# Hydrogeology and Quality of Ground Water in the Upper Arkansas River Basin from Buena Vista to Salida, Colorado, 2000–2003

By Kenneth R. Watts

Prepared in cooperation with the Upper Arkansas Water Conservancy District

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# Conversion Factors

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| meter (m) | 3.2808 | foot (ft) |
| mile (mi) | 1.609 | kilometer (km) |
| | **Area** | |
| acre | 0.4047 | hectare (ha) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| section (640 acres or 1 square mile) | 259.0 | square hectometer ($hm^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | **Volume** | |
| gallon (gal) | 3.785 | liter (L) |
| gallon (gal) | 0.003785 | cubic meter ($m^3$) |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| | **Flow rate** | |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| cubic foot per second ($ft^3$/s) | 0.02832 | cubic meter per second ($m^3$/s) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3$/d) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3$/s) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | **Radioactivity** | |
| picocurie per liter (pCi/L) | 0.037 | becquerel per liter (Bq/L) |
| | **Specific capacity** | |
| gallon per minute per foot [(gal/min)/ft] | 0.2070 | liter per second per meter [(L/s)/m] |
| | **Hydraulic conductivity*** | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | **Hydraulic gradient** | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| | **Transmissivity*** | |
| foot squared per day ($ft^2$/d) | 0.09290 | meter squared per day ($m^2$/d) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F–32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot [($ft^3$/d)/$ft^2$]. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [($ft^3/d$)/$ft^2$]ft. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). Concentrations in milligrams per liter (mg/L) may be converted to concentrations in milliequivalents per liter (meq/L) by multiplying the concentration in milligrams per liter by the reciprocal of the combining weight of the appropriate ion (Hem, 1985, p. 56).

# Hydrogeology and Quality of Ground Water in the Upper Arkansas River Basin from Buena Vista to Salida, Colorado, 2000–2003

By Kenneth R. Watts

## Abstract

The upper Arkansas River Basin between Buena Vista and Salida, Colorado, is a downfaulted basin, the Buena Vista–Salida structural basin, located between the Sawatch and Mosquito Ranges. The primary aquifers in the Buena Vista–Salida structural basin consist of poorly consolidated to unconsolidated Quaternary-age alluvial and glacial deposits and Tertiary-age basin-fill deposits. Maximum thickness of the alluvial, glacial, and basin-fill deposits is about 5,000 feet, but 95 percent of the water-supply wells in Chaffee County are no more than 300 feet deep. Hydrologic conditions in the 149-square mile study area are described on the basis of hydrologic and geologic data compiled and collected during September 2000 through September 2003. The principal aquifers described in this report are the alluvial-outwash and basin-fill aquifers.

An estimated 3,443 wells pumped about 690 to 1,240 acre-feet for domestic and household use in Chaffee County during 2003. By 2030, projected increases in the population of Chaffee County, Colorado, may require use of an additional 4,000 to 5,000 wells to supply an additional 800 to 1,800 acre-feet per year of ground water for domestic and household supply.

The estimated specific yield of the upper 300 feet of the alluvial-outwash and basin-fill aquifers ranged from about 0.02 to 0.2. Current (2003) and projected (2030) ground-water withdrawals by domestic and household wells are less than 1 percent of the estimated 472,000 acre-feet of drainable ground water in the upper 300 feet of the subsurface. Locally, little water is available in the upper 300 feet. In densely populated areas, well interference could result in decreased water levels and well yields, which may require deepening or replacement of wells.

Infiltration of surface water diverted for irrigation and from losing streams is the primary source of ground-water recharge in the semiarid basin. Ground-water levels in the alluvial-outwash and basin-fill aquifers vary seasonally with maximum water levels occurring in the early summer after snowmelt runoff peaks. Because of the drought during 2002, relatively large declines in ground-water levels occurred in about one-half of the monitored wells. Differences in water-level altitudes in shallow and deep wells indicate the potential for downward flow in upland areas and support results of preliminary cross-sectional models of ground-water flow. The apparent mean age of ground-water recharge ranged from about 1 to more than 48 years before 2001. The older (pre-1953) water was from wells that were located in ground-water discharge areas. Ground-water flow in the Buena Vista–Salida structural basin drains eastward toward the Arkansas River and, locally, toward the South Arkansas River.

Ground water in the alluvial-outwash and basin-fill aquifers generally is calcium-bicarbonate water type with less than 250 milligrams per liter dissolved solids. Nitrate concentrations generally were less than 1 to 2 milligrams per liter and do not indicate widespread contamination of ground water from surface sources.

## Introduction

Ground water is an important part of the water supply in the arid and semiarid mountains of the Southwestern United States. Between 1980 and 2000, the population of Chaffee County in the upper Arkansas River Basin of Colorado increased about 23 percent and is projected to increase an additional 70 percent by 2030 (Colorado Water Conservation Board, 2004). Ground water from individual domestic wells likely will be the primary source of water used to supply the increasing population of the upper Arkansas River Basin. Planners and resource managers, who must consider the effects of this projected growth in population and the likely increase in ground-water withdrawals, need an improved understanding of the hydrogeology of the ground-water system to evaluate effects of increased ground-water withdrawals on the area water resources. Because the use of domestic sanitary-waste-disposal systems (septic systems) also is likely to increase, planners and resource managers also must consider potential effects of population growth on the quality of ground water.

In June 2000, the U.S. Geological Survey (USGS), in cooperation with the Upper Arkansas Water Conservancy District (UAWCD), began a 3-year study of ground water in the upper Arkansas River Basin from Buena Vista to Salida, Colorado. Because of the drought in 2002 and its potential effect on ground water in the upper Arkansas River Basin, the study period was extended 1 year to collect additional water-level data. The objectives of the study were to (1) evaluate the hydrogeology of the aquifers, (2) determine ground-water flow directions and seasonal changes of ground-water levels, (3) evaluate the hydraulic connection between the aquifers, and (4) evaluate ground-water quality. The study was conducted in three phases: phase one was a compilation of available data to better define the hydrogeology of the principal aquifers; phase two consisted of establishment and operation of a water-level network and the collection of ground-water samples for chemical analyses; and phase three included analyses of the data compiled and collected during phases one and two.

## Purpose and Scope

This report describes the hydrogeology and quality of ground water in the principal aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, during 2000–2003. Hydrologic properties including hydraulic conductivity, specific yield, and drainable storage in the upper 300 ft of the subsurface of the principal aquifers are described. Conceptual models of cross-sectional ground-water flow are presented to illustrate regional ground-water flow from recharge to discharge areas. Short-term (2000–2003) and long-term (1990–2003) water-level trends are described. A map of the September 2003 water table is presented and estimated ground-water flow directions also are described. The mean age of ground-water recharge is described on the basis of tritium concentrations. Sustainability of the ground-water supply and potential effects of increased ground-water use are discussed in relation to future increases in ground-water use. The chemical and physical properties of ground water are described, and dissolved nitrate concentrations are discussed in relation to possible anthropogenic effects on the quality of ground water. Water-level and water-quality data collected during this study can be accessed online at the USGS Web site for Colorado, URL *http://co.water.usgs.gov/* and at URL *http://waterdata.usgs.gov/co/nwis/*.

## Hydrologic Setting

The study area is located in the upper Arkansas River Basin between Buena Vista and Salida in Chaffee County, Colorado (fig. 1). The upper Arkansas River Basin is an intermountain basin flanked by the Sawatch and Mosquito Ranges. The study area is about 149 mi$^2$ and includes only that part of the basin west of the Arkansas River that is underlain by alluvial, glacial, or basin-fill deposits and that is east of the San Isabel National Forest. Extensive development of ground-water resources on public land (national forest) west of the study area is unlikely. Locally, alluvial, glacial, and basin-fill deposits also are present east of the river in the upper Arkansas River Basin; however, those areas were not included in the study area.

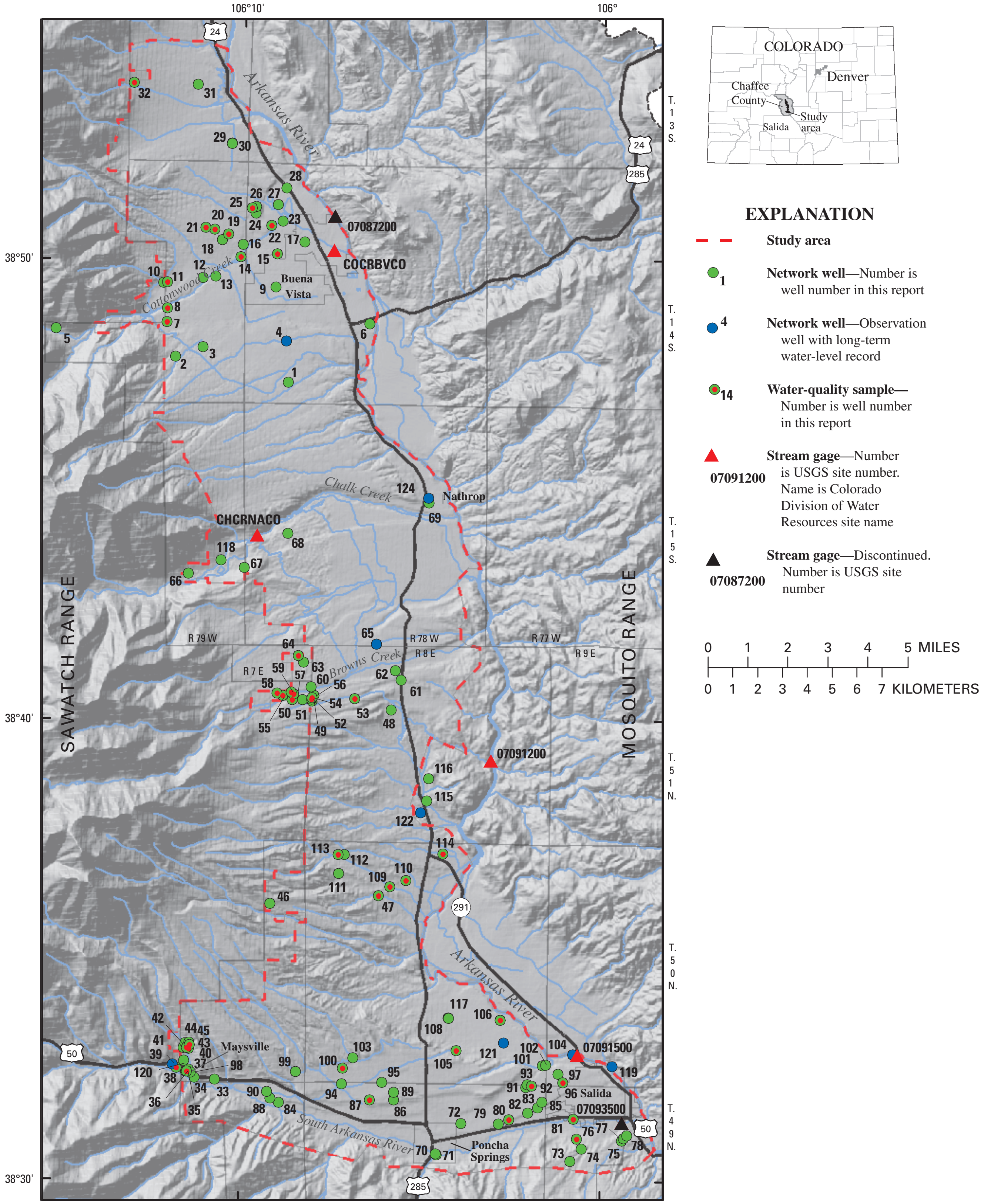
Runoff from precipitation, primarily snow, in the Sawatch Range is the major source of recharge in the study area. Surface water (snowmelt runoff) is diverted for irrigation of interstream areas and is an important source of ground-water recharge. Infiltration of surface water in stream channels, as streams flow across alluvial and outwash deposits, also is an important source of ground-water recharge. Precipitation on interstream areas may provide a small amount of recharge in areas in which ground water is not recharged by losing streams or surface-water diversions for irrigation. During drought years, when runoff is below normal and surface water is limited or not available for diversion, ground-water recharge likely is minimal. Tributary streams that cross the alluvial, glacial, and basin-fill deposits generally are sources of recharge near the mountain front but are ground-water discharge areas (drains) in downstream reaches. Generally, the Arkansas and South Arkansas Rivers, on the eastern side and near the southern end of the study area, respectively, are gaining reaches and are in discharge areas for the regional ground-water system.

### Climate and Runoff

The climate of the valley is semiarid with low humidity. During 1948–2003, average summer highs ranged from about 77 to 84°F and winter highs typically ranged from 40 to 52°F, with lows in the teens (Western Regional Climate Center, 2004). The mountains that surround the valley have a profound effect on the local climate and the water supply of the Arkansas River Basin in Colorado. Precipitation in the valley during 1948–2003 averaged about 10 in/yr. However, the surrounding mountains receive as much as 30 to 40 in/yr of precipitation, primarily as snow (Bureau of Land Management, 1998). Mean annual runoff from the mountains west of the study area decreases with decreasing altitude from more than 30 inches along the crests of the Sawatch Range to about 5 inches near the western side of the study area. Mean annual runoff within the study area decreases from west to east from about 5 inches to less than 2 inches (U.S. Geological Survey, 1970, as cited in Abbott, 1985).

### Population, Water Supply, and Wells

Demands on the ground-water supply in the study area have increased as the population of Chaffee County increased. The population of Chaffee County increased about 23 percent, from 13,227 to 16,242 people, from 1980 to 2000 (fig. 2) (U.S. Census Bureau, 2004). The population of Chaffee County is projected to increase by 11,300 people to about 27,500 people by 2030 (Colorado Water Conservation Board,



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 1.** Location of the study area, water-level and water-quality monitoring networks, and selected stream gages.

2004). The largest communities in Chaffee County are Buena Vista and Salida, whose populations were 2,195 and 5,504 people, respectively, in 2000. The remainder of the county's population, an estimated 8,543 residents, lived in small communities, subdivisions, and rural homes. In addition to full-time residents, many part-time residents have vacation homes in Chaffee County.

Surface-water diversions in Chaffee County primarily are used for irrigation but also are part of the public supply for Buena Vista and Salida. An estimated 77,000 acre-ft (an average of about 69 Mgal/d) of surface water was diverted for irrigation of about 22,070 acres in Chaffee County during 2000 (Hurston and others, 2004). Estimated use of ground and surface water for public supply was about 2,900 acre-ft during 2000 and averaged about 2.6 Mgal/d (Hurston and others, 2004).

Ground water from alluvial, glacial, and basin-fill deposits is the primary source of water for domestic and municipal supplies in the study area. The depths of 95 percent of the water-supply wells in Chaffee County in 2003 were 300 ft or less. In the rural part of the study area, domestic and household-use (household) wells are used for water supply. Individual domestic septic systems are used for sanitary waste disposal in rural areas. In general, a domestic well can be used for a single residence on a tract of at least 35 acres and for irrigation of 1 acre of lawn and garden. A household well can be used only for in-house use. Ground water also provides about 80 percent of the public supply for Buena Vista and Salida and is the source for the public supplies of Poncha Springs and for subdivisions in Chaffee County (Terry Scanga, Upper Arkansas Water Conservation District, Salida, Colorado, oral commun., 2005).

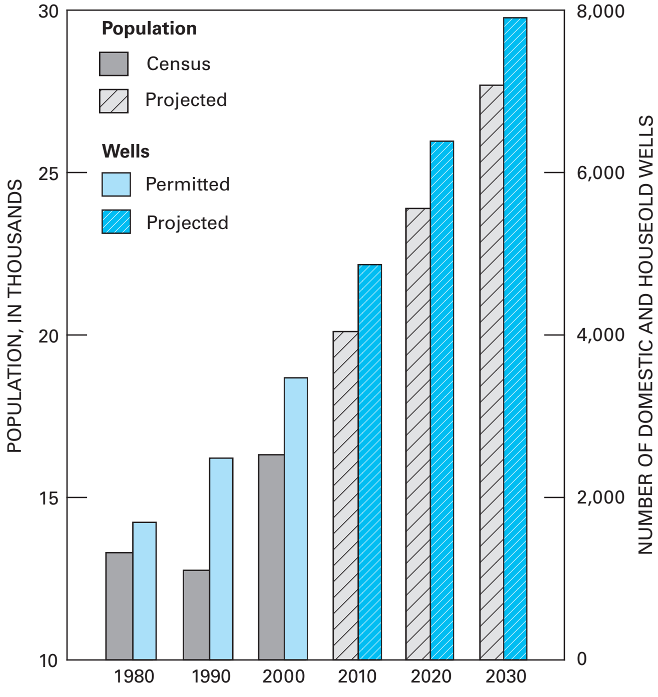


**Figure 2.** Population and estimated number of domestic and household wells in Chaffee County, Colorado, 1980–2000, and projected population and number of domestic and household wells, 2010–2030.

The number of permitted domestic and household wells in Chaffee County increased from an estimated 1,643 in 1980 to about 3,443 in 2000 (fig. 2). Part of the increase in the number of wells during 1980–2000 was caused by the increase in population, and part resulted from increased enforcement of administrative rules and regulations by the State Engineer's Office (SEO) of the Colorado Department of Natural Resources Division of Water Resources (Colorado Division of Water Resources, 1994). If the population of Chaffee County increases as projected, an estimated 4,000 to 5,000 additional domestic and household wells could be needed by 2030 (fig. 2).

## Water Rights and Augmentation Plans

Water rights in Colorado are administered by what is known as the prior appropriation system. This system of water allocation controls who uses how much water, the types of uses allowed, and when those waters can be used. A simplified way to explain this system is often referred to as "first in time, first in right." An appropriation is made when an individual physically takes water from a stream or aquifer and uses the water for a beneficial use. The first person to appropriate water and apply that water to beneficial use has the first (senior) right to use that water within a particular stream-aquifer system. Under Colorado law, the use of all subsurface water hydraulically connected to a surface stream, the pumping of which would have a measurable effect on the surface stream within 100 years, is tributary water and is subject to the doctrine of prior appropriation. Because surface water in the Arkansas River Basin is overappropriated, most ground water in the basin is considered tributary water. The water right of the court-decreed senior water-right holder on a stream system must be satisfied before any junior water rights, including wells diverting tributary ground water, are filled. If flow in the stream system is not sufficient to supply all water rights, then the junior water rights are out of priority (Colorado Division of Water Resources, 2003).

Generally in the upper Arkansas River Basin, a right to divert ground water requires an approved plan for augmentation to offset stream depletions. Since 1994, all wells, except for individual domestic wells on minimum 35-acre parcels, require an augmentation plan. Approval of augmentation plans for subdivisions must be obtained prior to SEO granting approval of a proposed water supply (Colorado Division of Water Resources, 2005a). Individual well owners and businesses in the Upper Arkansas Water Conservancy District (UAWCD) can purchase a water augmentation right through the UAWCD. Under the UAWCD augmentation plan, water is released from the nearest reservoir to replace water in the stream and offset the stream depletion caused by ground-water diversions (Upper Arkansas Water Conservancy District, 2005). In 2003, about 700 wells were included in the UAWCD augmentation plan. Most water-supply wells in the upper Arkansas River Basin between Buena Vista and Salida have augmentation plans. Ground-water diversions by municipalities and subdivisions also require augmentation plans to offset depletions of streamflow. In addition to augmentation plans for municipal supplies, an estimated 800 to 1,200 additional wells, which were not included in the UAWCD augmentation plan, had private augmentation plans (Terry Scanga, Upper Arkansas Water Conservancy District, Salida, Colorado, 2005, written commun.).

## Acknowledgments

The author thanks the many well owners in the study area for their cooperation and for access to their wells to measure water levels and collect water samples. The author also thanks the Colorado Water Conservation Board and Chaffee County for their support of this study, the city of Salida for information about municipal water supplies, and the towns of Buena Vista and Poncha Springs for access to municipal water-supply wells to measure water levels and collect water samples. The author also thanks Ralph (Terry) Scanga, Jr., General Manager of the Upper Arkansas Water Conservancy District, who provided information on augmentation plans and water administration in the upper Arkansas River Basin. The assistance of Mike Haley in collection of data for this study is gratefully acknowledged. The author also acknowledges Robert Stogner, whose attention to detail in collection and compilation of data was crucial in completing this study.

# Methods

This section of the report describes the methods of data collection including water-level measurement and sample collection and processing. This section of the report also describes quality-assurance measures used in this study.

## Water-Level Measurements

Ground-water levels were measured in 117 wells during September 2000 through September 2003. Water-level measurements of two wells were discontinued before the end of the study because of access problems. Ground-water levels were measured using either a graduated steel tape or an electric water-level sensor (U.S. Geological Survey, 2000a and 2000b) about five times per year, generally during March, May, July, September, and November. Measuring equipment was decontaminated with a chlorine bleach solution prior to insertion into a well using protocols established by the Colorado Division of Water Resources (2000). When a well was pumping or recently had been pumped, the water level was allowed to recover for about 10 to 15 minutes prior to measurement.

## Sample Collection and Processing

Ground-water samples for chemical analyses were collected during September and October 2001 using equipment and procedures as described in the National Field Manual for water-quality sampling (U.S. Geological Survey, variously dated). Most of the wells from which water samples were collected for this study were either domestic or household wells. Ground-water samples also were collected from two municipal water-supply wells. The specific conductance, pH, temperature, and dissolved-oxygen concentration of the water were monitored while the well was being purged; samples were collected when the values stabilized. Alkalinity of filtered water samples or acid-neutralizing capacity of unfiltered water samples were determined by titration. Ground-water samples were delivered to and analyzed by the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado. Filtered samples were analyzed to determine concentrations of dissolved ammonia, ammonia plus organic nitrogen, bromide, calcium, chloride, fluoride, iron, magnesium, manganese, nitrite, nitrite plus nitrate, orthophosphate, and phosphorus potassium, silica, sodium, solids, and sulfate. Unfiltered samples from selected wells were analyzed to determine the concentrations of total tritium. Concentrations of bicarbonate, carbonate, and hydroxide ions were calculated from the alkalinity or acid-neutralizing capacity. Descriptions of analytical methods used for chemical analyses can be reviewed at URL *http://nwql.usgs.gov/Public/pubs-public.html*.

As part of the study, one field blank was collected to evaluate the potential for cross contamination between sampling sites due to reuse of sampling equipment following cleaning and decontamination procedures. The field blank consisted of organic-free rinse water collected from laboratory-cleaned or field-decontaminated surfaces of sampling equipment. The field blank was processed in the same manner as environmental samples. Analytical results from the field blank indicated that the cleaning and decontamination procedures were effective. Two replicate samples were collected for chemical analyses and one replicate sample was collected for tritium analyses during the study. Comparison between the environmental and replicate samples indicated that concentrations of the normal environmental and replicate samples were approximately the same.

# Hydrogeology

The external boundaries, physical and hydrologic characteristics of the rocks and unconsolidated deposits, and recharge and discharge conditions in the upper Arkansas River Basin are the primary factors affecting the occurrence and movement of ground water in the study area. Geologic structures (faults) form the external boundaries of the basin. The hydraulic and storage characteristics of the rocks and unconsolidated deposits within the basin are related to their porosity. Porosity primarily is a function of the type of rock or deposit (lithology) and of postdepositional geologic factors (cementation, consolidation, dissolution, and fracturing). Recharge and discharge conditions are related to climate, ground-water diversions, surface-water diversions, and the hydraulic and storage properties of the aquifers. Brief descriptions of the geologic structure of the basin and the lithologic and hydrologic characteristics of the hydrostratigraphic units are described in the following sections. Recharge and discharge conditions are described later in the “Preliminary Conceptual and Cross-Sectional Models of Ground-Water Flow” section of the report.

## Geologic Setting

The upper Arkansas River Basin is in the northernmost structural basin of the Rio Grande Rift (Chapin and Cather, 1994). Uplift of the Sawatch and the Mosquito Ranges formed a graben (a deep structural basin bounded by normal faults), which is referred to as the “upper Arkansas Valley graben” (Scott, 1975). The upper Arkansas Valley graben includes two distinct structural basins, the Buena Vista–Salida and Leadville structural basins. The upper Arkansas Valley graben is deepest on its western side (Scott, 1975). The study area is located within the Buena Vista–Salida structural basin.

Rocks in the Buena Vista–Salida structural basin range in geologic age from Quaternary to Precambrian. Bedrock is exposed on the upthrown sides of a series of faults that bound the Buena Vista–Salida structural basin (fig. 3). The bedrock includes intrusive, volcanic, sedimentary, and crystalline rocks of Precambrian, Paleozoic, and Tertiary ages. Basin-fill deposits of Tertiary age overlie bedrock in the Buena Vista–Salida structural basin (Crouch and others, 1984). Alluvial and glacial outwash deposits of Quaternary age overlie the basin-fill deposits in about two-thirds of the study area (fig. 3). Glacial till of Quaternary age overlies bedrock in many of the mountain valleys west of the study area and overlies basin-fill deposits in about 4 mi$^2$ on the western side of the study area. The upper Arkansas Valley graben narrows to the north of the study area and bedrock separates deposits of Quaternary–Tertiary age in the Buena Vista–Salida structural basin from deposits of Quaternary–Tertiary age in the Leadville structural basin.

The generalized surface geology of the study area, shown in figure 3, was modified from the digital geologic map of Colorado (Green, 1992), which is based on the 1:500,000-scale geologic map of Colorado (Tweto, 1979). The geologic map of Tweto (1979) is based on generalizations of more detailed geologic maps of the study area (Scott, 1975; Scott and others, 1975).

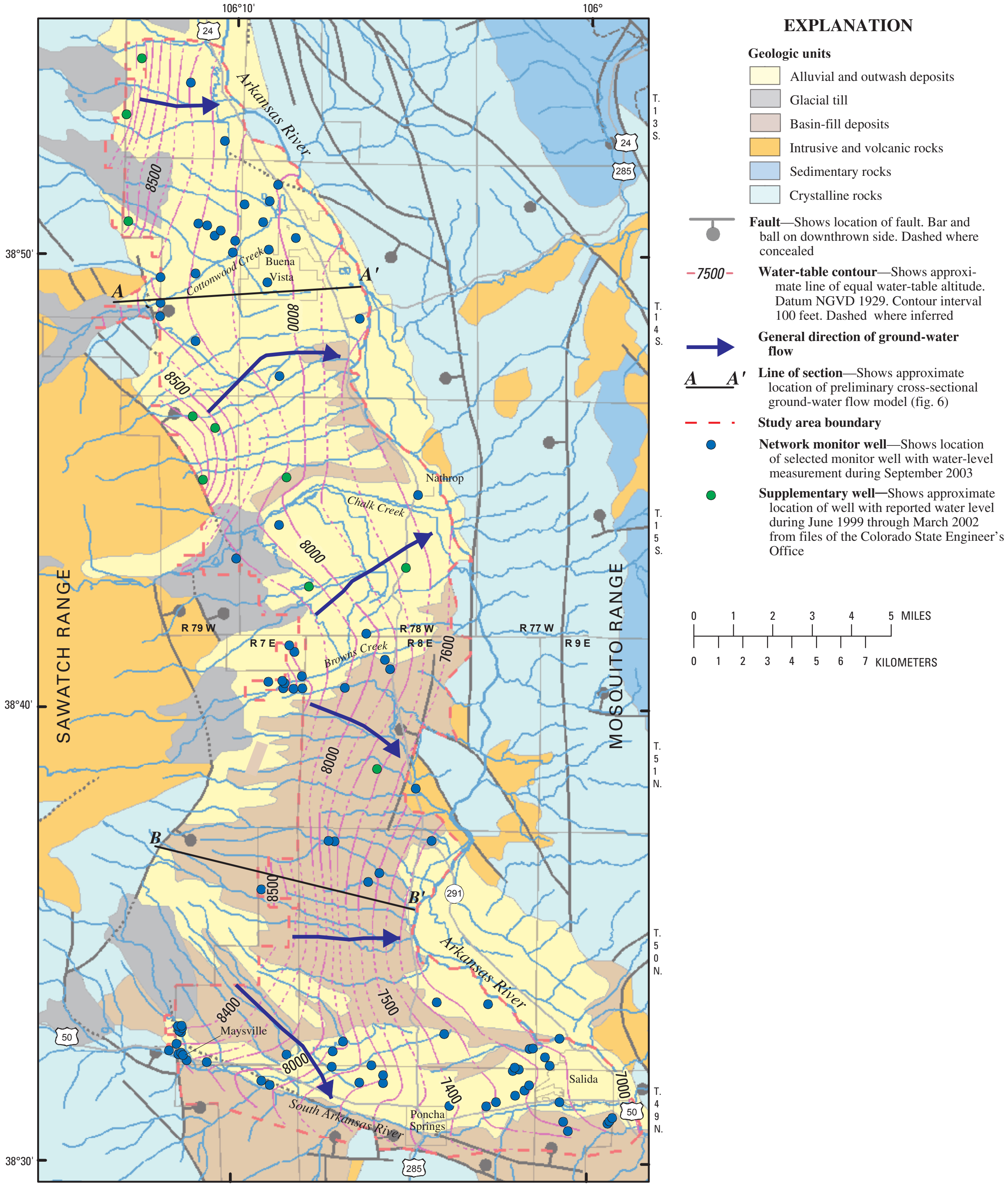
### Bedrock

Bedrock is present along most of the eastern and northern sides of the study area and in the mountains south and west of the study area (fig. 3). Bedrock, as used in this report, includes crystalline (igneous and metamorphic) rocks of Precambrian age, sedimentary rocks of Paleozoic age, and igneous rocks of Tertiary age. Granite is the primary Precambrian-age igneous rock. The Precambrian-age metamorphic rocks include gneiss and metamorphosed sedimentary and volcanic rocks (Scott, 1975; Scott and others, 1975). The Paleozoic-age sedimentary rocks do not affect ground-water conditions in the study area because they occur on the eastern flank of the Mosquito Range and dip to the east. It is not known whether Paleozoic-age sedimentary rocks underlie the basin-fill deposits in the study area. The Paleozoic-age sedimentary rocks are not described in this report. Brief descriptions of the Paleozoic sedimentary rocks are provided by Crouch and others (1984). The Tertiary-age igneous rocks include extrusive igneous (volcanic) rocks and intrusive igneous rocks (Scott, 1975; Scott and others, 1975). The Tertiary-age volcanic rocks include rhyolite and tuff. Rhyolite is an extrusive igneous rock that is the equivalent of granite. Tuff is a consolidated ash-flow deposit. The Tertiary-age intrusive igneous rocks primarily are granite and quartz monzonite. The bedrock typically is fractured; however, fractures in rocks tend to close with depths greater than a few hundred meters (Freeze and Cherry, 1979, p. 158).

### Basin-Fill Deposits

The basin-fill deposits consist of the Dry Union Formation of Tertiary age. The Dry Union Formation consists of “gray, yellowish-gray, reddish-gray or greenish-gray layers of clay, silt, sand, and gravel that are composed mainly of fragments of volcanic rocks but also containing Precambrian rocks” (Scott, 1975). The Dry Union Formation also contains white to gray volcanic ash beds, and some layers are cemented with calcium carbonate. The basin-fill deposits are heterogeneous, as indicated by cross stratification of sand and gravel layers and, locally, lateral continuity of layers within the formation is disrupted by faults (Scott, 1975). Scott (1975) and Scott and others (1975) estimated that the basin-fill deposits are more than 5,000 ft thick toward the western side of the upper Arkansas Valley graben. Crouch and others (1984) reported that maximum thickness of the basin-fill deposits, estimated on the basis of surface-geophysical surveys (Zohdy and others, 1971), is about 4,000 ft near Buena Vista and about 4,600 ft near Salida.

The lateral extent of the basin-fill deposits is defined by faults on the eastern, southern, and western sides of the Buena Vista–Salida structural basin (fig. 3). The most extensive surface exposures (outcroppings) of basin-fill deposits in the study area are in the area south of Browns Creek and in uplands on the flanks of the South Arkansas River Valley (fig. 3). North of Browns Creek, the basin-fill deposits are covered by Quaternary-age alluvial and outwash deposits or by Quaternary-age till. The basin-fill deposits are exposed along the northern side of the Chalk Creek Valley and along the western side of the Arkansas River for about 4 mi from the northern side of Chalk Creek Valley.



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

Geology modified from Green, 1992

**Figure 3.** Generalized surficial geology and altitude and configuration of the water table, September 2003.

### Glacial Outwash and Till

The glacial deposits include outwash and till of Quaternary age. There are nine sequences of multiple-stage glacial-outwash deposits, consisting mainly of tightly packed, rounded cobbles and boulders in the study area (Van Alstine, 1969). Outwash and associated alluvial deposits are the most widely distributed surface deposits in the study area, with a surface area of about 96 $mi^2$. Outwash is the predominant type of surface deposit in the Buena Vista area, in the area between Browns and Chalk Creeks, in the South Arkansas River Valley, and on terraces north of the South Arkansas River in the Salida and Maysville areas. Outwash deposits are similar to alluvial deposits and are better stratified and sorted than the glacial tills. Till generally is more consolidated than outwash deposits. Maximum thickness of glacial deposits (outwash and till) in the upper Arkansas River Basin, including the Buena Vista–Salida and Leadville structural basins and the Wet Mountain Valley, ranges from 0 to 500 ft (Crouch and others, 1984, table 1). Estimated composite thickness of outwash in the study area is about 100 ft (Scott, 1975; Scott and others, 1975), and thickness of the till in the study area was not reported.

### Alluvial Deposits

Recent alluvial deposits occur along the major streams in the study area and typically consist of 10 ft or less of sand, gravel, and cobbles with clay, and silt lenses (Scott, 1975; Scott and others, 1975). The alluvial deposits in the study area are lithologically similar to glacial outwash. Older alluvial deposits are found on terraces as much as 700 ft topographically higher than the Arkansas River (Scott, 1975). Thicknesses of the older alluvial deposits range from 15 to 80 ft in the study area. Combined thickness of alluvial deposits in the study area reportedly is about 165 feet (Scott, 1975; Scott and others, 1975).

## Hydrogeologic Setting

The Buena Vista–Salida structural basin also is a ground-water basin in which ground water occurs in the thick and porous alluvial, basin-fill, and glacial deposits that are bounded by fractured bedrock. Alluvial, basin-fill, outwash, and till deposits and bedrock of the Buena Vista–Salida ground-water basin can be classified as hydrostratigraphic units on the basis of their physical and hydrologic characteristics. A permeable hydrostratigraphic unit is an aquifer, and an impermeable or relatively impermeable hydrostratigraphic unit is a confining unit.

The alluvial deposits and glacial-outwash deposits have similar lithologic and hydrologic characteristics and, where saturated, are considered to be a single hydrostratigraphic unit, the alluvial-outwash aquifer. The alluvial-outwash aquifer is relatively porous and permeable. The glacial tills, which are heterogeneous mixtures of unsorted and unstratified clay, silt, sand, gravel, and boulders, are less permeable than the alluvial and glacial-outwash deposits and are considered to be a distinct hydrostratigraphic unit, the till aquifer. The basin-fill deposits consist of discontinuous and lenticular layers of clay, silt, sand, and gravel, in which the porosity and permeability may vary greatly within short distances laterally and vertically. The basin-fill aquifer consists of the saturated basin-fill deposits. The bedrock aquifer consists of fractured igneous and metamorphic rocks. Porosity and permeability of the bedrock aquifer are relatively small, in comparison with the porosity and permeability of the alluvial-outwash, basin-fill, and till aquifers.

## Hydrologic Properties

Physical properties of alluvial, basin-fill, and glacial deposits and bedrock in the study area have not been measured. Typical ranges of values for selected physical properties (porosity, hydraulic conductivity, specific yield, and specific retention) of geologic materials and rocks similar to those found in and near the study area are listed in table 1 and were modified from Eckis (1934), Freeze and Cherry (1979), Lohman (1979), Jorgensen (1980), Todd (1980), and Robson (1993). The typical values of specific yield for alluvial, basin-fill, and outwash deposits (table 1) are for clean, well-sorted materials. Because no measurements of grain size or physical properties for geologic materials from the study area were made, the relations in table 1 are only qualitative or relative estimates. The hydraulic-conductivity values (table 1) for alluvial materials from the Arkansas River Valley of Colorado (Lohman, 1979, table 17) are from the alluvial aquifer in the lower Arkansas River Valley east of Pueblo, Colorado, and may differ substantially from values that could be measured in the upper Arkansas River Basin.

The porosity, hydraulic conductivity, and specific yield and retention of the alluvial-outwash, till, basin-fill, and bedrock aquifers (table 2) were estimated on the basis of descriptions of the geologic materials that make up the aquifers (Crouch and others, 1984, table 1; Scott, 1975; Scott and others, 1975) and on typical values from table 1. Yields of wells completed in the study area (table 2) were estimated from data in the well files of the SEO and from Crouch and others (1984, table 1).

### Estimated Specific Yield

Specific yield of the upper 300 ft of the alluvial, basin-fill, and glacial deposits was estimated on the basis of descriptions of lithology from 842 driller's logs in and near the study area. Specific yield was estimated for only the upper 300 ft of the deposits because 95 percent of wells in the study area are less than 300 ft deep. In some parts of the study area, the alluvial-outwash deposits are thin, and wells are drilled through the alluvial-outwash aquifer into the basin-fill aquifer. Generally, it is not possible to differentiate between the

**Table 1.** Typical porosity, hydraulic conductivity, specific yield, and specific retention values for selected geologic materials.

[--, no estimate; <, less than]

| Geologic material | Porosity (percent)[1] | Hydraulic conductivity (feet per day)[1] | Hydraulic conductivity of alluvial materials in the Arkansas River Valley, southeastern Colorado (feet per day)[2] | Specific yield (percent)[3] | Specific retention (percent)[3] |
|---|---|---|---|---|---|
| Alluvial, basin-fill, and outwash deposits | | | | | |
| Gravel | 15 to 40 | [4]490 to 1,500 | 800 to 1,000 | 20 to 30 | 5 to 7 |
| Sand and gravel | 15 to 40 | 130 to 280 | -- | 28 to 32 | 7 to 8 |
| Sand | | | | | |
| Very coarse | 15 to 40 | 120 to 130 | 700 | 32 to 33 | 7 to 8 |
| Coarse | 15 to 40 | 110 to 120 | 250 | 33 to 34 | 7 to 10 |
| Medium to coarse | 15 to 40 | 85 to 110 | 100 | 28 to 34 | 7 to 14 |
| Medium | 15 to 40 | 56 to 85 | 50 | 28 to 33 | 8 to 14 |
| Fine to medium | 15 to 40 | 28 to 56 | 30 | 22 to 33 | 8 to 22 |
| Very fine, silty | 15 to 40 | 2.8 to 28 | 3 | 12 to 22 | 23 to 32 |
| Silt | [4]46 | [4]0.26 | -- | [4]8 | [4]38 |
| Clay | [4]42 | [4]0.0007 | 1 | [4]3 | [4]39 |
| Glacial till | | | | | |
| Till | [4]31 to 34 | [4]1.6 to 98 | -- | [4]6 to 16 | [4]15 to 28 |
| Bedrock | | | | | |
| Crystalline rocks | | | | | |
| Unfractured | [5]<1 to 5 | [5]<0.0001 | -- | [5]<5 | [5]<5 |
| Fractured | [5]<1 to 10 | [5]<130 | -- | [5]<10 | [5]<10 |
| Tuff | [4]41 | [4]0.2 | -- | [4]21 | [4]17 |

[1] Modified from Jorgensen (1980).

[2] Modified from Lohman (1979).

[3] Modified from Eckis (1934) as cited in Robson (1983).

[4] Modified from Todd (1980).

[5] Modified from Freeze and Cherry (1979).

**Table 2.** Lithologic description and estimated range of porosity, hydraulic conductivity, and specific yield, and reported well yields of the alluvial-outwash, till, basin-fill, and bedrock aquifers.

[<, less than]

| Aquifer | Lithologic description | Porosity (percent) | Hydraulic conductivity (feet per day) | Specific yield (percent) | Reported well yield (gallons per minute) |
|---|---|---|---|---|---|
| Alluvial outwash | Poorly stratified and poorly to well sorted silty sand and gravel. Locally contains cobbles and boulders. | 15 to 40 | 2.8 to 1,500 | 12 to 34 | 0.01 to 1,500 |
| Till | Non-sorted, non-stratified, moderately to firmly compacted sandy boulder tills. | [1]10 to 20 | [1]1.6 to 98 | [1]5 to 15 | 0.03 to 60 |
| Basin fill | Unconsolidated to poorly consolidated sand, gravel, and cobbles, with interbedded coherent siltstones and friable sandstones, and volcanic ash beds. | 15 to 40 | 0.0007 to 280 | <2 to 34 | 0.01 to 1,500 |
| Bedrock | Fractured crystalline rocks. | [2]< 1 to 10 | [2]<130 | [2]<10 | [3]< 1 to 10 |
| | Unfractured crystalline rocks. | [2]<1 to 5 | [2]<0.0001 | [2]<5 | [3]<1 to 10 |
| | Tuff. | [1]41 | [1]0.2 | [1]6 to 16 | [3]<1 to 18 |

[1] Todd (1980, tables 2.1, 2.5, and 3.1).

[2] Freeze and Cherry (1979, tables 2.2 and 2.4).

[3] Crouch and others (1984, table 1).

alluvial, outwash, and basin-fill deposits solely on the basis of driller's logs. Lithologic descriptions from the driller's logs were generalized into three material categories; fine-grained, mixtures of fine- and coarse-grained (poorly sorted), and coarse-grained materials. A specific-yield value was assigned to each lithologic interval on the driller's log on the basis of the generalized categories. Because the alluvial-outwash deposits are heterogeneous and may be poorly to well sorted, specific-yield values near the lower to middle of the ranges of values for similar geologic materials (table 1) were used. Fine-grained materials, like silt and clay, were assigned a specific yield of 0.01 (1 percent). Poorly sorted materials like sandy silt or silty sand were assigned a specific yield of 0.05 (5 percent). Well-sorted, coarse-grained materials, like sand and gravel, were assigned a specific yield of 0.2 (20 percent). Because driller's logs are subjective interpretations and their level of detail can vary substantially, estimates of specific yield made from them are considered approximations.

Point estimates of the thickness-weighted average specific yield for each 100-ft-thick interval of each log were converted to a TIN (triangulated integrated network—a topological surface defined by sets of three adjacent points) and were contoured using TINCONTOUR (Environmental Systems Research Inc., 1982–2000). The contours of estimated specific yield for the saturated part of each 100-ft-thick interval were then converted to a grid surface using TOPOGRID (Environmental Systems Research Inc., 1982–2000). The grids for the three 100-ft-thick intervals were summed using map algebra in GRID (Environmental Systems Research Inc., 1982–2000) and divided by the thickness of the saturated interval (300 ft minus the depth to water, in feet).

Comparison of the estimated specific yield (fig. 4) with the geologic map (fig. 3) indicates that the estimated specific-yield values are correlated with the surface geology. Estimated specific-yield values are relatively large, about 10 to 20 percent (0.1 to 0.2), in the Buena Vista and Chalk–Browns Creeks areas and in the South Arkansas River Valley, areas in which alluvial-outwash deposits are exposed at the surface (figs. 3 and 4). Estimated specific-yield values are relatively small, less than about 5 percent (0.05), in areas in which the basin-fill deposits are exposed at the surface (figs. 3 and 4). The estimated specific yield also is relatively small in areas in which there is little saturated thickness in the upper 300 ft of the unconsolidated deposits.

## Specific Capacity of Wells

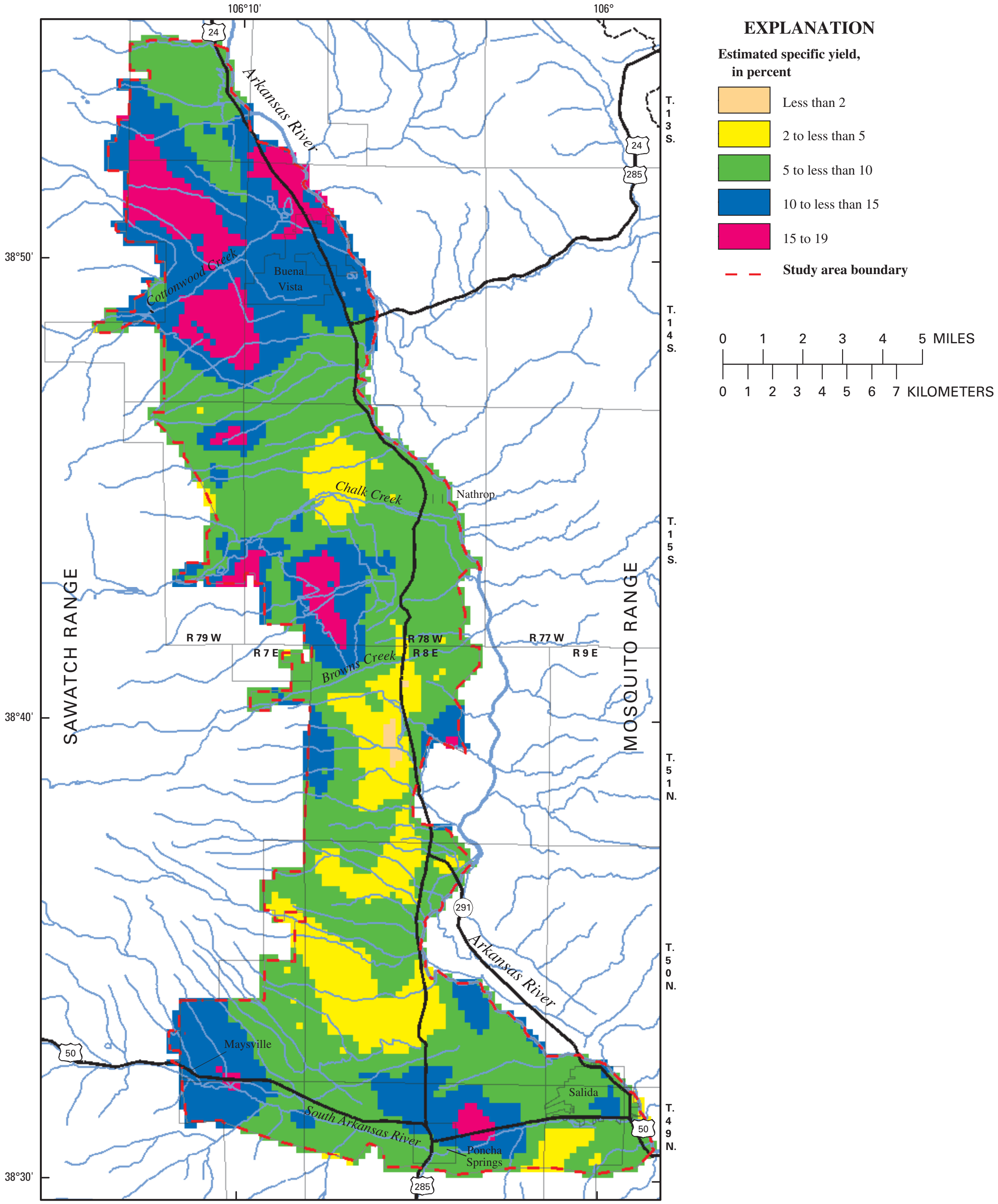
Data from the pump-performance tests were used to estimate specific-capacity values for wells completed in the alluvial-outwash and basin-fill aquifers (fig. 5). Specific capacity is the ratio between pumping rate and the drawdown of water level in the well due to pumping. If wells are relatively efficient and open to the entire saturated interval of the aquifer, then specific capacity is approximately proportional to the transmissivity of the aquifer. Transmissivity is the product of saturated thickness and hydraulic conductivity. Because most wells in the study area do not fully penetrate the aquifer, the specific-capacity values are only for that part of the aquifer contributing to the well.

Specific-capacity values for wells that are completed in the alluvial-outwash and basin-fill aquifers ranged from less than 0.01 to more than 10 gallons per minute per foot of drawdown [(gal/min)/ft]. The three-order-of-magnitude range of specific-capacity values (fig. 5) indicates the relative range in hydraulic properties that can be expected for the alluvial-outwash and basin-fill aquifers.

Specific capacities of wells in the study area appear to be inversely proportional to well depth and tend to be largest for wells less than about 100 ft deep and smallest for wells greater than 300 ft deep (fig. 5). This inverse relation of specific capacity and well depth likely is the result of a combination of factors, including confining conditions and the objective of drilling a water-supply well. Drawdown will be greater in a well that is completed in a confined aquifer than drawdown in an equivalent unconfined aquifer because of the large difference between the storage coefficient of the confined aquifer and the specific yield of the unconfined aquifer. One objective of drilling a water-supply well is to obtain an adequate well yield (pumping rate). If saturated coarse-grained deposits (clean sand and gravel) are present at shallow depths, then an adequate well yield generally can be obtained at a relatively shallow depth. Drawdown due to pumping of a well that is completed in coarse-grained deposits likely will be small and the specific capacity of the well likely will be relatively large. If saturated fine-grained deposits (clay, silt, or sandy clay and silt) are near the surface, a well likely will be drilled to a greater depth in order to obtain an adequate yield. Drawdown due to pumping of a well that is completed in fine-grained deposits likely will be large and the specific capacity of the well likely will be relatively small. Ground water in fine-grained materials also is more likely to be confined, which also results in greater drawdown in the pumped well and a smaller specific capacity.

## Alluvial-Outwash Aquifer

The alluvial-outwash aquifer consists of alluvial and outwash deposits, which are similar in lithology, and is the uppermost aquifer in about two-thirds of the study area (fig. 3). Thickness of the alluvial and outwash deposits in the study area is poorly defined but likely is less than 500 ft (Crouch and others, 1984). The porosity of the alluvial-outwash aquifer is variable and, depending primarily on grain size and sorting, may range from 15 to more than 40 percent (0.15 to 0.4). Specific yield of the alluvial-outwash aquifer likely ranges from 12 to 34 percent (0.12 to 0.34) but likely averages about 20 percent (0.2) because of its clay and silt content. The hydraulic conductivity of geologic materials similar to individual beds in the alluvial-outwash aquifer varies about seven orders of magnitude, ranging from 0.0007 to 1,500 ft/d (table 1). However, the specific capacity of wells completed in the alluvial-outwash aquifer only varies by about three



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 4.** Estimated specific yield of the upper 300 feet of alluvial, basin-fill, and glacial deposits in the study area.

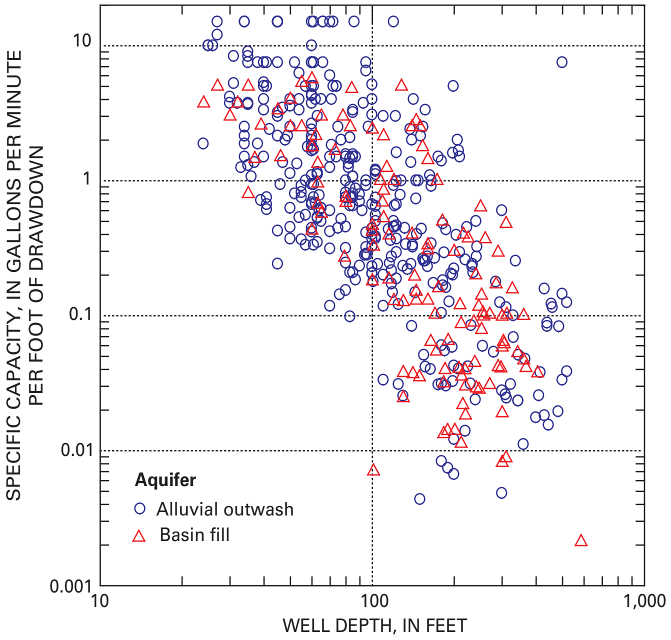


**Figure 5.** Relation between well depth and estimated specific capacity of wells in the alluvial-outwash and basin-fill aquifers in the study area.

orders of magnitude (fig. 5), and the hydraulic conductivity of the alluvial-outwash aquifer likely varies over a similar range because the deposits are predominantly sand and gravel. The alluvial-outwash aquifer is moderately to very permeable with hydraulic conductivity likely in the range of 10 to 1,000 ft/d and a median hydraulic conductivity of several hundred feet per day.

Reported well yields for 2,261 water-supply wells that are completed in the alluvial-outwash aquifer ranged from less than 1 to 1,500 gal/min (table 2). The median reported well yield was 15 gal/min. Drawdown of water levels during 347 pump-performance tests ranged from 1 to 315 ft, with drawdown to the well bottom during the test reported for about 25 percent of the tests. Large drawdown during a pump-performance test also may mean that test's pumping rate was larger than the sustainable pumping rate of the well.

## Till Aquifer

The till aquifer is the uppermost aquifer in about 4 mi$^2$ on the western side of the study area (fig. 3). Because till is an unstratified and heterogeneous mixture that is more consolidated than the alluvial and outwash deposits, till generally is less permeable than alluvial and outwash deposits. Todd (1980, p. 28) reported that till has a porosity of 31 to 34 percent (0.31 to 0.34), a specific yield of 6 to 16 percent (0.06 to 0.16), and a hydraulic conductivity of 1.6 to 98 ft/d (table 1). The till aquifer is a source of ground water for a few wells in the study area, and reported well yields of wells completed in the till aquifer range from 0.03 to 60 gal/min (table 2).

## Basin-Fill Aquifer

The basin-fill aquifer consists of saturated basin-fill deposits and is the uppermost aquifer in about one-third of the study area, primarily in the area south of Browns Creek and in uplands on the flanks of the South Arkansas River Valley (fig. 3). The basin-fill aquifer likely underlies the alluvial-outwash aquifer in most of the valley north of Chalk Creek. The basin-fill aquifer is heterogeneous and anisotropic, because of lenticular bedding of the basin-fill deposits and because, locally, bedding is disrupted by faults. Hydrogeologic data are sparse for the basin-fill aquifer for depths greater than several hundred feet below land surface. Scott (1975) estimated a probable maximum thickness of about 5,000 ft for the basin-fill deposits along the deep western side of the upper Arkansas Valley graben. Crouch and others (1984), based on geophysical surveys (Zohdy and others, 1971), estimated maximum thicknesses of the basin-fill deposits of about 4,000 and 4,600 ft near Buena Vista and near Salida, respectively. Permeability of the basin-fill aquifer varies laterally and vertically. The permeability of the rock materials (alluvial, basin-fill, and glacial deposits) is greatest in the upper 500 to 1,000 ft of the upper Arkansas Valley graben (Zohdy and others, 1971, p. 3).The basin-fill deposits are finer grained, and the basin-fill aquifer is less permeable, near the center of the basin (Crouch and others, 1984, p. 9).

Specific yield of geologic materials similar to those in the basin-fill aquifer could range from less than 2 to about 34 percent (0.02 to about 0.34) (tables 1 and 2). Specific yield of the upper 300 ft of basin-fill deposits, as estimated from driller's logs, generally is less than about 5 percent (0.05) (figs. 3 and 4).

The hydraulic conductivity of the basin-fill aquifer has not been determined by aquifer tests. Typical values for hydraulic conductivity of geologic materials similar to those of the basin-fill aquifer range from 0.0007 ft/d, for clays, to about 280 ft/d, for sand and gravel layers (table 1). Typical hydraulic conductivity of the basin-fill aquifer is probably in the range of 2.8 to 28 ft/d because the basin-fill deposits contain a large percentage of fine-grained materials (clay and silt). The hydraulic conductivity of the basin-fill aquifer probably is anisotropic (varies with direction of measurement) because the basin-fill deposits are heterogeneous and bedding is lenticular. The hydraulic conductivity of the basin-fill aquifer likely is largest parallel to bedding planes and smallest across bedding planes.

Reported well yields for 371 wells that are completed in the basin-fill aquifer ranged from less than 1 to 1,500 gal/min. The median reported yield for wells completed in the basin-fill aquifer was about 12 gal/min.

## Bedrock Aquifer

The porosity and permeability of the bedrock aquifer near the study area, where it consists of crystalline rocks, result primarily from fractures (Crouch and others, 1984).

Typically, porosity for fractured crystalline rock ranges from less than 1 to 10 percent and for unfractured crystalline rock ranges from less than 1 to 5 percent (Freeze and Cherry, 1979, p. 27). Specific yield of fractured crystalline rock is less than 10 percent and for unfractured crystalline rock is less than 5 percent. Estimated hydraulic conductivity of the bedrock aquifer likely ranges from about 0.01 to 130 ft/d where the bedrock is fractured and is less than 0.0001 ft/d where it is not fractured (modified from Freeze and Cherry, 1979, p. 27). In a few areas adjacent to the study area, the bedrock aquifer consists of tuff. Tuff may have both primary (intragranular) and secondary (fracture) porosity. Todd (1980, p. 28) reported that tuff has a representative porosity of 41 percent, a specific yield of 21 percent, and a hydraulic conductivity of about 0.2 ft/d. The porosity, hydraulic conductivity, and specific yield of tuff may vary considerably as a result of postdepositional geologic processes.

Reported yields of wells that are completed in bedrock aquifer near the study area, where the bedrock aquifer consists of fractured crystalline rocks, generally are less than 10 gal/min (Crouch, 1984, table 1). One well that is completed in tuff near the study area has a reported yield of 17 gal/min.

## Preliminary Conceptual and Cross-Sectional Models of Ground-Water Flow

Most wells in the study area are less than 300 ft deep, and little is known about the hydrogeology of the underlying basin-fill deposits, which are estimated to be as much as 5,000 ft thick (Scott, 1975). Ground-water flow in the permeable alluvial-outwash aquifer is primarily lateral and generally toward the Arkansas River and, locally, toward the South Arkansas River (fig. 3). Although the available data are not adequate to develop a rigorous model of three-dimensional ground-water flow, preliminary two-dimensional models of cross-sectional ground-water flow in the study area were used to evaluate conceptual models of regional ground-water flow.

A conceptual ground-water model is a written or graphical description of the factors that control the occurrence and flow of ground water in an aquifer or aquifer system. A conceptual model is an important initial step in a quantitative appraisal of ground-water flow. Two-dimensional models of cross-sectional ground-water flow can be used to test hypotheses about the flow system and to qualitatively identify the types of and locations at which additional data collection could better define the ground-water flow system. If the boundaries, dimensions, and hydraulic properties of the aquifers are known, even if only relatively, then the general distribution of hydraulic head and direction of ground-water flow in the alluvial-outwash and basin-fill aquifers can be estimated from the water-table map (fig. 3).

### Conceptual Model

The primary aquifers in the Buena Vista–Salida ground-water basin are the alluvial-outwash and basin-fill aquifers. The till aquifer was not considered in the conceptual model because the extent of the till aquifer in the study area is limited. The alluvial-outwash aquifer is moderately to very permeable and approximately isotropic. The basin-fill aquifer is less permeable than the alluvial-outwash aquifer and is anisotropic, with greater horizontal hydraulic conductivity than vertical hydraulic conductivity. The bedrock aquifer is relatively impermeable in comparison with the alluvial-outwash and basin-fill aquifers.

Although the water table fluctuates seasonally in response to seasonal changes in streamflow, surface-water diversions, and pumping, and the water table may decline substantially during extended droughts when recharge is minimal, over the long term the water table is approximately in a steady-state condition. On average, recharge from infiltration of streamflow, surface-water diversions, and precipitation maintain the water table in an approximate steady state. The Arkansas and South Arkansas Rivers generally are gaining streams in the study area and likely are regional ground-water discharge areas.

### Cross-Sectional Models

Preliminary models of cross-sectional ground-water flow (fig. 6) were developed to evaluate the conceptual model of regional ground-water flow. Approximate locations of the generalized cross sections (fig. 6) are shown in figure 3. The models also were used to qualitatively evaluate the sensitivity of potentiometric lines (lines of equal hydraulic head) and flow directions to the hydraulic properties of the aquifers. The potentiometric lines and the flow lines shown in figure 6 were computed using TopoDrive, a two-dimensional cross-sectional model for simulation and visualization of ground-water flow (Hsieh, 2001). The following conditions were assumed for these models of cross-sectional ground-water flow:

- The ground-water system is in an approximate steady-state condition,
- The alluvial-outwash aquifer is homogeneous and isotropic with a median hydraulic conductivity of 280 ft/d,
- The basin-fill aquifer is homogeneous and anisotropic with horizontal hydraulic conductivity of 2.8 ft/d and vertical hydraulic conductivity of 0.028 ft/d, and
- The bedrock aquifer is homogeneous and isotropic with hydraulic conductivity of about 0.0003 ft/d.

The values of hydraulic conductivity used in the models were selected for illustrative purposes only. Actual values for hydraulic conductivity of the alluvial-outwash, basin-fill, bedrock, and till aquifers have not been measured in the study area. The west-to-east cross sections represent vertical slices about 6.2 mi long (fig. 6*A*) and about 6.8 mi long (fig. 6*B*)

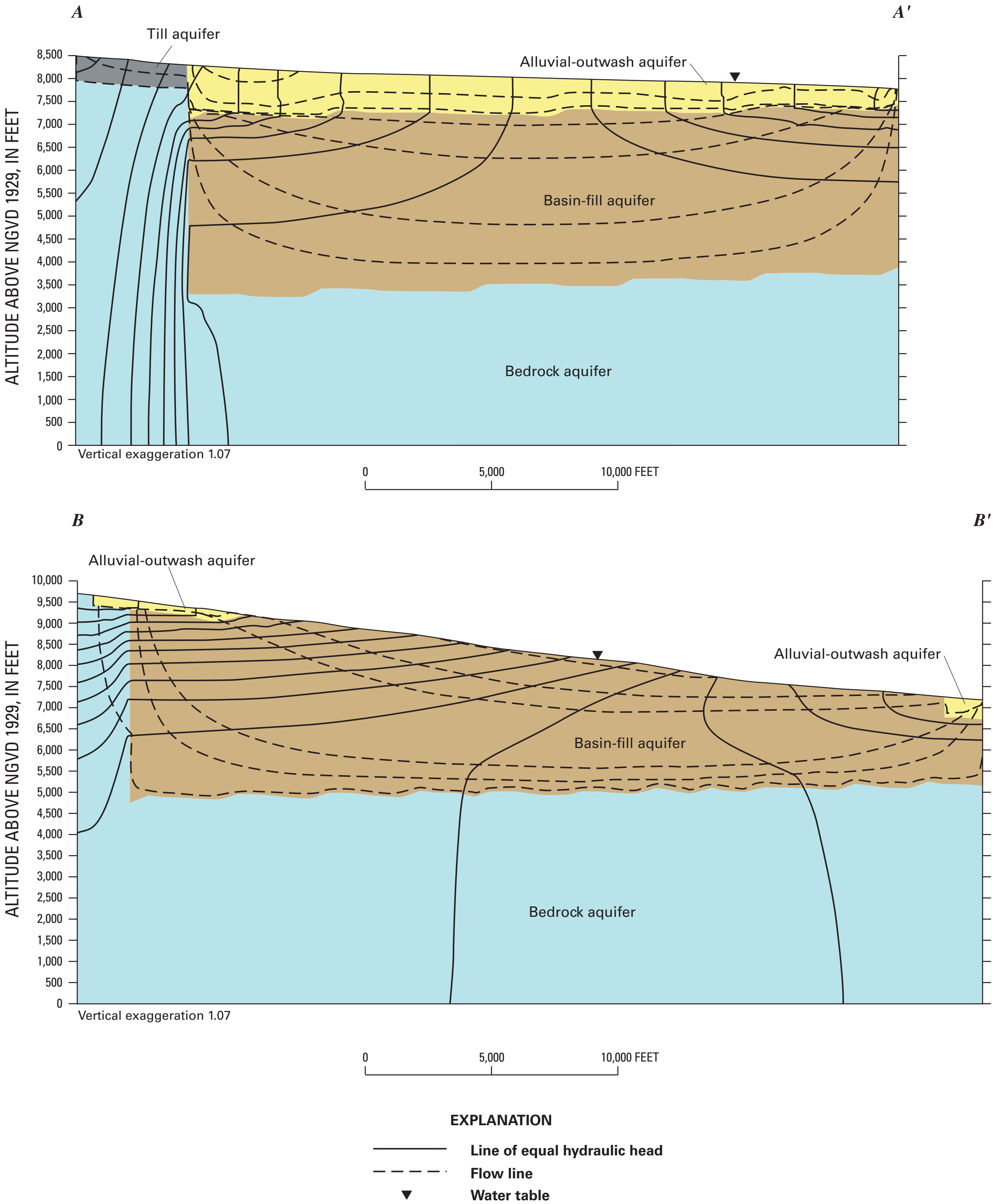


**Figure 6.** Preliminary cross-sectional models of ground-water flow (*A*) near Buena Vista, Colorado, and (*B*) northwest of Salida, Colorado.

across the basin. The upper surface in the cross-sectional models (figs. 6*A* and 6*B*) is the water table, as approximated from figure 3. Because the models assume steady-state conditions, no change in storage can occur and porosity values are irrelevant in the calculation of hydraulic heads and flow lines.

Figure 6*A* is a generalized cross-sectional flow model that is oriented approximately west to east in the northern part of the study area near Buena Vista, where the relatively thick and extensive alluvial-outwash aquifer is recharged primarily by surface-water diversions and losing streams (fig. 3). Because the alluvial-outwash aquifer is assumed to be isotropic, lines of equal hydraulic head are approximately vertical and ground-water flow in the alluvial-outwash aquifer primarily is horizontal. Because the assumed hydraulic conductivity was relatively large (280 ft/d), hydraulic gradients in the alluvial-outwash aquifer are relatively small, as indicated by the widely spaced lines of equal hydraulic head (figs. 3 and 6*A*). In the underlying basin-fill aquifer, lines of equal hydraulic head are not vertical. In recharge areas, hydraulic head decreases with depth in the basin-fill aquifer, indicating downward flow. About halfway across the cross section (fig. 6*A*), the flow lines in the basin-fill aquifer are subhorizontal and primarily indicate horizontal flow. Near the eastern side of the cross section, hydraulic heads in the basin-fill aquifer increase with depth and indicate upward flow (ground-water discharge) from the basin-fill aquifer to the alluvial-outwash aquifer near the Arkansas River, which is near the regional low in the water-table surface.

Figure 6*B* is a generalized cross-sectional flow model that is oriented approximately west to east in the south-central part of the study area, northwest of Salida and south of Browns Creek. In this area, the alluvial-outwash aquifer is relatively thin and present primarily near the Arkansas River. In this area, the basin-fill aquifer is recharged by infiltration of surface water from losing streams and precipitation and, locally, from infiltration of surface-water diversions. Hydraulic gradients in the basin-fill aquifer are relatively large, as indicated by the closely spaced lines of equal hydraulic head (figs. 3 and 6*B*). Hydraulic heads decrease with increasing depth and indicate downward flow in the western two-thirds of the basin. Hydraulic heads in the basin-fill aquifer increase with depth near the eastern side of the basin and indicate upward flow (ground-water discharge) to the alluvial-outwash aquifer near the Arkansas River.

Data to support the inferred lines of equal hydraulic head and directions of ground-water flow from the preliminary cross-sectional models (fig. 6) are sparse and not definitive. In the Browns Creek area, near the western side of the study area, differences in water levels in nearby shallow and deep wells (wells 49, 52, and 56) indicate a potential for downward ground-water flow. Crouch and others (1984) reported an anomaly (downward curvature) in a subsurface temperature profile in a 1,000-ft-deep test well (well 4, fig. 1 and table 3), which was interpreted as indicating downward flow within the basin-fill aquifer. Hydrologic interpretations of surface-geophysical surveys (direct-current electrical-resistivity profiles) near Buena Vista and Salida (Zohdy and others, 1971; Crouch and others, 1984) indicate that the most permeable rocks in the basin are in the upper 500 to 1,000 ft of the subsurface, that more permeable rocks occur at greater depths near the western side of the basin, and that near surface rocks are more permeable in the Buena Vista area than in the Salida area. The electric resistivity of earth materials is a function of rock type, porosity, pore size, and the dissolved-solids content of the water in the pores. An alternative interpretation of the geo-electric sections is that downward flow of water (recharge) with small dissolved-solids content in the permeable rocks on the western side of the basin is indicated by higher electrical resistivity at greater depths. Upward flow of water with larger dissolved-solids content near the eastern side of the basin is indicated by lower electrical resistivity at shallower depths.

## Water Levels

Water levels generally were measured four or five times per year, from September 2000 through September 2003, in 92 wells that are completed in the alluvial-outwash aquifer, 3 wells completed in the till aquifer, 19 wells completed in the basin-fill aquifer, and 3 wells completed in the bedrock aquifer (table 3; fig. 1). Three of the 92 wells that were measured four or five times per year and are completed in the alluvial-outwash aquifer, wells 4, 65, and 104, also are part of a long-term water-level monitoring network that is operated by the USGS in cooperation with the Southeastern Colorado Water Conservancy District and the UAWCD. Normally, water levels are measured twice per year in the long-term monitoring network wells. Wells 119, 120, 121,122, and 124 (table 3) also are part of the long-term water-level monitoring network and were measured twice per year during the study period.

Because most wells in the monitoring network are water-supply wells (domestic, household, or municipal wells), water levels are affected by pumping. When possible, water levels in the wells were allowed to recover for 10 to 15 minutes after pumping stopped before being measured. Water levels were measured in pumping or recently pumped wells for only 10 of about 1,600 water-level measurements made during the study. Measurements affected by pumping or recent pumping are qualified as “pumping” or “recently pumped” in the USGS Ground Water Site Inventory (GWSI) database. Table 3 lists selected information for wells in the monitoring network and for selected wells in the long-term water-level network that are located in the study area. Locations of the wells are shown in figure 1. Water-level data for Colorado, including water levels measured during this study, can be accessed at URL *http://co.water.usgs.gov* [click on the small map labeled “Directory of Project Information and Data-Collection Sites” and follow the instructions on the Web page] and at URL *http://waterdata.usgs.gov/co/nwis/*. For ease of site selection, use the USGS site identification numbers listed in table 3.

**Table 3.** Selected data for wells in the water-level and water-quality networks, September 2000–September 2003.

[--, no data; altitude is referenced to the National Geodetic Vertical Datum of 1929]

| Network well number | Site identification number | Aquifer | Water-level measurements September 2000–September 2003 | | | Water-quality sample date | Tritium sample[2] | Water-table map[3] | Land-surface altitude (feet) | Depth to top of open interval (feet)[4] | Depth to bottom of open interval (feet)[4] | Well depth (feet)[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Start date (long-term network well) | End date | Number of measure-ments | | | | | | | |
| 1 | 384720106084501 | Alluvial outwash | 10/08/2000 | 09/11/2003 | 15 | -- | -- | X | 8,125 | 91 | 120 | 120 |
| 2 | 384753106115401 | Alluvial outwash | 04/04/2001 | 05/09/2003 | 10 | -- | -- | -- | 8,490 | 178 | 478 | 478 |
| 3 | 384806106110801 | Alluvial outwash | 11/09/2000 | 09/11/2003 | 12 | -- | -- | X | 8,375 | 135 | 175 | 175 |
| [1]4 | 384815106084000 | Basin fill | 10/26/2000<br>(10/23/1971) | 09/10/2003 | 14 | -- | -- | -- | 8,086 | 599 | 1,000 | 1,000 |
| 5 | 384829106151301 | Bedrock | 09/27/2000 | 09/18/2002 | 11 | -- | -- | -- | 9,050 | 36 | 110 | 110 |
| 6 | 384836106063101 | Alluvial outwash | 10/08/2000 | 09/09/2003 | 15 | -- | -- | X | 7,845 | 31 | 38 | 38 |
| 7 | 384838106120801 | Alluvial outwash | 09/20/2000 | 09/09/2003 | 15 | 10/15/2001 | -- | X | 8,400 | -- | -- | 199 |
| 8 | 384856106120701 | Alluvial outwash | 09/28/2000 | 09/09/2003 | 15 | 10/15/2001 | -- | X | 8,365 | 63 | 78 | 78 |
| 9 | 384924106090701 | Alluvial outwash | 10/09/2000 | 09/09/2003 | 14 | -- | -- | X | 8,075 | 20 | -- | 57 |
| 10 | 384929106121401 | Alluvial outwash | 09/27/2000 | 09/11/2001 | 5 | -- | -- | -- | 8,355 | 88 | 108 | 108 |
| 11 | 384930106120801 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | 09/12/2001 | -- | X | 8,350 | 95 | 120 | 120 |
| 12 | 384935106110901 | Alluvial outwash | 10/08/2000 | 09/10/2003 | 15 | -- | -- | X | 8,210 | 20 | 63 | 63 |
| 13 | 384937106104801 | Alluvial outwash | 09/27/2000 | 09/19/2002 | 11 | -- | -- | | 8,202 | 33 | 45 | 45 |
| 14 | 385003106100601 | Alluvial outwash | 10/09/2000 | 09/09/2003 | 15 | 10/18/2001 | X | X | 8,105 | 70 | 100 | 100 |
| 15 | 385007106090501 | Alluvial outwash | 11/09/2000 | 09/10/2003 | 14 | 09/18/2001 | -- | X | 8,046 | 30 | 45 | 45 |
| 16 | 385019106100201 | Alluvial outwash | 09/21/2000 | 09/09/2003 | 15 | -- | -- | X | 8,115 | 59 | 80 | 80 |
| 17 | 385023106081901 | Alluvial outwash | 09/28/2000 | 09/10/2003 | 15 | -- | -- | X | 7,975 | -- | -- | 25 |
| 18 | 385026106103701 | Alluvial outwash | 03/10/2003 | 09/11/2003 | 4 | -- | -- | X | 8,220 | 57 | 77 | 77 |
| 19 | 385032106102601 | Alluvial outwash | 10/06/2000 | 09/09/2003 | 15 | 10/17/2001 | X | X | 8,205 | 68 | 86 | 86 |
| 20 | 385039106104901 | Alluvial outwash | 10/06/2000 | 09/09/2003 | 15 | 09/12/2001 | X | X | 8,275 | 100 | 180 | 180 |
| 21 | 385041106110501 | Alluvial outwash | 10/06/2000 | 09/09/2003 | 15 | 09/14/2001 | X | X | 8,320 | -- | -- | 178 |
| 22 | 385044106091501 | Alluvial outwash | 09/26/2000 | 09/09/2003 | 15 | 09/18/2001 | -- | X | 8,040 | 19 | 31 | 31 |
| 23 | 385050106085601 | Alluvial outwash | 10/09/2000 | 09/17/2002 | 11 | -- | -- | -- | 8,005 | 20 | 63 | 63 |
| 24 | 385100106094101 | Alluvial outwash | 11/09/2000 | 09/17/2002 | 9 | -- | -- | -- | 8,140 | -- | -- | 128 |
| 25 | 385107106094701 | Alluvial outwash | 09/27/2000 | 09/09/2003 | 15 | 09/13/2001 | X | X | 8,170 | 120 | 151 | 151 |
| 26 | 385109106094001 | Alluvial outwash | 09/25/2000 | 09/17/2002 | 11 | -- | -- | -- | 8,165 | 126 | 146 | 146 |
| 27 | 385112106090401 | Alluvial outwash | 04/03/2001 | 09/09/2003 | 13 | -- | -- | X | 8,025 | 20 | 25 | 35 |
| 28 | 385133106085001 | Alluvial outwash | 09/21/2000 | 09/09/2003 | 15 | -- | -- | X | 8,030 | 32 | 62 | 62 |
| 29 | 385231106102101 | Alluvial outwash | 10/06/2000 | 05/09/2002 | 9 | -- | -- | -- | 8,290 | 110 | 170 | 170 |
| 30 | 385231106102102 | Alluvial outwash | 07/18/2002 | 09/09/2003 | 6 | -- | -- | X | 8,290 | 157 | 237 | 237 |

**Table 3.** Selected data for wells in the water-level and water-quality networks, September 2000–September 2003.—Continued

[--, no data; altitude is referenced to the National Geodetic Vertical Datum of 1929]

| Network well number | Site identification number | Aquifer | Water-level measurements September 2000–September 2003 | | | Water-quality sample date | Tritium sample[2] | Water-table map[3] | Land-surface altitude (feet) | Depth to top of open interval (feet)[4] | Depth to bottom of open interval (feet)[4] | Well depth (feet)[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Start date (long-term network well) | End date | Number of measurements | | | | | | | |
| 31 | 385348106111901 | Alluvial outwash | 11/09/2000 | 09/09/2003 | 14 | -- | -- | X | 8,425 | 155 | 180 | 180 |
| 32 | 385349106130501 | Alluvial outwash | 10/06/2000 | 07/17/2003 | 11 | 09/12/2001 | -- | -- | 9,045 | 102 | 127 | 127 |
| 33 | 383211106104001 | Alluvial outwash | 9/28/2000 | 09/16/2003 | 15 | -- | -- | X | 8,200 | 70 | 100 | 100 |
| 34 | 383213106111401 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | -- | -- | X | 8,195 | -- | -- | 35 |
| 35 | 383221106112601 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | 09/19/2001 | -- | X | 8,237 | 21 | 31 | 31 |
| 36 | 383221106112801 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | -- | -- | X | 8,236 | 24 | 32 | 32 |
| 37 | 383223106112301 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | -- | -- | X | 8,250 | 32 | 60 | 60 |
| 38 | 383226106114401 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | 09/19/2001 | -- | X | 8,270 | 60 | 80 | 80 |
| 39 | 383235106113101 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | | -- | X | 8,385 | 83 | 120 | 180 |
| 40 | 383250106112401 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | 10/17/2001 | X | X | 8,380 | -- | -- | 199 |
| 41 | 383252106112601 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | 10/16/2001 | X | X | 8,395 | -- | -- | 199 |
| 42 | 383252106113201 | Alluvial outwash | 11/02/2000 | 09/16/2003 | 14 | -- | -- | -- | 8,400 | -- | -- | 285 |
| 43 | 383255106112201 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | 09/19/2001 | X | X | 8,445 | 157 | 175 | 175 |
| 44 | 383258106112901 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | -- | -- | X | 8,408 | 90 | 110 | 110 |
| 45 | 383259106112201 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | -- | -- | X | 8,472 | 135 | 175 | 175 |
| 46 | 383600106091001 | Basin fill | 09/27/2000 | 09/08/2003 | 13 | | | X | 8,760 | 55 | 130 | 130 |
| 47 | 383611106060901 | Basin fill | 10/08/2000 | 09/18/2003 | 15 | 09/20/2001 | -- | X | 7,600 | 83 | 100 | 183 |
| 48 | 384013106055001 | Basin fill | 09/28/2000 | 09/10/2003 | 15 | -- | -- | -- | 7,920 | 120 | 220 | 220 |
| 49 | 384025106080201 | Alluvial outwash | 05/08/2003 | 09/10/2003 | 3 | -- | -- | -- | 8,535 | 360 | 560 | 560 |
| 50 | 384026106083601 | Alluvial outwash | 09/28/2000 | 09/10/2003 | 15 | 09/13/2001 | X | X | 8,630 | 122 | 162 | 182 |
| 51 | 384026106081801 | Alluvial outwash | 05/17/2001 | 09/10/2003 | 12 | -- | -- | X | 8,550 | 150 | 180 | 180 |
| 52 | 384027106080301 | Alluvial outwash | 05/16/2001 | 09/10/2003 | 12 | 10/18/2001 | -- | X | 8,520 | 70 | 130 | 200 |
| 53 | 384028106065101 | Basin fill | 09/25/2000 | 09/10/2003 | 15 | 10/18/2001 | -- | X | 8,255 | 146 | 246 | 246 |
| 54 | 384029106080201 | Alluvial outwash | 05/17/2001 | 09/10/2003 | 12 | 10/18/2001 | -- | -- | 8,515 | 180 | 400 | 440 |
| 55 | 384031106085101 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | 09/18/2001 | X | -- | 8,655 | 160 | 323 | 323 |
| 56 | 384032106075901 | Alluvial outwash | 05/08/2003 | 09/10/2003 | 3 | -- | -- | -- | 8,490 | 340 | 540 | 540 |
| 57 | 384033106083301 | Alluvial outwash | 11/09/2000 | 09/10/2003 | 14 | 10/17/2001 | -- | X | 8,550 | 25 | 45 | 45 |
| 58 | 384035106090101 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | 09/14/2001 | X | X | 8,700 | 55 | 85 | 85 |
| 59 | 384036106083701 | Alluvial outwash | 10/08/2000 | 09/10/2003 | 15 | 01/00/1900 | X | X | 8,600 | 45 | 60 | 60 |

**Table 3.** Selected data for wells in the water-level and water-quality networks, September 2000–September 2003.—Continued

[--, no data; altitude is referenced to the National Geodetic Vertical Datum of 1929]

| Network well number | Site identification number | Aquifer | Water-level measurements September 2000–September 2003 | | | Water-quality sample date | Tritium sample[2] | Water-table map[3] | Land-surface altitude (feet) | Depth to top of open interval (feet)[4] | Depth to bottom of open interval (feet)[4] | Well depth (feet)[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Start date (long-term network well) | End date | Number of measure-ments | | | | | | | |
| 60 | 384043106080401 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | -- | -- | X | 8,465 | -- | -- | 200 |
| 61 | 384052106053401 | Basin fill | 09/29/2000 | 07/15/2003 | 15 | -- | -- | X | 7,945 | -- | -- | 149 |
| 62 | 384105106054301 | Basin fill | 09/29/2000 | 09/10/2003 | 15 | -- | -- | X | 7,990 | -- | -- | 73 |
| 63 | 384115106081601 | Alluvial outwash | 09/25/2000 | 09/09/2003 | 15 | -- | -- | X | 8,435 | 159 | 241 | 241 |
| 64 | 384123106082601 | Alluvial outwash | 10/06/2000 | 09/09/2003 | 14 | 09/12/2001 | X | X | 8,450 | 205 | 345 | 345 |
| [1]65 | 384141106061800 | Alluvial outwash | 04/04/2001<br>(10/06/1989) | 09/18/2003 | 13 | -- | -- | X | 8,060 | 15 | 50 | 50 |
| 66 | 384310106112901 | Till | 09/22/2000 | 09/19/2002 | 11 | -- | -- | | 8,350 | 30 | 45 | 45 |
| 67 | 384316106095601 | Till | 09/25/2000 | 09/09/2003 | 15 | -- | -- | X | 8,435 | 170 | 210 | 210 |
| 68 | 384403106084501 | Alluvial outwash | 10/08/2000 | 09/11/2003 | 15 | -- | -- | X | 8,145 | 60 | 208 | 208 |
| 69 | 384444106045001 | Alluvial outwash | 04/03/2001 | 09/09/2003 | 13 | -- | -- | X | 7,700 | 50 | 65 | 65 |
| 70 | 383035106043201 | Alluvial outwash | 07/18/2001 | 07/19/2003 | 6 | -- | -- | -- | 7,472 | -- | -- | 38 |
| 71 | 383034106043101 | Alluvial outwash | 10/07/2000 | 09/20/2002 | 3 | -- | -- | -- | 7,475 | -- | -- | 99 |
| 72 | 383115106035001 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 14 | -- | -- | X | 7,430 | 21 | 150 | 150 |
| 73 | 383026106004901 | Basin fill | 09/28/2000 | 09/17/2003 | 14 | -- | -- | -- | 7,570 | 147 | 247 | 247 |
| 74 | 383042106003001 | Basin fill | 10/07/2000 | 09/17/2003 | 15 | -- | -- | X | 7,325 | 50 | 70 | 70 |
| 75 | 383053105592301 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | -- | -- | X | 7,200 | -- | -- | 199 |
| 76 | 383055106003801 | Basin fill | 10/07/2000 | 09/10/2003 | 15 | 09/20/2001 | -- | X | 7,240 | 75 | 145 | 145 |
| 77 | 383056105592001 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | -- | -- | X | 7,190 | -- | -- | 199 |
| 78 | 383100105591501 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | -- | -- | X | 7,160 | 110 | 140 | 140 |
| 79 | 383114106024801 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | -- | -- | X | 7,325 | 20 | 63 | 65 |
| 80 | 383120106023101 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | 10/16/2001 | -- | X | 7,320 | 40 | 60 | 60 |
| 81 | 383121106004401 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | 09/20/2001 | -- | X | 7,125 | 20 | 35 | 35 |
| 82 | 383129106015901 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | -- | -- | X | 7,240 | 15 | 55 | 55 |
| 83 | 383136106014301 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 14 | -- | -- | X | 7,240 | 58 | 73 | 73 |
| 84 | 383141106085301 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 14 | -- | -- | X | 7,915 | 15 | 24 | 24 |
| 85 | 383143106013601 | Alluvial outwash | 09/27/2000 | 09/17/2003 | 15 | -- | -- | X | 7,235 | 20 | 63 | 63 |
| 86 | 383145106054201 | Alluvial outwash | 09/27/2000 | 09/16/2003 | 15 | -- | -- | X | 7,725 | 80 | 100 | 100 |
| 87 | 383145106062201 | Alluvial outwash | 10/09/2000 | 09/16/2003 | 15 | 09/14/2001 | -- | X | 7,770 | 48 | 110 | 110 |
| 88 | 383146106090701 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | -- | -- | X | 7,940 | -- | -- | 99 |
| 89 | 383155106054201 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 14 | -- | -- | X | 7,730 | -- | -- | 99 |

**Table 3.** Selected data for wells in the water-level and water-quality networks, September 2000–September 2003.—Continued

[--, no data; altitude is referenced to the National Geodetic Vertical Datum of 1929]

| Network well number | Site identification number | Aquifer | Water-level measurements September 2000–September 2003 | | | Water-quality sample date | Tritium sample[2] | Water-table map[3] | Land-surface altitude (feet) | Depth to top of open interval (feet)[4] | Depth to bottom of open interval (feet)[4] | Well depth (feet)[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Start date (long-term network well) | End date | Number of measurements | | | | | | | |
| 90 | 383155106091301 | Alluvial outwash | 09/26/2000 | 07/16/2001 | 5 | -- | -- | -- | 8,005 | -- | -- | 99 |
| 91 | 383202106020301 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | -- | -- | X | 7,255 | 25 | 60 | 60 |
| 92 | 383204106015301 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | 10/19/2001 | -- | X | 7,245 | 40 | 75 | 75 |
| 93 | 383206106020001 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 13 | -- | -- | X | 7,250 | 22 | 42 | 42 |
| 94 | 383206106070901 | Alluvial outwash | 09/21/2000 | 09/16/2003 | 15 | -- | -- | X | 7,865 | 41 | 66 | 66 |
| 95 | 383208106060201 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | -- | -- | X | 7,775 | 20 | 63 | 63 |
| 96 | 383209106010101 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | 09/20/2001 | -- | X | 7,185 | 20 | 95 | 95 |
| 97 | 383220106010901 | Alluvial outwash | 10/09/2000 | 09/17/2003 | 15 | -- | -- | X | 7,190 | 25 | 70 | 70 |
| 98 | 383220106112001 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | -- | -- | X | 8,230 | -- | -- | 67 |
| 99 | 383221106082501 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | -- | -- | X | 8,105 | 24 | 54 | 54 |
| 100 | 383226106070701 | Alluvial outwash | 09/26/2000 | 09/08/2003 | 15 | 09/14/2001 | -- | X | 7,925 | 57 | 87 | 87 |
| 101 | 383231106013501 | Alluvial outwash | 09/27/2000 | 09/17/2003 | 15 | -- | -- | X | 7,165 | 45 | 65 | 65 |
| 102 | 383231106013001 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | -- | -- | X | 7,163 | 39 | 54 | 54 |
| 103 | 383240106065001 | Alluvial outwash | 9/26/2000 | 09/08/2003 | 15 | -- | -- | X | 7,965 | 38 | 198 | 198 |
| [1]104 | 383246106004601 | Alluvial outwash | 10/25/2000<br>(05/30/1981) | 09/17/2003 | 14 | -- | -- | X | 7,100 | -- | -- | 20 |
| 105 | 383249106035801 | Alluvial outwash | 11/09/2000 | 09/08/2003 | 14 | 10/16/2001 | -- | X | 7,385 | 65 | 85 | 85 |
| 106 | 383330106024601 | Alluvial outwash | 09/28/2000 | 09/18/2002 | 10 | 10/17/2001 | -- | -- | 7,158 | -- | -- | 43 |
| 107 | 383330106024602 | Alluvial outwash | 03/24/2003 | 09/10/2003 | 4 | -- | -- | X | 7,158 | -- | -- | 60 |
| 108 | 383332106041201 | Alluvial outwash | 10/08/2000 | 09/17/2003 | 15 | -- | -- | X | 7,300 | 61 | 85 | 85 |
| 109 | 383622106055101 | Basin fill | 10/08/2000 | 09/11/2003 | 15 | 10/16/2001 | X | X | 7,540 | 64 | 164 | 164 |
| 110 | 383631106052401 | Basin fill | 09/25/2000 | 09/08/2003 | 15 | 09/13/2001 | X | -- | 7,470 | 245 | 365 | 365 |
| 111 | 383640106071601 | Basin fill | 09/27/2000 | 11/06/2000 | 2 | -- | -- | -- | 7,980 | 220 | 290 | 290 |
| 112 | 383652106070601 | Basin fill | 09/20/2000 | 09/09/2003 | 15 | -- | -- | X | 7,940 | 102 | 212 | 212 |
| 113 | 383705106071601 | Basin fill | 10/08/2000 | 09/09/2003 | 15 | 09/20/2001 | -- | X | 7,940 | 58 | 110 | 110 |
| 114 | 383706106042301 | Basin fill | 10/08/2000 | 09/08/2003 | 13 | 09/12/2001 | -- | X | 7,415 | 130 | 190 | 190 |
| 115 | 383818106044701 | Bedrock | 09/27/2000 | 09/10/2003 | 15 | -- | -- | X | 7,475 | 22 | 40 | 40 |
| 116 | 383844106044701 | Bedrock | 09/27/2000 | 09/10/2003 | 15 | -- | -- | -- | 7,605 | -- | -- | 313 |
| 117 | 383332106041202 | Alluvial outwash | 05/09/2003 | 09/17/2003 | 3 | -- | -- | -- | 7,300 | -- | -- | 199 |
| 118 | 384328106103501 | Till | 09/21/2000 | 09/21/2000 | 1 | -- | -- | -- | 8,295 | 50 | 65 | 65 |

**Table 3.** Selected data for wells in the water-level and water-quality networks, September 2000–September 2003.—Continued

[--, no data; altitude is referenced to the National Geodetic Vertical Datum of 1929]

| Network well number | Site identification number | Aquifer | Water-level measurements September 2000–September 2003 | | | Water-quality sample date | Tritium sample[2] | Water-table map[3] | Land-surface altitude (feet) | Depth to top of open interval (feet)[4] | Depth to bottom of open interval (feet)[4] | Well depth (feet)[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Start date (long-term network well) | End date | Number of measurements | | | | | | | |
| [1]119 | 383233105594201 | Alluvial outwash | 09/18/2001<br>(04/13/1990) | 09/17/2003 | 5 | -- | -- | -- | 7,045 | 20 | 25 | 25 |
| [1]120 | 383230106114701 | Alluvial outwash | 10/25/2000<br>(10/02/1980) | 09/16/2003 | 5 | -- | -- | -- | 8,235 | -- | -- | 45 |
| [1]121 | 383300106023501 | Alluvial outwash | 10/25/2000<br>(11/01/1971) | 09/17/2003 | 7 | -- | -- | -- | 7,185 | -- | -- | 88 |
| [1]122 | 383804106045101 | Alluvial outwash | 10/26/2000<br>(08/05/1981) | 09/18/2003 | 7 | -- | -- | -- | 7,485 | -- | -- | 53 |
| [1]124 | 384445106044801 | Alluvial outwash | 10/26/2000<br>(05/05/1989) | 09/18/2003 | 7 | -- | -- | -- | 7,690 | 46 | 66 | 66 |

[1] Long-term network.

[2] X, Tritium sample collected.

[3] X, Measurement used for water-table map (fig. 3).

[4] Below land surface.

Regression models and inspection of hydrographs were used to evaluate temporal trends in water levels of 104 wells, which were measured at least 10 times during 2000–2003. Linear regression models were used to evaluate multiyear trends; multiple linear regression models were used to evaluate seasonal trends; and the water-level response to drought (drought pattern) was identified by inspecting the hydrographs. The period of record was too short or the number of observations was too small for statistical analysis of trends for some wells. Water-level altitude was the dependent (response) variable for both the linear and the multiple linear regression models. The independent (predictor) variable for the linear regression models of multi-year trends was measurement date, as a decimal number equal to the year plus the product of the day of year and number of days in the year. The independent (predictor) variables for the multiple linear regression models of seasonal trends were the harmonic (sine and cosine) transformations of the product of the day of year and the number of days in the year. Linear regression models of multiyear trends of water levels were accepted as statistically significant, when the p-value (probability value) for a two-tailed t-test of the regression coefficient was less than 0.05. Multiple linear regression models of seasonal trends of water levels were accepted as statistically significant, when the p-value for either regression coefficient was less than 0.05.

## Alluvial-Outwash and Till Aquifers

Water-level hydrographs for selected wells in the study area are shown in figures 7–9 to illustrate typical patterns of water-level fluctuations that occurred in the alluvial-outwash and till aquifers during 2000–2003. In general, annual maximum (peak) ground-water levels occur after peak runoff in the late spring to early summer, and annual minimum (low) ground-water levels occur in early spring before snowmelt runoff begins. The water-level hydrographs (figs. 7–9) are grouped by areas, with hydrographs for the area near Buena Vista in figure 7, the area near Browns and Chalk Creeks in figure 8, and the Maysville–Salida area in figure 9. For ease of comparison, the vertical scale of the water-level hydrographs for all wells within each area are equal (fig. 7, vertical scale of 25 ft; fig. 8, vertical scale of 15 ft; and fig. 9, vertical scale of 40 ft). The hydrographs are arranged in order of decreasing water-level altitude (approximate upgradient to downgradient order).

Fluctuations in water levels in the network wells that were measured during the study (figs. 7–9) are assumed to be responses to changes in recharge and discharge conditions. Water levels in some of the wells had linear trends (fig. 7—well 12; fig. 8—well 60), seasonal patterns (fig. 7—wells 8, 22, and 17; fig. 8—wells 55, 68 and 69; fig. 9—44, 38, 33, and 84), or both (fig. 7—well 12). A drought pattern, a variation of a seasonal pattern, was identified in hydrographs for about one-half of the wells. The drought pattern likely was caused by lower than normal seasonal recharge from losing streams and surface-water

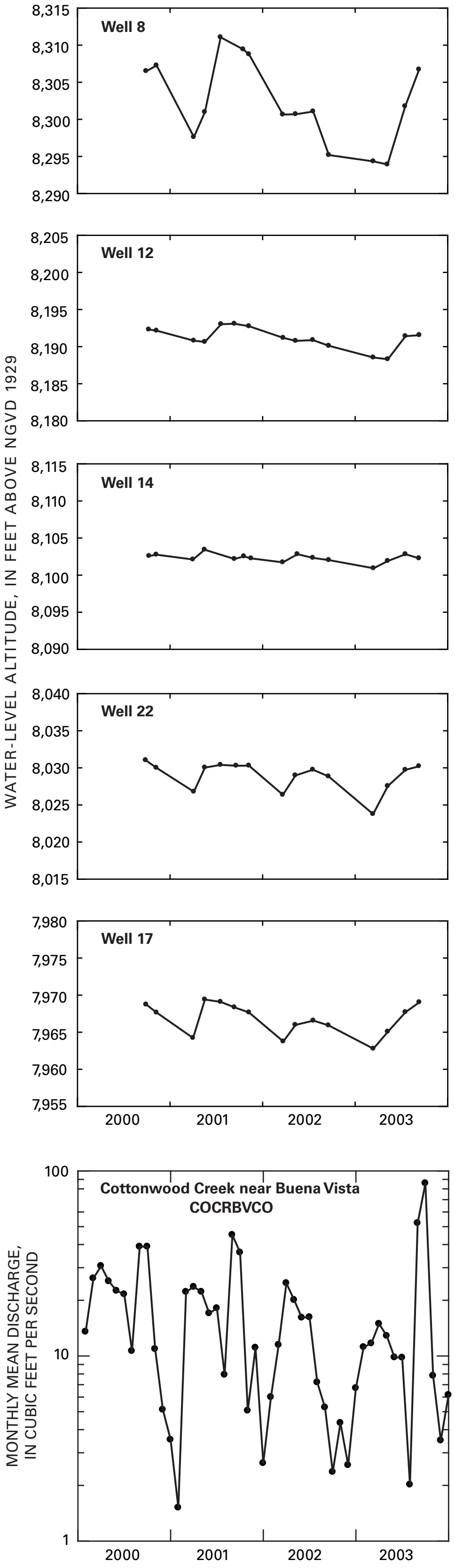


**Figure 7.** Water levels in the alluvial-outwash aquifer near and discharge of Cottonwood Creek near Buena Vista, Colorado, 2000–2003.

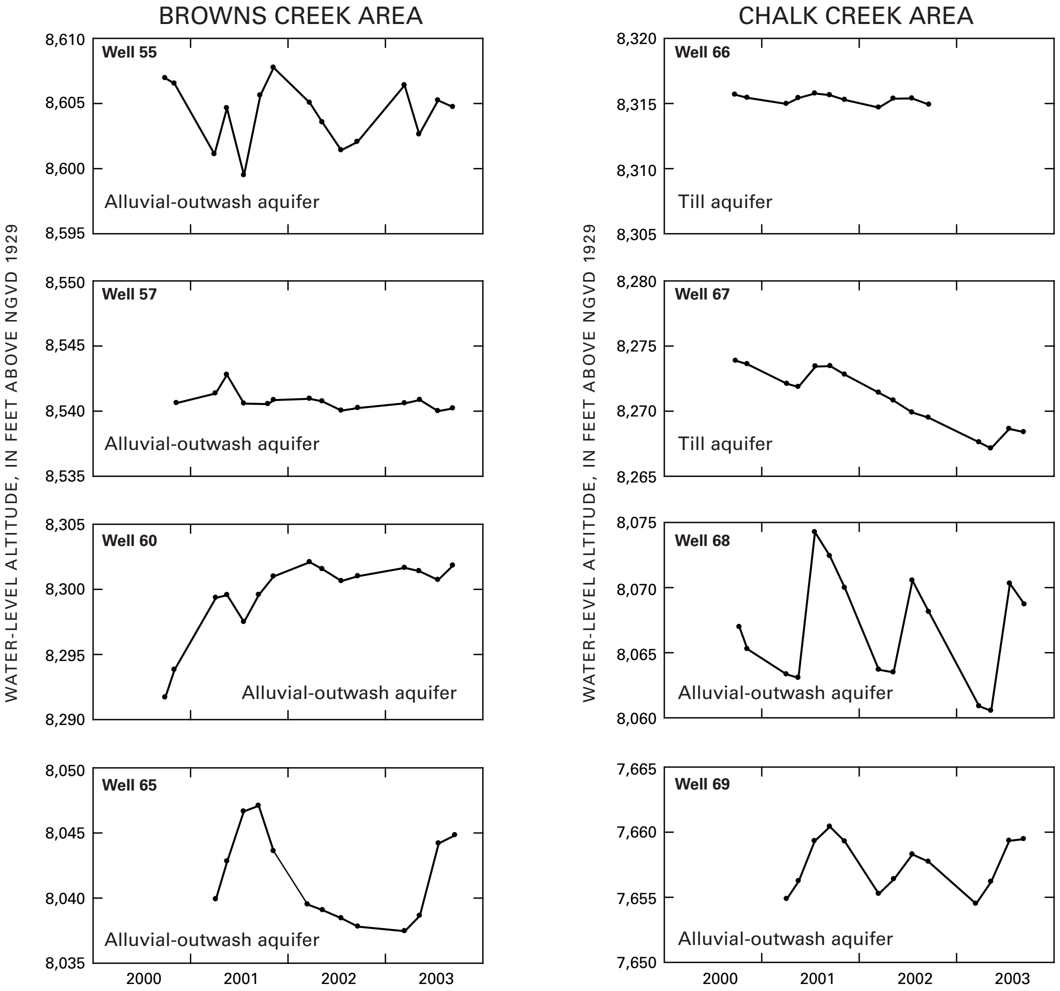


**Figure 8.** Water levels in the alluvial-outwash and till aquifers in the Browns Creek–Chalk Creek area, Colorado, 2000–2003.

diversions during the summer of 2002. The drought pattern is illustrated in the water-level hydrographs for selected wells (fig. 7—wells 8 and 12; fig. 8—well 65; fig. 9—wells 44, 38, 33, 84, 72, and 79).

Although water-level changes are a complex function of aquifer properties and recharge and discharge conditions, some inferences about the cause of the fluctuations can be made based on temporal trends and patterns. Simple linear trends, either upward or downward, indicate that water levels in the aquifer are responding to long-term (longer than seasonal) changes in recharge and discharge conditions. Relatively constant water levels (fig. 7 —well 14 and fig. 8 — well 57) with relatively small-amplitude seasonal changes may indicate that (1) the well is distant (spatially or temporally) from areas in which recharge and discharge occur, (2) recharge and discharge rates are in equilibrium, or (3) water levels in the well are not responsive to water-level changes in the aquifer. Relatively large-amplitude seasonal changes in water levels indicate that the well is in or near an area in which ground-water recharge or discharge, or both, vary seasonally. Relatively large seasonal water-level changes are likely in areas in which the alluvial-outwash aquifer is recharged by a losing stream or by infiltration of surface water diverted for irrigation or in which pumping rates vary seasonally.

Results from the trend analyses of water levels for the alluvial-outwash and till aquifers are summarized in table 4. The linear and seasonal trends and the drought pattern are not mutually exclusive. Linear trends were significant for 33 of 81 wells in the alluvial-outwash aquifer and one of three wells in the till aquifer. Water levels for wells 60 and 54 had upward trends of 2.37 and 10.39 ft/yr, respectively (table 4), which implies a decrease in discharge or an increase in recharge, or both. Water levels for 32 wells had downward trends that ranged from –0.52 to –12.2 ft/yr (table 4), which implies an increase in discharge or a decrease in recharge, or both. Seasonal trends of water levels were significant for 38 wells in the alluvial-outwash aquifer and 1 well in the till aquifer (table 4), as indicated by multiple linear regression models of water-level altitude as a harmonic function of measurement date. Water-level response to the drought of 2002 (drought patterns) were

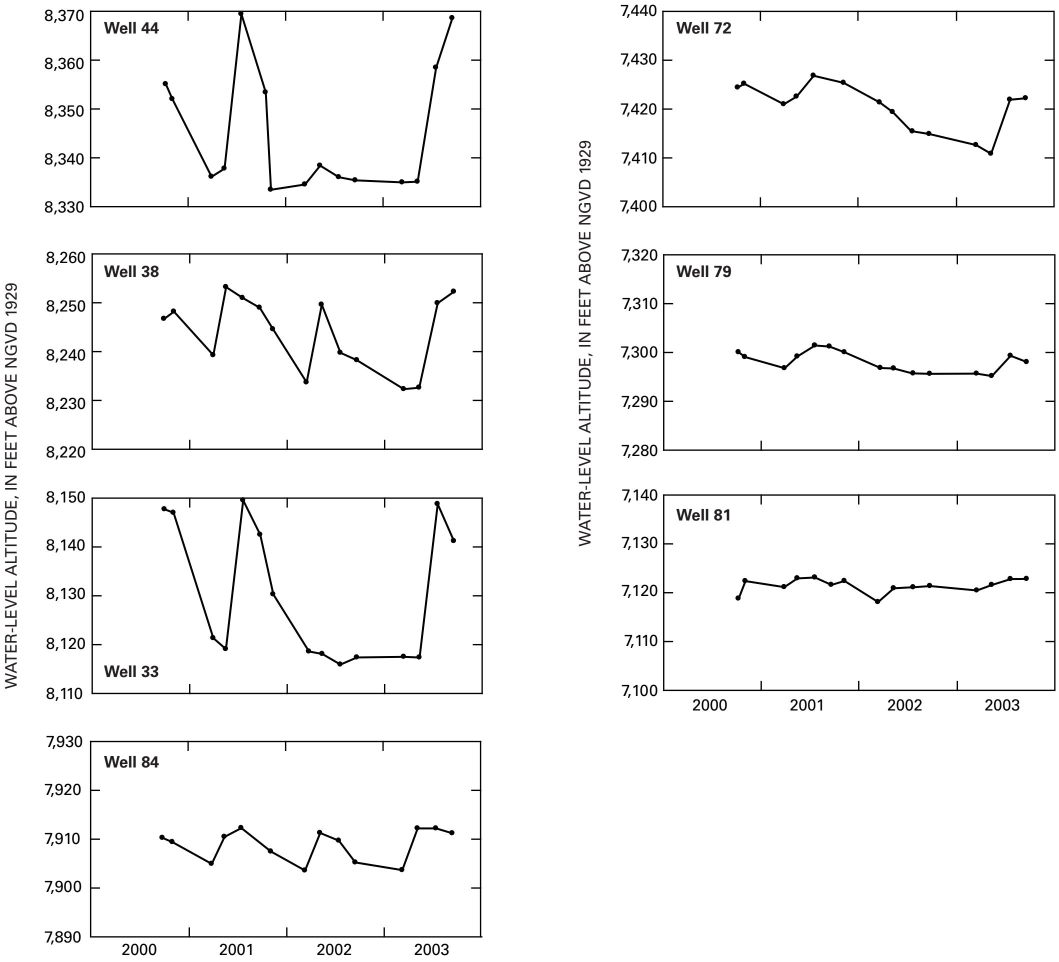


**Figure 9.** Water levels in the alluvial-outwash aquifer, Maysville-Salida area, Colorado, 2000–2003.

identified by inspection of hydrographs in water levels for 52 wells in the alluvial-outwash aquifer and 1 well in the till aquifer (table 4). Water levels for 19 wells had no significant linear or seasonal trends. The absence of linear trends for water levels in 49 wells during September 2000 to September 2003 (table 4) does not infer the absence of pre-September 2000 trends in water levels. The drought pattern was identified in water-level hydrographs for 10 wells that did not have statistically significant linear trends or seasonal patterns. The drought pattern is a temporary disruption of a normal seasonal pattern, which may have affected the tests for statistical significance of linear trends and seasonal patterns.

During 2002, the mean discharge of Cottonwood Creek near Buena Vista (fig. 7, site COCRBVCO) was about 10 ft$^3$/s, which was about 44 percent less than the mean discharge of about 18 ft$^3$/s during 2001 (Colorado Division of Water Resources, 2005b). Water levels in selected wells near Cottonwood Creek near Buena Vista (fig. 7) show the effects of generally decreasing streamflow (losses or diversions) from 2000 to 2003. Water levels in network well 8, which is located near the western (upgradient) side of the alluvial-outwash aquifer in a likely recharge area, declined more than 15 ft between its peak in the summer of 2001 to its low in the spring of 2003. Downstream, water levels in wells 12 and 14, which are located near Cottonwood Creek, declined only a few feet during the same period. Cottonwood Creek, near wells 12 and 14, is likely a gaining reach where ground water discharges to the stream. Farther downstream, water levels in network wells 22 and 17, which also are located near Cottonwood Creek, had seasonal fluctuations of about 5 ft and only a small decline in the seasonal high and seasonal low water levels during 2002. The relatively large range (5 ft) in seasonal fluctuations is likely caused by a combination of ground-water/surface-water interactions and ground-water withdrawals.

Water levels in the alluvial-outwash and till aquifers in the Browns Creek and Chalk Creek area (fig. 8) also declined in response to decreases in streamflow and surface-water diversions during the drought of 2002. Wells 55, 57, 60, 65, 68, and 69 are completed in the alluvial-outwash aquifer; wells 66 and 67 in the till aquifer. Water levels in wells 66, 67, and 57 had small seasonal fluctuations of a few feet. Water levels in well 67 also showed a downward trend during 2000–2003. Water levels in wells 55, 68, and 69 had relatively large seasonal fluctuations of 5 or more feet. Water-level fluctuations for well 65 (fig. 8)

**Table 4.** Summary of temporal trends in water levels in the alluvial-outwash and till aquifers in and near the study area, September 2000–September 2003.

[--, insufficient data for analysis]

| Network number[1] | Aquifer | Water-level measurements during September 2000–September 2003 | | | Linear trend (feet per year)[2] | Seasonal trend | Drought pattern |
|---|---|---|---|---|---|---|---|
| | | Start date | End date | Number of measurements | | | |
| 1 | Alluvial outwash | 10/08/2000 | 09/11/2003 | 15 | –2.80 | No | Yes |
| 2 | Alluvial outwash | 04/04/2001 | 05/09/2003 | 10 | NST | No | No |
| 3 | Alluvial outwash | 11/09/2000 | 09/11/2003 | 12 | –9.66 | No | No |
| 6 | Alluvial outwash | 10/08/2000 | 09/09/2003 | 15 | NST | Yes | Yes |
| 7 | Alluvial outwash | 09/20/2000 | 09/09/2003 | 15 | –12.20 | No | Yes |
| 8 | Alluvial outwash | 09/28/2000 | 09/09/2003 | 15 | NST | Yes | Yes |
| 9 | Alluvial outwash | 10/09/2000 | 09/09/2003 | 14 | –3.91 | Yes | Yes |
| [3]10 | Alluvial outwash | 09/27/2000 | 09/11/2001 | 5 | -- | -- | -- |
| 11 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | –4.00 | Yes | Yes |
| 12 | Alluvial outwash | 10/08/2000 | 09/10/2003 | 15 | –0.82 | Yes | Yes |
| [3]13 | Alluvial outwash | 9/27/2000 | 9/19/2002 | 11 | NST | No | -- |
| 14 | Alluvial outwash | 10/9/2000 | 9/9/2003 | 15 | NST | No | No |
| 15 | Alluvial outwash | 11/9/2000 | 9/10/2003 | 14 | NST | Yes | No |
| 16 | Alluvial outwash | 9/21/2000 | 9/9/2003 | 15 | –0.78 | No | No |
| 17 | Alluvial outwash | 9/28/2000 | 9/10/2003 | 15 | NST | Yes | Yes |
| 18 | Alluvial outwash | 3/10/2003 | 9/11/2003 | 4 | -- | -- | -- |
| 19 | Alluvial outwash | 10/6/2000 | 9/9/2003 | 15 | –1.92 | No | Yes |
| 20 | Alluvial outwash | 10/6/2000 | 9/9/2003 | 15 | –2.73 | No | Yes |
| 21 | Alluvial outwash | 10/6/2000 | 9/9/2003 | 15 | –4.32 | No | No |
| 22 | Alluvial outwash | 9/26/2000 | 9/9/2003 | 15 | NST | Yes | No |
| [3]23 | Alluvial outwash | 10/09/2000 | 09/17/2002 | 11 | NST | No | -- |
| [3]24 | Alluvial outwash | 11/09/2000 | 09/17/2002 | 9 | -- | -- | -- |
| 25 | Alluvial outwash | 09/27/2000 | 09/09/2003 | 15 | –4.65 | Yes | Yes |
| [3]26 | Alluvial outwash | 09/25/2000 | 09/17/2002 | 11 | –3.78 | No | -- |
| 27 | Alluvial outwash | 04/03/2001 | 09/09/2003 | 13 | NST | Yes | -- |
| 28 | Alluvial outwash | 09/21/2000 | 09/09/2003 | 15 | –1.15 | Yes | Yes |
| [3]29 | Alluvial outwash | 10/06/2000 | 05/09/2002 | 9 | -- | -- | -- |
| 30 | Alluvial outwash | 07/18/2002 | 09/09/2003 | 6 | -- | -- | -- |
| 31 | Alluvial outwash | 11/09/2000 | 09/09/2003 | 14 | –1.60 | No | No |
| 32 | Alluvial outwash | 10/06/2000 | 07/17/2003 | 11 | NST | No | No |
| 33 | Alluvial outwash | 09/28/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 34 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 35 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | –2.02 | Yes | Yes |
| 36 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | –2.13 | Yes | Yes |
| 37 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | –7.20 | Yes | Yes |
| 38 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 39 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | –1.61 | No | No |
| 40 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 41 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 42 | Alluvial outwash | 11/02/2000 | 09/16/2003 | 14 | –1.95 | No | Yes |

**Table 4.** Summary of temporal trends in water levels in the alluvial-outwash and till aquifers in and near the study area, September 2000–September 2003.—Continued

[--, insufficient data for analysis]

| Network number[1] | Aquifer | Water-level measurements during September 2000–September 2003 | | | Linear trend (feet per year)[2] | Seasonal trend | Drought pattern |
|---|---|---|---|---|---|---|---|
| | | Start date | End date | Number of measurements | | | |
| 43 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | NST | No | No |
| 44 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 45 | Alluvial outwash | 10/08/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 49 | Alluvial outwash | 05/08/2003 | 09/10/2003 | 3 | -- | -- | -- |
| 50 | Alluvial outwash | 09/28/2000 | 09/10/2003 | 15 | NST | No | No |
| 51 | Alluvial outwash | 05/17/2001 | 09/10/2003 | 12 | NST | No | No |
| 52 | Alluvial outwash | 05/16/2001 | 09/10/2003 | 12 | NST | No | Yes |
| 54 | Alluvial outwash | 05/17/2001 | 09/10/2003 | 12 | 10.39 | No | No |
| 55 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | NST | Yes | No |
| 56 | Alluvial outwash | 05/08/2003 | 09/10/2003 | 3 | -- | -- | -- |
| 57 | Alluvial outwash | 11/09/2000 | 09/10/2003 | 14 | NST | No | No |
| 58 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | NST | No | Yes |
| 59 | Alluvial outwash | 10/08/2000 | 09/10/2003 | 15 | –0.80 | No | Yes |
| 60 | Alluvial outwash | 09/27/2000 | 09/10/2003 | 15 | 2.37 | No | No |
| 63 | Alluvial outwash | 09/25/2000 | 09/09/2003 | 15 | –0.52 | No | No |
| 64 | Alluvial outwash | 10/06/2000 | 09/09/2003 | 14 | –3.19 | No | No |
| [1]65 | Alluvial outwash | 04/04/2001 | 09/18/2003 | 14 | NST | Yes | Yes |
| [3]66 | Till | 09/22/2000 | 09/19/2002 | 11 | NST | Yes | -- |
| 67 | Till | 09/25/2000 | 09/09/2003 | 15 | –2.22 | No | Yes |
| 68 | Alluvial outwash | 10/08/2000 | 09/11/2003 | 15 | NST | Yes | No |
| 69 | Alluvial outwash | 04/03/2001 | 09/09/2003 | 13 | NST | Yes | No |
| 70 | Alluvial outwash | 07/18/2001 | 07/19/2003 | 6 | -- | -- | -- |
| [3]71 | Alluvial outwash | 10/07/2000 | 09/20/2002 | 3 | -- | -- | -- |
| 72 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 14 | –3.04 | No | Yes |
| 79 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | Yes | Yes |
| 80 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | No | Yes |
| 81 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | No | Yes |
| 82 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | No | Yes |
| 83 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 14 | NST | No | Yes |
| 84 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 14 | NST | Yes | No |
| 85 | Alluvial outwash | 09/27/2000 | 09/17/2003 | 15 | NST | Yes | Yes |
| 86 | Alluvial outwash | 09/27/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 87 | Alluvial outwash | 10/09/2000 | 09/16/2003 | 15 | –12.09 | No | Yes |
| 88 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | NST | Yes | No |
| 89 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 14 | NST | No | Yes |
| [3]90 | Alluvial outwash | 09/26/2000 | 07/16/2001 | 5 | -- | -- | -- |
| 91 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | Yes | Yes |
| 92 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | –1.87 | Yes | Yes |
| 93 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 13 | NST | No | Yes |
| 94 | Alluvial outwash | 09/21/2000 | 09/16/2003 | 15 | –4.11 | No | Yes |

**Table 4.** Summary of temporal trends in water levels in the alluvial-outwash and till aquifers in and near the study area, September 2000–September 2003.—Continued

[--, insufficient data for analysis]

| Network number[1] | Aquifer | Water-level measurements during September 2000–September 2003 | | | Linear trend (feet per year)[2] | Seasonal trend | Drought pattern |
|---|---|---|---|---|---|---|---|
| | | Start date | End date | Number of measurements | | | |
| 95 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | NST | No | Yes |
| 96 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | NST | Yes | Yes |
| 97 | Alluvial outwash | 10/09/2000 | 09/17/2003 | 15 | NST | Yes | Yes |
| 98 | Alluvial outwash | 09/26/2000 | 09/16/2003 | 15 | NST | Yes | Yes |
| 99 | Alluvial outwash | 10/07/2000 | 09/16/2003 | 15 | NST | No | Yes |
| 100 | Alluvial outwash | 09/26/2000 | 09/08/2003 | 15 | NST | Yes | Yes |
| 101 | Alluvial outwash | 09/27/2000 | 09/17/2003 | 15 | –1.92 | No | Yes |
| 102 | Alluvial outwash | 10/07/2000 | 09/17/2003 | 15 | –1.48 | No | Yes |
| 103 | Alluvial outwash | 09/26/2000 | 09/08/2003 | 15 | NST | Yes | Yes |
| [1]104 | Alluvial outwash | 10/25/2000 | 09/17/2003 | 16 | NST | No | Yes |
| 105 | Alluvial outwash | 11/09/2000 | 09/08/2003 | 14 | NST | Yes | Yes |
| [3]106 | Alluvial outwash | 09/28/2000 | 09/18/2002 | 10 | –2.48 | No | -- |
| 107 | Alluvial outwash | 03/24/2003 | 09/10/2003 | 4 | -- | -- | -- |
| 108 | Alluvial outwash | 10/08/2000 | 09/17/2003 | 15 | –11.67 | No | No |
| 117 | Alluvial outwash | 05/09/2003 | 09/17/2003 | 3 | -- | -- | -- |
| [3]118 | Till | 09/21/2000 | 09/21/2000 | 1 | -- | -- | -- |
| [1]119 | Alluvial outwash | 09/18/2001 | 09/17/2003 | 6 | -- | -- | -- |
| [1]120 | Alluvial outwash | 10/25/2000 | 09/16/2003 | 5 | -- | -- | -- |
| [1]121 | Alluvial outwash | 10/25/2000 | 09/17/2003 | 7 | -- | -- | -- |
| [1]122 | Alluvial outwash | 10/26/2000 | 09/18/2003 | 7 | -- | -- | -- |
| [1]124 | Alluvial outwash | 10/26/2000 | 09/18/2003 | 7 | -- | -- | -- |

[1] Long-term water-level network.

[2] Linear trend: NST, no significant trend; positive value indicates an upward trend; negative value indicates a downward trend.

[3] Measurements discontinued.

were similar to those for well 8 (fig. 7) and likely also were a response to decreased streamflow and surface-water diversions during the 2002 drought.

Large decreases in water levels in many wells in the alluvial-outwash aquifer, north of the South Arkansas River Valley between Salida and Maysville (fig. 9), likely are related to the large decrease of streamflow and surface-water diversions during the 2002 drought. Ground-water levels in the South Arkansas River Valley near Salida (fig. 9, well 81) were relatively constant because of good hydraulic connection between the alluvial-outwash aquifer and the Arkansas River and because the area is a ground-water discharge area.

Long-term (multidecade) water-level hydrographs for the study area (fig. 10), although based on at most two measurements per year, generally showed a seasonal (sawtooth) pattern, with water levels increasing in the late spring and summer when streamflow is greatest, and then decreasing during the fall and winter. The sawtooth pattern likely is an artifact of measurement frequency. Locations of selected long-term water-level observation wells are shown in figure 1. The water-level hydrographs are arranged in order of decreasing water-level altitude, approximately in downgradient order. During the drought of 2002, water levels in some of the long-term water-level monitoring wells either did not recover during the spring/summer or had peaks that were substantially smaller than those in previous years. With the return to more typical streamflow conditions in 2003, water levels in some wells recovered but others continued a downward trend through 2003. Well 120, which is located in the Maysville area, had long-term water-level fluctuations of about 20 ft. Wells 65, 121, 122, and 124, which are located relatively close to the downgradient end (discharge area) for the regional ground-water system, had relatively stable long-term water-level trends until about 2002–2003. Wells 104 and 119, which are located near the Arkansas River and near Salida,

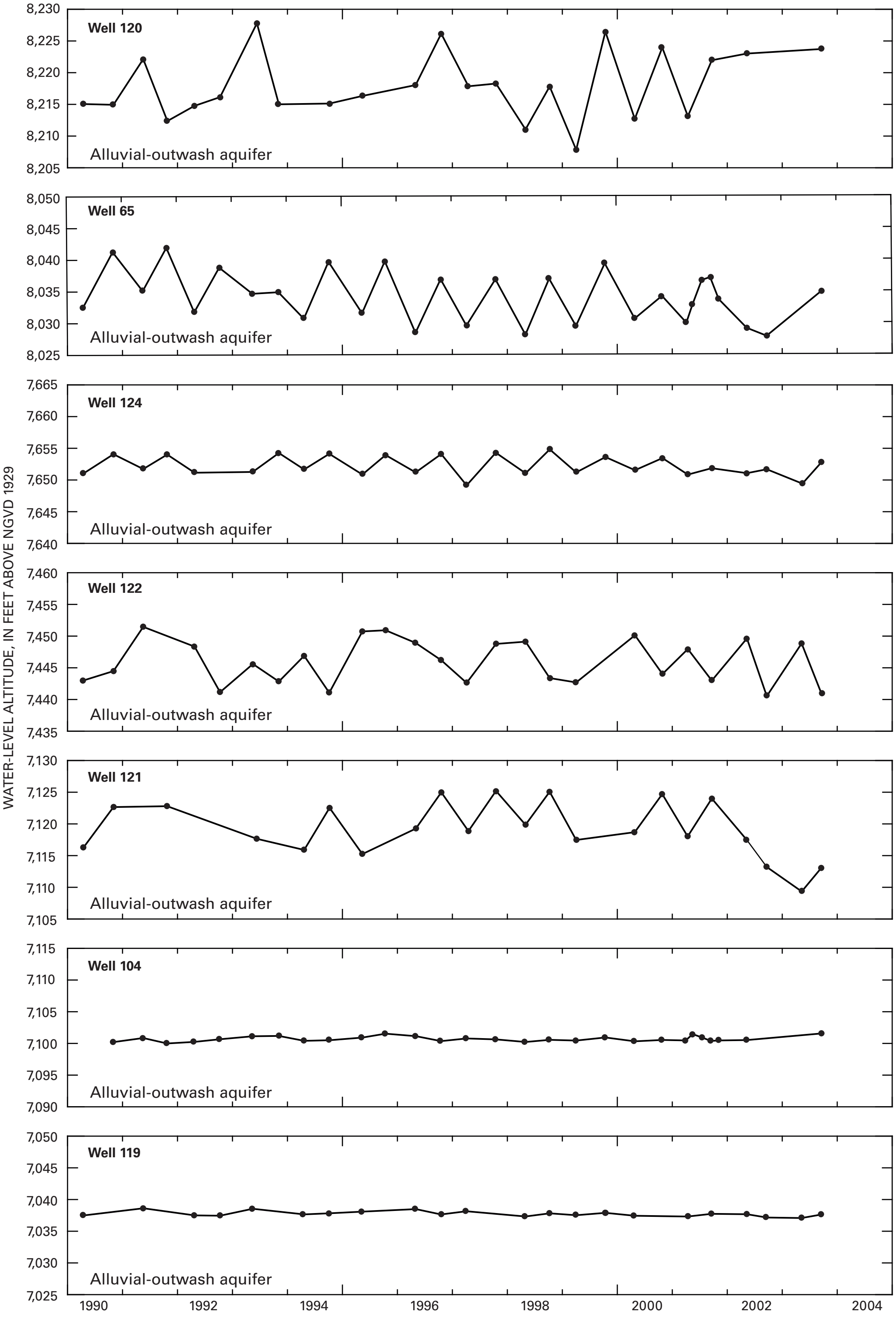


**Figure 10.** Water levels in selected long-term observation wells in Chaffee County, Colorado, 1990–2003.

showed no apparent long-term water-level trend, likely because of the hydraulic connection between the alluvial-outwash aquifer and the Arkansas River and their location in a ground-water discharge area.

## Basin-Fill Aquifer

Hydrographs of water-level altitudes during 2000 to 2003 are shown in figure 11 for five selected wells completed in the basin-fill aquifer in the area northwest of Salida. Hydrographs in figure 11 are plotted at a vertical scale of 25 ft for ease of comparison and are arranged in order of decreasing water-level altitude.

Water levels for well 46, which is near the upgradient end (western side) of the basin-fill aquifer (fig. 1), had a slight upward trend of 0.37 ft/yr from 2000 to 2003 and relatively low seasonal fluctuations, indicating that well 46 is not near a seasonally variable recharge source (table 5). Seasonal water-level fluctuations for well 113, which is located near a stream channel, were about 20 ft in 2001 but only about 10 ft in 2002. The decrease in amplitude of seasonal water-level fluctuation for well 113 probably results from a decrease in streamflow and recharge during 2002. Water levels in well 110, which is near the downgradient end (eastern side) of the basin-fill aquifer, had a downward trend of –2.86 ft/yr. Water levels in well 109 also had a downward trend of –1.01 ft/yr, though the trend was not statistically significant at a p-value of 0.05. Water levels in wells 109 and110 may be responding to long-term changes of recharge or discharge conditions. Water levels in well 114, which also is near the downgradient end of the basin-fill aquifer, did not have a linear trend or strong seasonal pattern, indicating that the well may be located near a regional discharge area for the basin-fill aquifer and is in an area distant (spatially or temporally) from sources of recharge.

Linear trends and seasonal and drought patterns were present in water levels of wells completed in the basin-fill aquifer (fig. 11 and table 5). Linear water-level trends were significant for 8 of 19 wells, which had been measured at least 10 times during September 2000–September 2003. Upward linear water-level trends of 0.37 and 0.3 ft/yr were identified for wells 46 and 73, respectively. Downward linear water-level trends that ranged from –1.3 to –4.06 ft/yr were identified for seven wells (table 5). Water levels had significant seasonal patterns in nine wells and drought patterns in six wells.

## Bedrock Aquifer

Water levels in well 5, which is completed in the bedrock aquifer near the study area, decreased about 4.4 ft between September 2000 and September 2002 and had a significant downward linear trend of about 1.65 ft/yr but did not have a statistically significant seasonal trend (table 5). Because water-level measurements in well 5 were discontinued in September 2002, the amount of water-level recovery in 2003 is unknown. Water levels in wells 115 and 116, which are completed in the bedrock aquifer near the study area, did not have significant linear or seasonal trends during the study period and were not significantly affected by the 2002 drought.

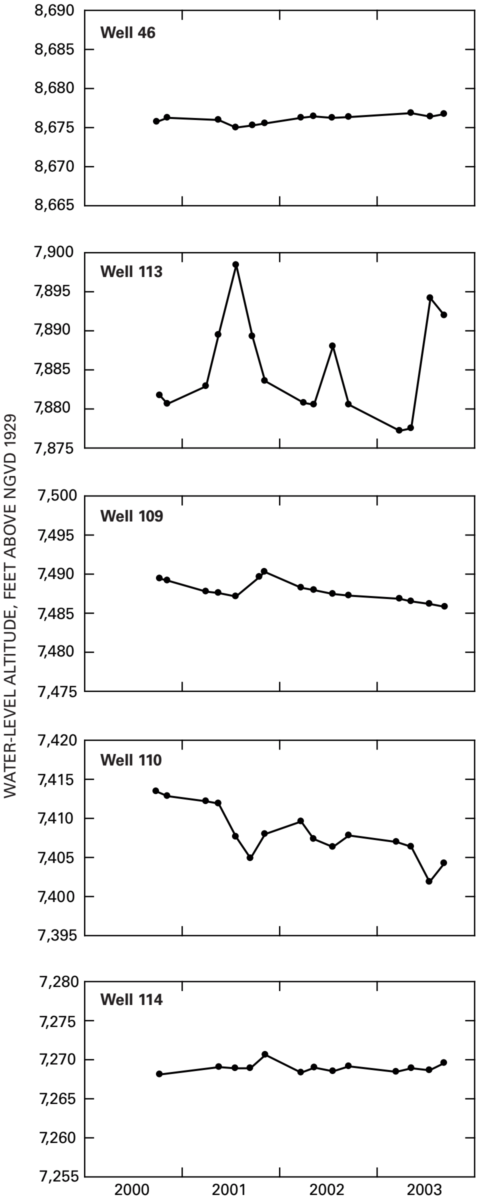


**Figure 11.** Water levels in the basin-fill aquifer northwest of Salida, Colorado, 2000–2003.

## Configuration of the Water Table

The water table is defined as the surface in an unconfined water body at which the pressure is atmospheric (Lohman and others, 1972, p. 14). It is defined by the levels at which water stands in wells that penetrate the water body just far enough to

**Table 5.** Summary of temporal trends in water levels in the basin-fill and bedrock aquifers in and near the study area, September 2000–September 2003.

[--, insufficient data for analysis]

| Network identification number[1] | Aquifer | Water-level measurements during September 2000–September 2003: Start date | End date | Number of measurements | Linear trend (feet per year)[2] | Seasonal trend | Drought pattern |
|---|---|---|---|---|---|---|---|
| [1]4 | Basin fill | 10/26/2000 | 09/10/2003 | 18 | –2.91 | No | No |
| [3]5 | Bedrock | 09/27/2000 | 09/18/2002 | 11 | –1.65 | No | -- |
| 46 | Basin fill | 09/27/2000 | 09/08/2003 | 13 | 0.37 | No | No |
| 47 | Basin fill | 10/08/2000 | 09/18/2003 | 15 | NST | Yes | No |
| 48 | Basin fill | 09/28/2000 | 09/10/2003 | 15 | –2.36 | No | Yes |
| 53 | Basin fill | 09/25/2000 | 09/10/2003 | 15 | –1.30 | No | No |
| 61 | Basin fill | 09/29/2000 | 07/15/2003 | 15 | –3.22 | Yes | Yes |
| 62 | Basin fill | 09/29/2000 | 09/10/2003 | 15 | NST | No | Yes |
| 73 | Basin fill | 09/28/2000 | 09/17/2003 | 14 | 0.30 | Yes | No |
| 74 | Basin fill | 10/07/2000 | 09/17/2003 | 15 | NST | Yes | No |
| 75 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | NST | Yes | No |
| 76 | Basin fill | 10/07/2000 | 09/10/2003 | 15 | NST | Yes | No |
| 77 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | NST | Yes | No |
| 78 | Basin fill | 09/28/2000 | 09/17/2003 | 15 | NST | Yes | No |
| 109 | Basin fill | 10/08/2000 | 09/11/2003 | 15 | NST | No | No |
| 110 | Basin fill | 09/25/2000 | 09/08/2003 | 15 | –2.86 | No | No |
| [3]111 | Basin fill | 09/27/2000 | 11/06/2000 | 2 | -- | -- | -- |
| 112 | Basin fill | 09/20/2000 | 09/09/2003 | 15 | –4.06 | No | Yes |
| 113 | Basin fill | 10/08/2000 | 09/09/2003 | 15 | NST | Yes | Yes |
| 114 | Basin fill | 10/08/2000 | 09/08/2003 | 13 | NST | No | Yes |
| 115 | Bedrock | 09/27/2000 | 09/10/2003 | 15 | NST | No | No |
| 116 | Bedrock | 09/27/2000 | 09/10/2003 | 15 | NST | No | No |

[1] Long-term water-level network.

[2] Linear trend: NST, no significant trend; positive value indicates an upward trend; negative value indicates a downward trend.

[3] Measurements discontinued.

hold standing water. If wells penetrate an unconfined aquifer to depths greater than a few feet, then the water level in the well may stand above or below the water table if an upward or downward component of ground-water flow exists.

The generalized configuration of the water table during September 2003 is shown in figure 3. The time period, September 2003, was selected because water levels had been measured in most wells in the network and because water levels in most wells had fully or partly recovered from the effects of the 2002 drought. Water-level data from selected wells in the monitoring network (table 3), supplemented with water levels for 10 selected wells from the SEO database, were used to prepare a contour map of the generalized configuration and altitude of the water table. Water levels in the 10 selected wells from the SEO database reportedly were measured between June 1999 and March 2002. Although these 10 water-level measurements were made before September 2003, they also preceded the 2002 drought and were considered representative of normal conditions. Although most of the wells measured during this study generally penetrate to depths substantially below the water table, the potentiometric surface defined by water levels in these wells probably is not substantially different from the water table because the aquifers are relatively transmissive. Water-level data were restricted to shallow wells when both shallow and deep wells were nearby. Land-surface altitudes at network wells were estimated from topographic maps. Land-surface altitudes at selected wells from the SEO database were estimated from 30-m digital elevation models (DEM) (U.S. Geological Survey, 2004). The approximate land-surface altitudes for selected locations near the Arkansas

River and South Arkansas River also were estimated from 30-m DEMs (U.S. Geological Survey, 2004) and also were used to contour the water table.

The contour interval for the water table was 100 ft. Potential errors in water-level altitudes may be as large as 40 ft because of error in estimating land-surface altitude. The water table is a continuous surface and is shown crossing the boundaries between the alluvial-outwash and basin-fill aquifers (fig. 3). Locally, perched water-table conditions may occur where permeable water-bearing deposits (older alluvial deposits as much as 700 ft topographically higher than modern streams) directly overlie relatively impermeable deposits, which in turn overlie permeable water-bearing deposits. Within the study area, the minimum altitude of the water table is about 7,000 ft near Salida, and the maximum is about 9,000 ft northwest of Buena Vista. The water-table surface generally slopes from west to east toward the Arkansas River. In the southern part of the study area, water-table contours bend upstream across the South Arkansas River Valley, indicating ground-water flow toward the valley. Generally, the water-table contours are more widely spaced in the alluvial-outwash aquifer, for example near Buena Vista, than in the basin-fill aquifer, for example south of Browns Creek (fig. 3). The lateral distance between contours is an indicator of the relative transmissivity of the alluvial-outwash and basin-fill aquifers. The more widely spaced contours indicate a smaller hydraulic gradient and infer that the alluvial-outwash aquifer is more transmissive than the basin-fill aquifer.

## Depth to Water

The depth to water (fig. 12) during September 2003 was calculated using the geographic information system ArcMap (Environmental Research System Institute, 1999–2003) as the difference between the altitude of the land surface and the altitude of the water table (fig. 3). Land-surface altitude was estimated from the 30-m DEM (U.S. Geological Survey, 2004). The depth to water (fig. 12) is less than 25 ft below land surface in the Buena Vista area, in part of the area between Browns and Chalk Creeks, northwest of Salida, and along portions of the Arkansas and South Arkansas Rivers. The estimated depth to water is greater than 300 ft below land surface on some stream divides and alluvial fans along the western side of the study area.

## Direction of Ground-Water Flow

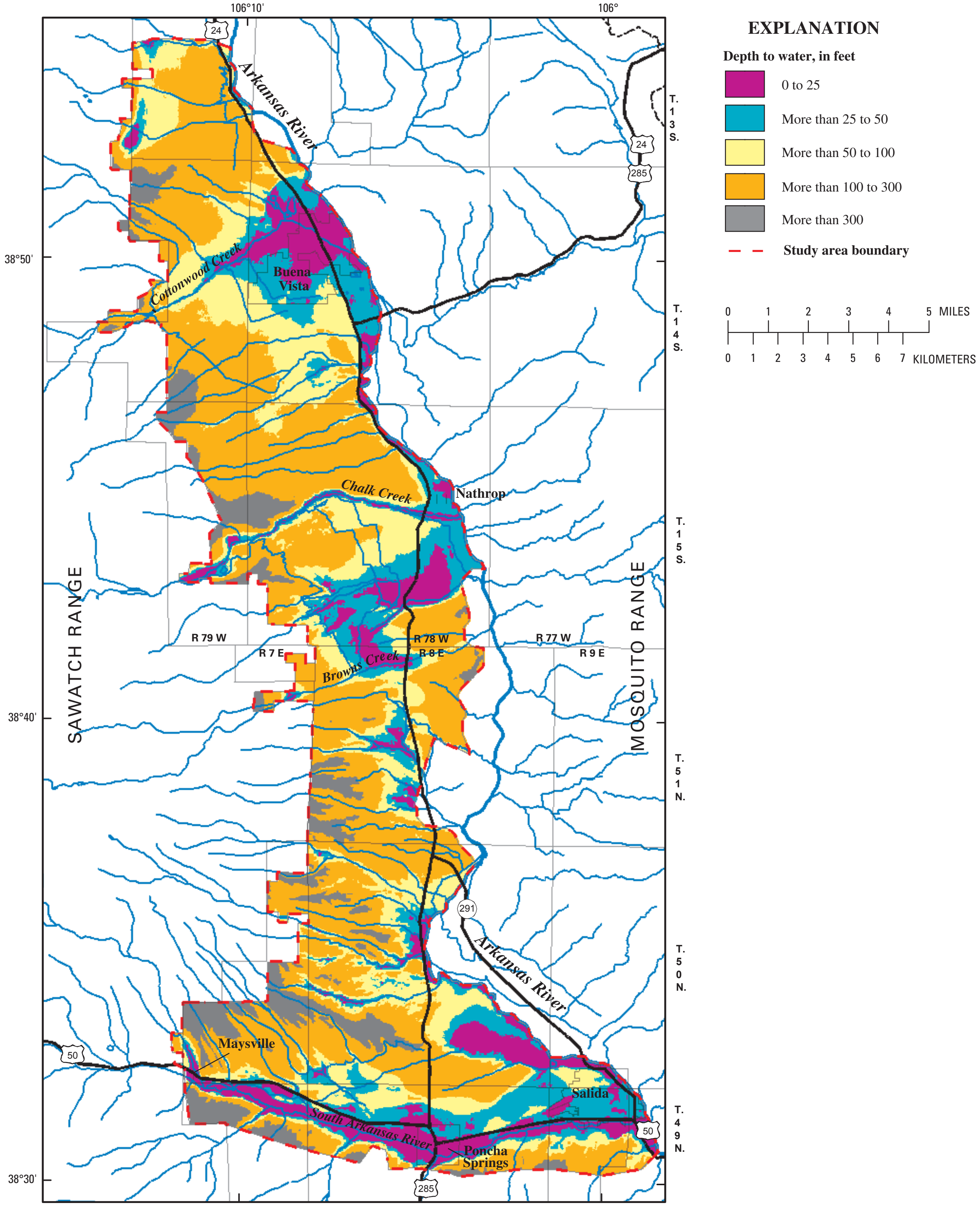
The direction of ground-water flow in the upper part of the alluvial-outwash and basin-fill aquifers can be estimated from the configuration of the water table (fig. 3). The direction of flow in a homogeneous and isotropic porous media is perpendicular to the potentiometric (water-table) contours and in the direction of decreasing hydraulic head (water-table altitude). Because the alluvial-outwash and basin-fill aquifers are neither homogeneous nor isotropic, the direction of ground-water flow estimated in this manner is only approximate. In general, ground-water flow is from west to east across the study area toward the Arkansas River. Near the southern end of the study area, ground-water flow converges from the north and south and discharges to the South Arkansas River Valley, as indicated by the upgradient deflections of the water-table contours (fig. 3).

The hydraulic gradient is the difference in water levels (potential) divided by the distance over which that difference in potential occurs. If consistent units of measurement are used, hydraulic gradient is a dimensionless ratio. A related concept is that of grade, which commonly is expressed in inconsistent units—for example, feet per mile (ft/mi). [A technical definition of hydraulic gradient is included in the Glossary.] Because hydraulic conductivity can vary in three dimensions and hydraulic gradient is inversely proportional to the hydraulic conductivity, hydraulic gradients also can vary in three dimensions. Hydraulic gradients occur in the horizontal and vertical directions. In alluvial sands, permeability (hydraulic conductivity) generally is largest in the direction of deposition, intermediate in the direction laterally perpendicular to deposition, and smallest in the direction vertically perpendicular to deposition (Pettijohn and others, 1973, p. 523–533).

Generally, horizontal-hydraulic gradients, as estimated from the product of the contour interval (100 ft) and the distance between adjacent water-table contours (fig. 3), are smaller in the permeable alluvial-outwash aquifer than in the relatively impermeable basin-fill aquifer. In the Buena Vista area, where the water table is in the alluvial-outwash aquifer, the horizontal-hydraulic gradient is about 0.02 (equivalent to a grade of about 100 ft/mi), whereas the horizontal-hydraulic gradient is about 0.08 (equivalent to a grade of about 400 ft/mi) in the basin-fill aquifer about 6 mi northwest of Salida. Because hydraulic gradient is proportional to the ratio of specific discharge (the rate of ground-water flow through a unit area) to hydraulic conductivity, the difference in horizontal hydraulic gradients is an indication that hydraulic conductivity of the alluvial-outwash aquifer is larger than that of the basin-fill aquifer.

Potential differences (differences in water levels at different depths of measurement) can develop in aquifers where there is a substantial component of vertical flow. Vertical-hydraulic gradient is the ratio of the differences in water levels (potential differences) to the length of the interval separating the points of measurement. Areas within the alluvial-outwash and basin-fill aquifers where vertical flow is likely and where vertical hydraulic gradients may be large include recharge areas, in which losing streams flow across permeable deposits near the mountains, and regional ground-water discharge areas, in which flow is upward.

Vertical-hydraulic gradients can be measured by constructing piezometer (well) nests with the piezometers open to different intervals in the aquifer. A piezometer is a small-diameter well, generally with an open end or short screened interval that is designed to measure the hydraulic pressure at a point in the aquifer. Precise measurement of relative measuring-point heights or altitudes is needed to minimize error and allow determination of small gradients. Because



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 12.** Generalized depth to water in the study area, September 2003.

these types of well nests have not been constructed in the study area and because altitudes of measuring points generally were estimated from topographic maps with 40-ft contour intervals, vertical hydraulic gradients could not be estimated.

Comparisons of water-level altitudes from May through September 2003 for a relatively shallow well (well 52) with water-level altitudes from two nearby and relatively deep wells (wells 49 and 56) show that substantial differences in water-level altitudes do occur with depth in the study area (table 6). The minimum distance separating the open intervals of paired shallow and deep wells can be approximated as the distance between the bottom of the open interval of the shallow well and the top of the open interval of the deep well. The depth to the bottom of the screened interval of well 52 (the shallow well) is 130 ft. Depths to the top of the screened intervals of wells 49 and 56 are 360 and 340 ft, respectively. These wells are located near Browns Creek on the western side of the study area (fig. 1). The vertical-hydraulic potentials ranged from about 232 to about 249 ft (table 6). The existence of a hydraulic potential does not prove that vertical flow is occurring, only that a potential for flow exists. Because the water-level altitude in well 52 (the shallow well) was higher than water-level altitudes in wells 49 and 56 (the deep wells), there is a potential for downward flow of ground water in this area. Downward flow in this area is consistent with the conceptual and preliminary models of cross-sectional ground-water flow (fig. 6).

### Effects of the 2002 Drought on Water Levels

Because of the drought in 2002, streamflow (snowmelt runoff) was less than normal, rights to divert surface water were often out of priority, and surface water was not always available for diversion when in priority. Consequently, water levels generally declined in 2002 because ground-water recharge from losing streams and irrigation also was less than normal. Water-level declines in the network wells were as much as 40 ft between July 2001 and July 2002 (fig. 13*A*). The largest declines (15 to 40 ft) occurred in wells near Maysville and in the irrigated area northwest of Poncha Springs. Intermediate water-level declines of 5 to 15 ft occurred in wells northwest of Salida, in the area where Cottonwood Creek enters the valley, near Buena Vista, and in the area near where highway 285 crosses Browns Creek. Water levels rose as much as 8 ft in a few wells. Because snowpack in the Sawatch Range was greater in 2003 than in 2002, streamflow in the study area was greater and ground-water levels in most wells began to recover in 2003. Ground-water levels recovered (rose) as much as 33 ft between July 2002 and July 2003 (fig. 13*B*). During 2003, water levels in many wells, with the exception of wells near Buena Vista and a few scattered wells throughout the rest of the study area, recovered to near pre-2002 levels. The relative rapid decline and recover of water levels in the alluvial-outwash and basin-fill aquifers indicate that the ground-water system in the Buena Vista–Salida area generally is sensitive (responsive) to changes in recharge and discharge conditions.

## Age of Ground-Water Recharge

Tritium samples were collected from 13 wells that were completed in the alluvial-outwash aquifer and from two wells that were completed in the basin-fill aquifer (table 7). Although tritium, an isotope of the hydrogen atom, is produced naturally in small amounts in the stratosphere, nuclear weapons testing during the 1950s and 1960s greatly increased the atmospheric concentrations of tritium. Concentrations of naturally produced (pre-nuclear age) tritium in precipitation ranged from 1 to 5 tritium units (TU), or about 3.19 to 15.95 picocuries per liter (pCi/L) (1 TU = 3.19 pCi/L) (U.S. Geological Survey, 2003). Natural and anthropogenic tritium combine with elemental hydrogen and oxygen to form a molecule of tritiated water that falls to the ground as precipitation. The half-life of tritium is 12.32 years (Lucas and Unterweger, 2000), which is the time required for the amount of the tritium isotope to decrease to one-half its initial value. Because tritium decays at a predictable rate and atmospheric testing of nuclear weapons during the 1950s and 1960s substantially increased concentrations of tritium in precipitation, it is possible to estimate the time the ground water has been isolated from the atmosphere by measuring concentrations of tritium in ground water. The presence or absence of tritium in water can qualitatively identify the time of last contact of ground water with atmospheric water (recharge) as pre-1953 (pre-modern) or post-1953 (post-modern). Theoretically, concentrations of tritium in water recharged before 1953 and sampled in 2001 should be less than 1 pCi/L (about 0.3 TU) or about one-sixteenth of initial values of 3.19 to 15.95 pCi/L.

Tritium concentrations in samples collected during September and October 2001 from 13 wells in the alluvial-outwash aquifer ranged from less than 1 to 31.7 TU (less than 1 to 101 pCi/L) (table 7). Error in tritium concentrations (table 7) averaged about 6.7 percent of the concentration. Tritium concentrations in samples collected during September and October 2001 from two wells in the basin-fill aquifer ranged from less than 1 to 7.5 TU (less than 1 to 23.9 pCi/L) (table 7).

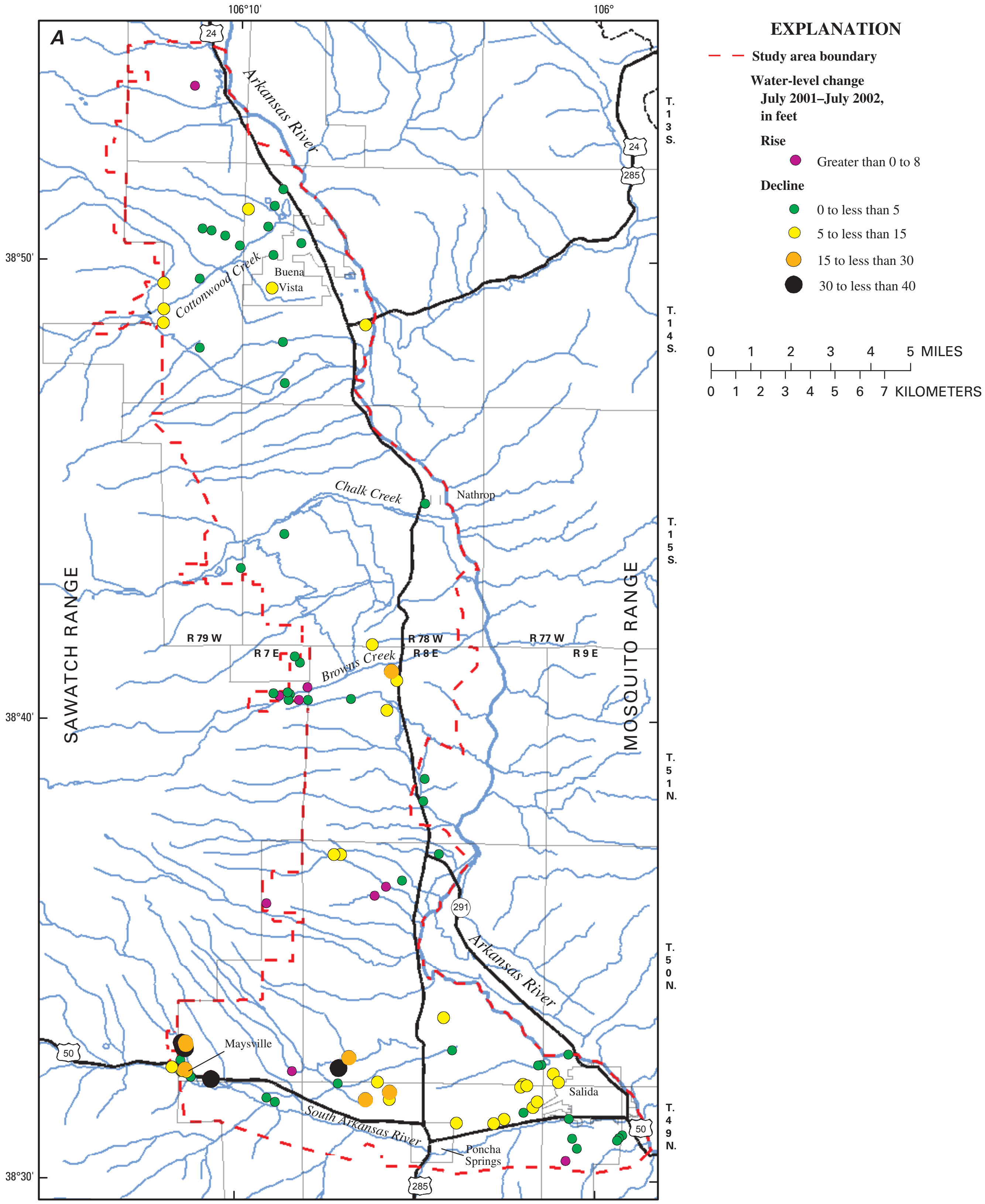
Figures 14*A*–*D* show estimated concentrations of tritium in precipitation and ground water in the study area during 1953–2001. Concentrations of tritium in precipitation in the study area (fig. 14*A*–*D*) were estimated from monthly concentrations of tritium in precipitation at Albuquerque, New Mexico (International Atomic Energy Agency, 2004). Because tritium concentrations vary with latitude, the concentrations of tritium in precipitation at Albuquerque were adjusted for the approximate 3.5-degree difference in the latitude of Albuquerque and the latitude near the middle of the study area. Rozanski and others (1991) estimated that the average latitudinal variation of tritium in the northern hemisphere is approximately 0.023 log TU per degree latitude. The latitudinal correction to tritium concentrations in precipitation at Albuquerque for the study area is about 0.08 log TU (0.023 log TU/degree latitude times 3.5 degrees of latitude $\cong$ 0.08 log TU). The tritium concentrations in precipitation for the study area, shown in figures 14*A*–*D*, were smoothed using a 12-month

**Table 6.** Estimated differences in water-level altitudes between selected wells near Browns Creek, May–September 2003.

| Network well number (table 3) | Date of measurement | Depth to top of screen (feet)[1] | Depth to bottom of screen (feet)[1] | Depth to bottom of well (feet)[1] | Relative depth | Estimated altitude of land surface (feet)[2] | Depth to water (feet)[1] | Altitude of water level (feet)[2] | Altitude of top of screen (feet)[2] | Altitude of bottom of screen (feet)[2] | Altitude of bottom of well (feet)[2] | Direction of vertical gradient | Estimated vertical hydraulic potential (feet) | Estimated vertical separation of screened intervals (feet) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | 05/08/03 | 70 | 130 | 200 | Shallow | 8,520 | 151 | 8,369 | 8,450 | 8,390 | 8,320 | Down | 232 | 215 |
| 49 | 05/08/03 | 360 | 560 | 560 | Deep | 8,535 | 398 | 8,137 | 8,175 | 7,975 | 7,975 | | | |
| 52 | 07/15/03 | 70 | 130 | 200 | Shallow | 8,520 | 148 | 8,372 | 8,450 | 8,390 | 8,320 | Down | 236 | 215 |
| 49 | 07/15/03 | 360 | 560 | 560 | Deep | 8,535 | 399 | 8,136 | 8,175 | 7,975 | 7,975 | | | |
| 52 | 09/10/03 | 70 | 130 | 200 | Shallow | 8,520 | 149 | 8,371 | 8,450 | 8,390 | 8,320 | Down | 235 | 215 |
| 49 | 09/10/03 | 360 | 560 | 560 | Deep | 8,535 | 398 | 8,137 | 8,175 | 7,975 | 7,975 | | | |
| 52 | 05/08/03 | 70 | 130 | 200 | Shallow | 8,520 | 151 | 8,369 | 8,450 | 8,390 | 8,320 | Down | 242 | 240 |
| 56 | 05/08/03 | 340 | 540 | 540 | Deep | 8,490 | 363 | 8,127 | 8,150 | 7,950 | 7,950 | | | |
| 52 | 07/15/03 | 70 | 130 | 200 | Shallow | 8,520 | 148 | 8,372 | 8,450 | 8,390 | 8,320 | Down | 249 | 240 |
| 56 | 07/15/03 | 340 | 540 | 540 | Deep | 8,490 | 366 | 8,124 | 8,150 | 7,950 | 7,950 | | | |
| 52 | 09/10/03 | 70 | 130 | 200 | Shallow | 8,520 | 149 | 8,371 | 8,450 | 8,390 | 8,320 | Down | 247 | 240 |
| 56 | 09/10/03 | 340 | 540 | 540 | Deep | 8,490 | 366 | 8,124 | 8,150 | 7,950 | 7,950 | | | |

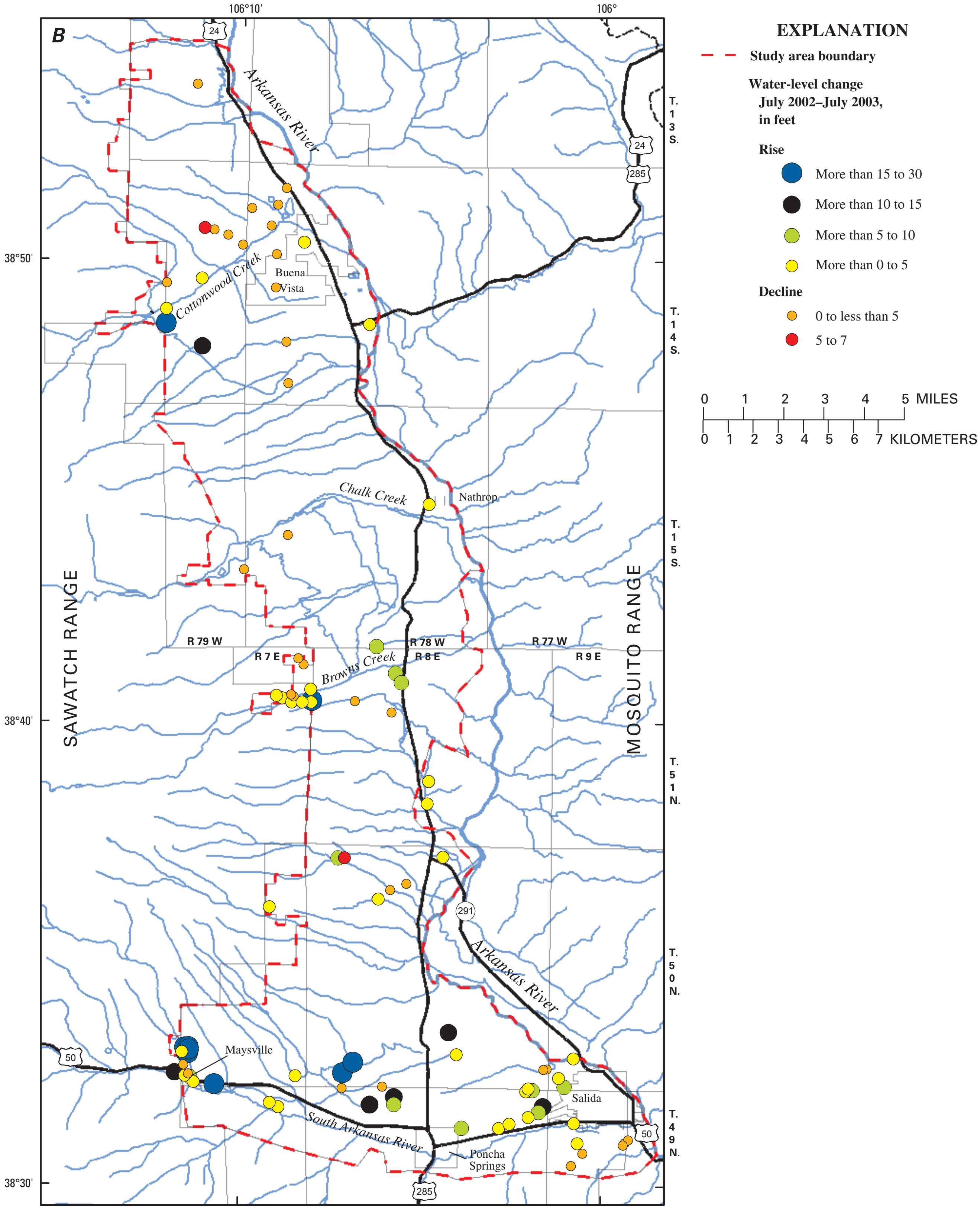
[1] Below land surface.

[2] Altitude is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 13.** Water-level change in the study area, (*A*) between July 2001 and July 2002 and (*B*) between July 2002 and July 2003.



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 13.**—Continued

**Table 7.** Tritium concentrations in ground-water samples from selected wells and apparent mean age(s) of ground-water recharge.

[<, less than; >, greater than]

| Network well number (table 3) | Aquifer | Well depth (feet)[1] | Depth to water (feet)[1] | Sample date | Tritium concentration (tritium units) | Tritium concentration (picocuries per liter) | Tritium counting error (two standard deviations) (picocuries per liter) | Approximate mean age(s) of ground-water recharge (years before 2001) |
|---|---|---|---|---|---|---|---|---|
| | | | | Buena Vista area | | | | |
| 14 | Alluvial outwash | 100 | 2.46 | 10/18/01 | < 1 | < 1 | 0.58 | >48 |
| 19 | Alluvial outwash | 86 | 51.24 | 10/17/01 | 31.7 | 101 | 6.4 | 30, 45 |
| 20 | Alluvial outwash | 180 | 86.66 | 09/12/01 | 29.4 | 93.8 | 6.4 | 30, 45 |
| 21 | Alluvial outwash | 178 | 107.1 | 09/14/01 | 20.8 | 66.2 | 4.5 | 29, 45–48 |
| 25 | Alluvial outwash | 151 | 84.14 | 09/13/01 | 11.0 | 35.2 | 2.6 | 13–18 |
| | | | | Browns Creek-Chalk Creek area | | | | |
| 50 | Alluvial outwash | 182 | 106.64 | 09/13/01 | 2.2 | 7.0 | 0.58 | >48 |
| 55 | Alluvial outwash | 323 | 49.38 | 09/18/01 | 15.7 | 50.2 | 3.2 | 23–26, 46–48 |
| [2]55 | Alluvial outwash | 323 | 49.38 | 09/18/01 | 16.2 | 51.8 | 3.2 | 23–26, 46–48 |
| 58 | Alluvial outwash | 85 | 37.26 | 09/14/01 | 9.9 | 31.7 | 1.9 | 3, 13–19, 48 |
| 59 | Alluvial outwash | 60 | 23.90 | 09/18/01 | 11.0 | 35.2 | 2.6 | 13–19, 48 |
| 64 | Alluvial outwash | 345 | 178.99 | 09/12/01 | 2.0 | 6.5 | 0.58 | >48 |
| | | | | Maysville area | | | | |
| 40 | Alluvial outwash | 199 | 65.62 | 10/17/01 | 10.9 | 34.9 | 2.6 | 13–18 |
| 41 | Alluvial outwash | 199 | 57.55 | 10/16/01 | 10.5 | 33.6 | 1.9 | 13–18 |
| 43 | Alluvial outwash | 175 | 105.30 | 09/19/01 | 11.2 | 35.8 | 2.6 | 13–18 |
| | | | | Northwest of Salida | | | | |
| 109 | Basin fill | 164 | 50.36 | 10/16/01 | 7.5 | 23.9 | 1.6 | 1 |
| 110 | Basin fill | 365 | 65.11 | 09/13/01 | <1 | <1 | 0.58 | >48 |

[1] Below land surface.

[2] Duplicate sample.

moving average. Theoretical concentrations of tritium for the ground-water samples (straight lines in figure 14*A*–*D*) for 1953–2001 were calculated from sample concentrations in 2001 and the half-life of tritium (12.32 yr).

Assuming a positive displacement model without mixing, the points of intersection of a ground-water tritium-concentration line with the precipitation tritium-concentration curve are the mean ages of ground-water recharge. If a ground-water tritium-concentration line does not intersect the precipitation tritium-concentration curve, then the recharge occurred before 1953. Because the ground water produced by a well could result from mixing of ground water with different tritium concentrations (different ages of recharge), the estimated age is qualified as the apparent mean age of ground-water recharge.

Tritium concentrations in ground water from wells in the Buena Vista area ranged from less than 1 to 31.7 TU (table 7). The apparent mean age of ground-water recharge for samples from wells in this area (fig. 14*A*) ranged from about 13 to more than 48 years before 2001, and apparent mean dates of ground-water recharge ranged from pre-1953 to 1988. Although well 14 is located near Cottonwood Creek and it was expected that water from this well would have tritium concentrations that indicated a relatively recent recharge, ground water from well 14 (fig. 14*A*) was recharged before 1953. Possible explanations for this apparent conflict between the age of ground water and the proximity of well 14 to a potential source of recent recharge (Cottonwood Creek) are that the well is located in a ground-water discharge area (gaining stream reach) or the well obtains water from a stagnation point in the flow system. In either case, little mixing of recent surface water with low tritium concentrations with ground water would occur. Water levels in well 14 (fig. 7) were relatively stable during September 2000–September 2003, with only small seasonal fluctuations that are likely related to stream stage. However, water levels for well 14 did not show the drought response typical of wells located in areas in which ground water is recharged by a losing stream (fig. 7—well 8). The apparent mean age of ground-water recharge for the sample from well 25 ranged from 13 to 18 years before 2001 (1983–88). The apparent mean age of ground-water recharge for the samples from wells 19 and 20 was 30 or 45 to 48 years before 2001 and from well 21 was 29 or 45 years before 2001. Because well 21 is upgradient from wells 19 and 20, the tritium concentrations of the water from these wells indicate that the ground water was recharged during 1971–72. The tritium concentration in water from well 21 was about one-third smaller than tritium concentrations in water from wells 19 and 20, indicating that recharge at well 21 is more recent than recharge at wells 19 and 20.

Tritium concentrations in ground water from wells in the Browns Creek–Chalk Creek area ranged from 2 to 16.2 TU (table 7). The estimated mean age of ground-water recharge from wells 50 and 64 was more than 48 years before 2001 (pre-1953) (fig. 14*B*). Well 50 is located south of Browns Creek, and depth to water was about 107 ft below land surface at the time of sample collection. The pre-1953 date of ground-water recharge for the sample from well 50 indicates that the aquifer is not well connected to Browns Creek, a perennial stream and potential source of recharge. Well 64 is located on the stream divide between Browns and Chalk Creeks and is upgradient from nearby sources of surface-water recharge (streams and surface-water diversions). The range in apparent mean ages of ground-water recharge from wells 55, 58, and 59 (fig. 14*B*) was not definitive because the lines for tritium concentration in ground water intercept the precipitation tritium-concentration curve at more than one point. The apparent mean ages of recharge were about 23–26 or 46–48 years before 2001 (1975–78 or 1953–55) for well 55; about 3, 13–19, or 48 years before 2001 (1998, 1982–88, or 1953) for well 58 ; and about 13–19, or 48 years before 2001 (1988, 1982, or 1953) for well 59. Wells 55, 58, and 59 are near but upgradient from Browns Creek near the western side of the study area. Well 55 is 323 ft deep, and wells 58 and 59 are relatively shallow, 85 and 60 ft deep, respectively. Although the apparent mean ages of recharge are not definitive, it is likely that the shallow ground water (wells 58 and 59) was recharged more recently than the deeper ground water (well 55). Because water-level altitudes at wells 55, 58, and 59 were higher than the altitude of Browns Creek, this indicates that stream reach probably is a gaining reach and that the source of ground-water recharge at these wells likely is from precipitation.

Tritium concentrations in ground water from three wells near Maysville ranged from 10.5 to 11.2 TU, and the apparent mean age of ground-water recharge ranged from about 13 to 18 years before 2001 (1983–88) (fig. 14*C* and table 7). The depths of wells 40, 41, and 43 are 199, 199, and 175 ft, respectively. About the time of sample collection in September and October 2001, the depths to water in the wells were about 66, 58, and 105 ft below land surface, respectively. The likely source of recharge to wells 40, 41, and 43 is surface water from the North Fork of the South Arkansas River. Water-level changes in the vicinity of these wells during September 2001–September 2003 (fig. 14*A* and 14*B*) show that, locally, the aquifer near the North Fork drains rapidly during a drought and recovers quickly when streamflow returns to normal. If ground water at these wells was recharged from local stream loss, then tritium concentrations should be about 5 TU, indicating recent recharge. In the general vicinity of these wells, water-level altitudes for these and nearby network wells indicate that ground-water flow, locally, is toward the North Fork. Because hydraulic gradients are toward the stream, recently recharged water along the stream would tend to drain back into the stream and not mix with older ground water.

Tritium concentrations in ground water from wells 109 and 110, which are completed in the basin-fill aquifer about 7 mi northwest of Salida (fig. 1), were 7.5 and less than 1 TU, respectively. The approximate mean ages of ground-water recharge were about 1 year before 2001 (2000) at well 109 and more than 48 years before 2001 at well 110 (pre-1953) (fig. 14*D* and table 7). Well 109 is 164 ft deep, near a stream channel, and had a depth to water of about 50 ft below land surface when the sample was collected. Well 110 is 365 ft deep, located on a stream divide, and had a depth to water of about 65 ft below land surface when the sample was collected. The source of recharge at well 109 is probably from infiltration of surface water. On the basis of differences in the concentrations of dissolved solids and major ions in samples from wells 109 and 110, which are discussed later in this report, well 110 may be located in an area in which older (pre-1953) ground water flows upward from deeper in the basin-fill aquifer.

## Sustainability of Ground-Water Supplies

If the population of Chaffee County increases as projected to 27,500 residents by 2030, then an additional 4,000 to 5,000 wells may be needed for domestic and household use. Because most of the additional population increase likely will reside in the study area, additional demand likely will be placed on the ground-water resources of the study area.

Resource managers and planners need to know the potential effects of increased ground-water pumping on the sustainability of the water supply. Sustainability of ground-water resources means different things to different people. Alley and others (1999, p. 2) define ground-water sustainability as “development and use of ground water in a manner that can be maintained for indefinite time without causing unacceptable environmental, economic, or social consequences.” The definitions of unacceptable environmental, economical, and social consequences are subjective and are likely to be perceived differently by different individuals and organizations. Some unintentional consequences that are likely to be considered unacceptable by most individuals and organizations include depletion of surface-water supplies, excessive drawdown of water levels at existing wells, ground-water depletion (mining), degradation of water quality, and drying up of wetlands and riparian areas. The purpose of this preliminary assessment of sustainability is to estimate the potential effects of projected increases in ground-water withdrawal for domestic and household use on ground-water storage and to identify other potential effects of increased pumping. Because the rates of ground-water recharge and discharge in the study area are not known, evaluation of the potential effects of increased ground-water withdrawals is difficult. Estimates of current (2003) and projected (2003–2030) ground-water withdrawals and consumptive use by domestic and household wells are compared to the estimated volume of drainable ground water stored within 300 ft of land surface.

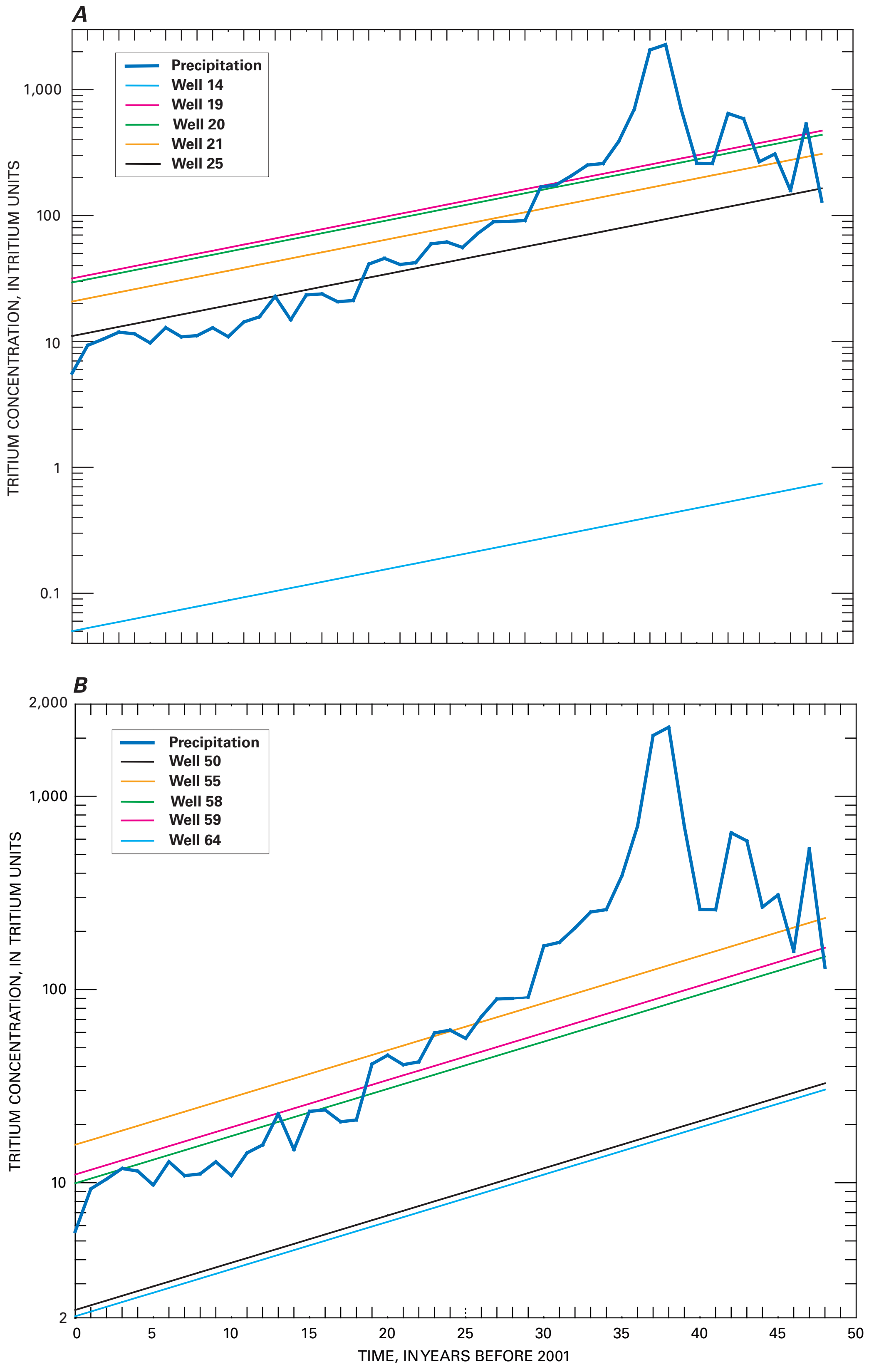


**Figure 14.** Estimated tritium concentrations in precipitation and ground water, from (*A*) the alluvial-outwash aquifer in the Buena Vista area, Colorado, 1953–2001; (*B*) the alluvial-outwash aquifer in the Browns Creek–Chalk Creek area, Colorado, 1953–2001; (*C*) the alluvial-outwash aquifer in the Maysville area, Colorado, 1953–2001; and (*D*) the basin-fill aquifer northwest of Salida, Colorado, 1953–2001.

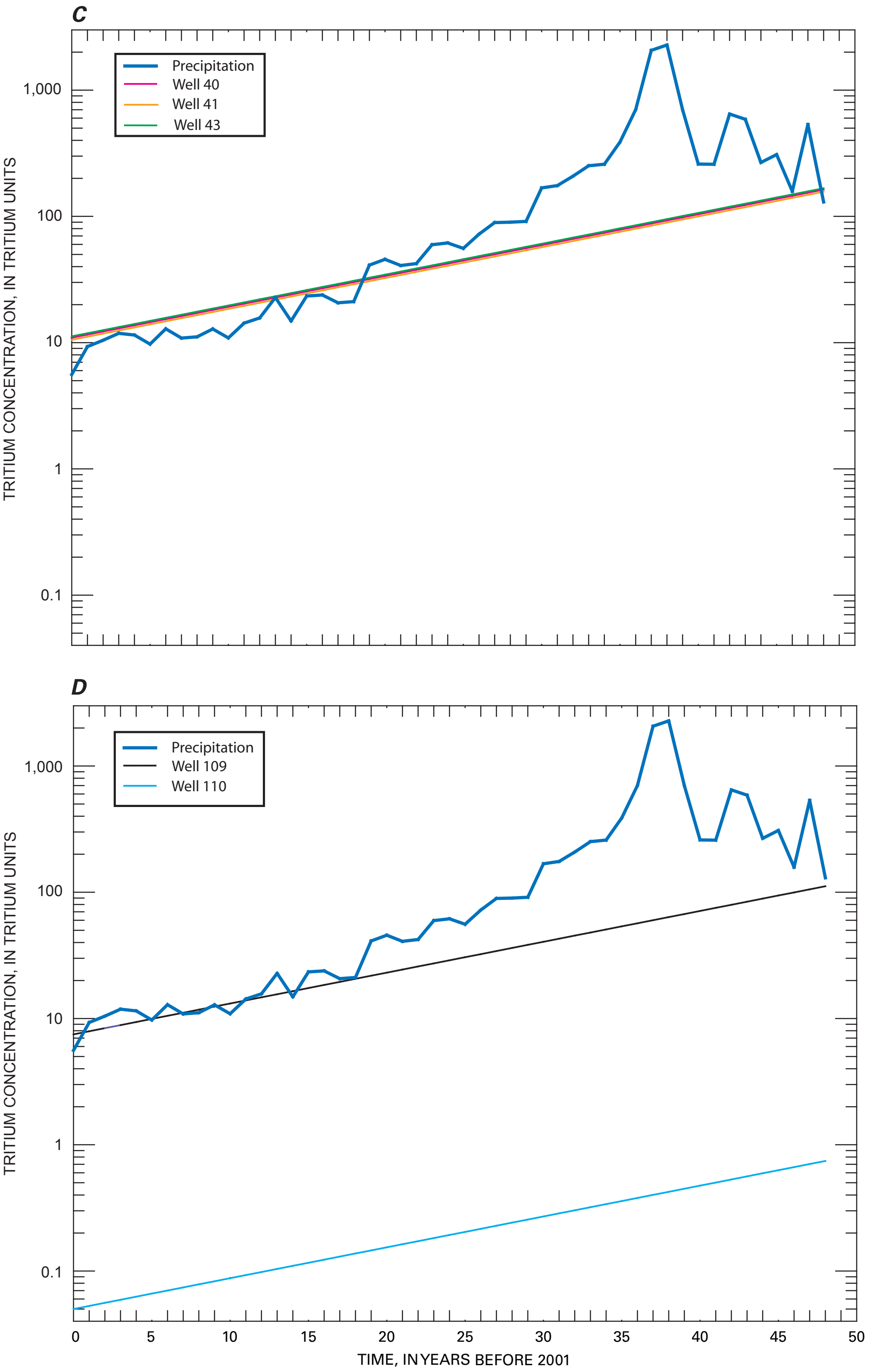


**Figure 14.**—Continued

## Ground-Water Storage

Storage is the amount of water stored in an aquifer. There are two types of storage in an aquifer, drainable storage and compressible storage. Drainable storage is the amount of water that can be drained from an aquifer. Compressible storage is the amount of water stored in the aquifer due to the compressibility of the aquifer and of the water itself. The compressible storage of an unconfined aquifer generally is small in comparison to its drainable storage. Changes in water levels in an aquifer indicate changes in storage. Changes in atmospheric pressure, overburden pressure, earth tides, and seismic waves also can cause short-term changes in water levels, primarily in confined or semiconfined aquifers, that are related to aquifer compressibility. In an unconfined aquifer, rising water levels indicate an increase in storage, and falling water levels indicate a decrease in storage.

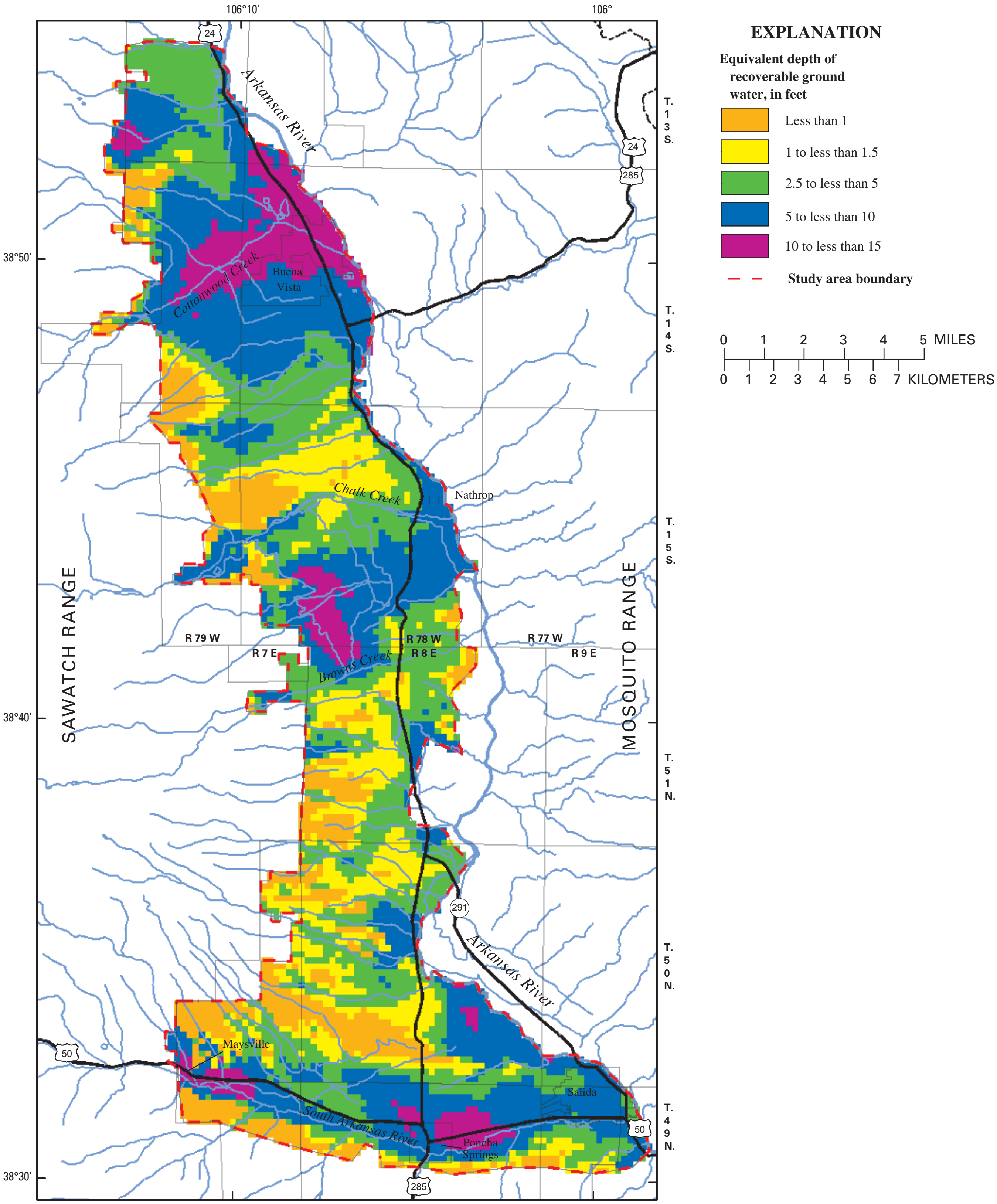
Pumping of ground water from a well causes changes in a ground-water system. As a well begins pumping from an unconfined aquifer, water initially is removed from storage in the well and near the well, and a cone of depression forms in the water table. [Cone of depression is defined in the Glossary.] As pumping continues, the cone of depression expands farther from the well until, eventually, the cone of depression either captures a source of additional water or contacts an impermeable (no-flow) boundary. If a source of additional water can be captured that is equal to the pumping rate, then the cone of depression stops expanding. If the additional source is a stream, then pumping will cause stream depletion. If the cone of depression reaches an impermeable boundary, then part of the water produced by the well will be supplied by additional drawdown or ground-water mining (depletion of ground water stored in the aquifer). The ultimate response of a ground-water system to ground-water withdrawal is an increase in recharge to the aquifer, a decrease in discharge from the aquifer, a change in storage in the aquifer, or, most likely, a combination of these responses.

Augmentation plans are required for most water-supply wells in the study area to mitigate stream depletion caused by ground-water withdrawals; however, depletion of ground-water storage still may occur. Depletion of ground-water storage could have the largest effects on ground-water sustainability in areas in which the alluvial-outwash and basin-fill aquifers are not readily recharged by infiltration from streams or infiltration of surface-water diversions because recharge from precipitation is small to nonexistent. Estimates of the volume of ground water in storage can provide a basis for evaluating the potential effects from increases of ground-water withdrawals on the sustainability of the ground-water resource.

The volume of drainable ground water stored in an aquifer can be estimated as the product of aquifer specific yield (fig. 4) and saturated thickness. Drainable ground water means water that will drain by gravity to a well. The equivalent depth of drainable ground water equals the volume of drainable ground water divided by area. The equivalent depth of drainable ground water in the study area within 300 ft of land surface during September 2003 (fig. 15) was calculated using ARC/INFO (version 8.0.2, Environmental Systems Research Inc., 1982–2000) and ArcMap (version 8.3, Environmental Systems Research Inc., 1999–2003). The volume of drainable ground water was calculated for three separate intervals of 0–100 ft, 100–200 ft, and 200–300 ft. These volumes were summed and divided by area to obtain the equivalent depth of drainable ground water stored in the upper 300 ft of the alluvial-outwash, basin-fill, and till aquifers. Saturated thickness of the upper 300 ft of the subsurface was calculated using ARC/INFO (version 8.0.2, Environmental Systems Research Inc., 1982–2000) as 300 ft minus the difference between the altitude of the September 2003 water-table surface (fig. 3) and the land-surface altitude. Land-surface altitude was estimated from the 30-m DEM (U.S. Geological Survey, 2004).

The area around Buena Vista is estimated to have an equivalent depth of drainable ground water of about 10–15 ft within 300 ft of land surface (fig. 15). Depths to water in this area generally are within 25–100 ft of land surface, and the specific yield, which was estimated on the basis of lithologic descriptions, is about 20 percent. In areas in which the basin-fill aquifer is the uppermost aquifer, or in which the saturated thickness of the alluvial-outwash aquifer is relatively thin, equivalent depth of drainable ground water generally is 5 to 10 ft within 300 ft of land surface. Estimated specific yield and saturated thickness of the basin-fill aquifer generally is smaller than that of the alluvial-outwash aquifer. Areas with less than 1 ft of drainable ground water primarily are in areas where the depth to water is relatively deep, along the southern and western sides of the study area and along topographic highs west-northwest of Salida. Generally, these areas also correspond to areas in which there were fewer network monitoring wells and consequently less confidence in the altitude of the water-table surface (fig. 3).

The volume of drainable ground water in storage in the 149-mi$^2$ study area, which is summarized in table 8, was estimated by multiplying the equivalent depth of drainable water (fig. 15) and area. The estimated volume of drainable ground water within 300 ft of land surface in September 2003 was 472,000 acre-ft. This is equivalent to an average depth of water of about 5 ft throughout the 149-mi$^2$ study area. Crouch and others (1984, p. 19) estimated about 3.8 million acre-ft of storage in a 200-mi$^2$ study area, which is a uniform equivalent depth of water of about 30 ft. Crouch and others (1984) used a uniform specific yield of 0.15 and uniform saturated thickness of 200 ft to estimate the volume of drainable ground water. The volume of drainable ground water was estimated for the analysis in this report using variable specific-yield values and variable saturated thickness. Figure 15 can be used to estimate the volume of drainable ground water within 300 ft of land surface that is available to supply wells in a given area by multiplying the estimated equivalent depth of drainable ground water by the size of the area of interest. For example, the volume of drainable ground water underlying a 35-acre parcel on which a proposed domestic well is anticipated to withdraw 1 acre-ft/yr of ground water can be calculated as the product



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 15.** Estimated equivalent depth of drainable ground water in the upper 300 feet of alluvial-outwash, till, and basin-fill aquifers in the study area, September 2003.

**Table 8.** Estimated volume of drainable water in the upper 300 feet of alluvial, outwash, till, and basin-fill deposits in the study area, September 2003.

| Depth interval (feet) | Estimated volume of drainable water (thousand acre-feet) |
|---|---|
| 0 to 100 | 86 |
| 100 to 200 | 169 |
| 200 to 300 | 217 |
| Total (0 to 300) | 472 |

of the area (35 acres) and the equivalent depth of drainable water estimated from figure 15. Assuming an equivalent depth of drainable water of 2 ft, the estimated volume of drainable water within 300 ft of land surface underlying the 35-acre parcel is 70 acre-ft (35 acres times 2 ft = 70 acre-ft). Without capture of additional water from outside or recharge within the parcel, withdrawal of 1 acre-ft/yr would deplete the drainable ground water in about 70 years. In areas in which the estimated equivalent depth of drainable water in the upper 300 ft is less than 1 ft, wells likely would need to be deeper than 300 ft to obtain adequate water supplies.

## Potential Effects of Increased Ground-Water Use

Potential effects of projected increases in ground-water withdrawals by an additional 4,000 to 5,000 domestic and household wells include increased capture of surface water from streams and rivers, capture of ground water that normally discharges to streams and rivers, capture of previously rejected recharge (precipitation), capture of ground water that normally discharges to springs and wetlands, and depletion of ground-water storage. Unintended consequences that could result if ground-water depletion (mining) occurs include increased pumping costs, decreased yields for existing wells, and replacement of existing wells that no longer provide sufficient yields.

## Estimated Withdrawals and Consumptive Use by Domestic and Household Wells, 2003–2030

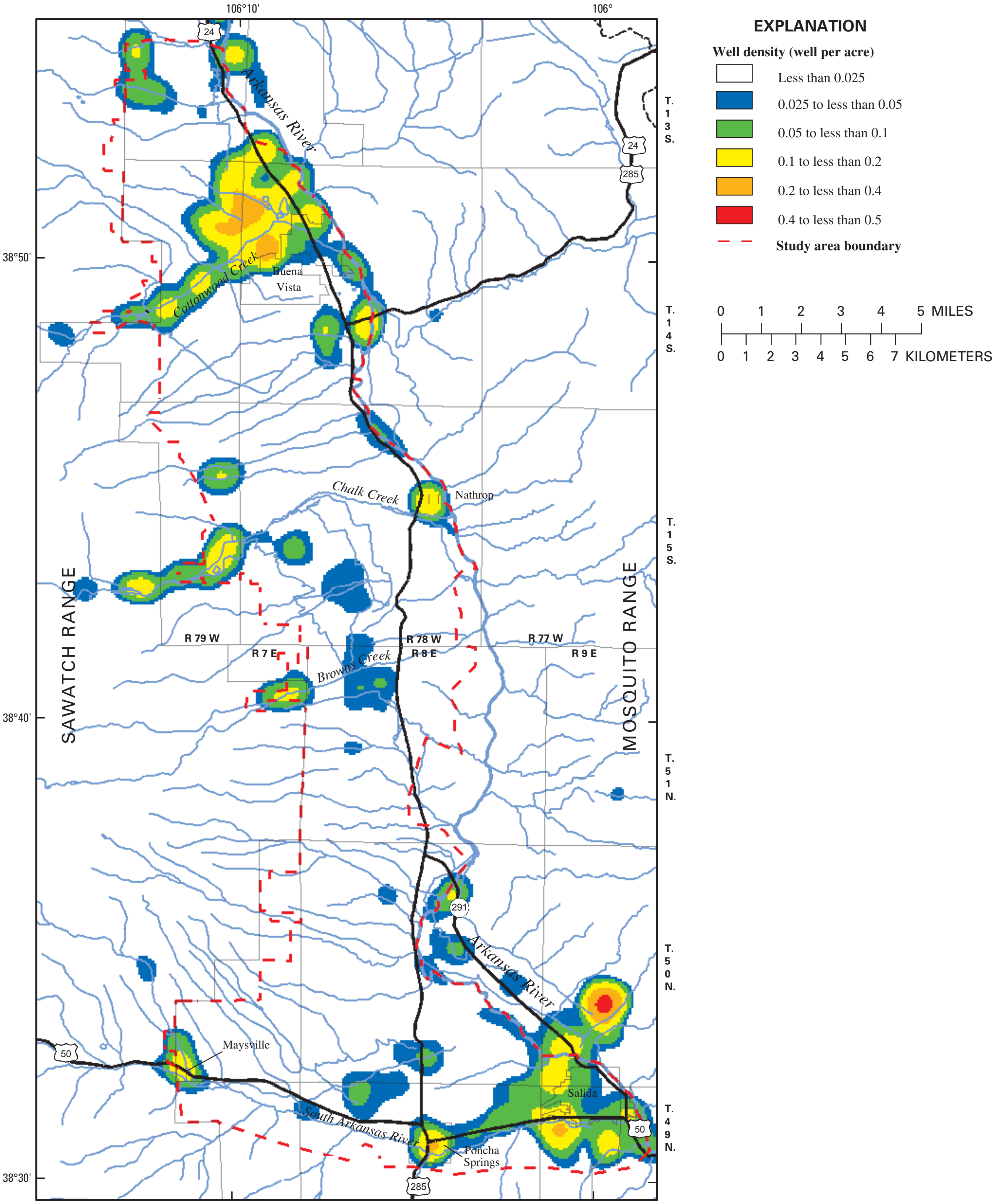
Current (2003) annual rates of ground-water withdrawal by a domestic or household well in the study area is an estimated 0.2 to 0.36 acre-ft/yr per household (Waskom and Neibauer, 2004), which is equivalent to an average rate of about 180 to 320 gal/d. [One acre-ft/yr is about 325,800 gallons per year or about 893 gallons per day.] For purposes of this estimate, it is assumed that a domestic or household well is used to supply water to a single household. The total volume of annual withdrawal for the estimated 3,443 domestic and household wells in Chaffee County during 2003 was an estimated 690 to 1,240 acre-ft (3,443 wells times 0.2 acre-ft/yr per well ≅ 690 acre-ft; 3,443 wells times 0.36 acre-ft/yr per well ≅ 1,240 acre-ft), which is a rate of about 0.6 to 1.1 Mgal/d. By 2030, an additional 800 to 1,800 acre-ft of ground water could be needed to supply 4,000–5,000 additional households. The combined withdrawal for the existing 3,443 wells plus the projected 4,000–5,000 wells is an estimated 1,490 to 3,040 acre-ft/yr. Under current and projected conditions, annual ground-water withdrawals for domestic and household wells are less than 1 percent of the estimated volume of drainable water in the upper 300 ft of unconsolidated deposits in the study area. Augmentation plans, which are required for most wells in the area, are used to replace (to a stream) that part of ground-water withdrawals that are assumed to be consumptively used. Most augmentation plans are based on a consumptive use for domestic-household supply of 10 percent of withdrawal. The remaining 90 percent of domestic-household withdrawals are assumed to be returned to the aquifer through septic systems. The augmentation plans require that the consumptive use be replaced to the system from other sources. If consumptive use is 10 percent of domestic-household withdrawals, then current (2003) consumptive use for domestic-household use is about 69 to 124 acre-ft/yr and projected 2030 consumptive use would be about 149 to 304 acre-ft/yr. In 2003, the UAWCD augmentation plan, which includes about 700 wells, supplied about 116 acre-ft of augmentation water to offset stream depletions (Upper Arkansas Water Conservancy District, 2004). An estimated 800 to 1,200 other wells in the area have private augmentation plans (Terry Scanga, Upper Arkansas Water Conservancy District, Salida, Colorado, written commun., January 12, 2005).

Augmentation plans are required for new water-supply wells permitted in the study area. If the consumptive-use and return rates (10 and 90 percent, respectively) are correct, then stream depletion would be mitigated by required augmentation plans. However, ground-water mining could still occur in those parts of the study area that are not near perennial streams or near areas irrigated with surface-water diversions.

## Well Density and Well Interference

Although ground-water withdrawals for domestic and household use are not a large proportion of the estimated volume of drainable water in the study area, locally, interference between wells could occur where wells are densely spaced. The well density of domestic and household wells in 2003 (fig. 16) is defined as the fractional number of wells per acre, and was computed using ArcMap (Environmental Systems Research Inc., 1999–2003). The inverse of well density is equivalent to the number of acres (lot size) per well.

Well density ranged from 0.2 to 0.4 well per acre in the area northwest of Buena Vista (fig. 16). A well density of 0.4 is equivalent to one well on each 2.5-acre tract and is equivalent to a total of 256 wells per square mile. The estimated combined annual withdrawals in 1 $mi^2$ at a well density of 0.4 and at an annual withdrawal rate of 0.36 acre-ft per well, is about 92 acre-ft and is equivalent to a constant discharge of about 57 gal/min. Theoretical drawdown of the water table is small from a single domestic or household well completed in the alluvial-outwash aquifer.



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 16.** Density of domestic and household wells in and near the study area, 2003.

The hypothetical drawdown relative to distance from a pumped well after continuous withdrawal at a constant rate for 1 year for two cases is shown in figure 17. Case 1 represents the hypothetical drawdown in the water table where wells are completed in the alluvial-outwash aquifer. Case 2 represents the hypothetical drawdown in the water table where wells are completed in the basin-fill aquifer. Two pumping rates are evaluated for each case: (1) a pumping rate of 0.223 gal/min, which is equivalent to the rate of a single domestic or household well that pumps continuously for 1 year to withdraw 0.36 acre-ft, and (2) a pumping rate of 57 gal/min, which is equivalent to the combined withdrawal rate of 256 domestic wells in a 1-$\mathrm{mi}^2$ area, each pumping at a continuous rate of 0.223 gal/min. Drawdown caused by pumping was calculated for distances within 0.5 mi (2,640 ft) of the pumped well at an elapsed time of 1 year. A modified form of the Theis nonequilibrium equation (Theis, 1935) was used to calculate drawdown for unconfined conditions. The modification of the nonequilibrium equation was based on the correction to drawdown in an unconfined aquifer (Jacob, 1963). The wells were assumed to fully penetrate a semi-infinite, homogeneous, isotropic, unconfined aquifer. For Case 1 (the alluvial-outwash aquifer), the following conditions were assumed: hydraulic conductivity was 280 ft/d, saturated thickness was 100 ft, and specific yield was 20 percent (0.2). For Case 2 (the basin-fill aquifer), the following conditions were assumed: hydraulic conductivity was 2.8 ft/d, saturated thickness was 100 ft, and the specific yield was 5 percent (0.05).

Drawdown in the water table at a distance of 0.5 mi (2,640 ft) from a single domestic well, for Case 1 (alluvial-outwash aquifer), was less than 0.01 ft after 1 year of constant withdrawal. [Note that in figure 17, drawdown is plotted using a logarithmic scale and with the order of the values reversed—smaller numbers at the top.] Actual drawdown in a pumping well likely will be greater than the hypothetical drawdown in the aquifer near the well because of frictional losses through the well screen. Generally, a domestic well does not pump continuously at relatively small and constant rate (0.223 gal/min). Instead, a domestic well pumps intermittently for short periods at a relatively large rate (10 to 15 gal/min) followed by long periods without pumping, during which water levels recover. The distance-drawdown curve for a well pumping at a constant rate of 57 gal/min for Case 1 also showed a relatively small response of less than about 0.1 ft at a distance of 2,640 ft from the well. The shape of the cone of depression of a well pumping at a rate of 57 gal/min is different than the shape of the overlapping cones of the 256 wells it represents, but the total volume of the cone of depression is equivalent.

The hypothetical drawdown relative to distance after 1 year of continuous withdrawal for Case 2 (basin-fill aquifer) is shown in figure 17. Drawdown for a well pumping at 0.223 gal/min from the basin-fill aquifer was about 10 times larger than for a well pumping at 0.223 gal/min from the alluvial-outwash aquifer (case 1). Drawdown for a well withdrawing at a constant rate of 57 gal/min (fig. 17) from the basin-fill aquifer was almost 72 ft near the well. When drawdown in an unconfined aquifer is a large proportion of the original saturated thickness, well yields generally cannot be held constant and decline in proportion to saturated thickness and pumping lift. The preceding hypothetical examples illustrate three facts about ground-water withdrawals and drawdown: drawdown is proportional to the pumping rate; drawdown will be relatively small if hydraulic conductivity and specific yield are relatively large; and drawdown will be relatively large if hydraulic conductivity and specific yield are relatively small.

Aquifer response to changes in recharge and discharge conditions commonly is predicted using a three-dimensional numerical model of ground-water flow. For example, a model can be used to predict changes in water levels in response to changes in snowmelt runoff or ground-water pumping. However, additional data are needed to support the development of a numerical model of ground-water flow for the alluvial-outwash and basin-fill aquifers. Additional data that are needed to develop a ground-water model include the following:

- Better definition of the extent and thickness of the aquifers,
- Aquifer tests to determine hydraulic and storage properties of the aquifers,
- Ground-water/surface-water interactions,
- Monitoring of the three-dimensional distribution and temporal variation of water levels,
- Water and consumptive use, particularly for domestic, irrigation, and municipal supplies,
- Surface-water inflow from the mountains and surface-water use within the valley, and
- Climatological data and recharge and evapotranspiration rates.

## Water Quality

Ground-water samples were collected during September and October 2001 from 39 water-supply wells (32 in the alluvial-outwash aquifer and 7 in the basin-fill aquifer) to characterize the general physical properties and chemical characteristics of ground water in the study area. Field and laboratory measurements of physical properties and results from laboratory analyses of ground-water samples discussed in this report can be accessed from the USGS water-quality database. The data can be accessed from the World Wide Web at the following Web sites: *http://waterdata.usgs.gov/nwis/qw/* or *http://co.water.usgs.gov/*. [Note: For easier access of water-quality data collected for this study, use the site identification numbers listed in table 3 to select sites with water-quality data.]

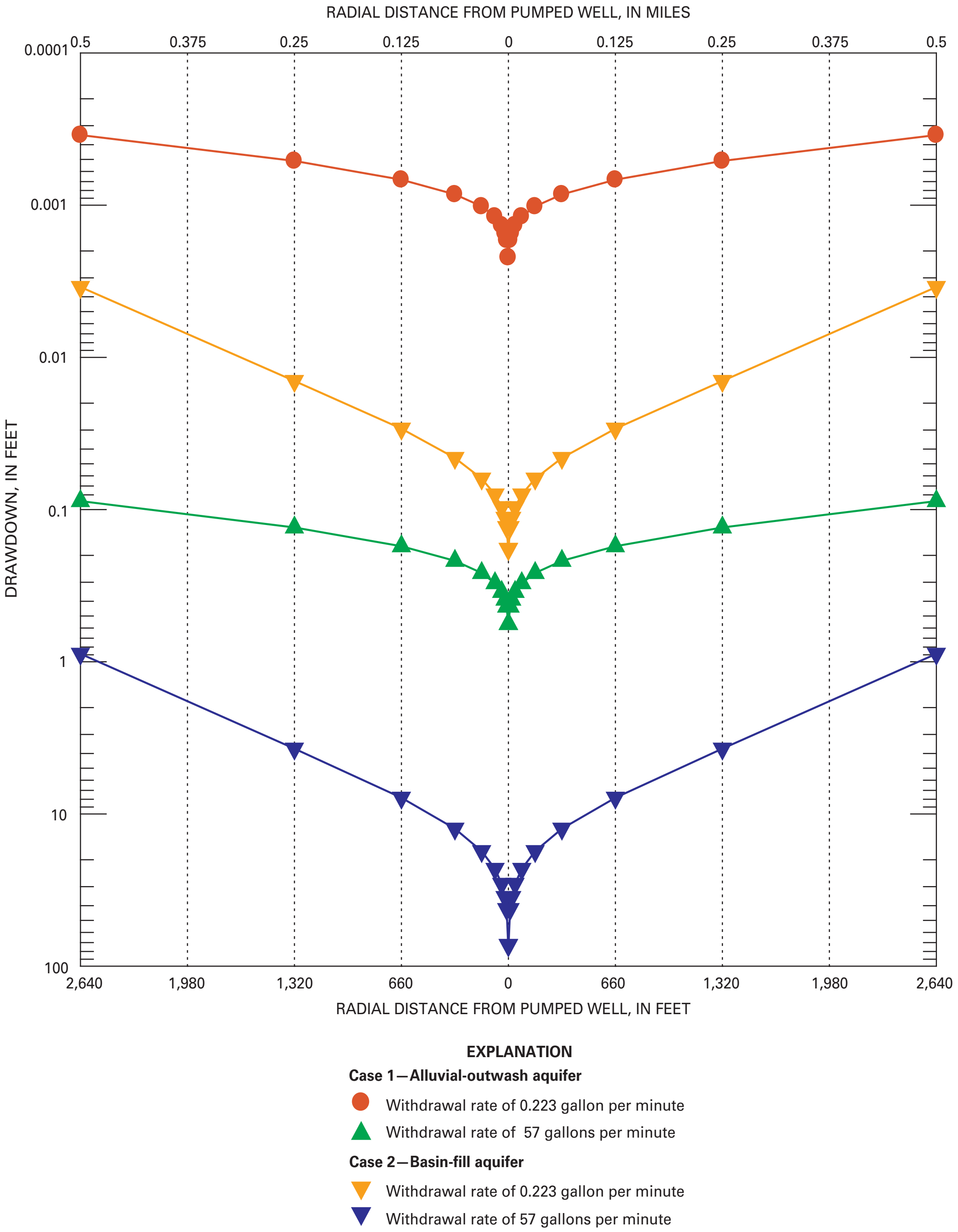


**Figure 17.** Effect of transmissivity and specific yield on drawdown within a radial distance of 2,640 feet of a hypothetical pumped well, after 1 year of constant withdrawal at rates of 0.223 and 57 gallons per minute: [Case 1—alluvial-outwash aquifer; transmissivity = 28,000 square feet per day; specific yield = 0.2; Case 2—basin-fill aquifer; transmissivity = 280 square feet per day; specific yield = 0.05].

The Colorado Department of Public Health and Environment (CDPHE) (2004a, 2004b) has established drinking-water standards for public water supplies and basic ground-water standards for domestic water supplies. The drinking-water standards refer to primary and secondary maximum contaminant levels (MCLs) and maximum contaminant level goals (MCLGs) for public water supplies (Colorado Department of Public Health and Environment, 2004a). The basic ground-water standards refer to domestic water-supply human-health standards and domestic water-supply drinking-water standards (Colorado Department of Public Health and Environment, 2004b). With the exception of the standards for fluoride, the basic ground-water standards are the same as the drinking-water standards for public supplies; therefore, standards will be referred to as primary or secondary maximum contaminant levels in this report. The basic ground-water standards also are the same as the Federal Secondary Drinking Water Standards, which were set to maintain ground water as a drinking-water source requiring very little treatment and, in the judgment of the U.S. Environmental Protection Agency (USEPA) Administrator, were required to protect the public welfare. Colorado drinking-water and basic ground-water standards can be accessed at the CDPHE Web site at URL *http://www.cdphe.state.co.us/*. The National drinking-water standards can be accessed at the USEPA Web site at URL *http://www.epa.gov/*.

Ground water in the study area is relatively low in dissolved solids and is predominantly a calcium-bicarbonate type of water. Some differences in the chemistry of the water from the alluvial-outwash and basin-fill aquifers and from different locales in the alluvial-outwash aquifer are discussed in the following sections of the report.

## Alluvial-Outwash Aquifer

Ground-water samples were collected from 32 wells that were completed in the alluvial-outwash aquifer (table 3). Locations of wells from which ground-water samples were collected are shown in figure 1.

### Physical Properties and Chemical Characteristics

Physical properties of ground water that were measured in the field during collection of ground-water samples included alkalinity for filtered samples or acid-neutralizing capacity (ANC) for unfiltered samples, pH, specific conductance, water temperature, and dissolved oxygen. Alkalinity or ANC was determined in the field to estimate the concentrations of dissolved bicarbonate, carbonate, and hydroxide. In most natural waters, alkalinity is produced by the bicarbonate and carbonate ions. Other anions that also can contribute to the alkalinity include hydroxide, silicate, borate, ammonium hydroxide, and hydrogen sulfide (Hem, 1985, p. 106). Selected physical properties (specific conductance, pH, water temperature, and dissolved oxygen) and concentrations of selected chemical constituents in water from the alluvial-outwash aquifer and from the basin-fill aquifer are summarized, using boxplots, in figures 18*A*–*D*. Concentrations of ions discussed in this report refer to concentrations of dissolved ions, unless stated otherwise.

Specific conductance describes the capacity of water to conduct an electrical current and provides an indication of ion concentrations or dissolved solids. On the basis of samples collected during this study, the concentration of dissolved solids (in milligrams per liter) in water in the alluvial-outwash aquifer can be estimated by multiplying the specific conductance (in microsiemens per centimeter at 25°C) by a factor of 0.6. Specific conductance of ground water in the alluvial-outwash aquifer in this study ranged from 84 to 479 µS/cm (microsiemens per centimeter at 25°C), with a median of 180 µS/cm (fig. 18*A*). The specific conductance of water increases with increased concentrations of dissolved solids (Hem, 1985). Although the CDPHE has not established drinking-water standards for specific conductance, the nonenforceable secondary maximum contaminant level for dissolved solids is 500 mg/L (milligrams per liter). Dissolved-solids concentrations in the alluvial-outwash aquifer ranged from 58 to 282 mg/L, with a median of 106 mg/L (fig. 18*A*), and were less than the secondary maximum contaminant level established by the CDPHE (2004b).

The CDPHE established nonenforceable secondary maximum contaminant levels of 6.5 to 8.5 standard units for pH in ground water. A pH value less than 7.0 indicates acidic properties, and a pH value greater than 7.0 indicates alkaline properties. The pH of water from the alluvial-outwash aquifer ranged from 6.4 to 7.9 standard units, with a median of 7.3 (fig. 18*A*). Based on measurements from this study, pH values generally were within the range established by the CDPHE.

The CDPHE has not established primary or secondary ground-water drinking-water regulations for water temperature or dissolved oxygen. However, temperature ranged from 8.5° to 16.0°C, with a median of about 12°C (fig. 18*A*). Dissolved oxygen ranged from 4.0 to 8.0 mg/L, with a median of about 6.2 mg/L (fig. 18*A*).

The concentrations of the dissolved major cations (calcium, magnesium, potassium, and sodium) and anions (bicarbonate, carbonate, chloride, and sulfate) in ground-water samples (figs. 18*B* and 18*C*) contributed most of the dissolved solids in water in the alluvial-outwash aquifer. Although basic cations and anions commonly are not considered contaminants, increased ion concentrations may provide information about potential sources of contaminants that are of concern such as nutrients, trace elements, and synthetic organic compounds.

In general, concentrations of dissolved solids tend to increase from recharge to discharge areas because ground water is in contact and can react with minerals in the aquifer as it flows downgradient. Because ground-water flow in the alluvial-outwash aquifer is relatively rapid, residence times in the aquifer are short and changes in concentrations and chemical composition of the ground water are relatively small.

Concentrations of dissolved calcium ranged from 8.6 to 74 mg/L, with a median of about 20 mg/L (fig. 18*B*). Calcium ions, along with magnesium and iron ions, cause water hardness and mineral buildup on pipes. The CDPHE has not established primary or secondary ground-water drinking-water regulations for calcium.

Concentrations of dissolved magnesium in water from the alluvial-outwash aquifer ranged from 0.87 to 23 mg/L, with a median of about 3.9 mg/L (fig. 18*B*). Anomalously large concentrations of dissolved magnesium of 23.3 and 18.4 mg/L were from wells 87 and 100, respectively, which are located northwest of Poncha Springs in an irrigated area. Concentrations of dissolved potassium in ground water from the alluvial-outwash aquifer ranged from 0.4 to 3.3 mg/L, with a median of about 1.2 mg/L (fig. 18*B*). The CDPHE has not established primary or secondary ground-water drinking-water regulations for magnesium or potassium.

Concentrations of dissolved sodium in water from the alluvial-outwash aquifer ranged from 4.0 to 69 mg/L, with a median of about 6.4 mg/L (fig. 18*B*). The maximum concentration of dissolved sodium of 69 mg/L was from a sample from well 105. Well 105 is about 2 mi northwest of Salida and is relatively shallow (85 ft deep). The cause of the anomalous concentration of dissolved sodium in ground water at this location is not known.

Concentrations of dissolved bicarbonate ranged from about 41 to about 274 mg/L, with a median of about 93 mg/L (fig. 18*C*). There was little dissolved carbonate in water from the alluvial-outwash aquifer; the maximum concentration was 0.7 mg/L. Dissolved chloride concentrations ranged from about 0.4 to 8.1 mg/L, and dissolved sulfate concentrations ranged from 0.1 to 29.1 mg/L (fig. 18*C*). The maximum concentration of dissolved sulfate was from a sample from well 105, which also had an anomalously large dissolved sodium concentration. Median concentrations of dissolved chloride and dissolved sulfate were about 1.6 and 7.8 mg/L, respectively. None of the samples from the alluvial-outwash aquifer had concentrations of dissolved chloride or dissolved sulfate that exceeded the secondary maximum contaminant levels of 250 mg/L established by CDPHE for dissolved chloride and dissolved sulfate in ground water.

Concentrations of other selected dissolved ions such as bromide, fluoride, nitrate (nitrite plus nitrate, as nitrogen), and silica are summarized in figure 18*D*. Concentrations of dissolved bromide ranged from 0.01 to 0.07 mg/L with a median of 0.02 mg/L. Concentrations of dissolved fluoride ranged from 0.2 to 1.7 mg/L and were less than the primary maximum contaminant level for drinking water of 4.0 mg/L and the secondary maximum contaminant level of 2 mg/L. Excessive fluoride in drinking water can cause discoloration of tooth enamel. Dissolved nitrite plus nitrate, as nitrogen, is discussed later in the "Indicators of Anthropogenic Effects on Water Quality" section. Concentrations of dissolved silica ranged from 9.5 to 28 mg/L, with a median of about 18 mg/L (fig. 18*D*). The CDPHE has not established primary or secondary ground-water drinking-water regulations for bromide or silica.

Concentrations of dissolved iron in 26 of 32 samples were less than the minimum reporting level of 10 μg/L (micrograms per liter) or were estimated values less than 10 μg/L; a boxplot is not presented for iron concentrations. Samples from wells 50 and 55 had anomalously large concentrations of dissolved iron of 139 and 656 μg/L, respectively, and concentrations of dissolved manganese of 23 and 64 μg/L, respectively. Wells 50 and 55 are located in the Browns Creek area at the western side of the study area. Both dissolved iron and dissolved manganese in water can cause staining of porcelain fixtures. Dissolved iron in water also can cause water hardness. The CDPHE has established secondary maximum contaminant levels in ground water for iron and manganese of 0.3 and 0.05 mg/L (300 and 50 μg/L), respectively. Concentrations of dissolved iron and dissolved manganese in water from well 55 exceeded these secondary maximum contaminant levels.

## Water Type

Concentrations of the dissolved major cations (calcium, magnesium, potassium, and sodium) and dissolved major anions (bicarbonate, carbonate, chloride, and sulfate) were converted from milligrams per liter to milliequivalents per liter for calculation of relative proportions (Hem, 1985, p. 56). The predominant cation is the cation that has a relative proportion of 50 percent or more of the total of major cations, expressed in milliequivalents per liter. Similarly, the predominant anion is the anion that has a relative proportion of 50 percent or more of the total of major anions, expressed in milliequivalents per liter. If no cation has a relative proportion of 50 percent or more, then the water type is mixed cation; if no anion has a relative proportion of 50 percent or more, then the water type is mixed anion.

Water from the alluvial-outwash aquifer throughout the study area is predominantly a calcium-bicarbonate water type (fig. 19) with low dissolved-solids content (fig. 18*A*). Locally, there are some differences in the proportions of the dissolved major cations (calcium, magnesium, potassium, and sodium) and dissolved major anions (bicarbonate, carbonate, chloride, and sulfate) in ground water. Relative proportions of the dissolved major ions for four areas (Buena Vista, Browns Creek, Maysville, and Salida–Poncha Springs) are shown with separate symbols in figure 19.

As water contacts geologic materials (soil, unconsolidated deposits, and rocks), its chemical composition tends to change and the concentration of dissolved solids tends to increase. In the study area, ground water in recharge areas generally is similar to surface water, with a calcium-bicarbonate water type and low dissolved-solids content. However, as the time of contact with geologic material increases, the concentrations of dissolved solids and the proportions of chloride, magnesium, sodium, and sulfate also tend to increase. Other possible causes of these differences in relative proportions of major cations and anions dissolved in water from the four areas include differences in the chemical composition of the

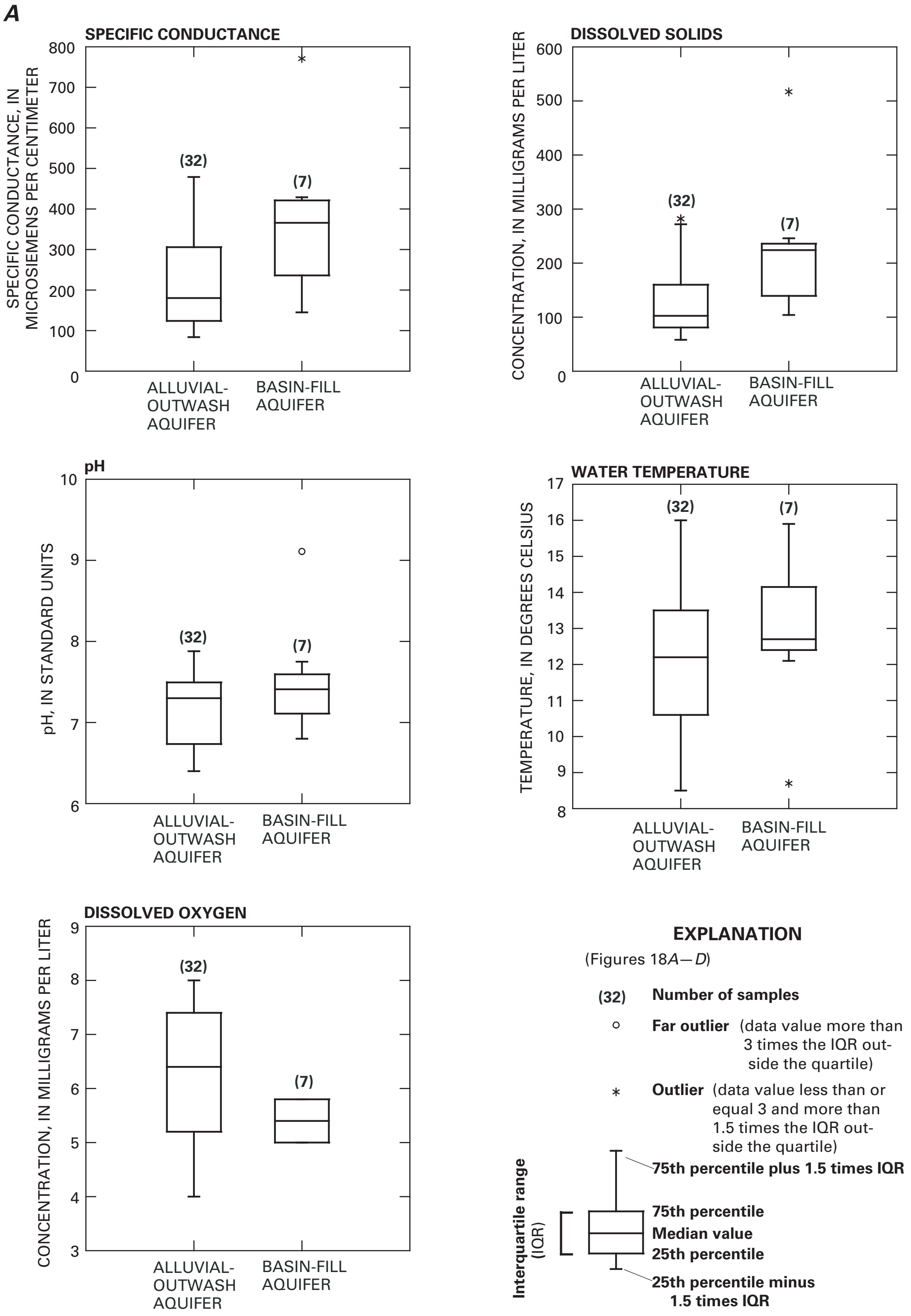


**Figure 18.** (*A*) Selected physical properties and concentrations of dissolved oxygen and dissolved solids in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; (*B*) concentrations of dissolved cations in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; (*C*) concentrations of dissolved anions in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; and (*D*) concentrations of dissolved bromide, fluoride, nitrite plus nitrate (as nitrogen), and silica in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001.

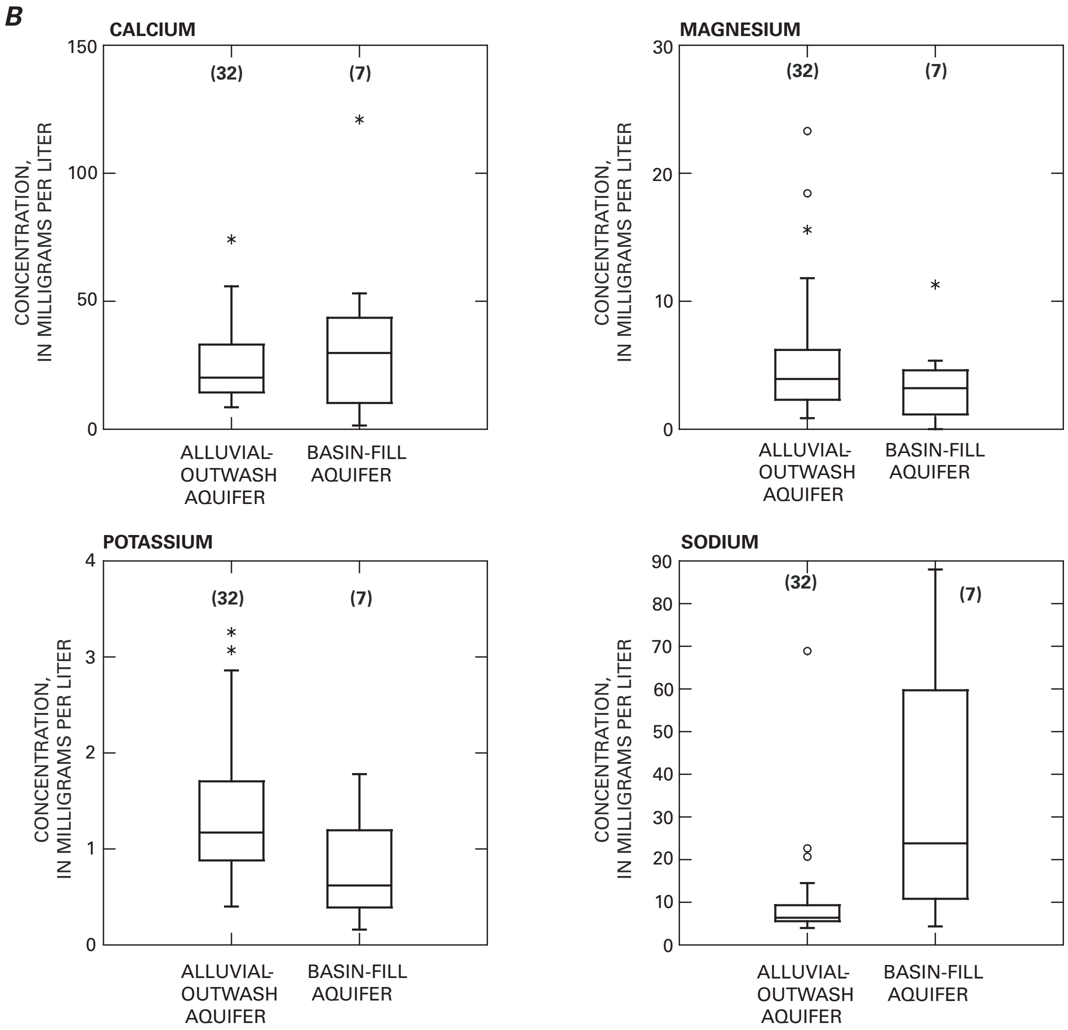


**Figure 18.**—Continued

source water or in the lithology of the aquifers. Water in the Salida–Poncha Springs area has an increased proportion of dissolved sodium and dissolved potassium relative to dissolved calcium, and water in the Maysville area (fig. 19) has an increased proportion of dissolved sulfate relative to dissolved bicarbonate. Causes for these differences in relative proportions of dissolved ions have not been identified.

## Indicators of Anthropogenic Effects on Water Quality

Concentrations of nutrients—nitrogen and phosphorus compounds—that are greater than background levels for ground water can indicate transport of contaminants from surface sources, such as chemical fertilizers, manure, and discharge from waste-treatment systems. With the exception of dissolved nitrite plus nitrate, as nitrogen, concentrations of dissolved nitrogen compounds (ammonia, ammonia plus organic nitrogen, and nitrite) generally were near or less than the minimum reporting limit for the constituent and were either estimated or qualified as less than the reporting level. Concentrations of orthophosphate for 10 of 32 samples from the alluvial-outwash aquifer were equal to or greater than the minimum reporting limit of 0.02 mg/L and ranged from 0.02 to 0.11 mg/L. Concentrations of phosphorus for 27 of 32 samples from the alluvial-outwash aquifer were equal to or greater than the minimum reporting limit, which varied from 0.004 to 0.006 mg/L, and ranged from 0.005 to 0.116 mg/L. Concentrations of orthophosphate and phosphorus are relatively small and do not indicate substantial anthropogenic effects on the quality of ground water from the alluvial-outwash aquifer. Because dissolved nitrite concentrations were reported as equal to or less than either 0.006 or 0.008 mg/L, concentrations of dissolved nitrite plus nitrate, as nitrogen, are assumed to approximate the concentrations of dissolved nitrate, as nitrogen. Dissolved nitrate concentrations in ground water from the alluvial-outwash aquifer ranged from 0.05 to 6.3 mg/L, as nitrogen, and are lower than the CDPHE drinking-water standard of 10 mg/L. The median concentration of dissolved nitrate was 0.34 mg/L. Based on the distribution of dissolved nitrite plus nitrate, as nitrogen,

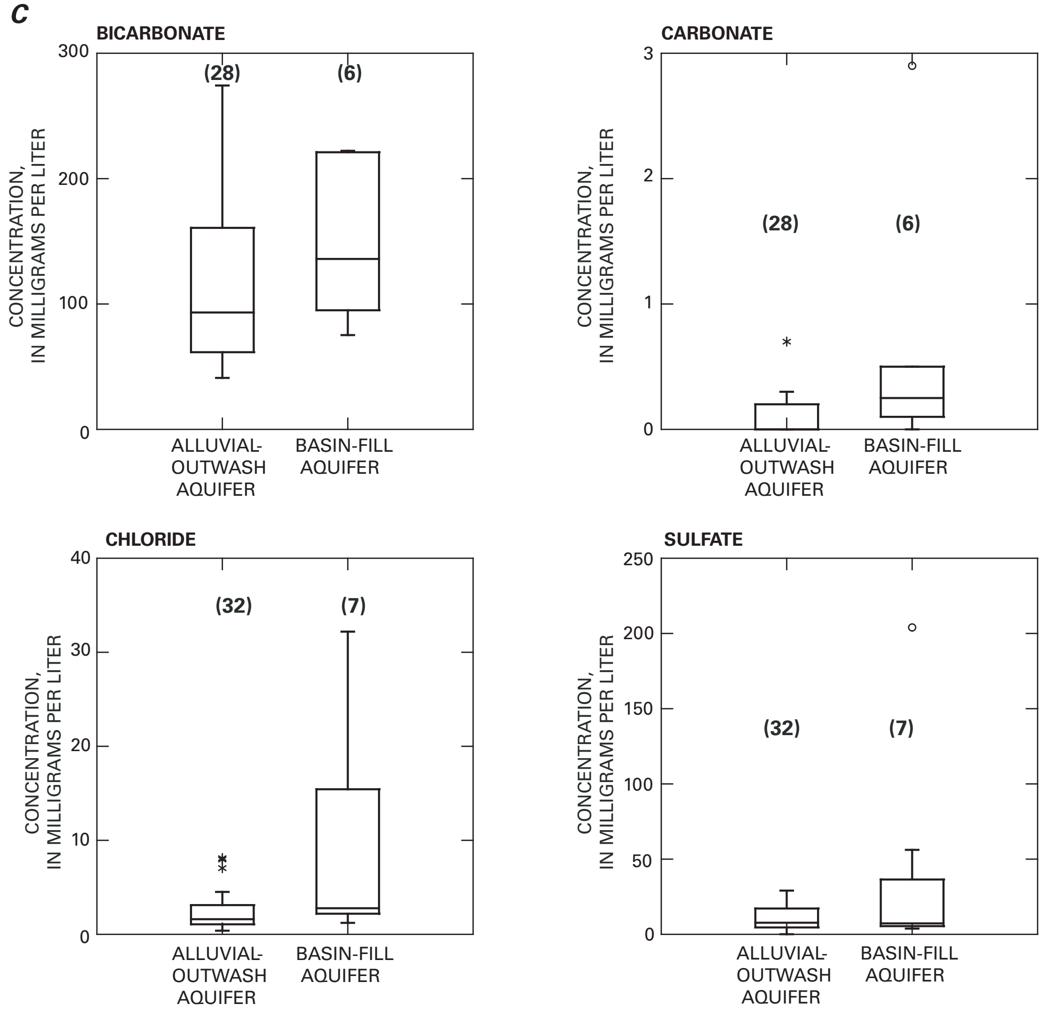


**Figure 18.** (*A*) Selected physical properties and concentrations of dissolved oxygen and dissolved solids in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; (*B*) concentrations of dissolved cations in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; (*C*) concentrations of dissolved anions in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001; and (*D*) concentrations of dissolved bromide, fluoride, nitrite plus nitrate (as nitrogen), and silica in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001.—Continued

concentrations (fig. 18*D*), dissolved nitrate concentrations greater than 1 to 2 mg/L and are considered to be greater than background concentrations. Concentrations of dissolved nitrite plus nitrate, as nitrogen, in samples from three wells were greater than background concentrations. Potential sources of high nitrate concentrations in ground water include poorly functioning septic systems, failure of a well's sanitary seal, and nearby agriculture sources (fertilizer and manure). The geographic distribution of dissolved nitrite plus nitrate, as nitrogen, in ground water in the study area (fig. 20) does not show a clustering of concentrations greater than 1 mg/L, indicating that the sources of nitrate are localized (point sources). As the population of Chaffee County increases, further study of nitrate in ground water may be needed to evaluate potential increases in nitrate loads from septic systems.

## Basin-Fill Aquifer

Ground-water samples were collected from seven wells that are completed in the basin-fill aquifer (table 3). Locations of wells from which ground-water samples were collected are shown in figure 1.

### Physical Properties and Chemical Characteristics

The specific conductance of samples from the basin-fill aquifer ranged from 145 to 771 µS/cm, with a median of about 366 µS/cm, which is about twice the median specific conductance of samples from the alluvial-outwash aquifer. On the basis of samples collected during this study, the concentration

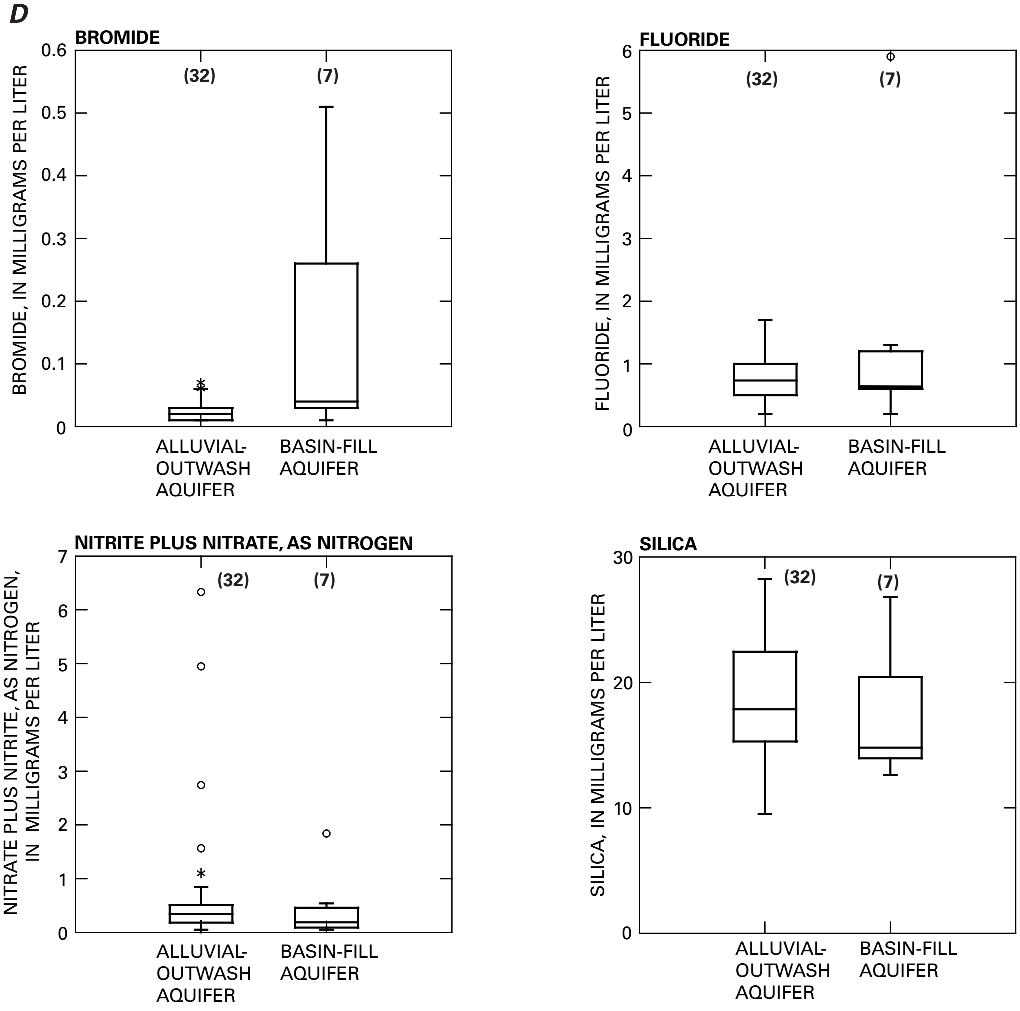


**Figure 18.**—Continued

of dissolved solids (in milligrams per liter) in water in the basin-fill aquifer also can be estimated by multiplying the specific conductance of the water (in microsiemens per centimeter at 25°C) by a factor of 0.6. The pH of ground water from the basin-fill aquifer ranged from 6.8 to 9.1 standard units with a median of 7.4 standard units. The pH of samples from well 110 was greater than the secondary maximum contaminant level of 8.5 standard units for pH in ground water, a nonenforceable standard established by CDPHE. Water from the basin-fill aquifer is slightly more alkaline than water from the alluvial-outwash aquifer. Temperature of ground-water samples ranged from 8.7° to 15.9°C, with a median of 12.7°C.

The concentrations of the dissolved major cations (calcium, magnesium, potassium, and sodium) (fig. 18*B*) and dissolved major anions (carbonate, bicarbonate, chloride, and sulfate) (fig. 18*C*) contributed most of the dissolved solids in water in the basin-fill aquifer. Concentrations of dissolved solids in water from the basin-fill aquifer ranged from 104 to 517 mg/L, with a median of 224 mg/L. The dissolved-solids concentration of 517 mg/L in the sample from well 114 was greater than the CDPHE secondary maximum contaminant level of 500 mg/L for dissolved solids. Dissolved calcium concentrations ranged from 1.5 to 121 mg/L, with a median of about 30 mg/L. Dissolved magnesium concentrations ranged from about 0.01 to 11 mg/L, with a median of about 3 mg/L. Dissolved sodium concentrations ranged from 4.3 to 88 mg/L, with a median of about 24 mg/L. The median concentration of dissolved sodium in water from the basin-fill aquifer is about four times the median concentration of dissolved sodium in water from the alluvial-outwash aquifer. Dissolved sodium concentrations in water from wells 47 and 100 were 87 and 88 mg/L, respectively, and were substantially larger than concentrations in other samples. The surface geophysical surveys (Zohdy and others, 1971; Crouch and others, 1984) showed a decrease in electrical resistivity of the subsurface with depth in this area, which can be attributed to increased concentrations of dissolved solids in ground water or increased clay content of the rocks, or both. The anomalous dissolved sodium concentrations could indicate upwelling of water from deeper in the basin-fill deposits but also could result from cation exchange of calcium for sodium along the ground-water flow path within the basin-fill deposits. Crouch

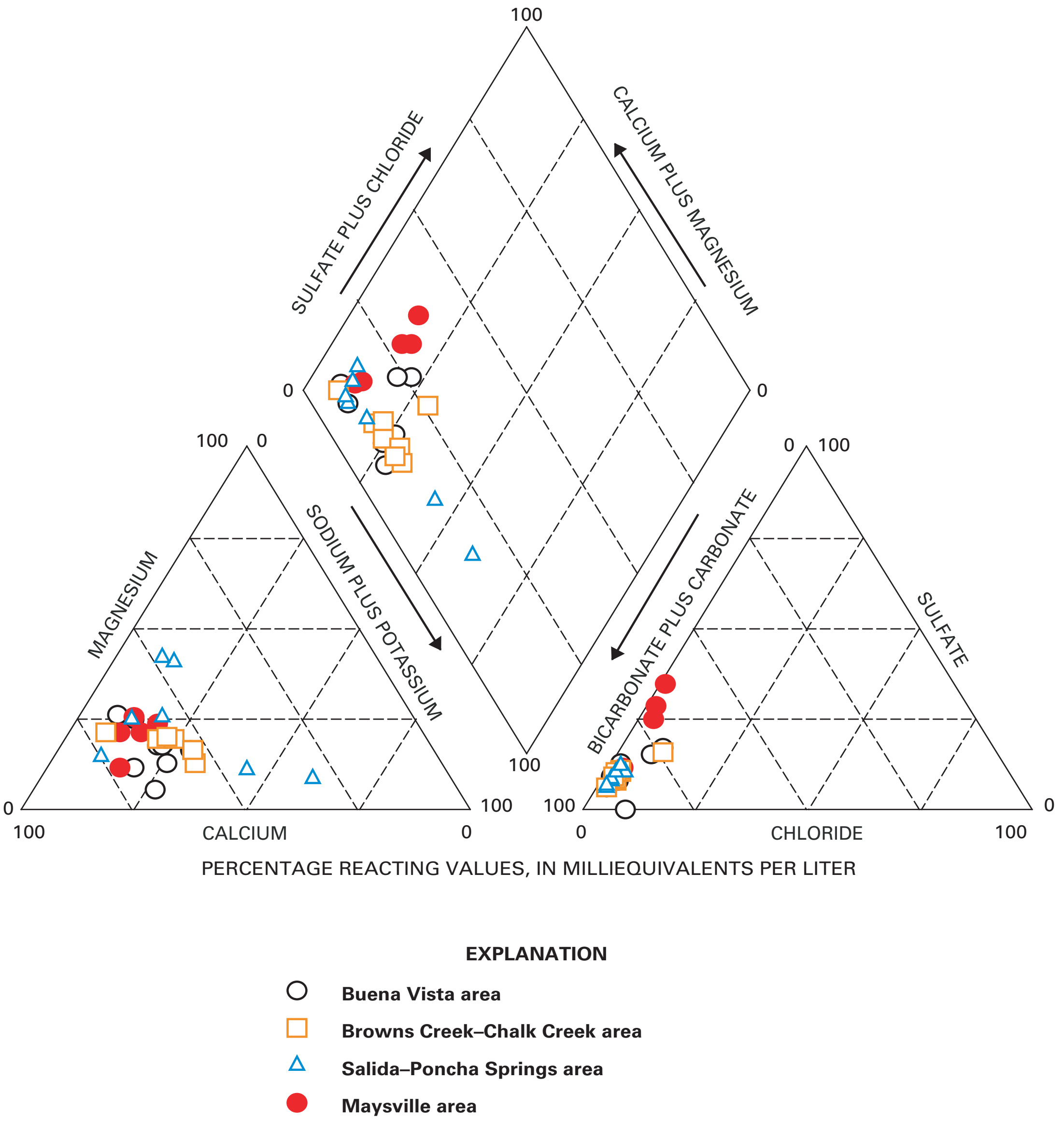
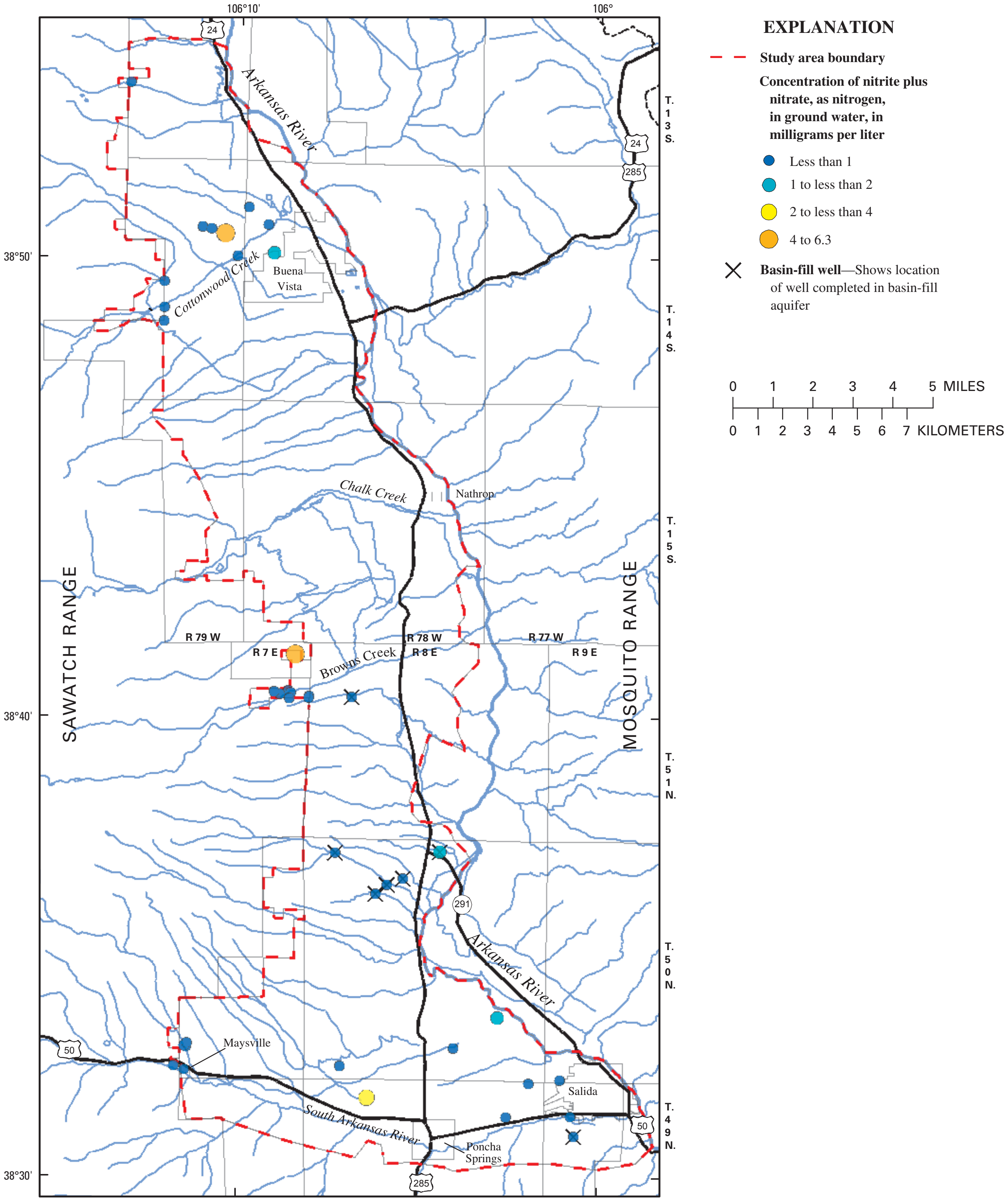


**Figure 19.** Relative proportions of dissolved cations and anions in water from the alluvial-outwash aquifer in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001.

and others (1984, fig. 21) showed that ground water in the area near wells 47 and 110 had a greater than typical concentration of dissolved solids; this also is an area in which upward flow is indicated by the preliminary cross-sectional flow models (fig. 6).

Dissolved bicarbonate concentrations in water from the basin-fill aquifer ranged from about 75 to 222 mg/L, with a median of about 136 mg/L. There was little dissolved carbonate in the ground water from the basin-fill aquifer, and the maximum concentration of dissolved carbonate was 2.9 mg/L. Dissolved chloride concentrations in water from the basin-fill aquifer ranged from about 1.2 to 32 mg/L and of dissolved sulfate from 3.8 to 204 mg/L. The dissolved chloride concentration in water from well 110 was 32 mg/L, and the dissolved sulfate concentration in water from well 114 was 204 mg/L. Median dissolved chloride and dissolved sulfate concentrations in water from the basin-fill aquifer were similar to those from the alluvial-outwash aquifer and were about 2.8 and 7.3 mg/L, respectively.

The concentrations of dissolved bromide, fluoride, nitrate (nitrite plus nitrate, as nitrogen), and silica are summarized in figure 18*D*. Dissolved bromide concentrations ranged from 0.01 to 0.51 mg/L, with a median of 0.04 mg/L. Dissolved fluoride concentrations ranged from 0.2 to 5.9 mg/L, with a median of 0.6 mg/L. The dissolved fluoride concentration in a sample from well 110 was 5.9 mg/L and exceeded the CDPHE secondary maximum contaminant level for fluoride of 2.0 mg/L. Concentrations of dissolved iron were less than the minimum reporting level of 10 µg/L in all samples except the sample from well 113, which had a concentration of 15 µg/L.



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Albers Equal Area Conic projection
Standard parallels 37°30'N and 40°30'N, central meridian 105°30'W

**Figure 20.** Concentrations of dissolved nitrite plus nitrate, as nitrogen, in water from the alluvial-outwash and basin-fill aquifers in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001.

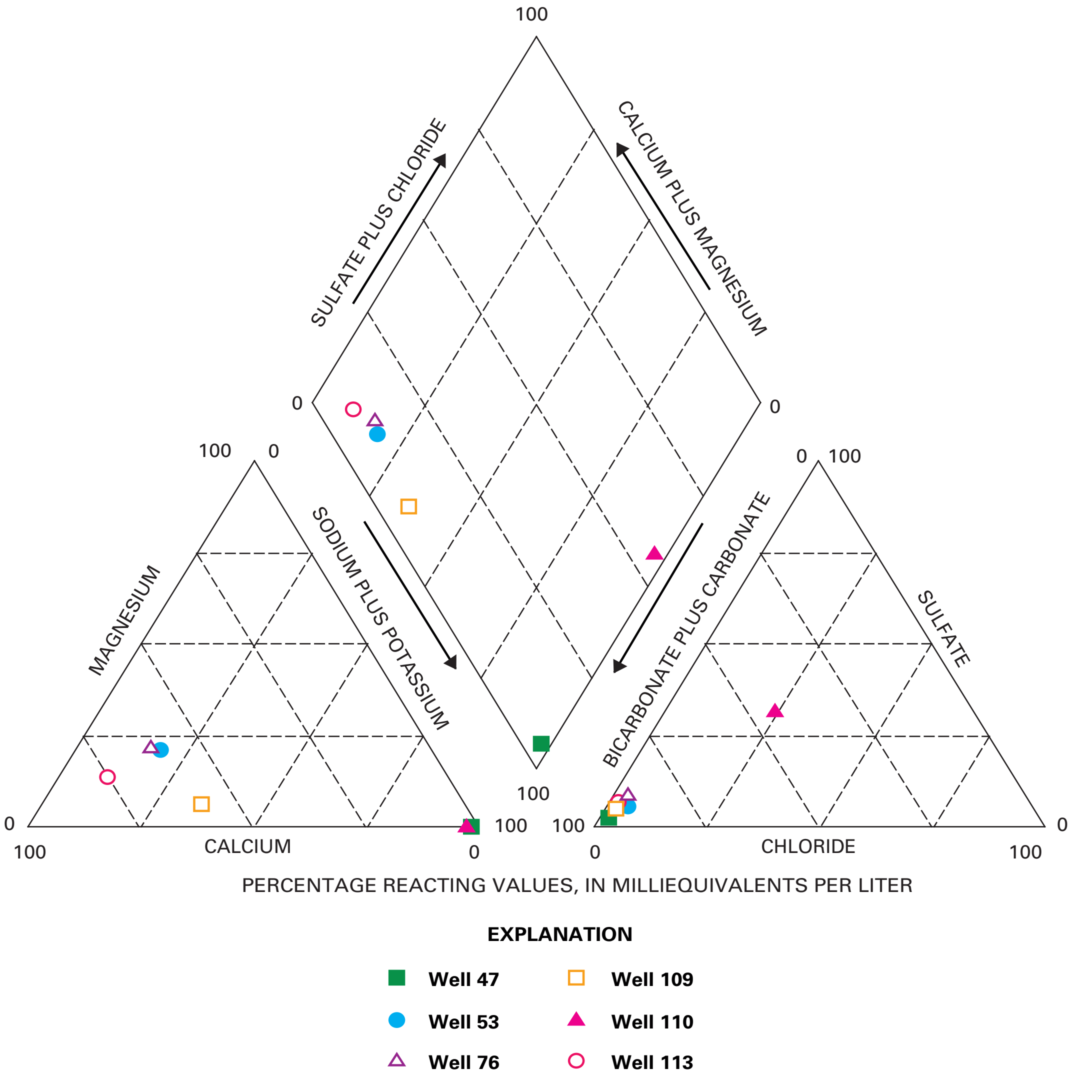


**Figure 21.** Relative proportions of dissolved cations and anions in water from the basin-fill aquifer in the upper Arkansas River Basin from Buena Vista to Salida, Colorado, September–October 2001.

Concentrations of dissolved manganese were less than the minimum reporting level of 3 µg/L in all samples except the sample from well 109, which had an estimated concentration of 2.5 µg/L.

## Water Type

Calcium is the predominant cation in water from the basin-fill aquifer. Bicarbonate is the predominant anion in water from the basin-fill aquifer at six of seven wells that were sampled during this study. Water from the basin-fill aquifer is predominantly a calcium-bicarbonate water type (fig. 21) with dissolved-solids concentrations generally less than 250 mg/L. Ion ratios for each water sample are shown with a separate symbol for each well in figure 21. The predominant dissolved cation in water from wells 47 and 110 was sodium and in water from all other wells was calcium. The predominant dissolved anion for water from all wells except well 110 is bicarbonate. Relative proportions of dissolved bicarbonate, chloride, and sulfate in water from well 110 are about 45, 25, and 32 percent, respectively, and water from well 110 is a mixed-anion water type. The difference between the relative ionic composition of water from wells 47 and 110 and the ionic composition of water for other samples collected from the basin-fill aquifer may indicate upwelling of water from deeper in the basin-fill aquifer.

## Indicators of Anthropogenic Effects on Water Quality

The minimum and maximum concentrations of dissolved nitrate (nitrite plus nitrate, as nitrogen) in water samples from the basin-fill aquifer were 0.05 and 1.84 mg/L, respectively, with a median of about 0.2 mg/L. Concentrations of orthophosphate for three of seven samples from the basin-fill aquifer were equal to or greater than the minimum reporting limit of 0.02 mg/L and ranged from 0.02 to 0.03 mg/L. Concentrations of phosphorus for seven samples from the basin-fill aquifer ranged from 0.005 to 0.037 mg/L. These small concentrations of dissolved nitrate, orthophosphate, and phosphorus do not indicate contamination from surface sources (agricultural or sanitary waste); however, only seven samples were collected from the basin-fill aquifer, and additional sampling would be needed to confirm these preliminary results.

### Comparison of Water Quality between the Alluvial-Outwash and Basin-Fill Aquifers

In general, water from the alluvial-outwash aquifer contains less dissolved solids than water from the basin-fill aquifer. Median concentrations of dissolved solids in samples from the alluvial-outwash and basin-fill aquifers were about 108 and 224 mg/L, respectively. Samples from the alluvial-outwash and basin-fill aquifers, with a few notable exceptions, have similar proportions of the major cations and anions (figs. 19 and 21). Water from both aquifers is typically a calcium-bicarbonate water type. Because the samples collected for this study from the basin-fill aquifer were from relatively shallow wells, no inferences can be made with these data on the quality of water from deeper in the basin-fill aquifer. The electrical-resistivity sections (Zohdy and others, 1971) indicate a downward decrease in electrical resistivity of the subsurface in the study area, which can be interpreted as indicating upward decrease in clay content or dissolved-solids concentration in ground water, or both, in the upper 500 to 1,000 ft of the basin-fill deposits. The shapes of the resistivity profiles (Crouch and others, 1984, fig. 2) support the preliminary cross-sectional models of ground-water flow with downward flow of recharge with low dissolved-solids content (low specific conductance) on the western (upgradient) side of basin and upward flow of water with relatively high dissolved-solids content (high specific conductance) on the eastern (downgradient) side of the basin (Crouch and others, 1984, fig. 21).

## Summary

Between 1980 and 2000, the population of Chaffee County in the upper Arkansas River Basin of Colorado increased about 23 percent and is projected to increase an additional 70 percent by 2030. The U.S. Geological Survey, in cooperation with the Upper Arkansas Water Conservancy District, conducted a study from 1999 through 2003 in the upper Arkansas River Basin between Buena Vista and Salida in Chaffee County, Colorado, to (1) evaluate the hydrogeologic characteristics of the aquifers, (2) determine ground-water flow directions and seasonal ground-water-level changes in the aquifers, (3) evaluate the hydraulic connection between the aquifers, and (4) evaluate ground-water quality of the aquifers. The principal aquifers described in this report are the alluvial-outwash and basin-fill aquifers.

The upper Arkansas River Basin between Buena Vista and Salida, Colorado, is located between the Sawatch and Mosquito Ranges in a downfaulted basin, the Buena Vista–Salida structural basin. The primary aquifers in the Buena Vista–Salida structural basin consist of poorly consolidated to unconsolidated, Quaternary-age, alluvial and glacial deposits and Tertiary-age basin-fill deposits. Maximum thickness of these deposits is an estimated 5,000 feet, but 95 percent of the water-supply wells in Chaffee County are less than 300 feet deep. The estimated specific yield of the upper 300 feet of the alluvial-outwash and basin-fill aquifers ranged from less than 2 percent (0.02) to about 20 percent (0.2), based on evaluation of more than 800 driller's logs. The specific capacity of wells in the area ranged from less than 0.01 to more than 10 (gal/min)/ft of drawdown. The hydraulic conductivity of the aquifers was estimated from driller's logs and typical values for similar geologic materials.

Conceptual models of regional ground-water flow in the Buena Vista–Salida structural basin indicate that flow in the alluvial-outwash aquifer primarily is lateral flow but that ground-water flow in the basin-fill aquifer has substantial components of vertical flow. Downward flow occurs in the upgradient (western) side of the basin to about two-thirds the distance across the basin, and upward flow occurs near the downgradient (eastern) side of the study area.

Water levels generally were measured five times per year in 117 wells, from September 2000 through September 2003, to evaluate seasonal ground-water level changes. Water-level measurements of two wells were discontinued before the end of the study. Water levels were measured twice per year in five additional wells that are part of a long-term water-level network. Water levels in many of the wells declined substantially during the extreme drought year of 2002, and most had recovered by September 2003. A map of the September 2003 water table shows that ground-water flow is generally from west to east toward the Arkansas River and, locally, toward the South Arkansas River. Water-table contours are widely spaced where the water table is in the alluvial-outwash aquifer and more closely spaced where it is in the basin-fill aquifer, indicating that the alluvial-outwash aquifer is more transmissive than the basin-fill aquifer.

Seasonal water-level fluctuations in many of the water-level monitoring wells indicated that the primary source of recharge to the system is infiltration of surface water from losing streams and from surface water diverted for irrigation. Concentrations of tritium in ground water indicated that the mean age of ground-water recharge was variable, ranging from about 1 to more than 48 years before 2001. The older (pre-1953) water was from wells that were located in ground-water discharge areas.

Currently (2003), annual withdrawal of ground water by an estimated 3,443 domestic and household wells completed in the alluvial-outwash and basin-fill aquifers in the Buena Vista–Salida structural basin is about 690 to 1,240 acre-feet. By 2030, projected annual withdrawals to supply an additional 4,000 to 5,000 domestic and household wells are estimated to require an additional 800 to 1,800 acre-feet. During September 2003, estimated storage of drainable water in the upper 300 feet of the alluvial-outwash and basin-fill aquifers was about 472,000 acre-feet. However, in some areas little water is available within 300 feet of the land surface. Current and projected rates of consumptive use by domestic and household wells are unlikely to substantially affect water supplies because of current augmentation plans and because most new wells require an augmentation plan to replace consumptive use. In densely populated areas, well interference could result in decreased water levels and well yields, which may require deepening or replacement of wells.

Ground water in the upper several hundred feet of the alluvial-outwash and basin-fill aquifers generally is calcium-bicarbonate water type with less than 250 mg/L (milligrams per liter) of dissolved solids. Nitrite plus nitrate concentrations in water from both aquifers ranged from 0.05 to 6.3 mg/L, and all sample concentrations were below the Colorado Department of Public Health and Environment's drinking-water standard of 10 mg/L. However, concentrations of nitrite plus nitrate, as nitrogen, in 3 of 32 samples from the alluvial-outwash aquifer were greater than the background level of 1–2 mg/L, indicating potential anthropogenic sources from the surface, such as septic systems or agricultural sources.

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# Glossary

## A

**Alluvial fan** A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream (especially in a semiarid region) at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of the stream suddenly decreases; it is steepest near the mouth of the valley where its apex points upstream, and it slopes gently and convexly outward with gradually decreasing gradient (Bates and Jackson, 1980, p. 16).

**Alluvium (alluvial deposit)** Clay, silt, sand, and gravel, or other rock materials transported by water and deposited in comparatively recent geologic time as sorted or semisorted sediments in riverbeds, estuaries, flood plains, and fans at the bases of mountain slopes deposited by running water (Thrush, 1968).

**Anisotropic** A condition in which a property (such as hydraulic conductivity) varies with the direction of measurement at a point in a geologic formation or an aquifer.

**Aquifer** A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Lohman and others, 1972).

**Aquifer test** A controlled field test designed to determine the hydraulic or storage properties or both of an aquifer, associated confining units, or both (modified from U.S. Geological Survey, 1989).

## B

**Basin fill** Sediment deposited by any agent, so as to fill or partly fill a structural basin (Bates and Jackson, 1980, p. 55 and p. 229).

**Bedrock** A general term for the rock, usually solid, that underlies soil or other unconsolidated, surficial material (Bates and Jackson, 1980, p. 60).

## C

**Cone of depression** A depression of the potentiometric surface in the shape of an inverted convex cone that develops around a well that is being pumped (U.S. Geological Survey, 1989).

**Confining unit (bed or zone)** A geologic formation, group of formations, or part of a formation of impermeable or distinctly less permeable material bounding one or more aquifers; a general term that replaces the terms aquitard, aquifuge, and aquiclude (Lohman and others, 1972, p. 5).

## D

**Drift [glacial geology]** A general term applied to all rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly from the ice or by running water emanating from a glacier. Drift includes unstratified material (till) that forms moraines and stratified deposits that form outwash plains, eskers, kames, varves, glaciofluvial sediments, and so forth (Bates and Jackson, 1980, p. 187).

## G

**Gneiss** A foliated rock formed by regional metamorphism, in which bands or lenticles of granular minerals alternate with bands or lenticles in which minerals having flaky or elongate prismatic habits predominate (Bates and Jackson, 1980, p. 267).

**Graben** An elongate, relatively depressed crustal unit or block, bounded by faults on its long sides. It is a structural form that may or may not be geomorphologically expressed as a rift valley (Bates and Jackson, 1980, p. 268).

**Granite (granitic rock)** A light-colored, coarse-grained, plutonic rock (igneous rock formed at great depth), which contains quartz as an essential component, along with feldspar and mafic minerals (Bates and Jackson, 1980, p. 271).

## H

**Head, static** The static head is the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The static head is the sum of the altitude head and the pressure head. The total head includes the static head plus the velocity head, which is the height that the kinetic energy of the liquid is capable of lifting the liquid. The velocity head equals the ratio of the velocity squared and two times the acceleration due to gravity. In most cases, velocity head is negligible (Lohman and others, 1972, p. 712).

**Heterogeneous** A condition in which the properties of a geologic formation or an aquifer are not uniform in structure or composition. Heterogeneity primarily is a function of the geologic environments under which the rock was formed and under which it has been altered.

**Homogeneous** A condition in which the properties of a geologic formation or an aquifer are uniform in structure or composition.

**Hydraulic conductivity, *K*,** The volume ($L^3$) of water at the existing kinematic viscosity that will move in unit time (t) under a unit hydraulic gradient (L/L) through a unit area ($L^2$) measured at right angles to the direction of flow (Lohman and others, 1972, p. 4). Hydraulic conductivity is not only a property of the porous media but includes the properties of the fluid (kinematic viscosity) and the acceleration due to gravity. The standard unit for hydraulic conductivity is cubic foot per day per square foot [$(ft^3/d)/ft^2$]. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience. If $K$ is independent of the direction of measurement, the porous medium is isotropic, but if it varies with direction of measurement, the porous medium is anisotropic. In most alluvial sediments, $K$ is generally greatest parallel to bedding and least perpendicular to bedding.

**Hydraulic gradient** The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head (Lohman and others, 1972, p. 8).

**Hydrostratigraphic unit** A formation, group of formations, or part of a formation, which by virtue of its porosity or hydraulic properties has a distinct influence on the storage and movement of ground water (American Nuclear Society, 1980). A permeable hydrostratigraphic unit is an aquifer, and an impermeable or relatively impermeable hydrostratigraphic unit is a confining unit.

## I

**Isotropic** A condition in which a property (such as hydraulic conductivity) is independent of the direction of measurement at a point in the aquifer or confining unit (Lohman and others, 1972, p. 9).

## L

**Limestone** A sedimentary rock consisting chiefly (more than 50 percent by weight or volume) of calcium carbonate, primarily in the form of the mineral calcite, and with or without magnesium carbonate (Bates and Jackson, 1980, p. 360).

## M

**Migmatite** A composite rock composed of igneous or igneous-appearing and metamorphic materials, which are generally visible to the naked eye (Bates and Jackson, 1980, p. 400).

## O

**Outwash [glacial geology]** Stratified detritus (chiefly sand and gravel) removed or “washed out” from a glacier by meltwater streams and deposited in front of or beyond the end moraine or the active margin of a glacier. The coarser material is deposited nearer to the ice (Bates and Jackson, 1980, p. 446).

## P

**Porosity** A property of a rock or soil containing interstices or voids. Porosity is expressed as the ratio of the volume of voids to the volume of the rock or soil, either as a decimal fraction or a percentage. A related term is effective porosity, which refers to the amount of interconnected pore space available for fluid transmission (Lohman and others, 1972, p. 10).

**Potentiometric surface** A surface that represents the static head and is defined by the levels to which water will rise in tightly cased wells. Where head varies appreciably with depth, a potentiometric surface is meaningful only if it defines the static head along a specified surface or stratum in the aquifer.

More than one potentiometric surface may be required to define the three-dimensional distribution of head in an aquifer. The water table is a particular potentiometric surface (Lohman and others, 1972, p. 11).

## R

**Rift** A long, narrow continental trough that is bounded by normal faults; a graben of regional extent. It marks a zone along which the entire thickness of the lithosphere has ruptured under extension (Bates and Jackson, 1980, p. 538).

## S

**Sandstone** A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material. Sandstone is the consolidated equivalent of sand, intermediate in texture between conglomerate and shale (Bates and Jackson, 1980, p. 554).

**Schist** A strongly foliated crystalline rock, formed by dynamic metamorphism, which can be split into thin flakes or slabs due to the well-developed parallelism of more than 50 percent of the minerals present, particularly those of lamellar or elongate prismatic habit, for example mica and hornblende (Bates and Jackson, 1980, p. 559).

**Specific retention** The ratio of (1) the volume of water that a porous medium, after being saturated, will retain against the pull of gravity to (2) the volume of the porous medium (Lohman and others, 1972, p. 12). Specific retention is the difference between porosity and specific yield.

**Specific yield** The ratio of (1) the volume of water that a porous medium, after being saturated, will yield by gravity to (2) the volume of the porous medium (Lohman and others, 1972, p. 12). Specific yield is the difference between porosity and specific retention.

## T

**Till** Dominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by and beneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape (Bates and Jackson, 1980, p. 653).

**Transmissivity** The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). Though spoken of as a property of the aquifer, it also embodies the saturated thickness of the aquifer and the properties of the contained liquid. The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

**Tuff** A general term for all consolidated pyroclastic rocks. Pyroclastic rock material is formed by volcanic explosion or aerial expulsion from a volcanic vent (Bates and Jackson, 1980, p. 669).