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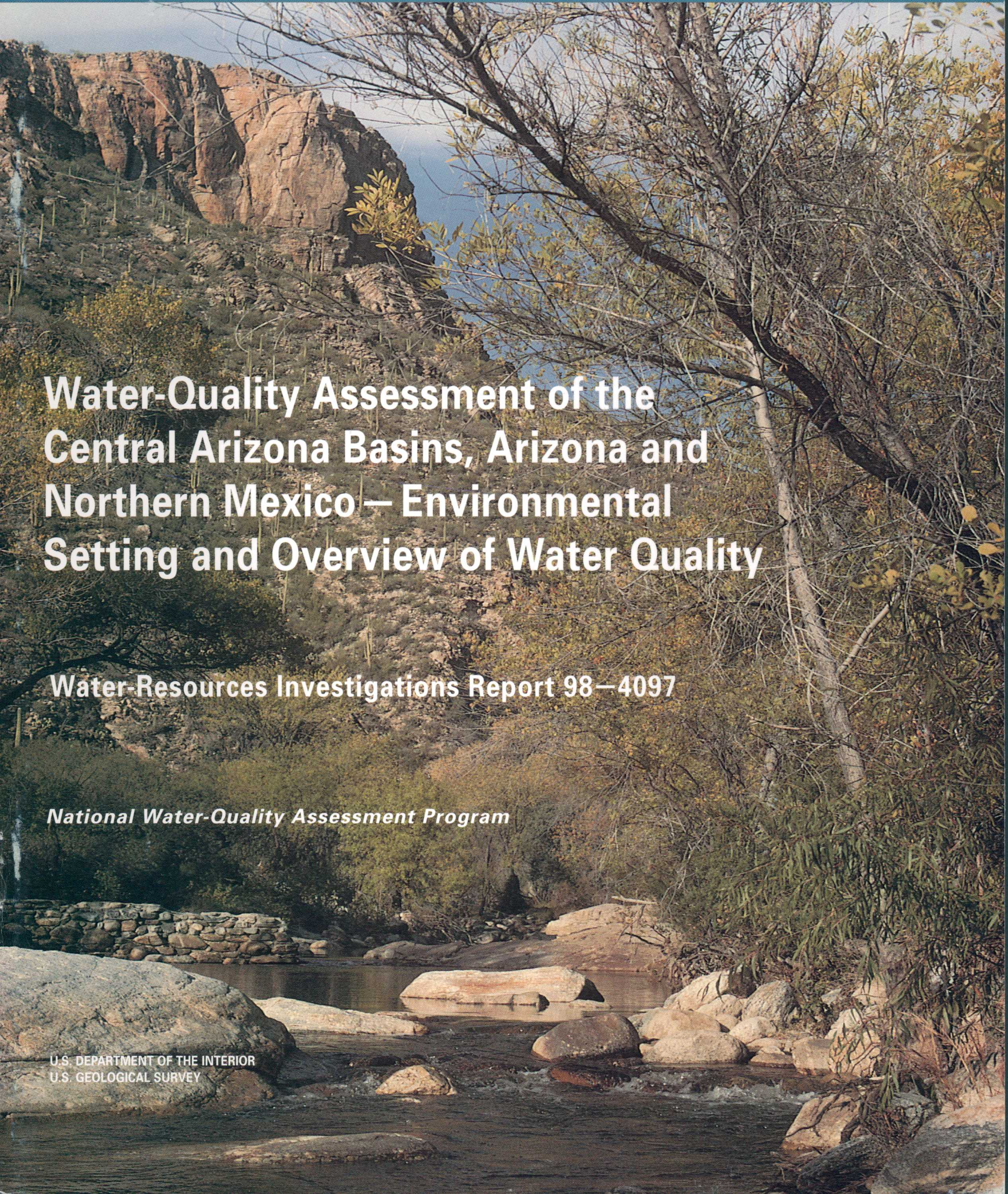

Water-Quality Assessment of the Central Arizona Basins, Arizona and Northern Mexico—Environmental Setting and Overview of Water Quality

Water-Resources Investigations Report 98–4097

National Water-Quality Assessment Program

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Cover photograph: Sabino Creek in the Catalina Mountains near Tucson, Arizona

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By G.E. CORDY, J.A. REES, R.J. EDMONDS, J.B. GEBLER, LAURIE WIRT, D.J. GELLENBECK, *and* D.W. ANNING

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Tucson, Arizona
1998

U.S. DEPARTMENT OF THE INTERIOR
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FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policymakers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resources agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for a specific contamination problem; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) program. In 1991, the USGS began full implementation of the program. The NAWQA program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA program are being achieved through ongoing and proposed investigations of 60 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

CONTENTS

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day

In this report, air temperatures are given in degrees Fahrenheit (°F), which may be converted to degrees Celsius (°C) by the following equation:

$$°C = (°F-32)/1.8$$

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C). Radioactivity is expressed in picocuries per liter (pCi/L) or picocuries per gram (pCi/g), which is the amount of radioactive decay producing 2.2 disintegrations per minute in a unit volume (liter) of water or mass (gram) of sediment. Chemical concentration in bottom sediment is given in grams per kilogram (g/kg), micrograms per gram (µg/g), milligrams per kilogram (mg/kg), or micrograms per kilogram (µg/kg). Grams per kilogram is equal to parts per thousands (ppt). Milligrams per kilogram and micrograms per gram are equal to parts per million (ppm). Fecal coliform and fecal streptococcal bacteria are reported in colonies per 100 milliliter (col/100 mL).

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water-Quality Assessment of the Central Arizona Basins, Arizona and Northern Mexico—Environmental Setting and Overview of Water Quality

By G.E. Cordy, J.A. Rees, R.J. Edmonds, J.B. Gebler, Laurie Wirt, D.J. Gellenbeck, *and* D.W. Anning

Abstract

The Central Arizona Basins study area in central and southern Arizona and northern Mexico is one of 60 study units that are part of the U.S. Geological Survey's National Water-Quality Assessment program. The purpose of this report is to describe the physical, chemical, and environmental characteristics that may affect water quality in the Central Arizona Basins study area and present an overview of water quality. Covering 34,700 square miles, the study area is characterized by generally north to northwestward-trending mountain ranges separated by broad, gently sloping alluvial valleys. Most of the perennial rivers and streams are in the northern part of the study area. Rivers and streams in the south are predominantly intermittent or ephemeral and flow in response to precipitation such as summer thunderstorms. Effluent-dependent streams do provide perennial flow in some reaches. The major aquifers in the study area are in the basin-fill deposits that may be as much as 12,000 feet thick.

The 1990 population in the study area was about 3.45 million, and about 61 percent of the total was in Maricopa County (Phoenix and surrounding cities). Extensive population growth over the past decade has resulted in a twofold increase in urban land areas and increased municipal water use; however, agriculture remains the major water use. Seventy-three percent of all water withdrawn in the study area during 1990 was used for agricultural purposes.

The largest rivers in the study area—the Gila, Salt, and Verde—are perennial near their headwaters but become intermittent downstream because of impoundments and artificial diversions. As a result, the Central Arizona Basins study area is unique compared to less arid basins because the mean surface-water outflow is only 528 cubic feet per second from a total drainage area of 49,650 square miles. Peak flows in the northern part of the study area are the result of snowmelt runoff; whereas, summer thunderstorms account for the peak flows in the southern part. Ground water is the primary water supply in most of Arizona and the only source of drinking water used by communities in the southern half of the study area. Years of overpumping have caused water tables in basin fill to drop below once-perennial streams leaving streambeds dry, water too deep to pump economically, pumping of poorer quality water with depth, and earth fissures resulting from subsidence after dewatering of sediments.

Natural processes—such as leaching of trace elements and major ions from geologic formations—and human activities—such as mining, agriculture, and urban development—have

major effects on the quality of surface-water and ground-water resources in the Central Arizona Basins study area. Surface-water quality standards in Arizona are based on the designated use of the water such as full or partial body contact, fish consumption, aquatic and wildlife uses, and agriculture. Maintaining the biological integrity (health) of surface waters in Arizona is an important part of ensuring that these waters are suitable for designated uses.

Important water-quality issues for surface water that are somewhat unique to Arizona include: (1) streamflows and riparian environments sustained by effluent from municipal wastewater-treatment plants that contains high concentrations of nutrients, potentially toxic trace elements and organic compounds, and fecal bacteria; (2) industrial, mining, agricultural, and municipal sources of contamination from Mexico; and (3) unpredictable high flows from major summer thunderstorms causing stream-channel changes; high suspended-sediment concentrations and loads; sewage overflows; and breaching, erosion, and washout of landfills and mining operations.

The quality of water in aquifers that are protected for drinking-water use is subject to standards that are in most cases equal to or more stringent than the primary drinking-water regulations of the U.S. Environmental Protection Agency. The general chemical and biological quality of ground water in the Central Arizona Basins study area is adequate for most uses. High concentrations of nutrients, specifically nitrate, have been found in ground water in many parts of the study area, and concentrations are highest in the southern part of the area. Other water-quality issues for ground water in parts of the study area are high concentrations of dissolved solids and trace elements; high radon activities; and contamination by pesticides, volatile organic compounds, and pathogenic bacteria.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) implemented a full-scale National Water-Quality Assessment (NAWQA) program. The long term goals of the NAWQA program are to describe the status and trends in the quality of a large, representative part of the Nation's surface-water and ground-water resources and to provide a sound, scientific understanding of the primary natural and human factors affecting the quality of these resources (Leahy and Wilber, 1991). In meeting these goals, the program will produce a wealth of information that will be useful to policymakers and managers at the Federal, State, and local levels. Sixty study units or study areas were planned nationwide that include most major river basins and aquifer systems. The study units range in size from 1,000 to 60,000 mi^2 and represent 60 to 70 percent of the Nation's water use and population served by public water supplies (Hirsch and others, 1988). Twenty of the 60 study units began their investigations in 1991, 16 additional studies started in 1994, and 15 studies began in 1997. The Central Arizona Basins study unit was among the 16 that began in 1994 and is referred to as the CAZB study area in this publication.

The CAZB study area includes most of central and southern Arizona and part of northern Mexico (fig. 1). For the CAZB NAWQA program, existing and new data will be collected and analyzed during an intensive data-collection phase from October 1995 through September 1998. Following this period of intensive study, a low-intensity monitoring phase will continue for 5 years leading into the next cycle of high-intensity and low-intensity sampling.

The CAZB study area represents an unusual opportunity among NAWQA study units to investigate water-quality issues in an arid environment. Unlike most areas of the Nation, much of the CAZB study area has only ephemeral or intermittent rivers and streams. Those rivers and streams that are perennial usually are diverted for agricultural and municipal use, and thus, seldom flow out of the study area except during floods. Ground water is a valuable resource in these areas of scarce surface water. In the CAZB study area, the quality of the limited water resources is critical

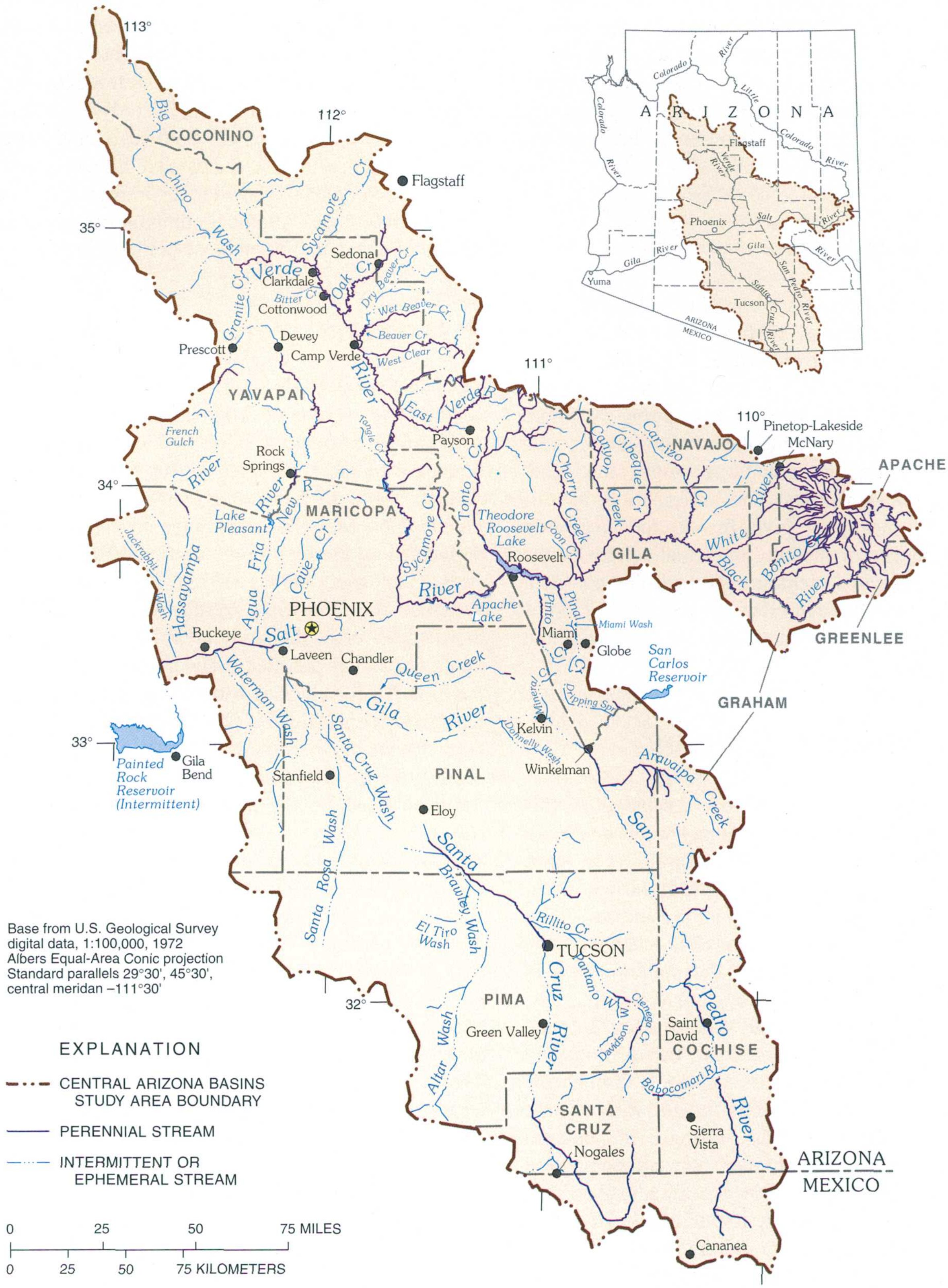


Figure 1. Central Arizona Basins study area.

to their value and use. Through the NAWQA studies of ground-water and surface-water quality and aquatic ecology, factors that affect water quality such as sediments, nutrients, and organic compounds from natural and anthropogenic sources will be described and their effects evaluated.

Purpose and Scope

This report describes the physical and environmental characteristics of the CAZB study area that may affect water quality and provides an overview of water quality. Information presented in this report will provide the basic setting for future reports that help to define the relations among land use, water quality, aquatic ecology, and other environmental factors. The information in this report is meant to give the reader a general understanding of the environmental setting of the CAZB study area including the hydrologic system and to provide an overview of water-quality issues related to surface water, aquatic ecology, and ground water.

ENVIRONMENTAL SETTING

The environmental factors discussed in this section have a role in determining water quality in the CAZB study area. Physiography, in part, controls and determines the path of surface water and ground water as do the geology and soils. The length of the flowpath or stream reach and the minerals and contaminants the water comes in contact with as it moves through or across the soils, sediments, and rocks affect water quality. Climate is a major factor in determining the quantity and quality of water that enters and flows through the study area. Population, land use, and water use are interrelated factors because changes in land use and water use are usually in response to population changes. For example, in the Phoenix area, a substantial increase in the population has resulted in the conversion of agricultural lands to urban land use and an increase in municipal water use. Contamination or degradation of water quality in the study area is commonly the result of current or past land uses and (or) water uses as in agricultural areas where fertilizers and pesticides applied to fields can contaminate surface water and ground water long after agricultural use has ceased.

The last part of this section introduces the ecoregions into which the CAZB study areas has been divided on the basis of broad-scale landscape features. Rather than a factor that affects water quality, ecoregions provide a framework for defining reference biological communities and the effects of water quality on those communities.

Physiography

The CAZB study area covers 34,700 mi^2 in central and southern Arizona including about 1,000 mi^2 in northern Sonora, Mexico (fig. 1). The boundary of the study area is, for the most part, defined by surface-water drainage divides, including the Mogollon Rim in the north (fig. 2), as delineated on the hydrologic unit map for Arizona (U.S. Geological Survey, 1975). Five major river systems—the Gila, Salt, Verde, Santa Cruz, and San Pedro—drain the study area. The Salt, Verde, Santa Cruz, and San Pedro Rivers are tributary to the Gila River, which is tributary to the Colorado River near Yuma (fig. 1). The San Pedro and Santa Cruz Rivers flow through Mexico; however, the headwaters of the Santa Cruz are in Arizona and the headwaters of the San Pedro are in Mexico (fig. 1).

The study area is in the Basin and Range Physiographic Province (Fenneman, 1931), which consists of generally north to northwestward-trending mountain ranges separated by broad, gently sloping alluvial valleys. Perhaps more pertinent to the NAWQA studies is the division of the CAZB study area into provinces on the basis of physiographic and hydrologic characteristics. These hydrologic provinces (fig. 2) are the Plateau Uplands, the Central Highlands, and the Basin and Range Lowlands (Arizona State Land Department, 1969). The central and southern parts of the study area, including the part in Mexico, are in the Basin and Range Lowlands Province; whereas, the northern part of the study area is in the Central Highlands Province, with the exception of some small areas along the northern boundary that are in the Plateau Uplands Province (fig. 2). For the purposes of discussion in this report and the CAZB

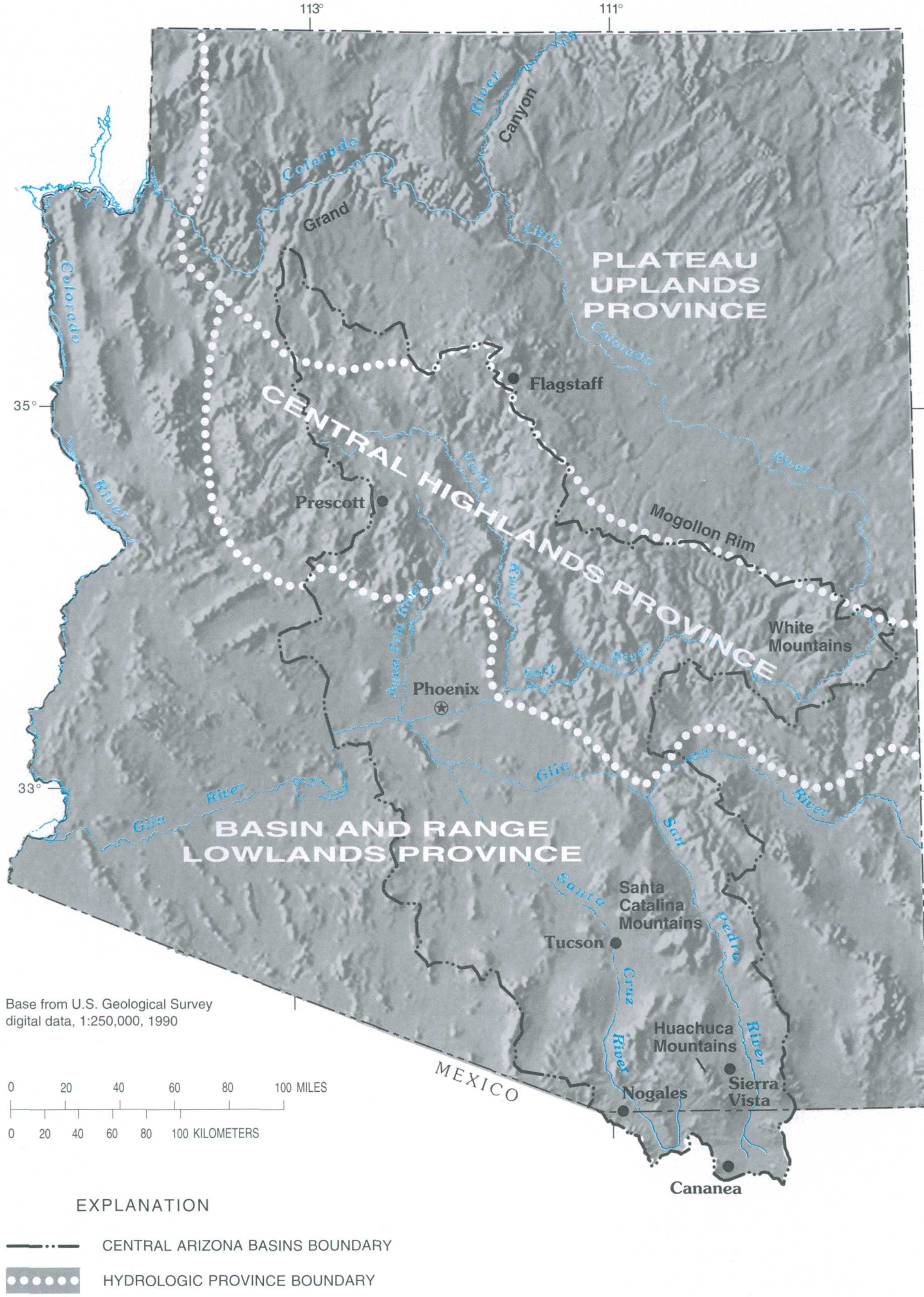


Figure 2. Physiography, hydrologic provinces, and physical features of the Central Arizona Basins study area.

NAWQA study, the small areas in the Plateau Uplands are included in the Central Highlands Province.

The Central Highlands Province is characterized by mountainous terrain with shallow intermontane basins (fig. 2) that represent a small part of the total area (Robertson, 1991). Altitudes range from about 2,000 ft near the confluence of the Salt and Verde Rivers to about 11,400 ft at Mt. Baldy in the White Mountains, southeast of McNary. Most of the perennial streams in the study area are in the Central Highlands. They flow from the Mogollon Rim (fig. 2) through the Central Highlands toward the Basin and Range Lowlands.

In contrast to the Central Highlands, the mountain ranges in the Basin and Range Lowlands generally are small in areal extent compared to the basins (fig. 2). The mountains are moderately to deeply dissected and rimmed by broad pediments. Large, oval basins are common in the area surrounding Phoenix; and to the south, the basins tend to be elongated. Altitudes range from about 800 ft above sea level west of Phoenix near the study-area boundary to about 9,470 ft at Miller Peak, southeast of Sierra Vista in the Huachuca Mountains. Ephemeral and intermittent streams are characteristic of the Basin and Range Lowlands.

Geology

The geology and structure of the CAZB study area are the result of several major tectonic events. From the perspective of understanding the current physiography and hydrology, the most important tectonic period was the Basin and Range disturbance, which began about 15 to 12 million years ago (Damon and others, 1984) and to a lesser degree, continues to the present in some areas (Shafiqullah and others, 1980). The large-scale normal faulting characteristic of the early part of this period formed the uplifted and downdropped blocks that are the basis for present-day topography. Several thousand feet of vertical displacement is common between the upthrown mountain blocks (horsts) and the downthrown valley blocks (grabens). Large thicknesses of basin fill, typically several thousand feet, have subsequently accumulated in the subsiding basins. The deepest basins are along a trend from Tucson to Phoenix that represents a pre-existing structurally low area referred to as the "Gila Low" by Peirce (1976). Basins along this trend contain basin-fill deposits that are 8,000 to 12,000 ft thick near the basin centers (Anderson and others, 1992). These basins include the Salt River Valley, which includes Phoenix; the Picacho Basin between Phoenix and Tucson near Eloy; and the Tucson Basin, which includes Tucson (fig. 3).

Pre-existing drainage patterns were altered by block faulting so that subsiding structural basins became the sites of deposition for sediments derived from the surrounding uplifted mountain blocks. Internal drainage consisting of short discontinuous streams coming from adjacent mountains developed in these closed basins. When higher basins filled sufficiently with sediment for the streams to flow over the lowest divides into the next lower basin, the stream drainages gradually became integrated (Damon and others, 1984).

The basins in the Central Highlands Province are characteristically different from those in the Basins and Range Lowlands. Anderson and others (1992), as a part of the Regional Aquifer Systems Analysis program of the USGS, summarized basin characteristics for several categories of basins in the study area. They noted that the basins in the Central Highlands contain as much as 500 ft of basin-fill sediments that are limited in areal extent and typically overlie a sequence of pre-Cenozoic sedimentary rocks (fig. 4*A*). Stream alluvium overlies the basin fill in some areas and is common along the flood plains.

In contrast, basins of the Basin and Range Lowlands contain basin-fill sediments that are 2,000 to as much as 12,000 ft thick (fig. 4*B*). These deposits overlie pre-Basin and Range sediments that were faulted along with the underlying bedrock during the Basin and Range disturbance. Generally, basin-fill sediments in these basins grade from coarse grained near the mountain fronts to fine grained in the centers of the basins. Basin fill can be divided into two or more units (upper and lower basin fill) in most basins on the basis of lithology and grain size. Mudstone and evaporite deposits are common at depth in the centers of many of these basins. Stream alluvium overlies basin fill and ranges from thin layers of sand and gravel to as much as 300 ft of coarse-grained sediments along major streams.

Figure 3. Generalized geology of the Central Arizona Basins study area (modified from Reynolds, 1988; and Coordinacion General de Los Servicios Nationales de Estadistica, Geografia E Informatica, 1981 and 1983a, b).

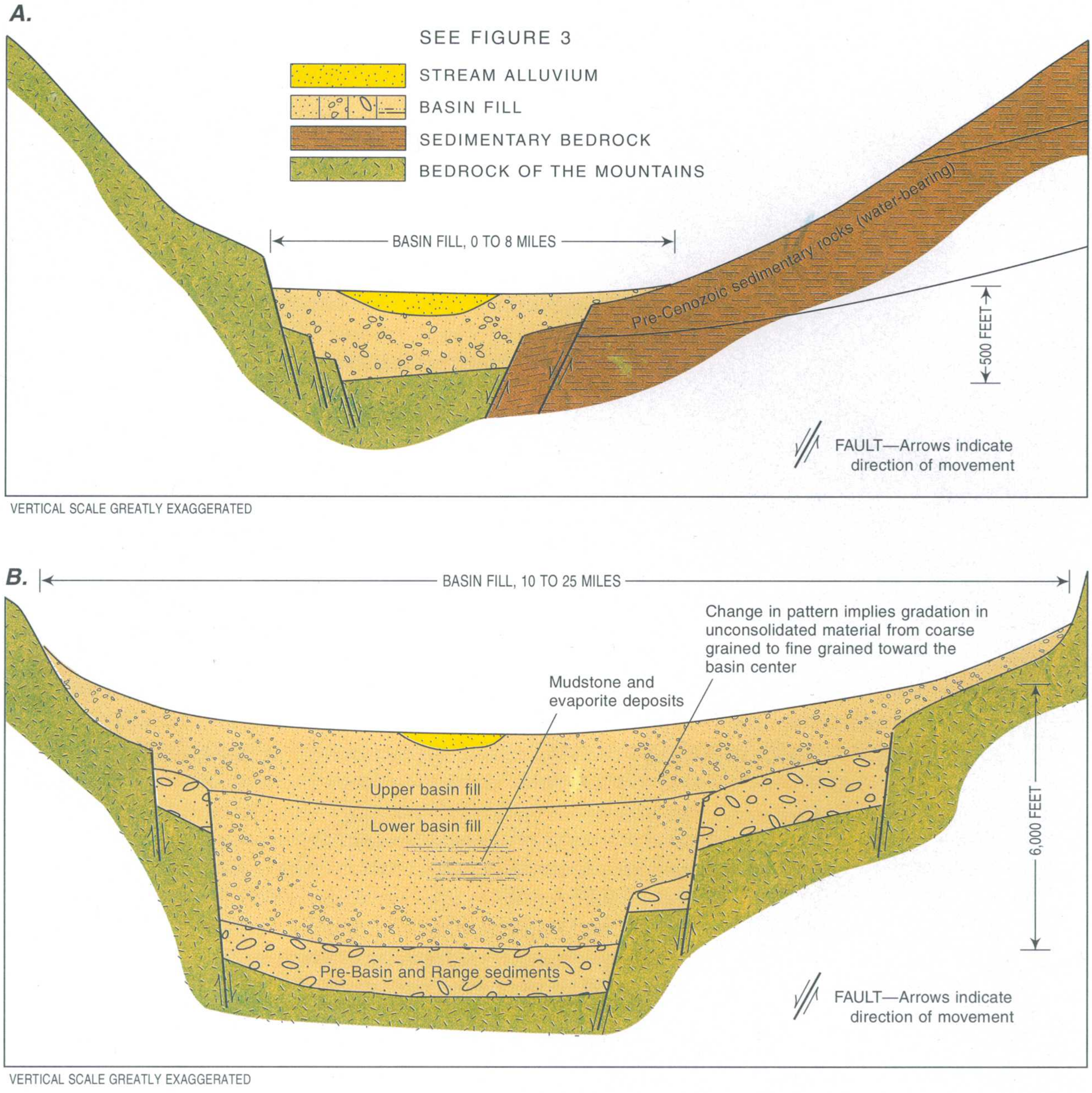


Figure 4. Generalized geologic sections of basins in the *A*, Central Highlands Province, and *B*, Basin and Range Lowlands Province (modified from Anderson and others, 1992).

For the purposes of the NAWQA study, the geology of the CAZB study area is divided into four major units based on lithology, hydrology, and physiography. These units are delineated on the basis of more detailed geologic maps of Arizona (Reynolds, 1988) and Mexico (Coordinacion General De Los Servicios Nacionales de Estadistica, Geografia E Informatica, 1981, 1983a, b). The units are (generally from oldest to youngest): bedrock of the mountains, sedimentary bedrock, basin fill, and stream alluvium (fig. 3). In general, the bedrock of the mountains forms the largely impermeable mountains and basement in the valleys beneath the basin fill. Some sedimentary rocks in the northern part of the study area are designated in a category separate from the bedrock of the mountains because these rocks may yield significant quantities of water and are potential aquifers. The basin fill is in the valleys between mountain ranges, and the stream alluvium includes deposits in present-day rivers, stream channels, and flood plains (Reynolds, 1988). A brief description of these units, by hydrologic province, follows.

Central Highlands

Much of the landscape of the Central Highlands is bedrock of the mountains (fig. 3), which is predominantly Mesozoic and Cenozoic volcanic rocks and Precambrian sedimentary, metamorphic, and granitic rocks. These rocks provide water locally from fractured and permeable zones, but they typically do not constitute major aquifers. In contrast, the sedimentary bedrock mainly consists of Paleozoic and Mesozoic limestone, sandstone, shale and related sedimentary deposits with some minor Cenozoic deposits near McNary (Reynolds, 1988). Some of these sedimentary rocks generally are permeable; thus, they store and transmit water better than the rocks classified as "bedrock of the mountains." Water from these sedimentary rocks is discharged to some basin-fill aquifers along the Mogollon Rim and in the Verde Valley (Anderson and others, 1992).

Basin-fill deposits in the Central Highlands consist of unconsolidated to moderately consolidated sediments of Cenozoic (middle Pleistocene to middle Miocene) age. Lake deposits of limestone, sandstone, and mudstone of the Verde Formation and interbedded volcanics form the basin-fill equivalent in the Verde Valley near Cottonwood (fig. 3, this report; Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). Elsewhere in the Central Highlands the character of the basin fill is less well known because few wells penetrate these deposits (Anderson and others, 1992). The basin-fill deposits are important because they are major water-bearing and water-yielding units in the Central Highlands.

Stream alluvium overlies the basin fill in some areas and consists of stream-channel and flood-plain deposits of poorly sorted boulders, cobbles, gravel, sand, and silt. Stream alluvium is usually of limited lateral extent in narrow erosional canyons and is less than 100 ft thick (Montgomery and Harshbarger, 1989) but may provide water locally when it is saturated and hydraulically connected to the basin fill.

Basin and Range Lowlands

In the Basin and Range Lowlands, the bedrock of the mountains is exposed in the hills and mountains and is found at depth in the basins underlying the basin fill. Rocks in this category include Precambrian metamorphic and granitoid rocks; Paleozoic sandstone, limestone, and shale; Mesozoic granitoid, volcanic, and sedimentary rocks; and Cenozoic granitic, volcanic, and sedimentary rocks (Reynolds, 1988). For the purposes of this report, the sedimentary bedrock is not differentiated in this province because, like the bedrock of the mountains, it yields little water except locally where saturated at depth and from fractures or other zones of secondary permeability.

The sediments defined as basin fill are the major water-yielding deposits in the basins of this province. Basin fill is also the geologic unit with the most extensive outcrop pattern in the Basin and Range Lowlands (fig. 3). The basin fill typically consists of Cenozoic unconsolidated to weakly consolidated sand, silt, and clay with little organic material preserved in the sediments. In many of the basins, there are lateral and vertical gradations in the physical and hydrologic character of the basin fill. The early development of topographically closed, continental basins created a particle-size gradient with the coarser sediments being deposited at the basin margins and an increase in fine-grained material near the centers of the basins (fig. 4*B*).

Many investigators have divided the basin fill into two or more units based on lithology, grain size, stratigraphic position, and other factors; however, in general, Anderson and others (1992) recognize three units: (1) lower basin fill, (2) upper basin fill, and (3) stream alluvium (fig. 4*B*). For the purposes of this report, the stream alluvium is not included in the basin-fill unit. Evaporite and mudstone deposits several thousand feet thick are characteristic of the lower basin fill. This unit is more consolidated, deformed, and finer grained than the upper basin fill. The upper basin fill is typically unconsolidated to weakly consolidated, undeformed, and notably lacking in fine-grained mudstone and evaporite deposits (Anderson and others, 1992).

Also included in the basin fill, though distinct from the sediments described above, are the "Pre-Basin and Range sediments" of Anderson and others (1992, p. B14; fig. *4B*, this report). These moderately to well-consolidated, fine- to coarse-grained continental deposits overlie erosional bedrock surfaces in most of the basins, were faulted along with older bedrock during the Basin and Range disturbance (Anderson and others, 1992), and underlie the younger, undeformed basin fill described above. When these deposits occur at depth, they are presumed to contain large volumes of water in storage (Anderson and others, 1992). Where these rocks are exposed in the mountains, they are typically unsaturated and are included with the bedrock of the mountains in figure 3.

Stream alluvium in the Basin and Range Lowlands has a greater areal extent than in the Central Highlands province (fig. 3) and was deposited after the filling of the basins as the present drainage system was established. The deposits characterized here as stream alluvium largely consist of unconsolidated cobbles, gravel, sand, and silt. Stream alluvium is typically 100 ft thick or less; however, in the Phoenix area the thickness is 200 to 300 ft (Laney and Hahn, 1986). When saturated, the stream alluvium is a productive aquifer in the Basin and Range Lowlands. The unit is of additional importance because it easily accepts, stores, and transmits surface runoff thus aiding recharge of the basin fill.

Soils

Soils are the outermost surface of the land, and represent one of the most important natural resources in the State of Arizona because, according to Hendricks (1985, p. 1):

> "...Soils provide sustenance for animals and man and support buildings and highways, while contributing to the economies of our cities, the productivity of our farms and rangelands, and the vitality of our wildlife and wilderness areas..."

Climate, organisms (mostly vegetation), parent material, topography, and time are the factors that control soil formation. The type of soil formed in an area, to some degree, determines the land use. For example, thin, poorly drained soils formed over shallow bedrock are not suitable for crop growth and thus are not developed for agricultural land use.

Hendricks (1985) compiled a map showing soil associations for Arizona at a scale of 1:1,000,000. Soil associations are landscapes that have distinctive proportional patterns of major and minor soils. These soil associations are grouped according to temperature and precipitation similarities because these factors are important influences on the nature of the soil that forms. Soil-association maps also are available for the part of the study area in Mexico (Instituto Nacional de Estadistica, Geografia E Informatica, 1982a, b, 1984a, b).

One of the factors upon which soil associations are based is soil drainage. The speed with which water is removed from the soil surface and moves through the soil itself is the natural soil drainage (Hendricks, 1985). Soils can range from excessively drained to very poorly drained. Soils in the CAZB study area are between these two extremes (fig. 5) according to a digital map from the State Soil Geographic (STATSGO) data base of the Natural Resources Conservation Service (U.S. Department of Agriculture, 1994).

In the Central Highlands, the soils are predominantly moderately to poorly drained (fig. 5) because they are underlain by shallow bedrock. Soils typically are shallow to moderately deep (referring to the thickness of the soil profile), gravelly, and fine grained (Hendricks, 1985). Soils form on flood plains, alluvial fans, rolling hills, and steep slopes. Cooler mean annual soil temperatures (less than 8°C to 15°C) and more precipitation (10 to 16 in./yr) are characteristic of these soils compared with soils developed in the Basin and Range Lowlands. The primary land uses are rangeland, wildlife habitat, and recreation with some cropland and urban use. These soils are unsuitable for community development in many areas because of poor permeability, high shrink-swell potential, steep slopes, and shallow depth to bedrock.

In the Basin and Range Lowlands, moderately to well-drained soils predominate in the western half of the area (fig. 5) where typically deep soils

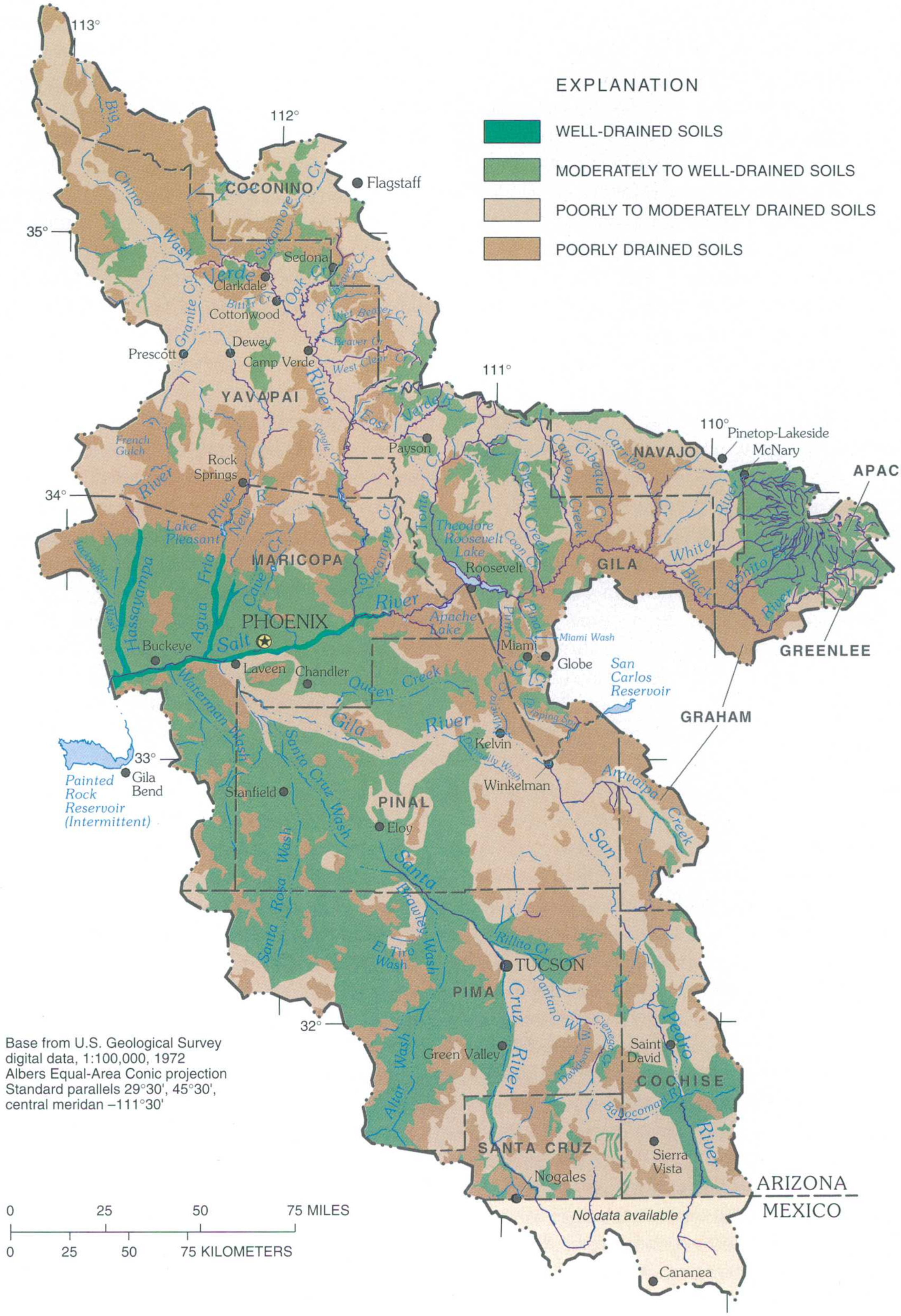


Figure 5. Drainage characteristics of soils, Central Arizona Basins study area (digital data from U.S. Department of Agriculture, 1994)

have formed over basin fill (fig. 3). Poorly drained soils are most abundant in the eastern half of the area, reflecting shallow soil development over extensive bedrock outcrops. In general, the soils are medium to fine grained, gravelly, and form on flood plains, gentle to steep slopes of old dissected alluvial fans and younger fan surfaces, and rock outcrops on hills and mountains (Hendricks, 1985). The mean annual soil temperatures typically range from 15°C to more than 22°C, and mean annual precipitation ranges from less than 10 to 16 in. Although rangeland and wildlife habitat are the major land uses by area, a substantial percentage of these soils are used as irrigated cropland and for urban land use.

The soils in the Basin and Range Lowlands are more conducive to growing crops than soils in the Central Highlands because of their fine-grained texture, which allows for greater water retention and warmer soil temperatures that encourage plant growth. Factors that limit the potential of these soils for community development in some areas include poor permeability, high lime content (caliche) or hardpan, moderate to high shrink-swell potential, steep slopes, and high gravel content (Hendricks, 1985).

Climate

The climate of the CAZB study area ranges from arid to semiarid and is characterized by its variability from place to place within the area and also by large differences in precipitation from one year to the next. Mean annual precipitation ranges from less than 10 in. on the lowest valley floors to more than 25 in. at some places in the mountains of the Central Highlands (Sellers and Hill, 1974; fig. 6, this report). Precipitation can be three times greater in wet years than in dry years at almost all locations, and wet years may have more than four times as much precipitation as dry years in the valleys of the Basin and Range Lowlands (fig. 7). Temperatures range from more than 46°C on summer afternoons in the lowest valleys to below -18°C on winter nights in the mountains.

Altitude is one of the most important controlling factors of climate in the CAZB study area. Precipitation increases and temperature decreases with increasing altitude during all seasons of the year. The large topographic relief within the study area contributes to the variability of precipitation and temperature. Mean monthly temperature and precipitation data for 1961 through 1990 at six weather stations of various altitudes in the study area (Owenby and Ezell, 1992) are shown in figure 6. Three of these stations, Buckeye, Casa Grande, and Tucson are in the Basin and Range Lowlands Province and the other three are in the Central Highlands Province. Diurnal temperature variations of 17°C or more are characteristic of the arid climate of the study area. Clear skies and low humidity allow heat to radiate away at night to a much greater degree than in a humid climate.

The quantity of runoff is also strongly influenced by altitude and is characterized by large differences from one year to the next. The larger quantity of rainfall and snowfall in the mountains of the Central Highlands Province gives rise to the major part of streamflow in the study area. Mean annual runoff for 1951 through 1980 ranged from less than 0.1 in. in the west-central part of the study area to more than 10 in. in the White Mountains (fig. 2) at the northeast boundary of the study area (fig. 8, this report; Gebert and others, 1987). The year-to-year variation in runoff is probably at least as great as the variation in total annual precipitation so average values shown in figure 8 may not be representative of any particular year.

Evaporation and the length of the growing season also are related to altitude and temperature. Average annual free water-surface evaporation (fig. 8) ranges from more than 65 in. in the western and central parts of the study area to less than 40 in. in the White Mountains (Farnsworth and others, 1982). The growing season, or 90 percent freeze-free period, can be expressed as the minimum number of consecutive days in which temperatures do not fall below 0°C in 9 out of 10 years. In the CAZB study area, this period is generally greater than 230 days in the valleys of the Basin and Range Lowlands Province, but it is less than 95 days at higher altitudes in the Central Highlands Province (Koss and others, 1988).

Commercial agriculture is concentrated in the valleys of the Basin and Range Lowlands Province where the growing season is longest and where multiple cropping during a single year can be practiced. Cotton, citrus, and other crops requiring

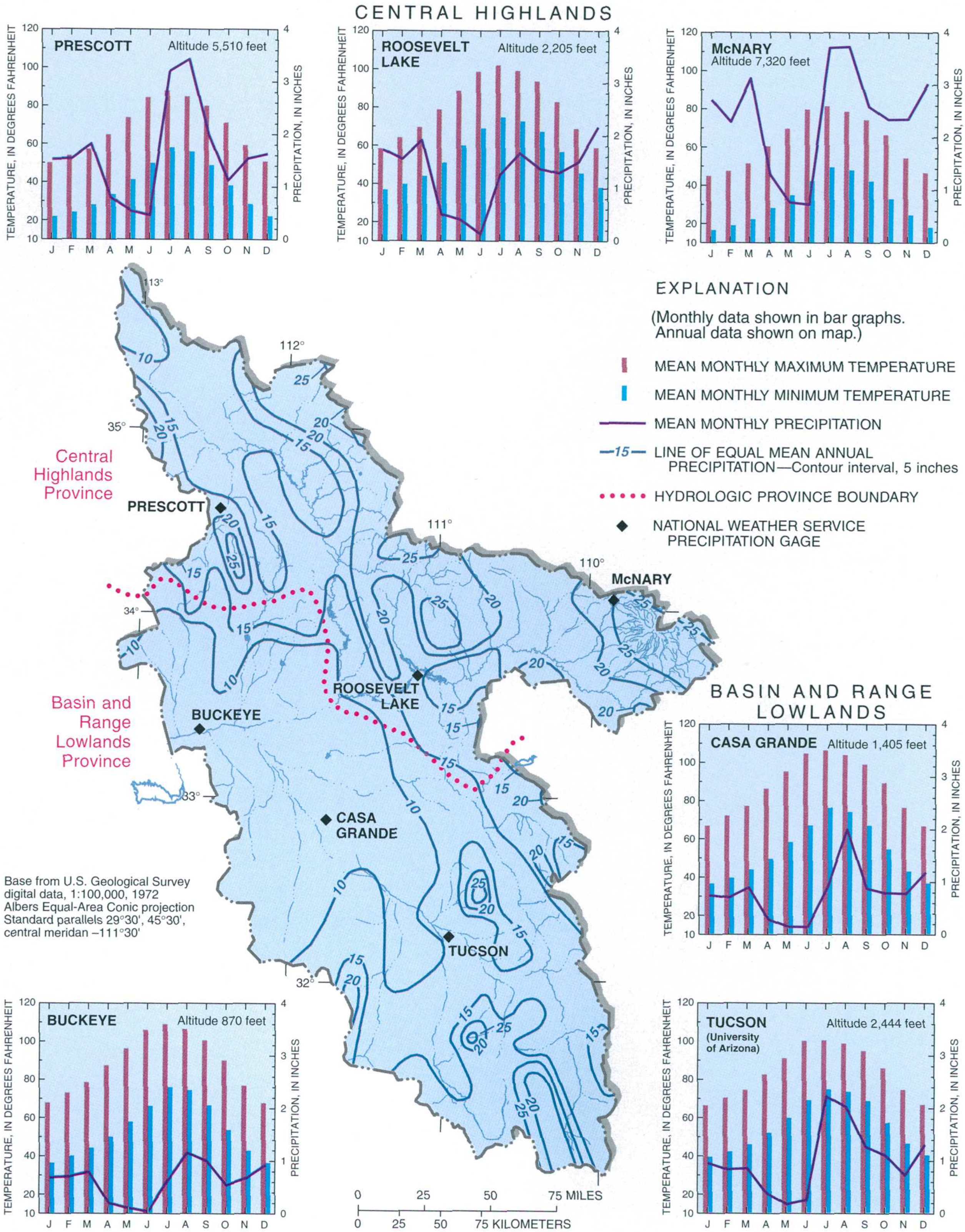


Figure 6. Mean annual precipitation, 1941–70; mean monthly precipitation; and mean monthly maximum and minimum temperatures for selected sites, 1961–90, Central Arizona Basins study area (precipitation, annual data modified from Sellers and Hill (1974); monthly data, Owenby and Ezell (1992); temperature, monthly data, Owenby and Ezell (1992); altitude, Sellers and Hill (1974)).

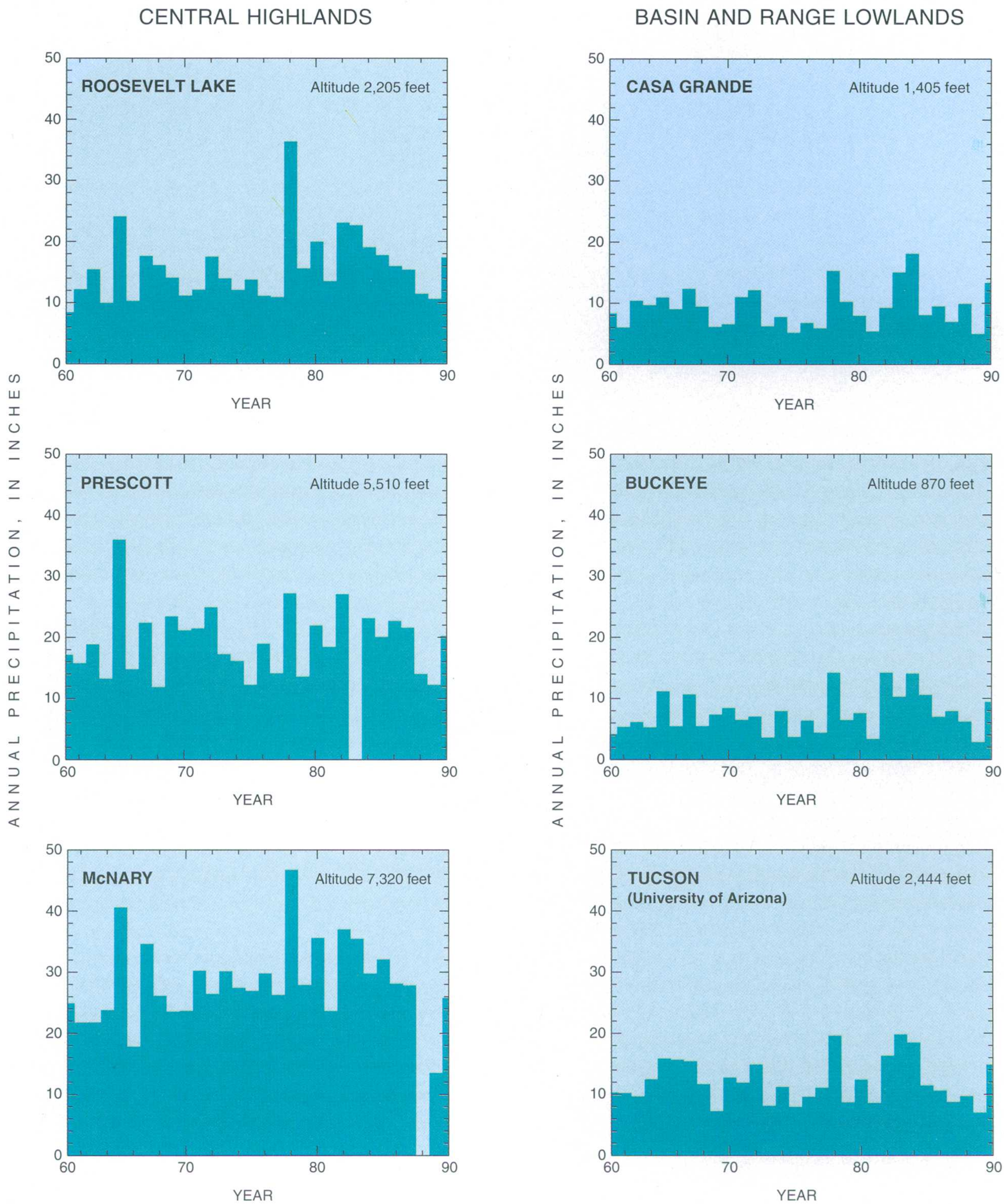


Figure 7. Total annual precipitation for 1961–90 at selected sites, Central Arizona Basins study area. Years with incomplete data are plotted as zero. Site locations shown in figure 6 (precipitation, annual data, National Climatic Data Center, 1960–90; altitude, Sellers and Hill, 1974).

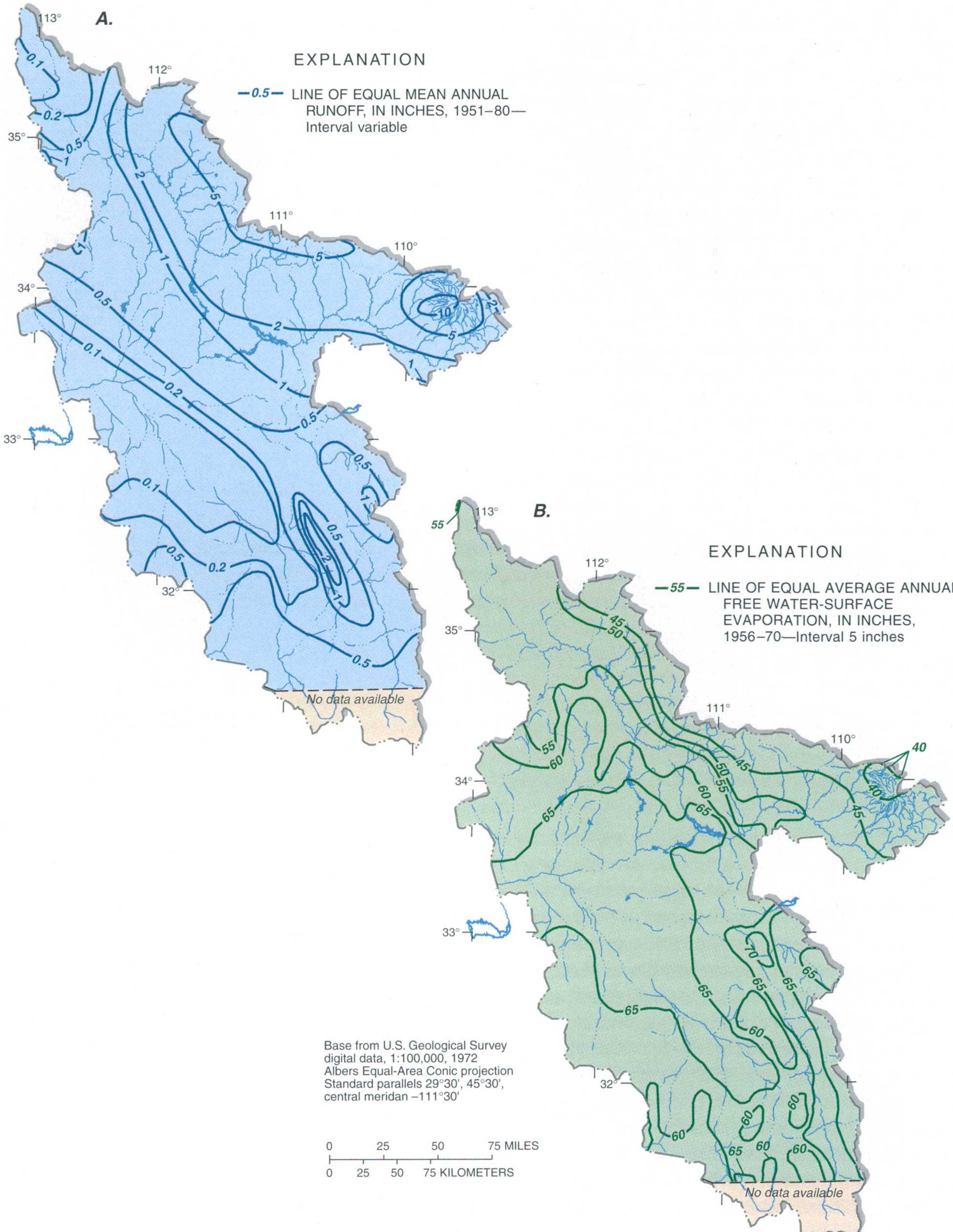


Figure 8. Mean annual runoff and evaporation, Central Arizona Basins study area. *A*, Mean annual runoff, 1951–80. *B*, Average annual free water-surface evaporation, 1956–70 (annual runoff, Gebert and others, 1987; evaporation modified from Farnsworth and others, 1982).

a long growing season are typical of the area. The high evaporation rates and low amounts of precipitation in the valleys of the Basin and Range Lowlands Province contribute to the need for large quantities of water for irrigation.

The CAZB study area is characterized by two rainy periods during the year separated by two dry periods. The best defined of these rainy periods occurs during July and August. The summer rains result from a northwestward flow of moist air from the Gulf of Mexico across Mexico into Arizona. These summer rains typically occur in the late afternoon or evening as convective thunderstorms. The storms are localized, typically last less than 30 minutes (Sellers and Hill, 1974), and are sometimes intense. The other rainy period runs from December through mid-March (Sellers and Hill, 1974) and includes snow at higher elevations. These winter storms are more widespread and result from moisture moving eastward from the Pacific Ocean into Arizona. Although the summer rains provide moisture to support the vegetation of the study area, it is the winter storms that provide the snowpack and the runoff that supplies most of the water to the reservoirs in the Central Highlands.

The dry period of May and June in both hydrologic provinces is well defined in most years, and little or no precipitation falls during that time (fig. 6). October and November also are dry but not as consistently dry as May and June.

Population

The majority of the population in the CAZB study area is in Arizona with a small percentage in Mexico. Arizona's population increased by about 35 percent between 1980 and 1990. Similarly, projections for the year 2000 are for a population of about 4.71 million (table 1), an increase of about 26 percent (Arizona Department of Water Resources, 1993). The warm arid climate, lower cost of living compared to many places in the Nation, and attractive tax and monetary incentives offered to industries who relocate have contributed to the population growth and increasing urbanization in central and southern Arizona. In addition, the population increases noticeably during the winter when retirees travel south for warmer weather.

South of the border in Mexico, population growth continues as residents of more rural parts of the country move to the border towns, such as Nogales, to work in factories and other industries. Population in the border town of Nogales, Mexico, increased by about 45,000 (69 percent) from 1981 to 1991, and an additional increase of about 45,000 people is expected by 2000 (table 1) as trade with Mexico increases and travel between the United States and Mexico becomes easier as a result of the North American Free Trade Agreement (NAFTA) between the two countries.

Phoenix, in Maricopa County, and Tucson, in Pima County, are the two largest and most densely populated cities in the study area (fig. 9). In 1990, Maricopa County's population constituted about 61 percent of the total for the study area, and Pima County's population was about 19 percent of the total. Population growth and urbanization in these areas are expected to continue into the next century with the proportions to the total population remaining about the same (table 1).

Land Ownership, Land Use, and Land Cover

Land in the State of Arizona is primarily owned by the Federal Government. Similarly, the CAZB study area has about 18,230 mi^2 of Federally owned land, which is almost 53 percent of the study area, and includes Native American reservation land—6,190 mi^2; national forests, national parks and monuments, wilderness areas, and wildlife refuges—9,190 mi^2; land held by the Bureau of Land Management—2,560 mi^2; and land designated for military use—about 290 mi^2. Most of the remainder of the study area is State, County, or municipally owned land with less than 5 percent of the study area in private ownership.

Rangeland is the major land use covering about 57 percent (19,800 mi^2) of the CAZB study area; forest covers 28 percent (9,810 mi^2); urban, 5 percent (1,800 mi^2); agriculture, 5 percent (1,800 mi^2); and less than 1 percent (320 mi^2) is transitional (quarries, bare rock, gravel pits, sandy areas, dry salt flats; fig. 10). The remaining

Table 1. County and city population totals for 1980 and 1990, and projections for 2000, Central Arizona Basins study area

[Percent of county area in the study area shown in parentheses. County and city population data from Valerie Rice, University of Arizona, Economic and Business Research Program, written commun. (1995); except data for city populations for 2000 from Arizona Department of Water Resources (1993); data for Phoenix from Maricopa Association of Governments (1997). Data for Sedona 1980, 1990, and 2000 from Lupe Galvez, Arizona Department of Economic Security, oral commun. (1995); data for Nogales, Mexico, from Lorey (1990)]

County	Population 1980	Population 1990	Percent change 1980–90	Projected 2000	Percent increase 1990–2000
Apache (9)	52,108	61,591	18	68,075	11
Cochise (32)	85,686	97,624	14	117,450	20
Coconino (12)	75,008	96,591	29	120,875	25
Gila (83)	37,080	40,216	8	47,900	19
Graham (18)	22,862	26,556	16	35,025	31
Greenlee (9)	11,406	8,008	-30	8,825	10
Maricopa (57)	1,509,175	2,122,101	41	2,741,950	29
Navajo (11)	67,629	77,658	15	87,775	13
Pima (56)	531,443	666,880	25	830,375	25
Pinal (99)	90,918	116,379	28	154,075	32
Santa Cruz (93)	20,459	29,676	45	36,950	25
Yavapai (67)	68,145	107,714	58	147,675	37
Total, CAZB	**2,571,919**	**3,450,994**	**34**	**4,396,950**	**27**
Mohave	55,865	93,497	67	154,325	65
La Paz	12,557	13,844	10	18,600	34
Yuma	76,205	106,895	40	139,975	31
Total, State	2,716,546	3,665,230	35	4,709,850	28

City	Population 1980	Population 1990	Projected 2000
Sierra Vista	24,937	32,983	38,373
Sedona	5,368	7,760	9,927
Globe	6,886	6,062	6,682
Payson	5,068	8,377	9,778
Phoenix	789,704	983,403	1,298,121
Tucson	330,537	405,390	455,703
Eloy	6,240	7,211	8,395
Nogales, Arizona	15,683	19,489	23,676
Prescott	19,865	26,455	32,636
Nogales, Mexico	[1]65,587	[2]110,851	155,740

[1]Data as of 1981.
[2]Data as of 1991.

4 percent of land-use types are wetlands, streams, lakes, and reservoirs that may hold varying quantities of water at any given time.

The digital land-use and land-cover geographic-information system data set for the CAZB study area was derived from the Geographic Information Retrieval and Analysis System (GIRAS) files dating from the mid-1970's (Mitchell and others, 1977). Using manual interpretation of National Atmospheric and Space Administration (NASA) high-altitude aerial photography and U.S. Department of Agriculture (USDA) National High-Altitude Photography products, together with earlier land-use maps and field surveys, multilayered digital-base maps were produced. These maps show vegetation, water, natural surface, and cultural features on the land surface. Digitization of these layers, along with adding feature attributes on the basis of the Anderson Level II Land-Use classification system, has produced a national land-use/land-cover data set at a resolution of 1:250,000 for most areas (Anderson and others, 1976). The CAZB land-use coverage has been updated with digital urban land-use data from the Maricopa Association of Governments, Pima County, and the University of Arizona.

Although rangeland covers the largest area, urban land uses, which include residential, commercial, industrial, and those used for transportation, communication, and utilities, are the fastest growing. Urban centers, especially Phoenix and Tucson, have had extensive population growth over the past decade (table 1),

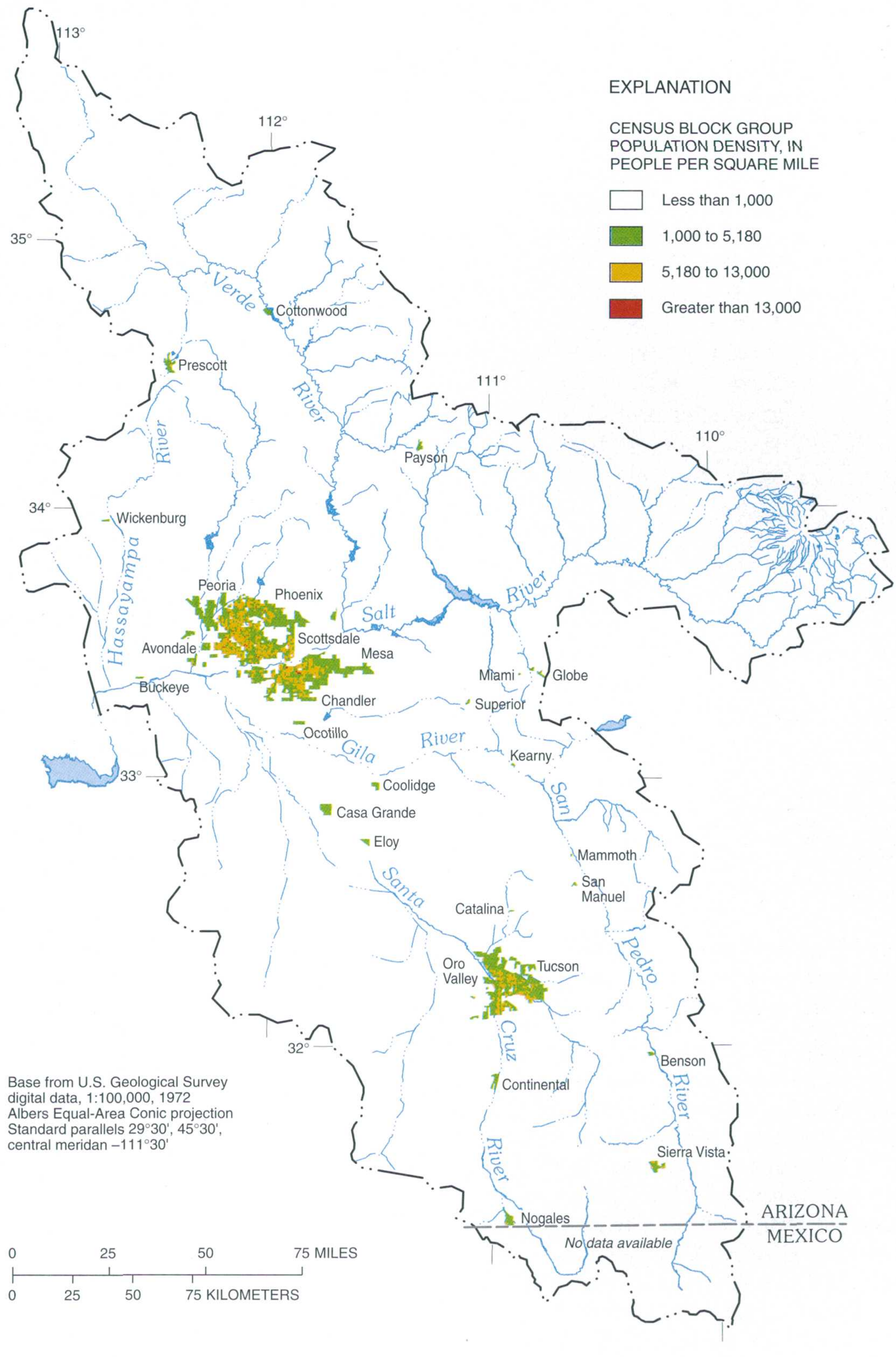


Figure 9. Population density, Central Arizona Basins study area (digital data from Hitt,1994).

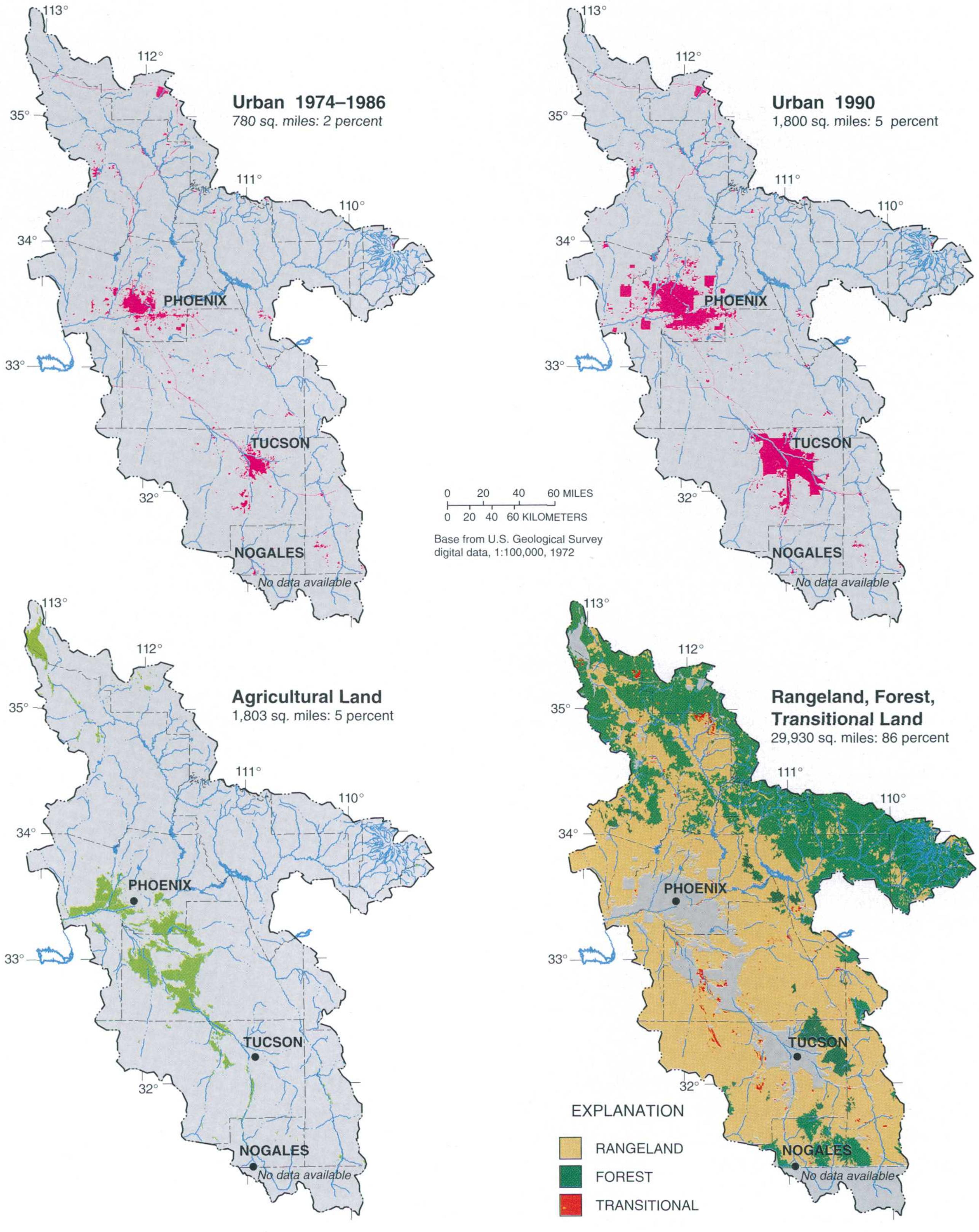


Figure 10. Distribution of major land-use classifications, Central Arizona Basins study area (digital data modified from Anderson and others, 1976; urban digital data for 1990 unpublished from Maricopa Association of Governments, Pima County, and the University of Arizona).

resulting in more than a twofold increase in urban land area from 1980 to 1990 (fig. 10).

This urban land-use "explosion" affects other land uses. Over the last decade, rangeland has decreased from about 20,600 to 19,800 mi^2, which is a 4-percent reduction. Agricultural areas, covering 1,800 mi^2, have decreased from about 1,900 mi^2 a decade ago, which is a 5-percent decrease. The main agricultural areas that have been affected by increased urban population and land use are in a corridor along the Santa Cruz River between Phoenix and Tucson (fig. 10) and the area west of Phoenix along the Gila River. The agricultural areas in the northern part of the study area (fig. 10) have not been as greatly affected by urban growth (Robert Hart, hydrologist, USGS, oral commun., 1995). The importance of these changes in land use are in the effects they can have on water use, water quantity, and water quality as discussed later in this report (see "Water Use" and "Overview of Water Quality").

Previously unrecognized, and therefore poorly documented, land uses affected by urban growth and agricultural and rangeland uses are wetlands and riparian areas. Wetlands and riparian areas commonly have high biodiversity, and in the arid Southwest, they also are of critical environmental importance as wildlife and fish habitats. Riparian habitats are those areas including "vegetation, habitats, or ecosystems that are associated with bodies of water (streams or lakes) or are dependent on the existence of perennial, intermittent, or ephemeral surface or subsurface water drainage" (Arizona State Parks, 1989). Riparian habitats include stream or lakeside areas used by wildlife for food, water, cover, or nesting/breeding purposes. Areally, riparian areas extend outward from the stream banks only as far as the water-bearing potential of the soils and geomorphology will support vegetation.

In the CAZB study area, distinct types of vegetation are associated with riparian areas in the Central Highlands, where streams are typically perennial, and in the Basin and Range Lowlands, where streams are intermittent or ephemeral (fig. 11). Along West Clear Creek (fig. 11), riparian vegetation consists of cottonwood/willow, mixed broadleaf, and mesquite that are confined to a narrow band of alluvium adjacent to the stream channel. In contrast, the vegetation along the San Pedro River (fig. 11) extends well beyond the stream channel, and reflects a broad alluvial flood plain. Notably, tamarisk is a major component on the San Pedro River along with mesquite and cottonwood/willow. Mixed broadleaf vegetation is absent.

In 1993, Arizona had about 5,022 mi of perennial streams that supported riparian areas (Arizona Game and Fish Department, 1993) of which 2,590 mi are in the study area (fig. 11). Riparian areas have been decreasing in size and number in Arizona as a result of a number of factors that include urban growth, loss of perennial streamflow resulting from increased use of surface-water and ground-water resources, cultivation of land for agricultural use, and overgrazing of rangeland.

Conversely, urban growth also has indirectly resulted in the re-establishment or retention of some riparian areas in the southern part of the study area where natural perennial flows ceased in the early 20th century. Perennial flow is now supplied by the discharge of treated sewage effluent downstream from wastewater-treatment plants. Most notably, the stretches of the Santa Cruz River from Nogales, Arizona, north to Tubac and from Tucson north to Marana, as well as the Salt and Gila Rivers downstream from the wastewater-treatment plants at 23rd Avenue and 91st Avenue in Phoenix are sections that have riparian communities sustained by effluent discharge to the riverbed. These stream reaches are referred to as effluent-dependent streams.

Water Use

Water use in the CAZB study area is a significant component of the hydrologic budget. Water demand is met by supplementing surface-water supplies with ground water, water imported from the Colorado River by the Central Arizona Project (CAP) canal (fig. 12), and to a small degree by reuse of treated sewage effluent. Large volumes of water are diverted from the Gila, Salt, and Verde Rivers and can be transported through canals several tens of miles to the location of use. Ground water may be used near a well, or it may be transported several miles through a canal to its place of use.

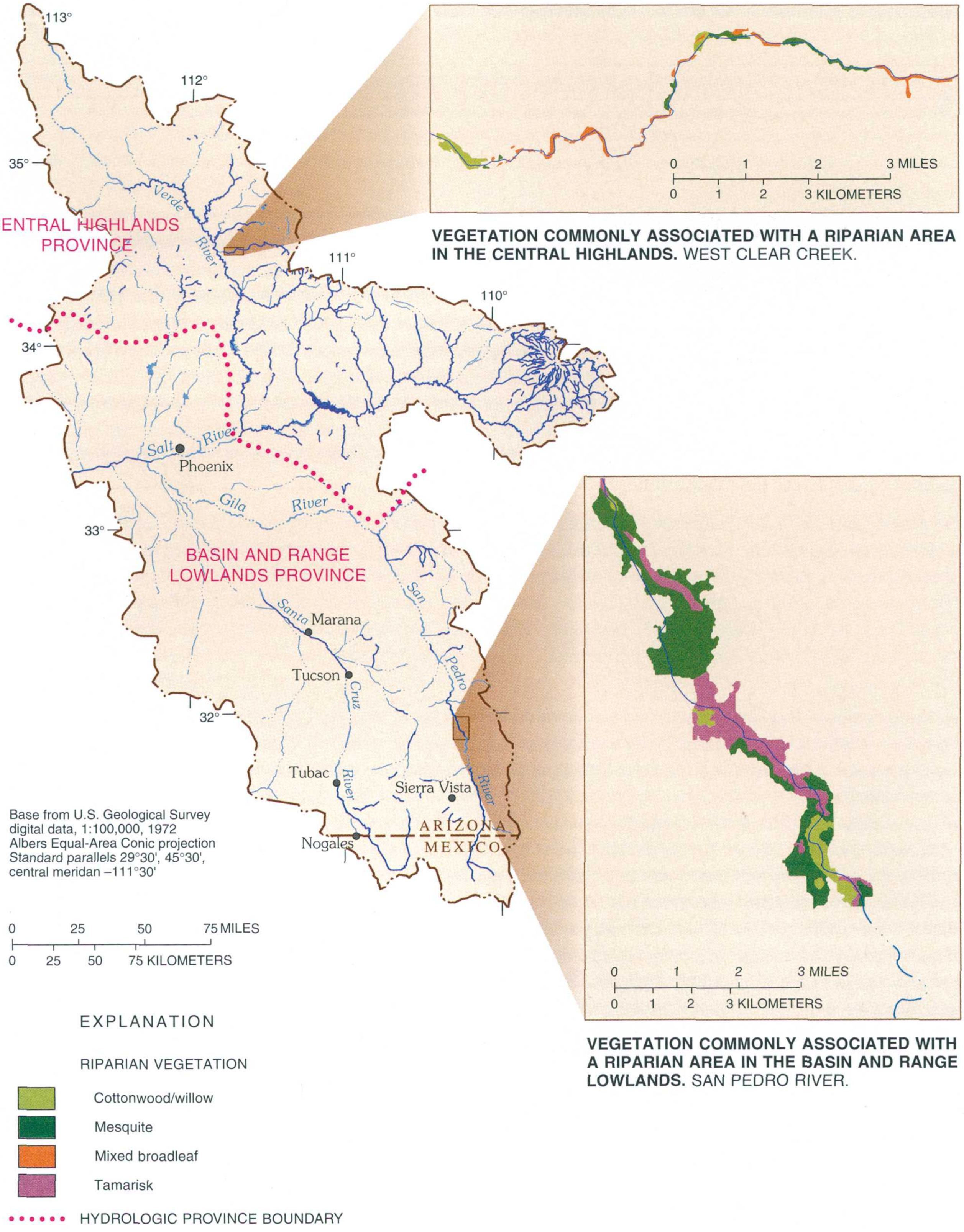


Figure 11. Riparian vegetation, Central Arizona Basins study area.

Figure 12. Principal perennial and intermittent or ephemeral rivers, streams, and washes, and related surface-water development features, Central Arizona Basins study area (perennial reaches, Arizona Game and Fish Department, 1993).

Water development in the CAZB study area began about 300 B.C. when the Hohokam Indians diverted water from the Salt River into hand-dug canals for crop irrigation (Baker and others, 1973). Intense surface-water development began in 1905 with the construction of Roosevelt Dam (fig. 12) on the Salt River. In later years, five other reservoirs were constructed on the Salt and Verde Rivers. They are now operated by the Salt River Project (SRP). Water stored in these reservoirs is ultimately diverted below the confluence of the Salt and Verde Rivers at the Granite Reef Diversion Dam east of Phoenix (fig. 12). On the basis of data from annual reports by the SRP and USGS, such as Salt River Project (1992) and Boner and others (1991), respectively, an average of about 85 percent of the total annual flow to Granite Reef Dam was diverted from the Salt River from 1935 to 1990.

Reservoir storage capacity in the CAZB study area has increased tremendously since the beginning of the 20th century, and there is currently (1995) about 3.8 million acre-ft of storage in the eight major reservoirs (table 2). Surface water from the Gila River is stored in San Carlos Reservoir and is diverted for irrigation at the Ashurst-Hayden Diversion Dam (fig. 12). According to data from the Gila Water Commissioner (1995), from 1937 to 1994, an average of 84 percent of the total annual flow at Ashurst–Hayden Dam was diverted from the river.

The Ashurst-Hayden and Granite Reef Diversion Dams are the two sites with the largest surface-water diversions in the study area. In fact, during 1990, about 80 percent of all nonimported surface-water withdrawals occurred at these two sites. The remaining 20 percent was diverted from the Agua Fria River to the Beardsley Canal near Phoenix (fig. 12), and from several small diversions in the Black, Gila, San Pedro, upper Verde, and upper Salt River watersheds.

Ground-water resources were initially developed by early settlers with hand-dug wells. Improvements in technology during the first half of the 20th century encouraged ground-water development (fig. 13). Annual ground-water withdrawals in the study area increased steadily from 100,000 acre-ft in 1915 to more than 4 million acre-ft in 1953 (Anning and Duet, 1994). Annual ground-water withdrawals remained high from the 1950's through the mid-1970's after which withdrawals began to decline. The decline in ground-water use may be the result of several factors including decreasing crop acreage and, thus, decreasing water demand; and several years of higher-than-normal precipitation.

Ground-water overdraft is a serious problem in the Basin and Range Lowlands Province. Many

Table 2. Major surface-water dams and reservoirs, Central Arizona Basins study area

[Source: Boner and others (1991); and Governor's Central Arizona Project Advisory Committee (1993). NA, not applicable]

River basin	Reservoir	Dam	Capacity (acre-feet)	Year of completion
Gila River	San Carlos Reservoir	Coolidge	867,000	1928
Gila River	NA	Ashurst-Hayden Diversion Dam	NA	1928
Gila River	NA	Gillespie (diversion dam)	NA	1921
Salt River	Theodore Roosevelt Lake[1]	Theodore Roosevelt	1,337,000	1911
Salt River	Apache Lake	Horse Mesa	245,000	1927
Salt River	Canyon Lake	Mormon Flat	58,000	1925
Salt River	Saguaro Lake	Stewart Mountain	70,000	1930
Verde River	Horseshoe Lake	Horseshoe	131,000	1946
Verde River	Bartlett Lake	Bartlett	178,000	1939
Salt River	NA	Granite Reef Diversion Dam	NA	1908
Agua Fria River	Lake Pleasant[2]	Waddell	158,000	1927
Agua Fria River	New Waddell Reservoir	New Waddell	908,000	1992

[1]Capacity increased to 1,609,000 acre-feet in 1996.

[2]New Waddell Dam was constructed to increase the capacity of Lake Pleasant in order to store imported CAP water.

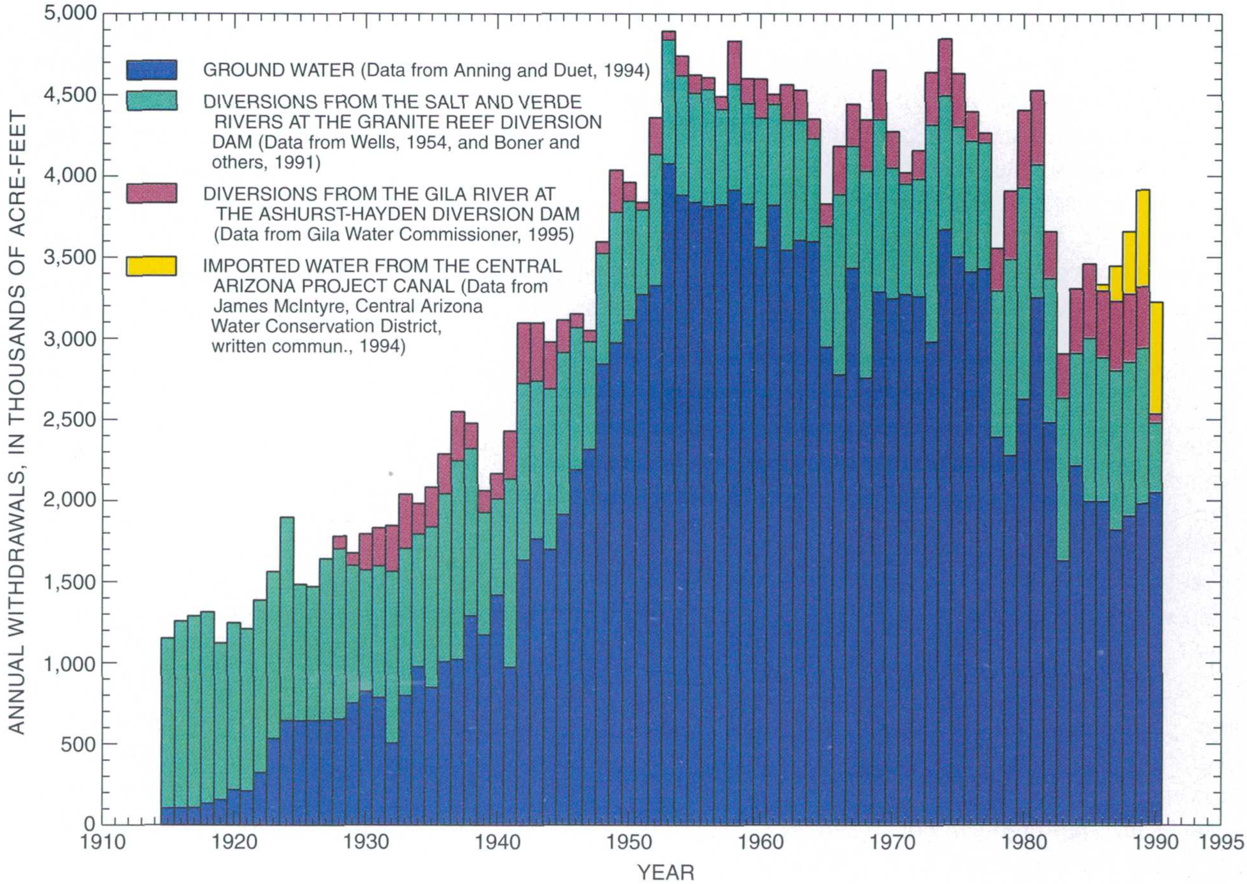


Figure 13. Annual ground-water withdrawals and major surface-water diversions, Central Arizona Basins study area, 1915–90.

streams that were once perennial are now dry because of extensive ground-water pumping. As water levels decline, increased energy consumption and costs are incurred when pumping from greater depths; and when water tables decline below pumps, wells go dry unless they are deepened. In addition, land subsidence and earth fissures may develop as a result of soils settling after dewatering from excessive pumping of water.

The Central Arizona Project (CAP) was developed to mitigate ground-water overdraft by providing an alternate source of water for agricultural and urban uses. The CAP is a 337-mile-long, concrete-lined canal bringing water from the Colorado River through Phoenix to Tucson (fig. 12). CAP deliveries in the study unit began in 1986 (fig. 13), and were as much as 688,000 acre-ft/yr in 1990 (James McIntyre, Central Arizona Water Conservation District, written commun., 1994).

Another source of water used to help mitigate ground-water overdraft is treated sewage effluent. In 1990, treated sewage effluent, used for agriculture or turf irrigation, represented 5 percent of all water used in the study area.

The predominant use of water in the CAZB study area is for agriculture. Seventy-three percent of all water withdrawn during 1990 was used for agricultural purposes—433,000 acre-ft from surface water, 1,530,000 acre-ft from ground water, 538,000 acre-ft imported by the CAP, and 197,000 acre-ft from effluent. About 97 percent of the agricultural water is used for the irrigation of crops, and the remainder is used for livestock watering.

Crop acreage within the study area (fig. 14) can be roughly approximated by adding together acreages from Maricopa, Pima, Pinal, Santa Cruz, and Yavapai Counties. Maricopa County includes several thousand acres, mostly cotton, outside the study area near Gila Bend. Cotton is the major crop covering 362,000 acres (about 565 mi^2; fig. 14). Nearly all crops in Arizona are irrigated;

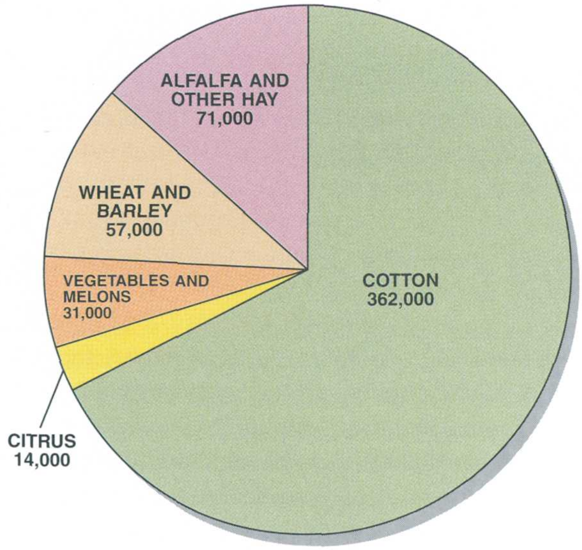


Figure 14. Estimated crop acreage, Central Arizona Basins study area, 1990 (Arizona Agricultural Statistics Service, 1991).

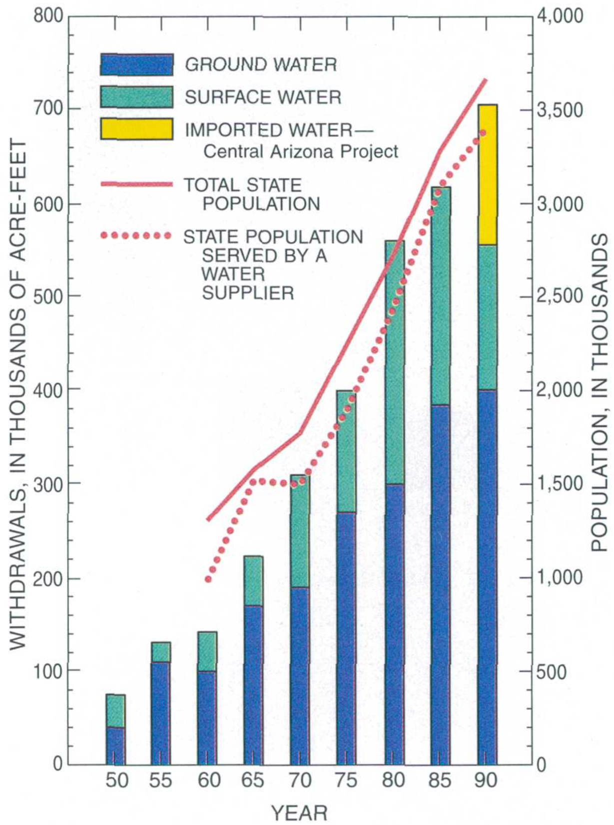


Figure 15. Population and municipal water use in Arizona, 1950–90 (MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988, 1993; James McIntyre, Central Arizona Water Conservation District, written commun., 1994).

surface-gravity techniques with ditches are used to irrigate about 90 percent of the acreage, and 10 percent is irrigated by either sprinkler or drip systems (Irrigation Journal, 1995).

Municipal water use is increasing as urban areas grow and replace agricultural land in the Phoenix and Tucson metropolitan areas (fig. 15). Most of the increase occurred within the study area. The increased municipal demand has been met with increased surface-water, ground-water, and imported-water deliveries. Increasing surface-water deliveries for municipal use in the Phoenix metropolitan area was possible by decreasing agricultural deliveries. Municipal surface-water and ground-water supplies were augmented with CAP water, which was first delivered to residents in the Phoenix metropolitan area in 1986 and to residents in the Tucson metropolitan area in 1992.

Industrial use accounts for about 6 percent of all water used in the study area. Industrial water is primarily used for electric-power production, metallic-ore extraction and refining, and for general industrial purposes. Ground water supplied 94 percent of the industrial demand in 1990.

Water-use patterns differ between the Central Highlands Province and the Basin and Range Lowlands Province (fig. 16). Only 4 percent of all water used during 1990 in the study area was used in the Central Highlands Province, with the remaining 96 percent being used in the Basin and Range Lowlands Province where most of the agricultural and municipal water use occurs. In 1990, about 20 percent of the water used in the Basin and Range Lowlands Province was surface water; whereas, in the Central Highlands Province, about 60 percent was surface water. Twenty-five percent of the water demand in the Basin and Range Lowlands Province is met with alternative water supplies of CAP water and treated sewage effluent; whereas, only 1 percent of the water demand in the Central Highlands is met with effluent. CAP water is not provided in the Central Highlands. Although agriculture is the major use of water in both provinces, municipal use is greater than industrial use in the Basin and Range Lowlands Province; whereas, in the Central Highlands, industrial use is greater than municipal use.

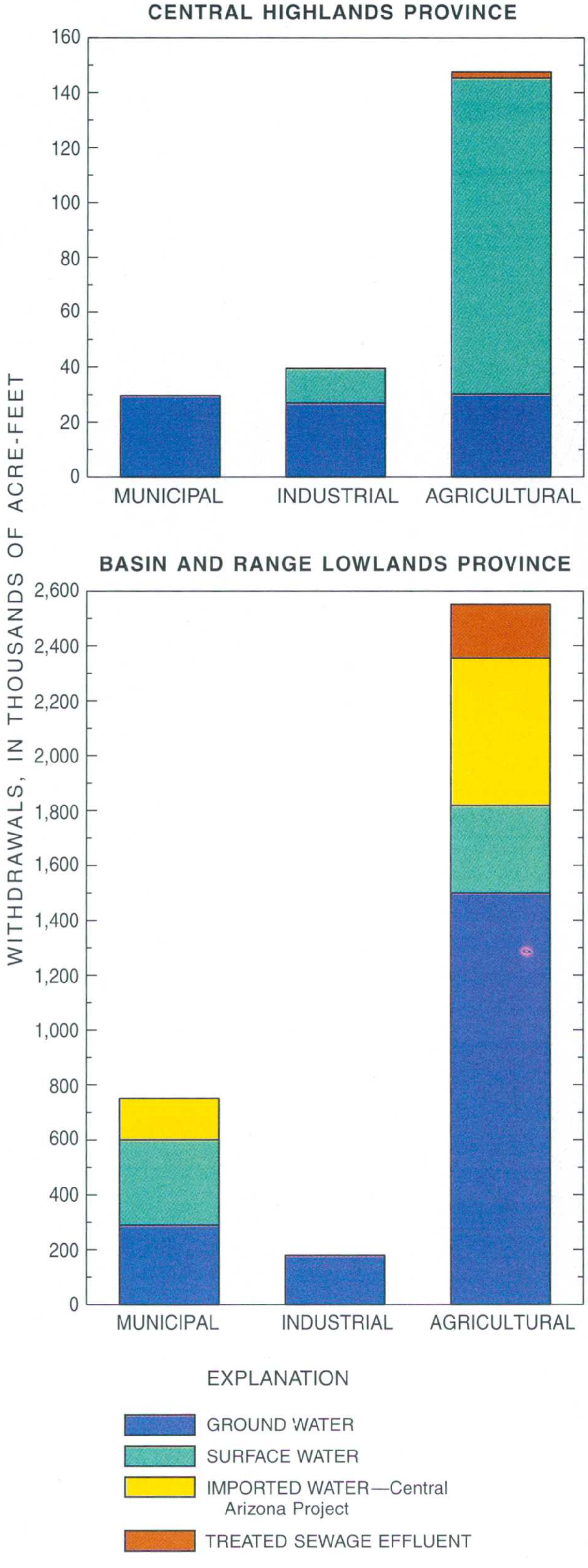


Figure 16. Total annual water withdrawals by hydrologic province, water source, and type of use, Central Arizona Basins study area, 1990.

Ecoregions

Ecoregions are geographic areas that are ecologically similar. Naturally occurring biotic assemblages would be expected to differ among ecoregions but generally would be similar within a given ecoregion. Ecoregions are mapped on the basis of associations of biotic and environmental factors that directly or indirectly determine the structure and function of ecosystems (U.S. Department of Agriculture, 1993). These factors include physiography, climate, soils, hydrology, and potential natural communities. The CAZB study area includes parts of four ecoregion provinces (fig. 17). The Chihuahuan Semi-Desert Province (11.2 percent of the study area) is in the southeastern part of the study area and the American Semi-Desert and Desert Province (43.9 percent) is in the southwest. These two ecoregions closely correspond to the Basin and Range Lowlands hydrologic province (fig. 17). The northern part of the area is composed of the Colorado Plateau Semi-Desert Province (29.2 percent) and the Arizona/New Mexico Mountains Semi-Desert/Open Woodland/ Coniferous Forest/Alpine Meadow Province (15.7 percent). These two ecoregions are included in the Central Highlands hydrologic province (fig. 17). Characteristics of the four ecoregions are shown in table 3.

Hydrologic System

In the 1980's, the USGS completed a series of regional studies of the surface-water and ground-water resources in the "Southwest Alluvial Basins" as part of the Regional Aquifer-System Analysis (RASA) program, which included most of the CAZB study area. Several publications that describe the geohydrology and water resources (Anderson and others, 1992; Anderson, 1995), geochemistry of ground water (Robertson, 1991), distribution of aquifer materials (Freethey and others, 1986), predevelopment-hydrologic conditions (Freethey and Anderson, 1986), and simulation of ground-water flow (Anderson and Freethey, 1996) in alluvial basins are valuable in understanding the hydrology of the CAZB study area.

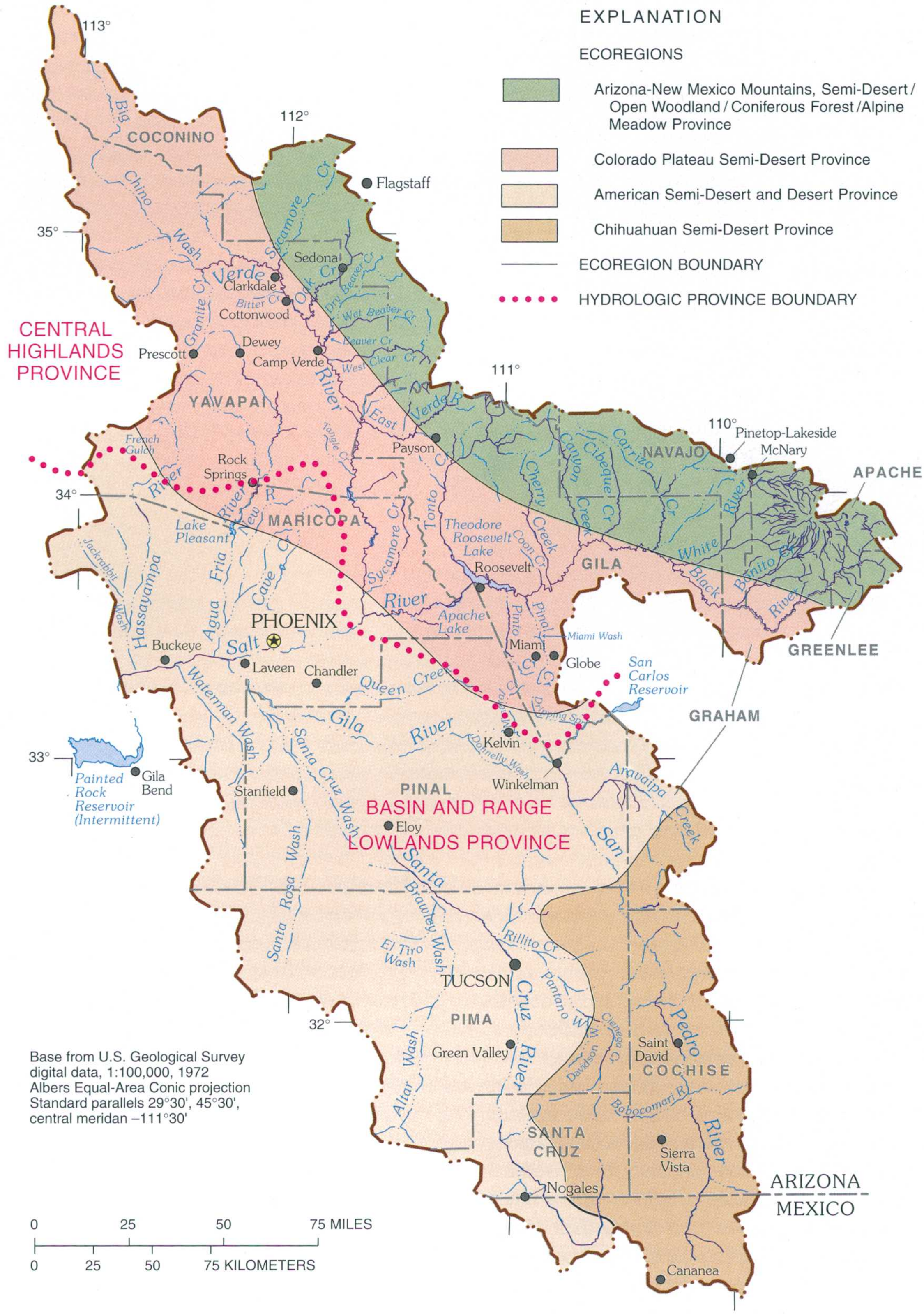


Figure 17. Ecoregions, Central Arizona Basins study area (Bailey and others, 1994).

Table 3. Characteristics of ecoregions, Central Arizona Basins study area

[Data from Bailey and others (1994). °F, degrees Fahrenheit]

Criterion	Chihuahuan Semi-Desert Province	American Semi-Desert and Desert Province	Colorado Plateau Semi-Desert Province	Arizona-New Mexico Mountains Semi-Desert/Open Woodland/Coniferous Forest/Alpine Meadow Province
Geomorphology	Plains, isolated mountains	Plains with isolated mountains	Mountains, hills, scarps, plains	Mountains, plains, hills
Stratigraphy/lithology	Paleozoic-Cenozoic complexes, alluvium	Cenozoic nonmarine sedimentary, granitic, and alluvial	Precambrian, Quaternary volcanics	Cenozoic volcanics, Mesozoic sedimentary
Soil taxa (temperature, moisture regimes)	Entisols, Aridisols (Thermic, Aridic)	Aridisols, Entisols (Thermic, Aridic)	Inceptisols, Entisols (Mesic, Thermic, Ustic)	Alfisols, Inceptisols (Frigid, Cryic, Udic)
Potential natural vegetation	Trans-Pecos desert shrub, Grama-tobosa prairie	Palo verde, creosote bush-bursage	Chaparral, pinyon-juniper, ponderosa pine	Ponderosa pine, gambel oak, white fir, Douglas fir
Elevation (feet)	2,600–8,500	300–3,500	3,000–7,400	6,000–12,600
Precipitation (inches)	8–13	3–8	10–25	20–32
Mean annual temperature (°F)	55–64	61–75	40–70	32–45
Growing season (days)	200–240	250–350	70–170	50–110
Surface-water characteristics	Few intermittent streams	Seasonal flowing streams	Few streams and rivers	Few perennial streams
Disturbance (land use)	Drought (range)	Flash floods (urban, range)	Fire, floods (range, agriculture)	Fire (forestry, range)

Surface Water

Surface water in central Arizona is a limited resource. All base flow is appropriated—and in many instances, overappropriated—for agricultural, municipal, and industrial (including mining) uses. Major surface-water-quantity issues in Arizona include adjudication of water rights in the Gila and Little Colorado River Basins, quantification of Native American water rights, flooding, and the interaction of surface-water and ground-water systems (Anderson and White, 1986). The re-establishment and maintenance of riparian communities is an issue that has gained importance in recent years. All surface water in the CAZB study area is tributary to the Gila River in the reach between Coolidge Dam and the Gila River above Gillespie Dam (fig. 12). Almost all water tributary to the Gila River that leaves the Central Highlands in the Salt, Verde, and Agua Fria Rivers is captured as it enters the Basin and Range Lowlands and is distributed. The distribution network includes four reservoirs on the Salt River, two on the Verde River, one on the Gila River, and one on the Agua Fria River (fig. 12, table 2).

The CAZB study area is unique when compared to less arid basins in that it has a mean surface-water outflow of only 528 ft^3/s from a total drainage area of 49,650 mi^2 (30 percent of which is outside the study area). The largest rivers—the Gila, Salt, and Verde—are perennial near their headwaters but become intermittent farther downstream because of impoundments and artificial diversions. Seasonal variations in streamflow losses to ground-water recharge and evapotranspiration further contribute to depletion of base flow. Consequently, average annual flow per square mile of contributing drainage area is only 0.011 $(ft^3/s)/mi^2$—one of the lowest runoff rates in the nation.

Altitude directly affects the quantity of precipitation and recharge to a basin (Anderson and others, 1992). The perennial streams with the largest base flows are in the Central Highlands Province. In the Basin and Range Lowlands, perennial streams are found in the mountainous higher elevations; whereas, the wide, braided, and often incised stream channels in broad alluvial basins are typically intermittent or ephemeral.

Streamflow variability within the study area is best illustrated by a comparison of two drainage basins of similar size—one in each hydrologic province. The Salt River at the streamflow-gaging station near Chrysotile (fig. 18, site 8) cuts through a narrow bedrock canyon draining the steep terrain along the Mogollon Rim in the Central Highlands. Mean annual discharge is 679 ft^3/s, and the maximum recorded discharge is 76,600 ft^3/s on January 8, 1993, from a drainage area of 2,849 mi^2 (Smith and others, 1995). The San Pedro River, in the Basin and Range Lowlands province, crosses an alluvial basin that is long and narrow, and landforms range from steep mountains to broad rolling plains. The streamflow-gaging station, San Pedro River near Redington (fig. 18, site 2), has no flow at times in most years for a comparable drainage area of 2,927 mi^2 (Smith and others, 1995). Because of lower elevation and less precipitation and runoff (Gebert and others, 1987; Anderson and White, 1986), the mean annual discharge of 43.7 ft^3/s (Smith and others, 1995) is about 15 times less than that of the Salt River. The maximum recorded discharge of 90,000 ft^3/s on September 28, 1926, for the San Pedro River near Redington is greater than that of the Salt River near Chrysotile.

Runoff, base-flow discharge, and the frequency and duration of floods are substantially greater in the Central Highlands, although the maximum peaks of flood events in both regions tend to be similar. Peak flows in rivers and streams in the Central Highlands occur from January through April and possibly into May from snowmelt off the Mogollon Rim (fig. 18, sites 9 and 12). In contrast, peak flows in the Basin and Range Lowlands tend to occur during the summer thunderstorm season in July and August (fig. 18, site 1). Flow in the major rivers—the Gila, Salt, and Verde—is not representative of natural flow in the Basin and Range Lowlands because flows are regulated, and peak discharges are artificially created. Major streams in both regions can be gaining (ground water discharging to the stream) or losing (streamflow recharging ground water) streams at different times of the year and from year to year.

Surface-water hydrology of major watersheds in the study area are discussed below in terms of hydrologic province. The Central Highlands encompass the rivers with the largest streamflow in the study area—the Salt and Verde Rivers—as well as perennial reaches of the upper Agua Fria and Hassayampa Rivers. Within the Basin and Range Lowlands, tributaries to the Gila River include the San Pedro and Santa Cruz Rivers and the lower Agua Fria and Hassayampa Rivers. Locations of streamflow-gaging stations and long-term variations in streamflow at representative gaging stations are shown in figure 18. Streamflow summary statistics and other pertinent information are given in table 4.

Central Highlands

The Salt River is the largest tributary to the Gila River (fig. 18) and begins at the confluence of the Black and the White Rivers in the mountainous eastern part of the study area. The Salt River is free flowing above Roosevelt Lake and has an average annual discharge of 923 ft^3/s (table 4) at the streamflow-gaging station on the Salt River near Roosevelt, Arizona (fig. 18, site 9; Smith and others, 1995). Tonto Creek, which also drains into Roosevelt Lake, has an average annual discharge of 163 ft^3/s (Smith and others, 1995). Downstream from Roosevelt Lake, the flow of the Salt River is controlled by a series of three more dams (fig. 12; table 2) and reservoirs built during 1905 to 1930. The highest recorded flood in Arizona history was a peak discharge of 300,000 ft^3/s in Phoenix during February 18–26, 1891 (Eychaner and Rehmann, 1991), and several floods have exceeded 100,000 ft^3/s in recent years.

The Verde River is the largest tributary of the Salt River and has an average annual discharge of 590 ft^3/s (table 4) below Tangle Creek above Horseshoe Dam (Smith and others, 1995). Perennial flow in the Verde River begins near Granite Creek (fig. 12) and is continuous for 140 miles to its confluence with the Salt River. At Granite Reef Dam near Phoenix, the entire base flow of the Salt and Verde Rivers is diverted for water supply in Phoenix and irrigation of about 250,000 acres in the Salt River Valley (Anderson and White, 1986).

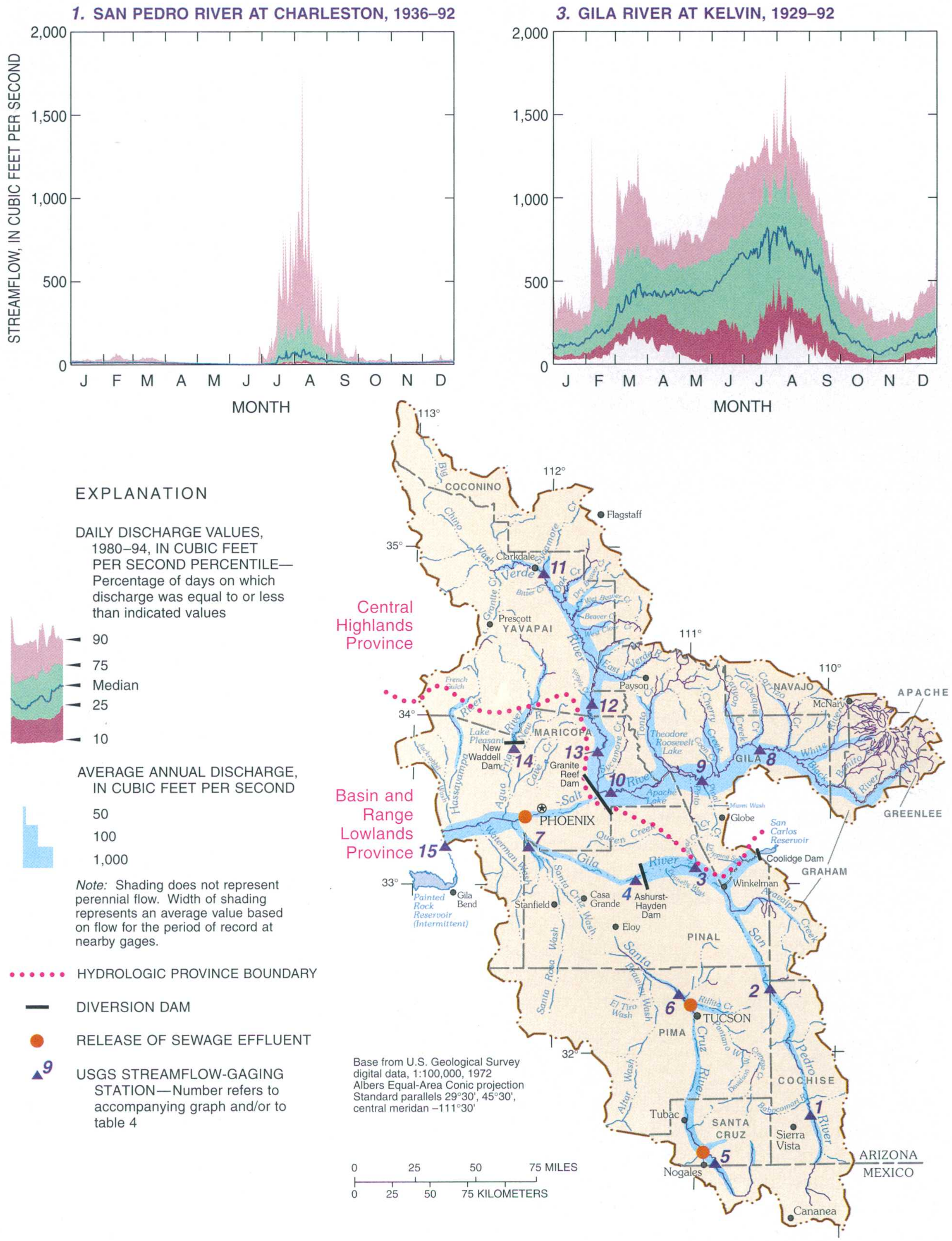
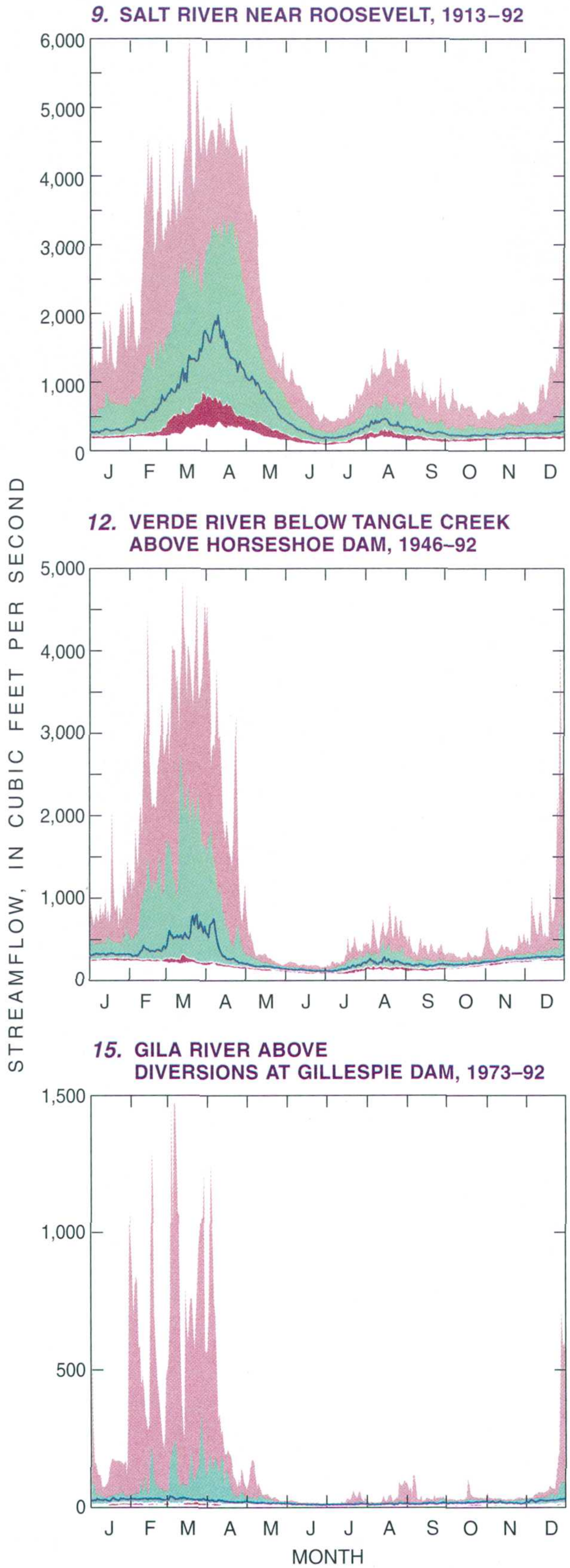


Figure 18. Daily discharge values and annual mean discharge at selected sites, average annual discharge of principal rivers, and locations of streamflow-gaging stations, Central Arizona Basins study area (average discharge for period of record, Smith and others, 1995).



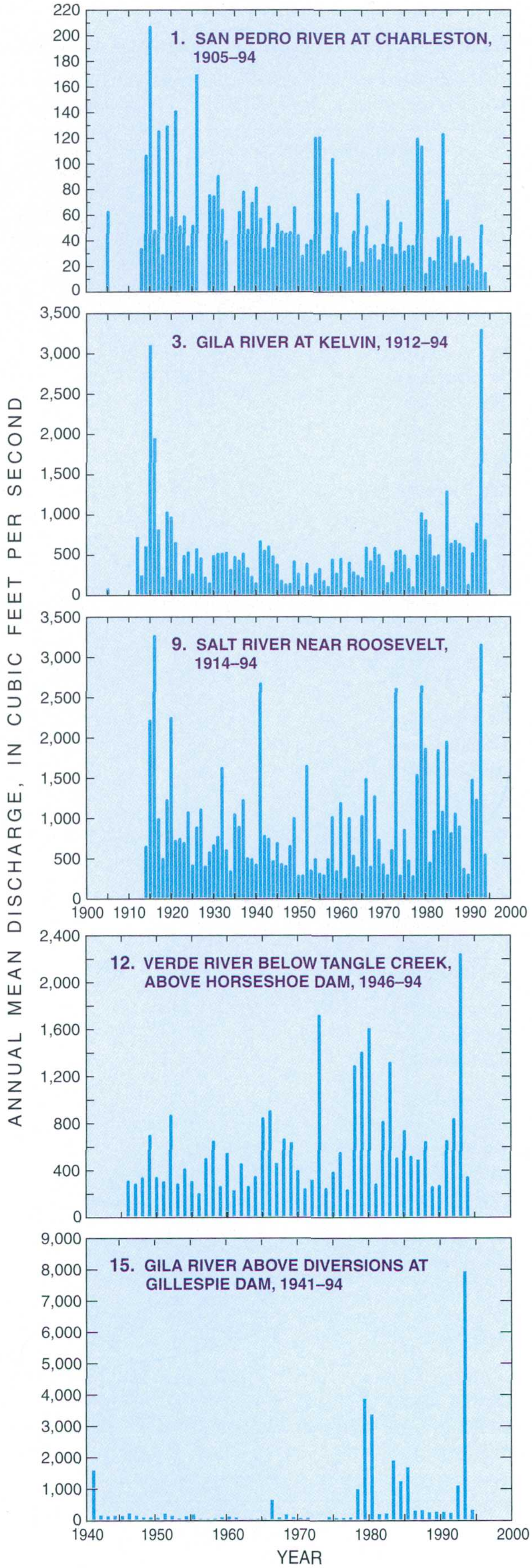


Figure 18. Continued.

Table 4. Selected streamflow characteristics of principal river basins, Central Arizona Basins study area

[Data from White and Garrett (1982); Smith and others (1994); Smith and others (1995); Gila Water Commissioner (1995). mi^2, square miles; ft^3/s, cubic feet per second; ---, not available; NA, not applicable; <, less than; >, greater than]

Streamflow-gaging station				Streamflow characteristics				
Station name and number	Site number on figure 18	Drainage area (mi^2)	Period of record, water years	Minimum daily discharge (ft^3/s)	Average annual discharge[1] (ft^3/s)	Maximum recorded discharge (ft^3/s)	Degree of regulation	Remarks
San Pedro River at Charleston (09471000)	1	1,234	1905, 1913–94	0.22	57.0	98,000	None	Diversions above station for irrigation of 3,200 acres in 1978, mostly by pumping of ground water, excluding unknown amounts in Mexico.
San Pedro River near Redington (09472000)	2	2,927	1944–46, 1951–94	No flow at times in most years	43.7	90,000	None	Diversions above station for 10,800 irrigated acres in 1978, excluding unknown amount in Mexico.
Gila River at Kelvin (09474000)	3	18,011	1911–94	No flow	538	100,000	Appreciable since 1928	Flow is regulated upstream at Coolidge Dam. San Pedro contributes majority of unregulated flow.
Florence-Casa Grande Canal (09475500)	4	NA	1936–94	No flow	335	1,290	Canal	Diversions for irrigation of as much as 100,000 acres.
Santa Cruz River near Nogales (09480500)	5	533	1913–22, 1930–34, 1935–94	No flow at times in most years	28.2	31,000	None	Diversion above station in Mexico for irrigation and municipal water supply.
Santa Cruz River at Ina Road near Tucson (09486490)	6	3,489	1991–92	44	72.4	---	Release of treated effluent	Most of base flow is effluent from municipal sewage-treatment plant.
Santa Cruz River near Laveen (09489000)	7	8,581	1940–46 1948–94	No flow most of the time	21.6	33,000	Agricultural returns	Much of the flow passing station is drainage, wastewater return, and pumpage from ground water used on irrigated lands upstream.
Salt River near Chrysotile (09497500)	8	2,849	1925–94	49	679	76,600	None	Several diversions for irrigation of about 3,100 acres upstream from station.
Salt River near Roosevelt (09498500)	9	4,306	1914–94	59	923	143,000	None	Several diversions for irrigation of about 4,000 acres above station and two transbasin diversions—one in and one out.
Salt River below Stewart Mountain Dam (09502000)	10	6,232	1930–94	No flow at times in recent years	1,040	75,200	Highly regulated	Four reservoirs above station. Entire flow is diverted at Granite Reef Dam for irrigation in Salt River Valley and for municipal use.

See footnote at end of table.

Table 4. Selected streamflow characteristics of principal river basins; Central Arizona Basins study area —Continued

Streamflow-gaging station				Streamflow characteristics				
Station name and number	Site number on figure 18	Drainage area (mi^2)	Period of record, water years	Minimum daily discharge (ft^3/s)	Average annual discharge[1] (ft^3/s)	Maximum recorded discharge (ft^3/s)	Degree of regulation	Remarks
Verde River near Clarkdale (09504000)	11	3,503	1916 1918–20 1966–94	55	198	53,200	None	Water quality generally good; however, grazing and mining may have an effect during first flush of high flows.
Verde River below Tangle Creek above Horseshoe Dam (09508500)	12	5,858	1946–94	61	590	145,000	Minor	None
Verde River below Bartlett Dam (09510000)	13	6,161	1888–94	No flow when gates in dam are closed	682 (adjusted for storage in reservoirs)	>150,000 in 1891; 110,000 in 1993	Highly regulated	Flow completely regulated by Bartlett Dam since 1939 and Horseshoe Dam since 1945 except during periods of spill. Downstream diversions for Phoenix municipal supply and Fort McDowell Indian Reservation.
Agua Fria River at Avondale (09513970)	14	2,077	1960–82	No flow at times most years	32	29,300	Appreciable	Flow partly regulated by Lake Pleasant, 35 mi upstream. Records may at times include wastewater from the Arizona Canal of the Salt River Project.
Gila River above diversions at Gillespie Dam (09518000)	15	49,650	1935–39 1940–71 1973–94	<5	528	130,000	Appreciable	Many large diversions above station for irrigation, municipal, and industrial use; flow of Gila River and tributaries upstream are regulated.

[1]Average discharge based on period of record indicated in Smith and others (1995).

Streams in the Central Highlands have short periods of high discharge and long periods of low discharge, which result in "average flow" being larger than the typical base flow. Base flow may vary seasonally depending on the quantity of water used by riparian vegetation and artificial diversions, although the year-to-year variation typically is small (Owen-Joyce and Bell, 1983). Base-flow characteristics are a function of many factors including precipitation and the properties of the regional aquifer.

Together, the Salt and Verde River drainages intercept most of the runoff and ground-water flow from the Mogollon Rim area in the northern part of the study area. The source of base flow in both rivers is ground water discharging gradually from sedimentary- and igneous-rock aquifers to the stream channel as seeps and springs. Several small springs with flows of less than 1.0 ft^3/s in the White River, Black River, and upper Salt River provide most of the salinity to the Salt River. Specific-conductance values of these springs were as much as 20,000 μS/cm (William B. Garrett, hydrologist, USGS, written commun., 1973; Edwin K. Swanson, Arizona Department of Environmental Quality, written commun., 1976; Feth and Hem, 1963). Springs also provide most of the base flow to several large tributaries of the Verde River. Many springs described in Feth and Hem (1963) and Owen-Joyce and Bell (1983) contribute about 8.5 ft^3/s to Sycamore Creek (fig. 1) and between 42 and 62 ft^3/s near the mouth of Oak Creek (fig. 1). Bubbling Pond Spring (9.2 ft^3/s) and Page Fish Hatchery Springs (17.8–31.2 ft^3/s) are the two largest springs.

Basin and Range Lowlands

The Gila River is regulated at the upstream study area boundary for irrigation and power generation by Coolidge Dam (fig. 12). Upstream from the dam, the Gila River drains 12,886 mi^2 of mountainous areas and grasslands of southwestern New Mexico and southeastern Arizona. About 70 mi below Coolidge Dam, the Gila River leaves the Central Highlands and enters the Basin and Range Lowlands. The nearest downstream gaging station is the Gila River at Kelvin (fig. 18, site 3). This site has an average annual discharge for the 83-year period of record of 538 ft^3/s (table 4). With the exception of unregulated floodwater—largely from the San Pedro River—almost all flow from the Gila River at Kelvin is diverted at Ashurst-Hayden Dam (fig. 18) into the Florence-Casa Grande Canal (table 4; fig. 18, site 4) for irrigation of about 100,000 acres (Smith and others, 1995). Between Ashurst-Hayden Dam and the metropolitan Phoenix area, Gila River streamflow is intermittent with most low flows created by irrigation return flow and discharge of treated sewage effluent from Chandler (fig. 1), southeast of Phoenix (Smith and others, 1995).

The San Pedro and Santa Cruz Rivers contribute flow to the middle reach of the Gila River. Both are low-elevation desert streams that flow north into Arizona from Mexico. Although these streams are predominantly intermittent or ephemeral, they can flow at high rates in response to intense thunderstorms. A flood peak can appear in a dry channel in a few minutes and disappear in a few hours with peak discharges commonly decreasing downstream (Eychaner and Rehmann, 1991).

The headwaters of the Santa Cruz River are in Arizona with a perennial reach that flows south into Mexico (fig. 18). As the river turns northward and flows back into Arizona, it becomes intermittent at times. Most of the base flow in the Santa Cruz River between Nogales, Arizona, and Tubac (fig. 18) is derived from treated sewage effluent from the Nogales International Wastewater Treatment Plant near Nogales, Arizona. North of Tubac to Tucson, the Santa Cruz is ephemeral and only flows during floods. Decades ago, natural base flow in the Santa Cruz River near Tucson was provided by ground water. As water use increased and water could be pumped from greater depths, natural base flow in the Santa Cruz River disappeared. Perennial flow near Tucson is from treated sewage effluent; and perennial flow near the mouth (site 7) is from return flow from about 240,000 irrigated acres (Smith and others, 1995). During normal flow conditions, the upper Santa Cruz drainage is essentially disconnected from the lower drainage to the north. The river channel disappears into a network of distributary channels near Casa Grande (fig. 18); however, during larger floods, which generally occur about once a decade, the Santa Cruz River may flow continuously to the confluence with the Gila River near Laveen (fig. 18, site 7).

The San Pedro River is "one of the last free-flowing riparian systems in the Southwest," according to David C. Goodrich, U.S. Agricultural Research Services (Erickson, 1998). The headwaters of the San Pedro River are in Mexico in the mountains near Cananea (fig. 18), and flow is perennial or intermittent (Vionnet and Maddock, 1992) with major perennial reaches in Arizona (fig. 18). Riparian areas along the river's broad flood plain are important habitats for birds and other wildlife; consequently, the San Pedro Riparian National Conservation Area was established by the Bureau of Land Management in 1988 to protect the flow in the river and the associated ecosystem. The San Pedro River, the flood-plain aquifer, and the deeper regional aquifer are hydraulically connected. Aquifer-system model (Vionnet and Maddock, 1992) and budget studies (Braun and others, 1992) indicate that as the quantity of water pumped from storage in the regional aquifer near Sierra Vista increases, flow in the San Pedro River could decrease. Current litigation over claims to water rights for the San Pedro by the Gila River Indian Community (downstream) could limit additional ground-water withdrawal in the area surrounding the San Pedro River.

Because of upstream impoundments and diversions, flow in the Gila River downstream from Ashurst-Hayden Dam is intermittent. Some reaches are dry except for flood runoff—including flood releases from dams on the Salt and Verde Rivers. Releases of municipal and irrigation wastewater have established perennial flow in the Gila River from near the confluence with the Salt River to Gillespie Dam. The mixture of agricultural return flows, seasonal floodwaters, and treated sewage effluent that flows past the streamflow-gaging station, Gila River above diversions at Gillespie Dam (fig. 18, site 15), produces an average annual discharge of 528 ft^3/s (table 4) for a 59-year period of record (Smith and others, 1995).

The two largest tributaries to the Gila River in this region—the Agua Fria and Hassayampa Rivers (fig. 18)—have perennial reaches near their headwaters in the Central Highlands but become broad, sandy washes with ephemeral flow to the south near the Gila River. The lower reach of the Agua Fria River is regulated in conjunction with the operations of the CAP at Waddell Dam. Below the dam, the lower Agua Fria River also receives discharges of treated sewage effluent from incorporated communities in the greater Phoenix metropolitan area (table 5). Storm runoff in the Hassayampa River rarely reaches the Gila River confluence (Arizona Department of Water Resources, 1994b) even though no dams impede the river; however, irrigation return flows in the lower reach of the Hassayampa River do reach the confluence most of the year.

Ground Water

Ground water is the primary water supply in most areas of Arizona (Arizona Department of Water Resources, 1994a) and currently is the only source being used for drinking water by communities in the southernmost part of the study area. Although CAP water is delivered to Tucson, it is not being used for municipal supply at this time (1997) because of a referendum by voters concerned about water quality. The referendum permits the use of CAP water for recharge and irrigation but prohibits its use as drinking water. A

Table 5. Effluent-dependent streams, Central Arizona Basins study area

[Data from the State of Arizona (1992). WWTP, wastewater-treatment plant]

Watershed	Stream reach
Middle Gila River Basin	Agua Fria River from Surprise WWTP outfall to 3.1 miles downstream from the outfall.
	Agua Fria River from El Mirage WWTP outfall to 5 miles downstream from the outfall.
	Agua Fria River from Avondale WWTP outfall to confluence with Gila River.
	Gila River from Florence WWTP outfall to 3.1 miles downstream from the outfall.
	Gila River from confluence with the Salt River to Gillespie Dam.
	Queen Creek from Superior WWTP to 5 miles downstream from the outfall.
	Unnamed wash from Luke Air Force Base WWTP outfall to the confluence with the Agua Fria River.
Salt River Basin	Pinal Creek from Globe WWTP outfall to 3.1 miles downstream from the outfall.
	Salt River from 23rd Avenue WWTP outfall to confluence with the Gila River.
San Pedro River Basin	Walnut Gulch from Tombstone WWTP outfall to confluence with the San Pedro River.
Santa Cruz River Basin	North Branch of the Santa Cruz Wash from the Casa Grande WWTP outfall to the confluence with the Santa Cruz Wash.
	Santa Cruz River from City of Nogales WWTP outfall to Josephine Canyon.
	Santa Cruz River from Roger Road WWTP outfall, Tucson, to Baumgartner Road crossing.
	Unnamed wash from Oracle WWTP outfall to confluence with Big Wash.
Verde River Basin	American Gulch from Payson WWTP outfall to the East Verde River.
	Bitter Creek from Jerome WWTP outfall to 1.5 miles downstream from the outfall.
	Jack's Canyon Wash from Big Park WWTP outfall to confluence with Dry Beaver Creek.

combination of ground water; surface water from the Verde, Salt, and Agua Fria Rivers; and CAP water fulfills municipal demands in the Phoenix area, and treated sewage effluent meets some industrial and agricultural demands. Both surface water and ground water are used to meet the demands in the Central Highlands.

Ground water in much of the study area is not being replenished at the same rate at which it is being withdrawn (Arizona Department of Water Resources, 1994a). Years of overpumping or ground-water "mining" have caused water tables to drop leaving once-perennial streams dry. Declining water levels have, in some areas, resulted in land subsidence and associated earth cracks, pumping of poorer quality water at depth, and ground water at depths from which it is economically infeasible to pump.

In 1980, the Arizona legislature enacted the Groundwater Management Code to minimize ground-water overdrafts and manage water supplies in several critical areas (Arizona Department of Water Resources, 1994a). Four Active Management Areas (AMA's)—Phoenix, Tucson, Prescott, and Pinal—were established in areas where ground-water overdraft was most severe (fig. 19). A fifth AMA was formed in 1994 when the Santa Cruz AMA split from the Tucson AMA. Ground-water use is extensively managed in the AMA's. Within the AMA's, the Code established a system of ground-water rights, precluded new agricultural land from being developed, and required new development to demonstrate a water supply that is assured for at least 100 years.

Each AMA has its own management goals. The goals of the Phoenix, Tucson, and Prescott AMA's are to achieve "safe yield," a balance between ground-water withdrawal and recharge, by 2025 (Arizona Department of Water Resources, 1994a). The Santa Cruz AMA wants to maintain safe-yield conditions and prevent long-term declines in local water tables. The Pinal AMA, where a majority of the water use is for agriculture, wants

> "...to extend the life of the agricultural economy for as long as feasible, while considering the need to preserve water supplies for future nonirrigation uses..."

(Arizona Department of Water Resources, 1994a).

Recent changes to the Arizona Groundwater Management Code have allowed the use of aquifers for storage and recovery of water. Projects have begun that will store water from the CAP and treated effluent in aquifers in the Phoenix and Tucson areas (Lluria, 1995; Megdal, 1995; Wilson and others, 1994).

The occurrence, recharge, movement, and discharge of ground water in the Central Highlands and Basin and Range Lowlands are described in the following sections. Substantial differences in these characteristics exist between the two provinces.

Central Highlands

The major aquifers in basins of the Central Highlands consist of stream alluvium and basin fill, which are hydraulically connected, limited in areal extent, and typically overlie pre-Cenozoic sedimentary rocks (sedimentary bedrock of fig 3; Anderson and others, 1992). Compared to the Basin and Range Lowlands, the Central Highlands have minimal water-storage capabilities and high runoff (Arizona Department of Water Resources, 1994b) because of the limited extent of permeable deposits. According to Anderson and others (1992), a large quantity of ground water is in storage in the stream alluvium and basin fill compared to the underlying consolidated-rock aquifers. In many places, the basin fill is absent, and saturated or partially saturated stream alluvium directly overlies saturated sedimentary rocks.

Along the northern boundary of the study area, a band of pre-Cenozoic consolidated sedimentary rocks (sedimentary bedrock, fig. 3) that is a barrier to flow in most basins outside the Central Highlands (Pool, 1986) may include important aquifers locally if the sedimentary bedrock is saturated and permeable. This condition occurs at Sedona where water is withdrawn from sandstone of the Supai Formation and the Redwall and Martin Limestones. Springs issue from the consolidated rock aquifers and contribute to the base flow of the Verde and Salt Rivers. Other consolidated rocks (bedrock of the mountains, fig. 3) may yield water as at the town of Payson where fracturing and weathering of the bedrock (Precambrian granite) have created secondary permeability (Arizona Department of Water Resources, 1994a).

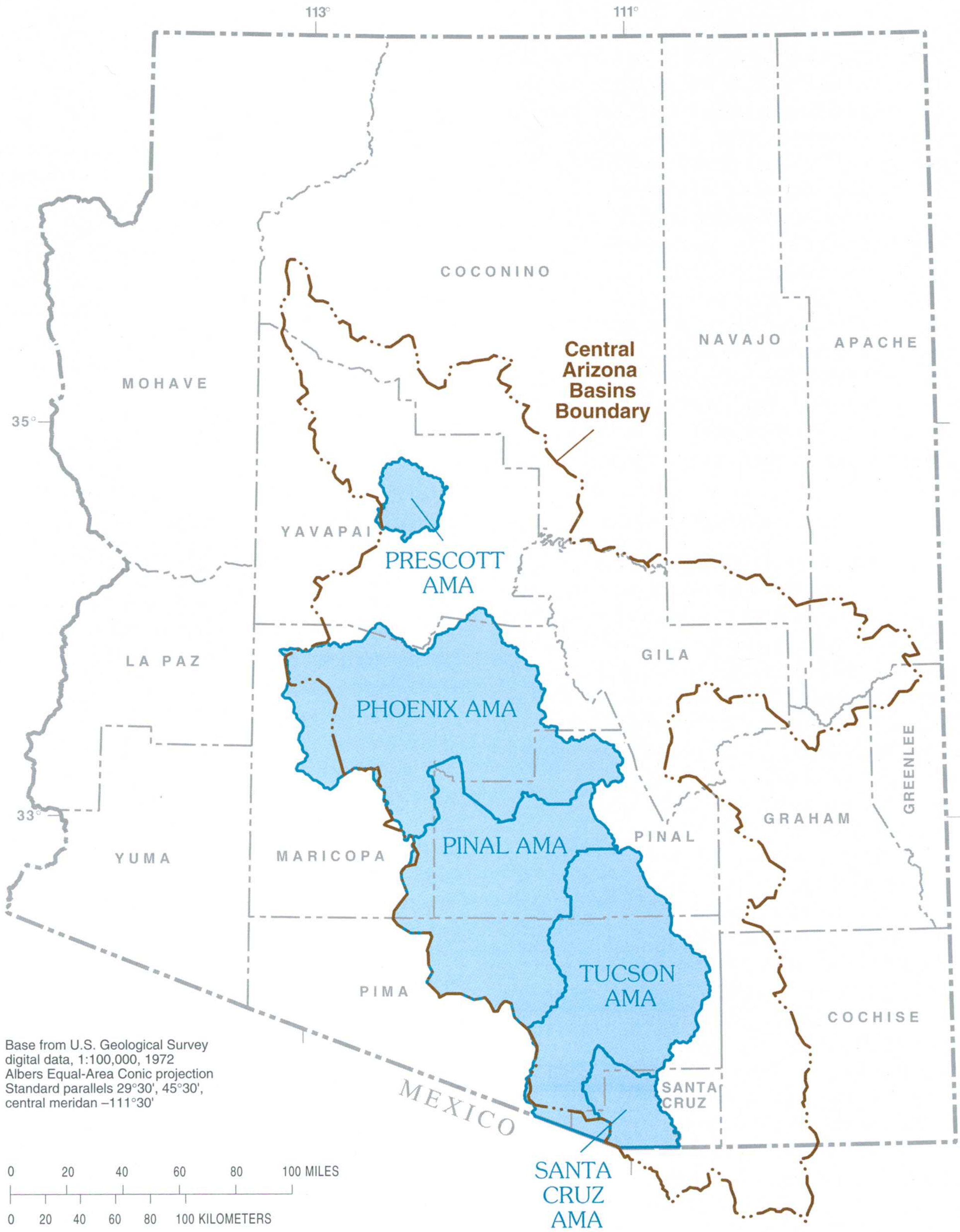


Figure 19. Active Management Areas (AMA's) for ground water in Arizona.

Ground water in the major aquifers of the Central Highlands is typically under unconfined conditions, and depth to water commonly ranges from land surface to a few tens of feet below land surface (Anderson and others, 1992). Water recharges the unconsolidated aquifers (basin fill and stream alluvium) by stream infiltration, underflow from surrounding bedrock aquifers, and to a lesser extent, by mountain-front recharge (Anderson and others, 1992, fig. 25). Ground water moves through the unconsolidated aquifers to points of discharge. Discharge occurs as base flow to streams, evapotranspiration, or in some areas by pumping. Underflow from one basin to another through unconsolidated aquifers does not occur because the aquifers are not hydraulically or physically connected (Anderson and others, 1992).

Basin and Range Lowlands

As in the Central Highlands, the major aquifers in the Basin and Range Lowlands are in the stream alluvium and basin fill. Consolidated mid-Tertiary deposits underlie the late Tertiary-Quaternary basin fill and are in hydraulic connection with it in many basins. Where saturated, the mid-Tertiary deposits are included as a part of the basin-fill aquifer in this report, and where they are exposed above the water table in mountain ranges, the mid-Tertiary sediments are included with the bedrock of the mountains (fig. 3).

Although smaller in volume than the basin fill or the mid-Tertiary deposits, stream alluvium is a highly productive aquifer where it is saturated along major stream courses. The stream alluvium is as much as 300 ft thick along the Salt River in the Phoenix area (Laney and Hahn, 1986); however, extensive ground-water pumping has lowered the water table below the base of the alluvium in some areas, and it is no longer an aquifer in those areas. Similarly in some other basins, ground-water production has exceeded the rate of recharge, ground-water levels have declined, and stream alluvium is now unsaturated. In the Basin and Range Lowlands, however, the high hydraulic conductivity of the stream alluvium (30 to as much as 100 ft/d; Anderson and others, 1992) permits the rapid infiltration of streamflow to recharge the underlying basin-fill aquifers. The specific yield from saturated stream alluvium ranges from 15 to 25 percent (Anderson and others, 1992).

Ground water in the stream alluvium is important for supporting riparian areas along stream courses. Phreatophytes use the shallow ground water in these deposits. The movement of water between the stream channel and the stream alluvium supports the base flow of the stream where the ground-water level is at or near the elevation of the streambed. In an interlocutory decision in the Gila River Adjudication, Judge Stanley Z. Goodfarb ruled (June 30, 1994) that ground water in the stream alluvium along flowing stream reaches is considered to be surface water for the purpose of establishing water rights in Arizona (Arizona Department of Water Resources, 1994a). Shallow ground water or "subflow" in alluvium is considered appropriable and subject to adjudication under the Goodfarb ruling. In other words, water being pumped from wells that extract water from the stream alluvium is no longer covered by the laws of ground-water ownership in Arizona, which state that water percolating through the soil belongs to the owner of the overlying property.

The most productive aquifers in the CAZB study area are the thick basin-fill deposits of unconsolidated to semiconsolidated clastic sediments contained in the structural basins in the Basin and Range Lowlands (fig. 3). Most major ground-water development in the study area has been from the basin-fill aquifers within each structural basin. Although the basin fill may be as much as 12,000 ft thick in some basins, the effective thickness of the aquifer systems is determined by the depth from which ground water can be economically withdrawn and by physical factors such as the presence of fine-grained sediments, low well yields, and variable chemical quality of the water (Freethey and others, 1986, sheet 1). Most water is obtained from the upper 1,000 ft of the aquifer (Anderson and others, 1992). Depth to ground water ranges from land surface near perennial streams and some irrigated areas to as much as 1,300 ft.

Ground water generally is under unconfined conditions in the basin-fill aquifers. Where extensive fine-grained sediments overlie permeable basin fill, as in the upper and lower San Pedro structural basins, ground water occurs under confined conditions (Anderson and others, 1992).

The hydraulic conductivity of the basin fill ranges from about 1 to 100 ft/d (Anderson and others, 1992, fig. 7). Wells may yield several thousand gallons per minute from coarse-grained strata but may yield only a few gallons per minute from fine-grained strata (Montgomery and Harshbarger, 1989). Wells withdrawing water from the lower parts of the basin fill generally yield less than those withdrawing water from the upper part, because the upper basin fill is less consolidated and cemented and generally coarser grained than the lower basin fill (Anderson and others, 1992).

In the Basin and Range Lowlands, the unweathered crystalline, volcanic, and consolidated sedimentary bedrock of the mountains (bedrock of the mountains, fig. 3) generally is impermeable and forms a flow boundary laterally and vertically for the basin-fill aquifers (Anderson and others, 1992). Basin fill, however, is hydraulically connected to fill in adjacent basins by a thin string of alluvium that allows ground water to move from basins of higher elevation to those of lower elevation (Anderson and others, 1992).

Very little of the precipitation that falls on the Basin and Range Lowlands directly recharges the ground-water system because of the high rates of evaporation. In fact, inflow and outflow to the aquifers commonly are small compared to the vast quantities of water that are stored in the basin-fill deposits. Freethey and Anderson (1986) prepared estimates of the ground water in storage in the basin fill to a depth of 1,200 ft below land surface before extensive development. For the major developed structural basins within the Basin and Range Lowlands, the quantity of water in storage ranges from 200 times to 2,000 times the quantity of annual ground-water inflow.

Most recharge to the ground-water system is by water that has been concentrated as surface runoff. Recharge occurs along mountain fronts where flow in ephemeral streams crosses from the impermeable bedrock of the mountains to the coarse-grained basin-fill sediments in the structural basins. Even more recharge to the ground-water system occurs along the axis of structural basins where major streams and rivers provide flow for longer periods of time and permeable stream alluvium readily accepts recharge (Anderson and others, 1992). The application of irrigation water in excess of crop needs provides recharge to underlying aquifers where the land is under cultivation and in urban areas where landscapes are overwatered. Seepage from irrigation canals is a major source of ground-water recharge in some areas particularly where the canals are unlined. Ground water also enters basins as underflow from structural basins upstream and leaves as underflow at the downstream end. The quantity of underflow depends on the bedrock configuration at the connections between structural basins and on the quantity of recharge within each basin.

In general, ground-water movement parallels surface-water movement within each structural basin and moves from the mountains bounding the basin toward the stream in the basin center in those structural basins with sufficient mountain-front recharge. Pumping of ground water has substantially altered the direction of ground-water movement in intensively developed structural basins and resulted in water-level declines of greater than 400 ft (Anderson and others, 1992, pl. 2). Movement is now toward the pumping centers particularly in the Salt River Valley near Phoenix (Thomsen and Miller, 1991, sheet 1) and in the agricultural area around Casa Grande (Thomsen and Baldys, 1985, sheet 1). Discontinuous, irregular fine-grained beds can be semiconfining layers that produce local variations in the direction of ground-water movement.

Most ground-water discharge from basin-fill aquifers in the Basin and Range Lowlands is by evapotranspiration, discharge to streams as base flow, underflow to downgradient basins, and by pumping in the agricultural and urban areas (Anderson and others, 1992). The pumping of ground water for irrigation and municipal use has added to or replaced natural discharge in the developed basins and makes additional ground water available for evapotranspiration.

Although recharge and discharge were about equal before development, ground-water pumping, especially since 1940, has caused total discharge to greatly exceed recharge. Depletion of ground water in storage has caused water-level declines of 400 ft or more in the East and West Salt River Valleys, the Stanfield area, and the Eloy area where large quantities of ground water are withdrawn for agricultural and urban use (Anderson and others, 1992, pl. 2). These large water-level declines have caused subsidence of the land surface that exceeds 17 ft in the West Salt River Valley (H.H. Schumann, hydrologist, USGS, oral commun., 1995).

OVERVIEW OF WATER QUALITY

In arid areas like the CAZB study area where water supply is limited, maintaining and ensuring the quality of that resource takes on an even greater importance than in areas with greater water resources. Natural processes such as leaching of trace elements and major ions from geologic formations and human actions such as mining, agriculture, and urban development have major effects on the quality of surface-water and ground-water resources in the CAZB study area. For the purposes of this report, elements that have been referred to as metalloids, metals, trace metals, minor constituents, or trace constituents in previous reports will be identified as trace elements.

The major water-quality issues identified in the CAZB study area by a liaison committee composed of representatives from a variety of local, State, and Federal agencies, as well as educational and volunteer organizations (Cordy, 1994) with interests in water quality are:

- Nitrate in ground water from natural and anthropogenic sources at concentrations that exceed National drinking-water standards;
- High concentrations of naturally occurring trace elements (fluoride, barium, arsenic, boron, and chromium) and high radon activities in ground water;
- Effects of contamination from acid-mine drainage on surface-water and ground-water quality, and human health;
- Effects of discharge of treated sewage effluent on surface-water and ground-water quality, aquatic life, and instream flows near Phoenix, Tucson, and Nogales, Arizona;
- Movement and fate of organic contaminants in ground water from industrial discharges, spills, landfills, and other point sources in urban areas;
- Effects of artificial recharge of CAP water on ground-water quality;
- Movement and fate of fertilizers, pesticides, and other contaminants from nonpoint sources such as irrigation return flow and stormwater runoff; and
- Effects of ground-water and surface-water quality on riparian areas and associated life.

Many of the major water-quality issues in the CAZB study area pertain to determining the effects, movement, and fate of contaminants. One of the goals of the NAWQA program is to answer some of the questions involving effects, fate, and transport of contaminants on surface-water and ground-water quality and aquatic biota (Gilliom and others, 1995).

An overview of surface-water quality, aquatic biota and bioaccumulation, and ground-water quality follows to familiarize the reader with some of the major water-quality issues in the study area and the sources of some of the important water properties and constituents.

Surface-Water Quality

The Arizona Administrative Code (State of Arizona, 1996) sets water-quality standards to protect human health, aquatic life, livestock, and wildlife in rivers, streams, intermittent and ephemeral washes, playas, reservoirs, natural ponds, and wetlands. Most manmade structures containing surface water, such as canals, manmade lakes, wastewater-treatment systems, lagoons, constructed wetlands, mining impoundments, and catchments, are excluded from this regulation. The standards apply to organic compounds, trace elements, ammonia, chlorine, pH, turbidity, bacteria, and other contaminants that are regulated by the U.S. Environmental Protection Agency (USEPA; U.S. Environmental Protection Agency, 1994a, 1996). The numeric water-quality standards vary depending on the designated use of the stream reach. For example, fish are less tolerant of chlorine than humans so the chlorine standard for stream reaches designated for aquatic and wildlife uses is stricter than that for domestic water sources (Tellman, 1992). Designated surface-water uses include fish consumption, full-body contact, partial body contact, domestic water source, aquatic and wildlife uses (cold-water and warm-water fisheries, ephemeral streams, and effluent-dependent streams), and agricultural uses (irrigation and livestock watering).

The Arizona Department of Environmental Quality (ADEQ) can apply stricter standards or set controls to limit degradation in some cases. If a stream reach is an outstanding State resource because of recreational or ecological features or because threatened or endangered species are associated with the reach, then the ADEQ can designate it as a "unique water" and apply stricter standards. Within the CAZB study area, Oak Creek and Cienega Creek (fig. 1) have been designated "unique waters." Oak Creek has special water-quality standards that have been prescribed for nitrogen, phosphorus, and chromium, which supplement those in the Arizona Administrative Code (State of Arizona, 1996). For Oak Creek and Cienega Creek, supplemental standards also prescribe that pH values do not change regardless of change in discharge. Additionally for Cienega Creek, supplemental standards also prescribe that turbidity be below 10 nephelometric turbidity units, that dissolved oxygen not decrease, and that temperature and total dissolved solids not increase owing to changes in discharge. Conversely, water-quality waivers may be granted on a discharger-specific basis—usually in the case of effluent-dependent waters. Cities or entities discharging treated effluent to ephemeral washes may be granted waivers from meeting standards for total phosphorus and total nitrogen at the point of discharge. A "point of compliance" downstream allows for nutrients to be removed by natural processes before standards must be met. Discharge of effluent to perennial streams is allowed in mixing zones where discharge is diluted by water that is already in the stream, and the "point of compliance" is at the downstream end of the mixing zone (Linda Tant, hydrologist, ADEQ, oral commun., 1997).

According to an annual water-quality assessment by the ADEQ (Marsh, 1994), the most common water-quality impairments in streams are high levels of trace elements, turbidity, salinity, and suspended solids. The most frequently cited cause given for these problems is that of natural ambient conditions. This is not surprising, given the arid climate; limited vegetative cover; widespread occurrence of sandy-bottom, ephemeral tributaries; and erodible exposures of geologic formations with mineral-bearing strata. In addition to the natural factors, the ADEQ (Marsh, 1994) has identified the human activities that contribute to the degradation of surface-water quality as:

- Agriculture (rangeland management, irrigation, and related activities);
- Hydromodification (stream-bank destabilization, channelization, dam construction, flow regulation, and removal of riparian vegetation), and
- Resource extraction (mines and sand/gravel operations).

Though not noted by the ADEQ, the effects of urban development also contribute to surface-water degradation in Arizona. The effects of urban development are included in other important surface-water quality issues in the study area, such as:

- Streamflows and riparian environments sustained by effluent from municipal wastewater-treatment plants that contains high concentrations of nutrients, potentially toxic trace elements and organic compounds, and fecal bacteria;
- Industrial, mining, agricultural, and municipal sources of contamination from Mexico; and
- Unpredictable high flows from major summer thunderstorms causing high suspended-sediment concentrations and loads; sewage overflows; and breaching, erosion, and washout of landfills and mining operations.

Although more than 75 percent of Arizona's original riparian habitat has been lost as a result of ground-water overdraft, development, and grazing (Tellman, 1992), many riparian areas are being re-established or newly established as the number of effluent-dependent streams increases (table 5; fig. 20).

The largest discharges of treated effluent in the study area are to the Salt and Agua Fria Rivers in Phoenix, the Santa Cruz River at Tucson, and the Santa Cruz River near Nogales, Arizona. At the Nogales International Wastewater Treatment Plant, sewage from Mexico and Arizona is treated and released according to a joint agreement between

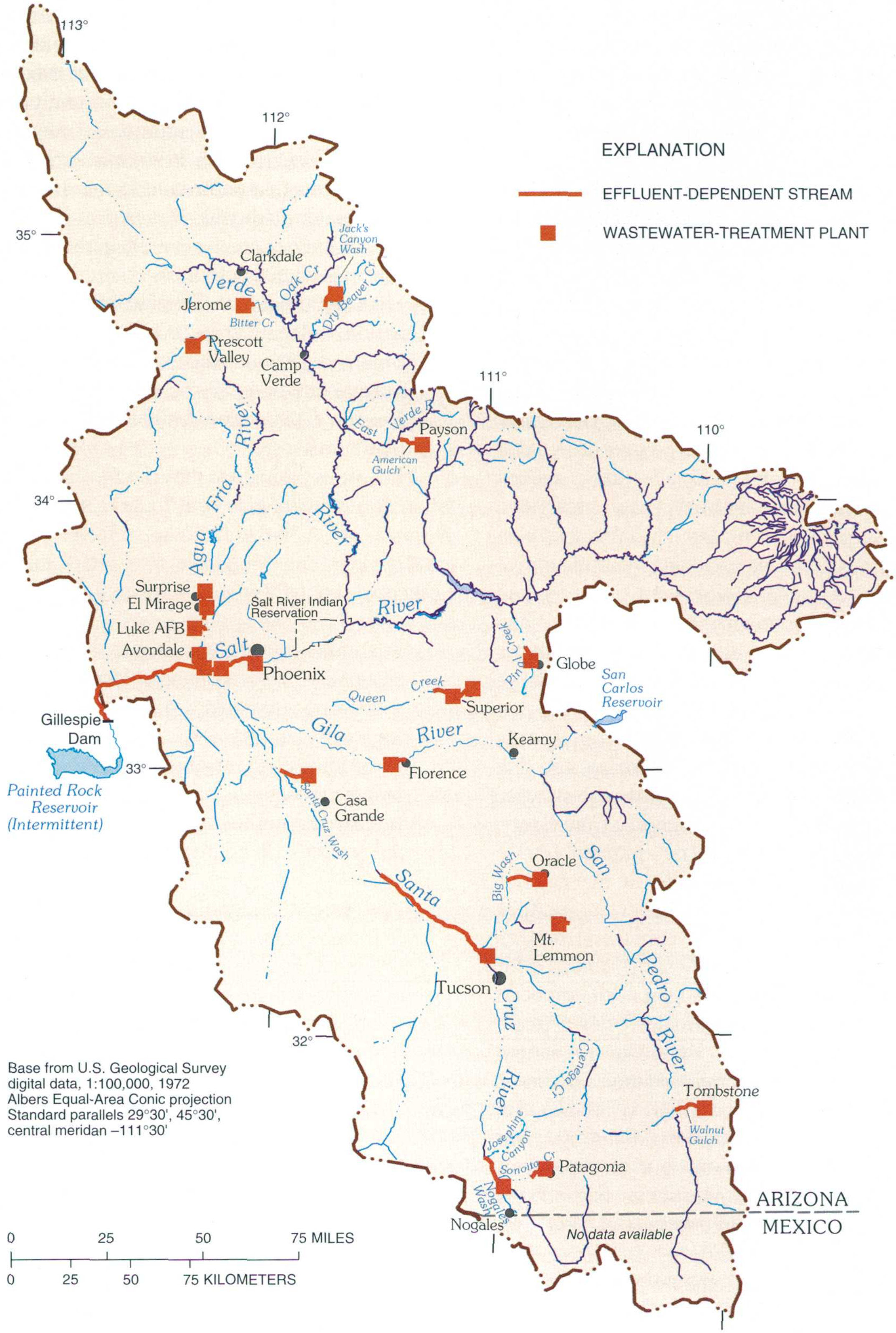


Figure 20. Effluent-dependent stream reaches, Central Arizona Basins study area (State of Arizona, 1996).

the two Nations. In all three areas, the volume of effluent released is increasing in response to the rapid growth in population, causing the length of each perennial (and riparian) reach to lengthen over time. A move toward alternative approaches for managing effluent—including reuse, constructed wetlands for improved treatment, and recharge basins to augment ground-water supplies—may prevent the increased quantities of effluent in the future from reaching these streams.

Water-quality monitoring along the border between the United States and Mexico at Nogales Wash (fig. 20), a tributary of the northward-flowing Santa Cruz River, detected high levels of fecal coliform bacteria, ammonia, and trace elements in surface water, primarily owing to gray-water (household and industrial wash water) and sewage discharges from inadequate pipelines and wastewater treatment in Mexico (Marsh, 1994). Fecal coliform bacteria have been measured at 160,000,000 col/100 mL in Nogales Wash, and at levels of 9,000 col/100 mL downstream from the Nogales International Wastewater Treatment Plant (University of Arizona, 1993). The State standard for effluent-dependent waters (State of Arizona, 1996) is 800 col/100 mL for the designated uses of full-body contact and aquatic and wildlife use.

In an effort to protect public health and provide abatement, international cooperative efforts have at times resorted to chlorinating streamflow in Nogales Wash. In addition, stormwater carries nonpoint-source pollutants such as oil, sediment, nitrates from agriculture, and occasionally untreated effluent. Several studies since 1988 have found high levels of volatile organic compounds (VOC's)—including tetrachloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE), trichloroethane (TCA)—in Nogales Wash, particularly in Mexico (Fry and Cervera, 1995). Roberto Sanchez and Richard Camp (Border Ecology Project, written commun., 1990) found high levels of toluene, ethylbenzene, xylene, methylene chloride, and benzene in samples from sewers in Nogales, Mexico. Organic and inorganic contaminants are known to occur on both sides of the international border.

Large floods in January 1993 resulted in overflows of raw sewage, breaching and erosion of landfills, and release of mining contaminants in the study area. These inadvertent releases were investigated by the ADEQ (Marsh, 1994). Raw sewage overflows were widespread, notably in Oak Creek, East Verde River, Pinal Creek, upper Santa Cruz River, and the Gila River at Kearny (fig. 20). Flooding also inundated the Tri-Cities Landfill on the Salt River Indian Reservation (fig. 20), which serves several cities and institutions in the Phoenix metropolitan area. Thousands of tons of landfill debris were carried away and deposited along the banks of the Salt and Gila Rivers for more than 100 mi downstream (Marsh, 1996). The 10-year to 25-year floods that occurred in many rivers throughout the study area in 1993 also resulted in several mine tailings or leachate spills (table 6) at mining operations that were not prepared for the above-average precipitation.

Mining activity is a significant source of trace elements, sediment, and turbidity in surface water; and active, inactive, and abandoned mines are found in almost every watershed throughout the study area (fig. 21). Personnel from the Coronado, Prescott, and Tonto National Forests have identified nearly 3,000 inactive and abandoned mines (Marsh, 1994). In addition, the Bureau of Land Management manages about 15 million acres in Arizona with about 30,000 mine claims. A major Federal and State task force, known as the Arizona Copper Mines Initiative, was implemented by the USEPA in 1992 to identify and mitigate problems with active, inactive, and abandoned copper mines in Arizona.

Dissolved Solids and Turbidity

Dissolved solids and turbidity are general indicators of the overall quality of surface water and are affected by natural and anthropogenic factors. The dissolved-solids concentration is the sum of the inorganic salts in solution in the water column. The State of Arizona requires monitoring of dissolved solids in surface water but does not enforce a numeric standard. The USEPA has a secondary maximum contaminant level (SMCL) of 500 mg/L for concentrations of dissolved solids in drinking water (U.S. Environmental Protection Agency, 1994b). Turbidity is the suspended-solid matter that may include clay, silt, finely divided organic and inorganic matter, and microscopic organisms. The USEPA maximum contaminant level (MCL) for turbidity in drinking water is

Table 6. Effects of floods of January 1993 on mining operations, Central Arizona Basins study area
[Data from Marsh (1994). NA, not applicable]

Stream reach	Watershed	Mine	Type of discharge
Pinto Creek	Salt River	Pinto Valley Mine of Magma Copper Company	Several thousand tons of copper tailings and several thousand gallons of acidic leachate.
Pinal Creek	Salt River	Old Dominion Mine (closed)	Several tons of copper tailings.
Gila River	Gila River	Ray Mine	Several thousand tons of copper tailings.
Mineral Creek and Pinto Creek	Gila and Salt Rivers	Gibson Mine	Copper-contaminated water.
El Tiro Wash	Santa Cruz River	ASARCO Silverbell Mine	Sustained release of acidic leachate to drainage.
Bitter Creek	Verde River	Phelps Dodge	Overflow of settling ponds.
Miami Wash to Pinal Creek	Salt River	NA	Unusually high water tables resulted in two major seeps of acidic ground water.
Queen Creek	Gila River	Magma Superior Mine	Berm failure at tailings pond discharged to streets of Superior and Queen Creek.
French Gulch	Hassayampa River	Zonia Mine	Damaged leach basin resulted in release of acidic leachate to drainage.

0.5–1.0 nephelometric turbidity unit (NTU; U.S. Environmental Protection Agency, 1994a). The State standards (State of Arizona, 1996) for turbidity for aquatic biota and wildlife in surface waters designated as warm water and effluent dependent is 50 NTU. For surface waters designated as cold water, the standard is 10 NTU.

Concentrations of dissolved solids in surface water vary widely throughout the CAZB study area, in part, because of a variety of natural factors. Natural contributors to dissolved-solids concentrations include saline springs on the upper Salt River with dissolved-solids concentrations approximating that of sea water. Despite dilution downstream, SMCL's for dissolved solids and chloride frequently are exceeded at the Salt River above Roosevelt Lake where the median dissolved-solids concentration is 984 mg/L (Baldys and others, 1995)—nearly three times higher than that of the Verde River above Horseshoe Dam (Baldys, 1990). Concentrations of dissolved solids, sodium, and sulfate increase in the Verde River near the mouths of Beaver Creek and West Clear Creek (Owen-Joyce and Bell, 1983) because the ground-water inflow to these streams has passed through salt and gypsum deposits in the Verde Formation.

Human activities, such as agriculture, contribute to increased dissolved-solids concentrations in the CAZB study area. At the downstream end of the study area, the Gila River above diversions at Gillespie Dam (fig. 18, site 15), base flow consists largely of agricultural return flows and treated sewage effluent from Phoenix municipalities. The median concentration for dissolved solids at this site is 2,570 mg/L (Baldys and others, 1995).

Accounts of water-quality problems including elevated dissolved-solids and trace-element concentrations related to mining activities have been documented in many parts of the CAZB study area including the Gila, Hassayampa, Agua Fria, Salt, and Verde River Basins (Marsh, 1994). Base flow in Pinal Creek (fig. 20) is contaminated by an acidic plume of ground water that originated from activities associated with large-scale copper mining near the communities of Globe and Miami (Brown and Favor, 1996). According to Stollenwerk (1996), the acidic part of the plume contains high concentrations of sulfate, calcium, iron, manganese, copper, aluminum, and zinc. Major changes in the chemistry of the ground-water plume in the early 1990's have resulted from remedial action such as removal of the major source of contaminants.

A water-quality trend analysis of streamflow at six sites in the Verde River Basin (Baldys, 1990) indicates an increasing trend in concentrations of dissolved solids and sulfate only at the Verde River near Camp Verde. According to Marsh (1994),

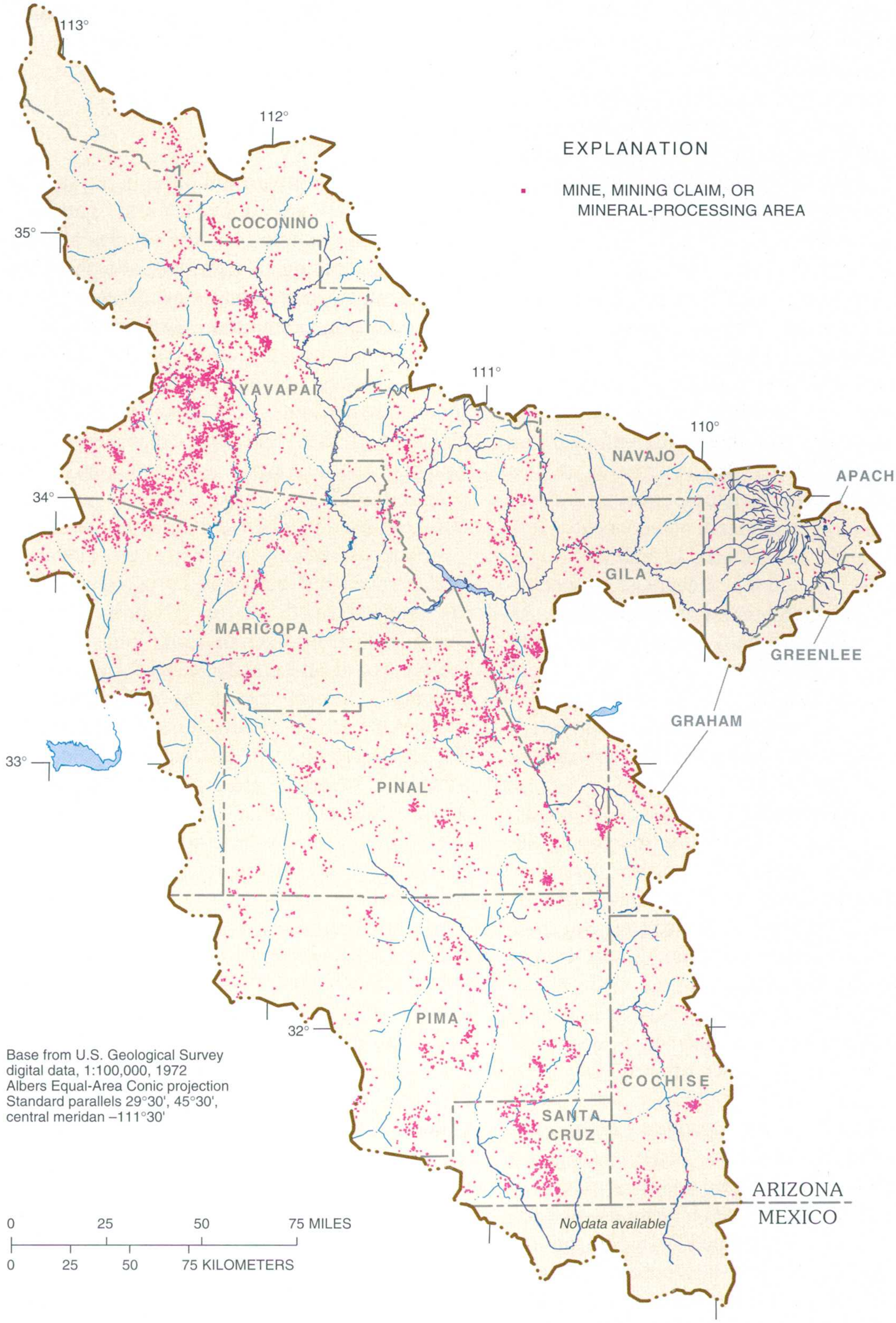


Figure 21. Mines (active, inactive, and abandoned), mining claims, and mineral-processing areas, Central Arizona Basins study area (digital data from Arizona State Land Department, 1994; http://www.state.az.us/gis3/alris/doc/azmines.txt).

extremely saline water seeps into the Verde River upstream at the Phelps Dodge Tuzigoot tailings (upstream from Oak Creek and Bitter Creek). In addition, Bitter Creek (fig. 20) contributes trace elements that could be transported to the Verde River during floods (Marsh, 1994). Bitter Creek is a potential USEPA Superfund cleanup site because of abandoned ore dumps near the mining community of Jerome.

Other human activities, such as urban and industrial development, add dissolved constituents to perennial streams and to intermittent and ephemeral streams during periods of rainfall runoff. Lopes and others (1995) reported that concentrations of dissolved solids in urban stormwater were less than that in streamflow of the Salt River, which means that stormwater dilutes most constituent concentrations except chemical and biological oxygen demand, and concentrations of oil, grease, and fecal bacteria. In addition, Lopes and others (1995) noted that a decrease in specific conductance (an indirect measure of concentrations of dissolved solids) of runoff during storms could indicate that most soluble constituents were washed off exposed surfaces in the initial runoff of a storm or that constituent concentrations were being progressively diluted by subsequent sustained flow.

As with concentrations of dissolved solids, there are many causes of turbidity. In general, the greatest variability in turbidity occurs in reaches that have sand channels with an abundant supply of fine sediment. Turbidity is reduced significantly below reservoirs because the sediments are caught and held behind the dams (Baldys and others, 1995). Elevated turbidity during low to moderate flows can indicate that a watershed is degraded. Chronic turbidity at low flows often is associated with irrigation return flows and with effluent-dependent stream reaches. Monitoring results from the ADEQ for the Verde River Basin (Marsh, 1994) demonstrate that turbidity—associated with accelerated erosion in the watershed and streambed modifications, particularly gravel mining—is a serious concern. Elevated turbidity on Beaver and Tonto Creeks (fig. 12) is attributed to sand and gravel mining within the stream channels. A decrease in vegetative cover caused by a large forest fire in 1990 in tributary basins of Tonto Creek and the East Fork of the Verde River may contribute to turbidity during rainfall and snowmelt runoff now and in the near future.

Nutrients

Nutrients (nitrogen and phosphorus species) in surface water are derived from natural and anthropogenic sources. Natural sources of nitrogen are soils and biological materials, and phosphorous is the result of the weathering of igneous rocks. Anthropogenic sources of nitrogen and phosphorous include fertilizers and human and animal wastes (Hem, 1985). Principal point sources of nutrients include wastewater-treatment plants, permitted industrial discharges, animal feedlots, and leakage from septic tanks. Major nonpoint sources include rangeland grazing and fertilizers used in urban and agricultural areas.

State of Arizona water-quality standards for total nitrogen and total phosphorus vary throughout the study area (State of Arizona, 1996). For example, total nitrogen and total phosphorous are not to exceed an annual mean of 1.00 mg/L and 0.10 mg/L, respectively, in the Verde River and its tributaries from the headwaters to Bartlett Lake (at Bartlett Dam; fig. 18). For the Salt River and its tributaries, except Pinal Creek, from the confluence of the Black and White Rivers to Roosevelt Lake total nitrogen and total phosphorous are not to exceed 0.60 and 0.12 mg/L, respectively (State of Arizona, 1996).

Data compiled on concentrations of ammonia plus organic nitrogen in the Gila River Basin (Baldys and others, 1995) contain many extreme values, although the median concentrations for eight streamflow-gaging stations within the CAZB study area were less than 1.0 mg/L, with the exception of the Gila River above diversions at Gillespie Dam. Water at this site is predominantly agricultural return flows and treated sewage effluent, and samples had a median total nitrogen concentration of 3.70 mg/L.

Maximum concentrations of ammonia plus organic nitrogen ranged from 1.4 mg/L at Agua Fria River below Waddell Dam to 47 mg/L at San Pedro River below Aravaipa Creek (Baldys and others, 1995). From 1980 to 1988, only a few of the more than 500 samples analyzed for total nitrite plus nitrate (as nitrogen) at eight sites in the Verde

River Basin exceeded 0.5 mg/L (Baldys, 1990). These data indicated that there were no point or nonpoint sources contributing water that contained high concentrations of nitrite plus nitrate.

Maximum concentrations of total phosphorus in samples collected in the Gila River Basin within the study area ranged from 0.16 mg/L at Agua Fria River below Waddell Dam to 40 mg/L at San Pedro River below Aravaipa Creek (Baldys and others, 1995). The highest median concentration was at Gila River above diversions at Gillespie Dam (1.7 mg/L). The median values of total phosphorus in samples from six locations in the Verde River Basin were substantially lower (0.05 mg/L or less; Baldys, 1990).

Trace Elements

In the study area, dissolved trace elements in streamflow are derived from natural sources such as metal-bearing geologic formations and anthropogenic activities such as mining and effluent discharge. Because of the widespread mineralization and associated mining in the study area, trace elements, such as beryllium, cadmium, copper, chromium, lead, manganese, mercury, nickel, zinc, arsenic, and cyanide, are found in streams and lakes (Marsh, 1994).

High concentrations of arsenic in water from the Verde River, which is used for municipal supply, create a potential problem for drinking-water supplies in Phoenix. Water from the Verde River is used to dilute the saline water of the Salt River and constitutes 30 percent of the flow to the Salt River, and 58 percent of the total arsenic load (Baker and others, 1994). The major source of arsenic is a mudstone unit within the Verde Formation near Camp Verde, described as a soft, whitish, evaporite deposit containing gypsum and salts (Baker and others, 1994; Owen-Joyce and Bell, 1983; Twenter and Metzger, 1963). All of the tributary streams entering the Verde River from Clarkdale to the East Verde River (fig. 20) receive ground-water inflow from the Verde Formation and contain arsenic concentrations of as much as 25 μg/L. The median concentration of dissolved arsenic for the Verde River above Horseshoe Dam (fig. 12) was 16.0 μg/L (Baldys, 1990), which is less than the USEPA interim MCL of 50 μg/L. If a lower standard is adopted, however, further dilution or mixing of Verde River water with other waters may be required for municipal distribution.

Boron and manganese concentrations typically exceed water-quality standards in some parts of the study area. In a statistical summary of data from surface-water sampling sites in the Gila River Basin (Baldys and others, 1995), the median concentration of total boron at the Gila River above diversions at Gillespie Dam was 2,000 μg/L, twice the State standard for total boron (1,000 μg/L) in surface water used for irrigation of agricultural lands (State of Arizona, 1996). Trend analyses indicate that total manganese concentrations are increasing at three sites—Pinal Creek at Inspiration Dam in Globe, Salt River near Roosevelt, and Agua Fria River near Rock Springs (fig. 1). The only median concentration for total manganese that exceeds the State standard (10,000 μg/L) is for water in Pinal Creek (21,500 μg/L; Baldys and others, 1995). Maximum concentrations of total manganese for Gila River at Winkelman (11,000 μg/L), San Pedro River below Aravaipa Creek (13,000 μg/L), Pinal Creek at Inspiration Dam (41,000 μg/L), and Agua Fria near Rock Springs (35,000 μg/L) exceed the State standard for waters used for agricultural irrigation (10,000 μg/L).

Elevated concentrations of manganese, copper, and other trace elements in acid-mine drainage in the Pinal Creek and Pinto Creek watersheds have contaminated streamflow and ground water (Marsh, 1994, p. 146). Both creeks drain into Roosevelt Lake. Other streams with elevated concentrations of trace elements associated with mining include the Gila River from Winkelman to Kelvin, Mineral Creek, and several locations on the Hassayampa and Agua Fria Rivers (Marsh, 1994).

Radionuclides

Limited data for radionuclides in surface water from four USGS streamflow-gaging stations in the Rillito Creek Basin in the Tucson area (Tadayon and Smith, 1994) indicate that suspended gross alpha activities (1,500 pCi/L) and gross beta activities (940 pCi/L) were highest in samples collected from Pantano Wash. In general, radionuclides tend to sorb on sediment; therefore, suspended gross alpha and gross beta activities tend to be higher for samples collected at higher flow regimes with high concentrations of suspended sediment as is typical of samples collected from the ephemeral and intermittent streams in the study area. Maximum values for dissolved gross alpha and gross beta activities were 240 (White and Garrett, 1984) and 22 pCi/L (U.S. Geological Survey, 1983), respectively, for two samples collected on the Gila River at Gillespie Dam from 1980 to 1983; however, radionuclide concentrations in nearly half of the 34 samples analyzed were below reporting limits during moderately high flows. Although the maximum gross alpha activities for these surface-water sites are higher than the limit for surface waters that are designated as domestic water sources (15 pCi/L; State of Arizona, 1996), the effect on human health is minimal because these sites do not supply water for human consumption.

Pesticides

Few investigators have analyzed pesticides in streamflow samples in the study area because of the ephemeral or intermittent nature of streams in the areas where most pesticide use occurs—namely in areas of agricultural and urban development. Stormwater runoff has been the focus of monitoring by the cities of Phoenix and Tucson as part of their compliance with the National Pollutant Discharge Elimination System (NPDES). The USGS, in cooperation with the Flood Control District of Maricopa County, monitored stormwater in three Phoenix area municipalities from 1991 to 1993 (Lopes and others, 1995). Organochlorine pesticides were seldom detected in urban stormwater and were not detected in streamflow or stormwater from drainage basins with largely undeveloped land. In stormwater samples from drainage basins with heavy industrial, residential, and commercial land use, concentrations of the insecticide, dichlorodiphenyltrichloroethane (DDT), were less than 0.10 µg/L; whereas, concentrations of the DDT degradation product, dichlorodiphenyldichloroethylene (DDE), were 0.04 to 1.1 µg/L. DDT and DDE could be residuals left over from the 1950's and 1960's when the land was used for agriculture, or they could be byproducts from the manufacture of other organochlorine pesticides that are still in use (Lopes and others, 1995).

In a USGS study of an ephemeral drainage in central Tucson, multiple organochlorine pesticides were detected at four sites in Rillito Creek and its tributaries (Tadayon and Smith, 1994). At one site, aldrin, chlordane, dichlorodiphenyldichloroethane (DDD), DDT, DDE, dieldrin, and endrin were detected in seven out of eight surface-water samples collected from 1987 to 1992. Chlordane was detected at all four sites sampled. Some of the pesticides could be the result of frequent use of chemicals to control weeds and insects (including termites) in an urban setting of multiple land uses.

The lower Hassayampa River, the Salt River below 23rd Avenue in Phoenix, and the Gila River from the confluence with the Salt River to Painted Rock Reservoir are impaired because of DDT metabolites and methylmercury found in fish and other aquatic wildlife (Marsh, 1994). Concentrations of toxaphene in biota at levels of concern for wildlife also have been found at the Hassayampa and Gila River sections (Marsh, 1994). As a result, a fish-consumption advisory is in effect in all three areas because these contaminants have bioaccumulated in the food chain to concern levels, and thus, present a health risk to people who consume the fish, turtles, crayfish, or other aquatic organisms.

Other Organic Compounds

The organic compounds detected in surface water in the study area are broadly classified as those that are regulated by the USEPA (referred to as priority pollutants), volatile organic compounds (VOC's), and oil and grease. With the exception of contaminants found in Nogales Wash, and those released by the 1993 floods—previously described in the introduction to this section—organic compounds were detected primarily in urban runoff in the CAZB study area.

The priority pollutants bis(2-ethylhexl)-phthalate and fluoranthene were detected in 5 of 15 surface-water samples collected from the Rillito Creek Basin in Tucson (Tadayon and Smith, 1994). Distribution of organic contaminants probably is the result of intense urbanization at the sites where detections occurred. In Phoenix, total phenols—components of automobile exhaust—were detected in about 55 percent of the urban stormwater samples collected by the USGS and the City of Phoenix from October 1991 to August 1993, and concentrations ranged from less than 1 to 1,900 μg/L (Lopes and others, 1995). The maximum concentration exceeds the aquatic and wildlife criteria of 1,000 μg/L established for the Salt River, the major river in the area, but does not exceed any human health limits (State of Arizona, 1996). Total phenols were detected in about 50 percent of the samples from the Salt River in Phoenix from 1991 to 1993, and concentrations ranged from 1 to 2 μg/L. In addition, Lopes and others (1995) found that organochlorine pesticides and semivolatile and volatile organic compounds were seldom detected in urban stormwater in the Phoenix area.

Few investigators have determined the occurrence and distribution of VOC's in streamflow in the study area. VOC's were not detected in samples of stormwater runoff collected at four sites in Tucson from 1987 to 1992 (Tadayon and Smith, 1994). In the Phoenix area, semivolatile and volatile organic compounds were detected in 7 of 30 runoff samples collected from light industrial and commercial drainage basins (Lopes and others, 1995). Detected compounds included polyaromatic hydrocarbons, plasticizers, and gasoline additives (methyl *tert*-butyl ether or MTBE). Sampling of water from Buckeye Canal, west of Phoenix, has resulted in one industry being cited by the ADEQ for nonsupport due to detections of bromoform, tetrachlorethane, dichloroethylene, and trichloroethane (Marsh, 1994).

Oil and grease, probably from roads and parking lots, are commonly detected in urban runoff. In the Rillito Creek Basin, oil and grease were detected in stormwater-runoff samples from all four sampling sites (Tadayon and Smith, 1994). In Phoenix, oil and grease, in concentrations ranging from less than 1 to 9 mg/L, were detected in about 80 percent of the urban-stormwater samples collected by the USGS and the City of Phoenix as part of the study by Lopes and others (1995).

Bacteria and Protozoans

Sewage effluent, urban runoff, and livestock grazing in riparian areas are the major sources of bacteria and protozoans in streamflow. Bacteria concentrations tend to be highest during the period of summer thunderstorms (July–August). As previously mentioned, effluent-dependent waters throughout the CAZB study area (table 5; fig. 20) are frequently out of compliance with State surface-water quality standards for bacteria, particularly fecal coliform bacteria. The highest levels of fecal coliform bacteria have been measured in streamflow contaminated by overflows of raw sewage in Nogales, Arizona, near the border between the United States and Mexico. The highest count of fecal coliform bacteria measured in Phoenix urban runoff (1,600,000 col/mL) also may be associated with sewer overflows (Lopes and others, 1995). In rural areas, high levels of fecal coliform bacteria are attributed to open-range livestock.

Giardia and *Cryptosporidium* are two protozoans commonly found in Arizona streams. *Giardia* appears to be linked to the presence of treated or untreated municipal wastewater in the stream; whereas, *Cryptosporidium* appears to be linked to cattle-grazing activities in the river bottoms (Marsh, 1994).

Sediment

High suspended-sediment concentrations are typical of streams in an arid region but can be exacerbated by human and animal activities—such as hydromodification of the stream channels and flood plains, agriculture, grazing, mining, and dam construction. In addition, sediment may carry inorganic and organic ions or compounds. Trace elements tend to adhere to the surface of sediment particles, and a strong positive correlation exists between decreasing sediment grain size and increasing trace-element concentrations (Horowitz, 1985).

Suspended-sediment concentrations rarely exceed several thousand milligrams per liter in the Central Highlands but often may be two to three orders of magnitude higher in the Basin and Range Lowlands. The two highest suspended-sediment concentrations measured in the Central Highlands, 25,600 mg/L at a discharge of 1,120 ft^3/s in Pinal Creek at Inspiration Dam and 11,700 mg/L at 122,000 ft^3/s in the Salt River near Roosevelt Lake, were measured during the peak flood of record in January 1993. The maximum suspended-sediment concentration measured in the Basin and Range Lowlands was 208,000 mg/L at a discharge of 600 ft^3/s in the San Pedro River at Winkelman on August 1, 1977. Snowmelt in the Central Highlands mobilizes less surficial material more slowly than runoff from thunderstorms. In addition, fewer sources of fine-grained material occur in the bedrock canyons of the Central Highlands, and more vegetative cover is available in this area to decrease erosion of surficial material. In contrast, river and stream drainages in the Basin and Range Lowlands are subject to torrential rains during summer thunderstorms, and an abundant supply of sediment can be transported in braided river channels. In addition, less vegetative cover is available in the Basin and Range Lowlands to hold surficial sediments.

Resource extraction (active, inactive, and abandoned mines; fig. 21) and natural mineralization are primary sources of trace elements that can attach to suspended sediments and be carried in surface water. Arsenic, beryllium, mercury, selenium, and copper (Marsh, 1994) occur in naturally high concentrations in rocks and (or) soils in the study area and thus provide a readily available source of contaminants. Sediments contaminated by these elements as well as lead, cadmium, zinc, and thallium have been documented in many parts of the study area as part of surface-water-quality monitoring programs of the ADEQ (Marsh, 1996).

Organic contaminants on sediments have been identified downstream from agriculture, point sources, and urban runoff. The most commonly identified organic compounds include DDT metabolites, toxaphene, dieldrin, and chlordane. Contaminated sediments have been found in the lower Hassayampa River and along the lower Salt River from Granite Reef Dam to its confluence with the Gila River, and from the Gila and Salt confluence to Painted Rock Reservoir—a reach length of 114 mi (Marsh, 1994).

Aquatic Biota and Accumulation of Contaminants in Bed Sediment and Biota

Descriptions of biological communities and habitat conditions are essential for an overall assessment of the status of water resources (Gilliom and others, 1995). Three taxonomic groups of aquatic biota—fish, macroinvertebrates, and algae—are sampled in the NAWQA program because they respond differently to various environmental stresses. Algae respond in days or weeks to changes in their environment and are valuable indicators of rapid changes in water-resource conditions; whereas, fish are longer-term accumulators on the basis of their life span (years to decades; Gilliom and others, 1995). Macroinvertebrates are between fish and algae and live in close association with the streambed sediments.

In addition to determining surface-water (water column) quality and describing aquatic communities and habitat, characterization of the occurrence and distribution of chemical contaminants in streambed sediment and biological tissues is part of the NAWQA program. Sediment samples are useful in determining the fate of contaminants many of which adsorb to fine sediment. Biological-tissue samples provide a direct measure of the availability of contaminants to aquatic organisms.

In 1992, ADEQ collected macroinvertebrates, algae, and water-quality samples and evaluated habitat at more than 100 surface-water sites (Spindler, 1996) in an effort to develop biological criteria (biocriteria) for assessment of water quality. Biocriteria complement chemical data when evaluating water quality and consist of narrative (or, in some cases, numeric) statements concerning the biological communities that are expected for given water bodies within stated use categories. This is the first effort to characterize stream systems for the entire State. Sampling sites were selected to represent conditions of little or no surficial disruption by grazing, mining, agriculture, or urban land uses. Aquatic macroinvertebrates and algae from pool and riffle habitats on small to medium-sized perennial streams were collected using standardized methods (Meyerhoff and Spindler, 1994) adapted from rapid bioassessment protocols of the USEPA (Plafkin and others, 1989). Macroinvertebrate and algae data indicate the biological health of aquatic communities and will be used to establish narrative biological criteria for inclusion in the State's rules for surface-water-quality standards (Spindler, 1996).

Aquatic Biota

Eighteen species of fish are indigenous (native) to the CAZB study area (Dr. W.L. Minckley, Professor, Arizona State University, written commun., 1995; table 7, this report). Of these, 1 species is extinct (the Monkey Spring pupfish, *Cyprinodon sp.*), and the remaining 17 are either listed as State or Federal threatened or endangered (T and E) species or are candidates for such listing. Of the 17 candidate or listed species, 6 have been extirpated (locally but not globally extinct) from the study area, although a number of these are the subjects of reintroduction efforts.

Macroinvertebrate data from the biocriteria sampling of ADEQ in 1992 (Spindler, 1996) showed that several taxa were found at all of the sites (Baetidae larvae, *Caenis, Choroterpes/Thraulodes*, other Leptophlebiidae larvae, and *Tricorythodes*); however, these taxa were dominant at desert lowland sites. Stoneflies were mainly found in high-altitude, cold-water streams; whereas, mayflies and caddisflies were widely distributed among the sites although particular taxa of mayflies and caddis flies were limited to the high-altitude streams.

Mayfly genera characteristic of such higher altitude streams were *Ameletus, Cinygmula, Epeorus, Ephemerella*, and *Paraleptophlebia*. Mayfly taxa that dominated desert streams were those from the families Baetidae and Leptophlebiidae, and the genera *Caenis, Choroterpes/Thraulodes*, and *Tricorythodes*. Mayflies typical of a transition zone between the higher altitudes and the deserts were *Isonychia, Rhithrogena, Serratella*, and *Traverella*.

Caddisfly families Brachycentridae, Glossosomatidae, Lepidostomatidae, and Limnephilidae appeared to be characteristic of higher altitude streams; whereas, the genera *Chematopsyche* and *Leptonema* were commonly found in higher order stream systems with large watershed areas. No caddis taxa were unique to desert streams; rather taxa common in all streams were found in greater abundances in the lowland streams.

Spindler (1996) concluded that the aquatic macroinvertebrate communities are most correlative with altitude and watershed area rather than ecoregion designation. Spindler (1996) found that aquatic-macroinvertebrate communities clustered into three general groups associated with: (1) montane upland streams, (2) desert lowland streams, and (3) large streams in a transition zone between the montane upland streams and desert lowland streams. Algae data from the biocriteria study had not been released at the time this report was prepared.

Reconnaissance surveys of aquatic invertebrates were made by ADEQ on two effluent-dependent reaches—one on the Santa Cruz River near Tucson and the other on the Salt and Gila Rivers near Phoenix (Lin Lawson, hydrologist, ADEQ, written commun., 1990). Few taxa were collected from these waters. Most types that were collected are considered tolerant of poor water quality. A more intensive study of the Santa Cruz River downstream from the Nogales International WWTP (Lawson, 1995) found that un-ionized ammonia near the treatment plant had severe effects on fish populations. Water quality improved downstream on the basis of measures of macroinvertebrate communities, but macroinvertebrate communities in the effluent-dependent reaches did not attain control-site conditions (Lawson, 1995).

Contaminant Accumulation in Aquatic Biota and Sediments

The findings of a number of studies of contaminant accumulation in aquatic biota and sediments within or adjacent to the CAZB study area are presented in this section on a stream-by-stream basis. Although some studies examined bioaccumulation in aquatic and terrestrial taxa (King and others, 1992; Baker and King, 1994; King and Baker, 1995), only those results pertaining strictly to aquatic organisms that are of interest to the CAZB study are discussed in this section. Conclusions and interpretations of studies used in this report are taken directly from the original source.

Table 7. Native fish species, Central Arizona Basins study area

[Data from Dr. W.L. Minckley, professor, Arizona State University, written commun., 1995. Listing status: Status of species under the Endangered Species Act: Endangered—species is in danger of extinction; threatened—species could become endangered if current populations were to decline; candidate 2—species is under study for potential listing as threatened or endangered. River basins: H, Hassayampa; AF, Agua Fria; S, Salt; V, Verde; SC, Santa Cruz; SP, San Pedro. River subbasins listed in parentheses () where species formerly present, now extirpated or extinct; brackets {} indicate species almost certainly present historically but no known specimens in museums]

Common name	Scientific name	Habitat	Abundance	Listing status	Subbasins where present
Gila trout	*Oncorhynchus gilae gilae*	Highland streams	Rare	Endangered	V, {AF}
Apache trout	*Oncorhynchus gilae apache*	Highland streams	Rare	Threatened	S
Longfin Dace	*Agosia chrysogaster*	Lowland streams	Frequent to locally common	Candidate 2	H, AF, S, V, SC, SP
Bonytail	*Gila elegans*	Large rivers	Extirpated[1]	Endangered	(S), (V), {SP}
Gila Chub	*Gila intermedia*	Mid-elevation streams	Sporadic	Candidate 2	H, AF, S, V, SC, SP
Roundtail Chub	*Gila robusta*	Lowland to mid-elevation streams	Rare	Candidate 2	S, V, SP
Spikedace	*Meda fulgida*	Large rivers to mid-elevation streams	Rare	Threatened	{H}, AF, S, V, SP
Woundfin	*Plagopterus argentissimus*	Large lowland rivers	Extirpated	Endangered	{S}, {V}
Colorado squawfish	*Ptychocheilus lucius*	Large lowland rivers	Extirpated[1]	Endangered	S, V, SP
Speckled Dace	*Rhinichthys osculus*	Large rivers to highland streams	Frequent to locally common	Candidate 2	H, AF, S, V, SC, {SP}
Loach minnow	*Tiaroga cobitus*	Mid-elevation streams	Rare	Threatened	AF, S, SC, {SP}
Sonora sucker	*Catostomus insignis*	Large rivers to mid-elevation streams	Frequent	Candidate 2	{H}, {AF}, S, V, SC, SP
Flannelmouth sucker	*Catostomus latipinnis*	Large lowland rivers	Extirpated	Candidate 2	{S}, {V}, {SP}
Desert sucker	*Catostomus clarki*	Large rivers to mid-elevation streams	Frequent to locally common	Candidate 2	H, AF, S, V, SC, SP
Razorback sucker	*Xyrauchen texanus*	Large lowland rivers	Extirpated[1]	Endangered	S, V, SP
Desert pupfish	*Cyprinodon macularius macularius*	Large rivers to low-elevation streams	Extirpated[1]	Endangered	{H}, {AF}, S, {V}, SC, SP
Monkey Spring pupfish	*Cyprinodon sp.*	Endemic to a single spring	Extinct	Extinct	(SC)
Sonoran topminnow (formerly Gila topminnow)	*Poeciliopsis occidentalis occidentalis*	Large rivers to low-elevation streams	Rare[1]	Endangered	{H}, AF, S, {V}, SC, SP

[1]Species has been reintroduced as part of recovery efforts.

Unlike the water-quality standards for surface water and ground water related to different uses, there is

> "...a critical lack of standards, criteria, or other guidances for assessing water quality based on sediment and fish/wildlife tissue monitoring..."

(Marsh, 1994). A variety of assessments have been used to evaluate contamination in tissue including the U.S. Fish and Wildlife Service's "levels of concern" that are defined as the 85th-percentile concentration of contaminants in fish tissue determined as part of the agency's National Contaminant Biomonitoring Program (NCBP; Schmitt and others, 1990; Schmitt and Brumbaugh, 1990). Many of the bioaccumulation reports discussed below use the NCBP 85th-percentile concentration.

San Pedro River—King and others (1992) reviewed background information pertaining to contaminants in the San Pedro River. Contamination by trace elements, sulfate, and water with low pH derived from spills at the Cananea Mine in the headwaters of the San Pedro River in Sonora, Mexico, has been documented (Arizona Game and Fish Department, 1980). Several spills from the mine have resulted in localized fish kills. Occasional major releases have eliminated all aquatic life for about 60 mi north of the Arizona-Mexico border (Arizona Game and Fish Department, 1980).

King and others (1992) reported that organochlorine pesticides, particularly DDE and DDT, were detected in fish from the river near St. David in 1986. Average concentrations of ammonia (6,460 µg/L) and antimony (111 µg/L), and maximum concentrations of lead (61 µg/L), arsenic (80 µg/L), and mercury (0.3 µg/L) were detected in surface-water samples taken near the Apache Powder Superfund site also near St. David (Clement International Corporation, 1992). These concentrations are higher than thresholds of expected effects on aquatic biota (King and others, 1992).

King and others (1992) collected sediment and biota samples from nine locations within the San Pedro River Basin in Arizona during July and August of 1987 to assess organochlorine and trace element concentrations. Seven of their sampling sites were on the mainstem of the San Pedro River from the border between Arizona and Mexico to the confluence with the Gila River. The other two sampling sites were on tributaries to the San Pedro River—the Babocomari River in the southern (upstream) part of the basin and Aravaipa Creek, in the northern part (downstream) of the basin. Aquatic biota were not collected from one location (St. David) probably because of a lack of streamflow to support aquatic organisms.

Composite samples of sediment, each consisting of three subsamples from the top 3.9 in., were obtained from each of the nine locations using a stainless steel spoon. Composite samples of 3 to 50 specimens of 5 species of fish [longfin dace, desert sucker, Sonora sucker (*Catostomus insignis*), black bullhead (*Ictalurus melas*), and green sunfish (*Lepomus cyanellus*)] were collected for analysis of organochlorine compounds and trace elements. The number of specimens collected was determined by the availability of fish and mass requirements for analysis (Kirke King, biologist, U.S. Fish and Wildlife Service, oral commun., 1995). Longfin dace were collected from seven of the eight stations from which aquatic biota were collected, the exception being the Babocomari River. Other species were collected from fewer locations.

King and others (1992) found no organochlorine compounds in sediments; however, concentrations of DDE in longfin dace ranged from 0.01 to 0.03 µg/g wet weight. DDE also was detected in tissue of desert sucker (0.01 µg/g) and green sunfish (0.02 µg/g). In addition to DDE, the chlordane component t-nonachlor was detected in longfin dace from two sampling locations at a concentration of 0.01 µg/g. King and others (1992) concluded that the low levels of organochlorine compounds detected suggested that resident biota probably were not affected by these substances. Difficulties with laboratory quality control precluded interpretation of the trace-element analyses (King and others, 1992).

Upper Gila River (upstream from San Carlos Reservoir in Arizona and New Mexico)—This section of the Gila River is immediately east of the CAZB study area; however, land uses along this section of the river may affect ecological and contaminant processes within the study area. The reservoir upstream from the boundary of the CAZB study area undoubtedly affects in-stream biology (Ward and Stanford, 1979).

As part of the U.S. Fish and Wildlife Service's NCBP described earlier, two composite samples of common carp (*Cyprinus carpio*) and one of largemouth bass (*Micropterus salmoides*) were collected from San Carlos Reservoir in 1984–85 (Schmitt and others, 1990; Schmitt and Brumbaugh, 1990). Fifteen of the 21 organic compounds for which analyses were made were not detected in the fish tissue. The six compounds detected were p,p' DDE; p,p' DDD; p,p' DDT; arochlor 1248 (a polychlorinated biphenyl); nonachlor, and toxaphene; however, they were in low concentrations (0.01 to 0.11 μg/g, wet weight) relative to national values (Schmitt and others, 1990).

Fish tissue also was analyzed for arsenic, cadmium, copper, lead, mercury, selenium, and zinc (Schmitt and Brumbaugh, 1990). Concentrations of arsenic and mercury in the largemouth-bass sample exceeded the NCBP 85th percentiles. Concentrations of both cadmium and zinc exceeded the NCBP 85th percentiles in both carp samples, and NCBP 85th-percentile concentrations of copper and lead were exceeded in one carp sample (table 8).

In a later study by Baker and King (1994), surface water, sediment, and fish tissue from San Carlos Reservoir and other locations on the upper Gila River were sampled in 1990. Only those data for fish tissue from San Carlos Reservoir are shown in table 9. Noting that it was a subjective value, Baker and King (1994) estimated the 90th percentile of organic compounds from the NCBP for purposes of comparison (table 9). Heptachlor was detected in tissues of largemouth bass at 0.03 μg/g, wet weight, a value equal to the estimated 90th percentile of the NCBP. No other organic analytes in fish tissue were equal to or greater than the estimated NCBP 90th percentiles. Although detected in all fish-tissue samples, concentrations of DDE were less than the estimated NCBP 90th percentile and criteria for the protection of wildlife of the National Academy of Sciences/National Academy of Engineering (NAS/NAE; U.S. Environmental Protection Agency, 1974) for DDT and metabolites. DDD was detected in one fish-tissue sample but also was less than the NCBP 90th-percentile and comparison concentrations of NAS/NAE (Baker and King, 1994).

Comparisons of inorganic-analyte results to the NCBP 85th percentile in fish-tissue samples from San Carlos Reservoir (Baker and King, 1994) revealed elevated concentrations of arsenic, cadmium, copper, mercury, and zinc (table 10). Selenium was less than the NCBP 85th percentile in all samples. Lead, antimony, beryllium, nickel, and silver were not detected in any of the samples. Non-NCBP analytes detected in fish-tissue samples from San Carlos Reservoir included aluminum, barium, chromium, iron, magnesium, manganese, molybdenum, strontium, tin, and vanadium. Baker and King (1994) did not compare data for aluminum, barium, iron, manganese, molybdenum, strontium, tin, or vanadium. Concentrations of cadmium, chromium, and mercury were compared to values that represent potential hazards to fish, wildlife, and invertebrates (Eisler, 1985; 1986; 1987). Baker and King (1994) reported values of cadmium (0.1 μg/g) and chromium (1.0 μg/g) in a carp sample that equaled and exceeded the values of Eisler (1985, 1986). All fish-tissue samples from San Carlos Reservoir except carp exceeded the mercury value (0.1 μg/g) reported by Eisler (1987), and high levels of mercury may cause adverse effects in fish-eating birds.

Middle Gila River (Coolidge Dam to Ashurst-Hayden Dam)—Low diversity and abundances of aquatic fauna are apparently characteristic of this section of the Gila River. Previous studies cited by King and Baker (1995) indicate that parts of the river were contaminated resulting in the elimination of aquatic life in the 1970's. Kepner and others (1983) postulated that reduced habitat diversity caused by large discharges from Coolidge Dam resulted in reduced populations of aquatic organisms (particularly fish and invertebrates). King and Baker (1995) collected no fish at 10 of 11 sampling locations and 3 species at 1 site (Gila River below Donnely Wash) on the middle Gila River during sampling done between June 1991 and May 1992; whereas, in surveys 10 years earlier, 10 species, all in low abundance, were collected along the river (Kepner and others, 1983). Differences in the goals of the studies, sampling locations, and sampling methods may explain these differences.

Table 8. Concentrations of trace elements in fish, San Carlos Reservoir, 1984-85

[Data from Schmitt and Brumbaugh (1990). Values in micrograms per gram wet weight; NCBP 85, National Contaminant Biomonitoring Program 85th-percentile concentration]

Species	Arsenic	Cadmium	Copper	Mercury	Lead	Selenium	Zinc
NCBP 85	0.27	0.05	1.0	0.17	0.22	0.73	34.2
Common carp	.14	.16	.92	.10	.17	.37	46.23
Common carp	.18	.16	1.15	.08	.25	.38	50.34
Largemouth bass	.43	.01	.88	.18	.02	.52	13.38

Table 9. Concentrations of organochlorine analytes in fish, San Carlos Reservoir, 1990

[Data from Baker and King (1994). Values in micrograms per gram wet weight; NCBP 90, National Contaminant Biomonitoring Program 90th-percentile concentration; <, less than; p,p'DDE, dichlorodiphenyldichloroethylene; p,p'DDD, dichlorodiphenyldichloroethane]

Species	Heptachlor	Total chlordane	p,p'DDE	p,p'DDD
NCBP 90	0.03	0.24	0.4	0.25
Channel catfish	.02	.03	.25	.01
Common carp	<.01	<.01	.12	<.01
Largemouth bass	.03	.04	.10	<.01
Channel catfish (edible portion)	<.01	<.01	.11	<.01
Largemouth bass (edible portion)	<.01	<.01	.01	<.01

Table 10. Concentrations of trace elements in fish, San Carlos Reservoir,1990

[Data from Baker and King (1994). Al, aluminum; As, arsenic; Ba, barium; Cd, cadium; Cr, chromium; Cu, copper; Fe, iron; Hg, mercury; Mg, magnesium; Mn, manganese; Mo, molybdenum; Se, selenium; Sr, strontium; Sn, tin; V, vanadium; Zn, zinc; <, less than. Values in micrograms per gram wet weight; NA, not applicable; NCBP 85, National Contaminant Biomonitoring Program 85th-percentile concentration (Schmitt and Brumbaugh, 1990)]

Species	Al	As	Ba	Cd	Cr	Cu	Fe	Hg
NCBP 85	NA	0.27	NA	0.05	NA	1.0	NA	0.17
Channel catfish	49	.2	1.3	<.05	0.9	1.0	65	.19
Carp	163	.1	4.3	.1	1.0	1.6	228	.08
Large-mouth bass	7	.3	.6	<.05	.8	.6	26	.17
Channel catfish, edible portions	1	.1	.5	<.05	<.1	.3	7	.32
Large-mouth bass, edible portions	1	.1	.5	<.05	<.1	.3	4	.32

Species	Mg	Mn	Mo	Se	Sr	Sn	V	Zn
NCBP 85	NA	NA	NA	0.73	NA	NA	NA	34.2
Channel catfish	432	4.5	0.9	.47	38	3.9	0.6	26.1
Carp	562	7.8	1.0	.51	55	3.2	.6	54.3
Large-mouth bass	484	2.0	1.0	.45	38	3.3	<.5	14.8
Channel catfish, edible portions	231	<.1	<.5	.21	.3	<.5	<.5	5.5
Large-mouth bass, edible portions	315	<.1	<.5	.51	.6	<.5	<.5	4.1

King and Baker (1995) sampled the middle Gila River for organochlorine and trace-element contamination of sediments and biota. Organochlorine compounds were not detected in sediment samples; however, DDE was detected at 0.05 μg/g (wet weight) in a composite sample of two common carp. A composite of two channel catfish (*Ictalurus punctatus*) contained DDE at 0.03 μg/g; whereas, DDE was not detected (detection level 0.01 μg/g) from a composite of five desert suckers (*Catostomus clarki*). King and Baker (1995) concluded that such concentrations were below thresholds considered hazardous to fish and wildlife.

Copper was the only trace element detected by King and Baker (1995) in sediment samples from middle Gila River that was present in concentrations higher than background levels for Arizona soils. Concentrations of copper in sediments from Mineral Creek (fig. 1), which drains an area of mining and mineralization southwest of Globe, were 2,660 mg/kg or 89 times higher than the mean value for the State. All four sites on the Gila River downstream from Mineral Creek had copper concentrations in sediments that exceeded background ranges.

Concentrations of contaminants in fish tissue were compared to the 85th percentiles of arsenic, cadmium, copper, mercury, selenium, and zinc reported from the NCBP (table 11; King and Baker, 1995). Concentrations of arsenic, cadmium, copper, mercury, and selenium in fish-tissue samples exceeded the NCBP 85th percentile in at least one species. King and Baker (1995) also note that concentrations of aluminum, boron, barium, cadmium, copper, iron, manganese, nickel, and vanadium found in a sample of desert sucker were two to eight times the values found in common carp and channel catfish; whereas, mercury, selenium, and zinc were highest in carp. Concentrations of mercury in all fish collected were higher than the level of concern (0.1 μg/g) for ingestion by fish-eating birds (Eisler, 1987). The carp sample had a selenium concentration of 1.10 μg/g wet weight, or 4.09 μg/g dry weight (King and Baker, 1995), which is higher than the level that is considered potentially harmful to predatory wildlife (3.0 μg/g, dry weight; Lemly, 1993). Beryllium, lead, and molybdenum were not detected in any of the fish samples.

Various Rivers and Canals (Bald Eagle Prey)—King and others (1991) collected fish samples from eight locations near bald eagle (*Haliaeetus leucocephalus*) nesting sites in order to assess contaminant levels in potential eagle prey. Seven of the eight sites are in or adjacent to the CAZB study area—Lake Pleasant (Agua Fria River), two sites on the Verde River (for the purposes of this report hereafter referred to as upper and lower), Tonto Creek (tributary to Salt River), Roosevelt Lake (Salt River), Salt River at Redmond, and San Carlos Reservoir (Gila River adjacent to the CAZB). According to King and

Table 11. Concentrations of trace elements in fish, middle Gila River

[Data from King and Baker (1995). Al, aluminum; As, arsenic; B, boron; Ba, barium; Cd, cadium; Cr, chromium; Cu, copper; Fe, iron; Hg, mercury; Mg, magnesium; Mn, manganese; Ni, nickel; Se, selenium; Sr, strontium; V, vanadium; Zn, zinc. Values in micrograms per gram wet weight; NA, not applicable; NCBP 85, National Contaminant Biomonitoring Program 85th-percentile concentration (Schmitt and Brumbaugh, 1990)]

Species	Al	As	B	Ba	Cd	Cr	Cu	Fe
NCBP 85	NA	0.27	NA	NA	0.05	NA	1.0	NA
Channel catfish	7.8	.48	<0.40	0.33	<.05	0.35	0.38	19
Common carp	17.3	.23	<.40	1.53	<.06	.40	2.15	35
Desert sucker	157.0	.38	.45	4.16	.06	.54	4.43	175

Species	Hg	Mg	Mn	Ni	Se	Sr	V	Zn
NCBP 85	0.17	NA	NA	NA	0.73	NA	NA	34.2
Channel catfish	.12	273	3.1	<0.12	.37	20.1	0.14	17.0
Common carp	.26	299	4.6	<.12	1.10	22.3	.24	28.2
Desert sucker	.13	353	40.5	.36	.64	22.0	.61	13.8

others (1991), the Salt River and Tonto Creek sites were not thoroughly sampled.

King and others (1991) used the geometric mean value of the NCBP for comparison of organochlorine compounds. Although chlordane was detected in some fish samples from all locations except Tonto Creek and the Salt River, the detected concentrations were below the geometric mean of the NCBP (Schmitt and others, 1990). DDE was detected in all samples; however, in some cases, concentrations of DDE were less than or about equal to the NCBP geometric mean. King and others (1991) also noted that concentrations of DDE in fish were less than the lower limit of concern for eggshell thinning in eagles. Dieldrin and PCB's were detected in low concentrations from only a few samples.

Levels of many inorganic analytes were greater than the NCBP 85th percentile. At least one sample from each location, except the Salt River and Tonto Creek, exceeded the NCBP 85th percentile for arsenic, copper, and zinc. Concentrations of cadmium exceeded the NCBP 85th percentile in at least one sample from the two sampling locations on the Verde River and in samples from Roosevelt Lake, and San Carlos Reservoir. Mercury was detected at concentrations higher than the NCBP 85th percentile in at least one sample from all locations except the lower Verde River site and Roosevelt Lake. Selenium was detected at concentrations higher than the NCBP 85th percentile in at least one sample from the two sites on the Verde River and in samples from Lake Pleasant, and San Carlos Reservoir.

Lead was detected at 0.67 μg/g in one fish from the Verde River (location not given); the NCBP 85th percentile is 0.22 μg/g. Beryllium was detected in fish from the Verde River and San Carlos Reservoir at 0.01 to 0.02 μg/g. Beryllium was not a NCBP analyte. Other non-NCBP analytes detected in fish tissue by King and others (1991) were aluminum, chromium, iron, manganese, and nickel.

King and others (1991) concluded that elevated trace-element concentrations, particularly mercury, but also cadmium and selenium, could potentially pose threats to eagles because of food-chain transfer. They noted that elevated trace-element concentrations were also a source of concern for the welfare of endangered fish species.

Historical Chlorinated Hydrocarbons in the Phoenix area—From 1965 to 1967, Johnson and Lew (1970) evaluated concentrations of DDT and metabolites, toxaphene, and dieldrin in fish tissues from the lower Colorado River; and from the Mesa, Tempe, and Buckeye canals associated with the Salt and Gila Rivers in the Phoenix area. In 12 of 23 samples from those canals in the Phoenix area, residues of DDT, DDE, or DDD exceeded the interim guideline of the Federal Drug Administration of 5 ppm for fish shipped in interstate commerce (Johnson and Lew, 1970).

Fish Advisories and Sediment Contamination—Marsh (1994) reports that 1,618 mi of about 5,600 stream miles assessed (29 percent) in Arizona were impaired by contaminants due to exceedances of various standards. In 1992, as a supplement to chemical criteria for surface water, the ADEQ adopted State standards for fish consumption to provide for the protection of human health (Marsh, 1994; State of Arizona, 1992).

Fish-consumption advisories have been issued for the following stream sections within the CAZB study area (Sam Rector, biologist, Arizona Department of Environmental Quality, oral commun., 1998):

- Salt River from 59th Avenue to the confluence with the Gila River,
- Gila River just above the confluence with the Salt River to Painted Rock Reservoir, and
- Hassayampa River from Buckeye Canal to the confluence with the Gila River.

Toxaphene, dieldrin, chlordane, metabolites of DDT, and mercury are listed as the contaminants or stressors of concern for all three river reaches (Marsh, 1994). Probable contaminant sources are agriculture, urban runoff, and point sources along all three reaches. Rural runoff is an additional probable source for the Hassayampa River. In addition, arsenic exceeded fish-consumption standards throughout the Verde River Basin, but further investigations of human-health risks are needed before a fish advisory is considered (Marsh, 1994).

Sediment contamination, defined as exceedances of State health-based guidance levels for human consumption of sediments, also has been documented for locations within riverine systems of the CAZB study area (Marsh, 1994; table 12).

Trace elements predominate as a result of mining influences and natural weathering of metal-bearing rocks.

Ground-Water Quality

The quality of water in Arizona's aquifers is monitored by the ADEQ through the aquifer protection program (Marsh, 1994). The cornerstone of this program is the State's aquifer water-quality standards (table 12; State of Arizona, 1996), which apply to aquifers that are protected for drinking-water use. These State standards or maximum-contaminant levels (MCL's) are in most cases equal to or more stringent than the primary drinking-water regulations of the USEPA (table 12; U.S. Environmental Protection Agency, 1994a, b).

The general chemical and biological quality of ground water in the CAZB study area is adequate for most uses; however, concentrations of some chemical constituents have been higher than limits set by the USEPA or ADEQ. In some cases, high concentrations of constituents found in ground water can be attributed to natural sources, but in other cases, they are the result of human activities.

High concentrations of dissolved solids in ground water are a concern in many parts of the CAZB, and high concentrations of specific elements, such as fluoride and sulfate, are problems in local areas. Concentrations of nutrients, specifically nitrate, that exceed primary drinking-water regulations of the USEPA (10 mg/L; table 12; U.S. Environmental Protection Agency, 1994a, b) have been found in ground water throughout the study area with the highest concentrations in the Basin and Range Lowlands. Chromium, arsenic, boron, barium, fluoride, selenium, and lead are found locally in high concentrations in ground water because of an oxidizing geochemical environment and human activities. Ground water in all of the alluvial basins has concentrations of dissolved oxygen higher than 3 mg/L because of the oxidizing geochemical environment (Robertson, 1991). Radon activities in ground water are a concern in many parts of the CAZB and can be attributed to natural sources. Two pesticides—1,2-dibromo-3-chloropropane (DBCP) and 1,2,dibromoethane (EDB)—used primarily in cotton fields and citrus orchards, have been detected in ground water near Phoenix (Daniel and others, 1988). Some sites with known contamination by volatile organic chemicals and petroleum hydrocarbons in ground water generally are in large urban areas. Large populations of fecal-indicator bacteria in ground water occur locally in the study area, generally where underground septic systems are present (Marsh, 1994).

Dissolved Solids

The dissolved-solids concentration can be an indicator of the chemical quality of ground water. The oxidizing geochemical environment for ground water in the study area increases the solubility of some elements such as fluoride and selenium (Robertson, 1991), which increases the concentrations of these elements in ground water.

Robertson (1991) and Kister (1973) found that concentrations of dissolved solids in ground water were less than 1,000 mg/L in most of the 72 basins sampled in central and southern Arizona. The highest concentrations in ground water (greater than 3,000 mg/L) were along the Salt and Gila Rivers (Kister, 1973). In the study area, natural sources of dissolved solids in ground water generally include feldspars, gypsum, anhydrite, halite, calcite, dolomite, and ferromagnesium minerals (Robertson, 1991). Anthropogenic sources include water recharged from irrigation activities, dissolution of natural sources by mining activities, and wastewater effluent (Marsh, 1994). Elements that contribute to dissolved solids in ground water in the CAZB study area generally are calcium, sodium, magnesium, potassium, chloride, fluoride, silica, sulfur (as sulfate), and carbon (primarily as bicarbonate) (Robertson, 1991).

Trends of dissolved-solids concentration with depth were identified in some alluvial basins, but the results were not statistically significant ($p < 0.05$; Robertson, 1991). The dissolved-solids concentration increases with increasing depth in some basins, and in other basins, concentrations decrease with increasing depth. In the west Salt River Valley, concentrations of dissolved solids in ground water from the shallowest hydrogeologic unit are higher than concentrations in ground water from underlying units (Brown and Pool, 1989).

Table 12. Primary drinking-water regulations and State of Arizona aquifer water-quality standards for selected constituents

[Values, in milligrams per liter, as total recoverable fraction unless otherwise noted; pCi/L, picocuries per liter; μg/L, micrograms per liter; col/100 mg/L, colonies per 100 milliliters; dashes indicate no established limit]

Constituent	Primary drinking-water regulations[1]: Maximum contaminant level	Primary drinking-water regulations[1]: Secondary maximum contaminant level	State of Arizona: Aquifer water-quality standards[2]
Inorganic constituents			
Chloride	—	250	—
Fluoride	4.0	2.0	4.0
Sulfate	[3]500	250	—
Dissolved solids	—	500	—
Nutrients			
Nitrate (as N)	10	—	10
Trace elements			
Arsenic	.05	—	.05
Barium	2	—	2
Beryllium	.004	—	.004
Cadmium	.005	—	.005
Chromium	.1	—	.1
Copper	1.3	1.0	—
Iron	—	.3	—
Lead	.015	—	.05
Manganese	—	.05	—
Mercury	.002	—	.002
Nickel	.1	—	.1
Selenium	.05	—	.05
Silver	—	.1	—
Zinc	—	5	—
Radionuclides			
Radium–226 (pCi/L)	[4]20	—	—
Radium–228(pCi/L.)	[4]20	—	—
Radium–226 plus radium–228(pCi/L).	5	—	5
Radon (pCi/L)	[4]300	—	—
Uranium	[4].020	—	—
Pesticides (μg/L)			
1,2-dibromo-3-chloropropane (DBCP)	.2	—	.2
2,4-dichlorophenoxyacetic acid (2,4-D)	70	—	70
2,4,5-trichlorophenoxypropionic acid (2,4,5-TP; Silvex)	50	—	50
1,2-dibromoethane (EDB)	.05	—	.05
Endrin	2	—	2
Lindane	.2	—	.2

[1]See footnotes at end of table.

Table 12. Primary drinking-water regulations and State of Arizona aquifer water-quality standards for selected constituents—Continued

Constituent	Primary drinking-water regulations[1]: Maximum contaminant level	Primary drinking-water regulations[1]: Secondary maximum contaminant level	State of Arizona: Aquifer water-quality standards[2]
Pesticides (μg/L)—Continued			
Methoxychlor	40	—	40
Toxaphene	3	—	3
Volatile organic constituents (μg/L)			
Trichloroethylene (TCE)	5	—	5
Tetrachloroethylene (PCE)	5	—	5
Methyl *tert*-butyl ether (MTBE)	[5]20–40	—	[35]
Total trihalomethanes (THM's)	—	—	100
Benzene	5	—	5
Vinyl chloride	2	—	2
Carbon tetrachloride	5	—	5
1,2-dichloroethane (1,2-DCA)	5	—	5
1,1-dichloroethylene (1,1-DCE)	7	—	7
1,1,1-trichloroethane (1,1,1-TCA)	200	—	200
Para-dichlorobenzene	75	—	75
Biological constituents			
Total coliform (col/100 mg/L)	([6])	—	([7])

[1]U.S. Environmental Protection Agency (1994a, b, 1996). The primary maximum contaminant levels are maximum limits for water delivered for public drinking-water consumption. The secondary maximum contaminant levels are nonenforceable guidelines that indicate an upper aesthetic limit.

[2]State of Arizona (1996). These standards apply to aquifers classified for drinking water protected use. Values in brackets are human health-based guidance levels (HBGL's) for ingestion of contaminants in drinking water and soil (State of Arizona, 1992).

[3]Proposed regulation (U.S.Environmental Protection Agency, 1996).

[4]Maximum contaminant levels for radium–226, radium–228, radon, and uranium are proposed standards under consideration. (U.S. Environmental Protection Agency, 1991a, b).

[5]U.S. Environmental Protection Agency (1997).

[6]If more than 40 samples, no more than 5 percent of the samples may be total coliform positive. If less than 40 samples, no more than one sample may be total coliform positive.

[7]State of Arizona (1996). For membrane filter technique, the number of coliform bacteria shall not exceed one per 100 milliliters in two samples collected within a 2-week period.

Three sites in the Central Highlands have concentrations of dissolved solids or individual constituents that exceed the drinking-water regulations of the USEPA. Locally, ground water near Camp Verde (fig. 1) in the Verde Valley contains concentrations of dissolved solids and fluoride that exceed the SMCL's of 500 mg/L and 2.0 mg/L, respectively, for drinking water determined by the USEPA (table 12; Marsh, 1994). In addition, selenium concentrations exceeded the primary MCL for drinking water set by the USEPA (table 12). The Verde Formation and local alluvial deposits are considered to be the sources of these constituents (Twenter and Metzger, 1963; Owen-Joyce and Bell, 1983). Concentrations of sulfate higher than the SMCL (250 mg/L; table 12) were identified as a problem in ground water north of Sedona (Marsh, 1994). In ground water near Globe, specific-conductance values (indicators of dissolved-solids concentration) of as much as 5,000 μS/cm are related to mining activities in the area (Marsh, 1994; Eychaner and Stollenwerk, 1985).

High concentrations of dissolved solids, sulfate, fluoride, and selenium are found at more sites in the Basin and Range Lowlands than in the Central Highlands (Marsh, 1994). In an ADEQ analysis of Statewide data, ground water near Phoenix and Casa Grande had the highest median concentrations of dissolved solids (950 and 525 mg/L, respectively; Marsh, 1994). Near Buckeye (fig. 1), west of Phoenix, ground water has been pumped from beneath agricultural lands to remove waters with high concentrations of dissolved solids (Arizona Department of Water Resources, 1994a). Large evaporite deposits near Eloy and Phoenix (Peirce, 1976) are a natural source of salts that cause high specific-conductance values locally. The halite deposit near Phoenix, referred to as the "Luke salt body," has resulted in specific-conductance values in ground water as high as 70,000 µS/cm (Gellenbeck, 1994).

Near Casa Grande, samples from seven sites had concentrations of dissolved solids that were higher than the SMCL, and one site had concentrations of dissolved selenium that were higher than the MCL (Marsh, 1994; Arizona Department of Water Resources, 1994a). According to Thomsen and Baldys (1985), the concentrations of dissolved solids in wells in the Casa Grande area increased from the 1950's to the early 1980's as a result of "dewatering of sediments and deepening of wells" related to heavy pumping. Some of the variation found in this area may be the result of changes in sampling techniques and analysis methods (Thomsen and Baldys, 1985).

Near Sierra Vista and south near the international border with Mexico, sulfate concentrations exceed the SMCL (table 12; Marsh, 1994). At a site in Green Valley (fig. 1), concentrations of dissolved sulfate in ground water that are higher than the SMCL are related to nearby mining (Marsh, 1994). Concentrations of dissolved fluoride that are attributed to local geologic deposits (Robertson, 1991) exceed the SMCL (table 12) in Casa Grande (Thomsen and Baldys, 1985; Robertson, 1991), Tucson (Laney, 1972), Phoenix (Osterkamp, 1974; Marsh, 1994), and Sierra Vista (Marsh, 1994).

Nutrients

Dissolved nitrate is the most common nutrient found in ground water within the CAZB study area. Many sources of nitrogen in the study area are associated with human activities and natural sources. Fertilizers, septic tanks, wastewater-treatment facilities, and concentrated animal-feeding operations have been mentioned as anthropogenic sources of nitrogen by previous investigators (Laney, 1972; Maricopa Association of Governments, 1978, 1979; Salt River Project, 1982, 1986; Hem, 1985; Arizona Department of Water Resources, 1994a; Marsh, 1994; and Robertson, 1991). Natural sources of nitrogen include decaying organic matter, weathering of rocks, and biological fixation associated with legumes followed by sufficient precipitation to leach nitrogen to the ground water (Laney, 1972; Hem, 1985; and Robertson, 1991).

In general, the highest concentrations of dissolved nitrate are in ground water in the Basin and Range Lowlands, although a few sites that have high concentrations of nitrate have been reported in the Central Highlands (Marsh, 1994; Arizona Department of Water Resources, 1994a). The largest number of public water systems in Arizona that had concentrations of dissolved nitrate that were higher than the MCL (10 mg/L; table 12) are in Maricopa and Pinal Counties (Marsh, 1994). Many studies of nitrate in ground water have focused on Phoenix and the surrounding communities—Buckeye, Chandler, Gilbert, Glendale, Mesa, Peoria—(Osterkamp, 1974; Kister, 1974; Maricopa Association of Governments, 1978, 1979; Salt River Project, 1982, 1986; Rice and others, 1989; and Gellenbeck, 1994) where high concentrations of dissolved nitrate have been identified since the early 1900's (Lee, 1905). These studies were done to determine the extent, trends, and sources of nitrate because ground water is a major source of drinking water in this area. Concentrations of dissolved nitrate do not appear to be consistently increasing or decreasing with time throughout this area and vary with the quantity of water pumped, the hydrogeologic unit in which the screened interval of the well is located, and the extent of irrigation activities (Maricopa Association of Governments, 1978; Salt River Project, 1986).

Agricultural activities, treated sewage effluent, dairy and feed lots, and natural sources could contribute nitrogen to the ground water (Gellenbeck, 1994).

Trace elements

Hexavalent chromium, arsenic, boron, barium, iron, manganese, mercury, lead, and copper have been identified in previous studies as environmental contaminants in the CAZB study area (Laney, 1972; Kister, 1973; Robertson, 1991; Arizona Department of Water Resources, 1994a; and Marsh, 1994). The oxidizing geochemical environment of ground water in the study area greatly increases the solubility of hexavalent chromium, arsenic, boron, barium, selenium, and lead; consequently, these elements often occur in higher than trace or minor concentrations (Robertson, 1991).

Natural and anthropogenic sources of trace elements in ground water have been identified in the study area. Ground water can leach minerals from the surrounding rocks or sediments, which are natural sources of trace elements. Volcanic rocks can provide hexavalent chromium, evaporite deposits can provide large amounts of boron, and geologic deposits that contain concentrated arsenic and barium can contribute these elements to ground water (Robertson, 1991). Anthropogenic sources of these trace elements include landfills, mining operations, and manufacturing activities such as the electronics, aviation, and plating industries (Marsh, 1994).

In the Central Highlands, concentrations of dissolved arsenic that are higher than the State standard of 0.05 mg/L (table 12) are found in ground water from the Verde Formation near Camp Verde (Owen-Joyce and Bell, 1983; Robertson, 1991; Arizona Department of Water Resources, 1994a; and Marsh, 1994). The source of arsenic in this area is believed to be oxidized arsenic compounds in a mudstone unit of the aquifer (Owen-Joyce and Bell, 1983). Concentrations of dissolved trace elements in ground water that exceed the MCL's or SMCL's (table 12) near Camp Verde include mercury (MCL), iron (SMCL), and manganese (SMCL; Owen-Joyce and Bell, 1983). Ground water from Dewey, near Prescott, contains high concentrations of dissolved arsenic (0.065 mg/L; Marsh, 1994). High concentrations of some dissolved trace elements in ground water have been attributed to mining activities as at Globe, where MCL's for lead, cadmium, and fluoride (table 12); as well as SMCL's for iron, manganese, and copper (table 12) are exceeded (Marsh, 1994; Eychaner and Stollenwerk, 1985).

In the Basin and Range Lowlands, dissolved arsenic is common in ground water. Near Casa Grande and Phoenix, concentrations of dissolved arsenic higher than the MCL are attributed to natural geologic sources (Marsh, 1994; Arizona Department of Water Resources, 1994a). Concentrations of naturally occurring dissolved hexavalent chromium that are higher than the MCL (table 12) have been found throughout much of the Basin and Range Lowlands (Robertson, 1991; Marsh, 1994). Near the Tucson International Airport, ground water contains dissolved chromium at concentrations higher than the MCL (Marsh, 1994). Near Phoenix, concentrations of barium from a landfill source are higher than the MCL, and high concentrations of boron attributed to natural sources occur locally (Marsh, 1994; Gellenbeck, 1994).

Radionuclides

Naturally occurring uranium, radon, and radium are sources of radioactivity in ground water and result in radon activities in the study area that are higher than the proposed MCL of 300 pCi/L (table 12; Marsh, 1994). In the Central Highlands, activities of radon were higher than 300 pCi/L in ground water near Prescott (Marsh, 1994; Arizona Department of Water Resources, 1994a). Ground water more than 1,000 ft below land surface near Casa Grande also contains high activities of radon (Arizona Department of Water Resources, 1994a). Radon activities of as much as 5,600 pCi/L have been found in ground water in the Phoenix area (Marsh, 1994).

Pesticides

Two pesticides—DBCP and EDB—have been detected in ground water near Phoenix at concentrations higher than the MCL's of 0.2 and 0.05 μg/L, respectively (table 12; Daniel and others, 1988). Detections in ground water occurred throughout the ground-water basin west of Phoenix at concentrations from less than 0.01 to 50 μg/L for DBCP and less than 0.01 to 10 μg/L for EDB (Daniel and others, 1988). These detections include the highest reported concentrations in Arizona (Daniel and others, 1988). Detections of DBCP or EDB occurred in ground water from 33 wells supplying drinking water at the time of sampling (Daniel and others, 1988). DBCP and EDB were applied to soil to control nematodes in cotton fields and citrus groves in the Phoenix area from the 1950's to the 1970's. DBCP was first detected in ground water in Arizona in 1979, which prompted several studies to determine the extent of ground-water contamination by pesticides (Kister and others, 1988; Daniel and others, 1988). Agricultural application, disposal, and spills of DBCP and EDB may have been sources of these constituents in ground water. EDB also is used as an antiknock chemical in gasoline (Daniel and others, 1988; Marsh, 1994).

In addition to DBCP and EDB, there have been unconfirmed detections of benzene hexachloride and DDT and its degradation products in ground-water samples (Marsh, 1994). In addition to the Phoenix area, the Arizona Department of Water Resources (1994a) states that near Eloy

> "...herbicide and pesticide contamination of groundwater, probably resulting from well backflow or from incorrect container disposal or spillage has been documented."

Volatile Organic Compounds and Petroleum Hydrocarbons

VOC's are found in ground water primarily in urban areas in the CAZB study area and generally are associated with gasoline stations, high-technology manufacturing facilities, landfills, airport facilities, and dry-cleaning operations (Marsh, 1994). Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), State Water Quality Assurance Revolving Fund (WQARF), and Installation Restoration Program (IRP) sites have been the focus of VOC investigations in the CAZB study area (Marsh, 1994; Arizona Department of Water Resources, 1994a). Trichloroethylene (TCE) is the most frequently detected VOC in ground water in Arizona on the basis of data from ADEQ (Marsh, 1994).

In the Central Highlands, near Payson, tetrachloroethylene (PCE) from a dry-cleaning facility is in ground water (Marsh, 1994). Near Prescott, VOC's from a landfill and leaking underground-storage tanks have been found in ground water (Marsh, 1994). In the Basin and Range Lowlands, areas that are affected by VOC's are primarily centered around the large urban areas—Phoenix and Tucson. Six CERCLA sites and 14 WQARF sites are currently under investigation in the Phoenix area (Marsh, 1994). Ten of those sites have VOC contamination from industrial facilities, specifically electronic manufacturers. Some wells operated by the City of Phoenix are no longer used as a result of unacceptable levels of VOC's. These unused wells include 11 wells that contained ground water with concentrations of TCE that ranged from 9 to 300 μg/L). Near Tucson, one CERCLA site and four WQARF sites are currently under investigation (Marsh, 1994). These five sites include landfills, dry-cleaning facilities, airport facilities, and various other industries.

Contamination of ground water by petroleum hydrocarbons is a significant problem throughout Arizona but primarily occurs in urban areas. Marsh (1994) states that about 10 to 20 percent of the 1,473 reported leaking underground-storage tanks have affected ground water. Benzene, toluene, ethylbenzene, and xylene (BTEX) are chemicals related to petroleum fuels that are most commonly detected in ground water near leaking underground storage tanks (Marsh, 1994). Contamination of ground water by jet fuel also has been identified at some military installations in the study area (Marsh, 1994).

Methyl *tert*-butyl ether, a gasoline oxygenate used in the Phoenix and Tucson areas to enhance octane and improve the quality of automobile emissions, also has been found in ground water. Two wells operated by the City of Phoenix are no longer used because concentrations of MTBE in the ground water ranged from 46 to 200 μg/L (Marsh, 1994), which exceeded the MCL for MTBE. Concentrations of MTBE in this range probably indicate a point source such as a leaking underground storage tank (Squillace and others, 1996).

Bacteria

Data on populations of fecal-indicator bacteria that relate to ground water in the CAZB study area are limited, but contamination is known to occur locally. Possible sources of fecal-indicator bacteria in ground water include leachate from septic tanks; possible pathways to humans include poor well construction and poor well seals (Marsh, 1994). Dewey, Pinetop-Lakeside, and Sedona (fig. 1) have been affected by fecal-indicator bacteria in ground water (Marsh, 1994). Coliform populations that exceed the MCL (table 12) have been attributed to discharges from septic systems (Marsh, 1994).

SUMMARY

The CAZB study area represents an unusual opportunity for the NAWQA program to investigate water-quality issues in an arid environment. The 34,700-square-mile study area includes central and southern Arizona and about 1,000 mi^2 in northern Mexico. For the purposes of the CAZB study, the area is divided into two hydrologic provinces—the Central Highlands in the north and the Basin and Range Lowlands in the south.

The Central Highlands Province is characterized by mountainous terrain with shallow intermontane basins. Most of the perennial streams are in this province. The basins in the Central Highlands contain as much as 500 ft of basin-fill sediments of limited areal extent. In contrast, the mountain ranges in the Basin and Range Lowlands are small in areal extent compared to the basins, which may contain basin-fill deposits as much as 12,000 ft thick. Streams in the Basin and Range Lowlands typically are intermittent or ephemeral.

For the purposes of the CAZB study, the geology of the area was divided into four major units on the basis of lithology, hydrology, and physiography. From oldest to youngest they are bedrock of the mountains, sedimentary bedrock, basin fill, and stream alluvium. In the Central Highlands and the Basin and Range Lowlands, the basin-fill deposits are the major water-yielding units. To a lesser degree, sedimentary bedrock (Central Highlands) and stream alluvium (Central Highlands and Basin and Range Lowlands) are sources of ground water locally. The soils overlying these geologic units typically are moderately to poorly drained in the Central Highlands because they are underlain by shallow bedrock, are moderately to well drained in the western half of the Basin and Range Lowlands, and are poorly drained in the eastern half.

The arid to semiarid climate is characterized as highly variable from place to place and from year to year. Temperatures can range from more than 46°C on summer afternoons in the lowest valleys to -18°C on winter nights in the mountains. Mean annual precipitation ranges from 10 to 25 in./yr, and precipitation can be three times greater in wet years than in dry years. The climate in the Basin and Range Lowlands results in high evaporation rates (as much as 65 in./yr) and a long growing season (230 days), which contribute to the need for large quantities of water for irrigation.

As the population of the CAZB study area has grown by almost 1 million people (34 percent) from 1980–90, urban land area has increased twofold as rangeland and agricultural lands were reduced by 4 and 5 percent, respectively. Riparian areas and wetlands also have decreased in number and size. The increase in population and urban growth has caused an increase in municipal water use, although agriculture still accounted for 73 percent of all water used in the study area in 1990. Colorado River water and treated sewage effluent are being used in central and southern Arizona to meet the increasing demands for water.

Because of the small amount of precipitation the study area receives, surface water is a limited resource, and all base flow is appropriated. The CAZB study area is unique compared to less arid basins because the mean surface-water outflow from the area is only 528 ft^3/s from a total drainage area of 49,650 mi^2. The largest rivers—the Gila, Salt, and Verde—are perennial near their headwaters but become intermittent farther downstream because of impoundments and artificial diversions. Seasonal variations in streamflow, losses to ground-water recharge, and evapotranspiration also contribute to the depletion of base flow. Peak flows in rivers and streams in the Central Highlands occur from January through April and possibly May from snowmelt off the Mogollon Rim; whereas, peak flows in the Basin and Range Lowlands are the result of summer thunderstorms in July and August.

Ground water is the primary water supply in most areas of Arizona and the only source of drinking water being used by communities in the southernmost part of the study area. Ground water in much of the study area is being withdrawn at a greater rate than it is being replenished, which results in declining water levels and associated land subsidence and earth cracks, pumping of poorer quality water at depth, and ground water at depths from which it is economically infeasible to pump. Five ground-water AMA's have been established to minimize overdrafts and manage water supplies in critical areas such as Phoenix and Tucson.

Ground water in the basin fill and stream alluvium in the Central Highlands is typically under unconfined conditions and depth to water commonly ranges from land surface to a few tens of feet. Recharge is by stream infiltration, underflow from the surrounding consolidated-rock aquifers, and to a lesser extent, mountain-front recharge. Discharge occurs as base flow to streams and evapotranspiration.

The most productive aquifers in the study area are the thick basin-fill deposits in the Basin and Range Lowlands. Ground water generally is unconfined, and depth to water ranges from land surface to as much as 1,300 ft. The main sources of recharge are from runoff along the mountain fronts, stream infiltration, seepage from irrigation, and underflow from upstream basins. Discharge is by evapotranspiration, discharge to streams as base flow, underflow to downgradient basins, and by pumping.

The most common water-quality impairments in streams are high levels of trace elements, turbidity, salinity, and suspended solids, which are frequently the result of natural ambient conditions. Human activities that contribute to degradation of water quality include agriculture, hydromodification, resource extraction, and urban development. Other important surface-water quality issues that result from human activity include: (1) streamflows and riparian environments sustained by treated sewage effluent that has high concentrations of nutrients, fecal bacteria, and potentially toxic trace elements and organic compounds; (2) industrial, mining, agricultural, and municipal sources of contamination from Mexico; (3) unpredictable high streamflows causing sewage overflows and breaching, erosion, and washouts of landfills and mining operations along stream channels.

For overall assessment of surface-water quality, descriptions of the biological communities and habitat conditions are essential. Of the 18 native fish species in the CAZB study area, 1 is extinct and the remaining 17 are listed as threatened or endangered on State or Federal lists. Macroinvertebrate and algal communities and water have been sampled by ADEQ at more than 100 sites in an effort to develop biological criteria for the assessment of water quality. Macroinvertebrate communities were found to be correlative with elevation and watershed size rather than ecoregion designation and corresponded to three general ecosystems similar in range to the hydrologic provinces in Arizona.

Determinations of the accumulation of contaminants in bed sediment and biota are used in the NAWQA program as an additional indicator of water quality. According to several studies, organochlorine pesticides have been detected in fish-tissue samples from the middle and upper Gila River and the San Pedro River. Trace elements were detected in fish tissue in the middle and upper Gila and in sediments in the middle Gila River. Fish-consumption advisories have been issued for sections of the Salt, Gila, and Hassayampa Rivers to protect human health.

The general chemical and biological quality of ground water in the CAZB study area is adequate for most uses; however, concentrations of chemical constituents such as nitrate; some trace elements, organochlorine pesticides, and volatile organic compounds; dissolved solids; radon; and fecal bacteria exceed State or Federal drinking-water regulations in some areas. Nitrate is the most common nutrient in ground water in the study area. Sources of nitrate include agricultural activities, treated sewage effluent, dairy and feed lots, and natural sources. The highest concentrations of nitrate are found in wells in the Basin and Range Lowlands where concentrations of dissolved nitrate may exceed the MCL of 10 mg/L for drinking water particularly in Maricopa and Pinal Counties. Nitrate concentrations for ground water in Phoenix and surrounding areas do not show a consistent increase or decrease through time but vary with the quantity of water pumped, screened interval of the well, and extent of irrigation activities.

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