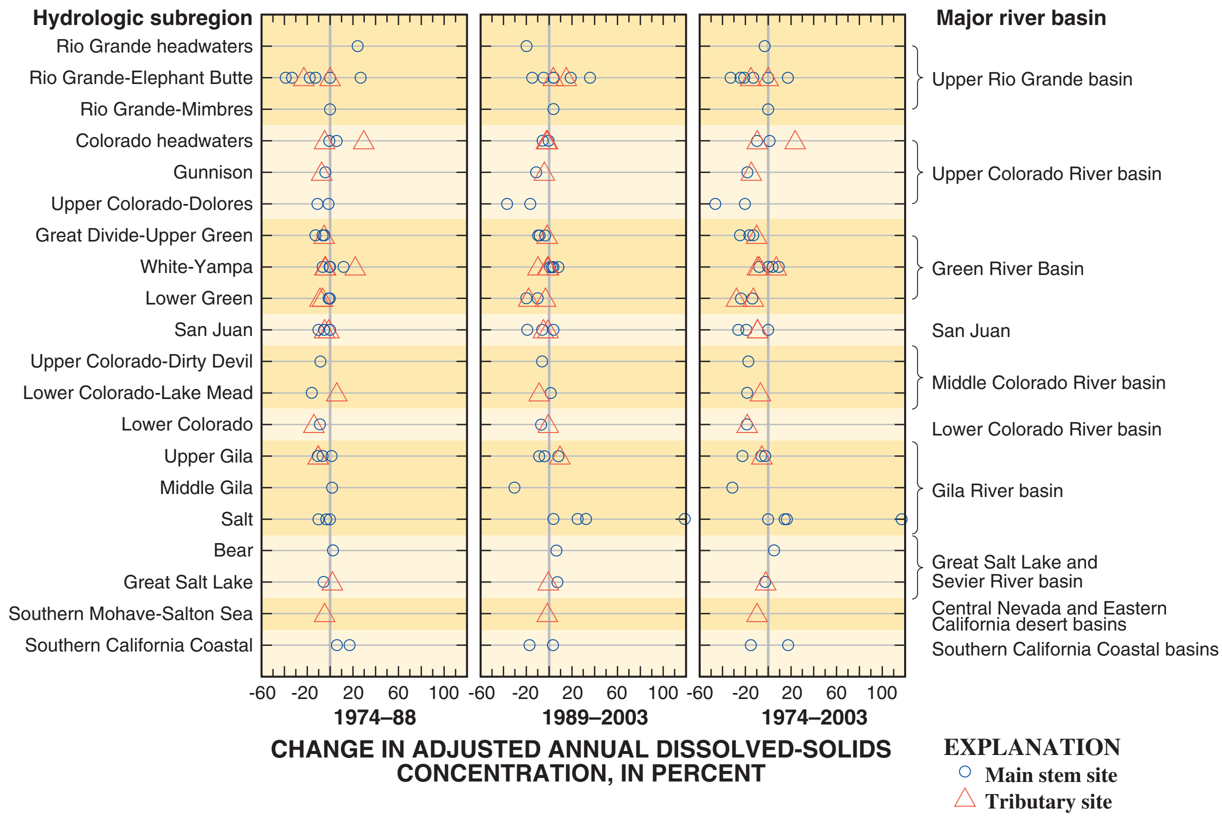

Figure 44. Distribution of period change in adjusted annual dissolved-solids concentration at a common set of surface-water-quality monitoring sites in hydrologic subregions of the Southwestern United States—1974–1988, 1989–2003, and 1974–2003.

The change in AADSCs varied most between periods at sites in the Rio Grande, Gila, and Southern California Coastal Basins (fig. 44). AADSCs were generally decreasing at sites in the upper Rio Grande Basin from 1974 to 1988 but were increasing during 1989–2003 at half the sites. The same general pattern occurred in the Gila River Basin due to changes in the Salt subregion. At the two sites in the Southern California Coastal Basins, AADSCs increased during 1974–88 then declined during 1989–2003 at one of those sites. The AADSCs declined at most sites in other Southwestern major river basins during both periods.

Trends in Dissolved-Solids Concentration in the Colorado River

Trends in annual flow-weighted mean dissolved-solids concentrations at selected sites on the Colorado River were investigated because the amount of economic damage resulting from dissolved solids in the Colorado River increases or decreases relative to the concentration of dissolved solids in the river. These annual concentration values represent ambient conditions and are appropriate to use for analyzing changes in dissolved-solids concentration that may affect the rivers suitability for a particular beneficial use, such as irrigation.

To enhance and protect the quality of water available in the Colorado River, dissolved-solids numeric criteria were established under the Colorado Basin Salinity Control Act of 1974 for three sites in or adjacent to the Lower Colorado River Basin: Colorado River below Hoover Dam, AZ-NV (site 09421500; 723 mg/L), Colorado River below Parker Dam, AZ-CA (site 09427520; 747 mg/L), and Colorado River above Imperial Dam, AZ-CA (site 09429490; 879 mg/L; Colorado River Basin Salinity Control Forum, 2005). For these sites, a time series plot of annual flow-weighted mean concentration for 1974–2003 with a locally weighted scatter plot smooth (LOWESS) shows trend movement (fig. 45). A linear trend slope (change in concentration per year; Sen, 1968; Theil, 1950; and Helsel and Hirsch, 1992) was determined to characterize the overall trend in each of these time-series data sets.

The relation between precipitation in the Upper Colorado River Basin and dissolved-solids concentration in the Colorado River can be seen by comparing the general patterns of precipitation departure from the 1973–2004 average (fig. 43) to changes in the dissolved-solids concentration at the Colorado River water-quality monitoring sites shown in figure 45. During the late 1970s, precipitation was generally near or below average and dissolved-solids concentration in the Colorado River was generally high and, in some cases, increasing. During the early to mid-1980s, precipitation was generally above average, and dissolved-solids concentration in the Colorado River decreased. During a relatively dry period in the late 1980s the dissolved-solids concentration in the Colorado River increased, and during a relatively wet period in the early 1990s, the dissolved-solids concentration decreased. During the dry period that began in 1999 and continued through 2003, the dissolved-solids concentration in the Colorado River began increasing, first at the most upstream site (Colorado River at Lees Ferry, AZ; site 09380000) in 1999 and then at downstream sites in subsequent years. Through 2003, however, there still was no increase in dissolved-solids concentration at the most downstream site, Colorado River above Imperial Dam, AZ-CA (site 09429490).

The dissolved-solids concentration in the Colorado River at Lees Ferry in the Middle Colorado River Basin is a measure of the initial quality of water being delivered to Colorado River water users downstream of this point. The aggregate of changes in dissolved-solids concentration throughout the upper basin and in Lake Powell, impounded by Glen Canyon Dam, are represented by trends in concentration at this site. Annual flow-weighted mean dissolved-solids concentrations in the Colorado River at Lees Ferry, for 1974 to 2003, varied from 416 to 597 mg/L and exhibited a downward trend. The overall trend slope for dissolved-solids concentration in the Colorado River at Lees Ferry was a decline of 2.3 mg/L per year which is the smallest downward trend of the four sites being considered. The LOWESS smooth of annual concentration time-series data for the Colorado River at Lees Ferry indicates that changes in dissolved-solids concentration at this site precede similar changes at downstream sites by about 2 to 4 years.

Water in Lake Mead, which is impounded by Hoover Dam, is diverted for municipal use in southern Nevada, while water in Lake Havasu, which is impounded by Parker Dam, is mostly diverted for municipal use in southern California and Central Arizona. Trends at the Colorado River below Hoover Dam and the Colorado River below Parker Dam were also downward. Annual flow-weighted mean dissolved-solids concentrations at the two sites varied from 512 to 723 mg/L and trend slopes were overall declines of 4.5 and 3.4 mg/L per year, respectively.

Water deliveries to Arizona and California water projects are diverted at the Imperial Dam; hence, dissolved-solids concentrations at this point in the Colorado River directly affect many agricultural water users. Annual mean dissolved-solids concentrations in the Colorado River above Imperial Dam, from 1977 to 2003, varied from 589 to 842 mg/L and also had a downward trend. The overall trend slope decline of 5.2 mg/L per year for the Colorado River above Imperial Dam represents the largest downward trend of these four sites. Annual flow-weighted mean dissolved-solids concentrations at the three sites on the lower Colorado River with numeric criteria did not exceed those criteria during 1974–2003 (fig. 45).

Changes in Adjusted Annual Dissolved-Solids Concentration in the Vicinity of Salinity-Control Projects

Maintaining acceptable levels of dissolved solids in surface-water supplies or reducing dissolved solids in those supplies is important to water-resource managers in the study area, particularly in the Upper Colorado River Basin. Consequently, many salinity-control projects have

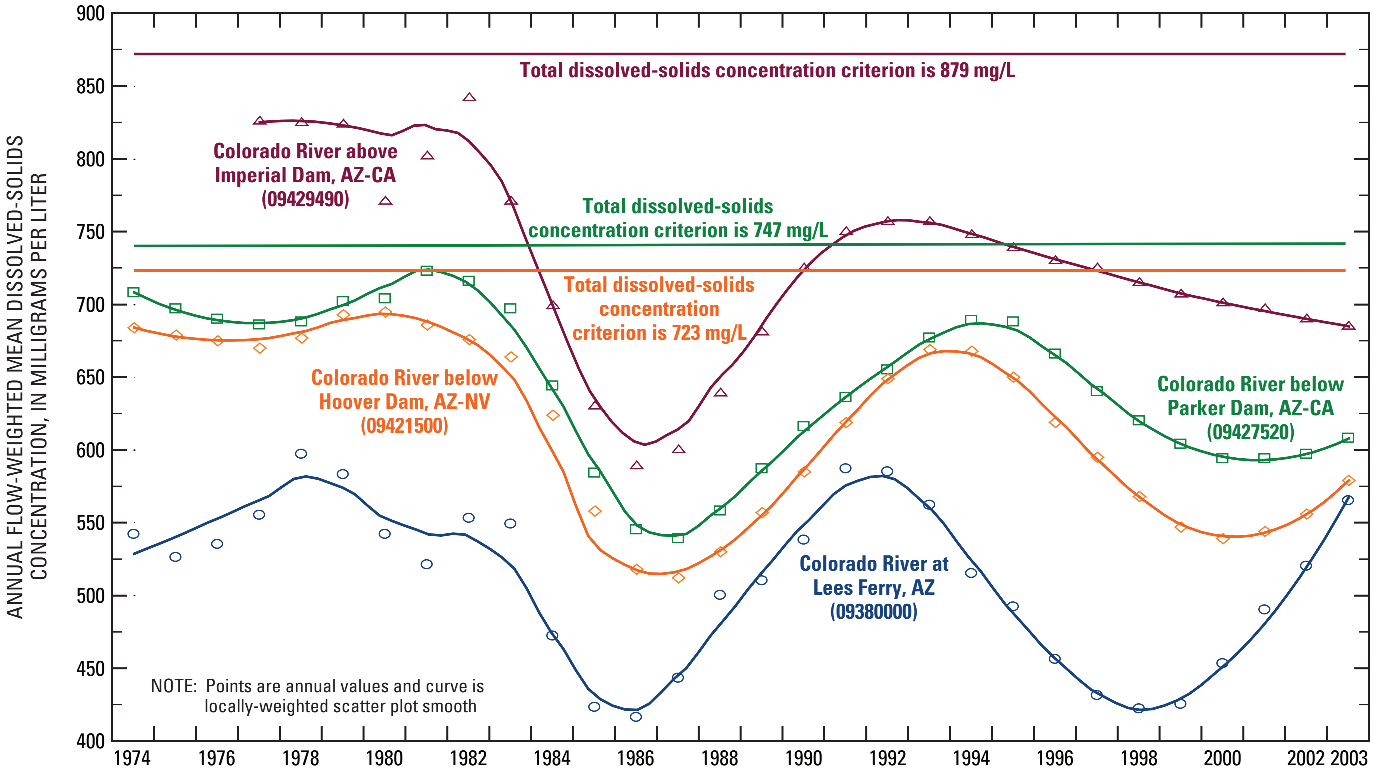

Figure 45. Annual flow-weighted mean dissolved-solids concentrations at four sites, 1974–2003; 09380000 Colorado River at Lees Ferry, AZ; 09421500 Colorado River below Hoover Dam, AZ-NV; 09427520 Colorado River below Parker Dam, AZ-CA; 09429490 Colorado River above Imperial Dam, AZ-CA (Dissolved-solids criteria from Colorado River Basin Salinity Control Forum, 2005).

been implemented in the study area (fig. 12; tables 6 and 7). Studies of dissolved solids in water supplies pre- and post-implementation of selected salinity-control projects have shown a reduction in dissolved solids subsequent to the implementation of those projects (Butler, 1998 and Butler, 2001). The changes and trends in adjusted annual dissolved-solids concentration identified in this report could be related to natural causes, such as geomorphic change or cycles of above- or below-normal precipitation. They also may be related to anthropogenic causes, such as changes in land and water use, reservoir management, transbasin exports, and implementation of salinity-control projects.

The period change in AADSCs at sites above and below selected salinity-control units is shown in table 33. Reductions in AADSC occurred at all of the sites downstream of the salinity-control units shown in table 33, for 1989–2003. AADSCs declined at most of the sites shown in table 33 that are upstream of salinity-control projects as well. The AADSC in the White River above Coal Creek, near Meeker, CO (site 09304200), which is upstream of the Meeker Dome Unit, however, increased 12 mg/L during 1989–2003. The AADSCs in the Uncompahgre River at Colona, CO (site 09147500; upstream of the Lower Gunnison Unit), and the San Juan River near Archuleta, NM (site 09355500; upstream of the San Juan unit) did not change during 1989–2003. Reductions in AADSCs at sites upstream of salinity-control projects were much less than reductions at sites downstream of those projects.

The net change in the dissolved-solids load from upstream of selected salinity-control projects to downstream of those projects was determined from the period change in dissolved-solids concentration and the median annual discharge for 1989–2003 at surface-water-quality monitoring sites upstream and downstream of those projects. For example, from 1989 to 2003, the theoretical dissolved-solids load in the Gunnison River, assuming the median annual discharge for 1989–2003, decreased by about 2,880 ton/yr above the Lower Gunnison Unit and decreased by about 161,600 ton/yr below the Unit: a net decrease of about 158,700 ton/yr in the drainage area containing the Lower Gunnison Unit. This decrease occurred due to processes in the drainage area containing the Lower Gunnison Unit. Similarly, from 1989 to 2003 the theoretical dissolved-solids load in the Colorado River and major tributaries upstream of the Grand Valley Unit decreased by about 330,700 ton/yr and decreased by about 461,300 ton/yr below the Unit. The net decrease of about 130,600 ton/yr occurred due to processes in the drainage area containing the Grand Valley Unit. A study by Butler (1998) showed that the combined dissolved-solids load in four tributaries to the Colorado River in the Grand Valley decreased about 72,000 ton/yr between 1973 and 1996. Because a substantial flow component in these tributaries is subsurface irrigation return flow it is likely that the decrease in dissolved solids reported by Butler was partly the result of implementing salinity-control units in the Grand Valley between 1980 and 1996. The theoretical reductions in dissolved-solids discharging from the drainage areas associated with the Paradox, Meeker Dome, and San Juan Units between 1989 and 2003 are about 242,000; 6,670; and 58,900 ton/yr, respectively. The Meeker Dome Unit was implemented during 1980–83, so there may have been a reduction in the dissolved-solids load discharging from the drainage area containing this Unit prior to 1989. In fact, the period change in the AADSC upstream of this Unit was -1 mg/L for 1974–88, and the period change downstream of the unit was -24 mg/L.

Table 33. Change in adjusted annual dissolved-solids concentration and dissolved-solids load at selected surface-water-quality monitoring sites upstream and downstream of salinity-control projects for the Upper Colorado River Basin, 1989–2003.

[USGS, U.S. Geological Survey; acre-ft/yr, acre-feet per year; mg/L, milligrams per liter; ton/yr, ton per year; ND, no data available; —, no values; BOR, Bureau of Reclamation; USDA, U.S. Department of Agriculture. See table 7 for description of the unit and figure 12 for location]

		Site(s) upstream of salinity-control program unit					Site(s) downstream of salinity-control program unit					
Salinity-control project	Implementation period	USGS site ID	Site name	Median annual streamflow, 1989-2003, acre-ft/yr	Period change[1] in adjusted annual dissolved-solids concentration, mg/L	Theoretical change[2] in dissolved-solids load for 1989-2003, ton/yr	USGS site ID	Site name	Median annual streamflow, 1989-2003, acre-ft/yr	Period change[1] in adjusted annual dissolved-solids concentration, mg/L	Theoretical change[2] in dissolved-solids load for 1989-2003, ton/yr	Net dissolved-solids load change between sites above the salinity-control program unit and sites below, ton/yr
Grand Valley Unit, Colorado	1980–98	09095500	Colorado River near Cameo, Colorado	2,170,000	-55	-162,700	09163500	Colorado River near Colorado-Utah State Line	3,498,000	-97	-461,300	-130,600
		09105000	Plateau Creek near Cameo, Colorado	100,000	-47	-6,390	—	—	—	—	—	—
		09152500	Gunnison River near Grand Junction, Colorado	1,485,000	-80	-161,600	—	—	—	—	—	—
Lower Gunnison Unit, Colorado	1991–95	09147500	Uncompahgre River at Colona, Colorado	161,600	0	0	09152500	Gunnison River near Grand Junction, Colorado	1,485,000	-80	-161,600	-158,700
		09128000	Gunnison River below Gunnison Tunnel, Colorado	706,400	-3	-2,880	—	—	—	—	—	—
Paradox Valley Unit, Colorado	1988–96	09169500	Dolores River at Bedrock, Colorado	129,000	-47	-8,240	09180000	Dolores River near Cisco, Utah	322,400	-571	-250,300	-242,100
Meeker Dome Unit, Colorado	1980–83	09304200	White River above Coal Creek, near Meeker, Colorado	336,900	12	5,500	09304800	White River below Meeker, Colorado	400,600	-3	-1,630	-7,130
Uinta Basin Unit, Utah	2000–2005	09279150	Duchesne River above Knight Diversion, near Duchesne, Utah	100,700	ND	ND	09302000	Duchesne River near Randlett, Utah	142,000	-181	-34,900	—
		09304800	White River below Meeker, Colorado	400,600	-3	-1,630	09306500	White River near Watson, Utah	404,200	-74	-40,700	—

See footnotes at end of table.

Table 33. Change in adjusted annual dissolved-solids concentration and dissolved-solids load at selected surface-water-quality monitoring sites upstream and downstream of salinity-control projects for the Colorado River, 1989–2003—Continued.

		Site(s) upstream of salinity-control program unit					Site(s) downstream of salinity-control program unit					
Salinity-control project	**Imple-mentation period**	**USGS site ID**	**Site name**	**Median annual streamflow, 1989-2003, acre-ft/yr**	**Period change[1] in adjusted annual dissolved-solids concen-tration, mg/L**	**Theoretical change[2] in dissolved-solids load for 1989-2003, ton/yr**	**USGS site ID**	**Site name**	**Median annual streamflow, 1989-2003, acre-ft/yr**	**Period change[1] in adjusted annual dissolved-solids concen-tration, mg/L**	**Theoretical change[2] in dissolved-solids load for 1989-2003, ton/yr**	**Net dissolved-solids load change between sites above the salinity-control program unit and sites below, ton/yr**
San Juan River Unit, New Mexico	1996–2002	09355500	San Juan River near Archuleta, New Mexico	736,800	0	0	09368000	San Juan River at Shiprock, New Mexico	1,203,000	-36	-58,900	-58,900
McElmo Creek Unit, Colorado	1990	—	ND	ND	ND	ND	09372000	McElmo Creek near Colorado-Utah State Line	38,400	-600	-31,300	—

[1]The change in adjusted annual dissolved-solids concentration from 1989-2003 is referred to as a "period change" in this report.

[2]The theoretical change in dissolved-solids load at water-quality monitoring sites was determined from the period change in adjusted annual dissolved-solids concentration and a constant discharge—the median annual streamflow for 1989–2003

Summary

By David W. Anning

The Southwest is an arid to semiarid region of the United States where the location and extent of economic and cultural activities are dependent in part on the availability and quality of water. The most extensively used water supplies in the Southwest are (1) basin-fill aquifers, which include the Rio Grande aquifer system, Basin and Range basin-fill aquifers, and California Coastal Basin aquifers, and (2) rivers such as the Colorado, the Rio Grande, and their tributaries. In many areas of the Southwest, dissolved solids in water resources are of concern because high concentrations degrade a water supply's suitability for certain uses. In response to this water-quality issue, the U.S. Geological Survey National Water-Quality Assessment program performed a regional study to describe (1) the spatial distribution of dissolved-solids concentrations in basin-fill aquifers, and dissolved-solids concentrations, loads, and yields in streams, (2) the natural and human factors that affect dissolved-solids concentrations, (3) the major sources and areas of accumulation of dissolved solids, and (4) the trends of dissolved-solids concentrations over time in basin-fill aquifers and streams, and to relate the trends to natural or human factors.

Dissolved-solids concentrations of ground water in the basin-fill aquifers of the Southwest ranged from less than 500 mg/L near basin margins where ground water is recharged from nearby mountains to more than 10,000 mg/L in topographically low areas of some basins or in areas adjacent to specific streams or rivers in the Basin and Range and Rio Grande aquifer systems. The area of the basin-fill aquifers with dissolved-solids concentrations less than or equal to 500 mg/L was about 57 percent for the Rio Grande aquifer system, 63 percent for the Basin and Range basin-fill aquifers, and 44 percent for the California Coastal Basin aquifers. At least 70 percent of the area of these three basin-fill aquifers had dissolved-solids concentrations less than or equal to 1,000 mg/L. Dissolved-solids concentrations greater than 3,000 mg/L were found in topographically low areas with brackish or saline lakes, playas and terminal basins, such as the Great Salt Lake and Desert in Utah; the Mojave Desert with its many playas, Death Valley, and Salton Sea area in California; the Black Rock Desert and Carson and Humboldt Sinks in Nevada; and the Tularosa Basin in New Mexico. Dissolved-solids concentrations greater than 3,000 mg/L were also found in ground water in the Basin and Range and Rio Grande aquifer systems near or along drainages of the Virgin, Gila and lower Salt Rivers in the Colorado River Basin, and the Jemez River and Rio Puerco in the Rio Grande Basin.

Dissolved solids in streams were described on the basis of median daily concentration, median annual load, and median annual yield data for 420 surface-water-quality monitoring sites. The time period with dissolved-solids data for individual sites varied but was at least 10 or more years between 1974 and 2003. Median dissolved-solids concentrations vary markedly among the sites in the Southwest, ranging between 22 and 13,800 mg/L, and also vary between different sites on the same stream. Dilute median daily dissolved-solids concentrations (those less than 100 mg/L) are predominately found at sites in the headwaters of the Rio Grande and Colorado, Green, San Juan, Truckee, and Carson Rivers. These areas are underlain by igneous and metamorphic rocks that are relatively resistant to the solvent action of water. Streams with median daily dissolved-solids concentrations greater than or equal to 500 mg/L are predominately found in areas in contact with less resistant, more soluble sedimentary rocks. Median daily concentrations generally increased in a downstream direction for sites on the Rio Grande and Colorado, Yampa, White, Green, San Juan, Gila, Bear, and Sevier Rivers.

Median annual dissolved-solids loads ranged from 60 ton/yr for a site on Elk Creek, a headwater tributary to the Colorado River, to 7.86 million ton/yr at Colorado River below Hoover Dam, AZ-NV. Typically, streams with the highest flows have the highest dissolved-solids loads. Most hydrologic subregions (22 of 28) had one or more sites with median annual loads greater than or equal to 100,000 ton/yr. Sites with these large loads were on the main stem of the major rivers—Rio Grande and Colorado, Gunnison, Green, White, Yampa, San Juan, Gila, Bear, Weber, Jordan, Salt, Verde, Sevier, Owens, and Santa Ana Rivers. Median annual loads greater than or equal to 100,000 ton/yr also were found at downstream sites of primary tributaries to the major rivers, and a few smaller tributaries that were in areas with soluble sedimentary rocks. Most hydrologic subregions (18 of 28) had sites with median annual dissolved solids loads that were less than 3,000 ton/yr. Sites with these smaller dissolved-solids loads typically were in headwater areas and (or) desert or drier areas of the major river basins, primarily sites with small median annual streamflow. Median annual loads for sites on the major rivers generally increased in the downstream direction, except where streamflow decreased substantially due to diversions and (or) streambed infiltration, typically in the downstream part of the river system.

Median annual yields ranged from 0.69 to 7,510 (ton/yr)/mi^2, and the mean for all 420 sites was 125 (ton/yr)/mi^2. Most sites (104 of 112) with median annual yields greater than 100 (ton/yr)/mi^2 were in the Colorado River Basin upstream from Lees Ferry and in the Bear and Great Salt Lake hydrologic subregions.

A conceptual model of the effects of natural and human factors on dissolved-solids concentrations in basin-fill aquifers and streams in the Southwest was developed through a synthesis of case studies for 12 selected areas in the 6 NAWQA Study Units in the Southwest. Much of the surface water and ground water in the Southwest originate from precipitation in upland, bedrock-dominated mountain areas. Dissolved-solids concentrations in precipitation are low, and as a result, concentration of runoff into mountain streams is low. Some precipitation infiltrates the soils and recharges bedrock aquifers, dissolving minerals from the rocks along this path. Where the ground-water flow path is through sedimentary rocks or evaporite deposits, spring discharge typically has high dissolved-solids concentrations. Streamflow in mountain streams is a mixture of surface runoff and ground-water discharge from springs. Concentrations are low in streams draining areas underlain by metamorphic and igneous rocks that are relatively resistant to the solvent action of water, whereas concentrations are high in streams draining areas underlain by sedimentary rocks that are less resistant to the solvent action of water.

Streamflow in the upland and mountainous areas of the Southwest is often stored in one or more reservoirs and used at a later time for power generation, municipal use, or agricultural use. Concentrations of reservoir inflow are typically variable over time; however, the inflows mix in the reservoir and as a result, concentrations of reservoir outflow are typically less variable. Evaporation from reservoirs has the effect of increasing dissolved-solids concentrations. Streamflow in the upland and mountainous areas is also diverted for use in other areas that may be many miles away. While transbasin diversions may not transport a large mass of dissolved solids to other areas, they result in the removal of high-quality water that would otherwise serve to help dilute high-concentration water sources in the originating basin.

Surface water and ground water eventually flow out of the upland and mountainous areas into lowland areas, which have flatter terrain and contain large basin-fill aquifers. Along the basin margins, streamflow is often diminished due to infiltration or due to diversion for offstream uses. Ground-water recharge of the basin-fill aquifers along the basin margin by streamflow infiltration or by subflow from adjacent bedrock-highland aquifers typically has low dissolved-solids concentrations in comparison to ground water in other parts of the aquifer.

Ground-water concentrations typically increase along flowpaths through basin-fill or alluvial deposits as a result of geochemical reactions with the aquifer matrix. In some parts of the aquifer, sediments that make up the aquifer matrix react with the ground water and release ions into solution. In other areas disseminated salts in the aquifer matrix or massive evaporite deposits are leached into the ground water. Ground-water concentrations in basin-fill aquifers may also increase as a result of evapotranspiration by natural vegetation or by agricultural crops. Dissolved-solids concentrations also can change as a result of mixing two or more subsurface waters; recharge from irrigation seepage, septic tank seepage, and percolation ponds or streambeds that infiltrate imported water or treated municipal wastewater; or seawater intrusion (in coastal areas).

Dissolved-solids concentrations in streams also change along their path through lowland areas due to evaporation and mixing processes. Concentrations in gaining stream reaches can increase as a result of mixing with ground water that has relatively high concentrations. Concentrations also change in streams that receive irrigation-return flows or releases from municipal wastewater-treatment plants. In areas with cold climates and significant urban development and road systems, use of road de-icers may also increase dissolved-solids concentrations in streams.

The enhancement or restriction of surface-water and ground-water outflow affects the accumulation of dissolved solids in water supplies. For example, pumpage of unconfined ground water from the San Luis Valley's Closed Basin Division Project into the Franklin Eddy Canal provides a means of draining ground water that contains relatively high dissolved-solids concentrations from the closed basin part of the San Luis Valley into the Rio Grande. This pumpage reduces evapotranspiration of shallow ground water and decreases the accumulation of dissolved solids in the ground-water system. In southern California, the Santa Ana Regional Interceptor pipeline drains high-concentration wastewaters directly to the ocean and prevents them from deteriorating good-quality water supplies. In some topographically open basins, such as those described for Central Arizona, the inflow of dissolved solids in surface-water supplies is greater than outflow, and dissolved solids accumulate. Dissolved solids also accumulate in topographically closed basins where there is no outflow, such as the Carson Sink. In these areas where outflow of water, and therefore, outflow of dissolved solids, is restricted or where inflow is greater than outflow, dissolved solids generally accumulate in areas with evapotranspiration of surface water or ground water by native vegetation or agricultural crops, or by evaporation in playas. Dissolved-solids concentrations increase in the water supply that is evaporated.

Significant source and accumulation areas of dissolved solids in the Southwest were determined by using a mass-balance analysis of the contributions and losses of dissolved solids for river systems in hydrologic accounting units of the Southwest. Contributions to river systems in each hydrologic accounting unit included inflows, internal deliveries, and imports; and losses included outflows, internal accumulation, and exports. These six terms were quantified by using predictions from the SPARROW model for dissolved-solids transport in the Southwest.

The SPARROW model related annual dissolved-solids loads in the ERF1_2 stream reach network to the reach catchment characteristics that represented (1) sources, (2) land-to-water delivery factors, and (3) factors that affect instream losses. Sources of dissolved solids in the SPARROW model include 12 geologic units, cultivated and pasture land, and imported water. Land-to-water delivery factors included runoff depth, drainage density, and percent barren land. Factors related to instream losses included change in discharge across the reach and percent area of the reach catchment containing Quaternary basin fill.

Significant source areas are accounting units where dissolved solids are released from internal sources and delivered to streams at high delivery rates. The most significant source areas of dissolved solids in the Southwest include the Colorado headwaters, Middle Gila, Lower Bear, and Santa Ana accounting units, where delivery rates were greater than 150 (ton/yr)/mi^2 during the period of study. In contrast, delivery rates were low—less than 15 (ton/yr)/mi^2—in the Mimbres, Great Divide closed basin, Bill Williams, Central Nevada desert basins, and Southern Mojave accounting units. Significant accumulation areas are those where dissolved solids transported in streams are retained internally at high accumulation rates. The highest accumulation rate by far was that for the Salton Sea accounting unit at 704 (ton/yr)/mi^2, which was more than twice as large as the second highest rate, 305 (ton/yr)/mi^2 for the Lower Gila-Agua Fria accounting unit. These two accounting units and the Middle Gila, Lower Bear, and Great Salt Lake accounting units, which had accumulation rates greater than 150 (ton/yr)/mi^2, were are amongst the most significant accumulation areas in the Southwest. Accumulation rates were low—less than 15 (ton/yr)/mi^2—in about 36 percent (17 of 47) of the accounting units.

Predictions from the SPARROW model were used to determine the relative significance of the various natural and human internal sources of dissolved solids in accounting units of the Southwest. Geologic units, which represent natural sources of dissolved solids, contribute 44 percent of the total internal deliveries for all accounting units in the Southwest. Of the 44 percent for geologic units, about 7 percent is from crystalline and volcanic rocks, 2 percent from eugeosynclinal rocks, 12 percent from Tertiary sedimentary rocks, 12 percent from Mesozoic sedimentary rocks, and 10 percent from Paleozoic and Precambrian sedimentary rocks. Cultivated lands (44 percent) and pasture lands (12 percent) are anthropogenic sources of dissolved solids, and contributed the remaining 56 percent of the total internal deliveries for all accounting units in the Southwest.

An analysis of trends in dissolved-solids concentrations in basin-fill aquifers and streams was performed to determine whether concentrations have been generally increasing or decreasing in recent years, and whether there are any patterns in the trends related to natural and human factors. Results of the trend analysis indicate that for the basin-fill aquifers concentrations of dissolved solids in most ground-water-quality monitoring wells did not change over time—the portion of wells with no trend in concentrations was 77 percent for 1974–88, 68 percent for 1989–2003, and 59 percent for 1974–2003. The smaller portion of all wells that had either an increasing trend or decreasing trend generally were dispersed evenly across the Southwest. The mixture of trends spatially and the lack of clusters of wells all having the same trend in a particular area suggests that trends in dissolved-solids concentrations tend to occur in localized areas and not across large regions.

For 1989–2003, the occurrence of trends in dissolved-solids concentrations of basin-fill aquifers were related to the depth to water below the land surface. The probability for a trend (either an increase or decrease) to occur was largest for wells with shallow depths to water, 42 percent where water was just below the land surface. The probability steadily decreased as the depth to water increased. The decreasing probability of a trend likely results from a larger travel distance and travel time for infiltrating water, and also an increased possibility for occurrence of and larger thickness of low-permeability sediments between the land surface and the aquifer that would retard infiltration. Wells with water levels under artesian conditions had a small probability of having a trend—only 8 percent. These wells likely have a confining unit that created the artesian conditions, and also prevented the aquifer from mixing with higher or lower dissolved-solids concentration infiltrating water. The lack of mixing, in turn, prevented the generation of a trend in concentrations over time due to mixing.

In comparison to conditions for ground-water-quality monitoring wells in the basin-fill aquifers, the presence of trends in dissolved-solids concentration in rivers were much more common. Changes in adjusted annual dissolved-solids concentration (AADSC) during 1974–88 were mixed throughout the Southwest with most major river basins having water-quality-monitoring sites in both the increasing and decreasing categories. Of the three time periods, 1974–88 had the largest percentage of sites with no change or increasing AADSCs. No change in AADSCs occurred at 24.2 percent of sites and an increase in AADSCs during 1974–88 occurred at 33.8 percent of the sites. Decreases in AADSCs occurred at 42.1 percent of the sites.

During 1989–2003, water quality relative to dissolved solids generally improved in major river basins of the Southwest. Adjusted annual dissolved-solid concentrations decreased at 51.1 percent of the sites included in the 1989–2003 trend analysis. In fact, there were four major river basins where AADSCs decreased at 75 percent or more of the sites. The fact that there was a decrease in AADSCs at nearly all of the sites on the main stem of the Colorado and Green Rivers is an example of how widespread these reductions in dissolved-solids concentrations were.

For 1974–2003, adjusted annual concentration decreased at nearly 70.3 percent of the sites, with the median period change for AADSC for all sites being -9 percent. Most of the sites included in trend analysis for this period are situated on the main stem of major rivers, as a result, the conclusions that are drawn from this data set relate more specifically to conditions in the major rivers.

An inverse relation between annual precipitation and annual mean dissolved-solids concentration in the Colorado River occurred during 1974–2003. Dissolved-solids concentrations were highest following a dry period in the late 1970s and lowest following a wet period in the early 1980s. The annual mean dissolved-solids concentration in the Colorado River near three of four major impoundments or diversions increased as a likely result of the drier period from 1999–2003. During 1974–2003, annual mean dissolved-solid concentrations did not exceed numeric criteria established for three locations on the lower Colorado River.

The changes and trends in adjusted annual dissolved-solids concentration identified in this report could be related to natural causes such as geomorphic change or due to anthropogenic causes such as changes in land and water use, reservoir management, transbasin exports, and salinity-control efforts. The period change in AADSCs at sites above and below selected salinity-control units were compared to determine if a relation between salinity control implementation and reductions in dissolved solids in surface water discharging from salinity-control units exists. Reductions in AADSCs occurred at all sites below salinity-control units, while changes were mixed at sites above salinity-control units. For three salinity control units, reductions in AADSCs were much less at sites above the units than at sites below those units.

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Tracey L. Suzuki, Technical Editor
John Callahan, Illustrator

For more information concerning the research in this report, contact the
Arizona Water Science Center Director,

U.S. Geological Survey, 520 N. Park Ave., Suite 221, Tucson, AZ 85719
http://az.water.usgs.gov

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