Water Quality in the Central Arizona Basins

Arizona, 1995–98

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

Circular 1213

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Front cover: Sabino Creek in Sabino Canyon near Tucson. The water is colored brown by natural tannin from plant material in the stream. *(Photograph by Gail E. Cordy.)*
Back cover: Left, view of Tucson from “A” Mountain; right, view of west side of the Whetstone Mountains, southeast of Tucson. *(Photographs by Alissa L. Coes.)*

Water Quality in the Central Arizona Basins, Arizona, 1995–98

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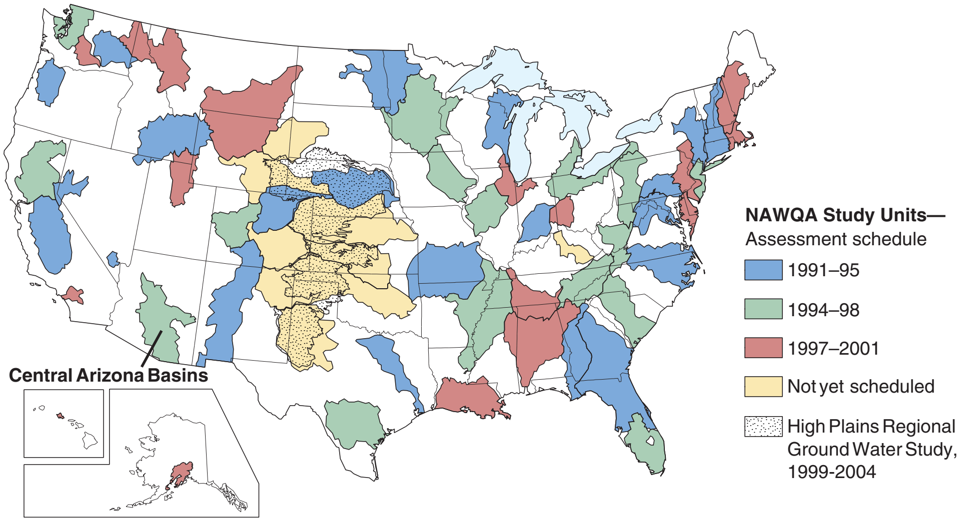
CONTENTS

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

THIS REPORT summarizes major findings about water quality in the Central Arizona Basins Study Unit that emerged from an assessment conducted between 1995 and 1998 by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program. Water quality is discussed in terms of local and regional issues and compared to conditions found in the 36 NAWQA study areas, called Study Units, assessed to date. Findings are also explained in the context of selected national benchmarks, such as those for drinking-water quality and the protection of aquatic organisms. The NAWQA Program was not intended to assess the quality of the Nation's drinking water, such as by monitoring water from household taps. Rather, the assessments focus on the quality of the resource itself, thereby complementing many ongoing Federal, State, and local drinking-water-monitoring programs. The comparisons made in this report to drinking-water standards and guidelines are only in the context of the available untreated resource. Finally, this report includes information about the status of aquatic communities and the condition of in-stream habitats as elements of a complete water-quality assessment.

Many topics covered in this report reflect the concerns of officials of State and Federal agencies, water-resource managers, and members of stakeholder groups who provided advice and input during the Central Arizona Basins assessment. Basin residents who wish to know more about water quality in the areas where they live will find this report informative as well.



THE NAWQA PROGRAM seeks to improve scientific and public understanding of water quality in the Nation's major river basins and ground-water systems. Better understanding facilitates effective resource management, accurate identification of water-quality priorities, and successful development of strategies that protect and restore water quality. Guided by a nationally consistent study design and shaped by ongoing communication with local, State, and Federal agencies, NAWQA assessments support the investigation of local issues and trends while providing a firm foundation for understanding water quality at regional and national scales. The ability to integrate local and national scales of data collection and analysis is a unique feature of the USGS NAWQA Program.

The Central Arizona Basins Study Unit is one of 51 water-quality assessments initiated since 1991, when the U.S. Congress appropriated funds for the USGS to begin the NAWQA Program. As indicated on the map, 36 assessments have been completed, and 15 more assessments will conclude in 2001. Collectively, these assessments cover about one-half of the land area of the United States and include water resources that are available to more than 60 percent of the U.S. population.

SUMMARY OF MAJOR FINDINGS

The Central Arizona Basins (CAZB) Study Unit of the National Water-Quality Assessment (NAWQA) Program covers 34,700 square miles in the Central Highlands and Basin and Range Lowlands hydrologic provinces. Phoenix was America's fastest growing city during the 1990s, and a population of about 3.8 million people is concentrated around the cities of Phoenix and Tucson. The climate is arid to semiarid, and dams on major perennial streams in the Central Highlands collect water for use in the Phoenix area. More than 50 percent of the water used in the Study Unit is ground water, which is often the sole source available. More than 70 percent of the water is used for agriculture, which accounts for 5 percent of the land use.

Stream and River Highlights

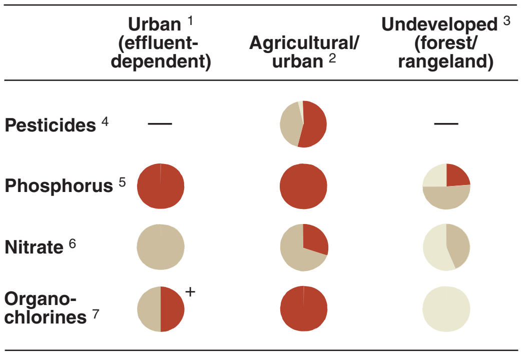
Most of the perennial streams in the Central Arizona Basins (CAZB) Study Unit drain relatively undeveloped basins in the Central Highlands that are covered by forests and (or) rangeland. The water quality of these forest/rangeland streams is primarily determined by natural factors, such as chemical weathering of rocks and soils. About 24 percent of samples from forest/rangeland streams had concentrations of phosphorus that exceeded the U.S. Environmental Protection Agency's (USEPA) desired goal for prevention of nuisance plant growth (eutrophication), whereas nitrate concentrations were typically less than the background levels for streams nationally. More than 75 percent of samples from the Salt River (above reservoirs) exceeded the USEPA drinking-water guideline for dissolved solids; however, rainfall and snowmelt runoff helped dilute these concentrations in reservoirs and in streamflow leaving the reservoirs.

In the Basin and Range Lowlands, streams typically flow only when it rains (ephemeral streams). Consequently, a small fraction of the nutrients and dissolved solids applied to the land surface by human, animal, and natural sources is transported to streams. The remaining dissolved solids and nutrients are accumulating in basins and can degrade ground-water quality.

Urban streams with perennial flow are sustained by the discharge of treated wastewater (effluent-dependent). Agricultural/urban streams are a combination of wastewater and irrigation return flows. All samples from both the effluent-dependent urban and agricultural/urban streams exceeded the USEPA's desired phosphorus goal for prevention of nuisance plant growth, and dissolved-oxygen concentrations were minimal for fish survival. Organochlorine compounds in streambed sediment and fish tissue from urban and agricultural/urban streams exceeded guidelines for protection of aquatic health and fish-eating wildlife.

- Effluent-dependent urban streams are valuable water resources; however, the water quality is poor.
- Organochlorine insecticides from past agricultural use persist in streams, streambed sediment, and fish tissue and are a concern because they exceed guidelines for protection of aquatic life and fish-eating wildlife.
- Insecticide concentrations in water from streams affected by agricultural and urban land uses were among the highest in the Nation.

Selected Indicators of Stream-Water Quality



🟥 Percentage of samples with concentrations **equal to or greater than** a health-related national guideline for drinking water, aquatic life, or water-contact recreation; or above a national goal for preventing excess algal growth

🟫 Percentage of samples with concentrations **less than** a health-related national guideline for drinking water, aquatic life, or water-contact recreation; or below a national goal for preventing excess algal growth

⬜ Percentage of samples with **no detection**

— Not assessed

[1] 91st Avenue Wastewater Treatment Plant, Santa Cruz River at Cortaro, Santa Cruz River at Tubac, Santa Cruz River near Nogales International Wastewater Treatment Plant (bed sediment only).

[2] Buckeye Canal near Avondale (surface water only), Hassayampa River near Arlington (surface water only), Buckeye Canal near Hassayampa (bed sediment only).

[3] San Pedro River at Charleston, Gila River at Kelvin, Salt River near Roosevelt, Verde River above West Clear Creek, Verde River below Tangle Creek, West Clear Creek.

[4] Insecticides, herbicides, and pesticide metabolites, sampled in water.

[5] Total phosphorus, sampled in water.

[6] Nitrate (as nitrogen), sampled in water.

[7] Organochlorine compounds including DDT and PCBs, sampled in bed sediment.

+ Although the 91st Avenue Wastewater Treatment Plant outfall is classified as urban, past agricultural land use in the area is the source of most organochlorine compounds at this site.

Trends in stream water quality

Water quality of forest/rangeland streams generally is improving over time. From 1950-90, dissolved-solids concentrations decreased in outflow from reservoirs as a result of dilution from increased precipitation and physical and chemical processes in reservoirs. A decrease in nutrient concentrations in forest/rangeland streams in the early 1980s to 1999 could be attributed to decreased contributions from natural sources, better land-use management practices upstream, or increased nitrogen use by aquatic life.

Major Influences on Streams and Rivers

- Natural factors such as chemical weathering of rocks and soil
- Precipitation
- Reservoirs
- Runoff from agricultural and urban lands
- Discharge of treated wastewater to streams

Ground-Water Highlights

Most of the ground water used in the CAZB Study Unit is pumped from basin-fill aquifers in the Basin and Range Lowlands. Water from major aquifers (basinwide) in the West Salt River Valley (WSRV), the Upper Santa Cruz Basin (USCB), and the Sierra Vista subbasin (SVS) generally meets existing USEPA standards and guidelines for drinking water with some exceptions. Nitrate and dissolved-solids concentrations in some samples from the WSRV and USCB exceeded USEPA drinking-water standards and guidelines. Shallow ground water from an agricultural area in the WSRV exceeded drinking-water standards and guidelines for nitrate and dissolved solids in more than 75 percent of samples. More than 90 percent of ground-water samples from the three basins exceeded the USEPA's proposed drinking-water standard for radon. A small percentage of samples exceeded drinking-water standards for arsenic, fluoride, and molybdenum. Samples from urban and agricultural areas contained low concentrations of numerous chemicals (pesticides and volatile organic compounds) that can be linked to household, industrial, and agricultural uses.

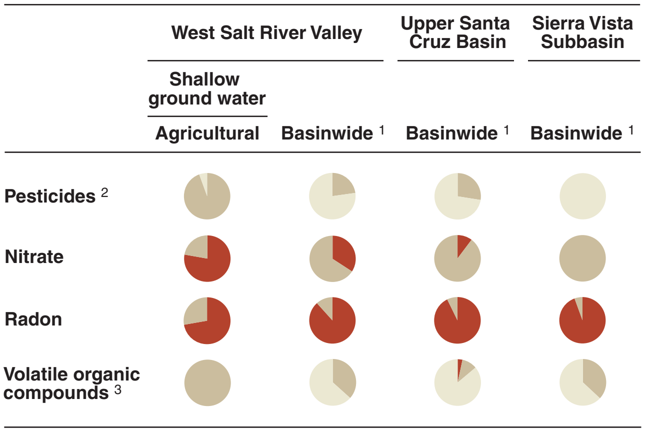
- Most of the deep wells yield old ground water that generally has not been affected by land uses in the last 50 years.
- Use of fertilizers and treated wastewater on agricultural and urban lands and the evaporation of irrigation water have resulted in the accumulation of nitrate and dissolved solids in shallow ground water.
- Adoption of draft or proposed USEPA drinking-water regulations for arsenic, radon, and uranium—constituents that occur naturally in the study area—will require most water suppliers and municipalities to treat their water to remove these constituents or find alternative supplies.
- Pesticides detected in ground-water basins with substantial agricultural and (or) urban development did not exceed USEPA drinking-water standards and guidelines.

Though trends in ground-water quality over time were not determined for the CAZB Study Unit, the data indicate possible future changes. As urban land use spreads with the growing population in the area, ground-water quality is likely to deteriorate, as indicated by detections of pesticides and volatile organic compounds in urban areas. Nitrate and dissolved solids accumulating in shallow ground water in the WSRV have the potential to degrade the quality of deeper drinking-water supplies.

Major Influences on Ground Water

- Geohydrology
- Dissolution of evaporites and other minerals
- Irrigation of agricultural and urban lands
- Agricultural and urban fertilizer and pesticide use

Selected Indicators of Ground-Water Quality



🟥 Percentage of samples with concentrations **equal to or greater than** a health-related national guideline or proposed regulation for drinking water

▨ Percentage of samples with concentrations **less than** a health-related national guideline or proposed regulation for drinking water

☐ Percentage of samples with **no detection**

[1] Most wells sampled as part of basinwide surveys were existing domestic (household) wells.
[2] Insecticides, herbicides, and pesticide metabolites, sampled in water.
[3] Solvents, refrigerants, fumigants, and gasoline compounds, sampled in water.

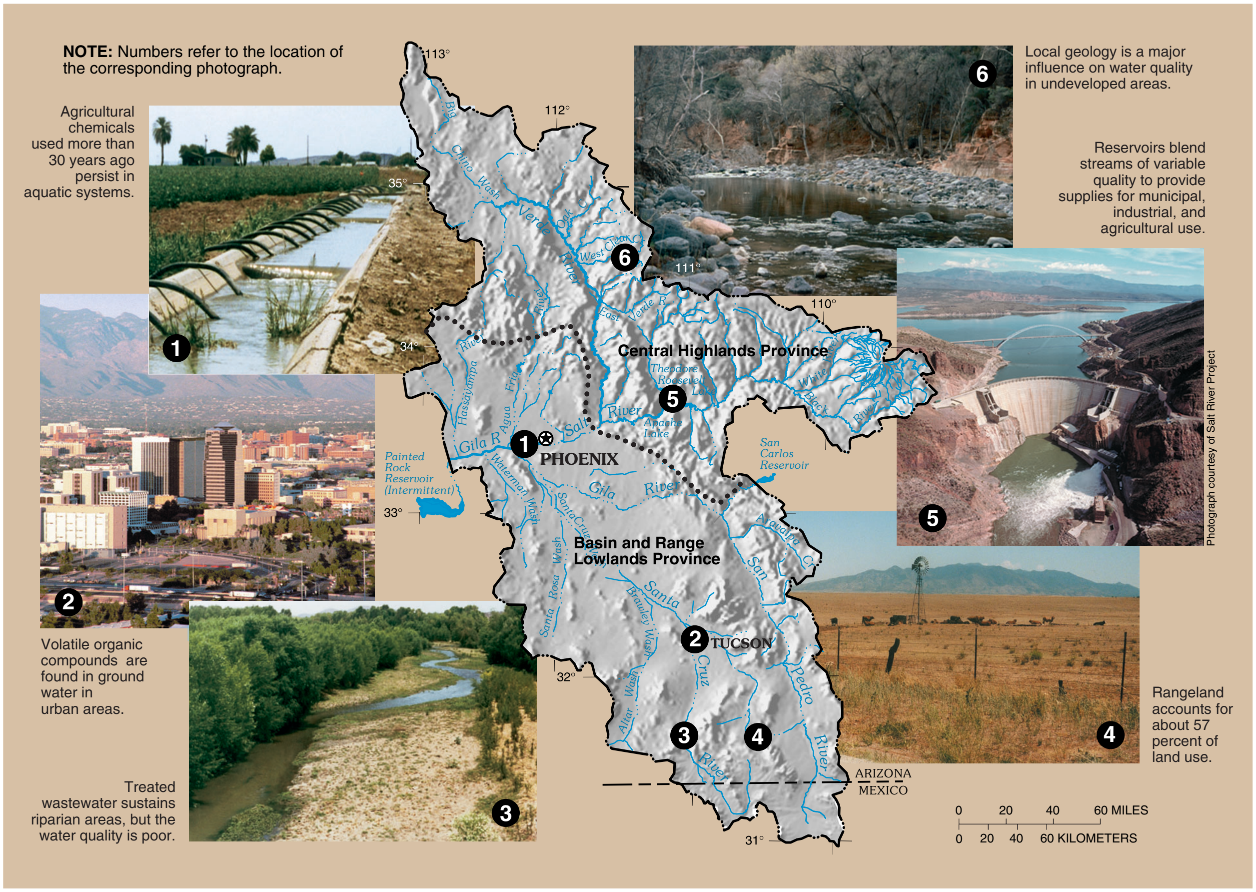
The Central Arizona Basins (CAZB) Study Unit encompasses a 34,700-square-mile area in central and southern Arizona and northern Mexico (fig. 1). The Study Unit includes large parts of two hydrologic provinces—the Central Highlands in the north and the Basin and Range Lowlands in the south (U.S. Geological Survey, 1969). Climate, hydrology, geology, land use, and water use are distinctly different in these two provinces.

The Central Highlands (fig. 1) have minimal development and are generally representative of natural conditions. Mountainous terrain with shallow, narrow intermountain basins predominates in the Central Highlands (Cordy and others, 1998). Forests and rangeland cover most of the province. The largest population is in the town of Prescott—35,785 (Arizona Department of Economic Security, rev. July 7, 2000), and small rural towns dot the region. Agricultural development is minimal except in the northernmost tip of the CAZB.

Most of the perennial streams in the Study Unit are in the Central Highlands (fig. 2). These streams derive their flow from mean annual precipitation of more than 25 inches in the mountains and from rainfall and snowmelt along the Mogollon Rim, which forms the northeastern border of the CAZB Study Unit.

Major streams having their headwaters in the Central Highlands include the Salt,Verde, and Agua Fria Rivers (fig. 2). These rivers flow year around (perennial) in their upper reaches but are captured for water supply for metropolitan Phoenix, power generation, and flood control before they reach the Basin and Range Lowlands.

Though streams provide most of the water for agricultural use in the Central Highlands, ground water is the main source for municipal and industrial supply (fig. 3). Much of the ground water is pumped from sedimentary deposits of limited



NOTE: Numbers refer to the location of the corresponding photograph.

Agricultural chemicals used more than 30 years ago persist in aquatic systems.

Volatile organic compounds are found in ground water in urban areas.

Treated wastewater sustains riparian areas, but the water quality is poor.

Local geology is a major influence on water quality in undeveloped areas.

Reservoirs blend streams of variable quality to provide supplies for municipal, industrial, and agricultural use.

Photograph courtesy of Salt River Project

Rangeland accounts for about 57 percent of land use.

Figure 1. The Central Highlands hydrologic province is mountainous compared to the large, elongate alluvial basins of the Basin and Range Lowlands. Reservoirs capture the perennial streams of the Central Highlands to provide water supplies for the Basin and Range Lowlands.

Base from U.S. Geological Survey digital data, 1:100,000, 1972
Albers Equal-Area Conic projection
Standard parallels 29°30', 45°30', central meridian 111°30'

Figure 2. Perennial streams in the Central Highlands, Colorado River water from the Central Arizona Project Canal, ground water, and treated sewage effluent fulfill water demands in the Basin and Range Lowlands.

extent in the valleys. As a result, some of the fastest-growing towns are being forced to seek alternative water supplies (Arizona Department of Water Resources, 1994). Natural factors such as dissolution of minerals in rocks and basin sediments are major influences on ground-water quality in the Central Highlands (Owen-Joyce and Bell, 1983; Marsh, 2000); however, activities such as mining have affected water quality locally (Brown and Favor, 1996).

The Basin and Range Lowlands (fig. 1) are characterized by a lack of perennial streams, the largest water demands, and reliance on ground water. Deep, broad alluvial basins separated by mountain ranges of small areal extent characterize this hydrologic province. The basins are filled with thick deposits of gravel, sand, silt, and clay and include interbedded evaporite deposits and volcanic rocks in places (Anderson and others, 1992). These basin-fill sediments can be 2,000 feet to as much as 12,000 feet thick and constitute the major aquifers that are often referred to as "basin-fill aquifers." The basin-fill aquifers contain large reserves of ground water that were recharged when Arizona's climate was much wetter than at present, possibly thousands of years ago.

Ephemeral streams are characteristic of the Basin and Range Lowlands (fig. 2). Very little natural streamflow is generated because the average annual rainfall is less than 10 to 15 inches except at the highest elevations. With the exception of some small, higher elevation streams and sections of the San Pedro River, most perennial streams in the Basin and Range Lowlands are effluent-dependent; that is, their flow is sustained all year by treated wastewater (fig. 2). Effluent-dependent streams have beneficial uses. They support riparian and aquatic communities where those communities would not otherwise exist. By recharging effluent, cities can accrue "credits" toward pumping of ground water from other locations in a basin (Arizona Department of Water Resources, 1994).

Rangeland is the predominant land use in the Basin and Range Lowlands. The two largest urban areas—Phoenix and Tucson—account for about 5 percent of the land use and include 75 percent of Arizona's 4.9 million people (Arizona Department of Economic Security, rev. July 7, 2000). Agricultural development, which is mostly west and south of Phoenix, is about 5 percent of the land use (Cordy and others, 1998). Cropland is the primary agricultural land use, and cotton is the main crop.

Water use in the Basin and Range Lowlands represents 96 percent of all water use in the CAZB Study Unit (Cordy and others, 1998). Agriculture is the largest water user (73 percent in 1990; fig. 3). Because of the general lack of surface-water resources in the Basin and Range Lowlands, ground-water is relied upon heavily to meet agricultural and municipal demands (fig. 3). In areas with substantial agricultural and (or) urban development, ground water has been and continues to be used more quickly than it can be replenished naturally. Ground-water levels have declined several hundred feet in areas with the heaviest pumping, and land subsidence has resulted in a loss in aquifer storage capacity (Arizona Department of Water Resources, 1994). To mitigate some of the problems caused by overpumping of ground water, Colorado River water is delivered to central Arizona by the Central Arizona Project (CAP) canal (fig. 2). CAP water is used for aquifer recharge and municipal and agricultural purposes.

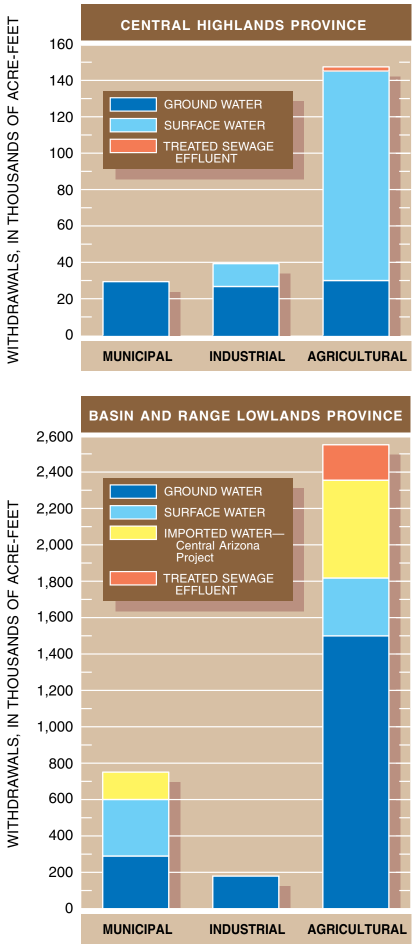


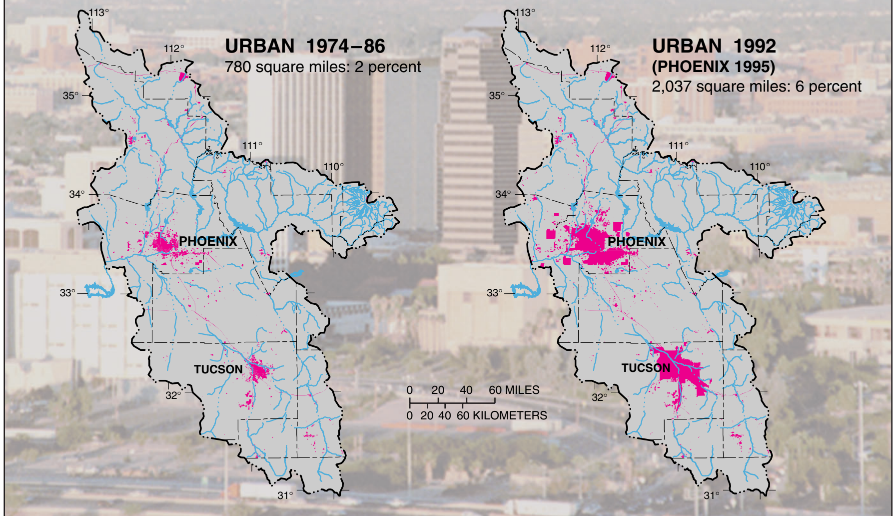
Figure 3. Water-use data for 1990 show the many sources of water used to meet demands in the CAZB Study Unit.

The study design focused on the effects of land use on water quality. Water, sediment, and biological samples were collected from streams in urban, agricultural, forest, and rangeland areas of the CAZB Study Unit to assess the overall quality of streams as well as the effects of specific land-use practices on stream-water quality (U.S. Geological Survey, 1999). At most sites, water samples were collected monthly from late 1995 through early 1998, and at some stream sites additional samples were collected during storms to assess the effects of stormwater runoff on water quality. Two stream sites were sampled twice monthly for 1 year to determine the occurrence and distribution of pesticides. A single round of sampling for contaminants in streambed sediment and fish tissue was completed in 1995–96 (See “Study Unit Design,” p. 26).

Ground water was sampled from wells in three alluvial basins in the Basin and Range Lowlands—the West Salt River Valley, the Upper Santa Cruz Basin, and the Sierra Vista subbasin. Existing wells were sampled in the three basins to assess overall water quality as well

Rapid population growth in central Arizona results in changes in land use.

As in many areas of the Southwestern United States, the population of Arizona is rapidly increasing. The population of the State increased from 2,716,546 in 1980 to 3,665,339 in 1990, an increase of 35 percent. Projections for 2000 indicate an additional 26 percent increase, to 4,924,350 (Arizona Department of Economic Security, rev. July 7, 2000). Much of this population increase has occurred in Tucson and metropolitan Phoenix (Maricopa County). As more and more people relocate to Arizona, desert and agricultural areas are being replaced by urban development. In addition to altering land use, this growth puts increasing demands on the limited water resources of this arid to semiarid area.



Urban land use increased substantially from 1974–86 to the early 1990s in the Phoenix and Tucson metropolitan areas.

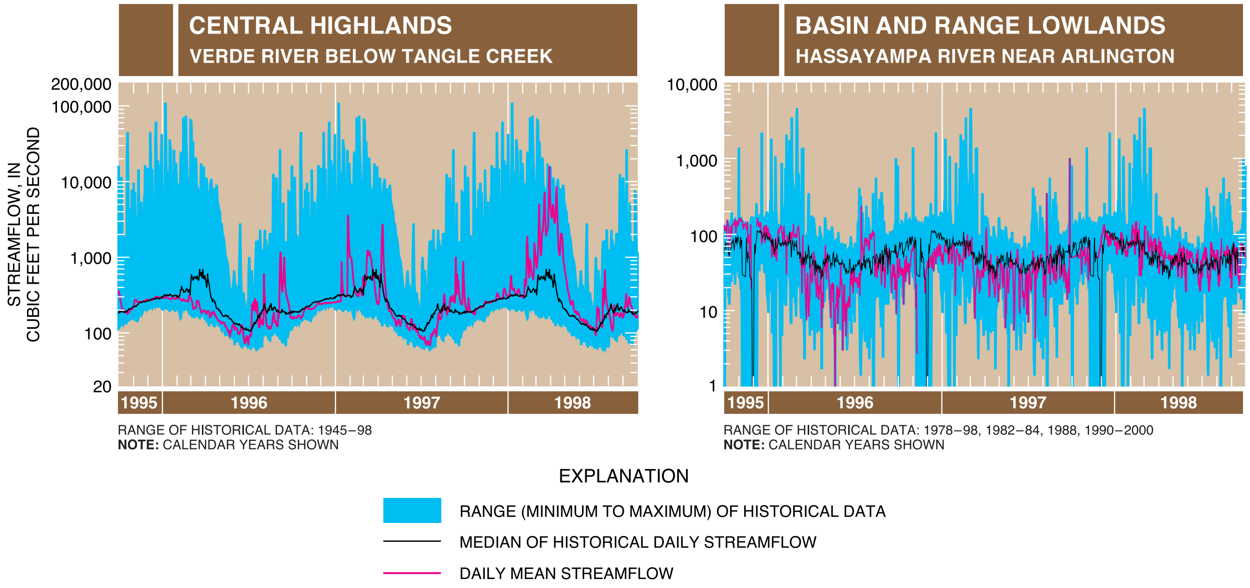


Figure 4. Streamflow in the Central Highlands increased each year from 1996–98 as indicated by the Verde River below Tangle Creek. In the Basin and Range Lowlands, streamflow is difficult to characterize because it is controlled by dams and (or) wastewater-treatment plants. For the Hassayampa River near Arlington, a Basin and Range Lowlands stream, summer streamflow in 1996 and 1997 was greater than the median historical daily value.

as the effects of human activities on water quality. In the West Salt River Valley, shallow monitoring wells were installed and sampled to determine the effects of irrigated agriculture on shallow ground-water quality. Existing ground-water-quality data were used to assess overall water quality in alluvial basins of the Basin and Range Lowlands that were not sampled.

This report is organized into sections on stream-water quality and ground-water quality. In each section, natural water quality, that is water that has been minimally affected by agricultural or urban development, is discussed followed by a discussion of the effects of human activities on water quality. This organization is designed to assist the reader in understanding the changes in natural water quality that result from human activities.

Understanding climatic and hydrologic conditions during the sampling period, 1995–98, is useful in interpreting the CAZB study results. The climate of the Study Unit is characterized by variability from place to place and also by large differences in precipitation from one year to the next. Precipitation can be three times greater in wet years than in dry years (Cordy and others, 1998).

In Central Highlands streams, represented by the Verde River below Tangle Creek (fig. 4), daily mean streamflow was successively higher from 1996 through 1998. Streamflow in 1998 generally was greater than the median of historical daily streamflow, and streamflow in 1996 was less than the median of historical daily streamflow (fig. 4).

Streamflow in the Basin and Range Lowlands is difficult to characterize because it is controlled by dams and (or) wastewater-treatment plants. The Hassayampa River near Arlington is an example of a Basin and Range Lowlands stream that is a combination of effluent and irrigation return flows most of the time, supplemented by flows from storm runoff (fig. 4). Streamflow at the site typically was less than the median historical daily streamflow during 1996 and 1997; however, summer streamflow in those years was greater than the median historical daily streamflow because of increased summer thundershowers. Streamflow during 1998 was about the same as the median of historical daily streamflow.

When streamflow exceeds base-flow as a result of rainfall or snow-melt runoff, dissolved-solids concentrations decrease in streams and reservoirs because of dilution. Nutrient concentrations increase with increased streamflow because precipitation and runoff carry more nutrients to streams.

Natural Stream Water Quality

In the CAZB Study Unit, perennial streams draining areas with little or no agricultural or urban land use represent baseline or “natural” conditions in the basins. These natural streams are referred to as “forest/rangeland streams” in this report because they drain basins that are 93 to 100 percent forest and (or) rangeland. Examples of forest/rangeland streams include the upper Verde, upper Salt, and upper Gila Rivers and West Clear Creek in the Central Highlands province and the upper San Pedro River in the Basin and Range Lowlands province. Because some of the forest/rangeland streams provide drinking water for Phoenix or recharge aquifers used for drinking water, the quality of these streams is compared to drinking-water standards and guidelines as well as to other water-quality criteria.

The water quality of forest/rangeland streams is primarily determined by natural factors. Processes such as chemical weathering of bedrock and soils, biological activity in soils (Likens and others, 1977), groundwater discharge to streams, and runoff determine the water quality of these streams. Locally, streamwater quality may be affected by agriculture, mining, or urban land use.

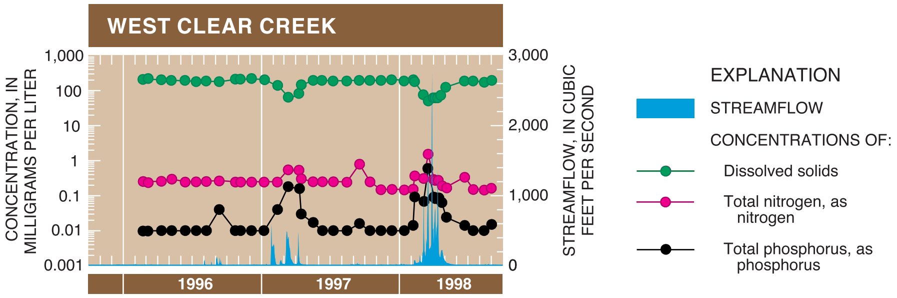


Figure 5. Concentrations of nutrients increase and concentrations of dissolved solids decrease during rainfall or snowmelt runoff.

Nutrient and dissolved-solids concentrations fluctuate seasonally in forest/rangeland streams. The patterns of rainfall and snowmelt runoff account for the seasonal fluctuations in concentrations of nutrients (fig. 5). Nutrient concentrations increase in streams during times of rainfall and snowmelt runoff because runoff carries nutrients washed off the land surface to streams, thereby increasing concentrations. Nitrogen in rainfall and snowmelt also adds to nutrient concentrations in streams. Conversely, during low streamflows, nutrient concentrations are lower because very little runoff reaches streams, and aquatic life in the streams take up the available nutrients.

Seasonal patterns of dissolved-solids concentrations are opposite to those of nutrients. During periods of low flow, the sources of streamflow are springs, which in some areas, such as the upper Salt River Basin, are quite saline (Feth and Hem, 1963). During periods of runoff, flow in streams is diluted, which lowers the dissolved-solids concentrations (fig. 5).

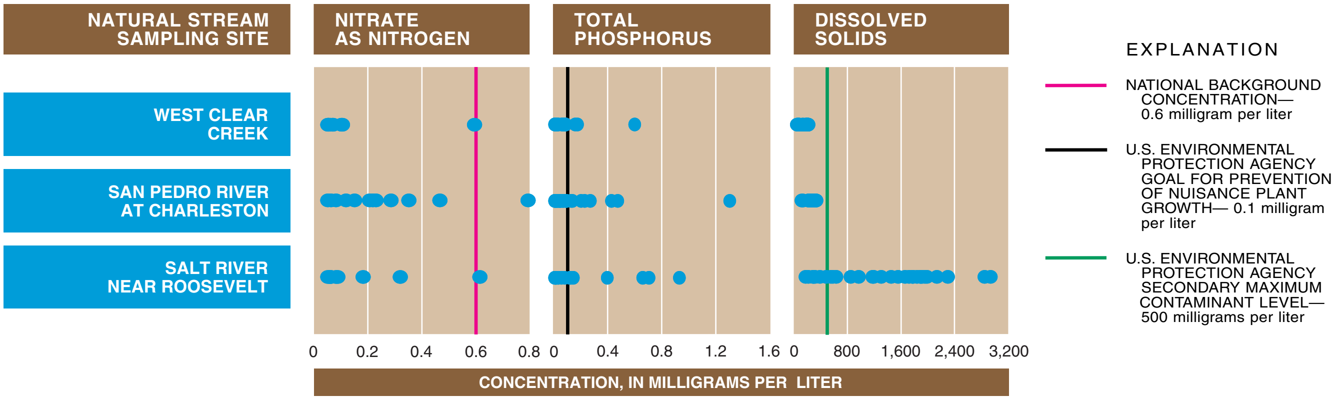


Figure 6. Nitrate concentrations in forest/rangeland streams are significantly lower than the maximum contaminant level of 10 mg/L. Most water samples from the upper Salt River exceeded the secondary maximum contaminant level for dissolved solids (500 mg/L) because saline springs sustain streamflow during periods of low flow.

Nitrate concentrations in forest/rangeland streams were significantly lower than the U.S. Environmental Protection Agency's (USEPA) Maximum Contaminant Level (MCL) of 10 mg/L. Nitrate was detected in 43 percent of the samples from forest/rangeland streams. None of the nitrate concentrations exceeded the MCL, which was established for the protection of human health (fig. 6), and less than 2 percent of the samples had concentrations of nitrate that were greater than the estimated national background concentration in streams of 0.6 mg/L (U.S. Geological Survey, 1999). Concentrations greater than background levels are generally considered to be the result of human activities. Samples that exceeded the background concentration were collected during high flows associated with rainfall or snowmelt runoff.

Twenty-four percent of the samples from forest/rangeland streams exceeded the USEPA desired goal for total phosphorus of 0.1 mg/L for the prevention of nuisance plant growth (fig. 6). The USEPA desired goal of 0.1 mg/L is the same as the estimated national background concentration for phosphorus (U.S. Geological Survey, 1999). Phosphorus enrichment in streams can lead to eutrophication; however, in the forest/rangeland streams, phosphorus concentrations exceeding the USEPA goal are generally limited to periods of rainfall and snowmelt runoff.

Dissolved-solids concentrations exceeded the USEPA Secondary Maximum Contaminant Level (SMCL) in 76 percent of samples from the upper Salt River. None of the samples from the upper San Pedro River or West Clear Creek exceeded the SMCL of 500 mg/L that is based on taste of drinking water (fig. 6). Samples that exceeded this drinking-water guideline were collected at times when streamflow was sustained by flow from springs. Saline springs drain into the upper Salt River (Feth and Hem, 1963), which accounts for the particularly large number of samples that exceeded the SMCL.

Total DDT concentrations in fish tissue samples from forest/rangeland streams were significantly less than the New York State guideline (Newell and others, 1987) for the protection of fish-eating wildlife. None of the other organochlorine pesticides and PCBs analyzed for were detected in fish tissue from forest/rangeland streams (Gebler, 2000). In addition, organochlorine compounds and PCBs were not detected in streambed sediment from these streams.

Stream water quality generally is improving on the basis of nutrient and dissolved-solids concentrations in forest/rangeland streams. Statistical analysis of nitrogen data for forest/rangeland streams indicates that concentrations have generally declined since the early 1980s (fig. 7). Phosphorus concentration data showed the same trend as nitrogen. In the upper, undeveloped parts of the Salt and Verde River Basins (upstream from reservoirs) the decrease in nutrients could be from a decrease in contributions from natural sources (see p. 10), a decrease as a result of better land-use management practices upstream, and (or) an increase in nitrogen use by aquatic life.

Dissolved-solids concentrations decreased substantially in outflow from reservoirs on the Verde River from 1950–90 (fig. 7). This downward trend, also seen on the Salt River, probably is caused by both increased rainfall and snowmelt runoff diluting the dissolved-solids concentrations and physical and chemical processes in the reservoirs that remove some dissolved solids from solution.

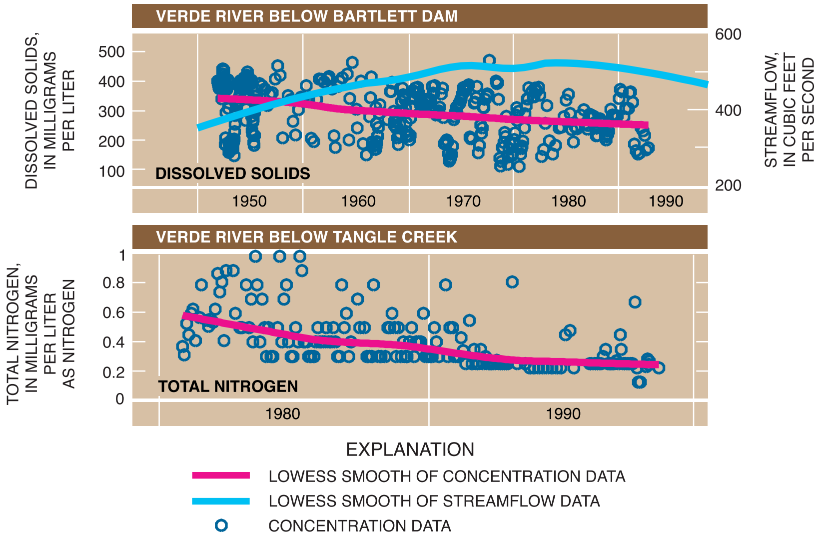


Figure 7. Water quality of forest/rangeland streams has improved, on the basis of decreases in dissolved-solids and nutrient concentrations during the past 30 to 50 years.

Effects of Human Activities on Stream Water Quality

Streams affected by human activities may have elevated concentrations of dissolved solids and nutrients from a variety of activities including urban and agricultural runoff. Manmade compounds such as pesticides and volatile organic compounds (VOCs) in streams are a direct result of human activities. To determine the factors affecting water quality in the CAZB, annual stream loads of dissolved solids (the mass of material transported in the water) entering the basins were compared to annual stream loads leaving the basins (see story at right). In addition, the quantifiable sources of nitrogen and phosphorus (nutrients) coming into major basins and leaving in streamflow were used to identify basins where water quality is affected by human activities (see p. 10). Water-quality characteristics of affected streams are indicative of the local effects of human activities.

Streams sampled in the CAZB that are affected by human activities can be divided into two main categories—effluent-dependent and agricultural/urban. Streamflow in effluent-dependent streams is almost entirely treated sewage effluent discharged from wastewater-treatment plants (WWTPs). These streams are referred to in this report as “effluent-dependent” or “effluent-dependent urban” streams (see p. 12) because the effluent reflects urban land uses. Some sampling sites in the CAZB receive irrigation return flows and rainfall runoff from agricultural fields as well as treated effluent, and these streams are referred to as “agricultural/urban” streams.

Dissolved solids are accumulating in basins with agricultural and urban irrigation.

Data collected as part of the CAZB NAWQA study indicate that in 1997, about 1.6 billion kilograms (kg) (1.76 million tons) of dissolved solids were carried into the Basin and Range Lowlands by streams draining the Central Highlands (Verde, Salt, and Gila Rivers) and by the Central Arizona Project (fig. 8). Only 440 million kg (0.48 million tons) were transported out of the study area in streams. The remaining 1.16 billion kg (1.28 million tons) are accumulating in soils, the unsaturated zone, and ground water in irrigated agricultural and urban areas.

Much of the streamflow from the Central Highlands and the Central Arizona Project Canal is used for irrigating agricultural fields and urban landscape. When plants are irrigated in the Basin and Range Lowlands, 50 to 80 percent of the water evaporates or is transpired by plants as pure water. The dissolved solids that were in the evapotranspired water remain in the soil or are concentrated in the water that remains. Over time these salts build up in soils and ground water. To prevent crop damage from salt accumulation, excess irrigation water is commonly applied to leach the salts out of the root zone.

Excess water that percolates below the root zone carries a higher concentration of salts than the original irrigation water (Cordy and Bouwer, 1999). If this deep-percolation water reaches the ground water, the upper part of the aquifer can be contaminated by dissolved solids, nutrients, and pesticide residues. Because deep-percolation water moves slowly through the unsaturated zone and ground water is several hundred feet deep in basins with substantial agricultural and urban development, the effects of the contamination may not be seen in ground water for years or decades after irrigation has declined or ceased.

Figure 8. Streams and the CAP canal brought 1.6 billion kilograms of dissolved solids into the Basin and Range Lowlands in 1997, but only 440 million kilograms left the area in streams. The remaining dissolved solids accumulated in soils, the unsaturated zone, and ground water.

What are the sources of nitrogen and phosphorus in basins?

Major sources of nitrogen and phosphorus that can be quantified include fertilizers, livestock-feeding operations (commercial feedlot and dairy operations), inputs to sewer and septic systems, atmospheric deposition, industrial wastes, and streamflow into basins. For the CAZB Study Unit, the quantities of nitrogen and phosphorus contributed by each source annually were determined for selected drainage basins. Sources were quantified using records of fertilizer sales by county, livestock population counts, population and housing census information, National Atmospheric Deposition data for Arizona, USEPA Toxic Release Inventory data, and stream water-quality data collected in the CAZB for the NAWQA Program (Anning, 1998). The quantifiable sources of nitrogen and phosphorus in three basins are shown in figure 9.

Many sources of nitrogen and (or) phosphorus, such as the weathering of geologic formations and soils or the decomposition of vegetation, contribute nutrients to the basins but are difficult, if not impossible, to quantify. As a result, these and other unquantifiable sources of nitrogen and phosphorus are shown in figure 9 with question marks (?) to indicate that the quantities are unknown and may actually exceed the quantifiable sources.

The quantifiable and unquantifiable sources of nitrogen and phosphorus in basins represent potential contributors of nutrients to streams; however, the quantity of nutrients contributed annually from each source does not necessarily reach the streams. Some nutrients may be taken up in terrestrial ecosystems, transported to the ground water, or volatilized to the atmosphere. Conversely, nutrients can enter streams directly when treated sewage effluent from WWTPs is discharged to stream channels or excess irrigation water from agricultural areas discharges to streams. Best management practices and regulation of point-source pollution are methods used to reduce or control the quantity of nutrients entering streams.

In the drainage basins of the upper San Pedro River, upper Salt River, and other perennial streams with minimal agricultural and urban land use, the largest quantifiable source of nitrogen coming into these basins is from precipitation (fig. 9). Sewer and septic systems, livestock-feeding operations, and fertilizers are the largest quantifiable sources of phosphorus in these basins.

In basins with substantial agricultural and (or) urban land use such as the middle Gila River, the quantities of nitrogen and phosphorus from quantifiable sources are much greater per unit area than those for basins with little or no agricultural or urban land use. Additionally, fertilizers, livestock-feeding operations, and sewer (WWTPs) and septic systems account for a larger part of the total nutrients in basins with agricultural and (or) urban land use than in basins without these land uses.

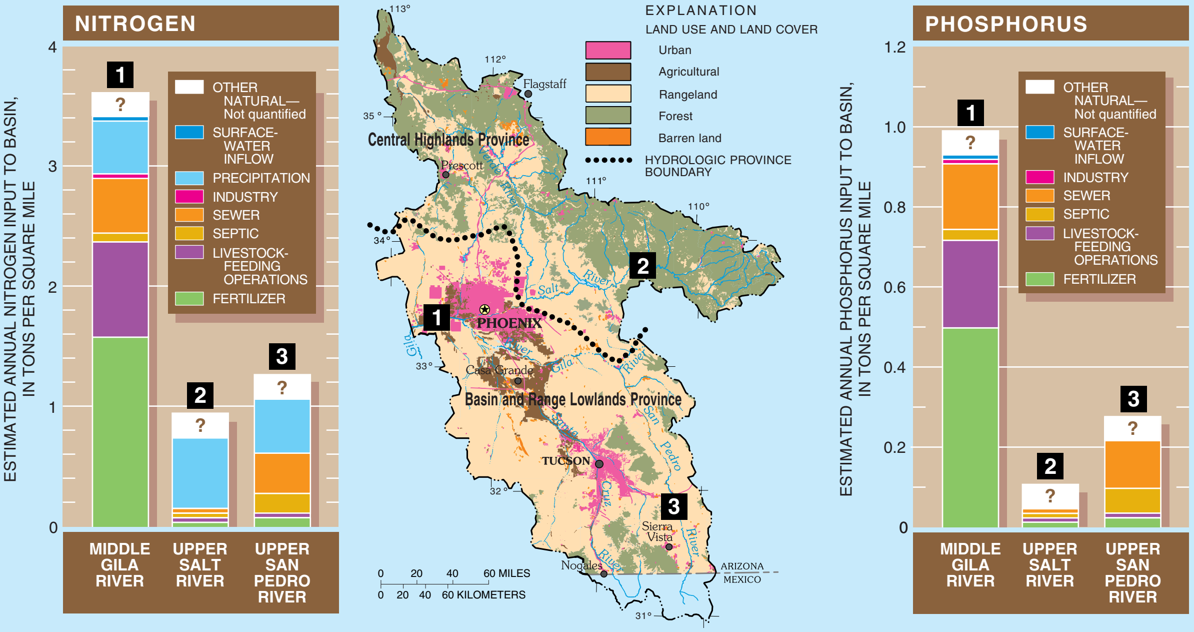


Figure 9. Precipitation and human wastes are the largest quantifiable sources of nitrogen and phosphorus entering basins with minimal agricultural and urban development. Human and animal wastes and fertilizers are the largest quantifiable sources entering basins with substantial agricultural and urban development.

Effluent-dependent streams

Nutrient concentrations in effluent-dependent streams exceeded the background concentrations found in forest/rangeland streams (see fig. 11). The 91st Avenue WWTP outfall near Phoenix and the Santa Cruz River at Tubac and at Cortaro Road (Tucson; see p. 26 for location of sites) are effluent-dependent streams that were sampled in the CAZB. Data from the San Pedro River at Charleston and the Salt River near Roosevelt represent background values for nutrients in the CAZB because these streams drain areas with relatively little urban or agricultural land use. By comparison, the nutrient concentrations at the effluent-dependent sites in the CAZB are elevated because the effluent discharged directly into the stream channels is a major source of nitrogen and phosphorus (U.S. Geological Survey, 1999).

Effluent-dependent streams can sustain riparian communities and aquatic life, but the water quality is poor. Some effluent-dependent streams in the CAZB can support valuable riparian communities with high biodiversity of terrestrial plants and animals; however, dissolved oxygen and phosphorus concentrations in these streams indicate that the water-quality is poor. At a minimum, most fish need 3 to 5 mg/L of dissolved oxygen (DO) over a long period of time to survive (Swenson and Baldwin, 1965). At the Santa Cruz River at Cortaro, DO concentrations were commonly lower than 3 mg/L (fig. 11), whereas concentrations at the other two effluent-dependent sites were in the minimal range. All the samples from the effluent-dependent streams exceeded the USEPA's desired goal for phosphorus of 0.1 mg/L for prevention of nuisance plant growth (eutrophication) (U.S. Environmental Protection Agency, 1986). Excessive algae and aquatic plant growth can lead to low DO concentrations (U.S. Geological Survey, 1999).

How much nitrogen and phosphorus actually leaves the CAZB Study Unit in streams?

A small fraction of nutrients applied to the land surface in the CAZB is transported to streams. The lack of rainfall in the Study Unit limits the transport of nutrients into streams and out of the basins. For the middle Gila River Basin, which includes most of the CAZB Study Unit, about 1,100 tons of nitrogen and 500 tons of phosphorus left the basin in 1998; these nutrient loads represent 1 percent of the quantifiable nitrogen and 2 percent of the quantifiable phosphorus for the basin. During 1996 and 1998, only 1 to 21 percent of the nitrogen and 3 to 48 percent of the phosphorus from quantifiable sources were transported out of basins in the CAZB in streamflow (D.W. Anning, U.S. Geological Survey, written commun., 1999).

Nutrient loads leaving the upper Salt and upper Verde River Basins in streamflow were greater during wet years (when streamflow was greater than the long-term average annual streamflow) than during dry years (when streamflow was less than the long-term average) (fig. 10). More nutrients were carried out of the Hassayampa River Basin in streamflow in 1996 than in 1998 because of more summer rainfall in 1996. Because runoff has higher concentrations of nutrients than does base flow (see fig. 5), wet years not only have additional streamflow but additional stream loads. Nutrients remaining in the basins are taken up by the plants and animals within the basin, adsorbed by streambed sediment (phosphorus only), volatilized to the atmosphere (nitrogen only), or transported to the ground water.

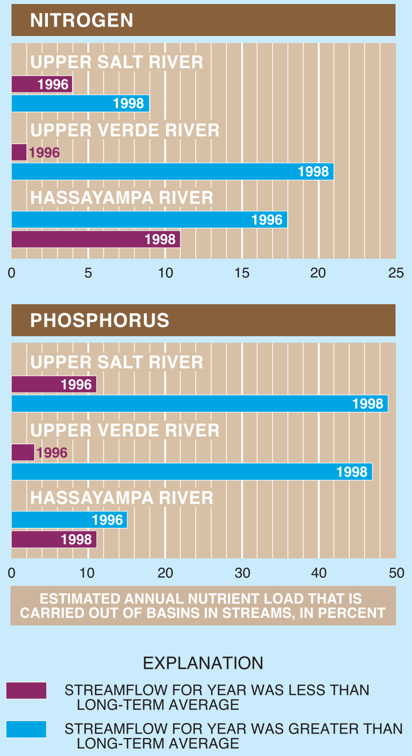


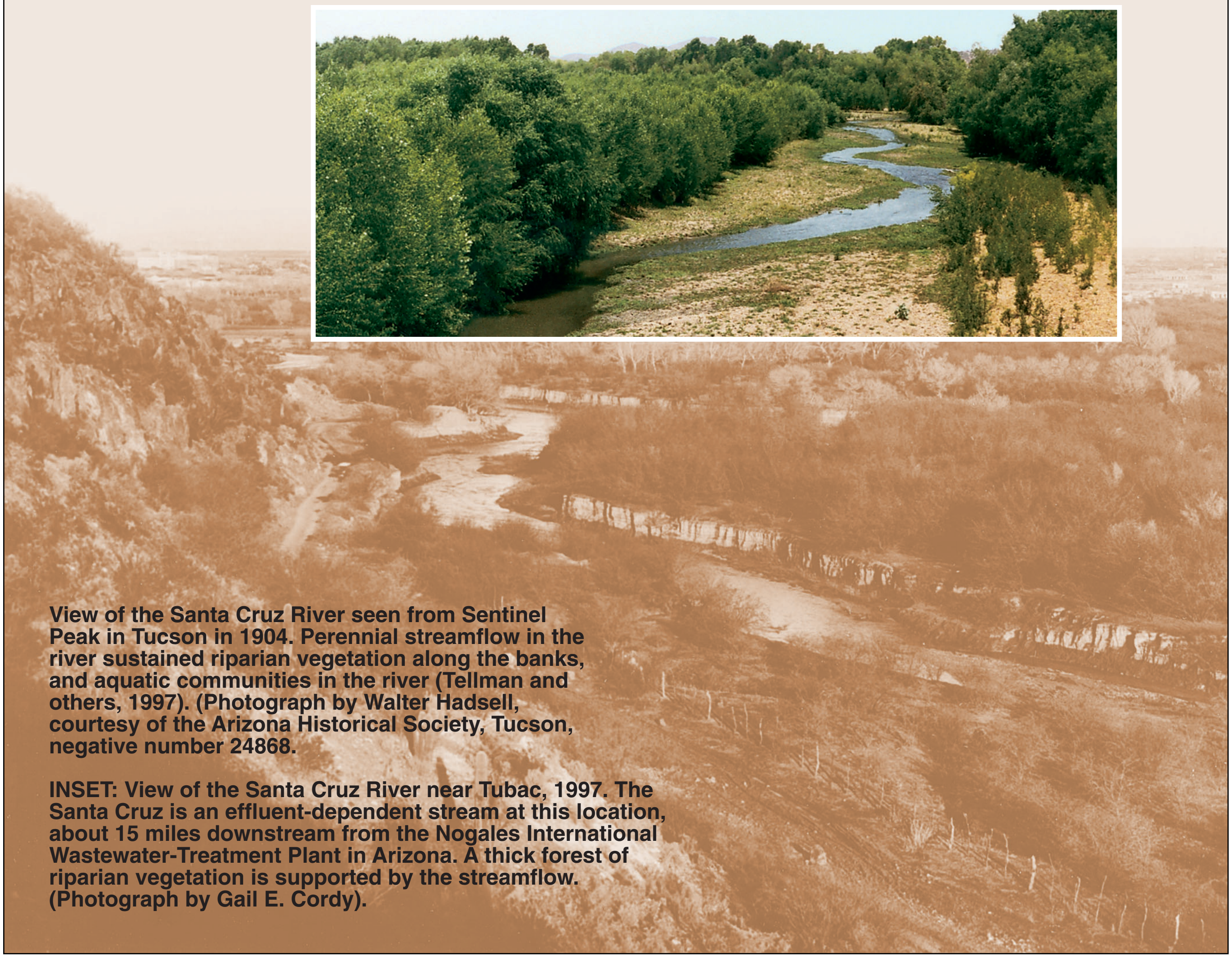
Figure 10. During years when average annual streamflow is greater than the long-term average, more nutrients are carried out of the basins in streams.

Effluent-dependent streams are valuable water resources in the CAZB

In many of the urban areas in Arizona, treated sewage effluent from wastewater-treatment plants is discharged into otherwise dry streambeds. Less than a century ago, some of these “effluent-dependent” streams, such as the Santa Cruz River in Tucson (see below) and the Salt River in Phoenix, had natural perennial streamflow, but ground-water pumping, damming of rivers, or other human activities have resulted in a loss of natural streamflow and associated riparian and aquatic communities (Tellman and others, 1997).

In the dry climate of Arizona, effluent-dependent streams provide perennial water resources with a variety of benefits. Effluent-dependent streams can support riparian communities with high biodiversity of terrestrial plants and animals. These streams support limited aquatic invertebrate and fish communities, which are food for organisms higher in the food chain. Riparian plant communities along these streams can help stabilize streambanks, reducing erosion and sedimentation. Trees and bushes provide plant material, creating habitat and food for aquatic organisms and shade that reduces evaporation. Effluent in streams is particularly important to cities and towns in Arizona because it recharges ground water in aquifers and can be used by cities to accrue “recharge credits” that allow for pumping elsewhere in the ground-water basin (Gelt and others, 1999).

Currently (2000), the water quality of effluent-dependent streams limits restoration of instream communities. If the water quality of these streams is improved by upgrading wastewater-treatment methods, it is likely that the streams would be able to support a greater number of aquatic species, and aquatic communities could even begin to resemble those of streams such as the upper San Pedro or upper Salt Rivers.



View of the Santa Cruz River seen from Sentinel Peak in Tucson in 1904. Perennial streamflow in the river sustained riparian vegetation along the banks, and aquatic communities in the river (Tellman and others, 1997). (Photograph by Walter Hadsell, courtesy of the Arizona Historical Society, Tucson, negative number 24868.

INSET: View of the Santa Cruz River near Tubac, 1997. The Santa Cruz is an effluent-dependent stream at this location, about 15 miles downstream from the Nogales International Wastewater-Treatment Plant in Arizona. A thick forest of riparian vegetation is supported by the streamflow. (Photograph by Gail E. Cordy).

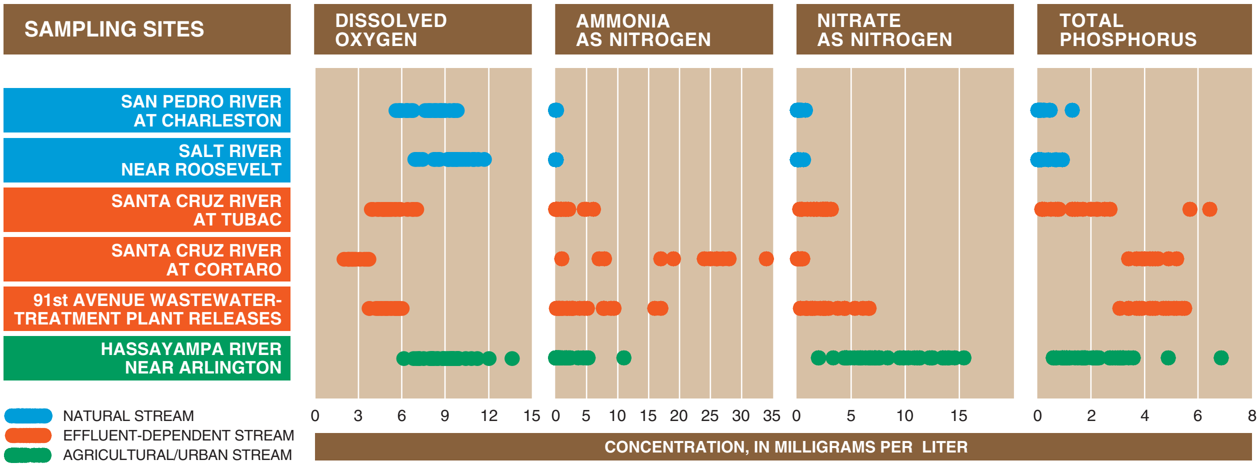


Figure 11. Nutrient enrichment in effluent-dependent streams contributes to abundant algal growth, which results in decreased dissolved oxygen and limited aquatic communities.

The level of sewage treatment and the distance effluent travels downstream from the discharge point influence the water quality of effluent-dependent streams. Ammonia concentrations in effluent at the Santa Cruz River at Cortaro are extremely variable and typically higher than those in the Santa Cruz River at Tubac or the 91st Avenue WWTP (fig. 11). Effluent at the Cortaro site has had secondary treatment, which results in nitrogen remaining in the effluent as ammonia (David Garrett, Pima County Wastewater, oral commun., 2000). In contrast, effluent sampled at the discharge point from the 91st Avenue WWTP has had tertiary treatment in which the ammonia is converted to nitrate. Converting ammonia to nitrate during treatment limits the direct threat of toxicity to fish that ammonia presents, but it does not change the potential for eutrophication of the stream (Mueller and others, 1996).

The lowest nutrient concentrations in effluent-dependent streams were at the Santa Cruz River at Tubac (fig. 11). Effluent in this stream receives secondary treatment and travels about 15 miles downstream to Tubac. As the effluent moves downstream, ammonia is lost to the atmosphere or converted to nitrate, some nitrate and phosphorus are taken up by plants and aquatic life, and phosphorus may be adsorbed by streambed sediments. Each of these processes reduces concentrations of nitrogen and (or) phosphorus, resulting in lower concentrations with distance downstream from the WWTP.

Abundant algal growth from nutrient enrichment in effluent-dependent streams may adversely affect aquatic organisms. Phosphorus, nitrate, and ammonia in effluent-dependent streams encourage algal growth. Chlorophyll *a* concentrations (fig. 12), which are indicators of the quantity of algae in a stream, were much higher in effluent-dependent streams than in forest/rangeland streams (Gebler, 1998).

Abundant algal growth and the resulting increase in decaying organic material in effluent-dependent streams can cause decreased DO concentrations, particularly at night when plants cease photosynthesis and decrease their oxygen production. The decreased DO can adversely affect aquatic invertebrates and fish.

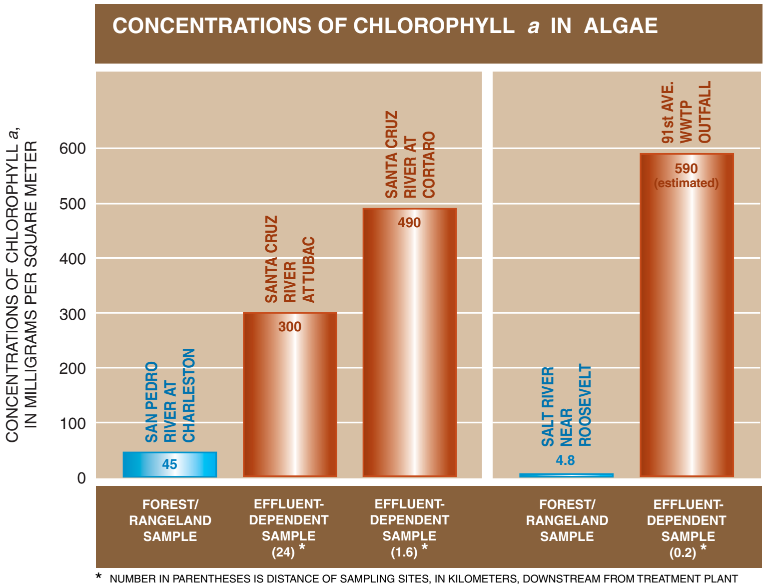


Figure 12. Nutrients in effluent-dependent streams encourage algal growth, as indicated by chlorophyll *a* concentrations.

Effluent-dependent streams support limited instream communities of aquatic invertebrates. The diversity of pollution-sensitive aquatic invertebrates such as mayflies, stoneflies, and caddisflies in effluent-dependent streams is very low, especially when compared to the high diversity in forest/rangeland streams (fig. 13). Pollution-tolerant species of aquatic worms and midges account for more than 90 percent of the numbers of aquatic invertebrates in effluent-dependent stream reaches sampled in the CAZB (fig. 14). In forest/rangeland streams, mayflies, stoneflies, and caddisflies were the most abundant of all aquatic invertebrate groups, which is consistent with good water quality and instream habitat (Gebler, 1998).

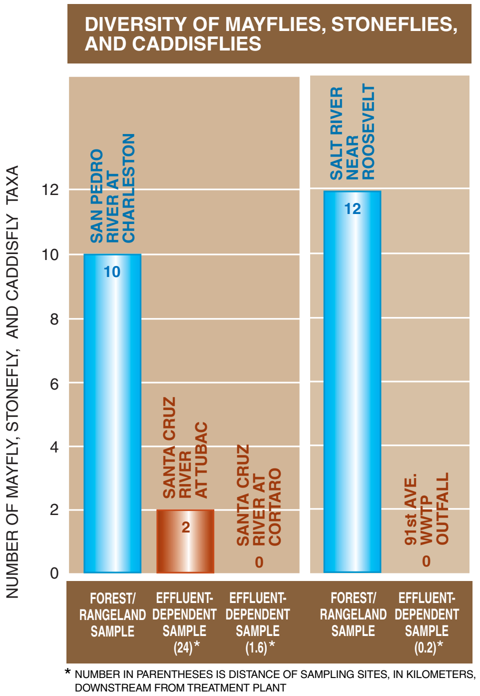


Figure 13. Aquatic invertebrate communities in effluent-dependent streams lack diversity.

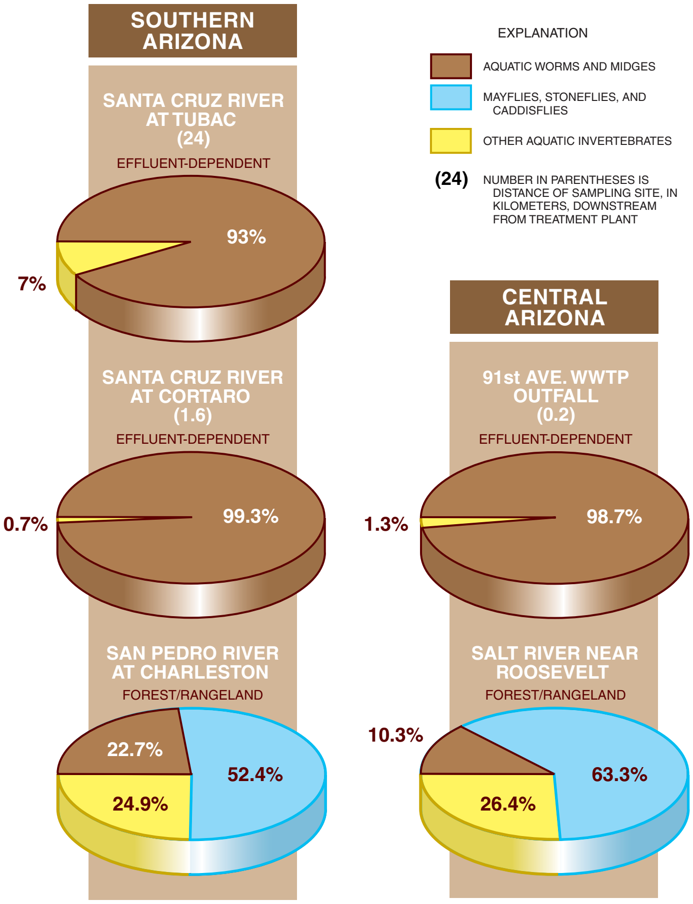


Figure 14. Pollution-tolerant aquatic invertebrates are most abundant in effluent-dependent streams.

Aquatic invertebrates are indicators of water quality

Aquatic invertebrates are animals such as worms and insects that live in water. Fly fishermen know that game fish such as trout and bass eat insects such as mayflies, stoneflies, and caddisflies. Biologists who study water quality have found that some aquatic invertebrates, such as certain aquatic worms and midges, can tolerate poor water quality. Many types of mayflies, stoneflies, and caddisflies are sensitive to water-quality degradation and are most abundant in streams with good water quality. Biologists can sample for aquatic invertebrates and determine the relative quality of the water by the numbers and types of invertebrates found.

Photograph by Steve Fend

Organochlorine pesticides and PCBs in streambed sediment and fish tissue from effluent-dependent streams exceeded guidelines for protection of aquatic life and fish-eating wildlife. Probable effect levels (PELs) for sediment (Canadian Council of Ministers of the Environment, 1999) were exceeded for DDE and total chlordane in samples from the 91st Avenue WWTP and at a site near the discharge point from the Nogales WWTP into the Santa Cruz River. The PEL is a concentration above which adverse effects to aquatic organisms are predicted to occur frequently. Exceedance of the PEL concentrations indicates that bottom-dwelling aquatic organisms may be adversely affected by toxicity. Total DDT (91st Avenue WWTP) and PCBs (Santa Cruz River at Tubac) in fish-tissue samples exceeded New York State guidelines (Newell and others, 1987) for the protection of fish-eating wildlife. These guidelines are being applied to findings from NAWQA Study Units nationwide. DDT, which breaks down to form DDE and DDD, is associated with past use of DDT in agricultural areas. Use of DDT was discontinued in Arizona in 1969. PCBs were primarily used in industrial and urban settings, but their use was discontinued in 1979. Exceedances of tissue guidelines can result in reduced reproductive ability and other possible adverse effects in wildlife that eat contaminated fish (Faber and Hickey, 1973).

Agricultural/urban streams

As in effluent-dependent streams, nutrient concentrations in agricultural/urban streams were elevated compared with concentrations in forest/rangeland streams (fig. 11). This is no surprise given that the two agricultural/urban streams—Buckeye Canal near Avondale and Hassayampa River near Arlington—receive effluent from the 91st Avenue WWTP in Phoenix. The effluent is mixed with ground water in Buckeye Canal and used to irrigate cotton and other crops. Downstream, effluent and irrigation return flows in Buckeye Canal are discharged into the Hassayampa River near Arlington. At this point, the water has been used and reused for agricultural irrigation, and nitrate concentrations are typically higher than those in the original effluent (fig. 11) because of the use of fertilizers in the agricultural area near Buckeye.

Herbicides were detected in streams soon after application to agricultural lands, but concentrations did not exceed guidelines for protection of aquatic life. In the West Salt River Valley west of Phoenix, the pre-emergent herbicides dacthal, EPTC, simazine, and trifluralin are applied to tilled fields prior to cotton planting in the early spring to control weeds. They may be reapplied in the fall to fields where winter crops are grown. These herbicides were detected in surface-water samples from the agricultural/urban streams in the early spring and fall, soon after application. Changes in concentrations of dacthal at the Hassayampa River near Arlington (fig. 15) are representative of the patterns seen for herbicide concentrations at both sites. Agricultural and rainfall runoff carry these pesticides to streams. Because streamflow at these sites is not used for drinking water but does sustain aquatic life, guidelines for the protection of aquatic life were used to evaluate water quality. Aquatic-life guidelines for simazine and trifluralin were not exceeded in any samples from these sites. There are no aquatic-life guidelines for dacthal and EPTC.

Organochlorine pesticides that persist in streambed sediment and in fish tissue from an agricultural/urban stream are a concern for aquatic ecosystem health. PEL concentrations for sediment were exceeded for DDE and DDT at the agricultural/urban stream site on the Buckeye Canal

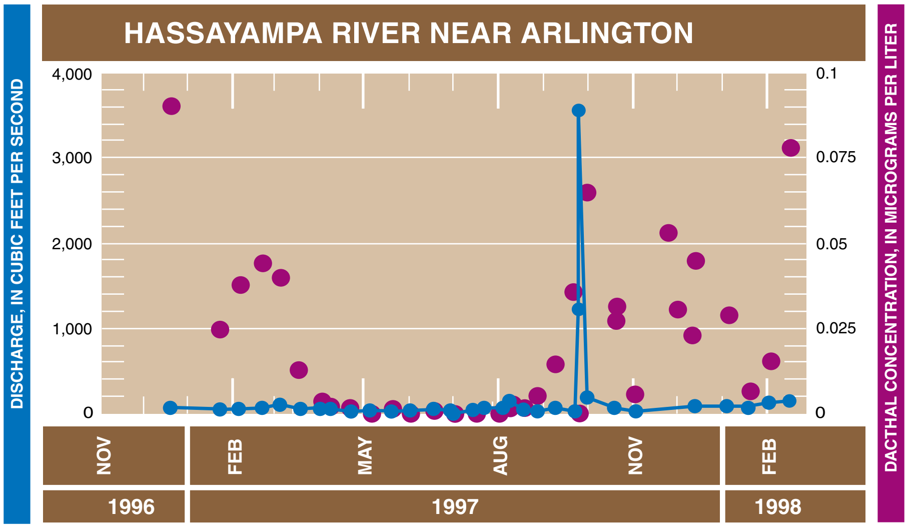


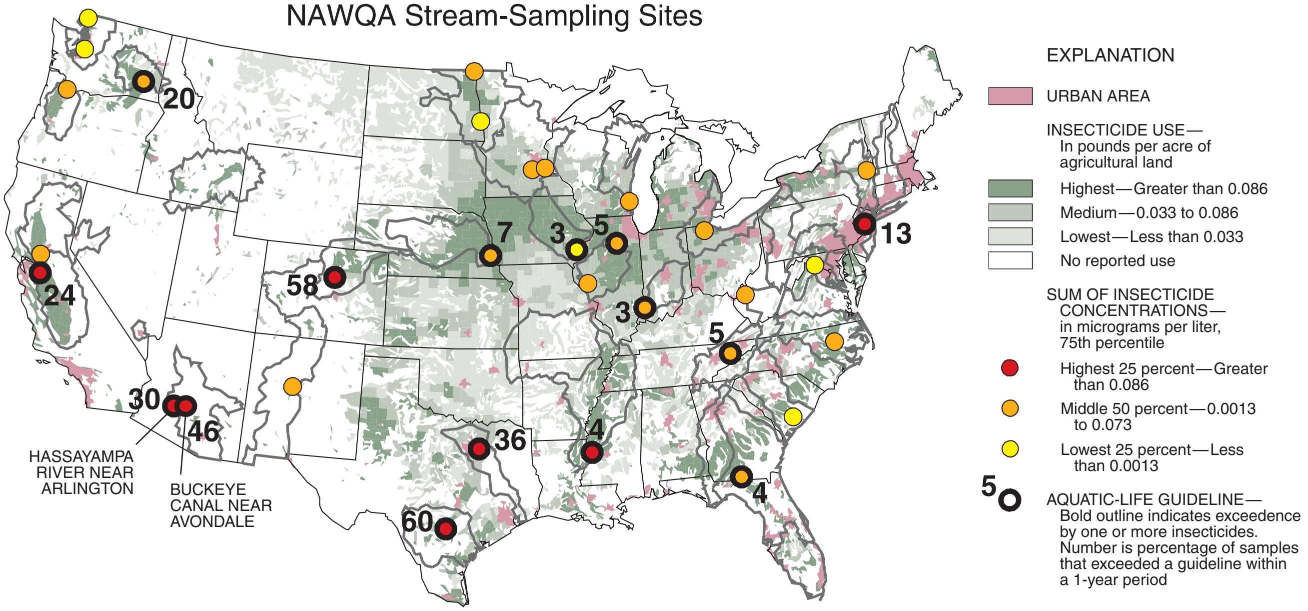
Figure 15. Herbicides were detected in streams soon after being applied to crops.

near the Hassayampa River (adjacent to the Hassayampa River at Arlington site, see p. 26). Concentrations of DDE in fish-tissue samples from this site exceeded guidelines established by New York State (Newell and others, 1987) for the protection of fish-eating wildlife. Concentrations of toxaphene in two out of three fish-tissue samples from the same site exceeded the National Academy of Science/National Academy of Engineering (1973) guideline for the protection of fish-eating wildlife. Past use of pesticides including DDT, toxaphene, and others on agricultural areas in the West Salt River Valley is the source of these pesticides. Though use of these pesticides was discontinued decades ago, the pesticides persist over time and their breakdown products continue to enter streams by erosion of contaminated soils, surface-water runoff, and atmospheric deposition. Exceedances of tissue guidelines indicate possible adverse effects, such as reduced reproductive ability and eggshell thinning, to birds and other wildlife that eat contaminated fish (Faber and Hickey, 1973).

In the CAZB Study Unit, insecticide concentrations in agricultural/urban streams are among the highest in the Nation

Pesticides in water were measured at 117 sampling sites on 114 rivers and streams across the United States as part of the NAWQA Program from 1992–1998. At each site, concentrations of all insecticides detected during a 1-year period were summed and categorized as low (lowest 25 percent), middle (middle 50 percent), and high (highest 25 percent) compared to concentrations at all of the sites monitored (see figure below). This information was compared, by county, to insecticide use during the early to mid-1990's on agricultural lands.

In the CAZB Study Unit, insecticide concentrations in streams with mixed agricultural/urban land use were among the highest in the Nation. These sites—the Buckeye Canal near Avondale and the Hassayampa River near Arlington in the West Salt River Valley—are dominated by treated effluent and irrigation return flows that contain insecticides from urban and agricultural land uses. Nearly one-half the samples (46 percent) collected from the Buckeye Canal during 1 year exceeded aquatic-life guidelines for one or more of the following insecticides: diazinon, malathion, lindane, and chlorpyrifos. At the Hassayampa River site, 30 percent of samples collected in a 1-year period exceeded aquatic-life guidelines for one or more of the following pesticides: chlorpyrifos, azinphos-methyl, DDE, dinoseb, malathion, diazinon, and parathion. Although these streams are not used for drinking water, the water quality does present a potential hazard to aquatic life. In addition, little is known about the effects of mixtures of pesticides, even at low concentrations, on aquatic life (Gilliom, 1999).



Insecticide concentrations in streams in the West Salt River Valley near Phoenix are among the highest in the Nation.

Natural Ground-Water Quality

It is important to understand how natural processes affect ground-water quality in order to identify the effects of urban and agricultural development under similar hydrogeologic conditions. In the CAZB, the majority of ground-water basins do not have significant urban or agricultural development. The ground-water quality in these basins is primarily a product of natural processes such as the interaction of ground water with rocks and sediment in the basins (Robertson, 1991).

Natural sources of dissolved-solids and nitrate can control ground-water quality in basins with minimal urban development. Specific-conductance values (an indirect measure of the dissolved-solids concentration) and nitrate concentrations for ground water in basins with minimal urban development increase northwestward from southeastern Arizona toward the central part of the State (figs. 16 and 17). The increasing specific-conductance values can be attributed to a corresponding increase in evaporite deposits in basin sediments from southeast to northwest (Gellenbeck and Coes, 1999). Evaporite deposits in the basins contain minerals such as halite (salt) and gypsum that can be easily dissolved in ground water. (Robertson, 1991). The increasing nitrate concentrations can be largely attributed to natural sources; however, human activities such as agriculture can be a source in some basins. In some locations in the CAZB, high nitrate concentrations in ground water reported prior to any agricultural or urban development indicate that natural sources of nitrate are present in some basins (Hem, 1985; Robertson, 1991; Gellenbeck, 1994; Gellenbeck and Coes, 1999). Dissolution of evaporite deposits, decay of buried organic matter, precipitation, weathering of rocks and soils, and fixation by microorganisms are just a few of the possible sources of naturally occurring nitrate in ground water.

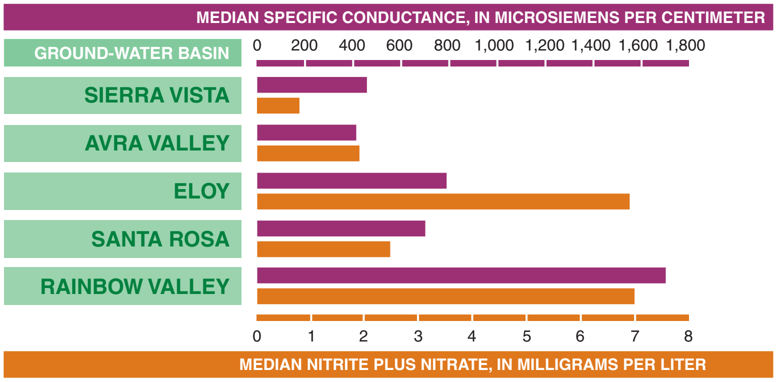


Figure 16. Nitrate concentrations and specific conductance values in ground water from basins with minimal urban development increase from the southeast to the northwest. (Basins shown below in figure 17.)

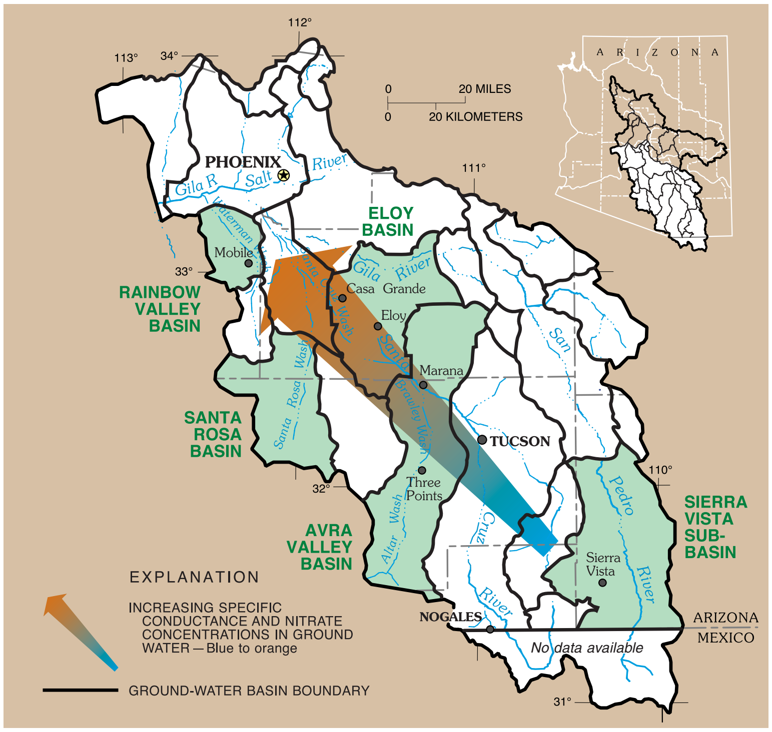


Figure 17. Increasing specific conductance values in ground water from southeast to northwest can be attributed to an increase in soluble evaporite deposits in basin sediments. Increasing nitrate concentrations in the same direction may be the result of naturally occurring nitrate and of human activities that include agriculture.

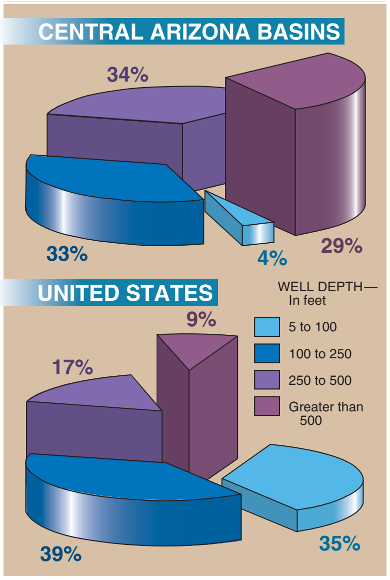


Figure 18. Ground water sampled in the CAZB Study Unit generally is from greater depths than ground water sampled in NAWQA Study Units across the Nation.

Quality of deep, older ground water unaffected by human activities

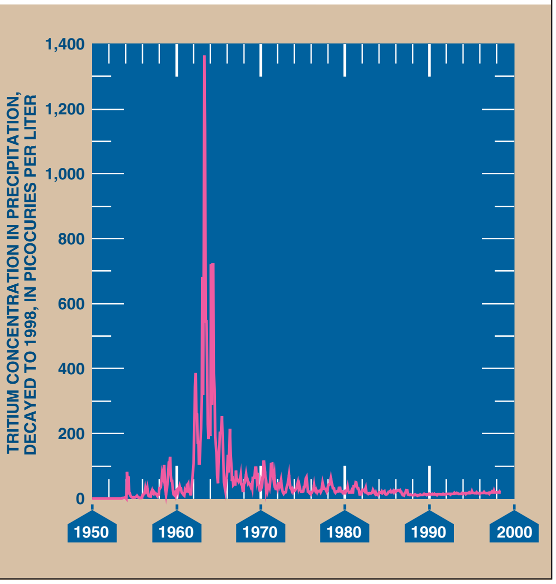
In general, ground water in Arizona is replenished (recharged) at very slow rates because of little precipitation, high evaporation losses, and the long distance water must travel to recharge deep aquifers. In the CAZB, 63 percent of the wells sampled that draw water from aquifers used for drinking water were at least 250 feet deep compared to 26 percent of NAWQA wells sampled nationwide (fig. 18). Recharge takes longer to reach deep aquifers than shallow aquifers; therefore, deep ground water typically was recharged earlier and is older than shallow ground water. Tritium age dating of ground water (see below) confirms that 55 percent of the wells sampled in the CAZB yielded ground water that was recharged prior to 1953 and possibly thousands of years earlier. For example, some ground water in the Upper Santa Cruz Basin was determined to be about 6,500 years old (Kalin, 1994). Across the Nation, only 27 percent of the NAWQA wells sampled for tritium yielded ground water that was recharged prior to 1953.

The age and depth of ground water in the CAZB have important implications for water quality and quantity. Because much of the deep ground water sampled in the CAZB was recharged prior to 1953 and has not mixed with younger recharge, drinking-water quality generally has not been substantially affected by human activities that took place after 1953. The movement of contaminants from the land surface to the deep ground water is hindered by the thickness of basin-fill sediments through which contaminants must travel. Ground-water quantity is affected because ground water pumped from deep aquifers is not being replaced by recharge (see p. 5), resulting in a net decrease in the quantity of ground water available for consumption.

Method for dating ground water

Tritium is a radioactive isotope that can be used to estimate whether ground water has been recharged before or after 1953. Large quantities of tritium were released to the atmosphere during testing of thermonuclear weapons from 1952 until the late 1960s. Atmospheric tritium is incorporated into water molecules in the atmosphere prior to precipitation and recharge to ground water. The concentration of tritium in ground water at a given time is controlled by both the quantity of tritium in the atmosphere when precipitation and recharge occur and the radioactive decay rate of tritium. Ground water that does not contain detectable tritium (less than 2.5 picocuries of tritium per liter) can be assumed to have been recharged prior to 1953, and ground water that does contain detectable tritium (more than 2.5 picocuries of tritium per liter) is assumed to contain some component of ground water that was recharged after 1953.

Tritium concentrations in precipitation are a guide for determining when ground water was recharged.



Concentrations of arsenic, fluoride, and molybdenum exceeded drinking-water standards in samples from major aquifers. The median arsenic concentration in ground water for the three CAZB basins sampled was 4 µg/L. One sample from the Upper Santa Cruz Basin and one sample from the West Salt River Valley exceeded the current MCL for arsenic of 50 µg/L; however, a new, lower standard of 5 µg/L has been proposed by the USEPA because of the cancer risk posed by arsenic in drinking water (U.S. Environmental Protection Agency, rev. August 25, 2000). When arsenic concentrations in ground water sampled in the CAZB are compared to the proposed standard, more than 50 percent of samples from aquifers in West Salt River Valley that are used for drinking water exceed 5 µg/L. Seventeen percent of samples in the Upper Santa Cruz Basin and 10.5 percent of samples in the Sierra Vista subbasin exceed 5 µg/L. The USEPA may not settle on 5 µg/L, but the new standard is likely to be significantly lower than the current MCL.

The median concentration of fluoride was 0.5 µg/L; about 2 percent of the samples exceeded the current MCL for fluoride of 4 µg/L. The median concentration of molybdenum was 3 µg/L; about 1 percent of the samples exceeded the current lifetime health advisory for molybdenum of 40 µg/L established by the USEPA.

Radon and uranium are detected in most ground-water samples. Radon is a colorless and odorless radioactive gas that is carried in the water pumped from wells (fig.19) and released to indoor air by activities such as cooking and showering. Breathing radon increases the risk of lung cancer (U.S. Environmental Protection Agency, rev. October 18, 1999). Radon is naturally formed in rocks and soils from the radioactive decay of radium, an intermediate product in the uranium decay process. In the CAZB Study Unit, radon was present in 100 percent of the samples, and uranium was detected in 90 percent of the samples. The median concentrations for radon and uranium were 584 picocuries per liter and 3 micrograms per liter, respectively. Currently (2000), there are no USEPA MCLs for radon and uranium; however, proposed MCLs could result in increased costs for water suppliers to treat drinking water for these constituents or find alternate supplies. Additional costs would probably be passed on to the water user (see information on proposed standards for arsenic, radon, and uranium on p. 20).

Effects of Human Activities on Ground-Water Quality

The contamination of major aquifers is largely controlled by hydrology and land use (U.S. Geological Survey, 1999). In the CAZB Study Unit, deep ground water that was recharged prior to 1953 typically has not been affected by human activities (see p. 18). In areas with recent recharge (after 1953), ground water is more likely to be contaminated by nutrients and man-made chemicals associated with urban and agricultural land uses.

Ground-water quality deteriorates in irrigated areas. Irrigation water that seeps downward is a principal source of ground-water recharge in irrigated areas of the CAZB. Dissolved-solids concentrations in seepage can be as much as five times those in the original irrigation water (Bouwer, 1990) because of concentration by evaporation and plant use (see p. 9). The greater the dissolved-solids concentration in the applied irrigation water, the greater the concentration in the seepage moving downward to the ground water.

To determine the effects of irrigated agriculture on shallow ground-water quality, nine monitoring wells were drilled and sampled in the southwestern part of the West Salt River Valley (see “Study Unit Design,” p. 26). Because the average depth to ground water in the nine wells is 32 feet (table 1) compared to 230 feet for wells sampled basinwide, irrigation seepage does not have to travel far to reach the shallow ground water in the agricultural area. Sources of irrigation water in this area include treated sewage effluent, water from the Salt River and CAP canal, irrigation return flows, and ground water. Dissolved-solids concentrations of these sources range from about 900 mg/L for treated sewage effluent (Tadayon and others, 1998) to 650 mg/L for CAP water and 470 mg/L for Salt River water (Salt River Project, 1997).

The median dissolved-solids concentration in water from the nine shallow wells exceeded 3,000 mg/L (table 1). In addition, the effects of nitrate from fertilizer applications and reuse of irrigation return flows were evident from the median nitrate concentration that was nearly twice the MCL of 10 mg/L (table 1).

Figure 19. Samples are collected at the well head for radon analysis to prevent possible sample contamination from exposure to the atmosphere.

Table 1. Median concentrations of nitrate and dissolved solids were highest in shallow ground water from an agricultural area in the West Salt River Valley

Study area	Median concentration, in milligrams per liter		Average depth to ground water, in feet
	Nitrate	Dissolved solids	
West Salt River Valley			
Agricultural area	*19.0*	*3,050*	*32*
Basinwide	*2.7*	*560*	*230*
Upper Santa Cruz Basin	*1.5*	*305*	*230*
Sierra Vista subbasin	*0.78*	*262*	*171*
U.S. Environmental Protection Agency drinking-water standard	[1]*10*	[2]*500*	

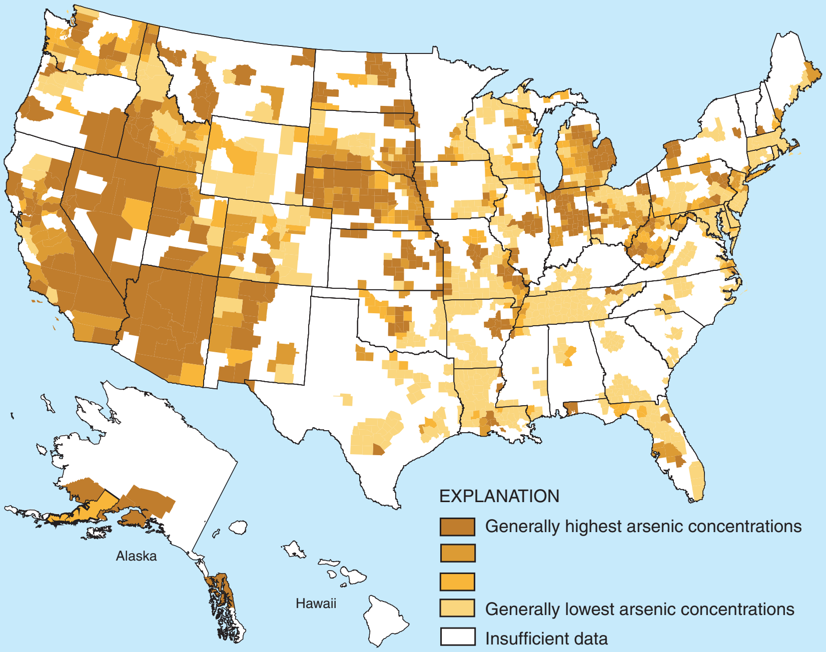
[1] Maximum Contaminant Level.
[2] Secondary Maximum Contaminant Level.

Proposed drinking-water standards for arsenic, radon, and uranium have major implications for ground-water supplies

During 1991–98, arsenic, radon, and uranium were measured in ground-water samples from 36 NAWQA Study Units across the United States. If the ground-water samples from these Study Units are representative of ground water across the Nation, MCLs (see Glossary) proposed by the USEPA for these constituents will affect many water suppliers and municipalities in the United States. Because ground-water supplies in many parts of the Nation will likely exceed the proposed MCLs, public-water systems would be required to either specifically treat their water to decrease concentrations of the constituents or find alternative sources of supply. Costs of these options would probably be passed on to water users.

Arsenic

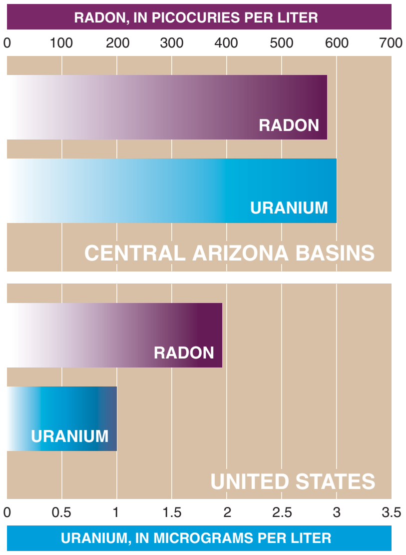
The current USEPA MCL for arsenic in drinking water, 50 µg/L, is under review after recognition of the risks of developing cancers (National Research Council, 1999). In 2000, the USEPA proposed a new, lower arsenic MCL of 5 µg/L (U.S. Environmental Protection Agency, rev. June 2, 2000). In samples collected in three CAZB basins, only 2 percent exceeded the current USEPA MCL; however, 32 percent exceeded the lower, proposed MCL. In samples collected across the Nation, only 0.6 percent exceeded the current USEPA MCL; however, 14 percent exceeded the lower proposed MCL. Arizona, including the CAZB, is among the areas in the Nation where 10 percent or more of ground-water samples are likely to exceed the lower MCL (figure at right; Welch and others, 2000).



High concentrations of arsenic in ground water are more widespread in the West.

Radon and uranium

Currently, USEPA MCLs for radon and uranium do not exist. Because of public health concerns, including increased risks for developing lung cancer, the USEPA proposed an MCL of 20 µg/L for uranium in 1991. In 1999, the USEPA proposed an MCL of 300 picocuries per liter (pCi/L) for radon; however, if States or water suppliers implement methods to lower radon levels in indoor air, they would only be required to meet an Alternate MCL (AMCL) of 4,000 pCi/L (U.S. Environmental Protection Agency, rev. April 21, 2000; U.S. Environmental Protection Agency, rev. October 18, 1999). Of the ground-water samples collected in the three CAZB basins, 9 percent exceeded the proposed uranium MCL, 91 percent exceeded the proposed radon MCL, and 1 percent exceeded the proposed radon AMCL. In the NAWQA samples collected nationwide, 4 percent exceeded the proposed uranium MCL, 61 percent exceeded the proposed radon MCL, and 4 percent exceeded the proposed radon AMCL (Dennis Wentz and others, U.S. Geological Survey, written commun., 1999). The Study Units with the highest radon concentrations were in the Colorado Rockies and the Eastern United States. Median concentrations of radon and uranium in the CAZB Study Unit were higher than median concentrations for the United States (figure at right).



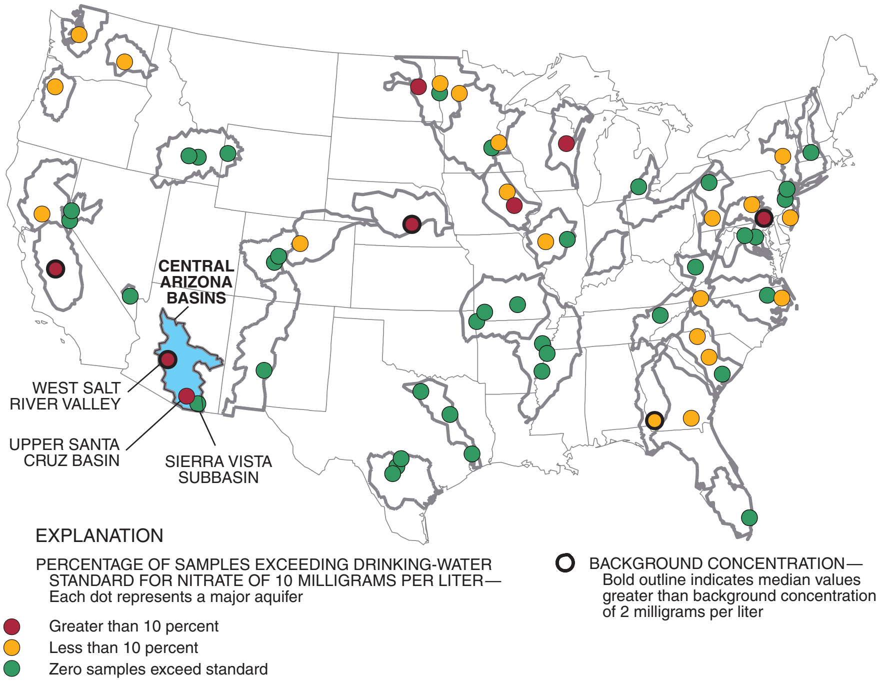
Median concentrations of radon and uranium in ground water in the CAZB exceeded those for the Nation.

Nitrate concentrations in ground water in the West Salt River Valley are among the highest in the Nation

The study of water quality in deep aquifers that provide drinking water in the West Salt River Valley is one of eight NAWQA ground-water studies nationwide that had more than 10 percent of samples that exceeded the USEPA MCL for nitrate of 10 mg/L (figure at right). Of 35 samples collected basinwide in the West Salt River Valley, 34 percent had concentrations greater than the USEPA MCL. Seventy-eight percent of shallow ground-water samples from the agricultural land-use study in the West Salt River Valley had concentrations greater than the USEPA MCL for nitrate. Only 10 percent of samples from the Upper Santa Cruz Basin and none of the samples from the Sierra Vista subbasin had concentrations that exceeded the USEPA MCL for nitrate.

Excessive nitrate in drinking water is a health concern for children and adults. In children, high nitrate concentrations can result in “blue-baby syndrome,” in which oxygen levels in the blood of infants are low, sometimes fatally so (National Governor’s Association, 1991).

Birth defects also have been attributed to high nitrate concentrations (National Governor’s Association, 1991). In adults, high nitrate concentrations have been associated with cancer (National Academy of Sciences, 1977).



The CAZB is one of eight Study Units in the Nation with nitrate concentrations in ground water that exceed the drinking-water standard in more than 10 percent of samples.

Sources of nitrate in the Central Arizona Basins Study Unit include evaporite deposits in basin sediments, precipitation, agricultural fertilizers, animal-feeding operations, WWTP outflow, and others (see p. 10). In areas with agricultural and (or) urban development, sources of nitrate related to human activities are prevalent, whereas precipitation and geologic sources of nitrate predominate in undeveloped areas.

The highest concentrations of nitrate and dissolved solids were in shallow ground water beneath an irrigated agricultural area. Shallow ground water from the agricultural land-use study area in the West Salt River Valley had median concentrations of nitrate (19 mg/L) and dissolved solids (3,050 mg/L) that exceeded the USEPA MCL and SMCL, respectively (table 1). Nitrate and dissolved solids from irrigation and agricultural practices are accumulating in shallow ground water (see p. 9 and 11). The shallow ground water in this area is not used for drinking water, and clay beds reduce the likelihood of contamination of the aquifers below that are used for drinking water (see p. 22).

Deeper ground water from urban, rangeland, and agricultural areas in other parts of the West Salt River Valley had a median nitrate concentration that was less than the MCL of 10 mg/L; however, the median concentration of dissolved solids exceeded the SMCL of 500 mg/L (table 1). Median concentrations of nitrate from the Upper Santa Cruz Basin and the Sierra Vista subbasin also were less than the MCL, and median concentrations of dissolved solids were less than the SMCL (table 1).

Clay beds that currently protect deep ground water from contamination may not do so in the future.

In the agricultural land-use study area of the West Salt River Valley (fig. 20), the tops of low-permeability clay beds are about 150 to 400 ft below the land surface. These clay beds impede the downward movement of irrigation seepage and reduce the likelihood of contaminants reaching deeper drinking-water supplies. Domestic wells in the area yield water from beneath the protective clay beds. Ground water above the clay beds has higher nitrate and dissolved-solids concentrations than ground water from beneath the clay beds (fig. 21). In this area, ground-water samples from above the clay beds had a median dissolved-solids concentration of 3,050 mg/L and a median nitrate concentration of 19.0 mg/L (table 1). Ground-water samples from below the clay beds had a median dissolved-solids concentration of 702 mg/L and a median nitrate concentration of 1.9 mg/L. Care must be taken in drilling and completing drinking-water wells below the clay beds to ensure that shallow ground water above the clay beds does not contaminate the well and aquifer below.

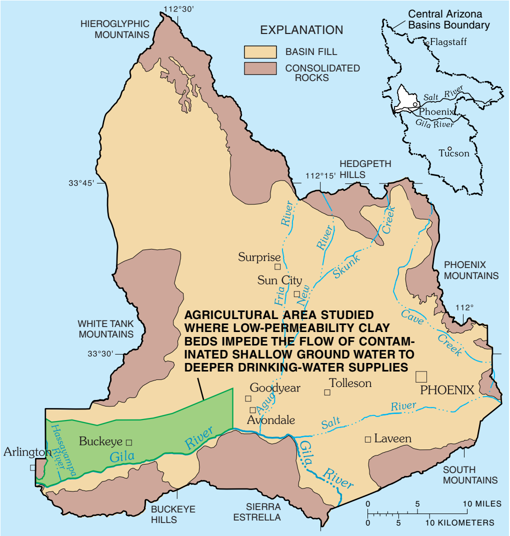


Figure 20. Low-permeability clay beds in an agricultural area in the West Salt River Valley reduce the likelihood of contamination reaching deeper drinking-water supplies.

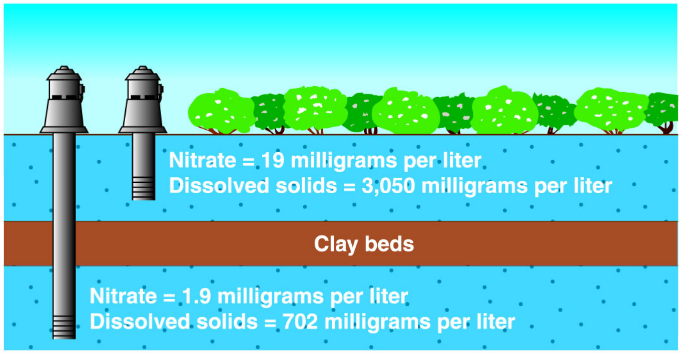


Figure 21. Ground water above the clay beds was recharged after 1953 and has been affected by agricultural activities.

Analyses of the tritium from ground water in this area indicated that water above the clay beds generally had been recharged after 1953, and water below the clay beds generally had been recharged before 1953 (see information about age dating ground water on p. 18). Although the clay beds currently reduce the likelihood that irrigation seepage will contaminate the ground water below, future large-scale withdrawals of ground water from below the clay beds could possibly result in the movement of shallow, poor quality water through the clay beds and into the domestic ground-water supply.

Occurrence and distribution of pesticides in ground water in the CAZB reflect both agricultural and urban land uses. Ten pesticides were detected in shallow ground water from the agricultural land-use study area in the West Salt River Valley, west of Phoenix (fig. 22). In other parts of the West Salt River Valley, consisting of agricultural, urban, and rangeland areas, eight pesticides were detected in ground water. Five pesticides were detected in ground water from the Upper Santa Cruz Basin, where there is a mixture of land-use types, but 60 percent of the basin is undeveloped rangeland (Coes and others, 2000). In the Sierra Vista subbasin, where urban and agricultural land uses are minimal (3.3 percent of basin; Coes and others, 1999) and have been minimal in the past, no pesticides were detected in ground-water samples. During 1996–98, the largest quantities of pesticides used among the three basins were for agriculture in the West Salt River Valley (Ken Agnew, University of Arizona, Pesticide Information and Training Office, written commun., 1999).

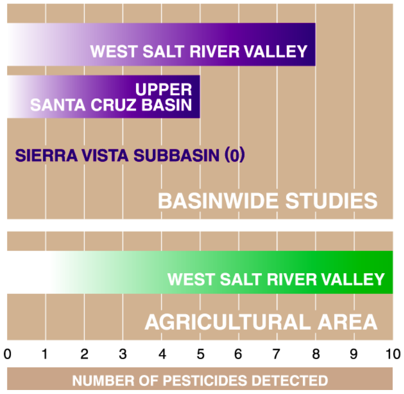


Figure 22. The largest number of pesticides was detected in an agricultural area in the West Salt River Valley.

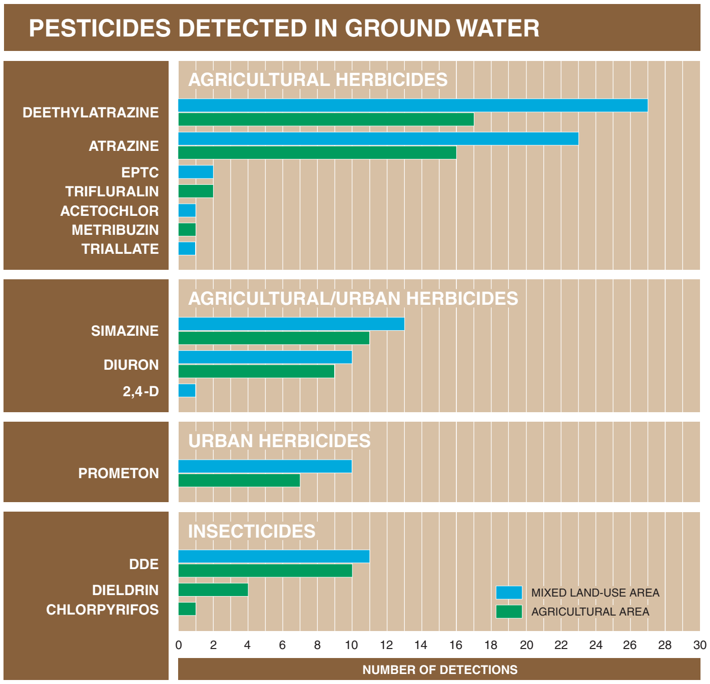


Figure 23. Most of the pesticides detected in ground water in the CAZB were herbicides used in agricultural and urban environments.

Most of the pesticides detected in ground water in the CAZB were herbicides used to control unwanted plants in urban and agricultural areas (fig. 23). Herbicide use in urban areas is indicated by detections of simazine and prometon in the West Salt River Valley and prometon and 2,4-D in the Upper Santa Cruz Basin. These herbicides are used primarily in nonagricultural areas (U.S. Geological Survey, 1999). Detections of atrazine and deethylatrazine (a breakdown product of atrazine) in the West Salt River Valley and the Upper Santa Cruz Basin are an indication that herbicides used in areas of present and historical agriculture are affecting ground-water quality. Atrazine is one of the most heavily used herbicides in agricultural areas in the United States (U.S. Geological Survey, 1999).

Concentrations of pesticides in ground water did not exceed drinking-water standards or guidelines. Although deethylatrazine, simazine, prometon, DDE, atrazine, and diuron were detected in more than 30 percent of the ground-water samples from the agricultural land-use study area of the West Salt River Valley, none of the concentrations exceeded drinking-water standards or guidelines. Similarly, pesticides detected in ground water from the basinwide sampling in the West Salt River Valley during 1996–98 did not exceed drinking-water standards or guidelines.

DDE was detected in 10 (56 percent) of the shallow ground-water samples from the agricultural land-use study area in the West Salt River Valley. Detections of DDE in this area are the result of the persistence of this insecticide breakdown product in the environment and the physical characteristics of the ground-water system in the area. In particular, the shallow depth to ground water in the agricultural land-use study area means that irrigation seepage and recharge, containing pesticides and their breakdown products, do not have to travel far to contaminate the ground water. Clay layers impede the movement of pesticides into the deeper aquifers in the area. The soils in the agricultural area have been identified as a source of DDE for the ground water (Brown, 1993). The only detection of DDE in the West Salt River Valley outside of the agricultural area was in a sample from the northern part of the Phoenix metropolitan area. DDE was not detected in samples from the Upper Santa Cruz Basin or the Sierra Vista subbasin.The large depths to ground water and small amounts of DDT used in most of the West Salt River Valley, the Upper Santa Cruz Basin, and the Sierra Vista subbasin limit the potential for introduction of DDE to the ground water.

Pesticides and Human Health

Laboratory studies, mostly on animals, have shown that pesticides can cause health problems such as birth defects, nerve damage, cancer, and disruption of the endocrine system (USEPA, rev. June 12, 2000). The health effects on humans are not adequately understood, particularly when estimating the risks of exposure to mixtures of pesticides in water (U.S. Geological Survey, 1999). The USEPA determines risk on the basis of toxicity and exposure to a single pesticide (U.S. Environmental Protection Agency, rev. November 17, 1999), whereas NAWQA studies in the CAZB (see p. 24) and nationwide have shown that most contamination in water occurs as pesticide mixtures (U.S. Geological Survey, 1999). The effects of exposure to low concentrations of pesticide mixtures in drinking water is not known and will require further study to determine if standards or guidelines can be developed.

Detections of multiple pesticides indicate the complexity of contamination from land-surface activities. No standards or guidelines currently exist for mixtures of pesticides in drinking water because their effect on human health is not known (U.S. Geological Survey, 1999). All 9 wells in the agricultural land-use study area had 3 or more pesticides detected, whereas only 3 of the 35 wells sampled basinwide in the West Salt River Valley had 3 or more pesticides detected, and none of the wells in the Upper Santa Cruz Basin had 3 or more pesticides detected (fig. 24). No pesticides were detected in the Sierra Vista subbasin.

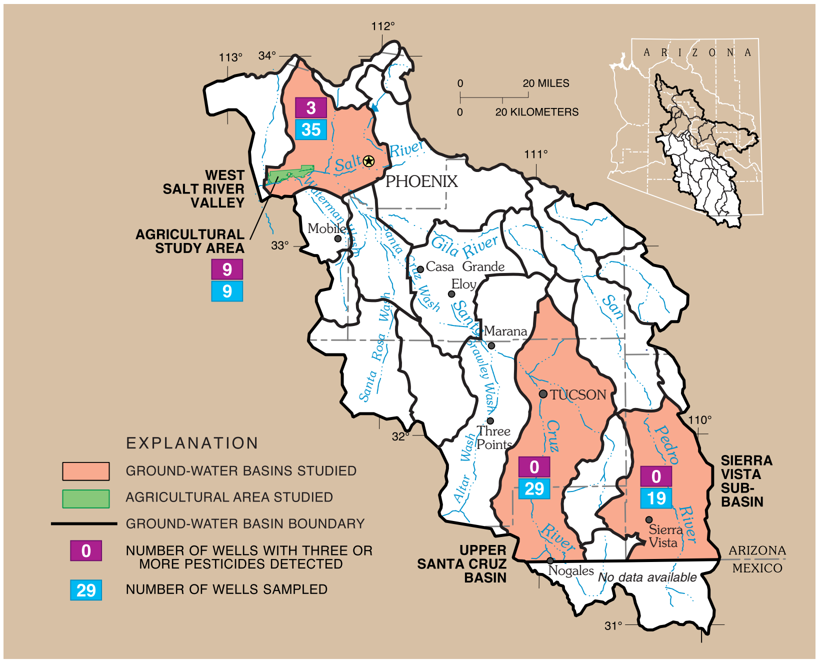


Figure 24. Multiple pesticides were detected in all nine monitoring wells in the agricultural land-use study area of the West Salt River Valley.

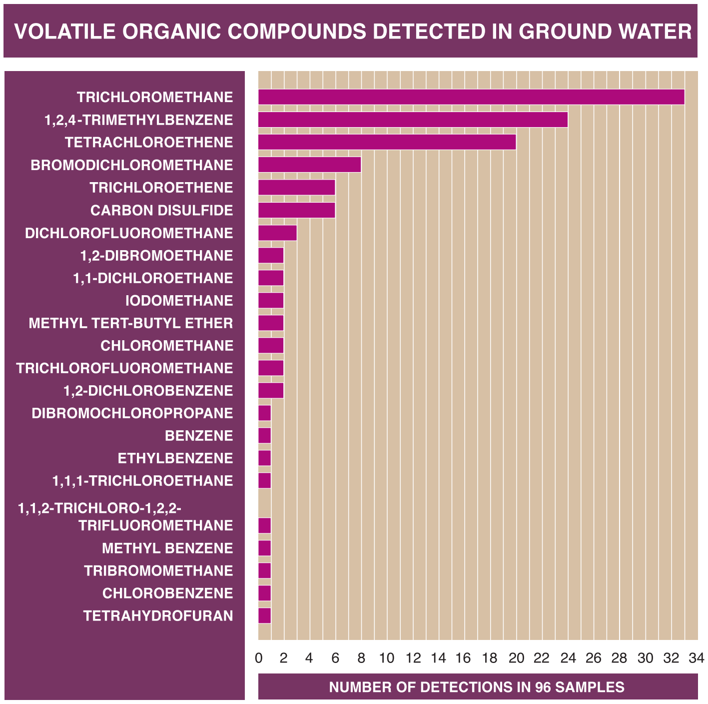


Figure 25. The VOCs trichloromethane, 1,2,4-trimethylbenzene, and tetrachloroethene were detected most frequently in ground water.

Volatile organic compounds (VOCs), including gasoline compounds, solvents, and refrigerants, have been identified as a major concern for ground-water contamination in Arizona (Marsh, 1994). Leaking underground storage tanks and disposal of solvents have been linked to most of the documented cases of ground-water contamination by VOCs. Electronic- and aerospace-manufacturing facilities use solvents for degreasing and are known to be sources of some of the largest VOC contamination problems in Arizona. Disposal of solvents from these types of facilities has occurred since the 1950s (Marsh, 1994). Dry-cleaning facilities also have been identified as sources of recent ground-water contamination by VOCs. Some municipal supply wells in the urban areas of Phoenix and Tucson are no longer used because of contamination by VOCs (Marsh, 1994).

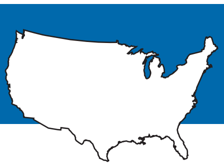
VOCs were detected in ground water from all three basins sampled during 1996–98 (fig. 25). Of the 96 samples collected, 33 (34 percent) contained trichloromethane, 24 (24 percent) contained 1,2,4-

trimethylbenzene, and 20 (21 percent) contained tetrachloroethene (otherwise known as perchloroethylene, PCE, a solvent commonly used in dry cleaning). Only two VOC detections exceeded drinking-water regulations—PCE (5.48 µg/L) in the Upper Santa Cruz Basin and 1,2-dibromoethane (0.080 µg/L) in shallow ground water in the agricultural area of the West Salt River Valley.

Shallow ground water from the nine wells in the agricultural land-use study area had the largest number of VOC detections (35). Ground water from the other 35 wells in the West Salt River Valley had 32 detections. The Upper Santa Cruz Basin (18) and the Sierra Vista subbasin (13) had fewer detections. The larger area of urban land use in the West Salt River Valley appears to be the reason for the greater number of detections there than in the other basins sampled.

Three wells that had five or more VOCs detected in ground water were located in the metropolitan area of Phoenix in the West Salt River Valley. The VOCs detected in these wells were either refrigerants, solvents and chemicals used to make solvents, or gasoline additives. These detections are typical of detections found in small-capacity wells in the metropolitan Phoenix area (Marsh, 1994). Combinations of solvents and gasoline additives are often detected in ground water because their use is widespread, not necessarily because they are from the same source (Squillace and others, 1999).

Detections of VOCs in ground water in the relatively undeveloped Sierra Vista subbasin indicate that ground water in localized areas of the subbasin may be affected by human activities. These detections are not widespread; therefore, the effects of human activity on present-day ground-water quality are not considered significant for the entire subbasin. These detections are an “early warning” of what could occur in the future in a basin that is presently considered minimally affected by urban activities.



Trichloromethane was the most commonly detected VOC in the Nation and in the CAZB Study Unit

Trichloromethane (chloroform), tetrachloroethene (PCE), and 1,2,4-trimethylbenzene were three of the five most commonly detected VOCs in the Nation and in the CAZB when concentrations above an assessment level of 0.1 µg/L were considered. The national data collected by the NAWQA Program during 1996–99 represent ambient ground water for all land-use types.Trichloromethane and PCE have been shown to cause cancer in laboratory animals from long-term exposure at concentrations greater than USEPA MCLs.

Trichloromethane is a by-product created during the use of chlorine to disinfect water, a solvent, and a degradation product of carbon tetrachloride. It can enter ground water from lawn irrigation, leaking sewers and water mains, and spills or improper disposal at industrial sites. The use of treated effluent from sewage-treatment plants for irrigation also provides a way for trichloromethane to reach the ground water in the CAZB, specifically in the agricultural land-use study area in the West Salt River Valley.

PCE is a solvent used primarily for degreasing and at dry-cleaning facilities. 1,2,4-trimethylbenzene is used to make trimellitic anhydride, dyes, and pharmaceuticals. Because there are many individual sources of these compounds in urban areas of the CAZB, it is diffcult to identify the exact sources of ground-water contamination without site-specific studies, which were beyond the scope of the NAWQA sampling program.

Five most frequently detected volatile organic compounds in the CAZB and the Nation

Central Arizona Basins Study Unit		Nation	
Compound name	Frequency of detection, in percent	Compound name	Frequency of detection, in percent
Trichloromethane	16	*Trichloromethane*	12
Chloromethane	6	*Toluene*	4
Tetrachloroethene	5	*Tetrachloroethene*	4
1,2,4-Trimethylbenzene	4	*Carbon disulfide*	4
Bromodichloromethane	2	*1,2,4-Trimethylbenzene*	4

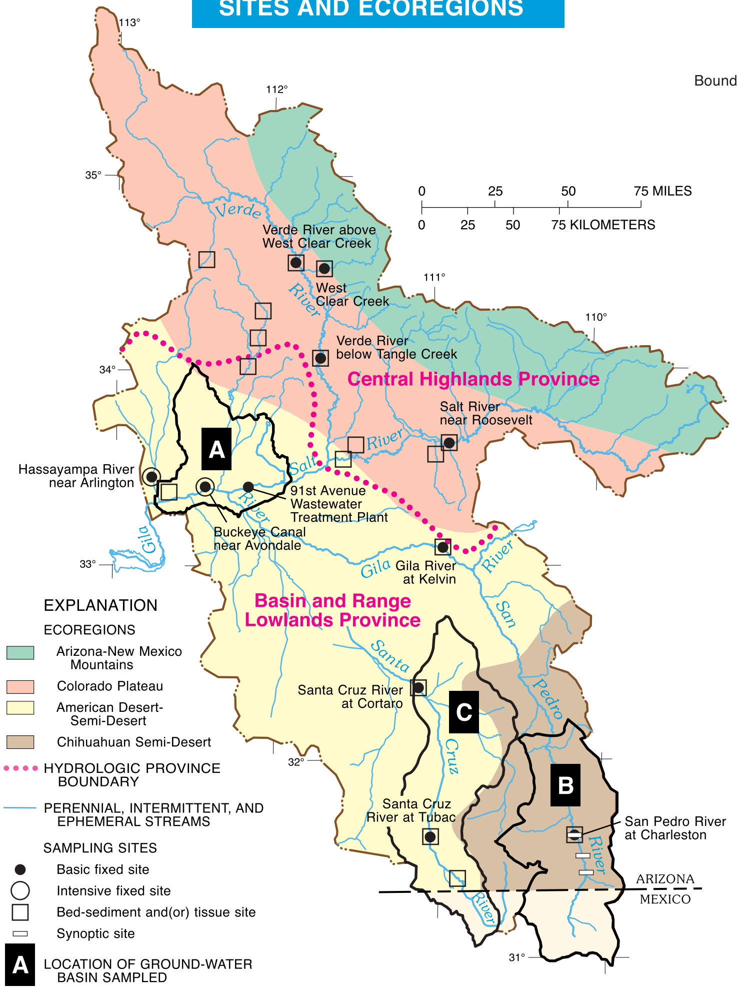
(Data include all land-use types; assessment level of 0.1 microgram per liter)

STUDY UNIT DESIGN

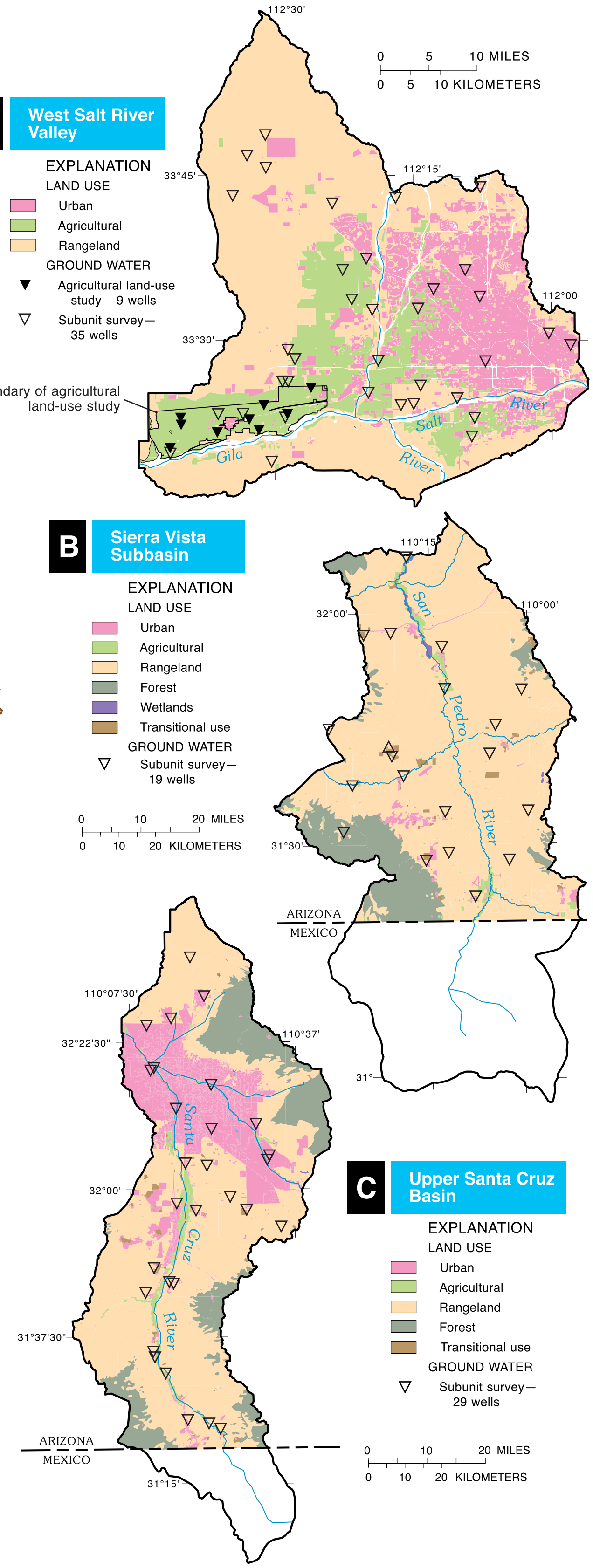
The Central Arizona Basins study was designed to provide nationally comparable water-quality data and address local and national questions about water quality. The primary goal of the study was to understand the human and natural factors that affect the chemistry of ground and surface water and communities of aquatic organisms.

Surface-water chemistry and biological-sampling sites were divided between the two main hydrologic provinces in the study area: the Central Highlands and the Basin and Range Lowlands (see above). Ground-water samples were collected in three basins in the Basin and Range Lowlands. Human activities were least in the Sierra Vista subbasin, greatest in the West Salt River Valley, and intermediate in the Upper Santa Cruz Basin. Effects of agricultural activities on ground water were studied in the western part of the West Salt River Valley.

STREAM-SAMPLING SITES AND ECOREGIONS



GROUND-WATER-QUALITY-SAMPLING SITES AND LAND USE



SUMMARY OF DATA COLLECTION IN THE CENTRAL ARIZONA BASINS, 1995–98

Study component	What data were collected and why	Types of sites sampled	Number of sites	Sampling frequency and period
Stream Chemistry				
Basic fixed sites, general water quality	Streamflow, dissolved oxygen, pH, alkalinity, specific conductance, temperature, nutrients, major ions, organic carbon, and suspended sediment were measured to determine occurrence and distribution.	Streams selected to represent urban, mixed agricultural/urban, and forest/rangeland land uses were distributed throughout the study area. Basins ranged from 0 miles (at point sources) to 18,011 square miles.	9	Monthly plus high flows Oct. 1995–Apr. 1998
Intensive fixed sites	Above constituents plus 87 pesticides and 85 volatile organic compounds.	Sites selected closer to urban and (or) agricultural areas so as to be more likely to reflect those land uses.	2	Monthly Jan. 1996–Dec. 1996, increased sampling frequency to approximately twice a month Dec. 1996–Feb. 1998
Fixed sites, dissolved organic carbon	Spectral characteristics of dissolved organic carbon from surface water were measured to determine sources.	Same sites as basic fixed sites and intensive fixed sites.	11	Monthly Jan. 1996–August 1997
Synoptic	Same as basic fixed sites, plus pesticides.	Three locations collocated with key sites for stream ecology synoptic.	3	Quarterly Jan. 97–Oct. 97
Contaminants in bed sediment	Trace elements and (or) organic compounds to determine occurrence and distribution in streambed sediments.	Depositional zones of most basic and intensive stream-chemistry sites plus additional sites.	17	Once May and June 1996
Contaminants in tissues of aquatic biota	Trace elements and (or) organic compounds to determine occurrence and distribution in tissues of fish, clams, and crayfish.	Same sites as sediment samples.	15	Once May and June 1996
Stream Ecology				
Basic sites	Communities of algae, invertebrates, and fish; and instream and riparian habitats surveyed to assess biological conditions of the study area.	Sites collocated with most basic and intensive stream-chemistry sites.	7 2	Once Oct. 1995–Jan. 1996 Annually 1995–1997
Synoptic	Communities of algae, invertebrates, and fish; and instream and riparian habitats surveyed to evaluate spatial variability.	Nine reaches along one segment of a stream with minimal anthropogenic influences.	9	Once Oct.–Dec. 1996
Ground-Water Chemistry				
Study Unit West Salt River Valley-mixed land use	Nutrients, major ions, trace elements, volatile organic compounds, radon, dissolved organic carbon, and pesticides to assess water quality of the basin's aquifers.	Existing domestic, public-supply, irrigation, livestock, and industrial wells.	35	Once 1996–1997
Study Unit Upper Santa Cruz Basin - mixed land use	Nutrients, major ions, trace elements, volatile organic compounds, radon, dissolved organic carbon, and pesticides to assess water quality of the basin's aquifers.	Existing domestic, public-supply, irrigation, livestock, and industrial wells.	29	Once 1998
Study Unit Sierra Vista subbasin - mixed land use	Nutrients, major ions, trace elements, volatile organic compounds, radon, dissolved organic carbon, and pesticides to assess water quality of the basin's aquifers.	Existing domestic, public-supply, irrigation, and livestock wells.	19	Once 1996
Land use West Salt River Valley - agricultural	Nutrients, major ions, trace elements, volatile organic compounds, radon, dissolved organic carbon, and pesticides to determine effects of agricultural land use on shallow ground-water quality.	Shallow monitoring wells.	9	Twice Aug. 1997 Feb. 1998

GLOSSARY

Anthropogenic—A condition or occurrence that is the result of, or is influenced by, human activity.

Aquatic-life criteria—Water-quality guidelines for protection of aquatic life. Typically refers to U.S. Environmental Protection Agency water-quality criteria for protection of aquatic organisms.

Aquifer—A water-bearing layer of soil, sand, gravel, or rock that will yield usable quantities of water to a well.

Background concentration- A concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.

Base flow—Sustained, low flow in a stream; ground-water discharge is the source of base flow in most places.

Basic fixed sites—Sites on streams at which streamflow is measured and samples are collected for temperature, salinity, suspended sediment, major ions and metals, nutrients, and organic carbon to assess the broad-scale spatial and temporal character and transport of inorganic constituents of streamwater in relation to hydrologic conditions and environmental settings.

Bed sediment—The material that temporarily is stationary in the bottom of a stream or other watercourse.

Bioaccumulation—The biological sequestering of a substance at a higher concentration than that at which it occurs in the surrounding environment or medium. Also, the process whereby a substance enters organisms through the gills, epithelial tissues, or dietary or other sources.

Biomass—The amount of living matter, in the form of organisms, present in a particular habitat, usually expressed as weight per unit area.

Breakdown product—A compound derived by chemical, biological, or physical action upon a pesticide. The breakdown is a natural process that may result in a more toxic or a less toxic compound and a more persistent or less persistent compound.

Concentration—The amount or mass of a substance present in a given volume or mass of sample. Usually expressed as milligrams per liter or micrograms per liter (water sample) or micrograms per kilogram (sediment or tissue sample).

Confining layer—A layer of sediment or lithologic unit of low permeability that bounds an aquifer.

Cubic foot per second (ft^3/s or cfs)—Rate of water discharge representing a volume of 1 cubic foot passing a given point during 1 second, equivalent to approximately 7.48 gallons per second or 448.8 gallons per minute or 0.02832 cubic meter per second.

Dissolved solids—Amount of minerals, such as salt, that are dissolved in water; amount of dissolved solids is an indicator of salinity or hardness.

Drainage basin—The portion of the surface of the Earth that contributes water to a stream through overland runoff, including tributaries and impoundments.

Drinking-water guideline—Nonenforceable Federal guideline regarding cosmetic (tooth or skin discoloration) or aesthetic effects (such as taste, color, odor).

Drinking-water standard—A threshold concentration in a public drinking-water supply, designed to protect human health or as defined here, standards are U.S. Environmental Protection Agency regulations that specify the maximum contamination levels for public water systems required to protect the public welfare.

Ecoregion—An area of similar climate, landform, soil, potential natural vegetation, hydrology, or other ecologically relevant variables.

Effluent—Outflow from a particular source, such as a stream that flows from a lake or liquid waste that flows from a factory or sewage-treatment plant.

Ephemeral stream—A stream or part of a stream that flows only in direct response to precipitation or snowmelt. Its channel is above the water table at all times.

Eutrophication—The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

Evaporite minerals (deposits)—Minerals or deposits of minerals formed by evaporation of water containing salts. These deposits are common in arid climates.

Evapotranspiration—A collective term that includes water lost through evaporation from the soil and surface-water bodies and by plant transpiration.

Infiltration—Movement of water, typically downward, into soil or porous rock.

Intensive fixed sites—Basic Fixed Sites with increased sampling frequency during selected seasonal periods and analysis of dissolved pesticides for 1 year. Most NAWQA Study Units have one to two integrator Intensive Fixed Sites and one to four indicator Intensive Fixed Sites.

Intermittent stream—A stream that flows only when it receives water from rainfall runoff or springs, or from some surface source such as melting snow.

Invertebrate—An animal having no backbone or spinal column.

Irrigation return flow—The part of irrigation applied to the surface that is not consumed by evapotranspiration or uptake by plants and that migrates to an aquifer or surface-water body.

Land subsidence—Compression of soft aquifer materials in a confined aquifer due to pumping of water from the aquifer.

Leaching—The removal of materials in solution from soil or rock to ground water; refers to movement of pesticides or nutrients from land surface to ground water.

Load—General term that refers to a material or constituent in solution, in suspension, or in transport; usually expressed in terms of mass or volume.

LOWESS smooth—LOcally WEighted Scatterplot Smoothing is a statistical method of defining a smooth curve through the middle of a scatterplot to highlight trends or patterns in the data.

Maximum Contaminant Level (MCL)—Maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are enforceable standards established by the U.S. Environmental Protection Agency.

Median—The middle or central value in a distribution of data ranked in order of magnitude. The median is also known as the 50th percentile.

Metabolite—A substance produced in or by biological processes.

Micrograms per liter (µg/L)—A unit expressing the concentration of constituents in solution as weight (micrograms) of solute per unit volume (liter) of water; equivalent to one part per billion in most stream water and ground water. One thousand micrograms per liter equals 1 mg/L.

Milligrams per liter (mg/L)—A unit expressing the concentration of chemical constituents in solution as mass (milligrams) of solute per unit volume (liter) of water; equivalent to one part per million in most stream water and ground water. One thousand micrograms per liter equals 1 mg/L.

Nutrient—Element or compound essential for animal and plant growth. Common nutrients in fertilizer include nitrogen, phosphorus, and potassium.

Organochlorine insecticide—A class of organic insecticides containing a high percentage of chlorine. Includes dichlorodiphenylethanes (such as DDT), chlorinated cyclodienes (such as chlordane), and chlorinated benzenes (such as lindane). Most organochlorine insecticides were banned because of their carcinogenicity, tendency to bioaccumulate, and toxicity to wildlife.

Perennial stream—A stream that normally has water in its channel at all times.

Pesticide—A chemical applied to crops, rights of way, lawns, or residences to control weeds, insects, fungi, nematodes, rodents or other "pests."

Picocurie (pCi)—One trillionth (10^{-12}) of the amount of radioactivity represented by a curie (Ci). A curie is the quantity of any radioactive nuclide in which the number of disintegrations is 3.7×10^{10} per second (dps). A picocurie yields 2.22 disintegrations per minute (dpm) or 0.037 dps.

Public-supply withdrawals—Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public water use.

Recharge—Water that infiltrates the ground and reaches the saturated zone.

Riparian—Areas adjacent to rivers and streams with a high density, diversity, and productivity of plant and animal species relative to nearby uplands.

Runoff—Excess rainwater or snowmelt that is transported to streams by overland flow, tile drains, or ground water.

Secondary maximum contaminant level (SMCL)—The maximum contamination level in public water systems that, in the judgment of the U.S. Environmental Protection Agency (USEPA), is acceptable to protect the public welfare. SMCLs are secondary (nonenforceable) drinking water regulations established by the USEPA for contaminants that may adversely affect the odor or appearance of such water.

Specific conductance—A measure of the ability of a liquid to conduct an electrical current.

Tolerant species—Those species that are adaptable to (tolerant of) human alterations to the environment and often increase in number when human alterations occur.

Trace element—An element typically found in only minor amounts (concentrations less than 1.0 milligram per liter) in water; includes arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc.

Volatile organic compounds (VOCs)—Organic chemicals that have a high vapor pressure relative to their water solubility. VOCs include components of gasoline, fuel oils, and lubricants, as well as organic solvents, fumigants, some inert ingredients in pesticides, and some by-products of chlorine disinfection.

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APPENDIX—WATER-QUALITY DATA FROM THE CENTRAL ARIZONA BASINS IN A NATIONAL CONTEXT

For a complete view of Central Arizona Basins data and for additional information about specific benchmarks used, visit our Web site at http://water.usgs.gov/nawqa/. Also visit the NAWQA Data Warehouse for access to NAWQA data sets at http://water.usgs.gov/nawqa/data.

This appendix is a summary of chemical concentrations and biological indicators assessed in the Central Arizona Basins. Selected results for this Study Unit are graphically compared to results from as many as 36 NAWQA Study Units investigated from 1991 to 1998 and to national water-quality benchmarks for human health, aquatic life, or fish-eating wildlife. The chemical and biological indicators shown were selected on the basis of frequent detection, detection at concentrations above a national benchmark, or regulatory or scientific importance. The graphs illustrate how conditions associated with each land use sampled in the Central Arizona Basins compare to results from across the Nation, and how conditions compare among the several land uses. Graphs for chemicals show only detected concentrations and, thus, care must be taken to evaluate detection frequencies in addition to concentrations when comparing study-unit and national results. For example, trifluralin concentrations in Central Arizona Basins agricultural streams were similar to the national distribution, but the detection frequency was much higher (76 percent compared to 21 percent).

CHEMICALS IN WATER

Concentrations and detection frequencies, Central Arizona Basins, 1995–98—Detection sensitivity varies among chemicals and, thus, frequencies are not directly comparable among chemicals

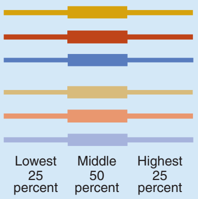
◆ Detected concentration in Study Unit

66 38 Frequencies of detection, in percent. Detection frequencies were not censored at any common reporting limit. The left-hand column is the study-unit frequency and the right-hand column is the national frequency

-- Not measured or sample size less than two

12 Study-unit sample size. For ground water, the number of samples is equal to the number of wells sampled

National ranges of detected concentrations, by land use, in 36 NAWQA Study Units, 1991–98—Ranges include only samples in which a chemical was detected



Streams in agricultural areas
Streams in urban areas
Streams and rivers draining mixed land uses
Shallow ground water in agricultural areas
Shallow ground water in urban areas
Major aquifers

National water-quality benchmarks

National benchmarks include standards and guidelines related to drinking-water quality, criteria for protecting the health of aquatic life, and a goal for preventing stream eutrophication due to phosphorus. Sources include the U.S. Environmental Protection Agency and the Canadian Council of Ministers of the Environment

| Drinking-water quality (applies to ground water and surface water)

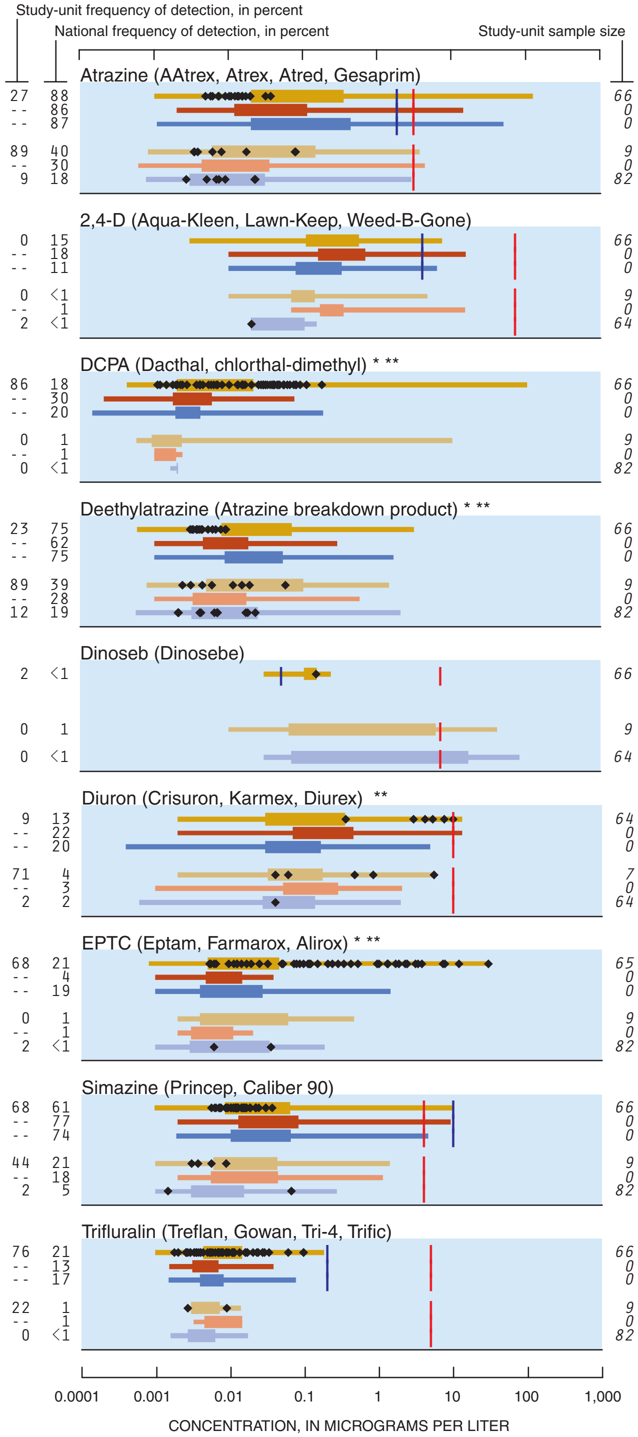
| Protection of aquatic life (applies to surface water only)

| Prevention of eutrophication in streams not flowing directly into lakes or impoundments

* No benchmark for drinking-water quality

** No benchmark for protection of aquatic life

Pesticides in water—Herbicides

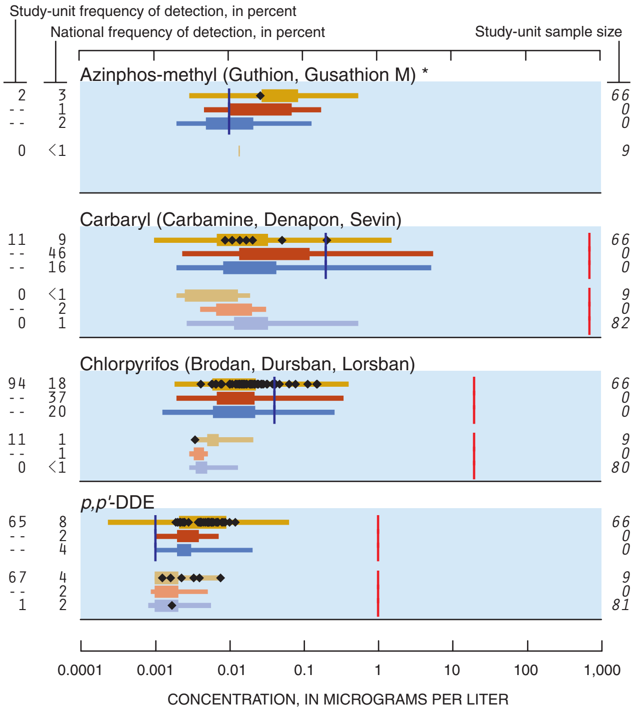


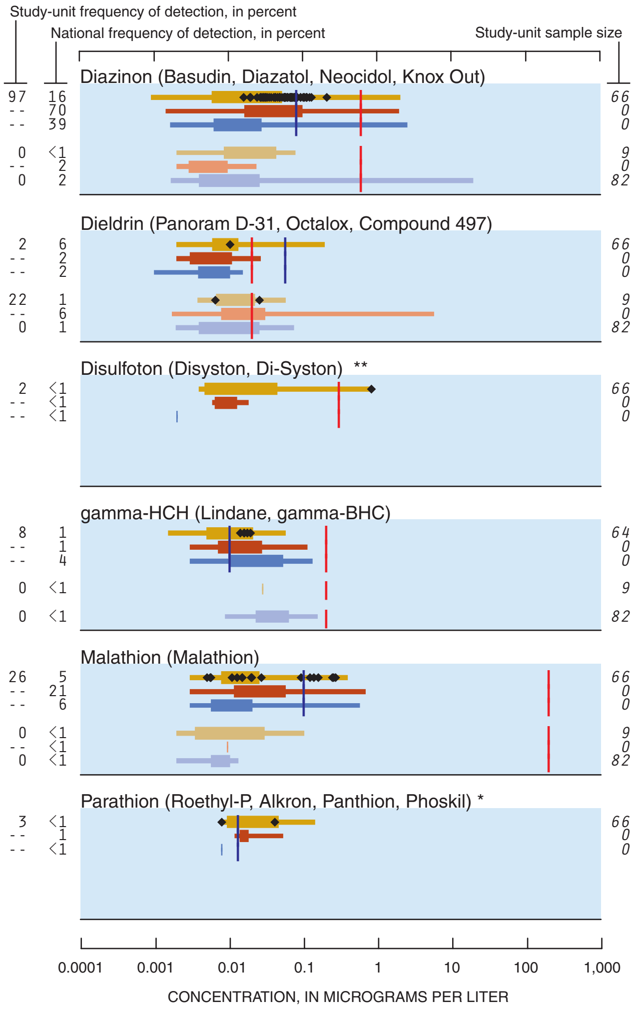
Other herbicides detected
Acetochlor (Harness Plus, Surpass) * **
Benfluralin (Balan, Benefin, Bonalan) * **
Cyanazine (Bladex, Fortrol)
Linuron (Lorox, Linex, Sarclex, Linurex, Afalon) *
Metribuzin (Lexone, Sencor)

Molinate (Ordram) * **
Pendimethalin (Pre-M, Prowl, Stomp) * **
Prometon (Pramitol, Princep) **
Pronamide (Kerb, Propyzamid) **
Propachlor (Ramrod, Satecid) **
Tebuthiuron (Spike, Tebusan)
Triallate (Far-Go, Avadex BW, Tri-allate) *

Herbicides not detected
Acifluorfen (Blazer, Tackle 2S) **
Alachlor (Lasso, Bronco, Lariat, Bullet) **
Bentazon (Basagran, Bentazone) **
Bromacil (Hyvar X, Urox B, Bromax)
Bromoxynil (Buctril, Brominal) *
Butylate (Sutan +, Genate Plus, Butilate) **
Chloramben (Amiben, Amilon-WP, Vegiben) **
Clopyralid (Stinger, Lontrel, Transline) * **
2,4-DB (Butyrac, Butoxone, Embutox Plus, Embutone) * **
Dacthal mono-acid (Dacthal breakdown product) * **
Dicamba (Banvel, Dianat, Scotts Proturf)
Dichlorprop (2,4-DP, Seritox 50, Lentemul) * **
2,6-Diethylaniline (Alachlor breakdown product) * **
Ethalfluralin (Sonalan, Curbit) * **
Fenuron (Fenulon, Fenidim) * **
Fluometuron (Flo-Met, Cotoran) **
MCPA (Rhomene, Rhonox, Chiptox)
MCPB (Thistrol) * **
Metolachlor (Dual, Pennant)
Napropamide (Devrinol) * **
Neburon (Neburea, Neburyl, Noruben) * **
Norflurazon (Evital, Predict, Solicam, Zorial) * **
Oryzalin (Surflan, Dirimal) * **
Pebulate (Tillam, PEBC) * **
Picloram (Grazon, Tordon)
Propanil (Stam, Stampede, Wham) * **
Propham (Tuberite) **
2,4,5-T **
2,4,5-TP (Silvex, Fenoprop) **
Terbacil (Sinbar) **
Thiobencarb (Bolero, Saturn, Benthiocarb) * **
Triclopyr (Garlon, Grandstand, Redeem, Remedy) * **

Pesticides in water—Insecticides



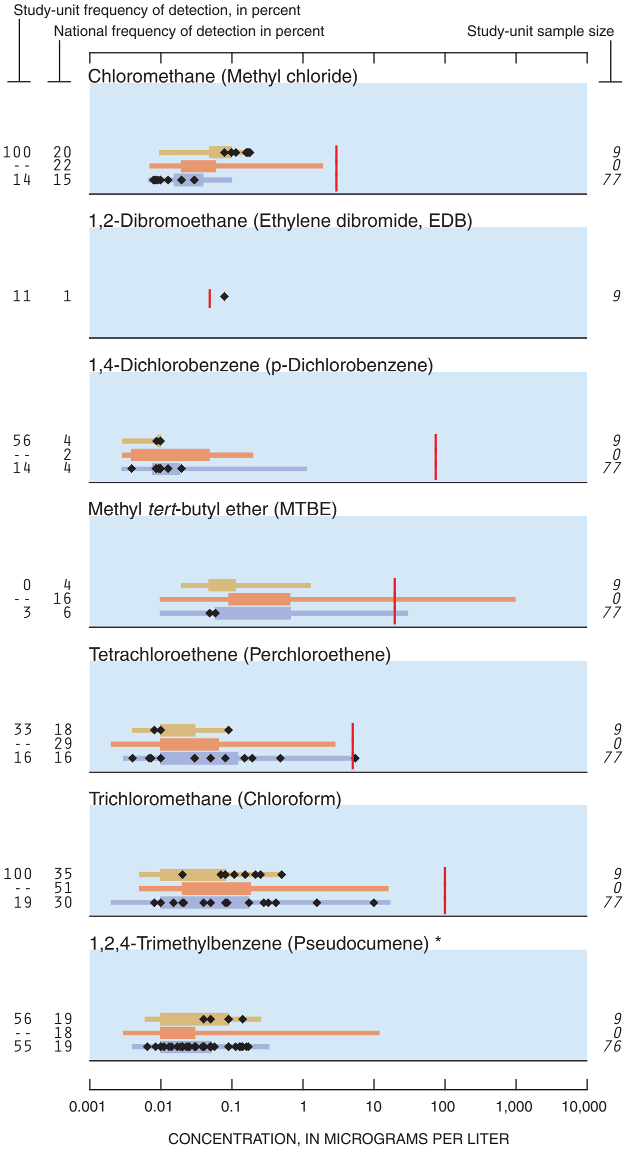


Other insecticides detected
Carbofuran (Furadan, Curaterr, Yaltox)
Methomyl (Lanox, Lannate, Acinate) **
Methyl parathion (Penncap-M, Folidol-M) **
Phorate (Thimet, Granutox, Geomet, Rampart) * **
Propoxur (Baygon, Blattanex, Unden, Proprotox) * **

Insecticides not detected
Aldicarb (Temik, Ambush, Pounce)
Aldicarb sulfone (Standak, aldoxycarb)
Aldicarb sulfoxide (Aldicarb breakdown product)
Ethoprop (Mocap, Ethoprophos) * **
Fonofos (Dyfonate, Capfos, Cudgel, Tycap) **
alpha-HCH (alpha-BHC, alpha-lindane) **
3-Hydroxycarbofuran (Carbofuran breakdown product) * **
Methiocarb (Slug-Geta, Grandslam, Mesurol) * **
Oxamyl (Vydate L, Pratt) **
cis-Permethrin (Ambush, Astro, Pounce) * **
Propargite (Comite, Omite, Ornamite) * **
Terbufos (Contraven, Counter, Pilarfox) **

Volatile organic compounds (VOCs) in ground water

These graphs represent data from 16 Study Units, sampled from 1996 to 1998



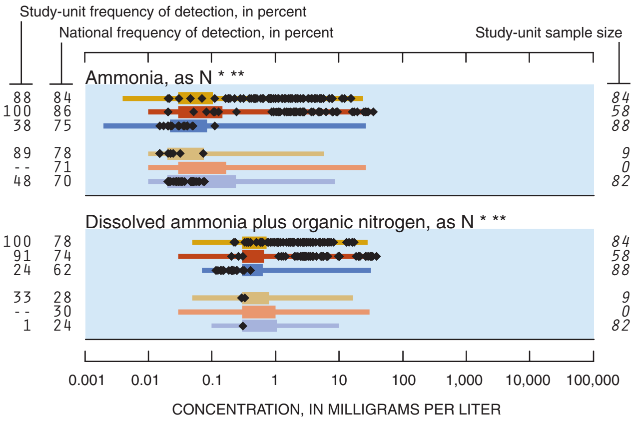
Other VOCs detected

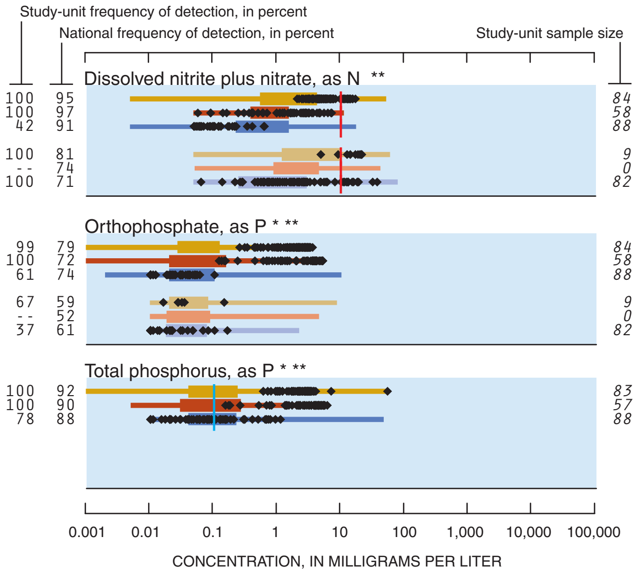
Benzene
Bromodichloromethane (Dichlorobromomethane)
Carbon disulfide *
1-Chloro-2-methylbenzene (*o*-Chlorotoluene)
Chlorobenzene (Monochlorobenzene)
Dichlorodifluoromethane (CFC 12, Freon 12)
1,1-Dichloroethane (Ethylidene dichloride) *
1,1-Dichloroethene (Vinylidene chloride)
Dichloromethane (Methylene chloride)
1,2-Dimethylbenzene (*o*-Xylene)
1,3 & 1,4-Dimethylbenzene (*m*-&*p*-Xylene)
1-4-Epoxy butane (Tetrahydrofuran, Diethylene oxide) *
Ethylbenzene (Phenylethane)
Iodomethane (Methyl iodide) *
Methylbenzene (Toluene)
2-Propanone (Acetone) *
Tribromomethane (Bromoform)
1,1,2-Trichloro-1,2,2-trifluoroethane (Freon 113) *
1,1,1-Trichloroethane (Methylchloroform)
Trichloroethene (TCE)
Trichlorofluoromethane (CFC 11, Freon 11)

VOCs not detected

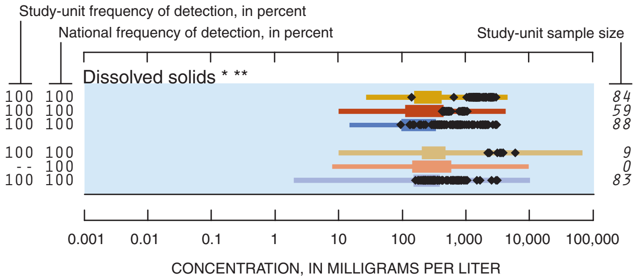
tert-Amylmethylether (*tert*-amyl methyl ether (TAME)) *
Bromobenzene (Phenyl bromide) *
Bromochloromethane (Methylene chlorobromide)
Bromoethene (Vinyl bromide) *
Bromomethane (Methyl bromide)
2-Butanone (Methyl ethyl ketone (MEK)) *
n-Butylbenzene (1-Phenylbutane) *
sec-Butylbenzene *
tert-Butylbenzene *
3-Chloro-1-propene (3-Chloropropene) *
1-Chloro-4-methylbenzene (*p*-Chlorotoluene)
Chlorodibromomethane (Dibromochloromethane)
Chloroethane (Ethyl chloride) *
Chloroethene (Vinyl chloride)
1,2-Dibromo-3-chloropropane (DBCP, Nemagon)
Dibromomethane (Methylene dibromide) *
trans-1,4-Dichloro-2-butene ((Z)-1,4-Dichloro-2-butene) *
1,2-Dichlorobenzene (*o*-Dichlorobenzene)
1,3-Dichlorobenzene (*m*-Dichlorobenzene)
1,2-Dichloroethane (Ethylene dichloride)
trans-1,2-Dichloroethene ((E)-1,2-Dichlorothene)
cis-1,2-Dichloroethene ((Z)-1,2-Dichloroethene)
1,2-Dichloropropane (Propylene dichloride)
2,2-Dichloropropane *
1,3-Dichloropropane (Trimethylene dichloride) *
trans-1,3-Dichloropropene ((E)-1,3-Dichloropropene)
cis-1,3-Dichloropropene ((Z)-1,3-Dichloropropene)
1,1-Dichloropropene *
Diethyl ether (Ethyl ether) *
Diisopropyl ether (Diisopropylether (DIPE)) *
Dimethylbenzenes (Xylenes (total))
Ethenylbenzene (Styrene)
Ethyl methacrylate *
Ethyl *tert*-butyl ether (Ethyl-*t*-butyl ether (ETBE)) *
1-Ethyl-2-methylbenzene (2-Ethyltoluene) *
Hexachlorobutadiene
1,1,1,2,2,2-Hexachloroethane (Hexachloroethane)
2-Hexanone (Methyl butyl ketone (MBK)) *
Isopropylbenzene (Cumene) *
p-Isopropyltoluene (*p*-Cymene) *
Methyl acrylonitrile *
Methyl-2-methacrylate (Methyl methacrylate) *
4-Methyl-2-pentanone (Methyl isobutyl ketone (MIBK)) *
Methyl-2-propenoate (Methyl acrylate) *
Naphthalene
2-Propenenitrile (Acrylonitrile)
n-Propylbenzene (Isocumene) *
1,1,2,2-Tetrachloroethane *
1,1,1,2-Tetrachloroethane
Tetrachloromethane (Carbon tetrachloride)
1,2,3,4-Tetramethylbenzene (Prehnitene) *
1,2,3,5-Tetramethylbenzene (Isodurene) *
1,2,4-Trichlorobenzene
1,2,3-Trichlorobenzene *
1,1,2-Trichloroethane (Vinyl trichloride)
1,2,3-Trichloropropane (Allyl trichloride)
1,2,3-Trimethylbenzene (Hemimellitene) *
1,3,5-Trimethylbenzene (Mesitylene) *

Nutrients in water

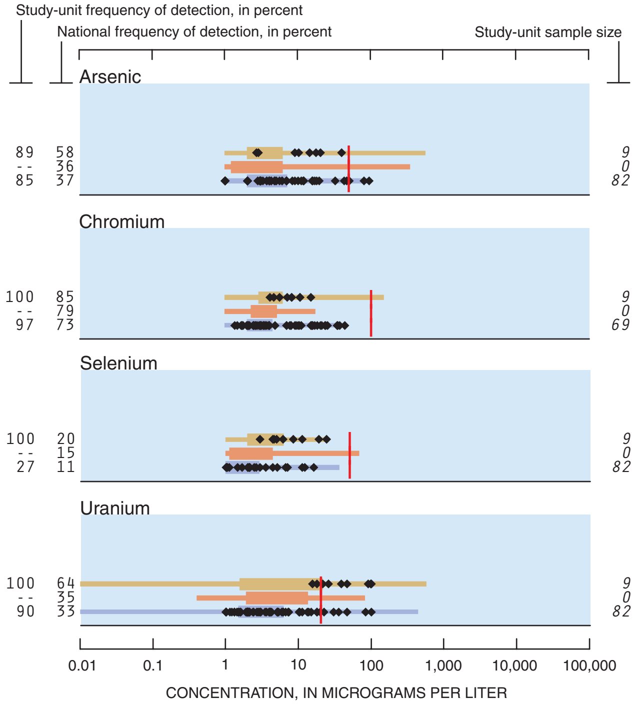


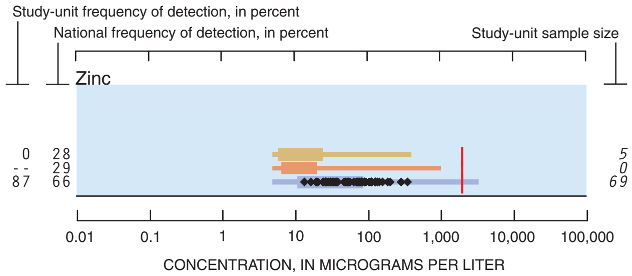


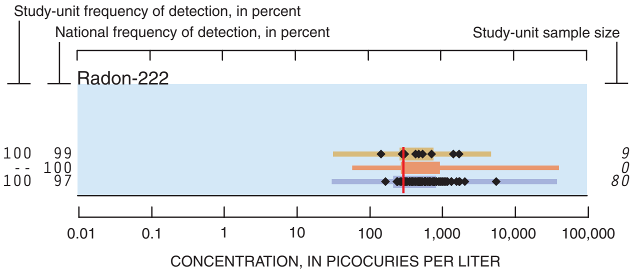
Dissolved solids in water



Trace elements in ground water







Other trace elements detected
Lead

Trace elements not detected
Cadmium

CHEMICALS IN FISH TISSUE AND BED SEDIMENT

Concentrations and detection frequencies, Central Arizona Basins, 1995–98—Detection sensitivity varies among chemicals and, thus, frequencies are not directly comparable among chemicals. Study-unit frequencies of detection are based on small sample sizes; the applicable sample size is specified in each graph

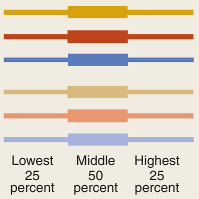
◆ Detected concentration in Study Unit

66 38 Frequencies of detection, in percent. Detection frequencies were not censored at any common reporting limit. The left-hand column is the study-unit frequency and the right-hand column is the national frequency

-- Not measured or sample size less than two

12 Study-unit sample size

National ranges of concentrations detected, by land use, in 36 NAWQA Study Units, 1991–98—Ranges include only samples in which a chemical was detected



Fish tissue from streams in agricultural areas
Fish tissue from streams in urban areas
Fish tissue from streams draining mixed land uses
Sediment from streams in agricultural areas
Sediment from streams in urban areas
Sediment from streams draining mixed land uses

National benchmarks for fish tissue and bed sediment

National benchmarks include standards and guidelines related to criteria for protection of the health of fish-eating wildlife and aquatic organisms. Sources include the U.S. Environmental Protection Agency, other Federal and State agencies, and the Canadian Council of Ministers of the Environment

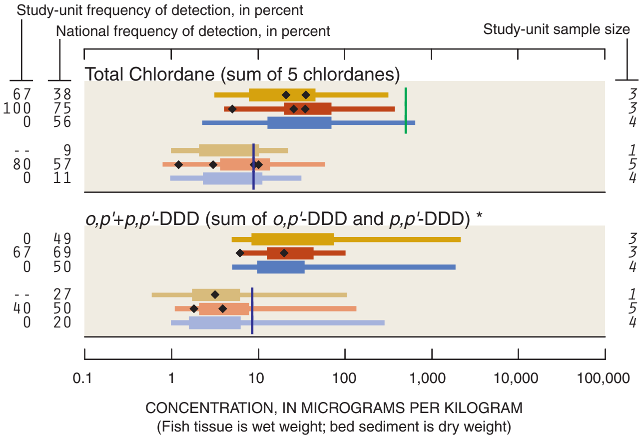
| Protection of fish-eating wildlife (applies to fish tissue)

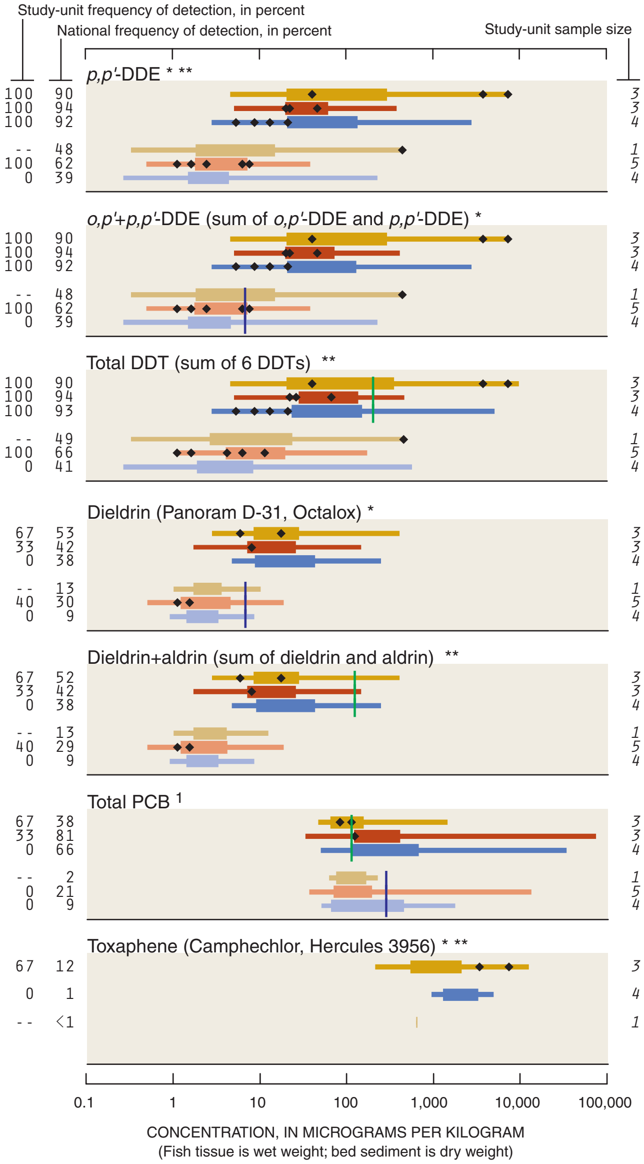
| Protection of aquatic life (applies to bed sediment)

* No benchmark for protection of fish-eating wildlife

** No benchmark for protection of aquatic life

Organochlorines in fish tissue (whole body) and bed sediment





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[1] The national detection frequencies for total PCB in sediment are biased low because about 30 percent of samples nationally had elevated detection levels compared to this Study Unit. See http://water.usgs.gov/nawqa/ for additional information.

Other organochlorines detected
Pentachloroanisole (PCA) * **
cis-Permethrin (Ambush, Astro, Pounce) * **
trans-Permethrin (Ambush, Astro, Pounce) * **

Organochlorines not detected
Chloroneb (Chloronebe, Demosan) * **
DCPA (Dacthal, chlorthal-dimethyl) * **
Endosulfan I (alpha-Endosulfan, Thiodan) * **
Endrin (Endrine)
gamma-HCH (Lindane, gamma-BHC, Gammexane) *
Total-HCH (sum of alpha-HCH, beta-HCH, gamma-HCH, and delta-HCH) **
Heptachlor epoxide (Heptachlor breakdown product) *
Heptachlor+heptachlor epoxide (sum of heptachlor and heptachlor epoxide) **
Hexachlorobenzene (HCB) **
Isodrin (Isodrine, Compound 711) * **
p,p'-Methoxychlor (Marlate, methoxychlore) * **
o,p'-Methoxychlor * **
Mirex (Dechlorane) **

BIOLOGICAL INDICATORS

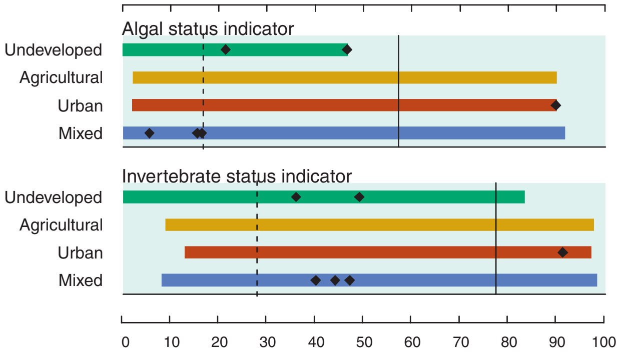
Higher national scores suggest habitat disturbance, water-quality degradation, or naturally harsh conditions. The status of algae, invertebrates (insects, worms, and clams), and fish provide a record of water-quality and stream conditions that water-chemistry indicators may not reveal. **Algal status** focuses on the changes in the percentage of certain algae in response to increasing siltation, and it often correlates with higher nutrient concentrations in some regions. **Invertebrate status** averages 11 metrics that summarize changes in richness, tolerance, trophic conditions, and dominance associated with water-quality degradation. **Fish status** sums the scores of four fish metrics (percent tolerant, omnivorous, non-native individuals, and percent individuals with external anomalies) that increase in association with water-quality degradation

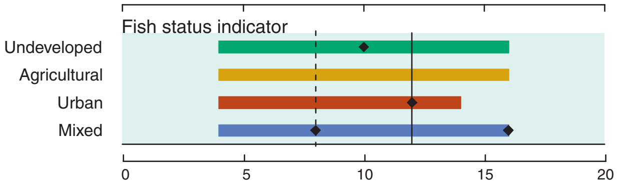
Biological indicator value, Central Arizona Basins, by land use, 1995–98

◆ Biological status assessed at a site

National ranges of biological indicators, in 16 NAWQA Study Units, 1994–98

🟩 Streams in undeveloped areas
🟨 Streams in agricultural areas
🟥 Streams in urban areas
🟦 Streams in mixed-land-use areas
—— 75th percentile
- - - 25th percentile





A COORDINATED EFFORT

Coordination with agencies and organizations in the Central Arizona Basins Study Unit was integral to the success of this water-quality assessment. We thank those who served as members of our liaison committee.

Federal Agencies
Bureau of Indian Affairs
Bureau of Reclamation
Centro de Investigación y Estudios Ambientales
Comisión Nacional del Agua
International Boundary and Water Commission
National Park Service
Natural Resources Conservation Service
Salt River-Pima Indian Community
Tohono O'odham Nation
U.S. Environmental Protection Agency
U.S. Fish and Wildlife Service (USFWS)
U.S. Department of Agriculture, Forest Service
U.S. Department of Agriculture, Water Conservation Laboratory

State Agencies
Arizona Department of Environmental Quality (ADEQ)
Arizona Department of Water Resources (ADWR)
Arizona Game and Fish Department (AzGF)
Arizona Geological Survey

Local Agencies
City of Phoenix
City of Tucson
Maricopa County
Pima Association of Governments
Pima County
Southern Arizona Association of Governments

Universities
Arizona State University
University of Arizona

Other public and private organizations
Arizona Toxics Information
Friends of the Santa Cruz River
Salt River Project
Southern Arizona Water Resources Association
The Nature Conservancy

We thank the following individuals and organizations for contributing to this effort.

Laurie Wirt (USGS) designed and guided the surface-water-quality sampling program for the CAZB from 1994 to 1996.

Doug Towne and Maureen Freark (ADEQ) coordinated with CAZB to design cooperative ground-water studies in the Upper Santa Cruz Basin and the Sierra Vista subbasin.

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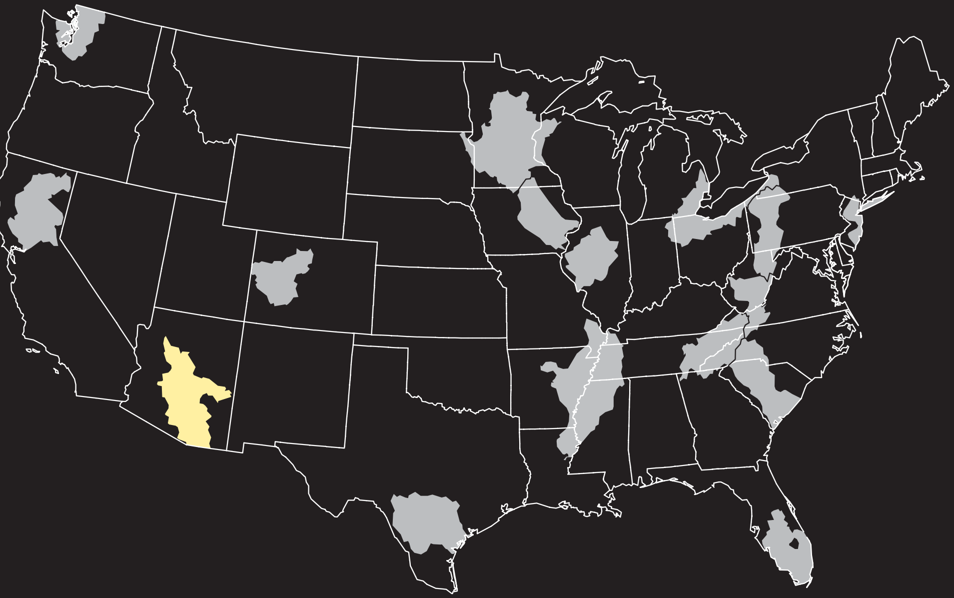
We extend special thanks and appreciation to our spouses, families, and friends, without whose support we could not have accomplished the work described herein.

NAWQA

National Water-Quality Assessment (NAWQA) Program
Central Arizona Basins



Cordy and others—Water Quality in the Central Arizona Basins
U.S. Geological Survey Circular 1213

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