

COLORADO

Ground-Water Quality

Ground water in Colorado (fig. 1) generally is suitable for most uses and constitutes 18 percent of the total water used. Of the total quantity of ground water used, 96 percent is for irrigation, 2 percent for public supply, 1 percent for rural domestic supplies, and 1 percent for livestock and industrial uses (U.S. Geological Survey, 1985, p. 153). Public supplies provide ground water to 320,000 people—11 percent of the 1980 population of 2,889,964 (U.S. Bureau of the Census, 1981).

Water in the principal aquifers (fig. 2) generally does not exceed national drinking-water standards for nitrate, sulfate, and iron; dissolved-solids concentrations generally are smaller than 1,000 mg/L (milligrams per liter). In some locales, contamination of ground water with inorganic and organic chemicals has resulted from waste disposal, mineral extraction and processing, and urbanization (fig. 3). In agricultural areas, dissolved-mineral content is increased by evapotranspiration and water use and reuse; also, increased nitrate plus nitrite concentrations may result from leaching of animal waste or nitrogen fertilizer. Pesticides applied on agricultural and forested land eventually may enter the ground-water system.

The Colorado Department of Health is responsible for coordinating efforts to protect the quality of the State's ground-water resources. The present public-water-supply monitoring program maintained by the Department has identified 55 of 546 public ground-water-supply systems that contain dissolved substances in concentrations that exceed State drinking-water standards (Colorado Department of Health, 1977). Routine testing is required by the Department for inorganic chemicals, selected organic chemicals (including trihalomethanes), and bacteria in public ground-water supplies. Trihalomethanes are a family of organic compounds, including chloroform, that results from a mixing of chlorine (for disinfection) with water containing natural organics. Tests for organic chemicals such as insecticides, herbicides, and solvents (including trichloroethylene) are not required for ground-water supplies. Private wells are not tested routinely; however, bacteria tests are required before the sale of a residence wherein the occupants must rely on ground water for their water supply.

WATER QUALITY IN PRINCIPAL AQUIFERS

Colorado has seven principal aquifers or aquifer systems (fig. 2A), all differing in water quality. The four aquifers consisting of unconsolidated deposits account for most of the withdrawals. These aquifers are the alluvial aquifer along the South Platte River and its tributaries, the alluvial aquifer along the Arkansas River and its tributaries, the High Plains aquifer in eastern Colorado, and the San Luis Valley aquifer system in the Rio Grande basin. The remaining three principal aquifers consist of consolidated rock: the Denver Basin aquifer system underlying parts of the South Platte and Arkansas River basins, the Piceance Basin aquifer system north-east of Grand Junction in the Colorado River basin, and the Lead-

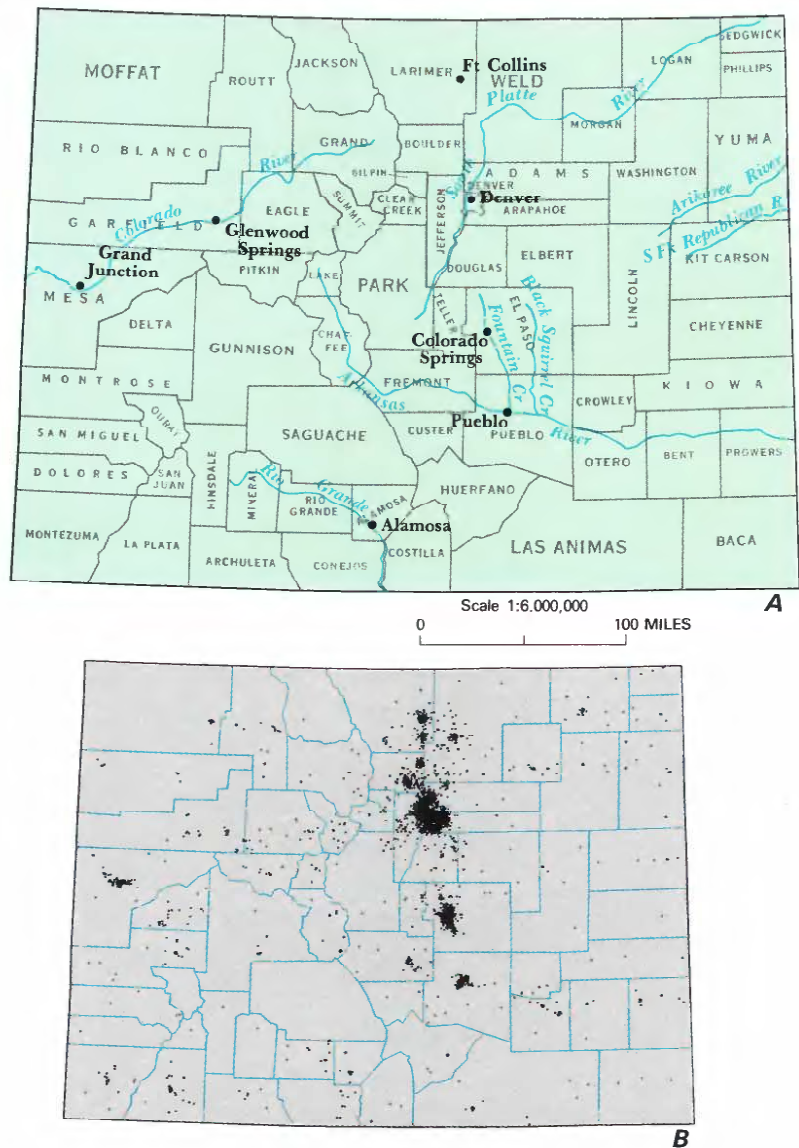


Figure 1. Selected geographic features and 1985 population distribution in Colorado. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

ville Limestone aquifer near Glenwood Springs in the Colorado River basin. Aquifers in the Dakota, Morrison, and Entrada Formations are not principal aquifers in Colorado but are shown in figure 2A because of their significance in adjacent States. In many areas of the State, wells yield water from other aquifers; however, these other aquifers provide only a small percentage of the total volume of water used.

BACKGROUND WATER QUALITY

The background water quality presented in this report does not represent pristine water quality. Before irrigation development,

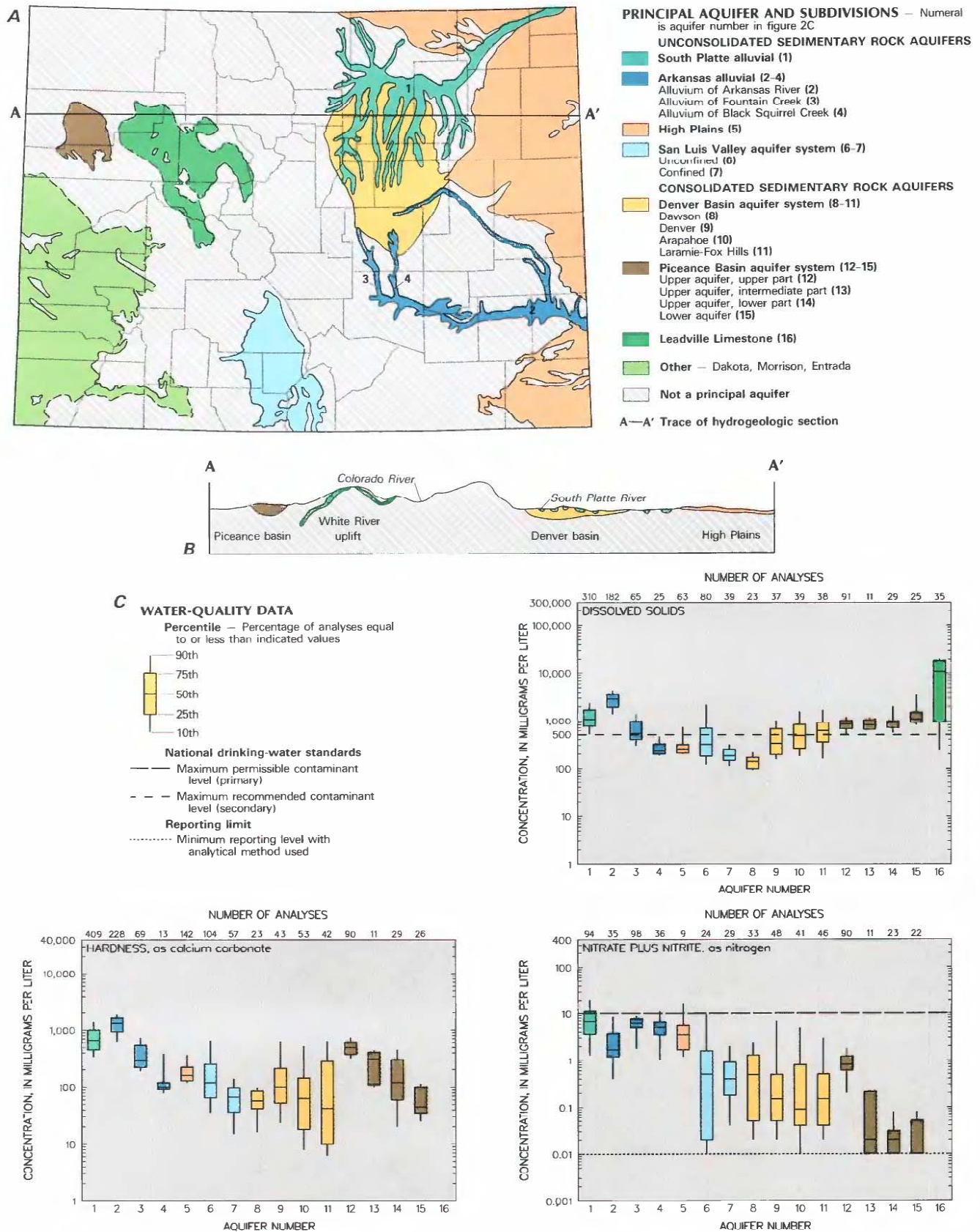


Figure 2. Principal aquifers and related water-quality data in Colorado. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1954-86. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1960a, b.)

for example, the alluvial aquifers had a much thinner saturated thickness than at present and may not have been hydraulically connected with many reaches of the South Platte and Arkansas Rivers; the quality of water in these aquifers before irrigation development is not known. Since as early as the 1860's, irrigation-water applications and ditch leakage have recharged the alluvial aquifers, raising water levels to the extent that water now discharges from those aquifers by evapotranspiration or seeps to streams, augmenting and sustaining flow for downstream diversions. It is the quality of water in these aquifers that is reported in this section. Since irrigation development began, use and reuse of surface water for irrigation has resulted in increased mineralization of water through evapotranspiration and drainage from irrigated land. Some of this surface water that is unused by plants enters the ground-water system and increases the dissolved-solids concentrations in the ground water. As a result, dissolved-solids concentrations increase in a downgradient direction in alluvial aquifers along the South Platte River, the Arkansas River (fig. 4), and the Rio Grande.

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2C. The summary is based on dissolved-solids, hardness as calcium carbonate, nitrate plus nitrite (as nitrogen), sulfate, and iron analyses of water samples collected from 1954 to 1986 from the principal aquifers in Colorado. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L sulfate, and 300 µg/L (micrograms per liter) iron.

The number associated with each of the aquifers in the discussion that follows refers to the location of the aquifer in figure 2A and the graphic summary of water-quality data in figure 2C. The national drinking-water standard (U.S. Environmental Protection Agency, 1986a) specifies a maximum permissible concentration for nitrate. However, most samples were analyzed for nitrate plus nitrite. Because nitrite is rapidly oxidized to nitrate, these values are comparable for oxygenated natural-water systems. Therefore, concentrations of nitrate plus nitrite are compared with the stan-

dard for nitrate; "nitrate concentrations" as used throughout this report refers to "nitrate plus nitrite concentrations (as nitrogen)."

South Platte Alluvial Aquifer

The South Platte alluvial aquifer (fig. 2A, aquifer 1) consists of about 4,000 mi² (square miles) of gravel, sand, silt, and clay along the South Platte River and tributaries in northeastern Colorado. About 1,100 Mgal/d (million gallons per day) of water is withdrawn from this aquifer for supplemental irrigation supply. Numerous public-supply systems and many individual rural-domestic and stock wells also derive water from this alluvial aquifer.

The median dissolved-solids concentration exceeded 1,000 mg/L. Recharge by percolation from surface-water applications, leakage from reservoirs and irrigation ditches, and leakage from the river results in a general increase in dissolved-solids concentrations in a downgradient direction. However, because of recharge from bordering deposits of dune sand, from the Denver Basin aquifer system, and from the High Plains aquifer, differences in quality are more apparent across the valley than downvalley. Water on the edges of the aquifer commonly had a smaller dissolved-solids concentration (Hurr and others, 1975) than water in the center of the valley. Water commonly was very hard; calcium and sulfate were the dominant constituents. Dissolved nitrate concentrations exceeded the national drinking-water standard in more than 25 percent of the samples.

Arkansas Alluvial Aquifer

The Arkansas alluvial aquifer consists of gravel, sand, silt, and clay in a 1- to 5-mile-wide band along the Arkansas River and tributaries in southeastern Colorado. The aquifer yields about 300 Mgal/d of water for supplemental irrigation supply and is the source of public supply for several cities. Water-quality data are adequate to divide the aquifer into three areas, each having different water-quality characteristics.

Water from the alluvial aquifer along the Arkansas River from Pueblo downstream to the State line (aquifer 2) had a median concentration of dissolved solids of 2,900 mg/L. The median concentration increased from 1,530 mg/L near Pueblo to 3,500 mg/L near the State line (fig. 4). The larger concentrations to the east limit the irrigated crops to those that are salt tolerant. Water from this aquifer was very hard. Water from more than 90 percent of the wells sampled contained concentrations of sulfate in excess of the national drinking-water standard.

Water from the alluvial aquifer along Fountain Creek (aquifer 3), a tributary to the Arkansas River that flows through Colorado

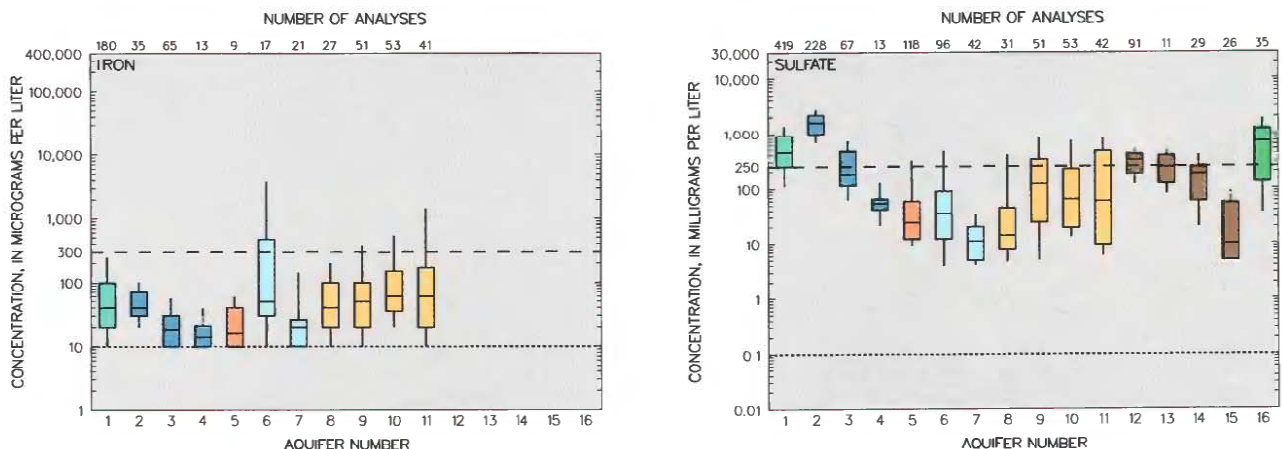


Figure 2. Principal aquifers and related water-quality data in Colorado—Continued.

Springs, had a median dissolved-solids concentration of 530 mg/L. Concentrations of dissolved solids, hardness, and sulfate increased toward the southern part of this aquifer (Cain and Edlmann, 1986). Water from this aquifer was moderately hard to very hard; sulfate concentrations exceeded the national drinking-water standard of 250 mg/L in water from fewer than one-half the wells sampled. Water from the northern part of the aquifer is used as a public water supply for Colorado Springs and several suburban communities.

Water from the alluvial aquifer along Black Squirrel Creek (aquifer 4), an ephemeral tributary to the Arkansas River east of Colorado Springs, had a median dissolved-solids concentration of 230 mg/L. Water from three-fourths of the wells sampled was moderately hard. None of the samples had concentrations of sulfate in excess of the national drinking-water standard.

High Plains Aquifer

The High Plains aquifer (aquifer 5) is composed mainly of unconsolidated to partly consolidated gravel and sand but also contains minor amounts of clay, silt, and caliche. About 900 Mgal/d of water is withdrawn from the aquifer for irrigation; a lesser quantity is withdrawn for rural-domestic and livestock use. In Colorado, the aquifer is divided by the Arkansas River into two sections—a northern section of about 11,000 mi² and a southern section of about 2,800 mi².

Data for the two sections are combined in figure 2C because the differences are small at the scale of that figure. In the northern section, the median dissolved-solids concentration was 230 mg/L; calcium and bicarbonate were the dominant constituents. The water was moderately hard to hard. In the southern section, the median dissolved-solids concentration was 470 mg/L; sodium and sulfate became more prevalent. Fluoride concentrations (not shown in fig. 2C) in water from some parts of the High Plains aquifer exceeded 2.0 mg/L. In part of Kiowa County, the reported dissolved-solids concentrations were as much as 2,140 mg/L (Gutentag and others, 1984); the very hard water commonly has naturally occurring sulfate, fluoride, and dissolved-solids concentrations exceeding national drinking-water standards.

San Luis Valley Aquifer System

The San Luis Valley aquifer system consists of unconsolidated gravel, sand, clay, and volcanic and volcanoclastic rocks in a 3,200-mi² basin near Alamosa. About 400 Mgal/d of water from the aquifer are used for supplemental irrigation supply, and lesser quantities are used for public and rural-domestic supply. The aquifer system comprises an unconfined aquifer less than about 130 feet thick and a confined aquifer as much as several thousand feet thick. The two aquifers are separated by discontinuous layers and lenses of fine-grained sand, clay, or volcanic rock.

Water from the unconfined aquifer in the San Luis Valley aquifer system (aquifer 6) had a median dissolved-solids concentration of 315 mg/L, and concentrations were larger than 2,200 mg/L in 10 percent of the samples. The water ranged from soft to very hard. Concentrations of sulfate had a median value of 36 mg/L, but sulfate was larger than 476 mg/L in 10 percent of the samples. More than 25 percent of the samples contained iron in excess of the 300 µg/L specified in the national drinking-water standard. The largest concentrations of dissolved constituents occurred downgradient in the central part of the valley northeast of Alamosa.

Water from the confined aquifer in the San Luis Valley aquifer system (aquifer 7) had a median dissolved-solids concentration of 184 mg/L. This water generally was softer and had smaller concentrations of dissolved solids and sulfate than water from the unconfined part of this aquifer system. Analyses of water from the confined aquifer indicate a downgradient increase in concentrations of dissolved solids (Emery and others, 1973).

Denver Basin Aquifer System

The Denver Basin aquifer system underlies a 6,700-mi² area of east-central Colorado near Denver. The system comprises four aquifers (Dawson, Denver, Arapahoe, and Laramie-Fox Hills), which have a maximum combined thickness of about 3,200 feet between Denver and Colorado Springs, and thin toward the margins of the bowl-shaped basin. The aquifers yield about 30 Mgal/d of water for public-supply, rural-domestic, and commercial use from beds of consolidated sandstone and conglomerate.

Water from the Dawson aquifer (aquifer 8), the uppermost aquifer in the system, had dissolved-solids concentrations smaller than 200 mg/L in most areas. The water was a calcium bicarbonate, sodium bicarbonate, or sodium sulfate type and ranged in hardness from soft to hard. Sulfate concentrations smaller than 25 mg/L, which prevailed in the central part of the aquifer, increased to more than 250 mg/L in a few areas on the margin of the aquifer. Iron concentrations generally ranged from 20 to 100 µg/L, but concentrations as large as 8,500 µg/L have been measured in water from this aquifer.

Water from the underlying Denver aquifer (aquifer 9) had dissolved-solids concentrations smaller than 700 mg/L in most areas. In the central part of the aquifer, the water is a calcium bicarbonate type; near the margins of the aquifer, the water is a sodium bicarbonate or sodium sulfate type. Sulfate concentrations ranged from 2 mg/L in the central part of the aquifer to more than 2,000 mg/L in a few areas at the aquifer margin. Iron concentrations generally ranged from 10 to 150 µg/L.

Water from the underlying Arapahoe aquifer (aquifer 10) generally had dissolved-solids concentrations smaller than 1,000 mg/L. Very hard water with sulfate concentrations larger than 1,000 mg/L may be present near the margins of the aquifer, but soft water containing less than 200 mg/L sulfate was common in most areas. Iron concentrations commonly ranged from 20 to 200 µg/L but exceeded 6,000 µg/L in water from a few widely scattered wells.

Water from the Laramie-Fox Hills aquifer (aquifer 11), the lowermost aquifer in the Denver Basin aquifer system, generally had dissolved-solids concentrations smaller than 1,200 mg/L. The sodium bicarbonate to sodium sulfate type water commonly is soft, but hard water may be present near the margins of the aquifer. Sulfate concentrations were smaller than 200 mg/L in most areas. Concentrations of iron commonly were less than 200 µg/L, but concentrations of as much as 79,000 µg/L have been measured. In areas of reducing conditions in the aquifer, sulfate minerals and natural organic matter may be reduced to hydrogen sulfide and methane gases. When these gases are present in sufficient concentrations, water pumped from this aquifer may have a putrid odor, may effervesce, and may be unacceptable for some uses.

Piceance Basin Aquifer System

The Piceance Basin aquifer system comprises two aquifers that underlie 1,600 mi² northeast of Grand Junction. The upper aquifer consists of stream-valley alluvium, the Uinta Formation, and the upper part of the Green River Formation. The lower aquifer consists of the middle part of the Parachute Creek Member of the Green River Formation. The two aquifers are separated by the oil-shale-rich Mahogany Zone. Near-surface ground water is the main source of supply for rural-domestic and agricultural use.

Water quality in the aquifer system changes with depth. Concentrations of nitrate, calcium, magnesium, and sulfate decrease with depth. Conversely, concentrations of dissolved solids, sodium, alkalinity, fluoride, boron, and lithium increase with depth. Water quality in the upper aquifer ranges from a very hard, mixed cation bicarbonate sulfate type near the top (aquifer 12) to a moderately hard, sodium bicarbonate type near the base (aquifer 14). At intermediate depths (aquifer 13), the water quality is intermediate.

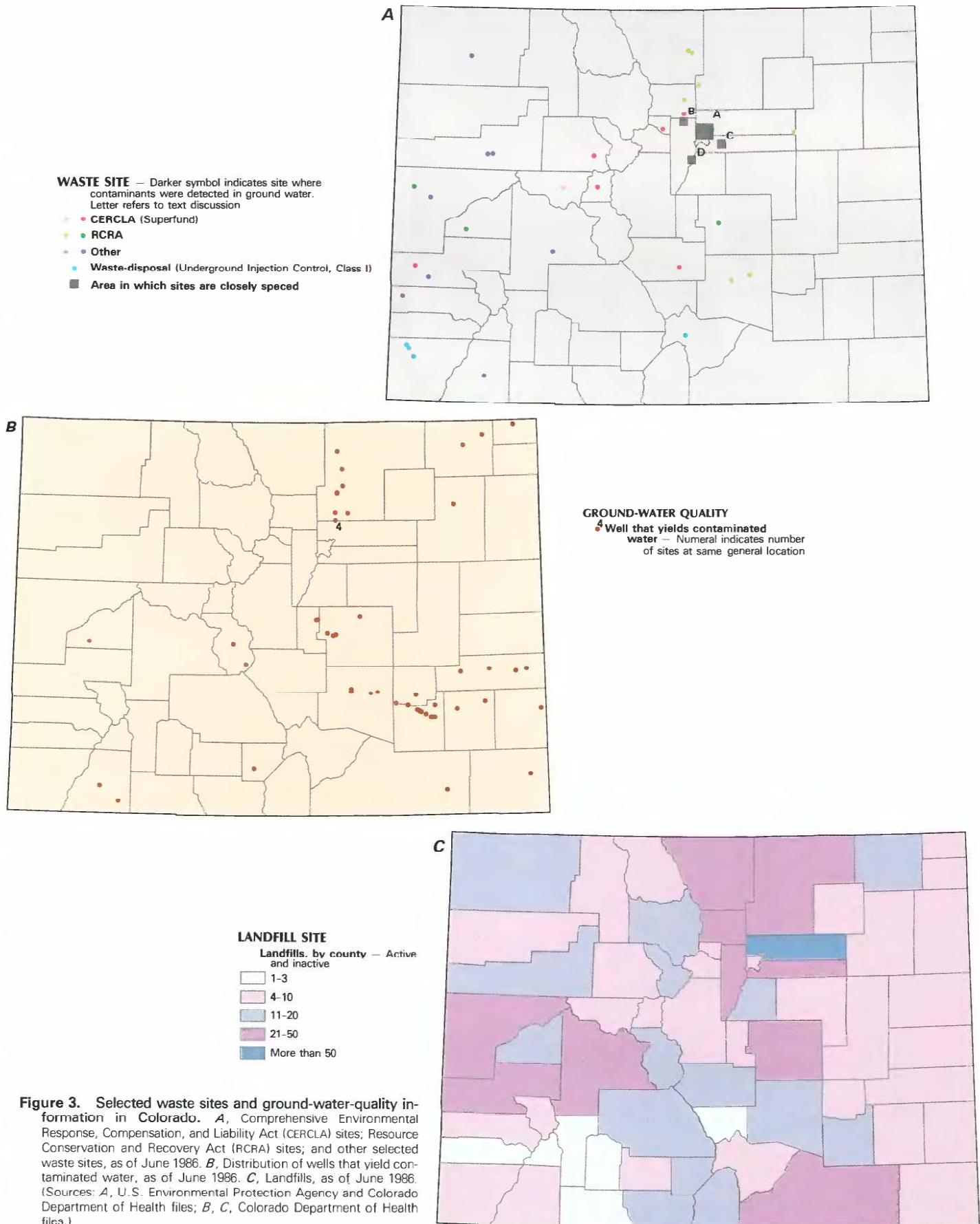


Figure 3. Selected waste sites and ground-water-quality information in Colorado. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of June 1986. *B*, Distribution of wells that yield contaminated water, as of June 1986. *C*, Landfills, as of June 1986. (Sources: *A*, U.S. Environmental Protection Agency and Colorado Department of Health files; *B*, *C*, Colorado Department of Health files.)

Water from the lower aquifer (aquifer 15) is a soft, sodium bicarbonate type. Dissolved-solids concentrations for samples from the lower aquifer generally ranged from 660 to 4,100 mg/L; however, concentrations as large as 30,000 mg/L have been measured and probably are the result of water that dissolves deposits of soluble salts along fractures, solution vugs, or in open boreholes. The usefulness of the water from the lower aquifer is limited by its sodium bicarbonate type as well as by large concentrations of fluoride and boron.

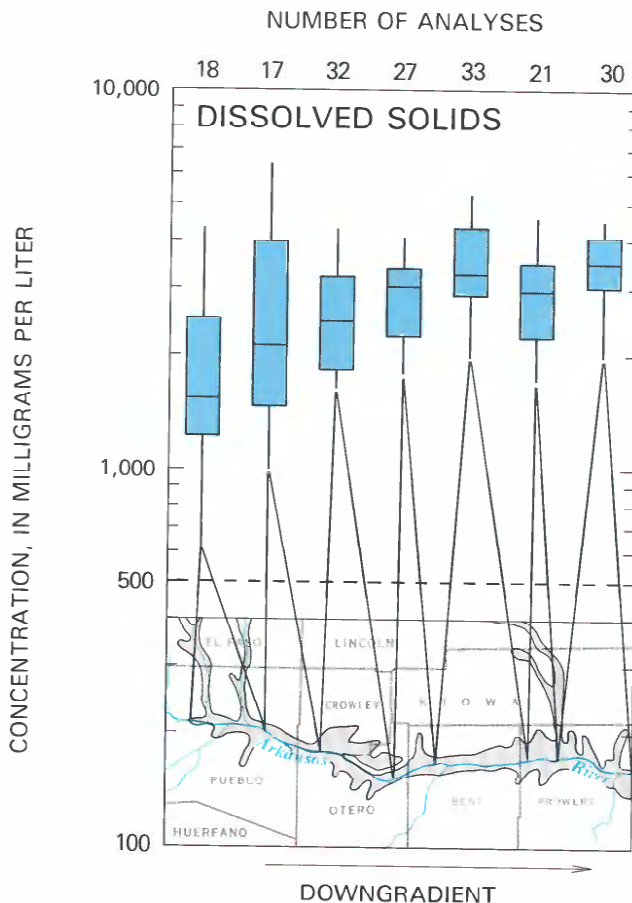
Leadville Limestone Aquifer

The Leadville Limestone aquifer (aquifer 16) underlies much of the northern part of western Colorado but has not been extensively developed as a water supply. Samples collected from springs and other discharge areas indicate that in zones less than 1,000 feet deep, dissolved-solids concentrations were smaller than 500 mg/L.

Data from deep wells and springs issuing from deep fracture systems, however, indicate that dissolved-solids concentrations increase with depth; values are larger than 200,000 mg/L in some samples. Some water samples from this aquifer had sulfate concentrations among the largest in the State.

Other Aquifers

In many areas of Colorado, water is available from other aquifers in quantities sufficient to be locally significant. The quality of water in these aquifers differs considerably. Water from some wells completed in the Dakota Sandstone in southeastern Colorado contains large concentrations of naturally occurring gross alpha radiation, uranium, radium, and radon (Felmlee and Cadigan, 1979; Crouch and others, 1984; Leonard, 1984). Also, water from a fractured crystalline rock aquifer west of Denver generally is acceptable for drinking but locally had gross alpha radiation in excess of 15 picocuries per liter (in 11 of 26 wells sampled) and significant differences in concentrations of 15 chemical constituents (Hall, 1979).



EXPLANATION
 Percentile — Percentage of analyses equal to or less than indicated value
 90th
 75th
 50th
 25th
 10th
 18 Number of analyses — Number of water-quality samples used in box-plot analysis for the alluvial aquifer along the indicated river reach
 — — National drinking-water standards
 Maximum recommended contamination level (secondary)

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has changed in some areas because of the effects of waste disposal, mineral extraction and processing, urbanization, and agriculture. Water-quality changes in some areas have been documented by areal investigations of the U.S. Geological Survey. More commonly, documentation of the changes is the result of an evaluation of a specific site. Water-quality changes have been investigated at 15 sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Of these 15 sites, 12 have been included in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c); 1 is being considered for possible inclusion in the NPL, and 2 are at Federal facilities. Water-quality changes have been documented at 9 of the 12 sites on the NPL and at the other 3 sites. Water-quality changes also have been documented at 7 of 19 sites where ground-water quality is monitored under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 and at 8 Uranium Mill Tailings Remedial Action Project (UMTRAP) sites under the Radiation Control Act of 1978. Remedial action has been recommended at 2 Department of Defense facilities under the Installation Restoration Program (IRP) (U.S. Department of Defense, 1986).

Figure 3A shows the location of CERCLA, RCRA, and IRP sites; sites identified as "other" include UMTRAP, Federal facility, and proposed CERCLA sites. In some areas, the sites are too closely spaced to show individually in figure 3A. Types of sites in each of these areas are identified in the following table:

Type of site	Area letter			
	A	B	C	D
	Number of sites in area			
CERCLA (Superfund) site	4	—	1	—
RCRA site	5	2	1	1
IRP (U.S. Department of Defense) site	2	—	—	—
Other				
U.S. Department of Energy site		1		
Proposed CERCLA site	—	—	—	1
Total number of sites	11	3	2	2

Away from these sites, there is no program for monitoring the quality of ground water, except for public-supply systems as required by the Colorado Department of Health. Constituent concentrations in ground water that exceed the State drinking-water standards (Colorado Department of Health, 1977) have been documented for wells that supply 55 public systems—gross alpha

Figure 4. Increase in dissolved-solids concentration downgradient in the Arkansas alluvial aquifer, Colorado, 1964-82. (Source: U.S. Geological Survey files.)

radiation in 19 systems, nitrate in 14 systems, fluoride in 10 systems, radium in 9 systems, selenium in 8 systems, arsenic in 2 systems, lead in 1 system, and gross beta radiation in 1 system (fig. 3B).

Waste Disposal

Contaminants have been detected in ground water at 7 of the 19 RCRA sites used for surface impoundment or disposal of hazardous waste. Contaminants from waste disposal have been detected in ground water at an additional 7 sites—4 sites listed in the NPL (U.S. Environmental Protection Agency, 1986c), 1 site being evaluated under CERCLA for possible inclusion in the NPL, and 2 sites at Federal facilities. Many of these sites are located near Denver.

Several investigations are in progress near the Rocky Mountain Arsenal where wastes from production of chemical-warfare agents and pesticides have been deposited by the U.S. Army and private companies. The Army is investigating contaminants in the arsenal area and contaminant migration in ground water north and northwest of the arsenal. The U.S. Environmental Protection Agency (EPA) is investigating the location, types, and possible sources of contaminants at several sites including Sand Creek industrial site southwest of the arsenal. This site includes a closed landfill, a former oil refinery, a chemical company, and closed acid-disposal pits. Contaminants include acidic wastes, pesticides, hydrocarbons, trichloroethylene, tetrachloroethylene, and other industrial solvents. The long history and multiple sources of contamination present a difficult problem in waste management. Trichloroethylene contamination of a public-water supply in southwestern Adams County (fig. 3A, area A) recently required a quick response to protect drinking water. To address the problem of protecting drinking water, an activated-carbon filtration system is used to remove trichloroethylene and other contaminants from the public water supply of the 30,000 residents served by the South Adams County Water and Sanitation District. Residences that formerly relied on shallow private wells in some areas have been connected to the now-treated public water supply.

Northwest of Denver in Jefferson County (fig. 3A, area B) are 2 RCRA sites and 1 Department of Energy (DOE) site. At the Rocky Flats Plant, chemical and nuclear wastes have been disposed or released at 91 sites, including a surface impoundment, a field on which liquid wastes were sprayed, and a landfill. Detailed assessments of possible ground-water contamination there are being developed by the Department of Energy.

Colorado has 783 known landfill sites (fig. 3C), 554 of which are closed. For many of these landfills, the composition of the deposited wastes is unknown, and ground-water contamination has not been investigated. However, evaluation of two landfills in the Denver area resulted in both being added to the NPL. At the Lowry landfill in Arapahoe County (fig. 3A, area C), trace concentrations of volatile organic compounds (benzene, toluene, and tetrachloroethylene) have been detected 0.3 mile from the landfill in water from the Denver Basin aquifer system (fig. 2A) despite the presence of thick shale beds that underlie the landfill and retard downward contaminant movement. At the Marshall landfill in Boulder County, contamination has been detected in water from alluvial aquifers both on and off the site. Contamination of the underlying bedrock aquifer has not been confirmed.

Mineral Extraction and Processing

Many of the waste-disposal sites where ground-water contamination has been documented (fig. 3A) are related to mineral extraction and processing. Two CERCLA sites include active uranium-processing facilities in Fremont and Montrose Counties, where molybdenum, selenium, and uranium have been introduced into ground water. Ground-water contamination also has occurred at the eight UMRAP sites.

Drainage from hundreds of abandoned mines and tailing piles produces acidic water containing large concentrations of heavy metals (cadmium, copper, iron, lead, manganese, and zinc). Although many of these mines and tailing piles do not overlie a principal aquifer, the drainage from them affects hundreds of miles of streams and may contaminate locally important aquifers. Sites near Leadville (Lake County) in the Arkansas River drainage and Central City (Gilpin County) in the South Platte River drainage are CERCLA sites at which contamination has been documented (fig. 3A). A large sudden discharge from Argo Mine drainage tunnel (draining mines near Central City) in 1980 introduced large concentrations of heavy metals into the South Platte River drainage; wells supplying drinking water were contaminated by the discharge. Large, sudden discharges from the Yak Tunnel (draining mines near Leadville) in 1983 and 1985 introduced large concentrations of heavy metals into the Arkansas River drainage. The Colorado Department of Health has identified the process of using cyanide to leach gold and silver from abandoned tailing piles as 1 of 11 activities that affect ground-water quality but which are not currently (1986) controlled.

Four Underground Injection Control Program (UIC) Class I wells (U.S. Environmental Protection Agency, 1984) inject nonhazardous fluids associated with carbon-dioxide production beneath aquifers used as sources of drinking water (see fig. 3A.) Nearly 1,000 brine-disposal wells not shown in figure 3A also are associated with oil and gas production (UIC Class II wells). Improper construction of oil and gas wells or corrosion of the well casing that allowed poor-quality deep ground water to migrate into freshwater aquifers may have been the cause of taste, odor, and color characteristics noted in water from a few private wells in Boulder County in 1984. Abandoned exploratory oil and gas wells also may provide hydraulic conduits for interaquifer movement of water or for discharge of ground water at the land surface where it could contaminate surface water.

Urbanization

From 1950 to 1980, the rural population in Colorado increased from 493,771 to 560,095, and the urban population increased from 831,318 to 2,329,869; 90.2 percent of the State's urban population lives along the Front Range from Fort Collins on the north to Pueblo on the south (fig. 1B). Within the urbanized areas, sources of contamination may include septic-disposal systems, leaking lagoons used for sludge disposal, accidental spills, leaking underground tanks used for storage of petroleum products, and the approximately 10,000 tons of sand and salt used annually for deicing roads in the State.

The use of septic disposal systems has resulted in biological contamination of private well-water supplies. Thousands of wells in Colorado reportedly are known to be or are suspected of being contaminated by septic systems. Shallow, fractured, crystalline-rock aquifers (not shown in fig. 2A) are particularly susceptible. Analyses of about 800 water samples from wells and springs in the mountainous part of Jefferson County indicated that the national drinking-water standard for coliform bacteria (an indicator of biological contamination) was exceeded in 20 percent of the samples, and the standard for dissolved nitrate was exceeded in 5 percent of the samples (Hofstra and Hall, 1975). Public-supply pumpage has induced recharge of nitrogen-containing sewage effluent from Fountain Creek into an alluvial aquifer (fig. 2A, aquifer 3) (Edelmann and Cain, 1985). As a result, median concentrations of nitrate in water from the aquifer have increased from less than 3 to 6 mg/L during the last 20 to 30 years, and some wells have been removed from production because of concentrations larger than specified in the national drinking-water standard. Water from 11 of 20 wells along Fountain Creek that were sampled in 1984 contained volatile organic compounds, including chloroform, 1,1,1-trichloroethane,

and trichloroethylene (Cain and Edelman, 1987). These compounds, which commonly are present in sewage effluent, are used as industrial solvents, dry-cleaning fluids, and septic-tank cleaners. Along the South Platte alluvial aquifer (fig. 2A, aquifer 1), 11 public-supply systems exceeded the drinking-water standard for nitrate, the sources of which may be agricultural as well as urban.

Agriculture

Irrigation practices affect the dissolved-solids concentrations in water from the South Platte alluvial aquifer, the Arkansas alluvial aquifer, the San Luis Valley aquifer system, and the High Plains aquifer. Evapotranspiration consumes water but leaves the salts. Water use and reuse have resulted in dissolved-solids concentrations increasing downgradient. This trend is shown in figure 4 for the Arkansas alluvial aquifer. Siebenthal (1910) reported that irrigation in the San Luis Valley resulted in alkali accumulation in the soil and the abandonment of some cultivated land around Mosca and Hooper (Alamosa County). Part of the abandoned land subsequently was reclaimed by soil drainage (Powell, 1958). In the High Plains, ground water along the valleys of the Arikaree and South Fork Republican Rivers, where depth to water generally is less than 20 feet and irrigated agriculture has been practiced since before 1950, has a larger dissolved-solids concentration than ground water in adjacent areas where depths to water are greater and irrigation has been practiced for a shorter time.

Nitrates may reach the ground water as leachate from animal wastes or commercial fertilizers. Irrigated agriculture along Black Squirrel Creek may have contributed to increased concentrations of dissolved nitrate in the alluvial aquifer (fig. 2A, aquifer 4) by providing infiltrating water that can transport these constituents. Dissolved nitrate concentrations are larger than 5 mg/L in areas that have been farmed for many years. In the unconfined aquifer of the San Luis Valley aquifer system (fig. 2A, aquifer 6), concentrations of nitrate exceed the 10-mg/L national drinking-water standard in the irrigated area northwest of Alamosa (Edelman and Buckles, 1984). In the High Plains aquifer (fig. 2A, aquifer 5), nitrate concentrations exceed the specified 10 mg/L in a few locations in Kiowa and Cheyenne Counties.

In addition to pesticides commonly used in irrigated agriculture, ethylene dibromide, which is used on forested areas to control the Mountain Pine Beetle, might be a potential source of ground-water contamination. However, analyses for pesticides in ground water have been insufficient to permit any conclusions about pesticide contaminations.

POTENTIAL FOR WATER-QUALITY CHANGES

The alluvial aquifers of the South Platte and the Arkansas River valleys, the unconfined aquifer in the San Luis Valley aquifer system, and, to a lesser extent, the High Plains aquifer are susceptible to contamination because of shallow water levels and locally permeable soils. Conditions such as these increase the likelihood that contaminants at the land surface may reach the ground-water systems. These aquifers also are susceptible to contamination because the aquifers are hydraulically connected with streams that may transport contaminants or that may be used for disposal of wastewater. Long-term increases in dissolved-solids concentrations may occur as a result of leaching of soils by irrigation return flow and evapotranspiration from the water table. Also, expected urbanization in these areas may result in increased quantities of wastewater discharged to streams and in changes in water use from irrigated agriculture to public-water supply.

The practice of applying fertilizers or insecticides directly with the irrigation water by linking a storage tank to the well (chemigation) could permit the introduction of a large quantity of undiluted insecticide or nitrogen fertilizer directly into the aquifer

through a well not equipped with a backflow-prevention device. In 1987, the Colorado Chemigation Act (C.R.S. 35-11-101 to 116) gave the Colorado Department of Agriculture the responsibility to administer a permit program for chemigation practiced on or after January 1, 1990.

Future water-quality changes in the Denver Basin aquifer system can be expected near the margins of the bedrock aquifers. In the deeper parts of the system, water-quality degradation may occur as hydraulic heads decline, but the effects are expected to be less severe than near the margins of the aquifers. Hydraulic-head declines in the bedrock aquifers may expand the area in which ground water, and any contaminants it contains, flows downward from alluvial aquifers into the bedrock aquifers. However, migration to deeper parts of the aquifer system probably will be slow.

The oil-shale resource in the Piceance basin aquifer system is enormous. Development of this resource in the Piceance basin aquifer system may result in increased concentrations of dissolved solids, sodium, alkalinity, fluoride, boron, lithium, potassium, sulfate, and organic substances in the near-surface ground water and in streamflow (Tobin and others, 1985).

The Leadville Limestone aquifer is susceptible to contamination owing to its shallow recharge area and relatively rapid ground-water movement. The aquifer contributes substantial quantities of water to streams, providing a pathway for ground-water contaminants to enter surface water. Water from the Leadville Limestone currently (1986) is not being developed for energy-related industry and expanding recreational communities but has potential for such future use. Such use could have major adverse effects on the water quality.

GROUND-WATER-QUALITY MANAGEMENT

On July 15, 1985, Governor Richard Lamm issued Executive Order No. D0049 85, relative to ground-water protection. The order (1) declared a statewide goal to ". . . provide maximum beneficial use of ground-water resources . . . by preventing or controlling those activities which have the potential to impair existing or future beneficial uses . . . or to adversely affect the public health"; (2) directed all State agencies to strive to achieve that goal; (3) gave the Colorado Department of Health primary responsibility for coordinating efforts within the State for protection of ground-water quality; and (4) directed the 14 agencies that deal with ground-water issues to sign a "Memorandum of Agreement for the Protection of the Quality of Groundwater Resources of the State."

The Colorado Department of Health is establishing a prevention-oriented, ground-water-protection program under the Colorado Water Quality Control Act. The initial phase established standards for beneficial uses statewide. For each beneficial use, a list of contaminants and concentrations that could impair the use was adopted. The Colorado Water Quality Control Commission, a governor-appointed body to administer the Colorado Water Quality Act, has adopted the standards (Colorado Water Quality Control Commission, 1987). Supplemental standards may be adopted in the future. The Commission has received proposals to adopt standards for organic compounds and radioactive materials that would apply irrespective of use classification and to adopt standards specific to the area near the Rocky Mountain Arsenal. Standards will not be enforceable until control regulations are adopted. The second phase includes adopting control regulations for facilities or activities that are not regulated with respect to ground water.

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Aquifer testing in the Redstone 21-9 geothermal well at Glenwood Springs, Colo., November 1984. Tera Therna Inc. participated with the U.S. Geological Survey, Wright Water Engineers, and the U.S. Bureau of Reclamation in conducting the test. The test was conducted to analyze the hydraulic properties of the Leadville Limestone and the Dyer Dolomite, to determine the degree of interconnection between these aquifers and the overlying alluvium, and to determine the effects of discharge of water through the wells on the nearby springs. During the 4-day test, the discharge of the well decreased from 2,300 to 1,740 gallons per minute and the temperature of the water ranged from 45 to 49° C. (Photograph by Arthur Geldon, U.S. Geological Survey.)

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