Ground-Water Hydrology of the Central Raton Basin, Colorado and New Mexico

United States Geological Survey Water-Supply Paper 2288

Prepared in cooperation with the U.S. BUREAU OF LAND MANAGEMENT

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Ground-Water Hydrology of the Central Raton Basin, Colorado and New Mexico

By ARTHUR L. GELDON

Prepared in cooperation with the
U.S. BUREAU OF LAND MANAGEMENT

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2288

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CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System (SI) units by using the following conversion factors:

Multiply	By	To obtain
Acre	4.047×10^{-1}	Hectare
Acre-foot (acre-ft)	1.233×10^{-3}	Cubic hectometer
Cubic foot (ft^3)	2.832×10^{-2}	Cubic meter
Cubic foot per second (ft^3/s)	2.832×10^{-2}	Cubic meter per second
Cubic foot per second per mile ($ft^3/s/mi$)	1.760×10^{-2}	Cubic meter per second per kilometer
Degree Fahrenheit (°F)	°C=5/9(°F–32)	Degree Celsius
Foot (ft)	3.048×10^{-1}	Meter
Foot per day (ft/d)	3.048×10^{-1}	Meter per day
Gallon (gal)	3.785	Liter
Gallon per minute (gal/min)	6.309×10^{-2}	Liter per second
Inch (in.)	2.540	Centimeter
Mile (mi)	1.609	Kilometer
Square foot per day (ft^2/d)	9.290×10^{-2}	Square meter per day
Square mile (mi^2)	2.590	Square kilometer

Altitudes are referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada. This datum is referred to as "sea level" in this report.

Ground-Water Hydrology of the Central Raton Basin, Colorado and New Mexico

By Arthur L. Geldon

Abstract

The watersheds of the Purgatoire and Apishapa Rivers contain most of the public coal lands in the Raton Basin. The U.S. Geological Survey, in cooperation with the U.S. Bureau of Land Management, investigated the hydrogeology of this area from 1978 to 1982, inventorying 231 wells, 38 springs, and 6 mines, and collecting ground-water samples from 71 sites.

The Raton Basin is an asymmetrical trough, containing 10,000 to 25,000 feet of sedimentary rocks that range in age from Pennsylvanian to Eocene. These rocks are intruded by Miocene igneous rocks, covered with Pleistocene and Holocene alluvium on pediments and in stream valleys, and underlain by Precambrian crystalline rocks. Bituminous coal occurs in the Vermejo and Raton Formations of Cretaceous and Paleocene age. Virtually all of the sedimentary rocks transmit water.

Stream alluvium is the most productive aquifer. Bedrock aquifers have smaller yields but greater distribution. The principal bedrock aquifers are the Cuchara-Poison Canyon and the Raton-Vermejo-Trinidad. Other formations are nearly impermeable or too deep to be utilized economically. The Cuchara-Poison Canyon aquifer provides small, nonsustainable yields to wells. Sandstone and coal layers in the Raton-Vermejo-Trinidad aquifer provide small, sustainable yields, but many of these beds are lenticular and can be missed easily by wells.

Water in alluvium typically is less mineralized than in bedrock but more susceptible to contamination. Sodium and calcium bicarbonate waters predominate in the area, but sodium chloride water commonly occurs in the Cuchara–Poison Canyon aquifer and may occur in the Pierre Shale. Plumes of sulfate-enriched water extend from coal mines into bedrock and alluvial aquifers. Dissolved-solids concentrations range from less than 500 milligrams per liter in calcium bicarbonate water to more than 1,500 milligrams per liter in sulfate and chloride waters. Much of the ground water is hard. Nitrogen is enriched in shallow ground water, and fluoride is enriched in deeper ground water. Levels of iron, manganese, zinc, and selenium locally exceed standards for domestic consumption.

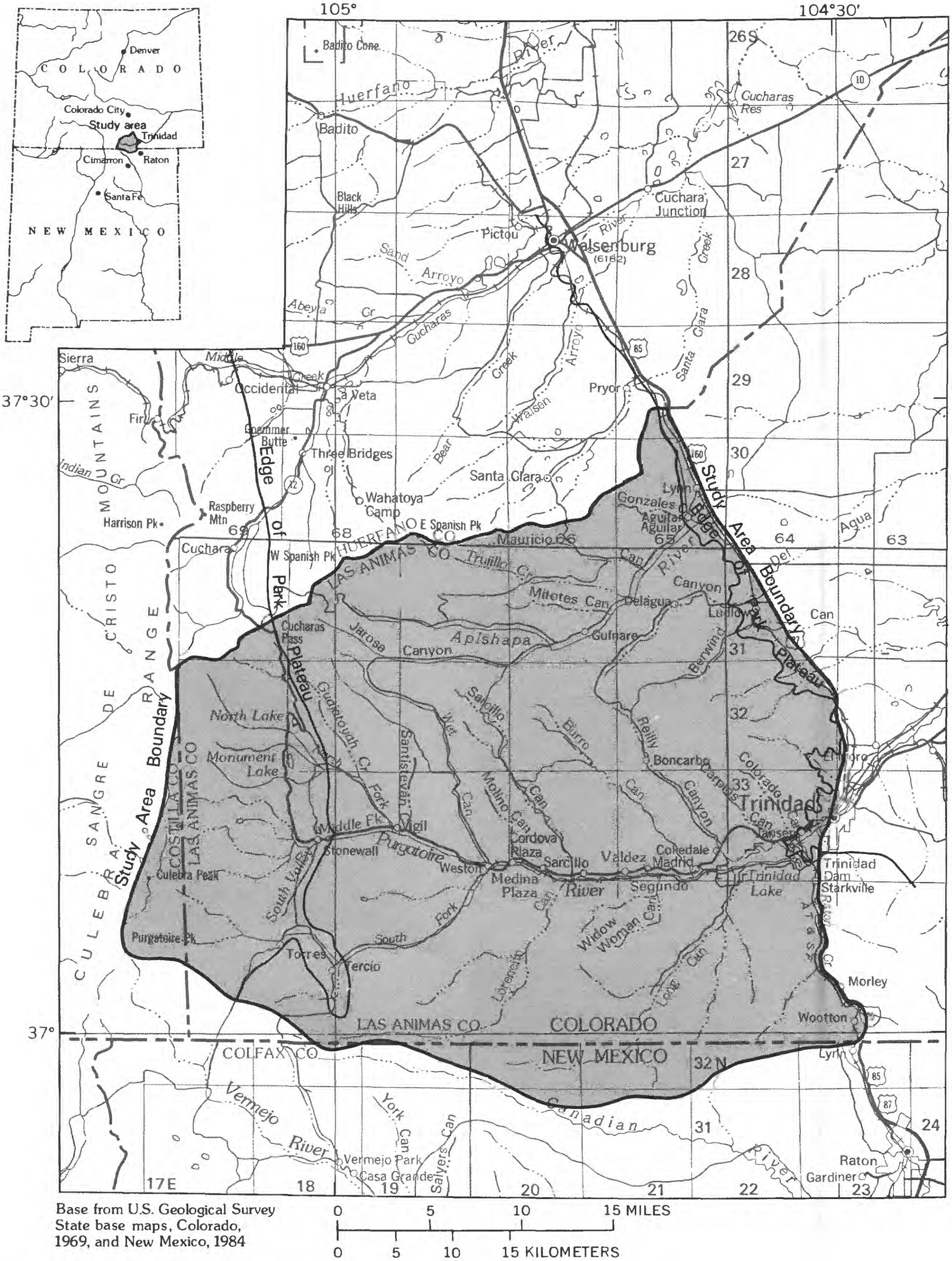
The Purgatoire River and its tributaries are predominantly gaining streams, but losing reaches occur. Water quality in streams is affected by tributary inflows, mine discharge, contact with and seepage from tailings, ground-water seepage, diversion ditches, and changes in stage. Ground water flows regionally from west to east and locally from stream divides to valleys. Depths to water vary from 500 feet beneath divides to less than 100 feet in valleys. Springs typically develop where valleys intersect the water table, at or below the contact between the Poison Canyon and Raton Formations, and in stream channels that are crossed by dikes or sills or underlain by shallow bedrock. Most of the water in regional circulation discharges into surface drainages before reaching the east side of the basin. Ground-water supplies probably are insufficient for expanded settlement and coal mining.

INTRODUCTION

The Raton Basin in southeastern Colorado and northeastern New Mexico contains 2.7 billion tons of bituminous coal reserves. Most of the public coal lands are in the watersheds of the Purgatoire and Apishapa Rivers. Water resources needed to mine coal are scarce in these watersheds, and potential conflicts exist between coal miners and other water users. Current water use is divided among dispersed livestock grazing, rural residences, small family farms, coal mines, and public supplies for small communities.

In anticipation of increased competition for water supplies caused by coal mining, the U.S. Geological Survey, in cooperation with the U.S. Bureau of Land Management, studied the existing hydrologic system in the Purgatoire and Apishapa watersheds. The area of this study includes much of Las Animas County, Colo., and small parts of Costilla County, Colo., and Colfax County, N. Mex. (fig. 1). The results of the study provide a basis for assessing the impacts of future coal mining.

Several previous reports discuss the hydrology of the study area and adjacent areas in the Raton Basin.



Base from U.S. Geological Survey State base maps, Colorado, 1969, and New Mexico, 1984

Figure 1. Location of study area (shaded).

Griggs (1948) described water availability and quality in Colfax County, N. Mex., southeast of the study area. Powell (1952) investigated the hydrology of alluvium in the flood plain of the Purgatoire River west of Trinidad, Colo. McLaughlin (1966) discussed the hydrogeology of Huerfano County, north of the study area. Water, Waste, and Land, Ltd. (1980) examined the impact of coal mining on surface and ground water near the Allen and Maxwell coal mines near Weston, Colo. Repplier and others (1981) mapped ground-water quality in the Colorado part of the Raton Basin. Howard (1982) and Abbott and others (1983) described the hydrology of the Raton Basin on a regional scale.

This report contains the results of an investigation of ground water in the watersheds of the Purgatoire and Apishapa Rivers west of a line connecting Aguilar and Trinidad, Colo. (fig. 1). It describes the availability and quality of water in aquifers likely to be affected by coal mining and the nature of ground-water flow and its relation to surface water.

Previous geologic and hydrogeologic reports, field investigations, and unpublished data were used to assess the hydrologic system. Field investigations were made in three phases:

1. During 1978 and 1979, wells in the study area and the rest of the Raton Basin in Colorado were inventoried, several aquifer tests were run, samples of water from wells were collected for chemical analyses, and a network of observation wells for recording annual fluctuations in ground-water levels was established in Las Animas County.

2. During 1981, additional wells, many springs, and several mine sites were inventoried in the study area; samples of water from additional wells and from some of the previously sampled wells were collected for chemical analyses; samples of water from springs and mine sites also were collected; seepage runs on five tributaries of the Purgatoire River were made; the observation-well network was modified; and a reconnaissance of hydrogeologic conditions was made.

3. During 1982 and 1983, a seepage run on the Purgatoire River was made, a sample of water from a mine shaft was collected for chemical analysis, and an underground coal mine in the area was visited to inspect ground-water seepage.

Unpublished data used in this report include coal company records of well logs, aquifer tests, ground-water quality, and observation-well water levels; well permits containing well logs and production test data filed with the Colorado Division of Water Resources State Engineer; well logs and aquifer test results at dam sites provided by the U.S. Bureau of Reclamation and U.S. Army Corps of Engineers; and coal exploration test-hole logs in files of the U.S. Geological Survey.

Acknowledgment is gratefully given to the many landowners in the area who allowed access to their property for the installation of gages, measurements of streamflow and ground-water levels, the collection of water samples, and the compilation of well and spring records. The author especially wishes to thank CF&I Steel Corp. and Kaiser Steel Corp. for allowing inspection of their mining operations and for providing well logs and records of water levels and water quality in monitoring wells that were used in the preparation of this report.

SYSTEM OF NUMBERING WELLS AND SPRINGS

Wells and springs in Colorado are numbered according to the U.S. Bureau of Land Management system, which is illustrated in figure 2. The first letter in the location number refers to the principal survey meridian; the second, the quadrant formed by the intersection of the meridian and a latitudinal baseline. The first number in the location number refers to the township; the second, the range; and the third, the section. Letters following the section number refer to the position within a section, which may be indicated as precisely as the quarter-quarter-quarter section. Quadrants and positions within a section are lettered counterclockwise from the northeast, beginning with the letter "A" (uppercase for quadrants, lowercase for positions within a section). When two or more wells or springs are located in the smallest subdivision, wells inventoried by the U.S. Geological Survey are assigned sequential numbers (affixed to the end of the location number). Uninventoried wells are generally not assigned sequential numbers. In figure 2, well SC03006521ccb2 is the second well in the northwest quarter of the southwest quarter of the southwest quarter, section 21, township 30 south, range 65 west, in the southwest quadrant of the sixth principal meridian. In informal references to location, meridian and quadrant designations may be dropped, and dashes instead of zeros may be placed between the township, range, and section numbers.

DATA BASE

From 1978 to 1982, the U.S. Geological Survey inventoried 231 wells, 38 springs, and 6 mine sites in the area (fig. 3). However, many more wells, springs, and mines exist than are cataloged. The Colorado Division of Water Resources (CDWR), State Engineer's Office, Denver, Colo., maintains a file of well-completion and pump-installation reports but does not verify that reported wells are correctly located or operable. During field investigations, the author was unable to locate many of the wells reported to be in the area by the CDWR.

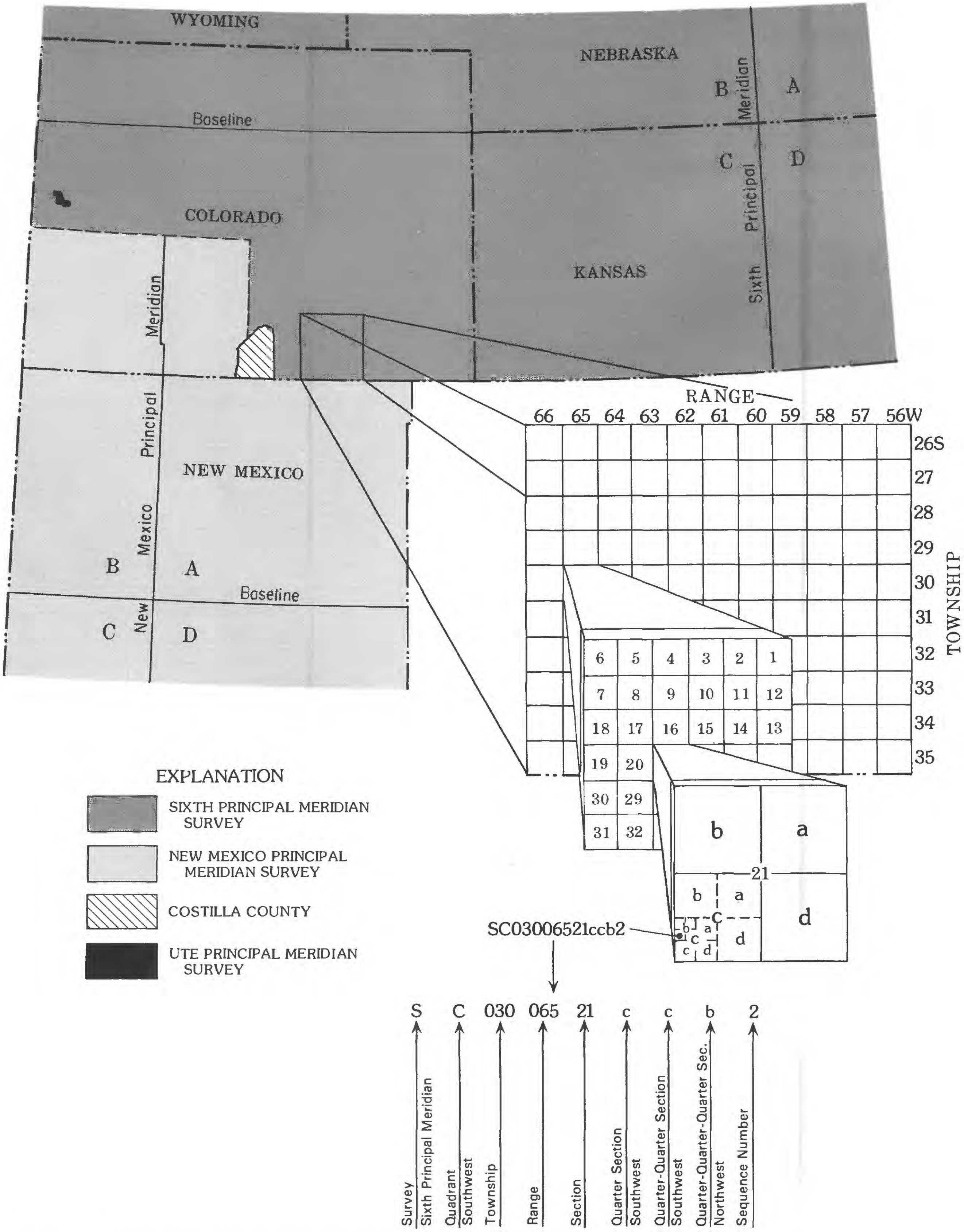
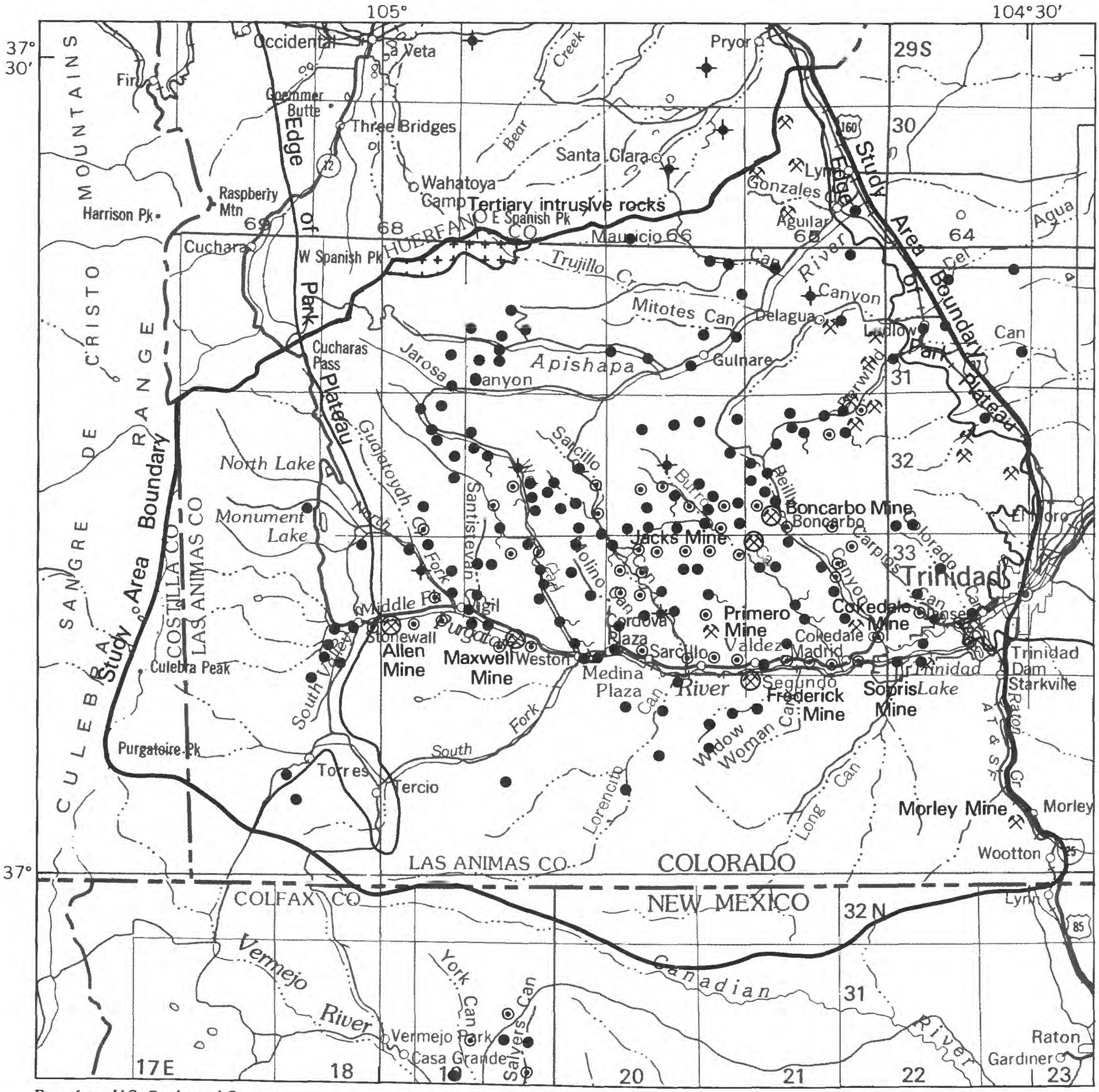


Figure 2. System of numbering wells and springs.



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

DATA SITES—All sites with ground-water data in the study area that were visited by the U.S. Geological Survey are shown. Most sites within 10 miles of the study area with aquifer test or water-level data used in the report are shown also

- ● Inventoried well developed for stock, domestic, public supply, irrigation, or commercial use
- ✦ U.S. Geological Survey observation well
- Inventoried spring
- ⨂ Inventoried mine-shaft discharge
- ◉ Site with 2 to 5 inventoried wells and springs
- O Site of Apishapa River alluvium aquifer tests
- ⚒ Coal mine

Figure 3. Location of inventoried wells, springs, and mine shafts in the central Raton Basin.

Many lithologic and geophysical logs of exploration holes were reviewed in preparing this report. Sources for these logs included American Stratigraphic Co., Petroleum Information, Inc., Petro-Well Data Library, Ltd., Rocky Mountain Well Log Service, and Kaiser Steel Corp.

Until 1983, the U.S. Geological Survey, in cooperation with the CDWR, annually measured water levels in selected wells across the State. In 1980 and 1981, the U.S. Geological Survey monitored water levels in seven wells in the study area. These wells were replaced in 1981 with six other wells. Water levels in these wells were measured for periods of 1 to 2 years.

To supplement this short record of observed water levels in assessing ground-water availability, records of 6 observation wells monitored by the U.S. Geological Survey in Huerfano County, Colo., and 29 observation wells monitored by Kaiser Steel Corp. at its York Canyon Mine in Colfax County, N. Mex., were incorporated into the investigation. All of these additional wells are in the Raton Basin, and most are within 25 mi of the study area.

In 1951 and from 1977 through 1982, the U.S. Geological Survey collected water samples from 50 wells, 16 springs, and 5 mines (fig. 4) for analyses of major ions and selected minor and trace elements. Temperature, specific conductance, and pH were measured with standard instruments when the samples were collected, and the samples were then prepared and analyzed according to methods described in Skougstad and others (1979). Additional analyses of water from six observation wells, two mine shafts, and one tailings dump by CF&I Steel Corp. were compiled from Water, Waste, and Land, Ltd. (1980). In all, 87 chemical analyses from 79 sites were compiled for this report.

Records of standard aquifer tests are scarce in the study area. This information includes five slug and pumping tests by the U.S. Geological Survey, two pressure tests by the U.S. Army Corps of Engineers, three pumping tests by the city of Aguilar, and seven slug and pumping tests by CF&I Steel Corp. Although numerous bailing tests are documented on well permits in files of the CDWR, this information is of dubious value without substantial corroboration by standard aquifer tests. To aid in the investigation, the results of 4 slug and pumping tests by the U.S. Geological Survey in Huerfano County and 15 slug and pumping tests by Kaiser Steel Corp. in Colfax County were incorporated into the report. Most of the information from Huerfano and Colfax Counties was obtained within 10 mi of the study area.

Information on well, spring, and minesite records, well-water levels, and ground-water quality is stored in U.S. Geological Survey computer files and can be obtained from the data report accompanying this interpretive study (Geldon and Abbott, 1984). Information on some of the ground-water sites also can be obtained from previous reports such as those of Powell (1952), Water, Waste, and Land, Ltd. (1980), and Howard (1982). Logs of some of the wells and exploration holes in the area and the results of all known aquifer tests in the area are included in a report by Geldon and Abbott (1984). Some aquifer tests are documented by Wilson (1965), Water, Waste, and Land, Ltd. (1980), and Howard (1982).

REGIONAL SETTING

Physiography

The study area (fig. 1) is bordered by Interstate Highway 25 on the east, the Purgatoire River–Canadian River divide on the south, the crest of the Culebra Range of the Sangre de Cristo Mountains on the west, and the Las Animas–Huerfano County line on the north. Most of the area is in the Park Plateau section of the Great Plains physiographic province (Fenneman, 1931, p. 40).

The Park Plateau is deeply dissected by two consequent streams, the Purgatoire and Apishapa Rivers, and their tributaries. The eastern escarpment of the plateau, supported by ledges of sandstone in the Trinidad Sandstone and Raton Formation, rises abruptly from the plains (fig. 5). On the west, the geologic formations underlying the plateau are warped vertically into hogbacks, the most prominent of which is the Stonewall, composed of Dakota Sandstone (fig. 6). The northwest side of the plateau rises gradually to two prominent igneous intrusions, the Spanish Peaks (fig. 7), which dominate the landscape.

Altitudes vary from 6,000 ft below the plateau escarpment near Trinidad to 14,047 ft on Culebra Peak. The altitude of West Spanish Peak is 13,626 ft and that of East Spanish Peak is 12,683 ft. Most of the area ranges from 6,400 to 8,400 ft in altitude.

Trinidad, in the southeast corner of the area, is the only major population center. Smaller communities include Stonewall, Weston, Medina Plaza, Segundo, Cokedale, and Aguilar; others shown on maps exist mainly in memory.

Climate

The climate is mainly semiarid, with annual precipitation ranging from 14 in. at Trinidad to greater than 40 in. in the Spanish Peaks and Culebra Range (fig. 8). July and August are the wettest months. During the summer, storms are localized, intense, and fast moving. November to February are the driest months. During the fall and winter, storms are regional and stationary. In most years, snowfall at lower altitudes remains on the ground for short periods, but a snowpack is retained at higher altitudes from November to June. Melting of this

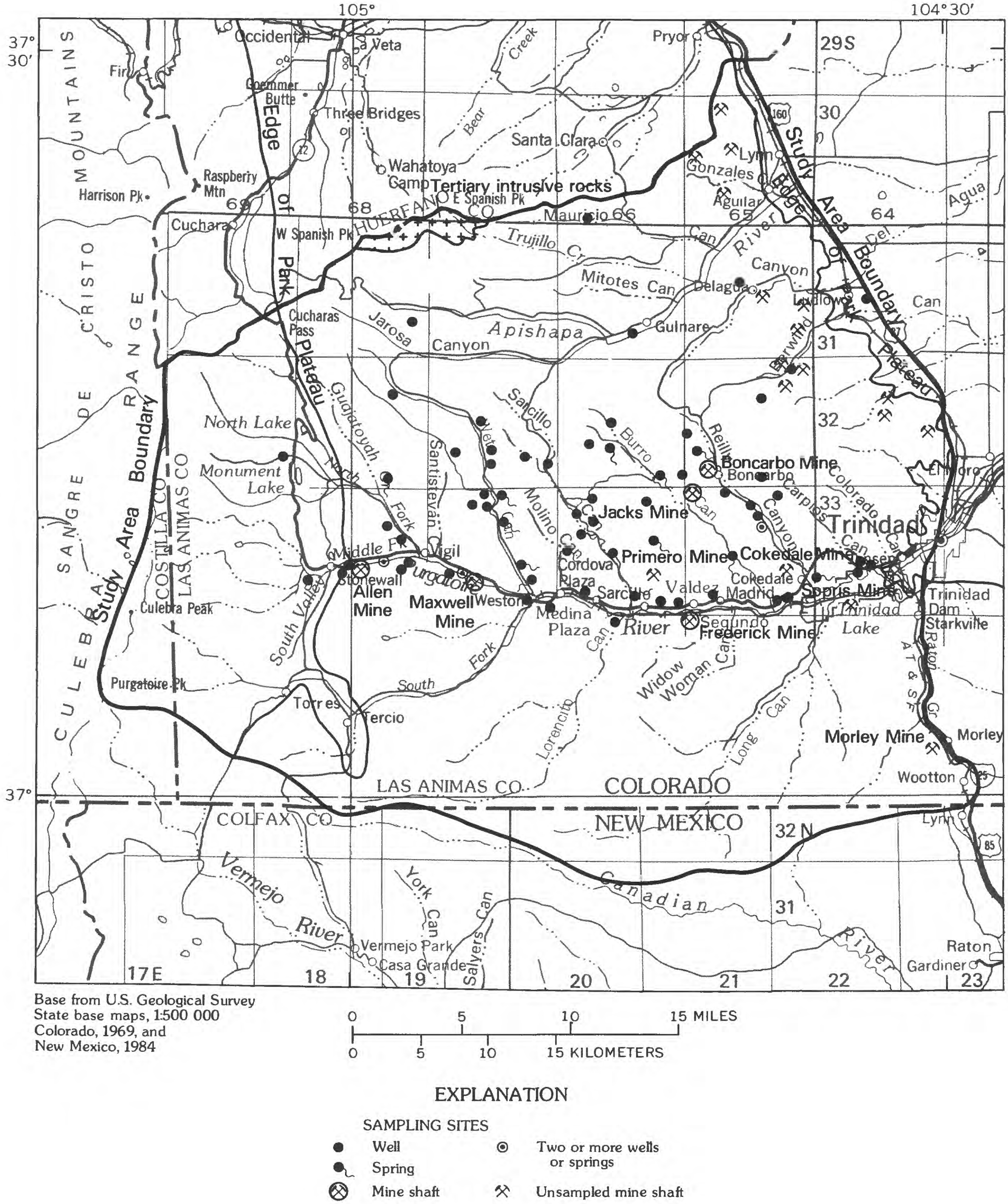


Figure 4. Location of sampled ground-water sites in the central Raton Basin.

Figure 5. Eastern escarpment of Park Plateau near Trinidad, Colo. View to the west from Interstate 25. Light-colored Trinidad Sandstone overlies dark-colored Pierre Shale in escarpment.

Figure 6. The Stonewall (Dakota Sandstone hogback) and Culebra Range near Tercio, Colo.

snowpack in the spring months swells streams with runoff.

Air temperatures fluctuate 3 to 5 °F per thousand feet of altitude but change little with latitude. As an example, the mean annual air temperature (1961–80) increases from 41.6 °F at North Lake (altitude 8,800 ft) to 51.6 °F at Trinidad (altitude 6,030 ft). This amounts to a change of 3.6 °F per thousand feet of altitude. However, Trinidad and Walsenburg, which are at about the same altitude but separated by about 30 minutes of

Figure 7. West Spanish Peak near Cuchara, Colo. The peak consists of syenodiorite and metamorphosed sedimentary rocks of the Huerfano and Cuchara Formations.

latitude, have approximately the same mean annual air temperature.

At any location, July is the warmest month and January is the coldest. Average July temperatures range from 73 °F at Trinidad to 54 °F in the Culebra Range, whereas average January temperatures range from 32 °F at Trinidad to 17 °F in the Culebra Range (based on U.S. Weather Bureau, 1959, p. 12–16, and records of the U.S. Weather Bureau and National Oceanic and Atmospheric Administration, 1920–81).

Drainage

The principal streams in the area are the Apishapa and Purgatoire Rivers, both of which are tributaries of the Arkansas River. The Apishapa watershed is 147 mi^2 and the Purgatoire watershed is 795 mi^2. Both streams cut across the regional structure and, thus, are classified as consequent.

The Apishapa River is a perennial stream; but, in some years, because of diversions for irrigation, no flow occurs for many days at Aguilar, at the eastern edge of the Park Plateau. In a rather short period of record (4 water years), the maximum recorded discharge at Aguilar was 5,200 ft^3/s (U.S. Geological Survey, 1982). The principal tributaries of the Apishapa River in the study area are Gonzales Canyon, Mauricio Canyon, Jarosa Canyon, Canyon del Agua, and Trujillo Creek. These canyons carry perennial flow in the vicinity of springs and ephemeral flow from storms and snowmelt.

The Purgatoire River (fig. 9) is a perennial stream that is depleted by diversions for irrigation of about 6,000 acres. Since August 19, 1977, the river has been completely regulated by Trinidad Dam, 2 mi upstream from Trinidad, Colo. Prior to completion of the dam, the average flow at Trinidad for 68 years of record was 83.3 ft^3/s (60,350 acre-ft/yr). The maximum discharge was 28,000 ft^3/s (in 1955), and periods of no flow occurred in the river in only 3 years—1896, 1950, and 1956 (U.S. Geological Survey, 1977). Peak flows have been reduced since completion of the dam, and from 1977 to 1981, the average discharge at Trinidad was 57.7 ft^3/s (41,800 acre-ft/yr).

The Purgatoire River is formed by the confluence of the South and Middle Forks at Weston, Colo. The principal tributaries in the study area include Wet Canyon, Lorencito Canyon, Sarcillo Canyon, Burro Canyon, Reilly Canyon, Long Canyon, Raton Creek, and Berwind Canyon.[1] As with the tributaries of the Apishapa River, streamflow in these canyons is intermittent to ephemeral (fig. 10).

Hydrographs of the Purgatoire and Apishapa Rivers (figs. 11 and 12) illustrate the phases of the annual runoff cycle. These rivers typically are at base flow from the end of October to early spring. During this time, storms may increase discharge slightly for a few days, and

[1]Berwind Canyon upstream from the Berwind ruins is referred to on topographic maps as Road Canyon. In this report, the entire canyon is referred to as Berwind Canyon, because the point at which the name changes does not correspond to a physiographic change.

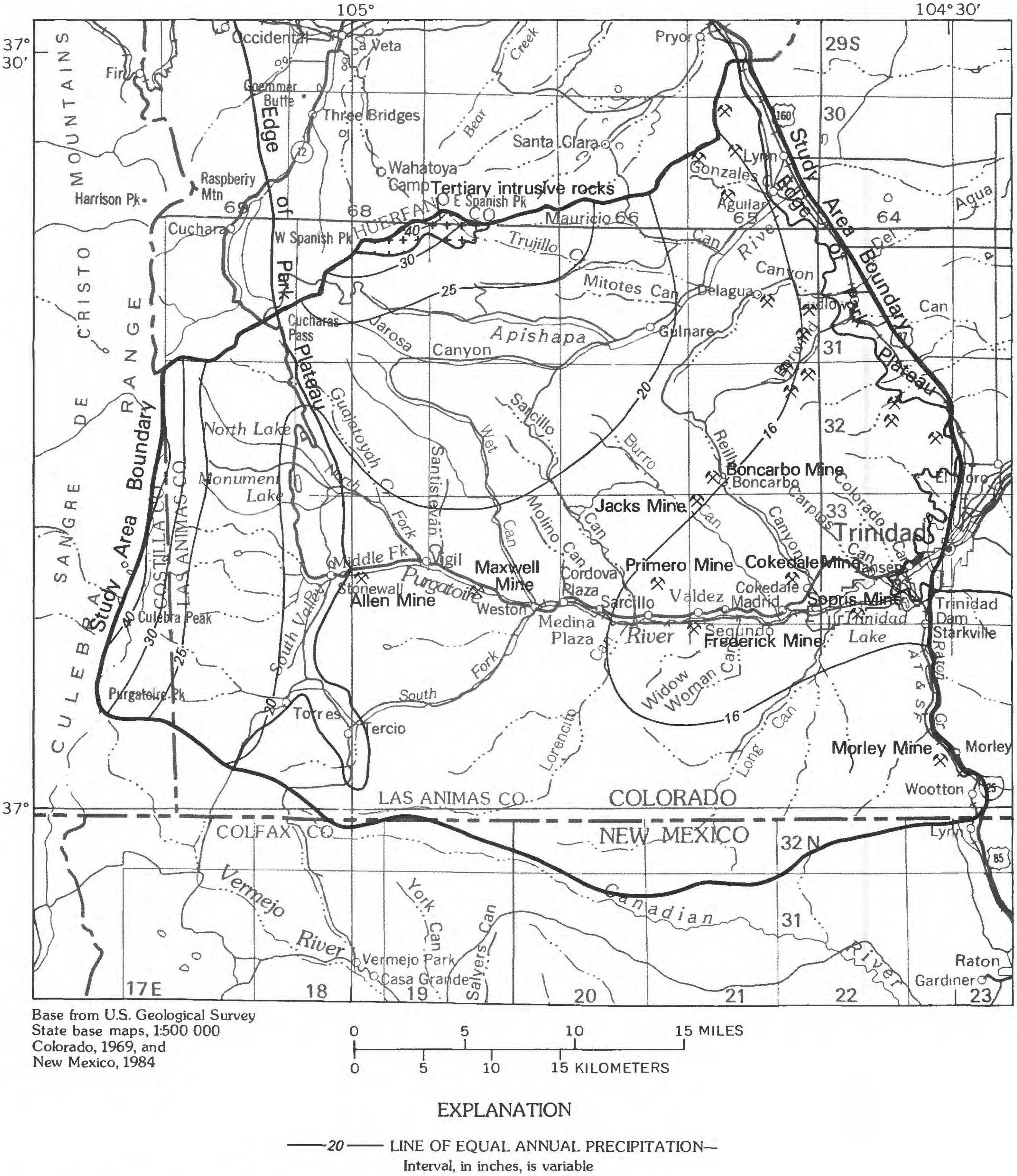


Figure 8. Normal annual precipitation, 1931–60, in the central Raton Basin.

subfreezing temperatures may decrease discharge for a few days. Beginning in March, April, or May, snowmelt from the Culebra Range and Spanish Peaks, induced by warming temperatures and precipitation, fills the channels with runoff. This spring runoff usually peaks between June and early August. Recession from the peak occurs over a few weeks. From July to October, thunderstorms result in rapid rises in runoff, immediately

Figure 9. Purgatoire River flowing past outcrop of the Raton Formation near Segundo, Colo. The river is swollen with storm runoff. In the outcrop, a lens of arkosic sandstone occurs between layers of carbonaceous shale.

Figure 10. Sarcillo Canyon near Segundo, Colo., showing channel cut into the Raton Formation and terrace alluvium. The Raton Formation here consists of interbedded arkosic sandstsone and carbonaceous shale.

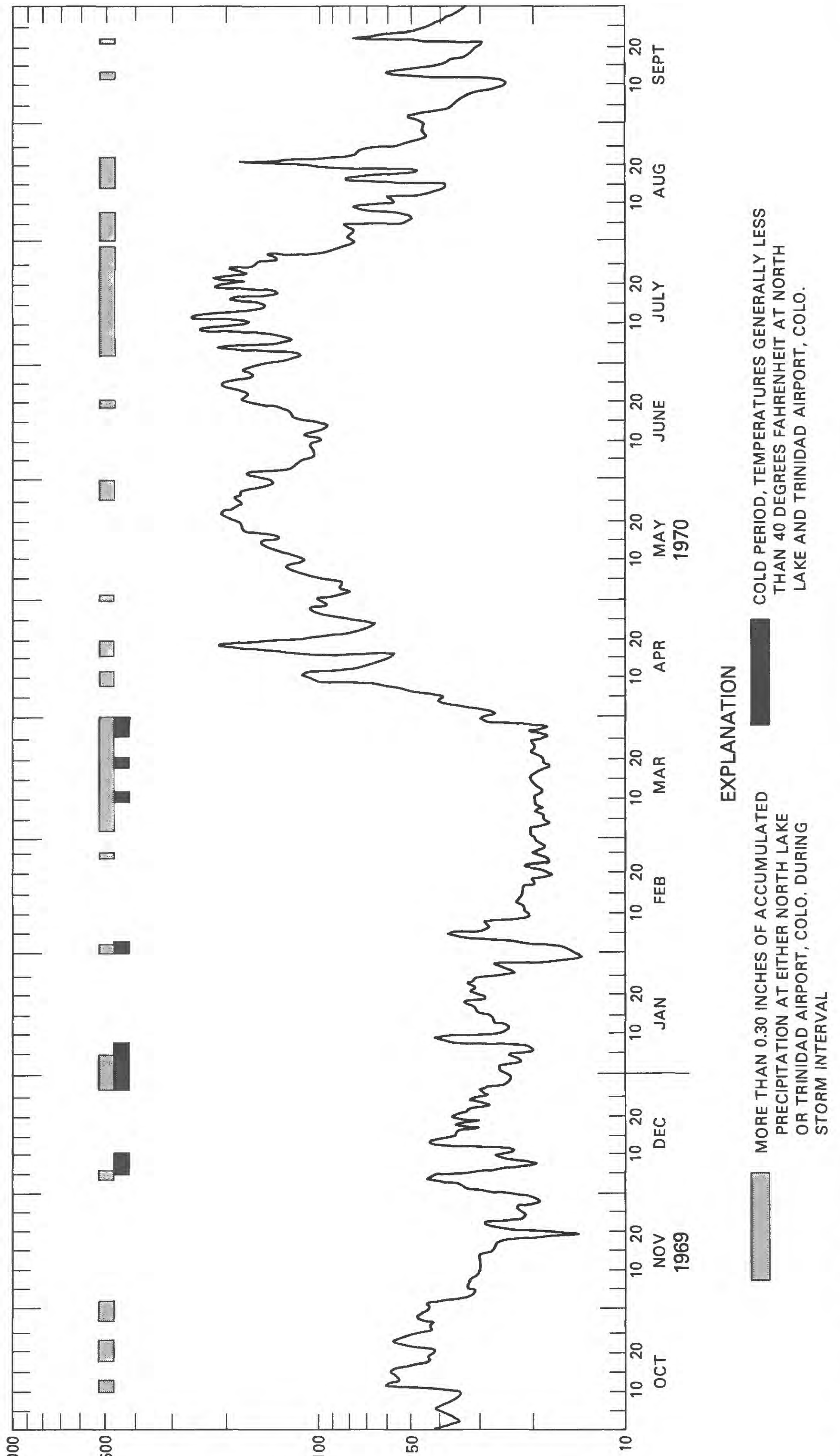


Figure 11. Discharge in the Purgatoire River at Trinidad, Colo., water year 1970.

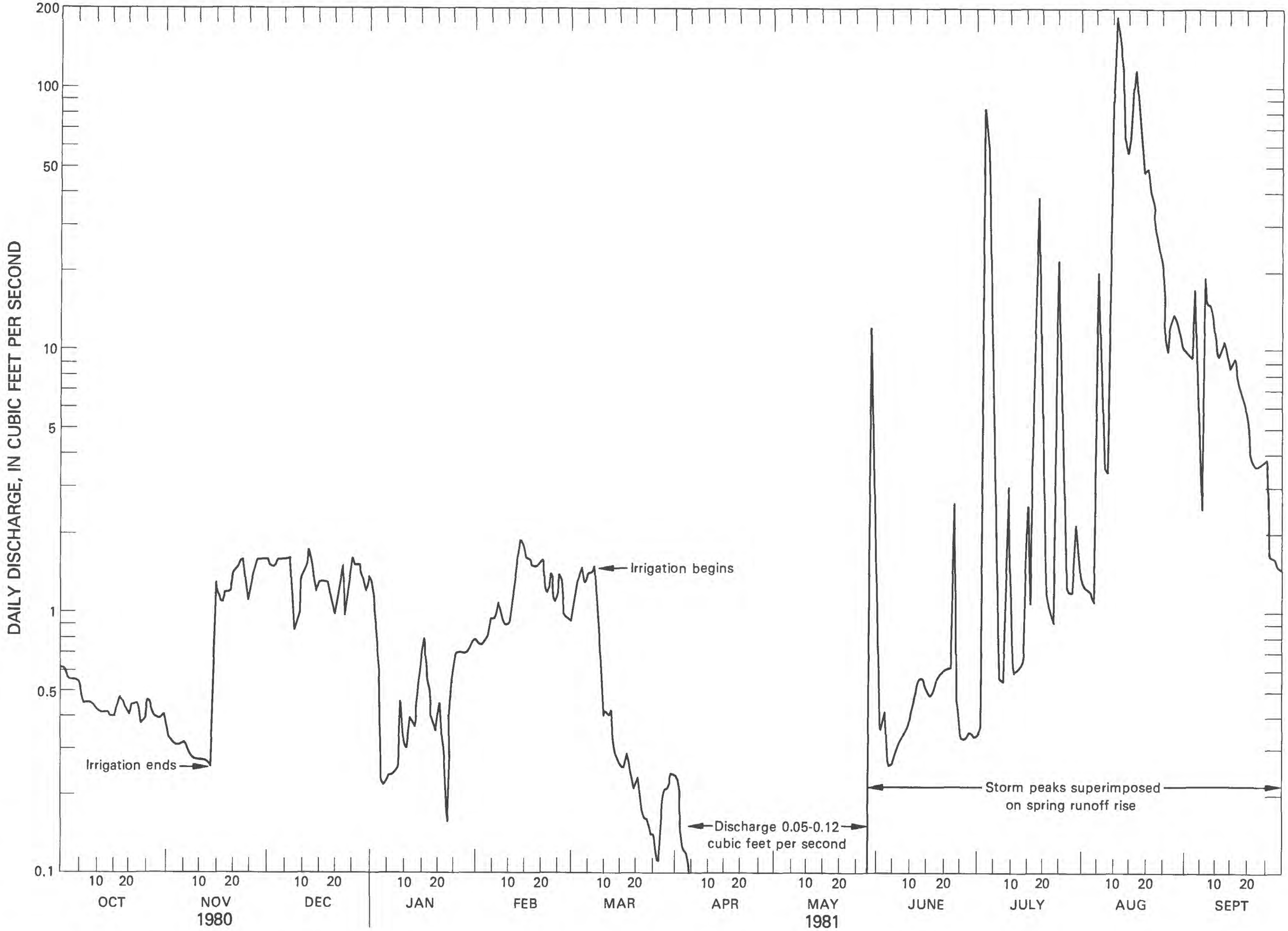


Figure 12. Discharge in the Apishapa River at Aguilar, Colo., water year 1981.

followed by rapid recessions. Diversions for irrigation result in abruptly decreased streamflow from late spring to early fall. Cessation of irrigation abruptly restores streamflow to a higher sustained level.

Hydrologic Cycle

The circulation of water between the atmosphere and the land is termed the hydrologic cycle (fig. 13). In the Raton Basin, water enters by precipitation. Snow gradually releases moisture to aquifers and streams as it melts, whereas contributions from rainfall are more immediate.

Some of the moisture stored by bedrock and alluvium as ground water is pumped from wells, and some of it discharges as springs. Ground water flows from bedrock through alluvium or directly into streams when the streams are not swollen by snowmelt or storm runoff. When streams are carrying higher than normal runoff, some of this moisture infiltrates bedrock and alluvium as bank storage.

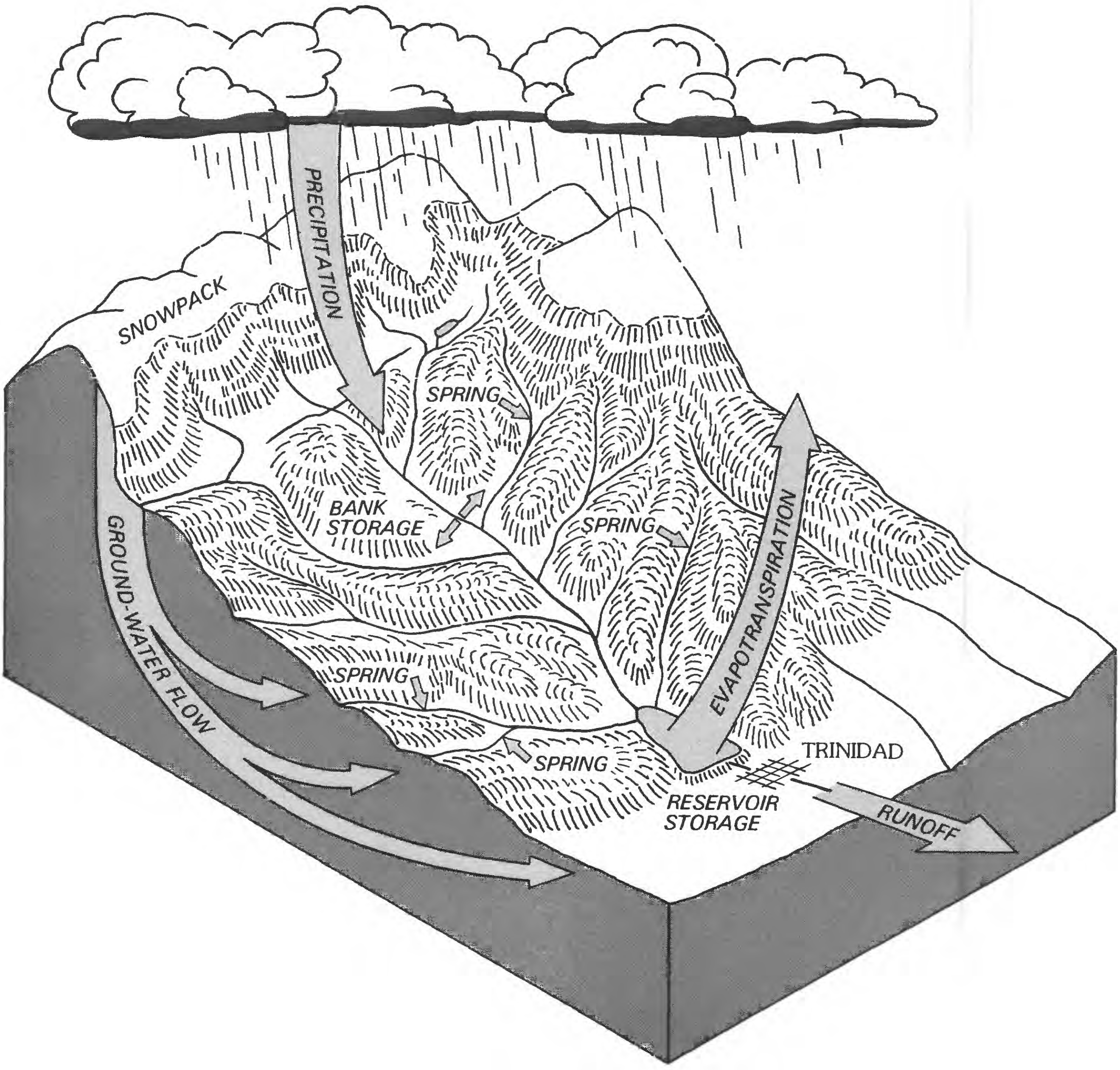


Figure 13. Hydrologic cycle in the central Raton Basin.

Some of the surface flow is diverted for irrigation. Much of this water is transpired by irrigated crops, but some of it evaporates and some of it returns to streams and aquifers. Some mines pump ground water from wells or divert surface water in order to operate but also release water from mine shafts into ponds and streams. The city of Trinidad diverts water from reservoirs for municipal use. Much of the water in the basin is consumed by evapotranspiration. Additional water leaves the area by surface runoff and ground-water flow.

GEOLOGY

Stratigraphy

Sedimentary rocks of Cretaceous to Eocene age underlie most of the area east of the western escarpment of the Park Plateau (fig. 14). Sedimentary rocks of Jurassic and Cretaceous age underlie valleys between the Park Plateau and the Culebra Range of the Sangre de Cristo Mountains. Sedimentary rocks of Pennsylvanian and Permian age and igneous and metamorphic rocks of Precambrian age form the Culebra Range. Igneous dikes, sills, and stocks of Tertiary age intrude the other formations in the area. The Spanish Peaks, the area's dominant topographic feature, are formed by two of these stocks. Metamorphic rocks formed by baking of sedimentary rocks during intrusion of the Spanish Peaks stocks occur on the upper slopes of the Peaks. Alluvium of Pleistocene and Holocene age fills stream valleys to varying depths and caps pediments.

The stratigraphy of the area is summarized in table 1. Detailed descriptions of the geology and geologic history are contained in reports by Griggs (1948), Wood and others (1951, 1956, 1957), Cobban (1956), Johnson and Wood (1956), Johnson and others (1956, 1958), Johnson (1968, 1969), Shaw (1956), Harbour and Dixon (1959), Pillmore (1969a, 1969b, 1976a, 1976b), Pillmore and Maberry (1976), Speer (1976), Billingsley (1977), Dolly and Meissner (1977), Danilchick (1979a, 1979b), Smith (1979), Berman and others (1980), De Voto (1980), Maughan (1980), and Tweto (1980).

The oldest rocks in the area are gneiss, schist, granite, and pegmatite of Precambrian age. Wood and others (1957, p. 11) estimated that the Precambrian rocks may be less than 10,000 ft deep beneath the eastern side of the Park Plateau and 15,000–25,000 ft deep beneath the western side of the Plateau.

Formations of Pennsylvanian to Jurassic age are in thrust-faulted contact with Precambrian rocks in the Culebra Range and, as revealed in wells drilled east of the study area, extend beneath the Park Plateau. These rocks consist of predominantly nonmarine and transitional sedimentary rocks of the Pennsylvanian Kerber, Sharpsdale, and Minturn Formations (De Voto, 1980), Pennsylvanian and Permian Sangre de Cristo Formation, Permian Yeso Formation and Glorieta Sandstone, Triassic Dockum(?) Group, and Jurassic Entrada Sandstone, Ralston Creek Formation, and Morrison Formation. The Sangre de Cristo Formation and Triassic rocks wedge out northeastward across the area as the Yeso Formation and Glorieta Sandstone thicken. Rocks of Pennsylvanian and Permian age are estimated by Wood and others (1956, 1957) to range in thickness from several thousand feet in the eastern part of the area to 20,000 ft in the western part. East of Trinidad, rocks of Permian and Triassic age or both are 160–180 ft thick. Jurassic rocks in the basin are 300–400 ft thick.

Deposits of a Cretaceous sea border the west side of the Park Plateau and extend beneath it to the eastern edge of the study area. The Purgatoire Formation and Dakota Sandstone, which together average about 200 ft thick, mark the advance of the sea. The Purgatoire Formation consists of the Cheyenne Sandstone Member, 50–105 ft thick, and overlying Kiowa Shale Member, 10–30 ft thick. The Cheyenne Sandstone Member is a yellowish-brown, fine- to coarse-grained, cross-stratified, conglomeratic and quartzitic sandstone. The Kiowa Shale Member is a gray to dark-gray carbonaceous shale. The Dakota Sandstone, 50–200 ft thick, consists of several beds of white to tan, fine- to coarse-grained, intricately jointed, cross-stratified quartzitic and conglomeratic sandstone, locally interbedded with gray to dark-gray shale (fig. 15).

The Dakota Sandstone is overlain by 3,100 ft of gray to dark-gray shale containing thin layers of limestone and sandstone that comprise the Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation (Fort Hays Limestone and Smoky Hill Marl Members), and Pierre Shale. The upper 100–300 ft of the Pierre Shale consists of interbedded shale and sandstone deposited in a fluctuating shoreline environment (fig. 16).

The final retreat of the sea is marked by deposition of the Trinidad Sandstone, a beach deposit, 45–310 ft thick. The Trinidad Sandstone consists of several beds of tan to light-gray, fine- to medium-grained, massive, well-cemented, slightly arkosic sandstone separated by thin beds of gray to tan, silty shale. The Trinidad Sandstone crops out in the escarpments of the Park Plateau and is more than 5,000 ft deep beneath the Spanish Peaks, on the west side of the plateau.

The Park Plateau is underlain principally by the Vermejo Formation of Cretaceous age, the Raton Formation of Cretaceous and Paleocene age, and the Poison Canyon Formation of Paleocene age, but remnants of the Cuchara and Huerfano Formations of

Table 1. Stratigraphy of the central Raton Basin

<table>
<tr><th>System</th><th>Series</th><th>Formation</th><th>Member</th><th colspan="2">Maximum thickness[1] (feet)</th><th>Description</th></tr>
<tr><td colspan="7">SEDIMENTARY ROCKS</td></tr>
<tr><td rowspan="2">Quaternary</td><td>Holocene</td><td>Stream alluvium</td><td></td><td colspan="2">12–70</td><td>Clay to boulder-sized detritus.</td></tr>
<tr><td>Pleistocene</td><td>Pediment alluvium</td><td></td><td colspan="2">40–50</td><td>Clay to boulder-sized detritus.</td></tr>
<tr><td rowspan="3">Tertiary</td><td rowspan="2">Eocene</td><td>Huerfano Formation</td><td></td><td colspan="2">2,000</td><td>Variegated shale and sandstone with basal conglomerate.</td></tr>
<tr><td>Cuchara Formation</td><td></td><td colspan="2">5,000</td><td>Pink and white sandstone with shale layers.</td></tr>
<tr><td>Paleocene</td><td>Poison Canyon Formation</td><td></td><td colspan="2">2,500</td><td>Tan, gray, and olive sandstone, conglomerate, and shale.</td></tr>
<tr><td rowspan="3">Tertiary and Cretaceous</td><td rowspan="3">Paleocene and Upper Cretaceous</td><td rowspan="3">Raton Formation</td><td>Upper</td><td rowspan="3">1,000–1,600</td><td>100–300</td><td>Gray, green, and tan siltstone, sandstone, and shale.</td></tr>
<tr><td>Middle</td><td>800–1,000</td><td>Dark-gray, carbonaceous, and silty shale with coal and sandstone lenses.</td></tr>
<tr><td>Lower</td><td>1–250</td><td>Tan to gray sandstone and conglomerate.</td></tr>
<tr><td rowspan="4">Cretaceous</td><td rowspan="4">Upper Cretaceous</td><td>Vermejo Formation</td><td></td><td colspan="2">80–550</td><td>Dark-gray, carbonaceous, and silty shale with coal and sandstone lenses.</td></tr>
<tr><td>Trinidad Sandstone</td><td></td><td colspan="2">45–310</td><td>Tan to gray sandstone.</td></tr>
<tr><td rowspan="2">Pierre Shale</td><td>Transition zone</td><td rowspan="2">1,800–2,300</td><td>100–200</td><td>Shale and sandstone.</td></tr>
<tr><td></td><td>1,700–2,100</td><td>Dark-gray shale with limestone and sandstone layers.</td></tr>
</table>

Cretaceous	Upper Cretaceous	Niobrara Formation	Smokey Hill Marl Member		500–750	Gray and tan calcareous shale.
			Fort Hays Limestone Member		15–40	Gray limestone.
		Carlile Shale	Codell Sandstone Member	190–225	10–30	Sandstone, shale, and limestone.
			Blue Hill Shale Member		180–195	Dark-gray shale.
		Greenhorn Limestone			20–30	Dark-gray limestone and shale.
		Graneros Shale			170–200	Dark-gray shale.
	Lower Cretaceous	Dakota Sandstone			50–200	White to tan sandstone.
		Purgatoire Formation	Kiowa Shale Member		10–30	Dark-gray carbonaceous shale.
			Cheyenne Sandstone Member		50–105	Yellowish-brown sandstone
Jurassic to Pennsylvanian	Undivided				2,000–20,000	Conglomerate, sandstone, shale, limestone, and coal.
IGNEOUS AND METAMORPHIC ROCKS						
Tertiary	Miocene	Stocks				Syenodiorite, granodiorite, granite, and syenite porphyry.
		Dikes and sills				Granite to gabbro in composition.
Precambrian	Undivided					Gneiss, schist, granite, pegmatite, and quartzite.

[1] All formations present in the area, except Precambrian rocks, are locally removed by erosion. The ranges in thickness given represent measured thicknesses revealed in outcrops and drilled sections.

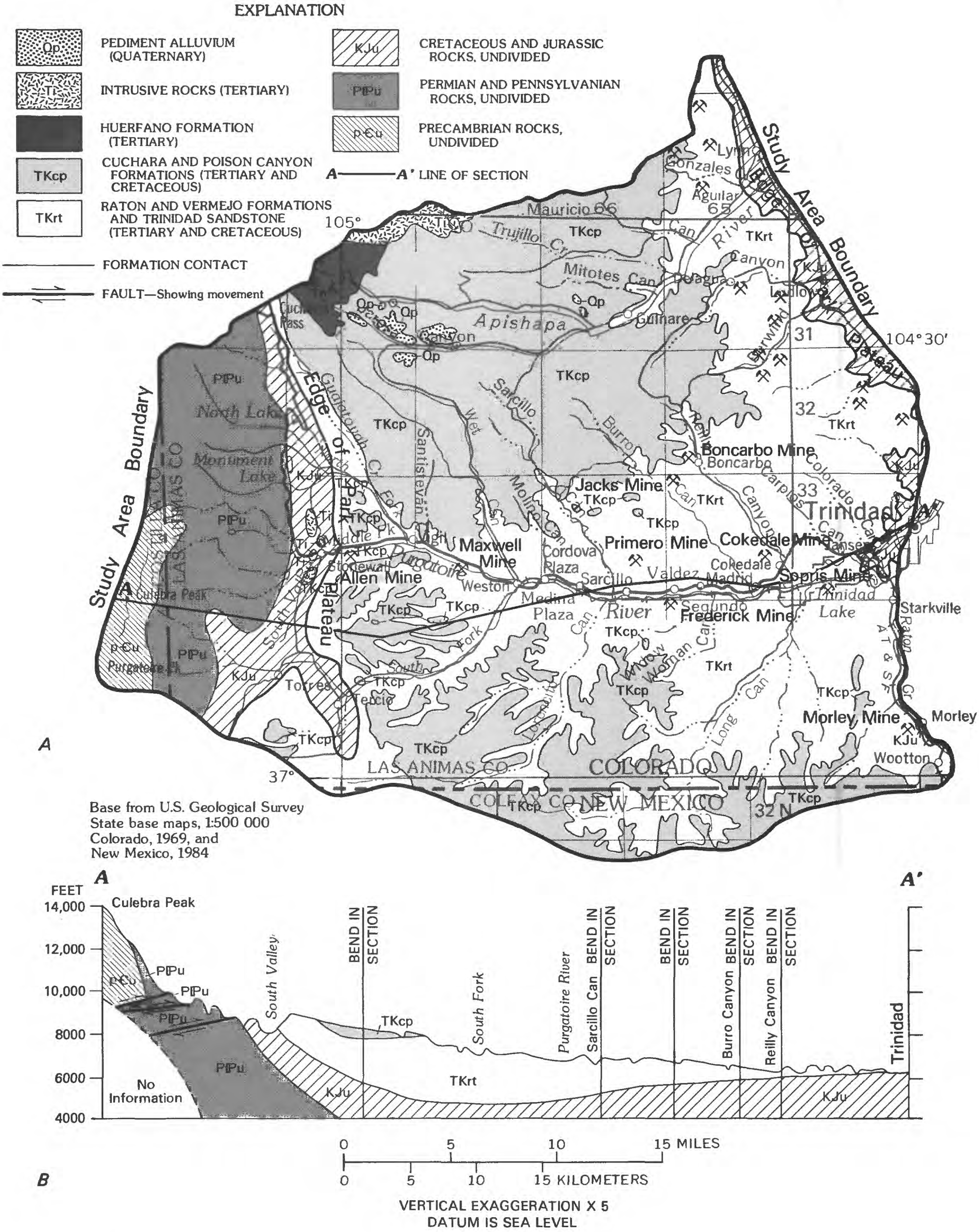


Figure 14. Geology of the central Raton Basin; *A*. Map; *B*. Cross section.

Figure 15. Dakota Sandstone in Graneros Gorge near Colorado City, Colo. The Dakota Sandstone forms the cliffs bordering Graneros Creek on the northeastern structural boundary of the Raton Basin.

Figure 16. Trinidad Sandstone overlying Pierre Shale in Berwind Canyon near Ludlow, Colo.

Eocene age crop out in the vicinity of the Spanish Peaks. The Vermejo Formation increases in thickness from 80 ft in the Trinidad area to 550 ft near the Spanish Peaks. It consists of gray to dark-gray, carbonaceous and sandy shale with lenses of tan, gray, and gray-green, slightly arkosic sandstone and coal (fig. 17). The Vermejo Formation rests conformably on the Trinidad Sandstone over most of the Raton Basin and is unconformably overlain by the Raton Formation. Both the Vermejo and Raton Formations are coastal-plain deposits.

Figure 17. Vermejo Formation in Purgatoire River valley at Trinidad Dam near Jansen, Colo. The formation here consists of carbonacaeous shale (dark) with interbedded arkosic sandstone (light).

Figure 18. Raton Formation in Purgatoire River valley near Madrid, Colo. The formation here consists of interbedded arkosic sandstone, shale, and coal. View is to the north.

The Raton Formation, 1,000–1,600 ft thick, consists of three members, which have not been rigorously defined. At the base of the formation, there are one to several beds of massive tan to gray sandstone and conglomerate that form prominent ledges and are overlain by several hundred feet of interbedded tan to gray, arkosic graywacke and quartzose sandstone; gray to dark-gray siltstone; sandy shale; carbonaceous shale; and thin, lenticular coalbeds. The middle member (fig. 18) consists of about 1,000 ft of carbonaceous and sandy

Figure 19. Poison Canyon Formation in Wet Canyon near Weston, Colo. The formation here is a massive arkosic sandstone with thin interbeds of olive shale. The formation typically weathers into rounded shapes.

shale with discontinuous sandstone layers and thick, lenticular coalbeds. In the upper 100–300 ft of the formation, interbedded arkosic and graywacke sandstone, grayish-green siltstone, and tan to gray shale intertongue with and grade into the Poison Canyon Formation.

Deposits of terrestrial origin cap the Park Plateau. The Poison Canyon Formation consists of 2,500 ft of conglomerate and interbedded tan to greenish-yellow shale (fig. 19). The Cuchara Formation unconformably overlies the Poison Canyon Formation and consists of 5,000 ft of red, pink, and white massive sandstone interbedded with thin to thick beds of red, gray, and tan shale. The Huerfano Formation overlies the Cuchara Formation and consists of 2,000 ft of maroon, gray, and green shale with red, white, and tan sandstone, and a basal conglomeratic sandstone. Rocks of the Cuchara and Huerfano Formations are metamorphosed to conglomeratic quartzite, hornfels, and slate adjacent to the West Spanish Peak stock.

The Tertiary intrusive rocks include the Spanish Peaks stocks, three smaller stocks, and numerous dikes and sills. These rocks were emplaced 20–25 m.y. ago (Smith, 1979, p. 37) in the Miocene Epoch. The Spanish Peaks consist of two stocks, one composed of syenodiorite porphyry, forming West Spanish Peak, and one composed of granite porphyry and granodiorite porphyry, forming East Spanish Peak. Three small stocks between Cuchara Pass and Tercio are composed of syenite porphyry, granodiorite, and granite porphyry. Dikes, including a radial swarm extending from the Spanish Peaks and a subparallel east-west set north of the Purgatoire River, and sills, which are located on the eastern and western edges of the area and in the valley of the Purgatoire River, are composed of porphyritic, lamprophyric, coarse-grained, and fine-grained varieties of granite, granodiorite, syenite, syenodiorite, diorite, syenogabbro, and gabbro (fig. 20).

Pediment alluvium of probable Pleistocene age that was shed from the rising Rocky Mountains occurs as erosional remnants overlying the Cuchara and Poison Canyon Formations in the upper Apishapa River drainage. These deposits generally are less than 10 ft thick (Wood and others, 1956) but are known to be 42 ft thick at one locality. They consist of predominantly coarse-grained detritus.

Pediment alluvium of probable Pleistocene and Holocene age abuts the eastern escarpment of the Park Plateau. This deposit is estimated from the depths of wells in the area to be 40–50 ft thick. Because shale and siltstone are the dominant rock types nearby, the deposit probably contains considerable clay and silt.

Stream alluvium is found in the valleys of the Purgatoire and Apishapa Rivers and their tributaries. According to Powell (1952, p. 8), valley cutting began during Pleistocene time. Subsequently, valleys were filled

Figure 20. Bear Canyon Spring flowing over igneous dike in Bear Canyon near Ludlow, Colo. The dike blocks the flow of water in the channel alluvium, forcing the water to the surface. When photographed in August 1981, the spring was discharging at the rate of 4 gal/min. View is upstream.

to levels higher than at present with alluvium derived from the mountains to the west. Later erosion removed most of this material, but the old channels cut into the bedrock still are partly filled. Cycles of stream cutting and deposition have continued into Holocene time.

The thickness and character of stream alluvium change along the length of valleys and across them. In the Purgatoire River valley, the observed maximum thickness of the alluvium is 41 ft, but in some sections the alluvium is no more than 12 ft thick. The alluvium in the Apishapa River valley has an observed maximum thickness of 45 ft. In tributary canyons, the alluvium is as much as 70 ft thick, but it usually is less than 50 ft thick. The stream alluvium predominantly is sand and gravel where canyons are cut into the Poison Canyon and Cuchara Formations. The alluvium generally is gravelly clay or silt where canyons are cut into the Vermejo and Raton Formations, except in modern channels and flood plains, where the alluvium predominantly is sand and gravel.

Coal Deposits

The Raton Basin coal region, which extends from north of Walsenburg, Colo., to Cimarron, N. Mex., covers an area of 2,140 mi^2 (Carter, 1956). An area of 1,154 mi^2 north of the Colorado-New Mexico State line is known as the Trinidad coalfield (which is considered by some investigators to be two fields, the Trinidad coalfield south of the Huerfano–Las Animas County line and the Walsenburg coalfield north of the county line). An area of 986 mi^2 in New Mexico is known as the Raton coalfield.

The presence of coal in the Trinidad coalfield was first reported by military expeditions in 1848 (Johnson, 1961, p. 132). Mining activity in the Trinidad coalfield began in 1873 and reached a climax between 1900 and 1930, when 155,833,369 tons were produced (Johnson, 1961, p. 170–173). Cumulative production in the Trinidad coalfield through 1975 was 247,500,000 tons (Amuedo and Bryson, 1977, p. 47). As of 1981, six mines were licensed to operate in the coalfield (Kelso and others, 1981). Four of these mines, the Allen Mine, Maxwell Mine, Helen Mine, and Trinidad Basin Mine, are in Las Animas County. Two of the mines, the Colorado Coal Mine No. 1 and the Viking Mine, are in Huerfano County. In 1980, these six mines had a combined production of 865,699 tons, 88 percent of which came from CF&I Steel Corp.'s Allen and Maxwell Mines (figs. 21 and 22). The Allen, Maxwell, and Helen Mines are underground mines; the others are strip mines. In 1974, the inferred remaining reserves of coal 4 ft or more thick with less than 3,000 ft of overburden amounted to 2.7 billion tons, of which about 1.9 billion tons were in Las Animas County (Amuedo and Ivey, 1974, tables II–1 and II–3).

Commercial coal deposits are found in the Vermejo and Raton Formations of Cretaceous and Paleocene age (fig. 23). These deposits are at or near the surface on the edges of the Park Plateau and in the valleys of the Purgatoire and Apishapa Rivers and their tributaries but are more than 3,000 ft deep near the Spanish Peaks. Deposits of coal in the Trinidad field that are 3 ft or more thick and accessible by strip mining were estimated by Speltz (1976, p. 38) to total 13.6 million tons in 1976, of which 12.8 million tons were in Las Animas County.

The Vermejo Formation contains as many as 14 coalbeds more than 14 in. thick, and the Raton Formation as many as 33 coalbeds more than 14 in. thick (Johnson, 1961, p. 154–155). The number of beds increases toward the center of the area, as the coal-bearing formations thicken from 0 to about 2,600 ft. Coalbeds in the Vermejo Formation generally are thicker, more persistent, more regular in thickness, and less widely spaced than those in the Raton Formation. Individual beds in the Vermejo Formation attain a maximum thickness of more than 15 ft, whereas those in the Raton Formation are no more than 10 ft thick (Amuedo and Ivey, 1974, pl. 2–12).

Stratigraphic correlation of coalbeds from mine to mine is difficult because of the manner in which the coal was deposited. Having formed in highly transitional coastal plain and stream environments, the coalbeds are very lenticular. Because individual beds may thicken, split, or entirely disappear within a distance of less than a mile, different mines have assigned different names to the same coalbed, and different beds have been assigned the same name at different mines. A stratigraphic correlation of coalbeds by Boreck and Murray (1979, p. 49–50) is shown in figure 23*B*. A correlation by Amuedo and Ivey (1974) is similar, but some coalbeds are placed in different zones, and the vertical arrangement of some zones is reversed.

The coal in both formations is similar in appearance. It generally is bright and glassy but may contain beds of charcoal-like material. It may be either compact and hard or brittle and crumbly. It generally has good rectangular fracture, but it may break into rounded masses. Impurities such as sulfur and pyrite (iron sulfide) generally are sparse. Where sills have intruded the coalbeds, the coal is altered to natural coke. North of the Spanish Peaks, the coal generally is high-volatile C bituminous steam-grade; south of the peaks, it generally is high-volatile A, B, and C bituminous coking grade.

Structure

The Raton Basin is an asymmetrical trough, the axis of which trends generally northward from the vicinity of Cimarron, N. Mex., to Huerfano Park, Colo. (fig. 24). On the west side of the basin, resistant sandstones cap a dissected upland known as the Park Plateau.

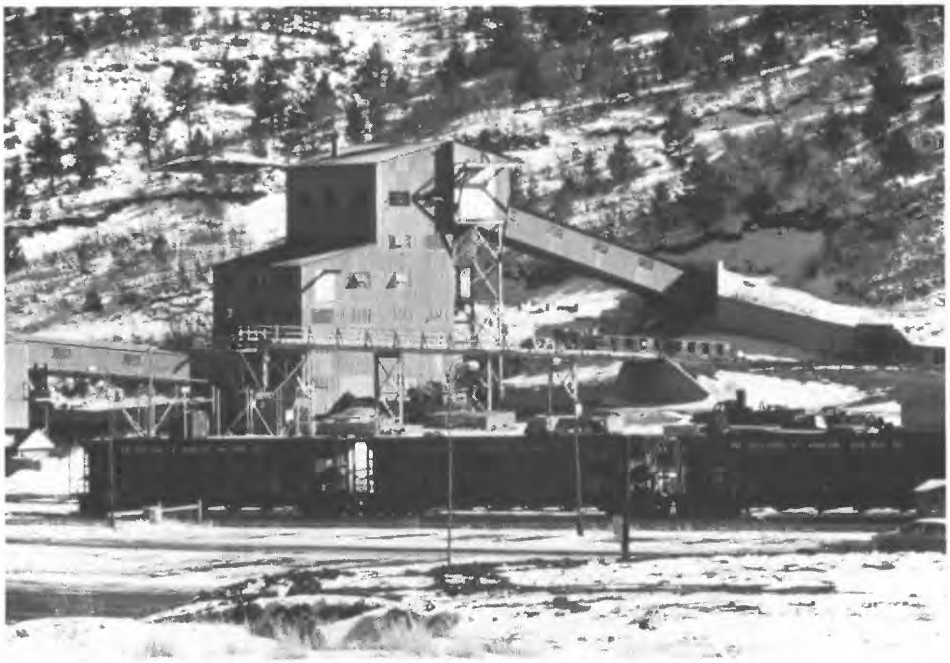


Figure 21. The Allen Mine near Weston, Colo.

The axis of the basin in Colorado is called the La Veta syncline. The structurally lowest part of the basin is north of the Spanish Peaks, as indicated by structural contours on top of the Trinidad Sandstone (fig. 24). The east limb of the syncline dips generally less than 5° away from the Apishapa and Sierra Grande arches. Because of thrust faulting on the west side of the basin, the rocks forming the west limb of the syncline are vertical to overturned within a short distance of the axis.

The axis of the basin is interrupted in two places. South of the Spanish Peaks, the axis is split by a plunging anticline and shifted from Wet Canyon into Sarcillo Canyon (fig. 24). On the north side of the basin, the Greenhorn anticline plunges southward and divides the synclinal axis into two segments. The western segment retains the "La Veta" designation, and the eastern segment is called the Delcarbon syncline.

Folds and faults modify the regional structure. The Vermejo and Tercio anticlines straddling the Colorado–New Mexico State line form an anticlinorium that brings Pierre Shale to the surface through a cover of Trinidad, Vermejo, Raton, and Poison Canyon rocks. The Pierre Shale also is exposed in the center of the Morley dome. In the northwestern corner of the basin, complexly arranged folds and thrust faults expose formations ranging from Pennsylvanian to Tertiary. Along the southern and eastern margins of the Wet Mountains, a high-angle reverse fault, a normal fault, and several tear faults have emplaced Precambrian rocks against Mesozoic rocks. Folds with small amplitude occur throughout the basin. Clusters of normal faults with small displacements occur near Sarcillo Canyon and in the northeastern corner of the basin below the crest of the Apishapa arch.

Some structural disruption accompanied the intrusion of igneous rocks. Intrusion of the Spanish Peaks stocks created radial fractures that filled with magma, resulting in a prominent dike set. Intrusion of the East Spanish Peak stock intensely fractured and faulted sedimentary rocks that came up with the magma and domed beds of the Cuchara Formation west and south of the stock (Johnson, 1968, p. 5–6). Intrusion of the Black Hills magma in the nose of the Greenhorn anticline domed overlying sedimentary rocks. Intrusion of a large sill between the Purgatoire Formation and the Dakota Sandstone at Morley, Colo., caused the Morley dome (Johnson, 1968, p. 6).

GROUND WATER

Virtually all of the formations in the Raton Basin transmit water (table 2). Ground water moves from areas of recharge to areas of discharge (fig. 25). Bedrock aquifers are replenished by precipitation in outcrop areas and by seepage from alluvium in stream valleys. Water moves laterally through pores and bedding planes of permeable layers and downward through fractures connecting permeable layers. By a combination of lateral

Figure 22. The Maxwell Mine near Weston, Colo. Production of coal from a seam in the Raton Formation began in 1976 and was suspended in 1982.

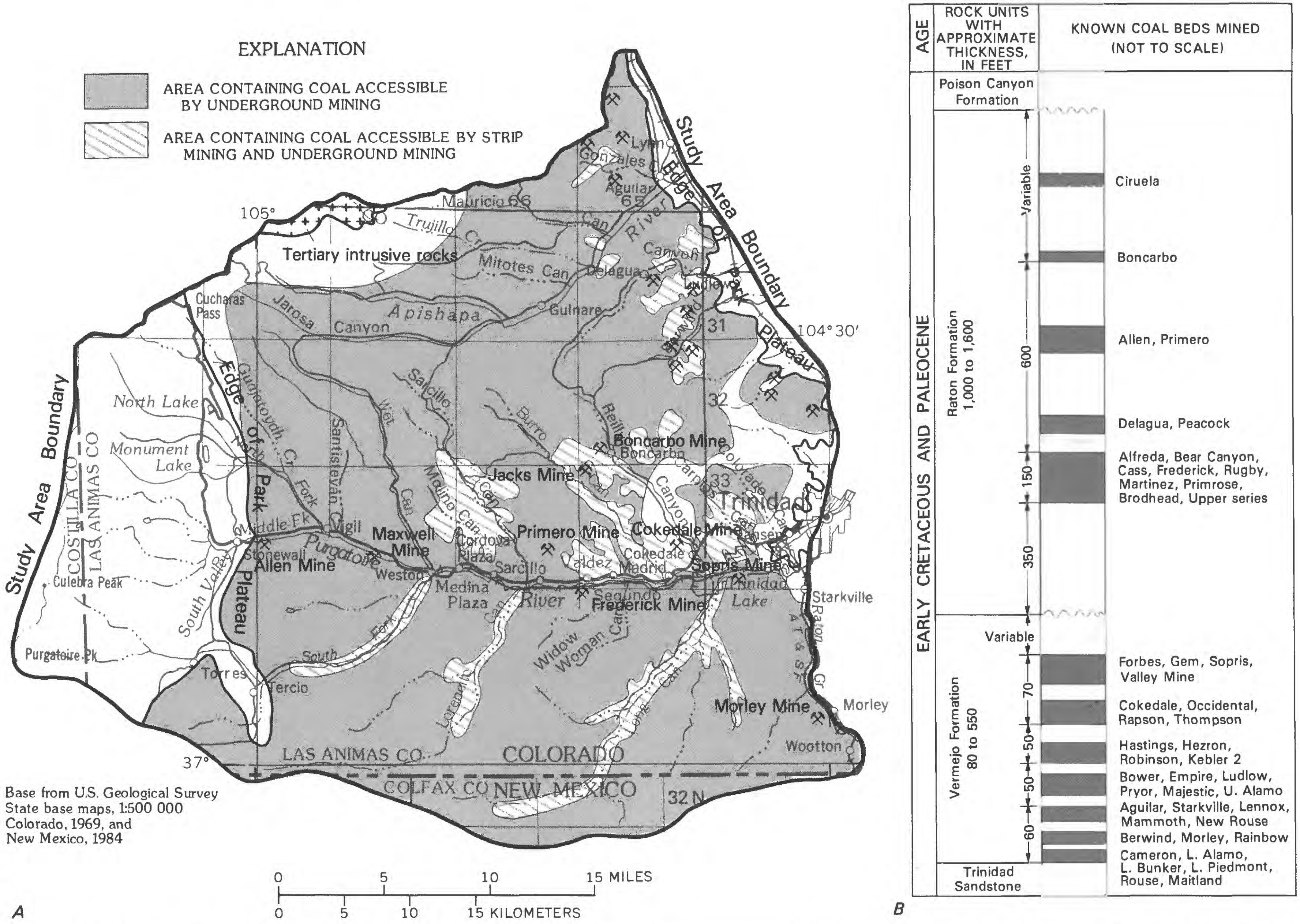


Figure 23. Coal resources of the Raton Basin in the Purgatoire and Apishapa River drainages. *A*, Map showing distribution of deposits; B, Column showing coal stratigraphy.

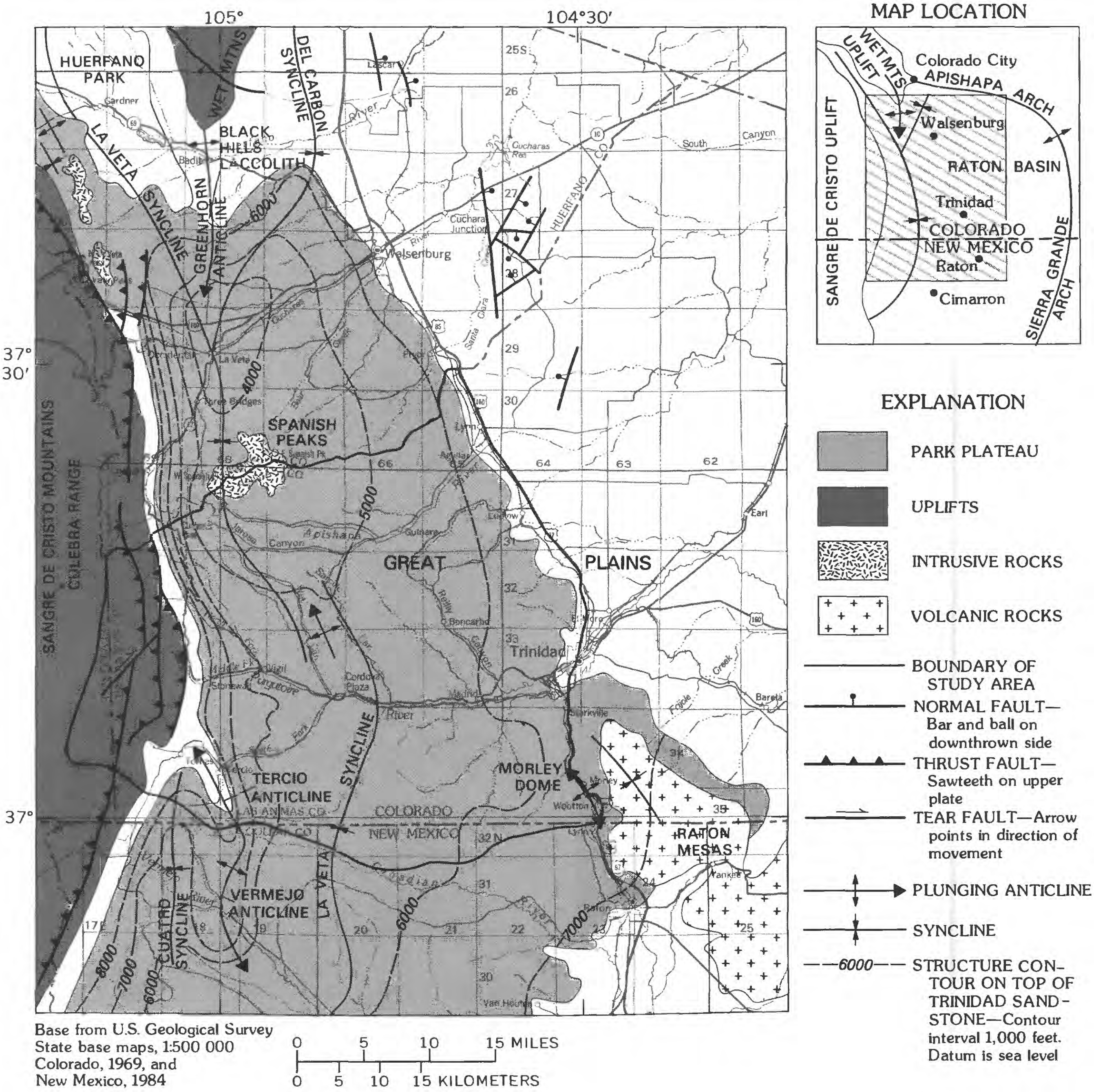


Figure 24. Geologic structure of the Raton Basin (from Johnson, 1969).

and vertical movement, water may descend to an underlying geologic formation or discharge to a well, mine, or spring. In the central Raton Basin, ground water flows regionally from west to east. However, local flow from stream divides to valleys intercepts much of the water in regional circulation. The remaining water moves sluggishly and is highly mineralized from prolonged contact with shale and coal.

Availability

Ground water occurs in alluvium and bedrock under unconfined conditions, in confined layers and perched zones within bedrock, and in near-surface fractured and weathered zones of formations not otherwise likely to yield water. The principal bedrock aquifers in the area are the Cuchara–Poison Canyon, the Raton–Vermejo–Trinidad, the Fort Hays–Codell, the

Table 2. Hydrologic description of formations in the central Raton Basin

[---, indeterminate; <, less than]

System	Formation	Member	Maximum thickness (feet)	Physical characteristics	Measured yield: Wells (gallons per minute per 10 feet of drawdown)	Measured yield: Springs (gallons per minute)
Quaternary	Stream alluvium		12-70	Clay to boulder-sized detritus	8-290	<1-95
	Pediment alluvium		<10-50	Clay to boulder-sized detritus	Unknown, probably none to small.	Unknown, probably none to small.
Tertiary	Intrusive igneous rocks.		---	Granitic to gabbroic stocks, dikes, and sills.	Unknown, probably none to small.	Unknown, probably none to small.
	Huerfano Formation		2,000	Variegated shale and limestone		
	Cuchara Formation		5,000	Pink and white sandstone with shale.		
Tertiary and Cretaceous.	Poison Canyon Formation.		2,500	Tan, gray, and olive sandstone, conglomerate, and shale.	0.07-33	7.0 from one spring.
	Raton Formation		1,000-1,600	Gray, green, and black shale, siltstone with sandstone, coal.		
Cretaceous	Vermejo Formation		80-550	Gray and black shale, siltstone with sandstone, coal.	0.04-16	0.1-35
	Trinidad Sandstone		45-310	Tan and gray sandstone with shale partings.		
	Pierre Shale		1,800-2,300	Dark-gray shale with limestone and sandstone beds.		
	Niobrara Formation.	Smoky Hill Marl Member.	500-750	Gray and tan calcareous shale	Unknown, probably 0-20, with large drawdowns.	Unknown
		Fort Hays Limestone Member.	15-40	Gray limestone		
	Carlile Shale	Codell Sandstone Member.	10-30	Sandstone with shale and and limestone beds.		
		Blue Hill Shale Member.	180-195	Dark-gray shale		
	Greenhorn Limestone.		20-30	Dark-gray to gray limestone and shale.	Unknown, probably 0-5, with large drawdowns.	Unknown.
	Graneros Shale		170-200	Dark-gray shale		
	Dakota Sandstone		50-200	White and tan sandstone		
	Purgatoire Formation.	Kiowa Shale Member.	10-30	Dark-gray, carbonaceous shale	Unknown, probably 10-100.	Unknown.
		Cheyenne Sandstone Member.	50-105	Yellowish-brown sandstone		
Jurassic	Undivided		300-400	Shale, siltstone, and sandstone, including Entrada Sandstone.	Unknown, probably small from sandstone layers; none to small elsewhere.	Unknown, probably small from sandstone layers; none to small elsewhere.
Permian and Pennsylvanian.	Undivided		2,000-20,000	Sandstone, shale, and limestone		
Precambrian	Undivided		---	Gneiss, schist, granite, pegmatite, and quartzite.	Unknown, probably none to small.	Unknown, probably none to small.

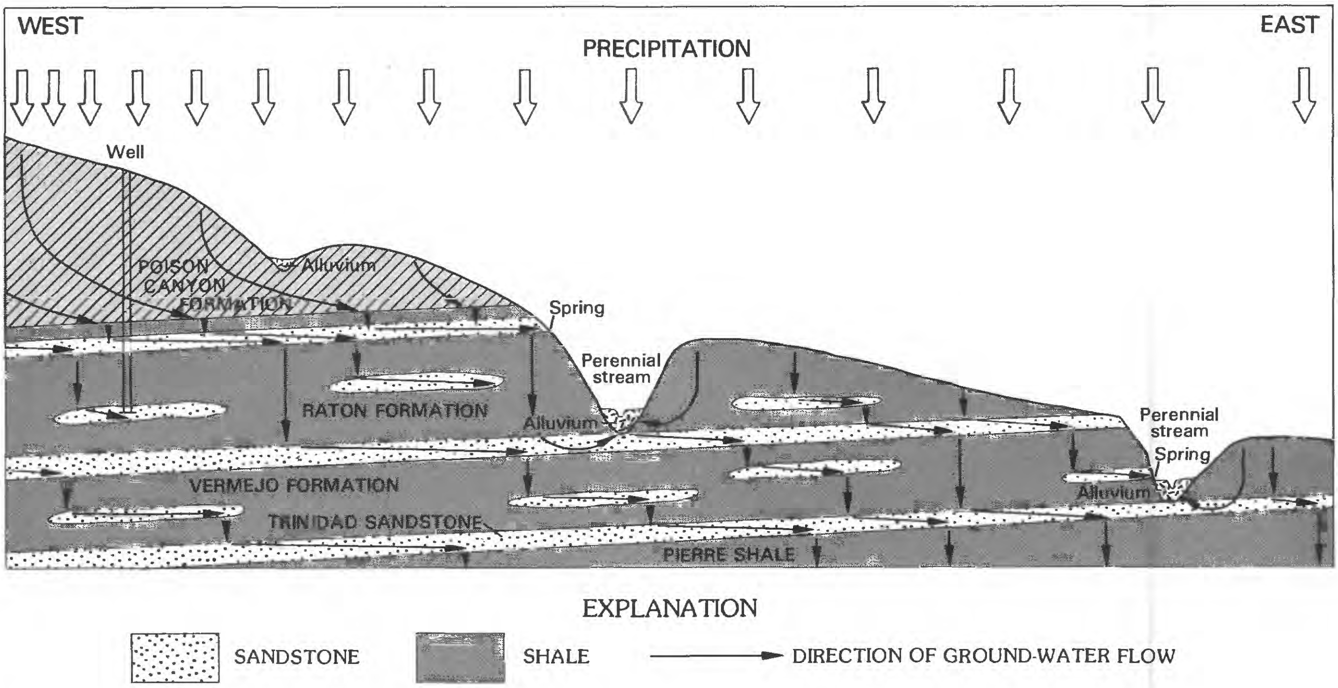


Figure 25. Schematic representation of ground-water flow in the central Raton Basin.

Dakota–Purgatoire, and the Entrada. Within these units, sandstone and conglomerate layers transmit most of the water, and shale and coal layers usually retard flow. However, fractured shale, siltstone, coal, and limestone layers also transmit water. Formations and members of formations composed largely of shale, including the Huerfano Formation, the Pierre Shale, the Smoky Hill Marl Member of the Niobrara Formation, the Blue Hill Shale Member of the Carlile Shale, the Graneros Shale, and the Morrison Formation, retard the downward movement of ground water and confine flow within the aquifers. Precambrian and Tertiary igneous and metamorphic rocks, unless highly fractured, act as barriers to ground-water flow.

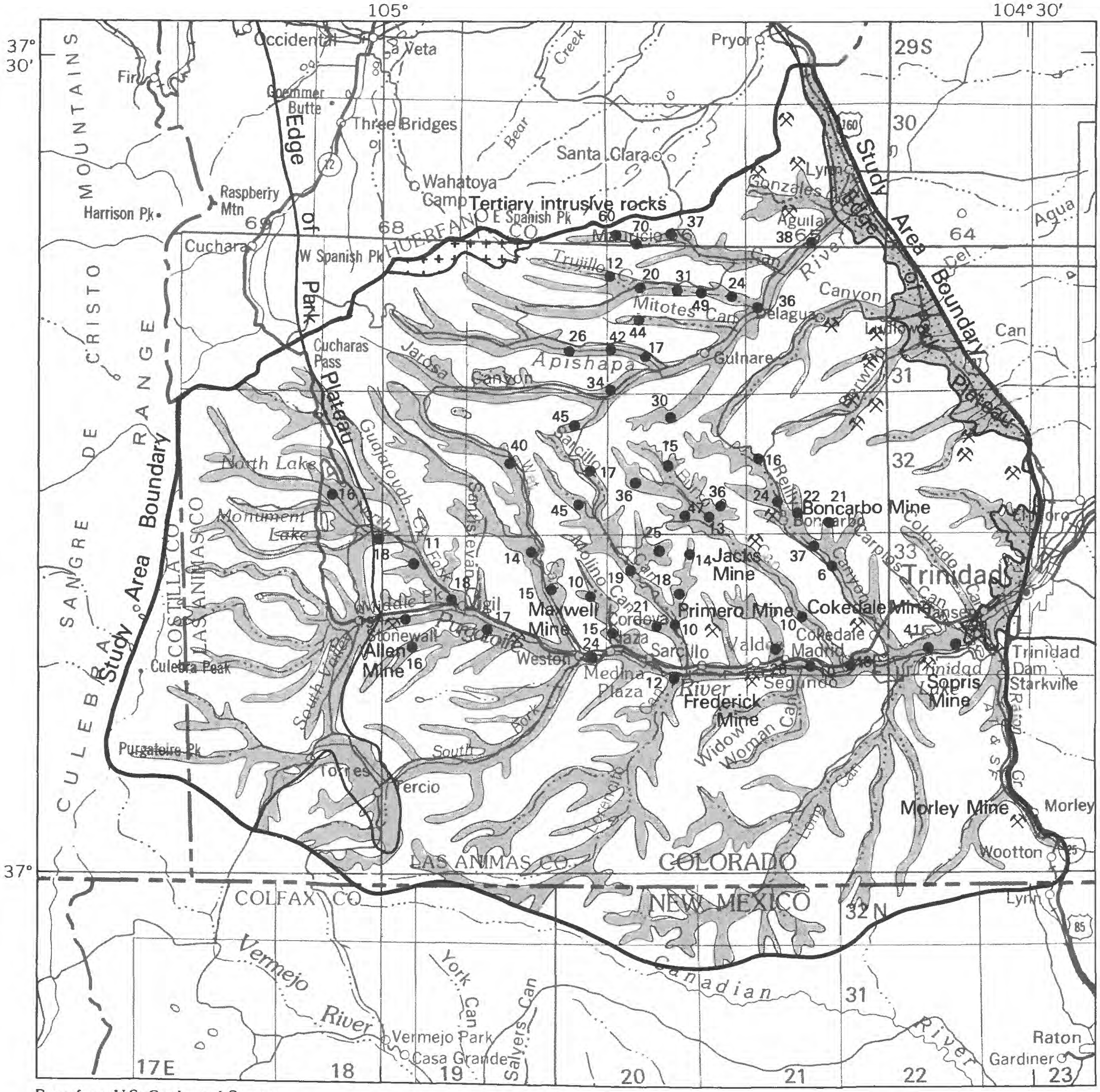
Alluvium

The alluvial aquifer consists of stream alluvium, deposited in the flood plains of the Purgatoire and Apishapa Rivers and their tributaries, and pediment alluvium, deposited in the upper part of the Apishapa River drainage and on the plains east of the Park Plateau (fig. 26). The alluvium is Holocene and Pleistocene in age.

The alluvium of the Purgatoire River consists of sand and gravel containing clay lenses, cobbles, and boulders (Powell, 1952, p. 8–12). The sand and gravel are derived from both igneous and sedimentary rocks. In drilling 42 exploration holes during 1951, the Colorado Water Conservation Board discovered that the thickest and coarsest alluvium occurs in buried channels. A layer of clay that eroded into the valley from adjacent slopes locally covers the sand and gravel along the edges of the valley. The observed maximum thickness of the alluvium along the river ranges from 12 to 41 ft. The alluvium is nearly saturated adjacent to the Purgatoire River, but less than a foot of the alluvium contains water near the edges of the valley. The width of the alluvium ranges from a few feet in the Culebra Range to more than 4,000 ft near Trinidad, Colo.

The alluvium of the Apishapa River consists of sand, gravel, and clay, with cobbles and boulders. Unlike the alluvium of the Purgatoire River, the alluvium of the Apishapa River has not been extensively drilled. The alluvium of the Apishapa River probably is coarser than that of the Purgatoire River because the Apishapa River is cut into terrane composed mostly of sandstone, conglomerate, and igneous rocks, whereas the Purgatoire River is cut into terrane composed, in large part, of shale and siltstone. From place to place, the Apishapa alluvium ranges from 17 to 42 ft thick. The width of this alluvium ranges from a few feet on the slopes of West Spanish Peak to more than 2,000 ft near Aguilar, Colo.

Alluvium is present in all of the larger canyons and many of the smaller canyons that are tributaries of the Purgatoire and Apishapa Rivers. In terrane underlain by the Cuchara and Poison Canyon Formations, this alluvium predominantly consists of sand and gravel. In terrane underlain by the Raton and Vermejo Formations, the alluvium predominantly consists of silt



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

STREAM ALLUVIUM

PEDIMENT ALLUVIUM

BEDROCK

● 24 WELL—Number is thickness of alluvium, in feet

Figure 26. Distribution of alluvium in the central Raton Basin.

and clay, with gravel to cobble-sized rock fragments in terraces adjacent to modern channels, and discontinuous layers of sand and gravel in the channels. Deposits of alluvium in canyons cut into Cuchara-Poison Canyon terrane are generally thicker and broader than deposits of alluvium in canyons cut into Raton-Vermejo terrane. Maximum thicknesses of the tributary alluvium from place to place generally range from 30 to 50 ft, but the alluvium in the upper part of Mauricio Canyon is 60–70 ft thick.

East of the Park Plateau, coalescing alluvial fans overlying an erosional surface cut into the Pierre Shale form a pediment. Wells in this area are drilled either to the base of the alluvium or into the Pierre Shale, but logs of these wells are not available. Inventoried wells are 32–77 ft deep; therefore, the pediment alluvium is estimated to be no more than 40–50 ft thick. It probably is saturated only a few feet above the base.

In the upper Apishapa River drainage, remnants of an older pediment deposit eroded from the rising mountains to the west consist of coarse-grained detritus, generally less than 10 ft thick. A well west of Gulnare, Colo., penetrated 20 ft of sand and 4 ft of "boulders" that did not contain any water. Therefore, it is likely that thinner remnants of this pediment deposit also do not contain water.

Most wells in the alluvium are hand dug; these wells typically are less than 30 ft deep, 2–4 ft wide, and rock walled or concrete lined to bedrock. Drilled wells may be deeper to provide a reservoir or to draw water from bedrock in addition to the alluvium. These wells typically are 6–9 in. in diameter and cased with steel a few feet into bedrock. Only one inventoried well is known to contain perforated casing.

Yields from the alluvium depend on the well construction and the composition and saturated thickness of the alluvium. Powell (1952, p. 11) estimated that the alluvium of the Purgatoire River probably would yield about 120 gal/min per 10 ft of drawdown,[2] based on a pumping test in Huerfano River alluvium, which is coarser than alluvium of the Purgatoire. The tested Huerfano River alluvium yielded 230 gal/min per 10 ft of drawdown (Wilson, 1965). The Apishapa River alluvium, which probably is similar to alluvium in the flood plain of the Huerfano River, yielded 50–290 gal/min per 10 ft of drawdown in three pumping tests, averaging 160 gal/min per 10 ft. In tributary canyons, where the alluvium generally is finer than the alluvium of the Purgatoire and Apishapa Rivers, wells yielded 8.3–40 gal/min per 10 ft of drawdown in three bailing tests, averaging 22 gal/min per 10 ft.

Springs issue from the alluvium of tributary canyons where bedrock is close to the surface or where igneous dikes and sills cross the stream channels (fig. 20). In the summer of 1981, when streams essentially were at base flow, springs issuing from the alluvium of tributary canyons discharged from less than 1 to 95 gal/min; discharges increased in the summer of 1981 after rainstorms and in the winter of 1981 and fall of 1982 during periods of snowmelt. Spring discharges generally increase down the gradient of canyons as the seepage from bedrock accumulates in the alluvium. However, some canyons, such as Wet Canyon, have losing reaches where water flows from the channel alluvium into bedrock.

Canyons on the west side of the area generally have more springflow than canyons on the east side of the area. This occurs primarily because rocks on the west side are coarser and more capable of transmitting water than rocks on the east side.

Values of alluvial transmissivity in the study area and immediately adjacent parts of the Raton Basin ranged from 0.14 to 4,680 ft^2/d in 13 slug and pumping tests. Values of hydraulic conductivity ranged from 0.014 to 187 ft/d in these tests. Three additional values of transmissivity and hydraulic conductivity were determined from bailing tests of wells in the Apishapa River valley, using a relationship between specific capacity and transmissivity (fig. 27). These empirical determinations probably are reasonably correct because they are in accord with values of transmissivity and hydraulic conductivity calculated elsewhere in the area from standard tests. One additional value of hydraulic conductivity was estimated by Water, Waste, and Land, Ltd. (1980, p. 25) from a pumping test of a well completed in alluvium of the Purgatoire River. The wide range of transmissivity and hydraulic-conductivity values shown in table 3 reflects both the diverse composition of the alluvium and the heterogeneous methods used to determine these properties. Generally, the alluvium deposited by the Purgatoire and Apishapa Rivers transmits water more readily than the alluvium deposited in tributary canyons.

Alluvium generally is a better aquifer than bedrock, but because the alluvium is unconfined and recharged mostly by precipitation and channel runoff, the amount of water stored in the alluvium varies substantially in response to precipitation cycles. During periods of lower than normal precipitation, water levels in wells may fall sharply and, during prolonged drought, wells may go dry.

[2]Although the standard unit of specific capacity (discharge divided by drawdown) is gallons per minute per foot of drawdown, most wells in the area are likely to be drawn down 10 ft or more during routine use. Thus, yields expected with 10 ft of drawdown are reported.

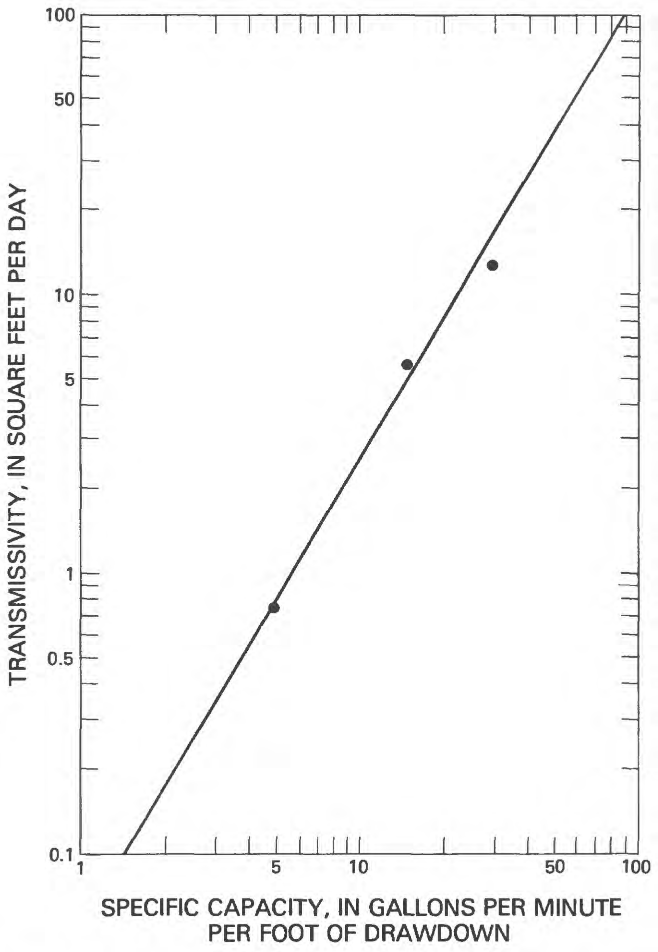


Figure 27. Relation of specific capacity to transmissivity in wells completed in alluvium of the Apishapa River near Walsenburg, Colo.

In the canyon of the Vermejo River and in York Canyon, about 5–9 mi south of the study area, water levels in eight observation wells fluctuated 2.9–11.6 ft between 1979 and 1981; the average fluctuation was 5.8 ft. Typical hydrographs (fig. 28) indicate that the highest water levels occurred from May to September. In the spring and early summer, the aquifer is recharged by the large channel runoff resulting from melting of the snowpack. In late summer, the aquifer is recharged by channel runoff from thunderstorms.

In the valley of Apache Creek, about 31 mi north of the study area, annually recorded water levels in an observation well fluctuated over a range of 9.1 ft between September 1951 and April 1983 (fig. 29). Low water levels in 1951–57 and 1964–68 probably resulted from abnormally heavy pumping in the area. In the 25 years from 1958 to 1983, there has been no systematic rise or fall in the water table near the well.

In an average year, the alluvium in the study area is estimated to contain about 6,800 acre-ft of recoverable water (table 4). This estimate was based on a planimetered area of 29.3 mi^2 (18,752 acres), an estimated average saturated thickness of 9.0 ft (weighted by area of occurrence), and an average specific yield of 0.04 (determined from a test of Huerfano River alluvium, referenced in Wilson, 1965, p. 84).

Igneous Rocks

The Tertiary igneous rocks are barriers to flow. Springs, such as Dike Spring (SC03306521bbb) in Burro Canyon and Bear Canyon Spring (SC03206511cbd) in Bear Canyon, issue from stream alluvium where sills and dikes cross the channels and disrupt flow in the alluvium.

Huerfano Formation

The Huerfano Formation, of Eocene age, does not readily transmit water to wells. No wells are completed in this formation in the study area and, according to McLaughlin (1966, p. 82), production of usable quantities of water is unlikely, except possibly from a conglomeratic sandstone layer near the base of the formation.

Cuchara–Poison Canyon Aquifer

The Cuchara–Poison Canyon aquifer consists of the Cuchara Formation, which is Eocene, and the Poison Canyon Formation, which is mostly Paleocene but is considered to be Cretaceous where it intertongues with the Raton Formation in the northwestern and southwestern parts of the Raton Basin (outside the study area). The Cuchara and Poison Canyon Formations are considered to be a single aquifer because of similar composition.

Depths to the top of the underlying Raton–Vermejo–Trinidad aquifer indicate that the Cuchara and Poison Canyon Formations are more than 2,800 ft thick in the study area. Massive arkosic sandstone and conglomerate sandstone are the primary sources of water. Shale layers generally confine flow to specific beds but transmit water where they are fractured.

Depths to water commonly are less than 100 ft, but water may be 100–200 ft deep beneath stream divides, especially along the eastern and southern edges of outcrop (fig. 30). In these areas, the Poison Canyon Formation is drained by springs, lateral seepage to stream alluvium, and downward percolation to the Raton Formation. The aquifer mostly is unconfined near the surface, except where it is covered by the Huerfano Formation.

Well depths range from 48 to 250 ft, averaging 110 ft in 38 wells. Nearly all wells are drilled. Most wells are 5–8 in. in diameter. Typically, the casing extends to the top of the highest producing horizon.

Table 3. Summary results of hydraulic tests in alluvium of the central Raton Basin

[---, no entry because only one test was available]

Source of alluvium	Number of tests	Transmissivity (feet squared per day)		Hydraulic conductivity (feet per day)	
		Range	Mean	Range	Mean
Huerfano River[1]--------	1	4,680	---	187	---
Apishapa River---------	3	0.78-13	6.52	0.16-4.3	1.78
Mitotes Canyon---------	[2]1	0.13	---	0.026	---
Jarosa Canyon----------	[2]1	0.041	---	0.002	---
Sarcillo Canyon--------	[2]1	0.56	---	0.037	---
Purgatoire River-------	[3]4	0.14-4.2	1.50	0.014-1,880	470
York Canyon[1]-----------	5	17-570	150	0.79-82	18
Salyers Canyon[1]--------	1	84	---	4.25	---

[1]Not a tributary of the Apishapa or Purgatoire Rivers.

[2]Transmissivity and hydraulic conductivity estimated from specific capacity, using figure 27.

[3]Transmissivity not calculated from one test. Hydraulic conductivity in this test estimated from pumping data.

According to drillers' logs, yields from wells completed in the Cuchara–Poison Canyon aquifer generally ranged from 0.07 to 1.4 gal/min per 10 ft of drawdown, averaging 0.7 gal/min per 10 ft in 16 bailing tests (fig. 31). According to residents in the area, wells commonly do not yield sustainable water supplies and are pumped dry during normal household use. In a few areas, particularly in Mauricio Canyon and near the junction of Jarosa Canyon and the Apishapa River, wells yielded 1–33 gal/min per 10 ft of drawdown in bailing tests. Where the Poison Canyon Formation crops out south of the Purgatoire River, it is deeply dissected and probably contains water only near its base. There, wells would probably yield very small, nonsustainable supplies of water. The only spring known to issue from this aquifer in the study area, Logging Canyon Spring (SC03306835bdd), yielded 7.0 gal/min in August 1981.

Hydraulic properties of the Cuchara–Poison Canyon aquifer have not been determined by standard aquifer tests. However, specific capacities obtained in bailing tests and the relation of specific capacity to transmissivity in stratigraphically equivalent formations in the adjacent Denver Basin (fig. 32) were used to estimate hydraulic properties in the study area. Estimated transmissivity values in 22 tests ranged from 0.20 to 575 ft^2/d and averaged 52 ft^2/d; estimated hydraulic-conductivity values in seven tests ranged from 0.062 to 15 ft/d and averaged 3.2 ft/d. Estimated values of transmissivity and hydraulic conductivity are probably typical of the range of values to be expected for that part of the aquifer developed in shallow domestic and stock wells in the central Raton Basin but are not representative of the entire thickness of the aquifer at any site, because none of the tested wells penetrate the aquifer completely.

The potentiometric surface in the aquifer (fig. 33) slopes generally eastward but is deflected toward stream valleys because of flow from the aquifer into the valleys. In five wells, water levels rose 1 to 11 ft between 1978 and 1981, probably because annual precipitation increased in the area during this period (National Oceanic and Atmospheric Administration, 1965–83).

Long-term water-level fluctuations in a well completed in the Poison Canyon Formation near La Veta, Colo., about 8 mi north of the study area (fig. 34), are typical of the aquifer's response to changes in water availability. Water levels in this well fluctuated 3.3 ft between May 1954 and April 1983. The water table at the well was about a foot lower in 1971–81 than in the previous 17 years, probably as a result of pumping in the area. However, the water table recovered in 1983 after a winter with a larger than normal snowfall.

In an average year, the Cuchara–Poison Canyon aquifer is estimated to contain about 24,000 acre-ft of recoverable water (table 4). This estimate was based on a

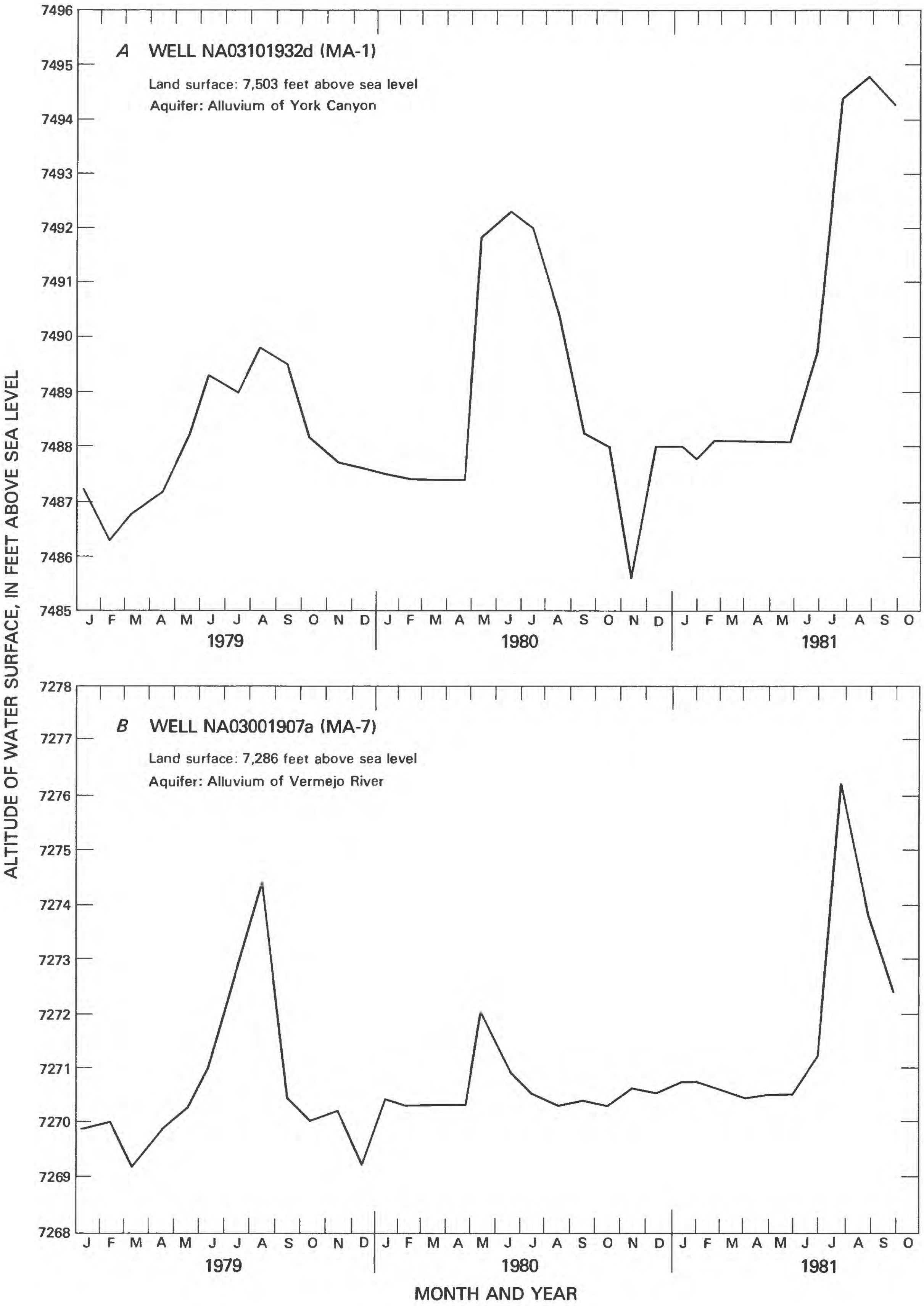


Figure 28. Recorded water levels in observation wells completed in alluvium at York Canyon Mine, N. Mex., 1979–81. *A*. Well MA–1; *B*. Well MA–7.

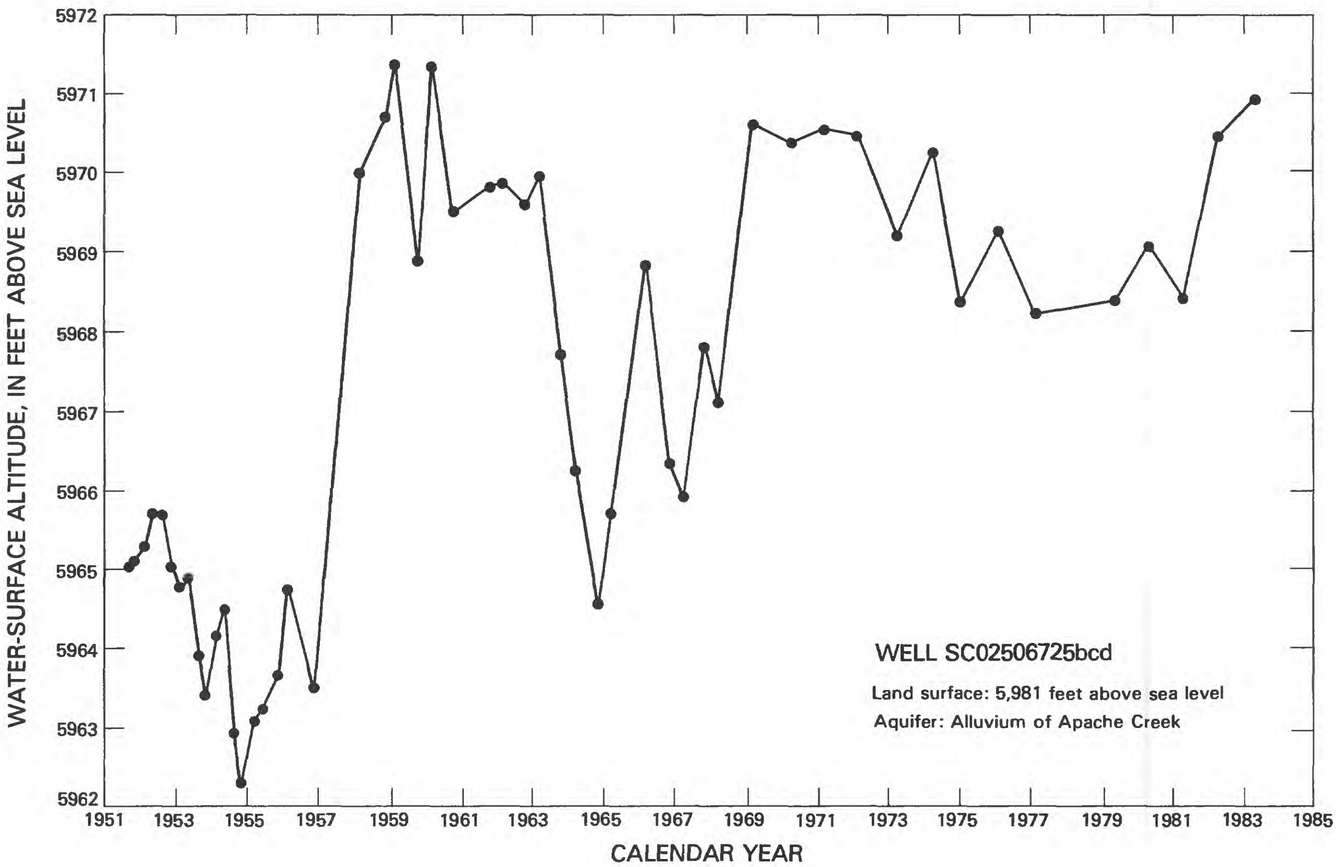


Figure 29. Recorded water levels in alluvium of Apache Creek near Walsenburg, Colo., 1951–83.

planimetered area of 330 mi^2 (211,200 acres), an estimated average saturated thickness of water-bearing material of 280 ft, and an estimated average storage coefficient of 0.0004. The average saturated thickness of water-bearing material was calculated as the average saturated thickness of the Cuchara–Poison Canyon aquifer (weighted by area) times the average ratio of water-bearing material (siltstone, sandstone, and conglomerate) to total formation thickness in the stratigraphically equivalent Dawson Formation of the Denver Basin. This ratio is 0.45 (Robson, 1983, table 1). The average storage coefficent of the Cuchara–Poison Canyon aquifer was estimated from storage coefficients of the Dawson aquifer (Robson, 1983, fig. 14).

Raton–Vermejo–Trinidad Aquifer

The Raton–Vermejo–Trinidad aquifer consists of the Raton Formation of Cretaceous and Paleocene age and the Vermejo Formation and Trinidad Sandstone of Cretaceous age. These three formations are considered to be a single aquifer because of compositional and hydrological similarity between the Raton and Vermejo Formations and similarity between sandstone layers in these formations and those in the Trinidad Sandstone. Depths to the top of the formations comprising the aquifer range from 0 to more than 2,800 ft (fig. 35).

The Trinidad Sandstone and the Vermejo and Raton Formations range in thickness from 0 to more than 2,500 ft (fig. 36). Thicknesses were determined from unpublished exploration hole and well logs, published isopach (thickness) maps of the Vermejo Formation and Trinidad Sandstone (Johnson and Wood, 1956, p. 29–30), and differences between structural contours on top of the Trinidad Sandstone (Amuedo and Ivey, 1974, p. 13) and topographic contours. In outcrop areas, the aquifer includes only the saturated part of the three formations. In these areas, depths to water range from 18 to 100 ft in stream valleys to as much as 500 ft beneath stream divides (fig. 30). In stream valleys, ground water is relatively shallow because local flow systems direct water toward the valleys. Beneath stream divides, ground water is relatively deep because local flow systems direct water away from the divides. Springs occur in valleys where the topographic surface intersects the water table.

Water is transmitted primarily by sandstone layers, but thick coal seams and fractured siltstone and shale layers also transmit water. Within the Raton and Ver-

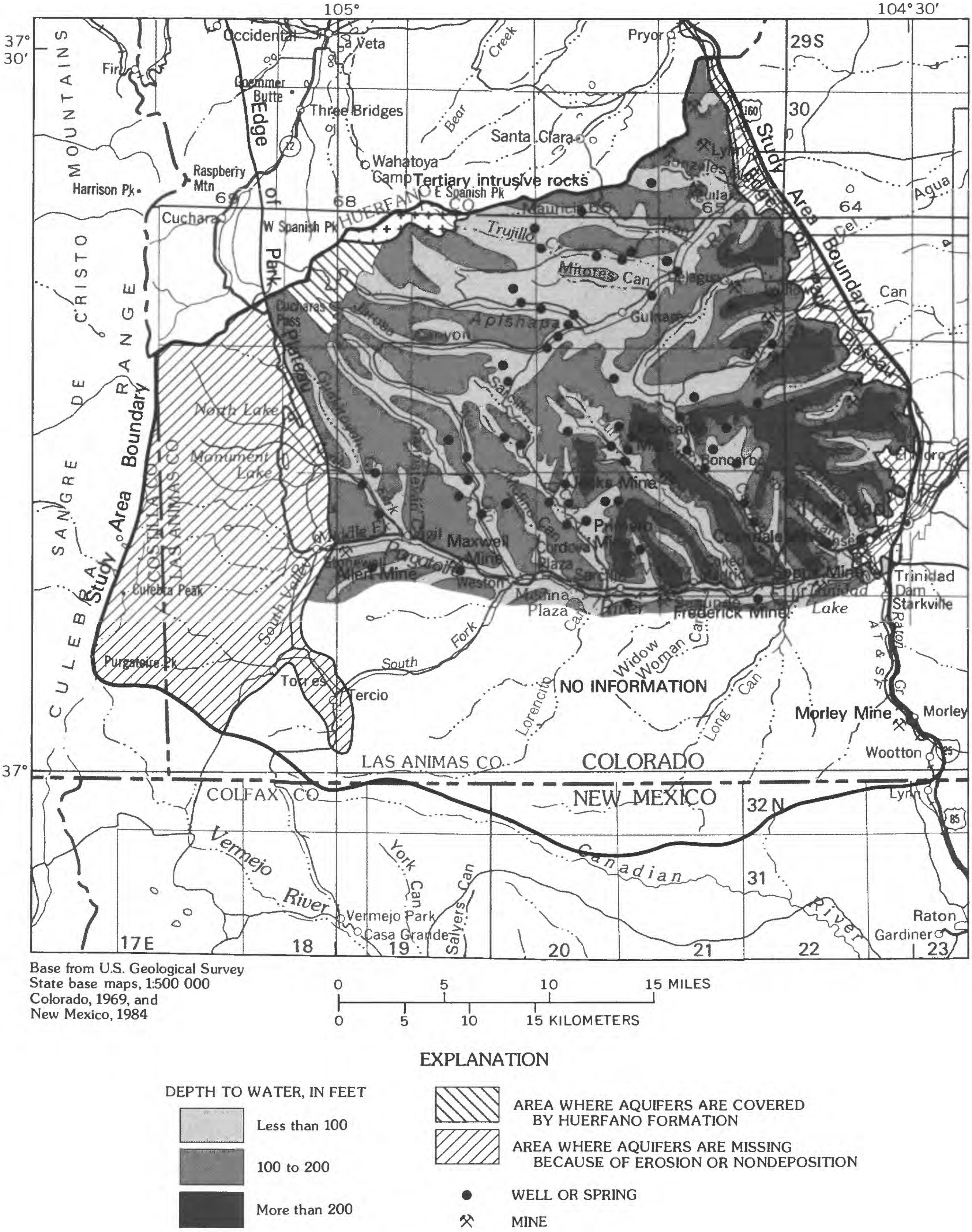


Figure 30. Depth to water in the Cuchara–Poison Canyon and Raton–Vermejo–Trinidad aquifers in the central Raton Basin.

Table 4. Estimated volume of recoverable ground water from aquifers in the central Raton Basin

[Volume of recoverable ground water=area times saturated thickness of water-bearing material times storage coefficient or specific yield. Bracketed figures are estimates. ---, not applicable]

	Alluvium						
	Purgatoire River	Apishapa River and Jarosa Canyon	Tributaries	Western valleys	Pediments	Total	Average
Area (square miles)[1]----------	2.03	1.17	21.6	1.41	3.09	29.3	---
Thickness (feet)--------------	15	31	35	[45]	[40]	---	34.5
Depth to water (feet)---------	8.8	[21]	[25]	[30]	[39]	---	---
Saturated thickness (feet)----	6.2	[10]	[10]	[15]	[1]	---	9.0
Saturated thickness of water-bearing material (feet).	---	---	---	---	---	---	9.0
Storage coefficient or specific yield.	---	---	---	---	---	---	0.04
Volume of recoverable ground water (acre-feet).	---	---	---	---	---	---	[2]6,800

[1]One square mile equals 640 acres.
[2]Rounded to two significant figures.

mejo Formations, sandstone layers comprise 11–47 percent of the rock in 28 exploration holes over 300 ft deep. Coal layers in these exploration holes comprise 1–7 percent of the rock (table 5). On average, sandstone and coal comprise 29 percent of the Raton and Vermejo Formations. The total thickness of sandstone and coal in the Raton and Vermejo Formations and the Trinidad Sandstone exceeds 800 ft in the center of the basin (fig. 37).

Except for the upper and lower 100 to 300 ft of the Raton Formation and the Trinidad Sandstone, sandstone layers in the Raton–Vermejo–Trinidad aquifer tend to thicken and thin irregularly (fig. 9). Individual layers may be as much as 30–50 ft thick. As evidenced by springs, water is transmitted most commonly through pores and bedding planes of slabby, arkosic sandstone layers, but fractures in sandstone also yield water (fig. 38). Underlying shale layers and thin coal seams confine water in the sandstone layers (fig. 39).

Several commercially thick coal seams are known to transmit water. The Ward well (SC03206636aac), which yielded 10 gal/min with 93 ft of drawdown when bailed, intersects a shaft of the abandoned Boncarbo coal mine. According to Warren Taylor, a longtime resident of the area, water collecting in the Boncarbo mine hampered operations. Jacks Mine, in Burro Canyon, and the Boncarbo mine, both of which are excavated into the Boncarbo seam, intermittently discharge less than 1 gal/min through tailings blocking the shafts. The Martinez well (SCO3306505aac) is an abandoned air shaft of a mine, which also penetrated the Boncarbo seam. A shaft of the abandoned Frederick coal mine, located at Valdez, Colo., discharged 31–37 gal/min in 1983; diffuse seepage occurs along the outcrop of the mined coal seam.

The Allen Mine near Weston, Colo., had an average discharge in 1980 of 73 gal/min from approximately 6 mi^2 of shaft area. The nearby Maxwell Mine had an average discharge in 1980 of 15 gal/min from approximately 0.12 mi^2 of shaft area. When expanded to the size of the Allen Mine, it is estimated that the Maxwell Mine will have an average discharge of 179–193 gal/min (Water, Waste, and Land, Ltd., 1980, p. 30–31). In 1983, most of the water in the Maxwell Mine was found to originate from the coal seam, which varies from 5 to 10 ft in thickness. Most of the water was either dripping from fractures or seeping diffusely at the face of the shafts. Some water was flowing upward from the floors, and a little water was dripping from the roofs of shafts.

Because ground water is pumped from mines to enable them to operate, a cone of depression in the water table forms around the mine shafts, with the face of the shaft functioning as a seepage face (fig. 40*A*, *B*). This

Table 4. Estimated volume of recoverable ground water from aquifers in the central Raton Basin—Continued

Cuchara-Poison Canyon					Raton-Vermejo-Trinidad				
Continuous north of Purgatoire River	Continuous south of Purgatoire River	Erosional outliers	Total	Average	Uncovered	Covered by continuous outcrop	Covered by erosional outliers	Total	Average
236	93.3	1.03	330	---	444	329	1.03	774	---
929	[200]	[100]	---	721	1,155	1,894	1,492	---	1,470
98	98	[98]	---	---	162	0	0	---	---
831	102	[2]	---	623	993	1,894	1,492	---	1,377
---	---	---	---	280	---	---	---	---	535
---	---	---	---	0.0004	---	---	---	---	0.0003
---	---	---	---	[2]24,000	---	---	---	---	[2]80,000

seepage face moves forward as the mine shaft progresses (fig. 40*C*). It decreases in size and eventually disappears during times when mining operations are temporarily halted but pumping continues (fig. 40*D*, *E*). After mining ends and the pumps are removed, the water table returns to a level slightly lower than premining conditions (fig. 40*F*) because the abandoned mine shaft, even if filled with debris, is more permeable than the unmined bedrock and becomes a permanent conduit for ground-water flow to the surface.

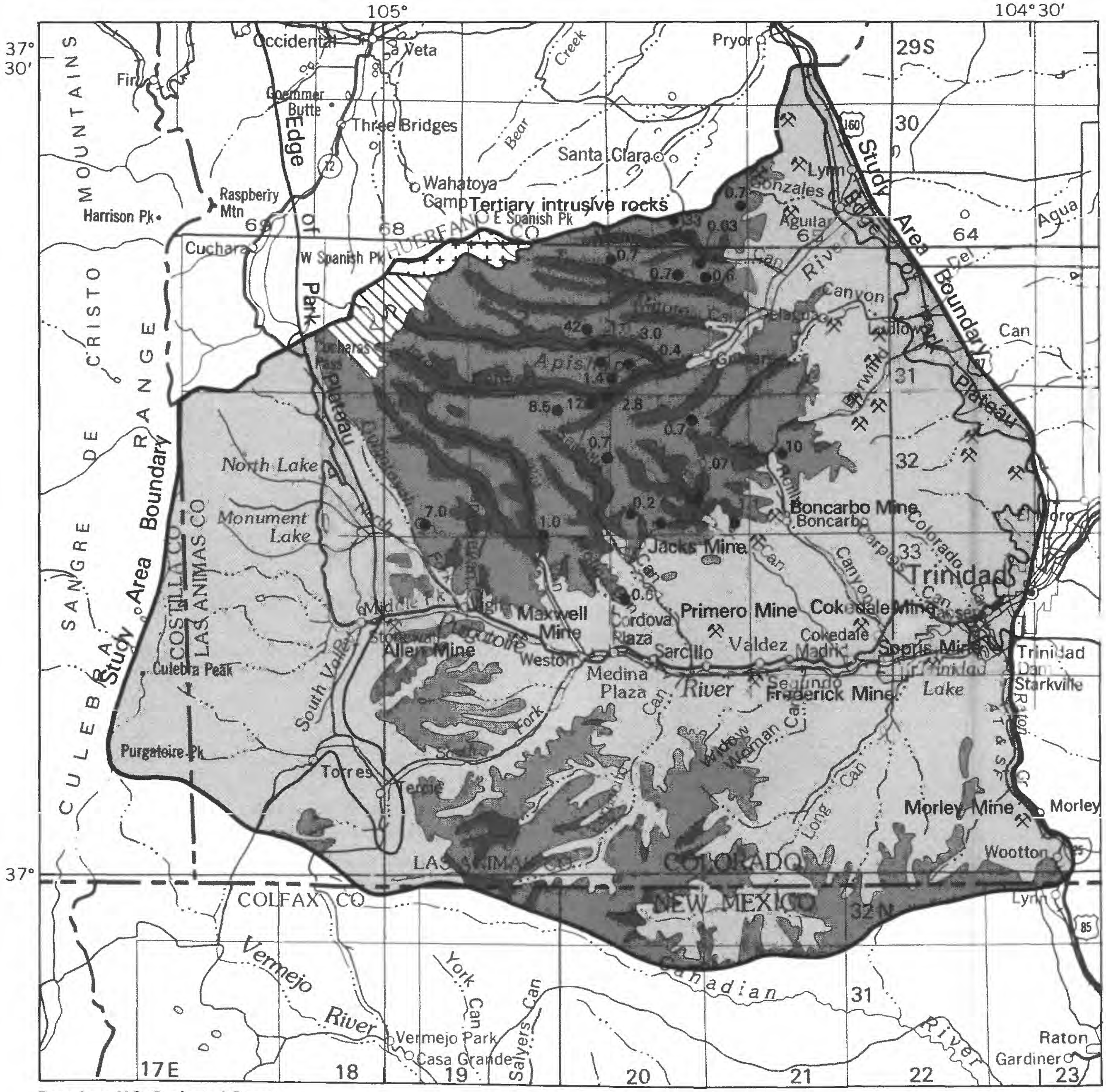
Well depths in the Raton–Vermejo–Trinidad aquifer typically range from 50 to 504 ft, averaging 145 ft in 55 wells. A few wells dug by early settlers are less than 50 ft deep, and some water wells converted from exploration holes and mine shafts, gas wells, and observation wells are 500–1,800 ft deep. Wells typically are 5–8 in. in diameter, but dug wells may be 2–4 ft wide, and wells converted from exploration holes typically are 4 in. in diameter. Drilled wells typically are cased with steel, but some wells are cased with plastic. In most wells, the casing extends to the top of the highest producing horizon.

According to drillers' logs, yields from wells completed in the aquifer ranged from 0.04 to 16 gal/min per 10 ft of drawdown, averaging 2.4 gal/min per 10 ft in 61 bailing tests (fig 41). Discharges from seven springs ranged from 0.1 to 35 gal/min, averaging 11 gal/min in the spring and summer of 1981.

Most wells and springs are located near the contact between the Poison Canyon and Raton Formations, because water descending through permeable sandstone in the Poison Canyon Formation cannot move as rapidly through siltstone and shale of the Raton Formation and perches at, above, or just below the contact with the lower formation.

If the Raton Formation contains sandstone lenses or other permeable layers near the Poison Canyon contact, then wells developed in this area, such as wells *B–E* in figure 42, produce water within 100 ft of the surface. Otherwise, wells have to be extended deeper into the Raton Formation to produce water (for example, wells *A* and *F*, fig. 42). Wells drilled in stream valleys (for example, well *H*, fig. 42) may have relatively large yields because of perched water. Because multiple water-transmitting layers exist within the aquifer, deepening wells to reach additional water may increase yields. For example, deepening well *B* in figure 42 to include both zones II and III could result in a larger yield from the well.

Transmissivity and hydraulic-conductivity values determined from aquifer tests or estimated from bailing tests using figure 32 vary substantially within short distances. Transmissivity values in 83 tests ranged from 0.019 to 215 ft^2/d and averaged 20 ft^2/d (table 6). Hydraulic-conductivity values in 26 tests ranged from 0.002 to 45 ft/d and averaged 2.2 ft/d (table 6). Sandstone and coal have about the same water-transmitting properties. Fractured siltstone and shale can be very permeable, but these rocks usually have little permeability where they are not fractured. Compositional heterogeneity in the Raton and Vermejo Formations causes much of the variation in reported hydraulic



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS CROP OUT
- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE COVERED BY ALLUVIUM
- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE COVERED BY HUERFANO FORMATION
- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION
- ●0.7 WELL—Number is yield in gallons per minute per 10 feet of drawdown
- ●7.0 SPRING—Number is yield in gallons per minute

Figure 31. Hydrologic features of the Cuchara-Poison Canyon aquifer in the central Raton Basin.

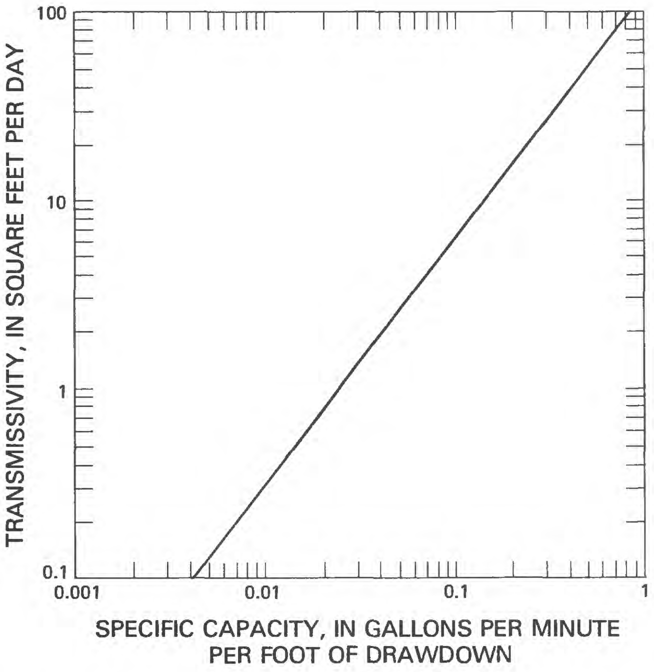


Figure 32. Relation of specific capacity to transmissivity in bedrock aquifers in the Denver Basin. Modified from Robson (1983, fig. 3).

properties, but some of this variation results from inconsistent methods of data collection and interpretation. Reported values generally should not be considered representative of the entire thickness of the aquifer at any site because few wells penetrate the aquifer completely. Reported values probably are representative of the range in transmissivity and hydraulic conductivity to be expected in typical shallow domestic and stock wells.

The potentiometric surface in the Raton–Vermejo–Trinidad aquifer slopes generally eastward but is deflected toward stream valleys because of local flow systems between stream divides and valleys (fig. 43). Regional flow is from west to east. Moreover, little ground water is available on the east side of the area because water discharging into valleys is carried away by streams or stored in alluvium.

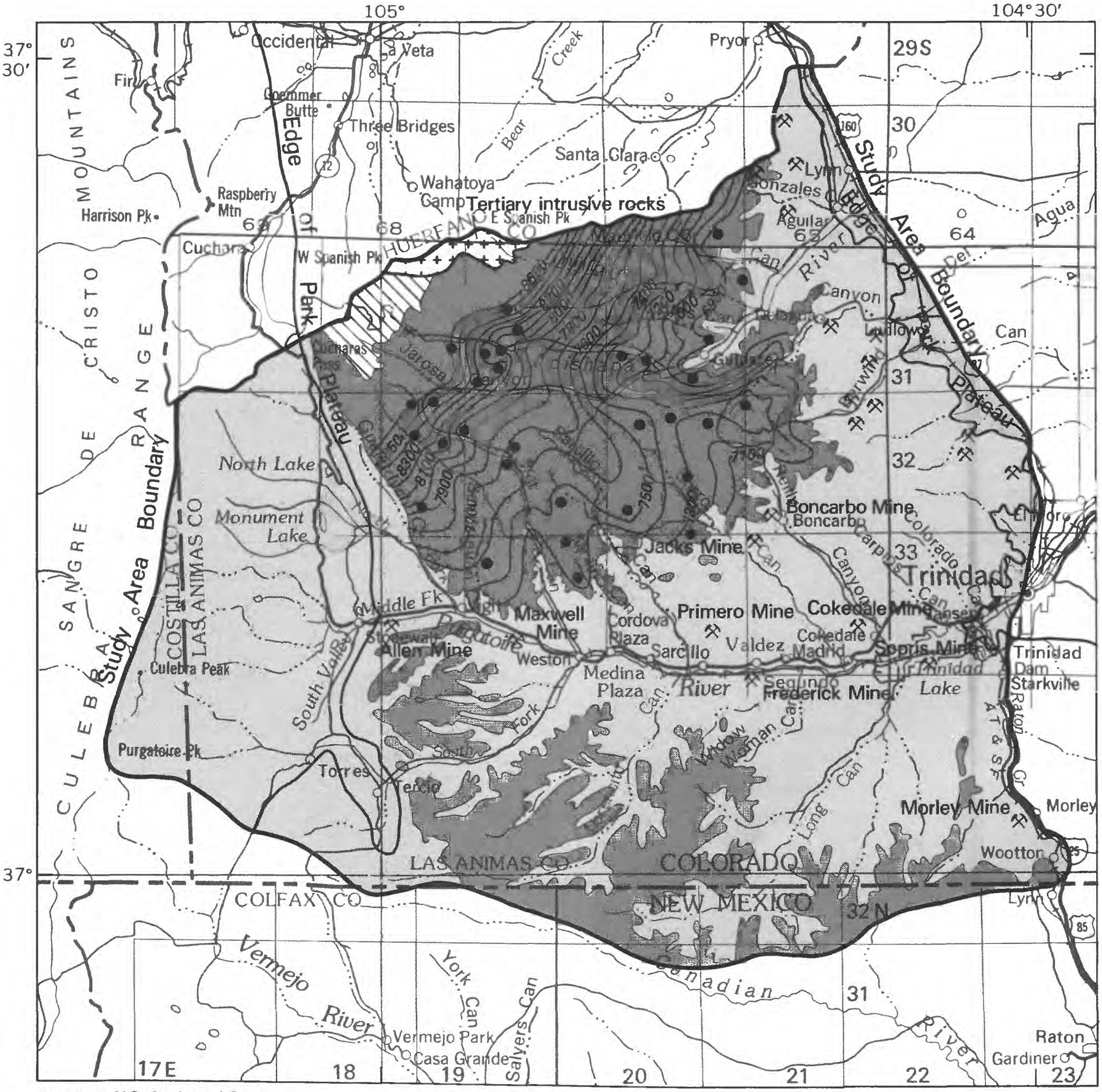
Potentiometric surface maps usually can be used to calculate hydraulic gradients. However, in an aquifer with multiple water-bearing layers, such as the Raton–Vermejo–Trinidad aquifer, quantitative inferences can be misleading when water levels from more than one water-bearing layer are composited. For example, in figure 44, which simulates observed conditions in the study area, the actual potentiometric surface, constructed only from water levels in a single layer, ABCFG, slopes to the right, but a potentiometric surface constructed without regard to well completion, ABCDEFG, has apparent reversals of slope. These reversals represent head differences between water-bearing layers and not the regional hydraulic gradient. Consequently, regional potentiometric maps for the Raton–Vermejo–Trinidad aquifer, such as figure 44, should not be used for quantitative evaluation of hydraulic properties.

Water levels in wells fluctuate from year to year in response to changes in water availability. From 1978 to 1981, water-level changes in wells during successive inventories in the Purgatoire River drainage ranged from +18 to –14 ft (fig. 45). Proximity of wells to the contact between the Poison Canyon and Raton Formations apparently affected the amount of change. Water-level rises may have been caused by infiltration of perched water at or near the contact between the two formations. Perched water was available because of larger than normal precipitation in 1979 and 1981. Response to this potential recharge diminished with distance from it.

Water-level fluctuations between 1979 and 1981 in 10 observation wells completed in the Raton Formation at the York Canyon coal mine about 5 to 9 mi south of the study area generally were 7 ft or less. No relation existed between the amount of fluctuation and either the composition (sandstone or coal), transmissivity, or depth of a confined producing layer (for example, fig. 46*A*–*C*). Seasonally fluctuating water levels were evident in only one well, M–11 (fig. 46*D*), which is completed in an unconfined part of the aquifer. In this well, water levels were highest from late spring to early fall and lowest in the winter months; the highest water levels occurred at times of the year when water is most available—in the spring, when the ground is saturated with snowmelt, and the summer, when thunderstorms are common. In four of the wells (for example, fig. 46*E*), water levels fluctuated sharply by as much as 23 ft between August 1979 and June 1980. This erratic behavior may have been in response to unreported mine operations.

Annually recorded water levels in a well completed in the Trinidad Sandstone near Walsenburg, Colo., about 18 mi north of the study area (fig. 47), demonstrate long-term variations in potentiometric head. Water levels in this well fluctuated by 7.3 ft between August 1949 and April 1983. Since 1955, the potentiometric surface at this well has risen 3–7 ft, mostly in response to decreased use of the well.

In an average year, the Raton–Vermejo–Trinidad aquifer is estimated to contain about 80,000 acre-ft of recoverable water (table 4). This estimate was based on a planimetered area of 774 mi^2 (495,360 acres), an estimated average saturated thickness of water-bearing material of 535 ft, and an estimated storage coefficient of 0.0003. The average saturated thickness of water-bearing material was calculated as the average saturated thickness of the Raton and Vermejo Formations (weighted by area) times the average ratio of sandstone and coal to total thickness in these formations, plus the average thickness of the Trinidad Sandstone. The average ratio of



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS CROP OUT
- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION
- AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE COVERED BY HUERFANO FORMATION
- —*7400*— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in a tightly cased well. Contour interval 100 feet. Datum is sea level
- ● WELL

Figure 33. Potentiometric surface in the Cuchara–Poison Canyon aquifer, May 1978, in the central Raton Basin.

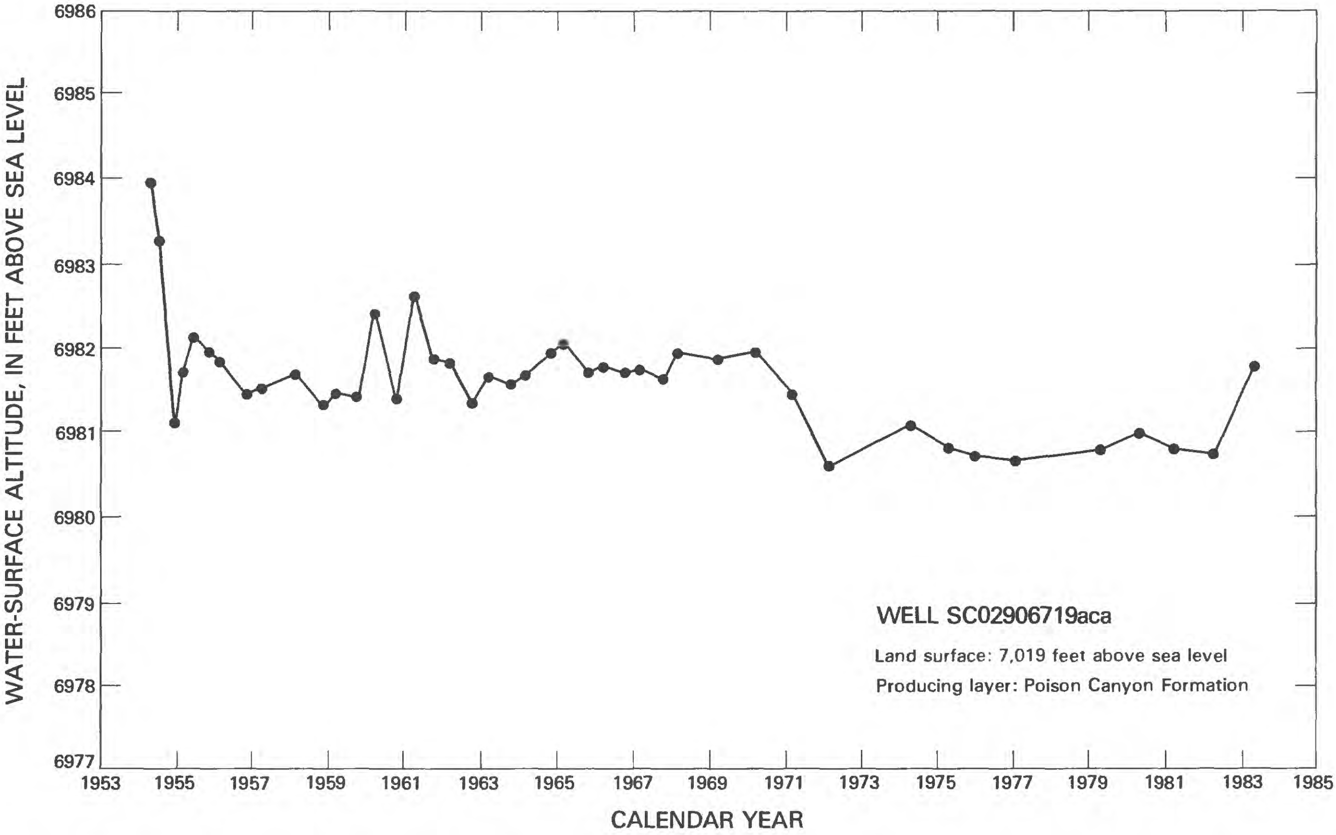


Figure 34. Recorded water levels in the Cuchara–Poison Canyon aquifer near La Veta, Colo., 1954–83.

sandstone and coal in the Raton and Vermejo Formations is 0.29. The average thickness of the Trinidad Sandstone is 191 ft. The average storage coefficient of the Raton–Vermejo–Trinidad aquifer was estimated from storage coefficients of the stratigraphically equivalent Denver, Arapahoe, and Laramie–Fox Hills aquifers in the Denver Basin (Robson, 1983, figs. 15–17).

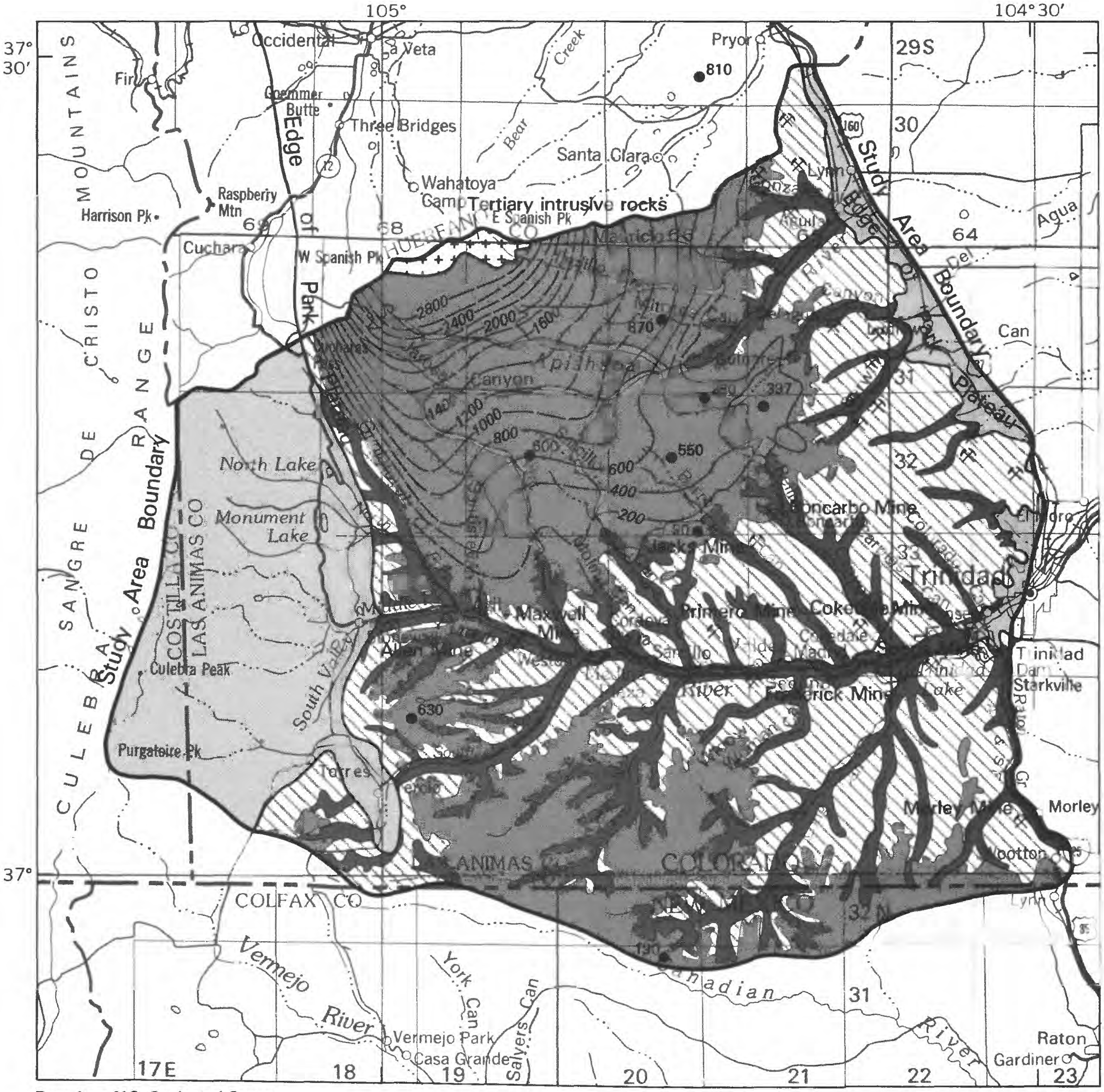
Cretaceous Marine Shale and Limestone

Formations occurring stratigraphically between the Trinidad and Dakota Sandstones, including the Pierre Shale, the Niobrara Formation, the Carlile Shale, the Greenhorn Limestone, and the Graneros Shale, are nearly impermeable. Based on information from other parts of the basin and several wells in the study area, wells drilled into shale are likely to be dry; however, fractured and weathered shale beneath covering alluvium east and west of the Park Plateau could produce several gallons per minute. Limestone layers in the Pierre Shale and the Smoky Hill Marl Member of the Niobrara Formation may yield 10 to 20 gal/min, whereas the Fort Hays Limestone Member of the Niobrara Formation and the Greenhorn Limestone likely will yield less than 10 gal/min. Interbedded sandstone and shale in the upper 160–300 ft of the Pierre Shale could yield as much as 5–10 gal/min from wells drilled through overlying Cretaceous and Paleocene rocks in the Park Plateau. All wells drilled into these shale and limestone formations are likely to have pumping drawdowns of several tens to more than a hundred feet. In the study area, Cretaceous marine shale and limestone are used as sources of water only in the plains region east of the Park Plateau, where better supplies are not available.

Dakota–Purgatoire Aquifer

The Dakota Sandstone and the Cheyenne Sandstone Member of the Purgatoire Formation and their stratigraphic equivalents throughout the Great Plains are considered to be a regional aquifer. Locally, the Kiowa Shale Member of the Purgatoire Formation and its stratigraphic equivalents are thick enough to separate the Dakota Sandstone and Cheyenne Sandstone Member into two aquifers. In most of the study area, the Dakota Sandstone and Purgatoire Formation are either removed by erosion or are generally more than 2,500 ft deep (fig. 48).

In the area between Cucharas Pass and Torres, however, these formations are less than 2,500 ft deep and are relatively accessible. Although outcrops are narrow and drained, wells drilled into the Dakota Sandstone and



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

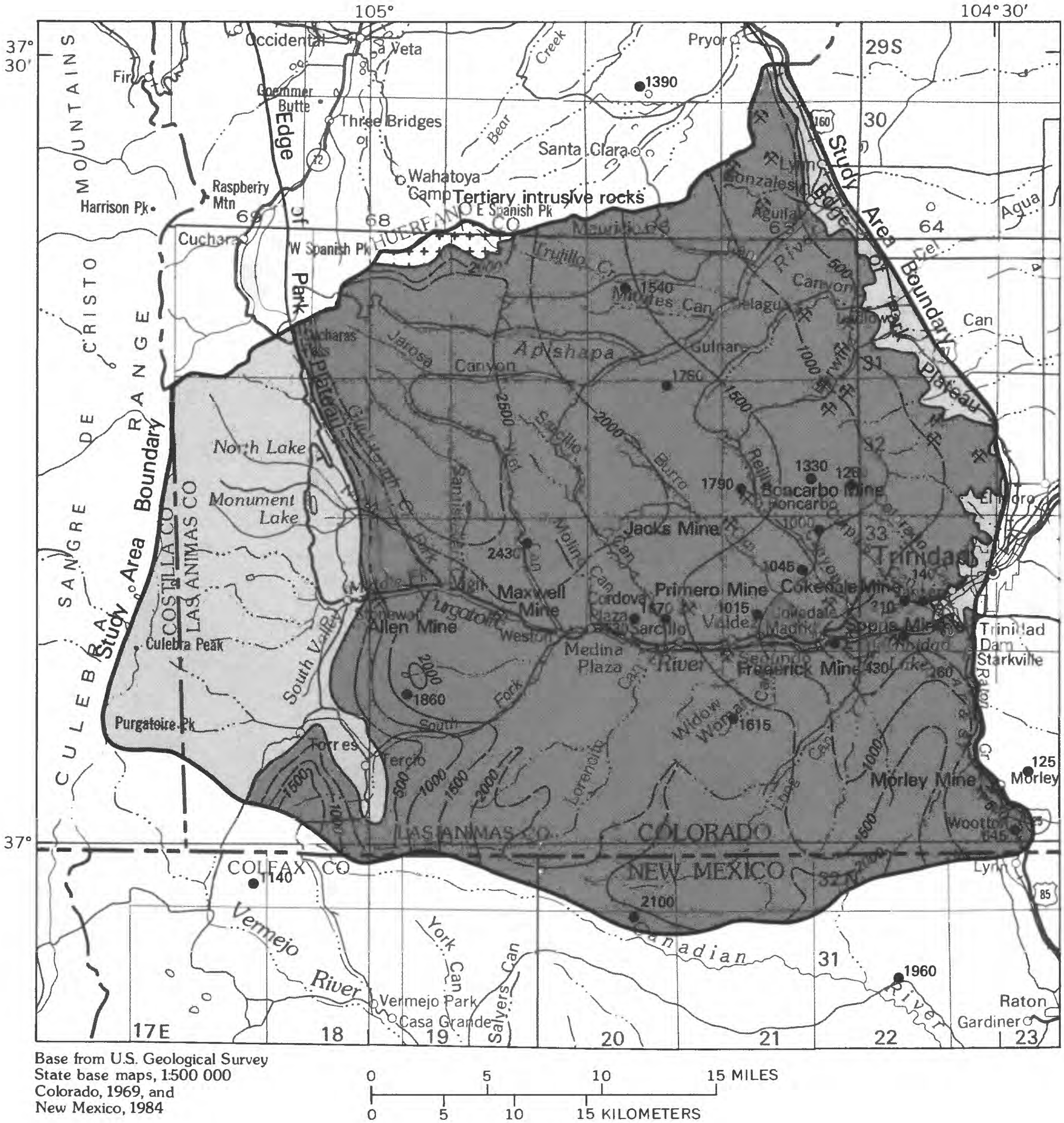
0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

- AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS CROP OUT
- AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE COVERED BY ALLUVIUM
- AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE COVERED BY TERTIARY FORMATIONS
- AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION
- —200— LINE OF EQUAL DEPTH TO AQUIFER—Dashed where approximately located. Interval 200 feet. Datum is land surface
- ●550 BOREHOLE—Number is depth to top of Raton-Vermejo-Trinidad aquifer, in feet below land surface
- ⚒ MINE

Figure 35. Depth to top of the Raton–Vermejo–Trinidad aquifer in the central Raton Basin.



EXPLANATION

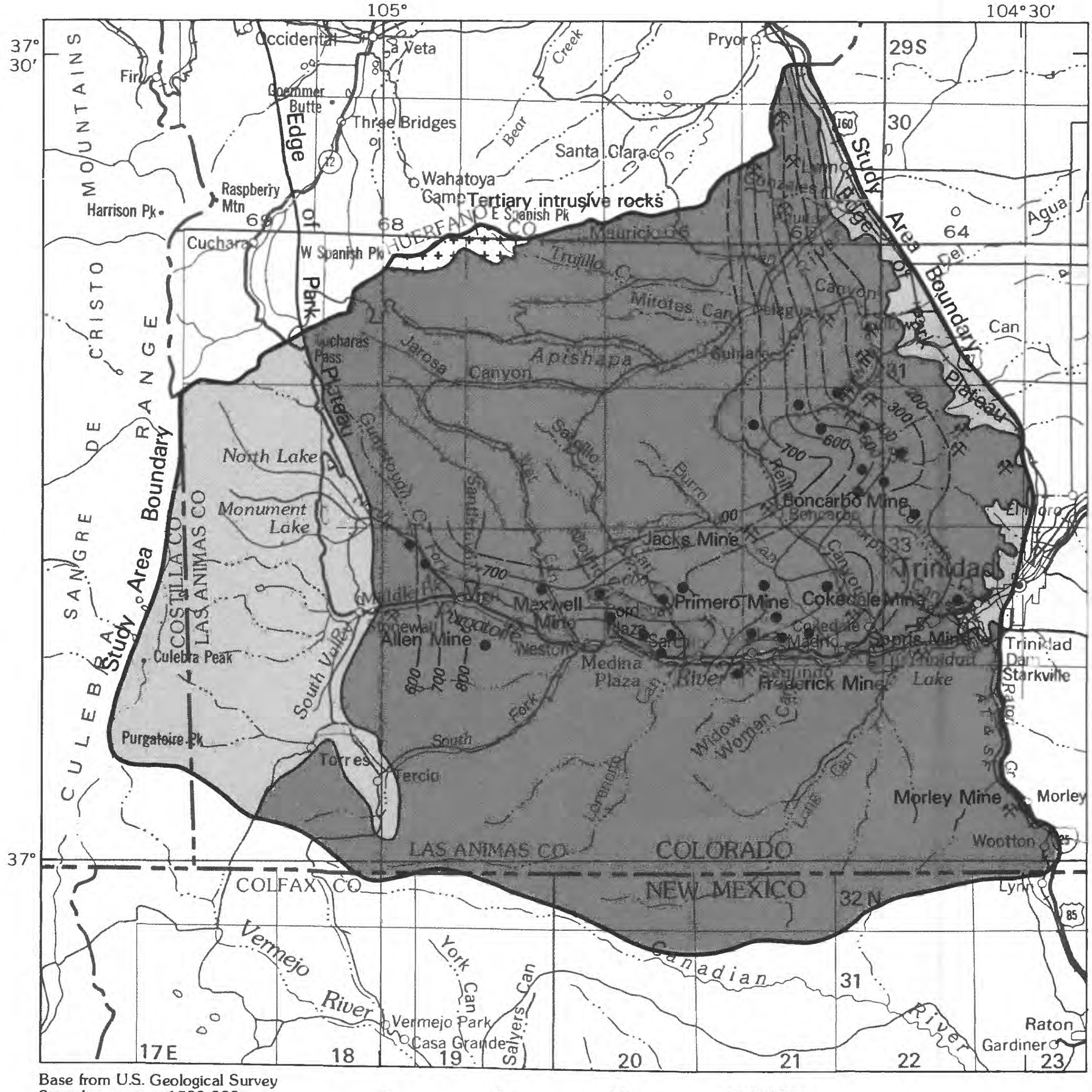
AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE PRESENT

AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION

—500— LINE OF EQUAL THICKNESS OF TRINIDAD SANDSTONE, VERMEJO AND RATON FORMATIONS—Dashed where approximately located. Interval 500 feet

●140 BOREHOLE—Number is thickness of Trinidad Sandstone, Vermejo and Raton Formations, in feet

Figure 36. Thickness of the Trinidad Sandstone and Vermejo and Raton Formations in the central Raton Basin.



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

- [dark shading] AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE PRESENT
- [light shading] AREA WHERE TRINIDAD SANDSTONE AND VERMEJO AND RATON FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION
- —500— LINE OF EQUAL THICKNESS OF SANDSTONE AND COAL—Dashed where approximately located. Interval 100 feet
- ● BOREHOLE
- ⚒ MINE

Figure 37. Thickness of sandstone and coal in the Trinidad Sandstone and Vermejo and Raton Formations in the central Raton Basin.

Table 5. Thickness and composition of the Raton and Vermejo Formations in the central Raton Basin

Site	Thickness (feet)				Composition (percent)		
	Sandstone	Siltstone and shale	Coal	Total	Sandstone	Coal	Water-transmitting layers
SC29066026dbc	574	624	19	1,217	47	2	49
SC32064019dbd	94	262	4	360	26	1	27
SC32064032bda	47	251	4	302	16	1	17
SC32065003cda	165	459	25	649	25	4	29
SC32065004cda	168	404	28	600	28	5	33
SC32065007cba	239	430	23	692	35	3	38
SC32065009ddd	235	598	28	861	27	3	30
SC32065014abd	134	259	17	410	33	4	37
SC32065024cab	183	376	18	577	32	3	35
SC32065025aaa	189	917	20	1,126	17	2	19
SC32065026dbb	212	770	31	1,013	21	3	24
SC33065002cbb	200	498	12	710	28	2	30
SC33065015acc	362	519	29	910	40	3	43
SC33065016ccd	274	530	46	850	32	5	37
SC33065018ac	296	946	34	1,276	23	3	26
SC33065020caa	145	390	10	545	27	2	29
SC33065029bd	251	563	26	840	30	3	33
SC33065030db	82	213	6	301	27	2	29
SC33066015bab	93	333	16	442	21	4	25
SC33066019cba	123	360	22	505	24	4	28
SC33066001bad	50	373	27	450	11	6	17
SC33066028caa	129	340	14	483	27	3	30
SC33066029ada	129	266	10	405	32	2	34
SC33067013cda	74	438	18	530	14	3	17
SC33067014dcc	171	582	37	790	22	5	27
SC33067015add	56	282	22	360	16	6	22
SC33067029bda	144	298	31	473	30	7	37
SC33069003dac	120	365	4	489	25	1	26
Average					26	3	29

Purgatoire Formation through overlying alluvium, shale, and limestone are likely to yield water. Valley-fill alluvium in the Cucharas Pass–Torres area stores water, which slowly percolates down to the Dakota-Purgatoire aquifer through fractures in the overlying rocks. At the same time, water is confined in the aquifer because rocks above and below have less lateral permeability.

Most wells penetrating the Dakota-Purgatoire aquifer will be artesian; throughout most of the area, water is likely to flow from these wells. Based on information from other parts of the basin (Griggs, 1948; McLaughlin and others, 1961; McLaughlin, 1966; and U.S. Geological Survey, unpublished well logs), wells completed in the Dakota-Purgatoire aquifer will likely yield 10–100 gal/min per 10 ft of drawdown. The Dakota-Purgatoire aquifer is not likely to be used, however, because overlying bedrock and alluvium yield comparable or better supplies of water.

Pre-Cretaceous Rocks

Pre-Cretaceous rocks are not utilized as sources of water in the study area, but they may yield water to wells in areas of outcrop. Precambrian crystalline rocks and sedimentary rocks of Pennsylvanian and Permian age in the Sangre de Cristo Mountains in Huerfano County yield small quantities of water from fractures, bedding planes, and weathered zones, and similar yields can be expected in the study area. No wells are known to be completed in Jurassic aquifers within the Raton Basin,

Figure 38. Berwind Spring issuing from the Raton Formation in Berwind Canyon near Ludlow, Colo. Most of the water emanates from pores and bedding planes of an arkosic sandstone layer. Some water also issues from fractures in the rock and from channel alluvium. When photographed in August 1981, the spring was discharging at the rate of 27.5 gal/min.

Figure 39. Tokar Spring issuing from the Raton Formation in Sarcillo Canyon near Segundo, Colo. Water issues from an arkosic sandstone layer, covered with tailings from a small coal mine, into a trough. Water is confined in the sandstone by a thin layer of coal.

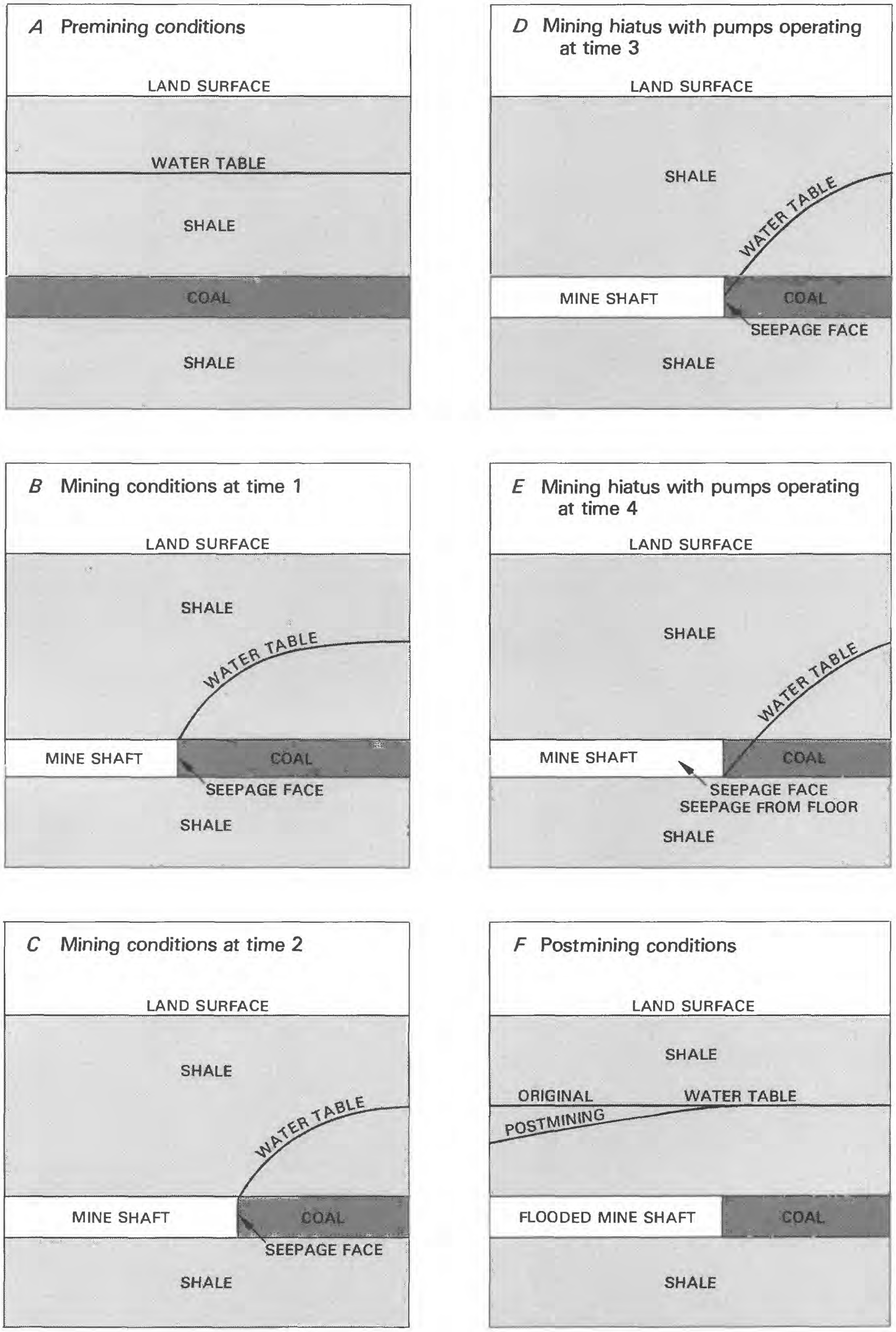
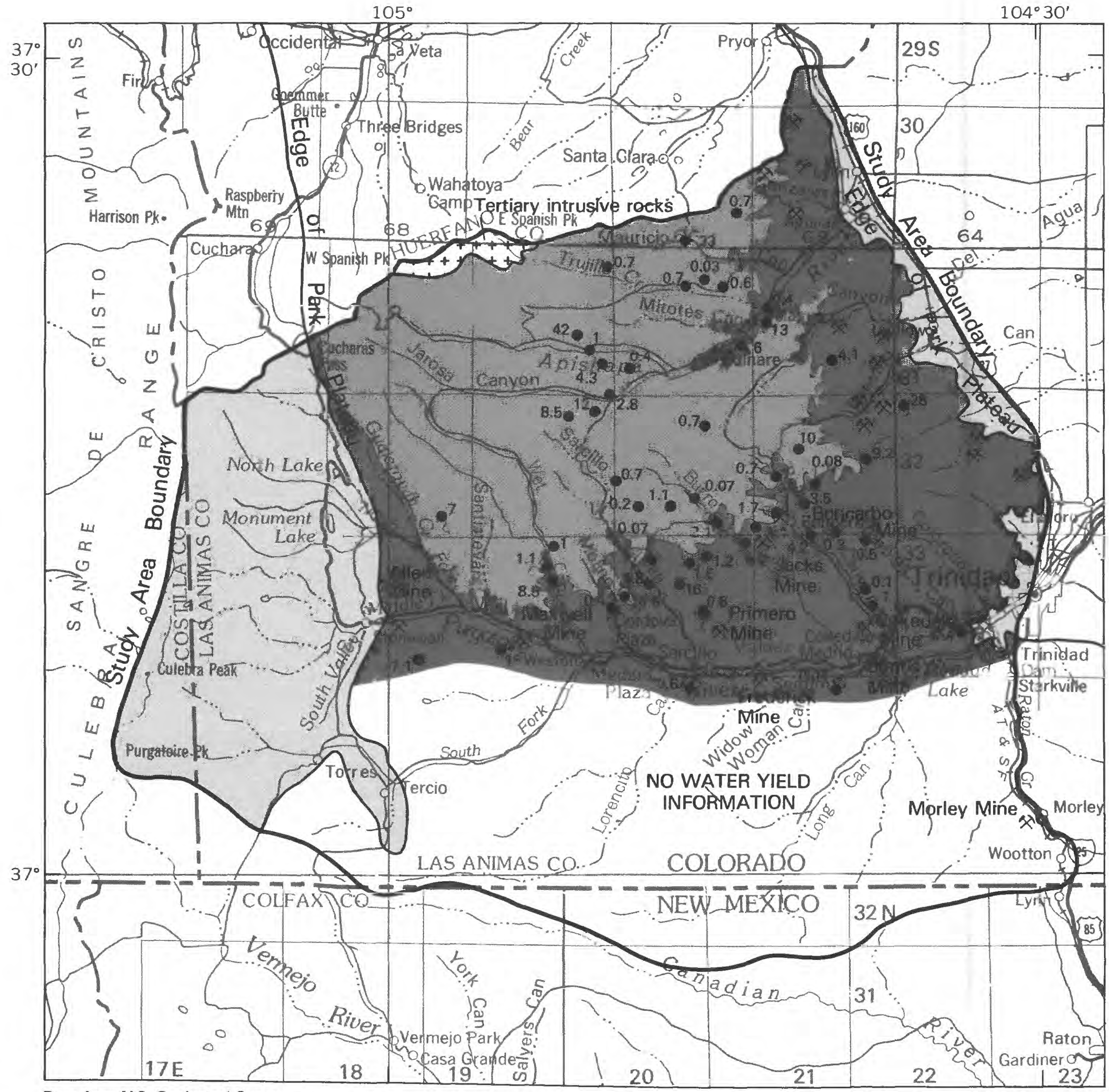


Figure 40. Effects of an underground coal mine on the water table.



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES
0 5 10 15 KILOMETERS

EXPLANATION

- AREA WHERE REPORTED YIELDS ARE FROM CUCHARA-POISON CANYON AQUIFER
- AREA WHERE REPORTED YIELDS ARE FROM RATON-VERMEJO-TRINIDAD AQUIFER
- AREA WHERE TRINIDAD SANDSTONE AND VERMEJO, RATON, POISON CANYON, AND CUCHARA FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION
- CONTACT BETWEEN RATON AND POISON CANYON FORMATIONS
- 0.7 WELL—Number is yield in gallons per minute per 10 feet of drawdown
- 7 SPRING—Number is discharge in gallons per minute
- MINE

Figure 41. Yields from the Cuchara–Poison Canyon and Raton–Vermejo–Trinidad aquifers in the central Raton Basin.

Table 6. Summary results of hydraulic tests in the Raton–Vermejo–Trinidad aquifer in the central Raton Basin

[Sources: Water, Waste, and Land, Ltd.(1980); Howard (1982); Colorado Division of Water Resources State Engineer's Office (written commun., 1981); Kaiser Steel Corporation (written commun., 1981); and U.S. Geological Survey files]

Type	Number of tests	Transmissivity (feet squared per day)			Number of tests	Hydraulic conductivity (feet per day)		
		Minimum	Maximum	Mean		Minimum	Maximum	Mean
		By test for all rock types						
Bailing[1]	59	0.10	215	23	2	0.002	0.61	0.31
Slug	17	.019	56	7.9	17	.002	2.66	.23
Pressure	5	3.43	18	10	5	.16	1.06	.47
Pumping	2	28	91	60	2	5.66	45	25
All	83	.019	215	20	26	.002	45	2.2
		By rock type for all tests						
Sandstone	11	0.027	30	7.9	11	0.002	2.66	0.35
Coal	6	.56	28	8.8	6	.06	5.66	1.1
Siltstone	2	11	91	51	2	1.06	45	23
Mixed	6	.48	56	11	6	.002	.28	.06
All	25	.027	91	12	25	.002	45	2.3

[1]Transmissivity values determined in bailing tests were estimated using figure 32.

but the Entrada Sandstone and sandstone layers within the Morrison Formation underlying valleys separating the Sangre de Cristo Mountains from the Park Plateau may yield as much as 10 gal/min (McLaughlin, 1966, p. 59–61).

Quality

Chemical analyses of ground water collected at 70 sites from 1977 to 1983 (table 7) were reviewed during this investigation to determine background water quality as a means of assessing the impacts of planned coal mining in the area. Conclusions about the water quality in hydrologic units were made where there were sufficient data to justify extrapolation. Potential health problems were highlighted by comparing water quality in the study area with water-quality standards set by the U.S. Environmental Protection Agency and other regulatory agencies.

Average compositions of ground water in individual aquifers are distinctive (fig. 49). The average composition of water in the alluvium is calcium bicarbonate. The average composition of water in the Raton–Vermejo–Trinidad aquifer is sodium bicarbonate. In nine analyses of water from the Cuchara–Poison Canyon aquifer, the average composition was sodium chloride; however, many types of water occur in this aquifer, and nine analyses may be insufficient to establish an average composition. In one analysis of water from the Pierre Shale, the composition was sodium chloride. This sample may not represent the typical composition of water from the Pierre Shale in the study area, but it is included for comparison.

Water from the alluvium generally contains fewer dissolved solids than water from bedrock aquifers (fig. 49). In samples taken within 1 mi of each other, dissolved-solids concentrations were always smaller in water from alluvium than in water from bedrock aquifers (fig. 50). However, concentrations of sulfate usually were larger in water from alluvium and springs than in water from wells developed in bedrock. Sulfate concentrations probably are larger at shallower depths because of: (1) oxidation of hydrogen sulfide in outflowing ground water; and (2) introduction of leached sulfate by inflowing surface water.

Concentrations of fluoride are inversely related to concentrations of nitrogen. Fluoride is more concentrated at depth, possibly because of proximity to igneous sources. Alternatively, deeper water presumably has a longer residence time, which allows more dissolution of fluoride minerals. Nitrogen usually is more concentrated near the surface, possibly because of contamination from human and animal wastes and fertilizers or because of nitrogen-fixing bacteria in the soil zone.

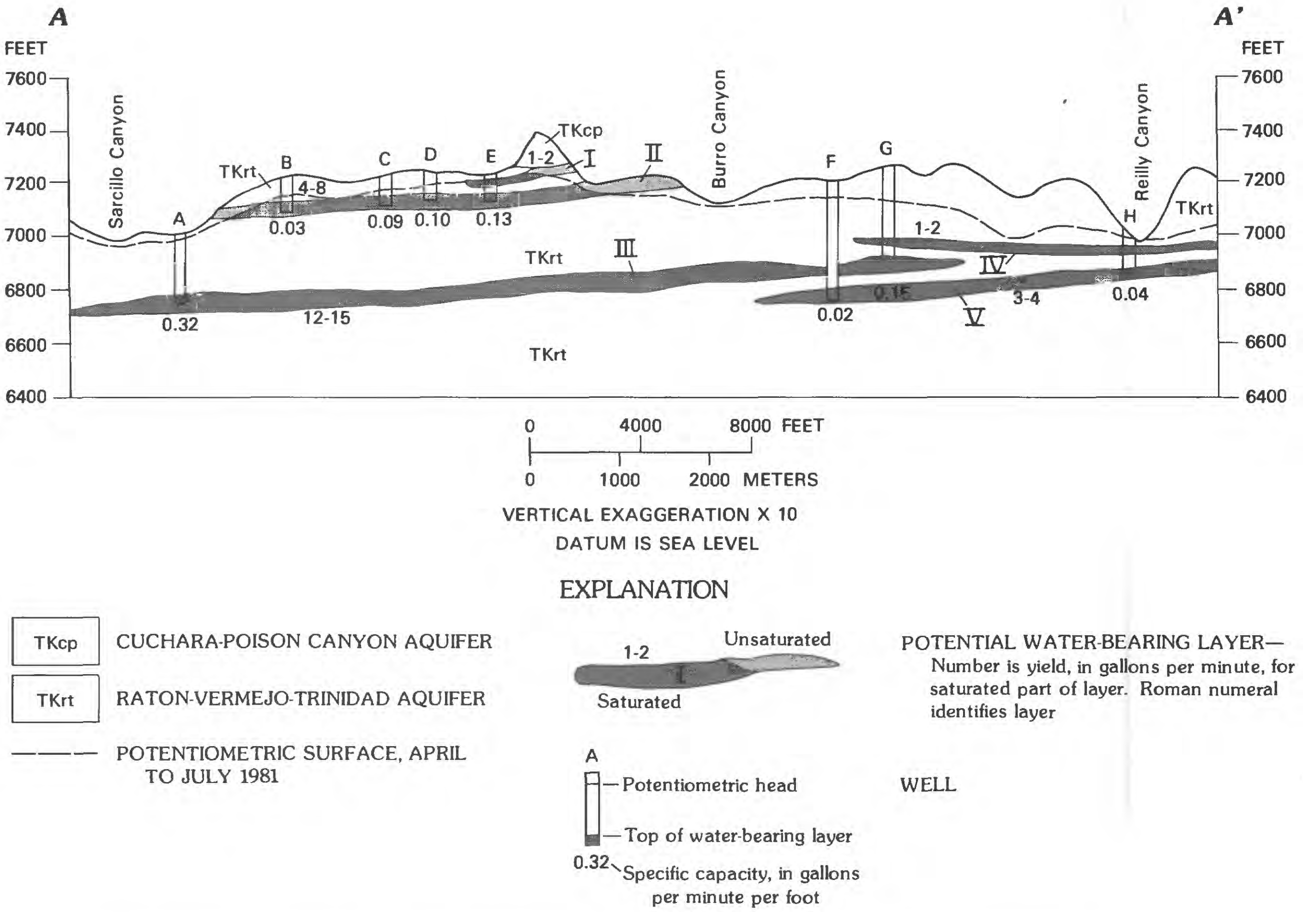


Figure 42. Features of water-bearing layers in the Raton–Vermejo–Trinidad aquifer in the central Raton Basin.

If only the specific conductance is known, the dissolved-solids concentration may be estimated from figure 51. For the same specific conductance, the estimated concentration of dissolved solids is larger in bedrock aquifers than in alluvium.

Concentrations of dissolved trace metals rarely exceed recommended levels (tables 8 and 9). Concentrations of boron and selenium in excess of water-quality standards are associated with the mining of coal in the Raton and Vermejo Formations. Concentrations of iron, manganese, and zinc in excess of water-quality standards generally are caused by corrosion of well casing and plumbing. Iron enrichment also may be caused by the dissolution of pyrite, an iron sulfide mineral. Concentrations of vanadium in excess of water-quality standards occur without apparent cause in mining effluent from the Raton Formation, in the Cuchara–Poison Canyon aquifer, and in the Pierre Shale.

Alluvium

In the Purgatoire River valley and in Wet, Sarcillo, Burro, Reilly, and Mauricio Canyons, the alluvium contains mostly calcium bicarbonate water. However, the water has been altered to sodium bicarbonate and sodium sulfate types near the Allen, Primero, Frederick, Burro Canyon group, Boncarbo, and Cokedale coal mines. Downstream from the confluence of the Middle and South Forks of the Purgatoire River, magnesium calcium bicarbonate water may result from dissolution of a magnesium silicate mineral from a local source, possibly an igneous intrusion. Compositional changes generally do not persist far downstream from individual point sources of minerals. However, the concentration of dissolved solids generally increases in a downstream direction because of the cumulative inflow of bedrock ground water and contaminants.

The concentration of dissolved solids in 20 analyses ranged from 200 to 1,000 mg/L and averaged 463 mg/L. However, the concentration exceeded 3,000 mg/L in a well contaminated by mining effluent. Those minerals most affected by mining activity were sulfate and selenium. The concentration of sulfate ranged from 5 to 200 mg/L in 13 analyses of water unaffected by mining activity but was as large as 1,500 mg/L in 7 analyses of

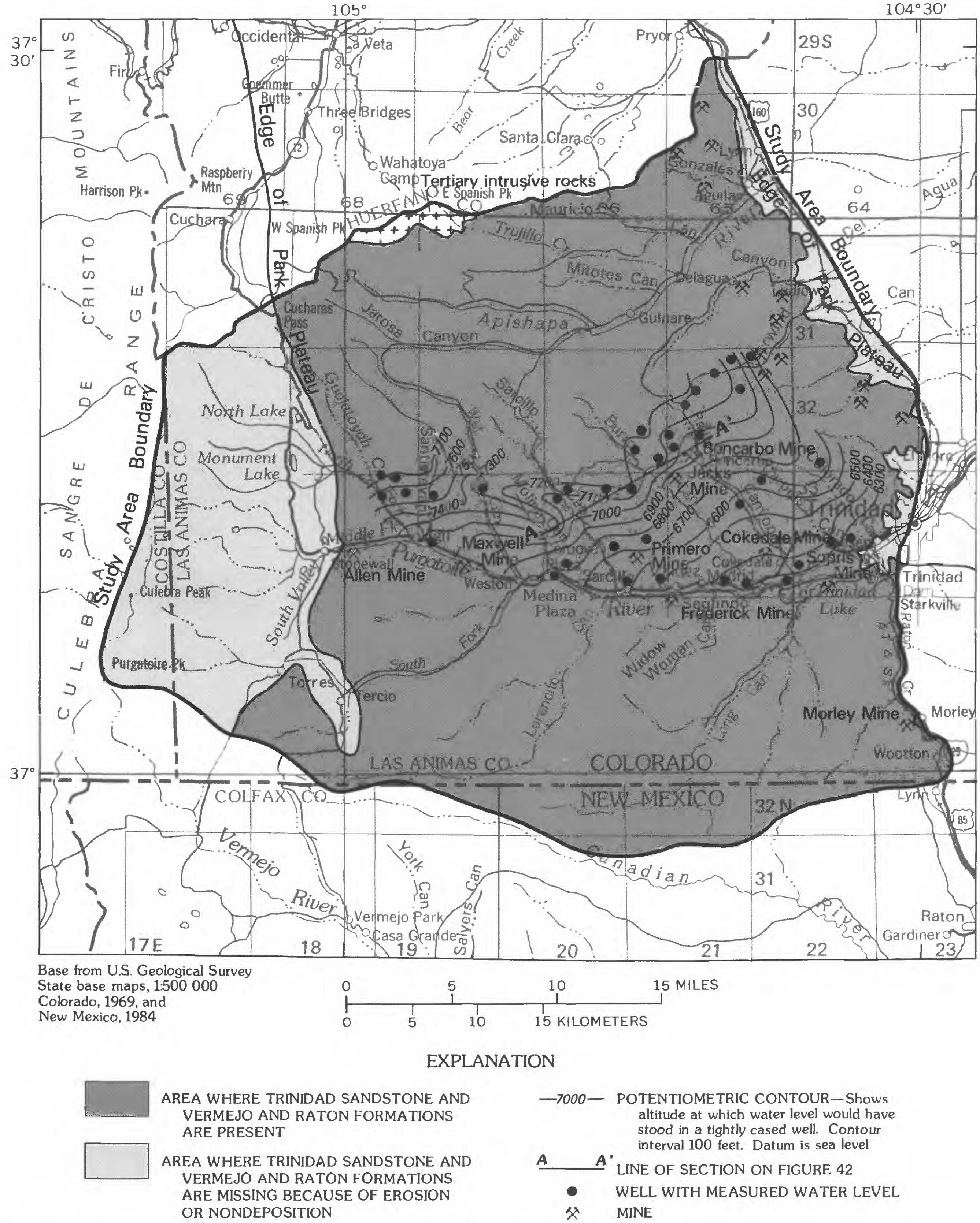


Figure 43. Potentiometric surface in the Raton–Vermejo–Trinidad aquifer, April–July 1981, in the central Raton Basin.

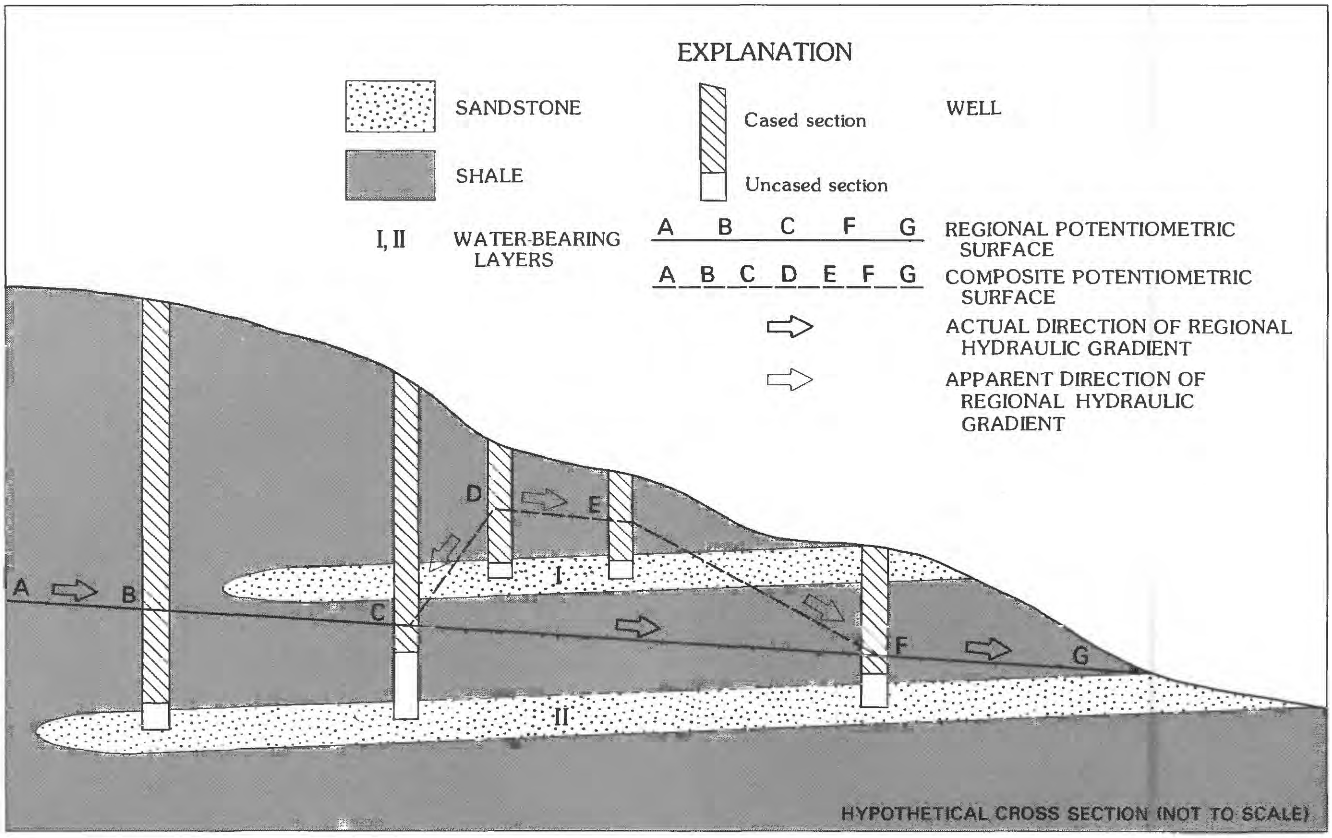


Figure 44. Comparison of real and apparent directions of regional ground-water movement determined from potentiometric surfaces.

water from sources near coal mines. Selenium concentrations, which ranged from 0 to 10 μg/L in most analyses, were as large as 13 μg/L in water near abandoned coal mines. Chloride typically was a minor constituent in all analyses. Fluoride concentrations averaged 0.4 mg/L in 21 analyses. Nitrogen concentrations averaged 1.6 mg/L in 17 analyses but were as large as 6 mg/L. Hardness values in 20 analyses ranged from 100 to 260 mg/L, which, according to criteria in Hem (1970, p. 225), characterizes the water in the alluvium as moderately hard to very hard.

Cuchara–Poison Canyon Aquifer

The Cuchara–Poison Canyon aquifer contains calcium bicarbonate, sodium bicarbonate, calcium chloride, and sodium chloride waters (fig. 52). Major changes in chemistry radiate outward from the Spanish Peaks intrusions and possibly are related to the migration of fluids from the intrusions. Changes related to depth affect sulfate, nitrogen, and fluoride concentrations. Sulfate and nitrogen concentrations are larger toward the surface; fluoride concentrations are larger away from the surface.

The concentration of dissolved solids in nine analyses ranged from 250 to 4,500 mg/L, averaged 1,100 mg/L, and was largest in sodium chloride water (fig. 52). Chloride was an important constituent, even in water where it was not the dominant anion. Chloride concentrations ranged from 6.8 to 2,600 mg/L. Sulfate concentrations, which ranged from 1.0 to 100 mg/L (fig. 53), increased from an average of 15 mg/L at depths of more than 100 ft, to an average of 76 mg/L at depths of less than 100 ft. Nitrogen concentrations ranged from 0.09 to 120 mg/L and increased from an average of 0.11

Table 7. Chemical analyses of ground water in the central Raton Basin, 1977–83

Hydrologic unit	Number of sites with chemical analyses of water		
	Wells	Springs	Mines
Alluvium	12	9	0
Cuchara-Poison Canyon aquifer	8	1	0
Raton-Vermejo-Trinidad aquifer	25	7	7
Pierre Shale	1	0	0

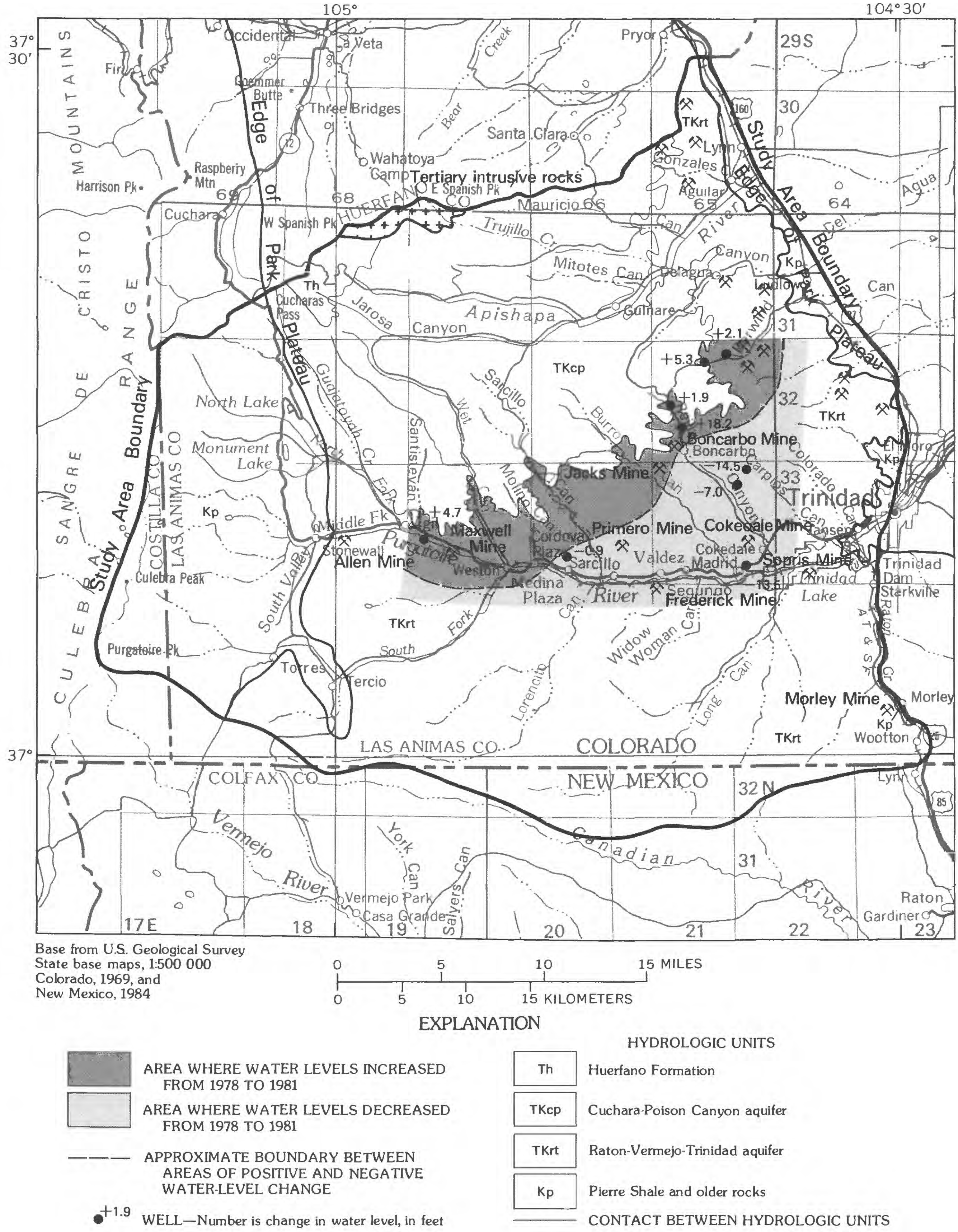


Figure 45. Changes in ground-water levels, 1978–81, Purgatoire River drainage, Colorado.

mg/L at depths of more than 100 ft to 20 mg/L at depths of less than 100 ft. Fluoride concentrations ranged from 0.3 to 2.9 mg/L and decreased from an average of 2.1 mg/L at depths of more than 100 ft to 0.9 mg/L at depths of less than 100 ft. Hardness values ranged from 120 to 1,000 mg/L in all types of water except sodium bicarbonate; hardness values in sodium bicarbonate water ranged from 15 to 70 mg/L. The calcium bicarbonate, calcium chloride, and sodium chloride waters are classified as hard to very hard; the sodium bicarbonate water is classified as soft to moderately hard.

Raton–Vermejo–Trinidad Aquifer

Water in the Raton–Vermejo–Trinidad aquifer typically is a sodium bicarbonate type with 300–1,500 mg/L of dissolved solids. However, near abandoned coal mines on the eastern side of the area, the water may be a sodium bicarbonate-sulfate or sodium sulfate type with more than 1,500 mg/L of dissolved solids (fig. 54). Water issuing from springs and from depths of less than 60 ft is most often a calcium bicarbonate type, containing sulfate as an important secondary anion and less than 500 mg/L of dissolved solids. Coincident with calcium and sulfate enrichment, magnesium, silica, nitrogen, and selenium also are more abundant at shallower levels in the aquifer; in addition to sodium and bicarbonate, fluoride is less abundant at shallower levels in the aquifer (fig. 55).

The effect of depth on the concentration of sulfate is shown in figure 56. In the example given, which represents a hypothetical site, the concentration of sulfate in water from the Raton–Vermejo–Trinidad aquifer at a depth between 60 and 350 ft is about 180 mg/L. At the same site, water in the aquifer at a depth of less than 60 ft would probably contain about 220 mg/L of dissolved sulfate; water in springs issuing from the aquifer would probably contain about 360 mg/L of dissolved sulfate; and water in alluvium overlying the aquifer would probably contain about 490 mg/L of dissolved sulfate. In other words, a concentration of dissolved sulfate in water at depths of 60–350 ft in the Raton–Vermejo–Trinidad aquifer is doubled at the shallowest depths in the aquifer and nearly tripled in water from overlying alluvium.

The chemistry of mining effluent is substantially different than that of water from wells and springs. In seven samples of water collected from mine shafts between 1977 and 1983, the average concentration of sulfate was 440 mg/L. This was five times larger than the average concentration in concurrently sampled water from wells and springs. The water from mines also contained significantly larger concentrations of potassium, sodium, bicarbonate, nitrogen, selenium, and dissolved solids than the water from wells and springs. The water seeping from tailings dumps may be even

Table 8. Water-quality standards

[Sources: Freeze and Cherry (1979, p. 386); U.S. Environmental Protection Agency (1977a, 1977b); and Hem (1970, p. 224–226)]

Constituent	Recommended concentration limit (milligrams per liter)	Effect of excess constituent
Boron	0.75	Damages fruit and nut trees.
Chloride	250	Kills fish.
Fluoride	1.8	Mottles teeth.
Hardness (calcium and magnesium as calcium carbonate).	120	Inhibits sudsing and encrusts pipes.
Iron	.3	Imparts undesirable taste to water and stains laundry.
Manganese	.05	Same as iron effects.
Nitrogen	10	Causes lethal blood diseases in infants.
Selenium	.01	Causes gastrointestinal and skin damage and mental disorders.
Sulfate	250	Has laxative effect.
Zinc	5.0	Imparts bitter taste to water and damages crops.

more mineralized than the water from mine shafts. Water seeping from a tailings dump near the east portal of the Allen Mine in May 1980 was a sodium sulfate solution with 2,600 mg/L of dissolved solids (Water, Waste, and Land, Ltd., 1980, p. 51).

Plumes of water moving from mines and tailings dumps into nearby bedrock and alluvium contaminate water contained in these aquifers. However, acid mine drainage into streams, which is prevalent in eastern coal areas, has not been observed. In fact, mining effluent is somewhat more alkaline than the water from wells and springs. The pH of mining effluent ranges from 7.3 to 9.2; the pH of water from wells and springs typically ranges from 7.5 to 8.0 but may exceed 8.0 in mined areas. A pH of 7.0 is neutral; a pH of less than 7.0 indicates acidic water; a pH of more than 7.0 indicates an alkaline water.

When the effects of surficial processes upon the sulfate concentration in analyzed samples are eliminated (using fig. 56), the distribution of sulfate in water of the Raton–Vermejo–Trinidad aquifer indicates that sulfate concentrations in ground water are significantly larger near coal mines (fig. 57). In the eastern part of the area, which has been extensively mined since the early 1900's, background sulfate concentrations are 25 to 100 mg/L, but concentrations of more than 250 mg/L occur around mined areas. In the western part of the area, which contains fewer and more widely scattered mines, back-

Table 9. Concentration of trace elements in ground water in the central Raton Basin

[---, no entry because only one analysis was available; <, less than]

Source	Number of analyses	Boron (micrograms per liter)			Iron (micrograms per liter)			Manganese (micrograms per liter)			Zinc (micrograms per liter)			Selenium (micrograms per liter)			Vanadium[1] (micrograms per liter)		
		Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Alluvium------------------	17	10	360	50	<10	2,300	210	<1	760	120	<3	5,200	540	0	13	5	0	3	2
Cuchara-Poison Canyon aquifer.	9	10	80	40	<10	1,100	240	4	340	64	<3	1,400	310	0	8	2	0	36	8
Raton-Vermejo-Trinidad aquifer.	29	0	380	50	<10	790	170	0	240	38	<3	1,600	110	0	9	2	0	3	1
Raton-Vermejo-Trinidad mines.	5-6	20	1,500	330	30	750	290	10	240	60	30	380	100	0	20	7	5	22	13
Pierre Shale-------------	1	860	---	---	50	---	---	10	---	---	60	---	---	0	---	---	31	---	---

[1]Fewer analyses of vanadium exist than for other constituents: In the alluvium, there are 9 analyses; in the Cuchara-Poison Canyon aquifer, 5 analyses; in the Raton-Vermejo-Trinidad aquifer, 21 analyses; in the Raton-Vermejo-Trinidad mines, 2 analyses; and in the Pierre Shale, 1 analysis.

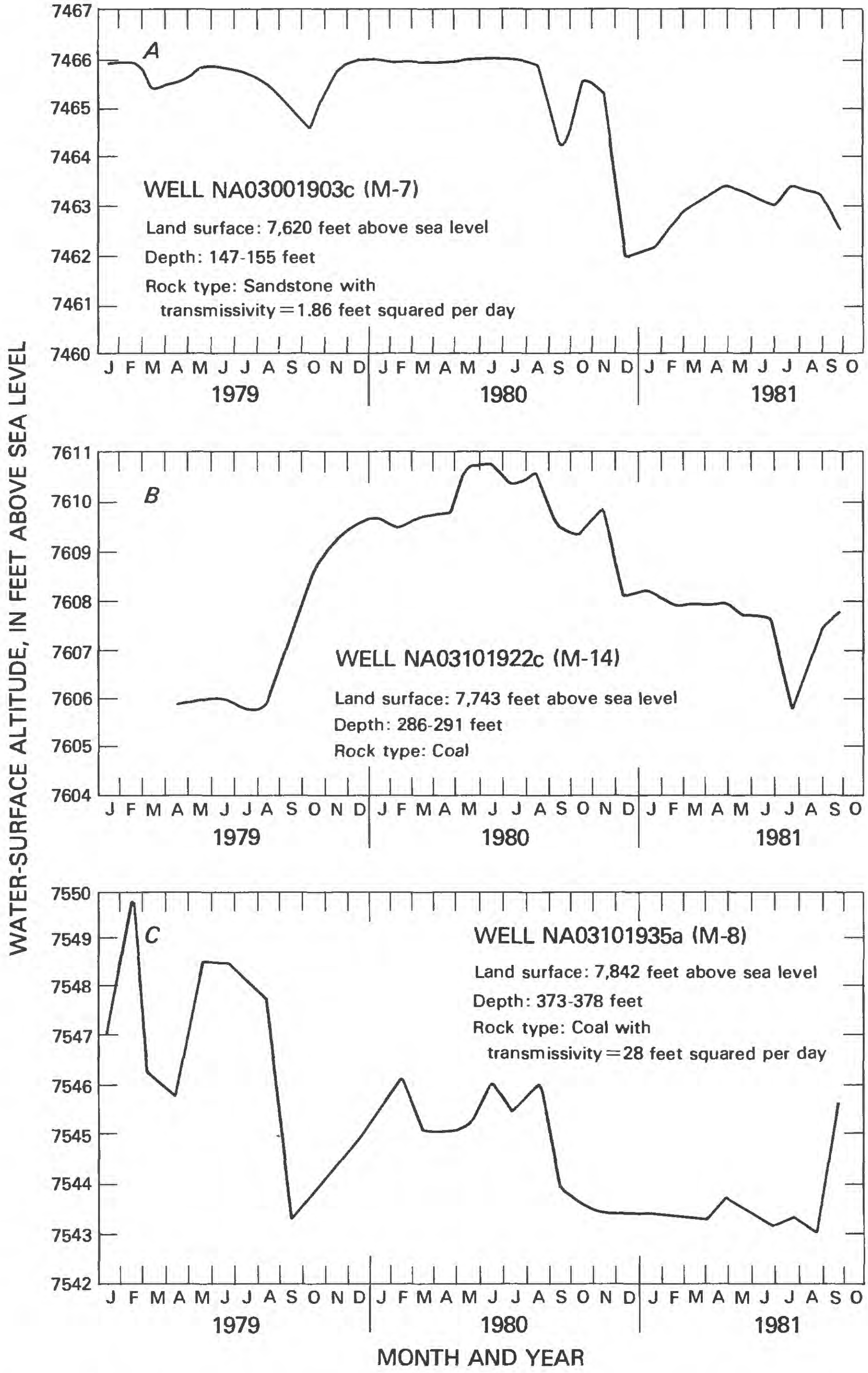
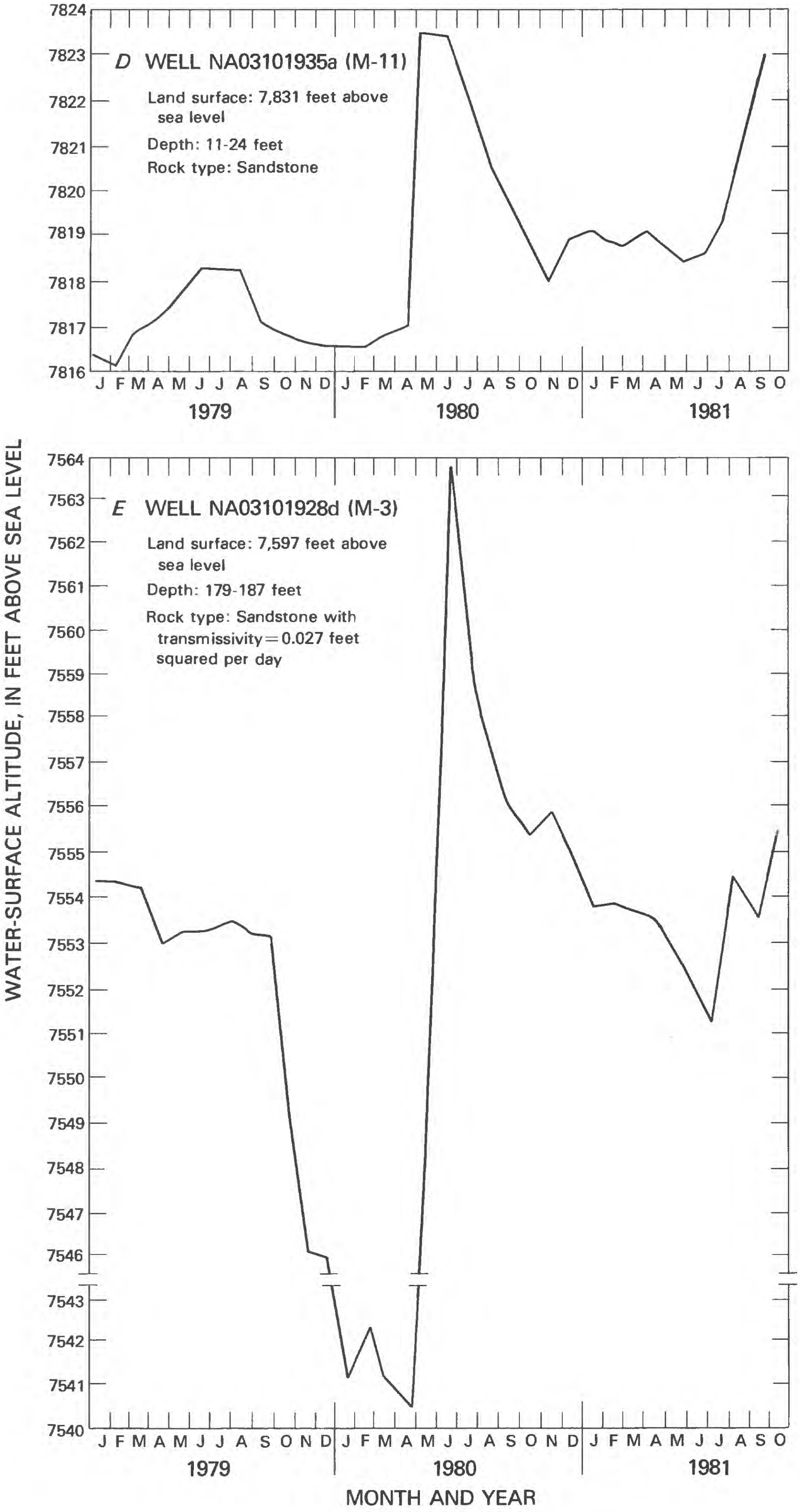


Figure 46 (above and facing page). Recorded water levels in observation wells completed in the Raton Formation at the York Canyon Mine, N. Mex., 1979–81.

ground sulfate concentrations are less than 25 mg/L, but concentrations of 25 to more than 250 mg/L occur around individual mines. The extent and magnitude of sulfate enrichment are less around the newer mines than around the older mines because oxidation of sulfur-containing minerals in the coal, such as pyrite, and ground-water transport of sulfate have been occurring for a longer time in the older mined areas.

Chloride was a minor constituent in most analyses, with concentrations ranging from 6 to 30 mg/L. However,



D WELL NA03101935a (M-11)
Land surface: 7,831 feet above sea level
Depth: 11-24 feet
Rock type: Sandstone
E WELL NA03101928d (M-3)
Land surface: 7,597 feet above sea level
Depth: 179-187 feet
Rock type: Sandstone with transmissivity = 0.027 feet squared per day
WATER-SURFACE ALTITUDE, IN FEET ABOVE SEA LEVEL
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O
1979
1980
1981
MONTH AND YEAR

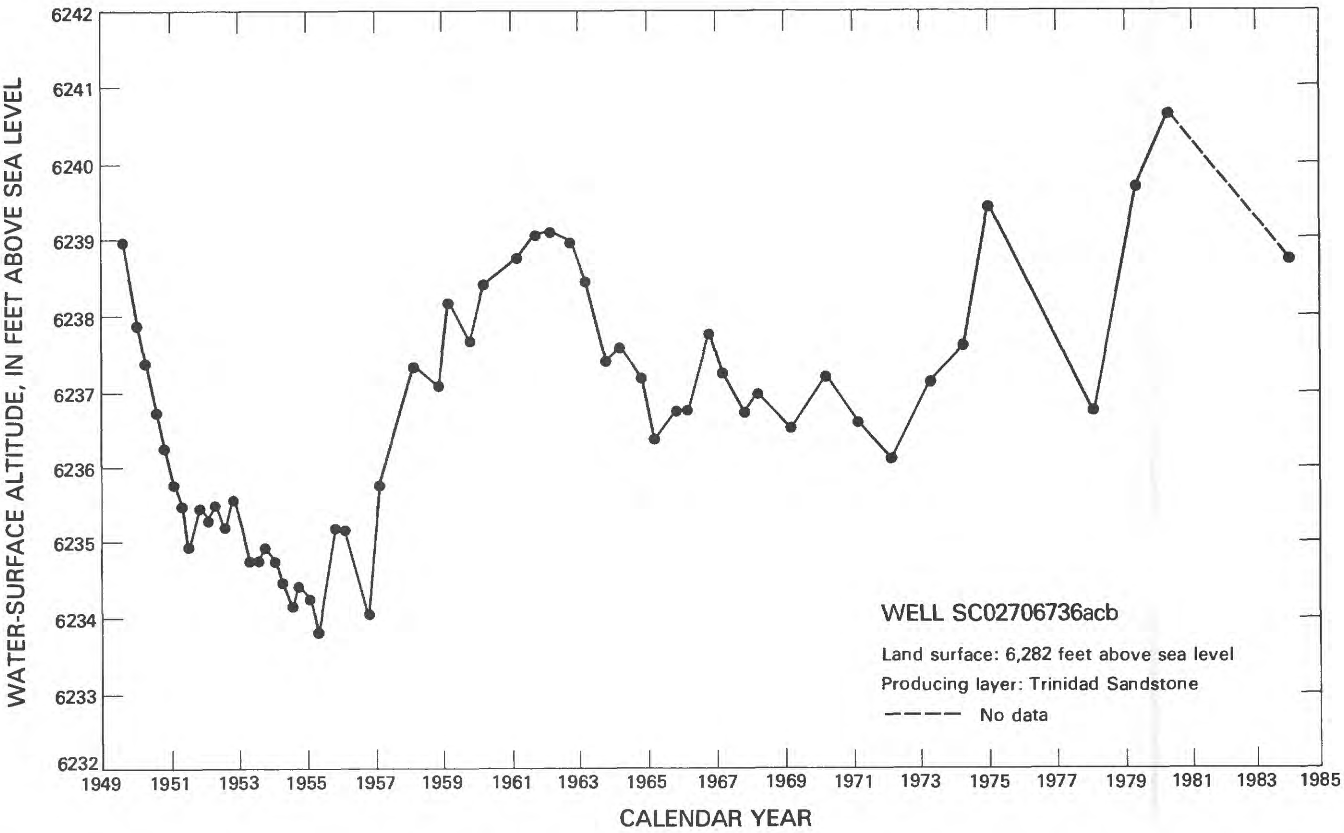


Figure 47. Recorded water levels in the Raton–Vermejo–Trinidad aquifer near Walsenburg, Colo., 1949–84.

chloride concentrations in three wells in the eastern part of the area ranged from 100 to 680 mg/L. According to Freeze and Cherry (1979, p. 242), such large concentrations of chloride are characteristic of water that has been in prolonged circulation along regional flow paths. Large chloride concentrations in water from the eastern side of the study area support potentiometric data in indicating an eastward direction of regional ground-water flow.

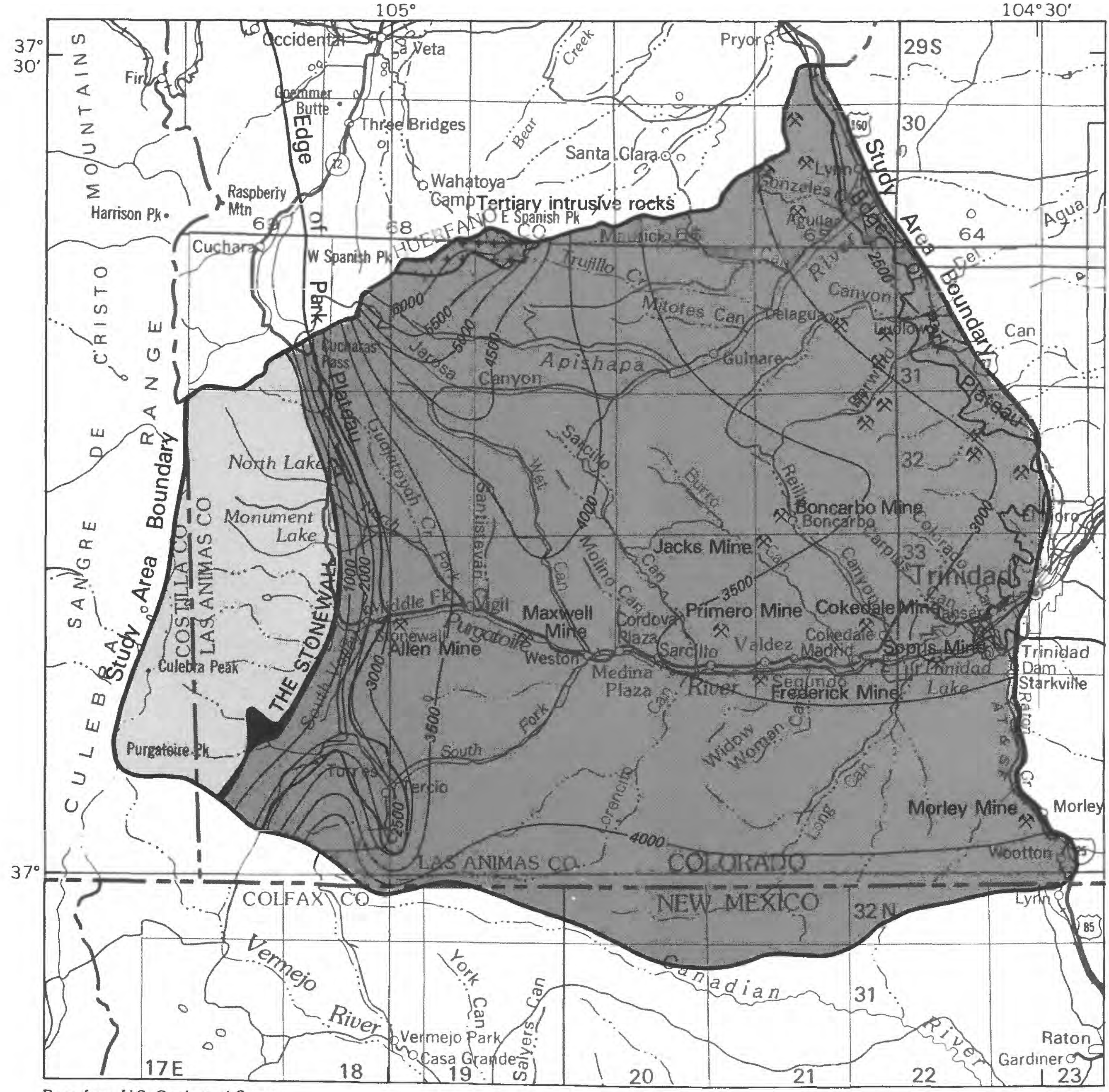
Nitrogen concentrations increase toward the surface as fluoride concentrations decrease. Nitrogen concentrations in 30 analyses ranged from 0 to 77 mg/L and increased from an average of 0.44 mg/L at depths of more than 60 ft to an average of 6.8 mg/L at depths of less than 60 ft. Fluoride concentrations ranged from 0.2 to 6.1 mg/L and decreased from an average of 2.0 mg/L at depths of more than 60 ft to an average of 0.6 mg/L at depths of less than 60 ft.

Water in the aquifer is soft to very hard. Hardness values in 32 analyses ranged from 6 to 860 mg/L and averaged 180 mg/L.

Hydrogen sulfide, which was not analyzed, was detected by its characteristic odor in several wells and reportedly occurs in others (table 10). The occurrence of hydrogen sulfide cannot be predicted from available information, but it seems likely that the gas originates from decaying organic matter and is likely to occur in water confined in coal and carbonaceous shale. Because this gas is volatile, drilling into or through these layers in most instances allows the hydrogen sulfide to dissipate.

Table 10. Occurrence of hydrogen sulfide in water of the Raton–Vermejo–Trinidad aquifer in the central Raton Basin

Well	Occurrence
SC03206510dcc	Reported sulfur smell, which dissipated while the well was temporarily out of use and a nearby well was pumped.
SC03306421cca	Observed sulfur smell.
SC03306510bdd	Observed sulfur smell.
SC03306510ddc	Observed sulfur smell and milky appearance.
SC03306534cac	Reported sulfur taste until well was deepened from 60 to 120 feet.
SC03306602bcd	Observed sulfur smell, developed with use of well.
SC03306604ddd	Reported sulfur smell until well was vented.
SC03306605bcd	Reported sulfur smell if well is not pumped often.
SC03306605dbd	Reported slight sulfur smell if well is not pumped often.
SC03306703ccc	Observed sulfur smell.



Base from U.S. Geological Survey
State base maps, 1:500 000
Colorado, 1969, and
New Mexico, 1984

0 5 10 15 MILES

0 5 10 15 KILOMETERS

EXPLANATION

AREA WHERE DAKOTA SANDSTONE IS PRESENT

AREA WHERE DAKOTA SANDSTONE IS MISSING BECAUSE OF EROSION OR NONDEPOSITION

DAKOTA SANDSTONE OUTCROP

—3000— LINE OF EQUAL DEPTH TO DAKOTA SANDSTONE—Interval is 500 feet, except west of Stonewall, Colo., where it is 1000 feet. Datum is land surface

Figure 48. Approximate depth to the top of the Dakota Sandstone in the central Raton Basin. Contours are drawn between points at the center of each township. Each point is the calculated difference between topographic contours on the U.S. Geological Survey 1:250,000 quadrangles and structural contours in McLaughlin (1966, pl. 4).

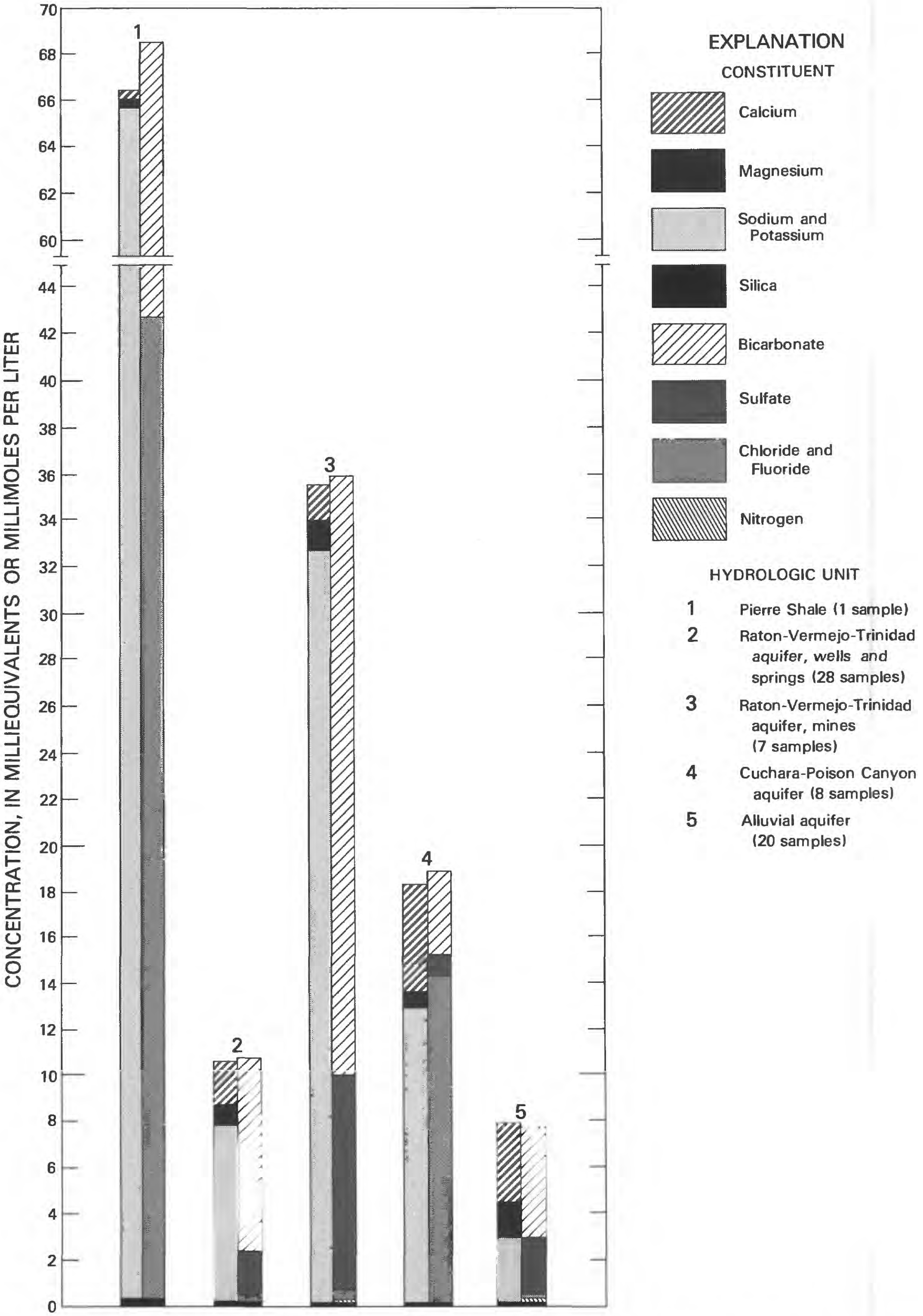


Figure 49. Average concentrations of major dissolved constituents in ground water in the central Raton Basin.

Pierre Shale

A sample of water from the Pierre Shale, collected from well SC03106421bab, is a sodium chloride type containing 3,810 mg/L of dissolved solids. Bicarbonate is an important secondary anion. Important minor and trace constituents include fluoride (2.1 mg/L) and boron (860 μg/L). The chemistry of this water is unusual

Table 11. Summarized results of Purgatoire River gain-loss study, November 17 and 18, 1982[1]

[---, no measurement was made; negative sign in front of discharge indicates an outflow]

Date measured	Inflow or outflow	Discharge (cubic feet per second)	
		Measured	Cumulative
11-17-82	Middle Fork Purgatoire River near Stonewall	12.0	12.0
	Storz Pond intake	-.004	---
	Storz Pond return	.54	---
	Allen Mine effluent	.009	---
	Vialpando ditch intake	-.40	12.1
	Unobserved gain	.7	---
	North Fork Purgatoire River	13.0	25.8
	Unobserved gain	4.5	---
	Maxwell Mine effluent (through Ciruela Canyon)	.001	30.3
	Wet Canyon	.61	---
	South Fork Purgatoire River	12.6	---
	Stage change	-5.2	---
	Unobserved loss	-1.0	37.3
11-18-82	Unobserved gain	1.7	---
	Lorencito Canyon	1.28	40.3
	Unobserved loss	-7.0	---
	Sarcillo Canyon	.54	33.8
	Unobserved gain	2.8	---
	Frederick Mine	.083	---
	Burro Canyon	.14	[2]36.8

[1]Discharges of less than 0.4 cubic foot per second were measured volumetrically or with a 3-inch modified Parshall flume. All other measurements were made with current meters. Measurements not used in the interpretation are not shown. All measurements made at the time of the study are listed in the data report, Geldon and Abbott (1984).

[2]Average of four discharge measurements in the reach between Valdez and Madrid, Colo. The measurements were 37.2 cubic feet per second at Valdez, 36.4 cubic feet per second below Valdez, 37.2 cubic feet per second above Burro Canyon, and 36.5 cubic feet per second at Madrid (below Burro Canyon).

because water from other formations in the central Raton Basin rarely contains such large concentrations of chloride. The sample of water from the Pierre Shale was collected from a relatively deep well (252 ft) that apparently is fed by water in deep regional circulation.

RELATION OF GROUND WATER TO SURFACE WATER

Gain-Loss Studies

Measurements of discharge in the Purgatoire River and five tributaries were made at closely spaced intervals along certain reaches to determine if the streams lose or gain ground water. Measurements were made at times of the year when the streams were at base flow, so that small inflows and outflows of ground water would not be obscured by the much larger runoff from storms and snowmelt.

Purgatoire River

Measurements were made at 35 sites along a 22-mi reach between Stonewall and Madrid, Colo., on November 17 and 18, 1982 (table 11). No precipitation occurred during these 2 days, but a small amount of rain and snow fell between October 28 and November 10. Runoff from these storms moved through the area prior to the measurements (fig. 58). During the period of measurement, the river was steadily receding from storm-induced high flows that occurred in September and was affected by diurnal freezing and thawing near the

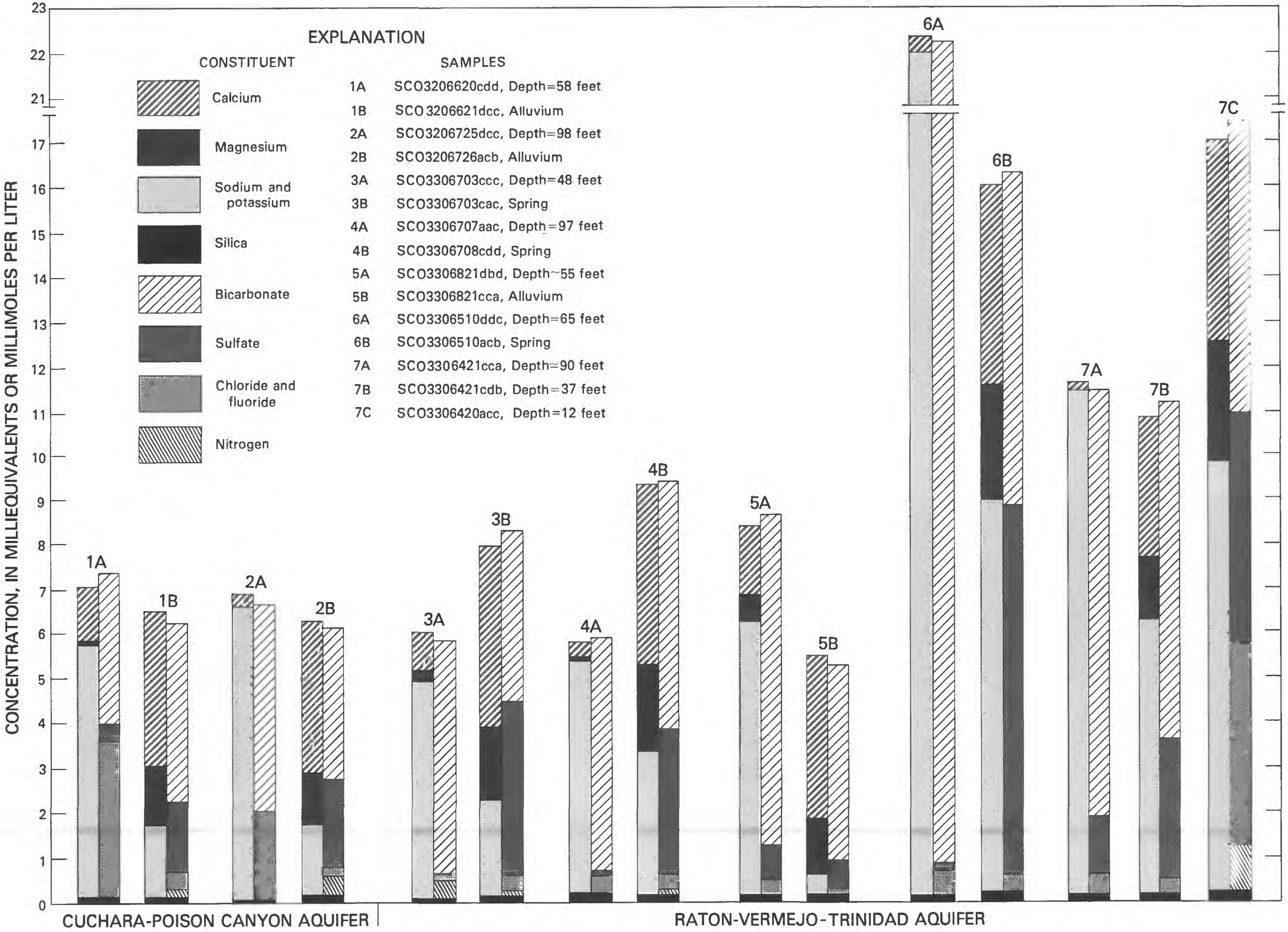


Figure 50. Differences in ground-water chemistry as a function of depth in paired samples from the central Raton Basin. Concentrations are in milliequivalents per liter except silica, which is in millimoles per liter.

banks. On November 17, the stage fell 0.03 ft during the day, and the discharge at Madrid, Colo., decreased from 42.0 to 36.8 ft^3/s. On November 18, the stage and discharge were constant during the day. Based on 10 years of record, the average discharge in the Purgatoire River at Madrid is 22.5 ft^3/s (U.S. Geological Survey, 1982); thus, discharges recorded during the period of measurement are exceeded about 30 percent of the time.

During the period of measurement, two diversion ditches were known to be in operation. Although water normally is withdrawn from the river for operation of the Maxwell and Allen coal mines, the Maxwell Mine was shut down at the time of the study, and the Allen Mine, which was operating at reduced capacity, did not divert water during the 2 days when the streamflow was measured. However, both the Allen and the Maxwell Mines continuously released small discharges of effluent into the river, and the Allen Mine discharged several hundred gallons per minute of water several times each day. One such release was observed entering the river immediately prior to the start of measurements.

The gain-loss study revealed that most of the base flow in the Purgatoire River between Stonewall and Madrid is attributable to inflowing tributaries. During the period of measurement, the three forks of the river contributed 75 percent of the cumulative base flow at Madrid (fig. 59); the flow from each fork was about equal. Four canyons entering the river between Stonewall and Madrid—Lorencito, Wet, Sarcillo, and Burro—contributed 5 percent of the cumulative base flow at Madrid. The base flow in Lorencito Canyon was about twice that in Wet Canyon, which had a slightly greater base flow than Sarcillo Canyon and about four times more flow than Burro Canyon.

Man-made structures (mines and ditches), including the Allen, Maxwell, and Frederick Mines, and the Storz Pond return ditch, contributed 1 percent of the cumulative base flow at Madrid. Most of this water came from Storz Pond, which is apparently partly fed by ground water, because more water flowed from the pond to the river than was diverted to the pond from the river.

Nineteen percent of the cumulative base flow at Madrid resulted from unobserved inflows. Some of these inflows entered from side canyons as underflow. Some underflow probably came from Molino Canyon and two draws near Valdez, where streamflow in the channels disappeared within a few hundred yards of the Purgatoire River. A gain of 0.7 ft^3/s between the Allen Mine and the North Fork of the Purgatoire River probably resulted from underflow through alluvium of the North Fork. Gains of 4.5 ft^3/s between the North Fork and the Maxwell Mine, 1.7 ft^3/s between the South Fork of the Purgatoire River and Lorencito Canyon, and 2.5 ft^3/s between Sarcillo Canyon and Valdez, Colo., occurred in relatively short reaches, probably from undetected point sources, such as the return flow from an irrigation ditch. These gains probably did not result from diffuse ground-water seepage, which would require seepage rates greatly in excess of those in tributary canyons entering along the study reach. Seepage rates in these canyons should be similar to seepage rates in the Purgatoire River because all streams in the study reach cut through identical formations.

During the period of measurement, the only observed losses resulted from a change in river stage and two diversion ditches. As the stage fell 0.03 ft on

Table 12. Summarized results of gain-loss studies on tributaries of the Purgatoire River, June–August 1981

[Negative sign indicates outflow. Discharge measurements were made with current meters, 3-inch modified Parshall flume, and volumetrically]

Date	Inflow or outflow	Discharge (cubic feet per second)
	Wet Canyon	
8-4-81	Upper Wet Canyon Spring	0.16
8-4-81	Loss to ground water	-.069
8-4-81	Hidden Spring	.078
8-4-81	Rock Crack Spring	.019
8-5-81	Gain from ground water	.022
8-5-81	Wet Canyon above Weston	.21
	Sarcillo Canyon	
8-4-81	Upper Sarcillo Canyon (Outhouse) Spring	0.003
7-1-81	Garcia Spring	.015
7-1-81	Tokar Spring	.004
7-23-81	Gain from ground water	.22
7-23-81	Sarcillo Canyon at Segundo	.24
	Burro Canyon	
6-24-81	Upper Burro Canyon Spring	0.002
6-24-81	Trujillo Spring	.022
6-24-81	Loss to ground water	-.004
6-24-81	Jacks Mine (Burro Canyon group) discharge	.0002
6-24-81	Gain from ground water	.043
6-24-81	Burro Canyon near Madrid	.063
	Reilly Canyon	
6-23-81	Upper Reilly Canyon Springs	0.004 (estimated)
6-23-81	Chinaman Canyon Spring	.040
6-23-81	Boncarbo Mine discharge	.008 (estimated)
7-21-81	Loss to ground water	-.051
7-21-81	Midway School Spring	.0002 (estimated)
7-21-81	Gain from ground water	.050
7-21-81	Reilly Canyon at Cokedale	.051
	Berwind Canyon	
8-6-81	Upper Berwind Canyon Springs	0.017
8-6-81	Bear Canyon Spring	.009
8-6-81	Berwind Spring	.061
8-6-81	Loss to ground water	-.072
8-6-81	Berwind Canyon near Ludlow	.015

Table 13. Rates of seepage into tributaries of the Purgatoire River

[---, not determined]

Canyon	Method 1 (June-August 1981)			Method 2 (November 17-18, 1982)		
	Length of reach (miles)	Ground-water inflows (cubic feet per second)	Seepage rate (cubic feet per second per mile)	Length of canyon (miles)	Discharge at mouth (cubic feet per second)	Seepage rate (cubic feet per second per mile)
Wet	7.0	0.28	0.040	18.5	0.61	0.033
Sarcillo	6.7	.24	.036	14.4	.54	.038
Burro	8.7	.067	.008	18.9	.14	.007
Reilly	9.6	.094	.010	---	---	---
Berwind	5.5	.087	.016	---	---	---
Lorencito	---	---	---	48.5	1.28	.026

November 17, the discharge at Madrid, Colo., decreased by 5.2 ft^3/s. Two ditches, the Storz and Vialpando, withdrew 0.40 ft^3/s from the river. A loss of 7.0 ft^3/s between Lorencito Canyon and Sarcillo Canyon, less than 1 mi downstream, occurred so abruptly that it probably resulted from an undetected diversion. A loss of 1.0 ft^3/s between the Maxwell Mine and Medina Plaza may have resulted from either undetected diversions or seepage into channel alluvium. Had the study been done during the irrigation season (April to September), streamflows would have been reduced more by ditch operations. Had the Allen and Maxwell Mines been operating at their full capacities, streamflows would have been reduced further.

On the whole, the Purgatoire River between Stonewall and Madrid is a gaining stream (fig. 60). Losses occurring between the Maxwell Mine and Medina Plaza and between Lorencito and Sarcillo Canyons as a result of diversions and, possibly, channel seepage are more than offset by gains from tributaries, mine drainage, return flow from a man-made pond (possibly partly fed by ground water), and underflow from side canyons. Diffuse ground-water seepage probably occurs also, but measurements were not precise enough to confirm its existence. In the 5.5 mi between Valdez and Madrid, Colo., the discharge of the river is stable, despite small inflows from the abandoned Frederick Mine and Burro Canyon.

Purgatoire River Tributaries

Measurements of discharge were made in five canyons—Wet, Sarcillo, Burro, Reilly, and Berwind—from June to August 1981 (table 12). During each series of measurements, no runoff occurred from storms. Although evapotranspiration is at its peak during the summer, losses from streamflow probably were small during the period of measurement. No irrigation ditches exist in these canyons, and pumps used to irrigate small gardens were not operating at the time of each series of measurements. Most points of discharge in each canyon were measured on the same day or on consecutive days, but in Sarcillo, Burro, and Reilly Canyons as much as 30 days elapsed before all points of discharge were measured. During the elapsed time, observed discharges at specific sites appeared to change very little.

Most canyons gained discharge from head to mouth. Losses to channel alluvium and bedrock occurred in all canyons except Sarcillo Canyon. Losses exceeded gains only in Berwind Canyon. Most of the observed inflow resulted from springs, but a very small amount came from mines. The most profuse springs—Hidden (Wet Canyon), Berwind (Berwind Canyon), and Chinaman (Reilly Canyon)—discharged 0.04–0.08 ft^3/s. Measured and estimated discharges from mines—Jacks Mine in Burro Canyon and the Boncarbo Mine in Reilly Canyon—were 0.0001 and 0.01 ft^3/s. Unobserved inflows probably resulted from ground water. In Wet and Sarcillo Canyons, springfed underflow from side canyons apparently caused the unobserved gains in streamflow in the lower reaches. In Burro and Reilly Canyons, springs that were not detected because of inaccessibility probably caused the unobserved gains.

Rates of seepage into tributary canyons of the Purgatoire River range from 0.007 to 0.040 ft^3/s per mile (table 13). These rates were determined in two ways. In the first method, the sum of all ground-water inflows in a study reach was divided by the length of the reach. In the second method, the discharge at the mouth of a canyon was divided by the length of the canyon (including all side canyons). Results of the two methods compared favorably. If the seepage rate along the Purgatoire River across the Park Plateau is similar to seepage rates in tributary canyons (which cut through the same geologic

Table 14. Interpreted results of specific-conductance measurements along the Purgatoire River, November 17 and 18, 1982

[Measurements not used in the interpretation are not shown. All measurements made at the time of the study are included in Geldon and Abbott (1984). N/A, not applicable; ---, not determined; E, estimated]

Inflow or outflow	Cumulative discharge (cubic feet per second)	Specific conductance (micromhos per centimeter)			
		At point of inflow or outflow	Cumulative		
			Calculated	Measured	Contribution
Middle Fork Purgatoire River---	12.0	285	285	285	N/A
Storz Pond intake--------------	12.0	285	285	---	0
Storz Pond return--------------	12.5	480	293	---	+8
Allen Mine, east portal--------	12.5	1,620	293	---	0
Allen Mine, sewage plant-------	12.5	370	293	---	0
Allen Mine, operations and tailings.	12.5	N/A	335	---	+42
Vialpando ditch----------------	12.1	335	335	335	0
North Fork Purgatoire River----	25.1	265	299	---	-36
North Fork underflow (?)-------	25.8	1,260E	325	325	+26
Unidentified point sources-----	30.3	325E	325	325	0
Maxwell Mine effluent----------	30.3	940	325	325	0
Wet Canyon---------------------	30.9	680	333	---	+8
South Fork Purgatoire River----	43.5	365	343	---	+10
Losses and stage change--------	37.3	300E	350	350	+7
Lorencito Canyon---------------	38.6	545	356	---	+6
Sarcillo Canyon----------------	39.1	650	360	---	+4
Unidentified point sources-----	33.8	300E	370	370	+10
Ground water and point sources-	36.6	490E	373	---	+3
Frederick Mine shaft-----------	36.7	4,290	382	382	+9
Frederick Mine tailings--------	36.7	N/A	389	---	+7
Burro Canyon-------------------	36.8	1,110	392	392	+3

formations), then ground-water inflows to the Purgatoire River in the 26.4 mi between Stonewall and Trinidad Dam should be between 0.18 and 1.06 ft^3/s during most of the year.

Mass-Balance Studies

Measurements of specific conductance and the concentrations of dissolved constituents were made at several points along the Purgatoire River and four tributary canyons between Stonewall and Trinidad, Colo., and at all known points of inflow and outflow along each of these streams. Measurements were made at times of the year when the streams were at base flow in order to detect small ground-water inflows and outflows that might be otherwise obscured by the much larger runoff from storms and snowmelt.

Purgatoire River

Measurements of specific conductance were made at 35 sites in the 22-mi reach between Stonewall and Madrid, Colo., on November 17 and 18, 1982 (table 14). The impact of individual inflows or outflows on the cumulative specific conductance of the river was assessed by the formula:

$$q_cC_c = q_+C_+ + q_iC_i - q_oC_o \quad (1)$$

where

q_c = the cumulative discharge of the river downstream from the inflow or outflow;
C_c = the specific conductance of the river downstream from the inflow or outflow;
q_+ = the measured discharge of the Purgatoire River upstream from an inflow or outflow;
C_+ = the specific conductance of the river upstream from an inflow or outflow;
q_i, q_o = the discharge of an inflow, outflow; and
C_i, C_o = the specific conductance of an inflow, outflow.

A difference between the calculated and measured specific conductances downstream from an inflow or

Table 15. Interpreted results of mass-balance studies along tributaries of the Purgatoire River, June–August 1981

Inflow or outflow	Constituents (milligrams per liter)								
	Calcium	Magnesium	Potassium	Sodium	Bicarbonate	Sulfate	Chloride	Silica	Dissolved solids
Wet Canyon									
Upper Wet Canyon Spring	99	23	2.2	52	268	200	12	11	543
Loss to alluvium	99	23	2.2	52	268	200	12	11	543
Hidden Spring	81	20	2.3	48	232	190	11	11	482
Rock Crack Spring	81	21	2.5	46	232	170	23	9.2	471
Loss to alluvium	90	22	2.3	50	249	193	13	11	510
Gain from ground water[1]	59	20	2.9	67	293	120	7.9	9.6	440
Wet Canyon near mouth:									
Calculated	72	20	2.6	60	274	150	9.8	10	469
Measured	77	48	2.1	44	256	130	9.8	10	415
Sarcillo Canyon									
Upper Sarcillo Canyon Spring[2]	68	14	1.5	36	207	96	5.6	12	361
Garcia Spring[3]	6.7	.6	2.1	120	317	5.0	13	8.0	314
Tokar Spring	82	24	2.3	73	341	160	12	9.5	535
Gain from ground water[4]	55	18	2.11	56	268	100	9.2	11	394
Sarcillo Canyon near mouth:									
Calculated	52	17	2.1	60	276	95	9.4	11	390
Measured	62	21	2.7	65	256	160	11	7.2	460
Burro Canyon									
Upper Burro Canyon Spring	70	16	1.6	36	244	76	15	10	353
Trujillo Spring	80	19	1.2	49	329	87	11	9.3	424
Loss to alluvium	79	19	1.2	48	322	86	11	9.4	418
Burro Canyon mines[5]	7.6	9.8	7.0	720	1,439	390	21	3.1	1,870
Gain from ground water[6]	70	32	4.0	200	415	400	11	11	935
Burro Canyon near mouth:									
Calculated	73	28	3.2	155	389	303	11	10	778
Measured	70	38	3.4	140	378	280	20	11	759
Reilly Canyon									
Chinaman Canyon Spring	66	16	1.6	41	244	64	7.3	11	342
Upper Reilly Canyon Springs[7]	57	16	2.0	33	219	82	7.0	9.1	317
Loss to alluvium	65	16	1.6	40	241	66	7.3	11	340
Boncarbo mines[5]	7.6	9.8	7.0	720	1,439	390	21	3.1	1,870
Lower Reilly Canyon springs[6]	70	32	4.0	200	415	400	11	11	935
Reilly Canyon near mouth:									
Calculated	63	26	3.7	204	458	312	11	10	861
Measured	68	29	7.1	190	341	390	16	12	885

[1]Chemical analysis of water from spring SC03306726acd.
[2]Chemical analysis of water from well SC03206726acb.
[3]Chemical analysis of water from well SC03306608cac.
[4]Chemical analysis of water from well SC03306621abd.
[5]Chemical analysis of water from mine SC03306606cdd.
[6]Chemical analysis of water from spring SC03306510acb.
[7]Chemical analysis of water from well SC03206519bca.

outflow revealed sources of dissolved constituents other than those observed or calculated from streamflows. If the specific conductance of an inflow or outflow was unknown, it was estimated by the formula:

$$C_u = \frac{q_c C_c - q_+ C_+ - q_i C_i + q_o C_o}{q_u} \quad (2)$$

where

C_u = the unknown specific conductance;
q_u = the discharge of the inflow or outflow with the unknown specific conductance; and all other terms are the same as in equation 1.

If the estimated specific conductance appeared unreasonable relative to known specific conductances for similarly derived water, then an additional inflow or outflow was indicated.

The specific conductance of the Purgatoire River increased from 285 µmho/cm at Stonewall to 392 µmho/cm at Madrid (table 14). The largest individual increase, 42 µmho/cm, apparently resulted from mining operations and contact with tailings at the Allen Mine (fig. 61). Mining effluent and tailings at the abandoned Frederick Mine (fig. 62) increased specific conductance in the river by 16 µmho/cm. Observed discharges at the Allen and Maxwell Mines had no detectable effect on the specific conductance of the river.

During the study, the North Fork of the Purgatoire River had the best quality of the three forks that unite to form the main stem downstream from Weston, Colo. The North Fork at its confluence with the Middle Fork had a specific conductance of 265 µmho/cm; in contrast, the Middle Fork at the confluence had a specific conductance of 335 µmho/cm. The addition of water from the North Fork to that of the Middle Fork decreased the specific conductance downstream by 10 µmho/cm. The South Fork at its confluence with the Middle Fork had a specific conductance of 365 µmho/cm. The addition of water from the South Fork to that of the Middle Fork increased the specific conductance downstream by 10 µmho/cm. Differences in quality among the three forks apparently are caused by mining activity. The North Fork has no mines along it, whereas the Middle and South Forks are bordered by active and abandoned coal mines and tailings dumps.

Perennial inflow from tributary canyons also increased specific conductance in the river. Inflow from Wet Canyon, with a specific conductance of 680 µmho/cm, increased the specific conductance of the river by 8 µmho/cm. Inflow from Lorencito Canyon, with a specific conductance of 545 µmho/cm, increased specific conductance in the river by 6 µmho/cm. Inflow from Sarcillo Canyon, with a specific conductance of 650 µmho/cm, increased specific conductance in the river by 4 µmho/cm. Inflow from Burro Canyon, with a specific conductance of 1,110 µmho/cm, increased specific conductance in the river by 3 µmho/cm. Tributary inflow has a larger specific conductance than water in the Purgatoire River because flow in the tributaries is sustained mostly by ground water, which is more mineralized than surface water.

A small amount of the observed increase in specific conductance in the study reach was caused by unidentified point sources, ground-water seepage, and a stage change that occurred on the first day of the study. Point sources (including, possibly, intermittent release of large volumes of water from the Allen Mine, diversions to or releases from irrigation ditches, and sewage effluent) and ground-water seepage added 13 µmho/cm of specific conductance to the river. A stage change, resulting in a decrease in discharge of 5.2 ft^3/s, and a loss to either channel seepage or diversion ditches of 1.0 ft^3/s increased the specific conductance of the river by 7.0 µmho/cm.

Purgatoire River Tributaries

Chemical analyses of ground water and surface water in four canyons—Wet, Sarcillo, Burro, and Reilly–were made from June to August 1981. In each canyon, the cumulative effect of inflows and outflows on the chemistry of streamflow in the canyon was assessed by comparing the analyzed concentrations of nine constituents near the mouth with the discharge-weighted average of these constituents in all known or inferred inflows and outflows (table 15).

In most cases, fairly good agreement occurred between observed and expected concentrations of constituents. Significant differences (usually more than 15 percent) with respect to sodium in Wet Canyon; magnesium, sulfate, and silica in Sarcillo Canyon; and potassium, bicarbonate, sulfate, and chloride in Reilly Canyon probably reflect imprecise estimation of the chemical composition of unobserved inflows. Thus, all inflows and outflows were reasonably accounted for by mass-balance calculations.

The study showed that the specific conductance in most Purgatoire River tributaries increases in a downstream direction, mainly as a result of inflowing ground water. The specific conductance in Wet Canyon actually decreased. The largest increases occurred in Burro Canyon and Reilly Canyon, on the eastern side of the area. The rate of increase was largest in canyons with significant coal-mining activity and smallest in canyons with no coal-mining activity. However, measurements were not sufficiently precise to detect an influence of mining effluent and tailings on water quality. Differences in water quality among the tributaries also could be explained by eastward increases in the proportion of outcropping Raton Formation to Poison Canyon Formation and the depth of circulation of inflowing ground water.

SUMMARY AND CONCLUSIONS

The Raton Basin is a region where the greatest deterrent to the development of coal and gas may be the scarcity of water. In the watersheds of the Apishapa and Purgatoire Rivers, wells produce only a few gallons per minute from bedrock and stream deposits. In the hills above the Purgatoire River, one man has drilled six wells trying to find a sustainable supply of water. Nearby, a woman has drilled four wells without much luck. In some

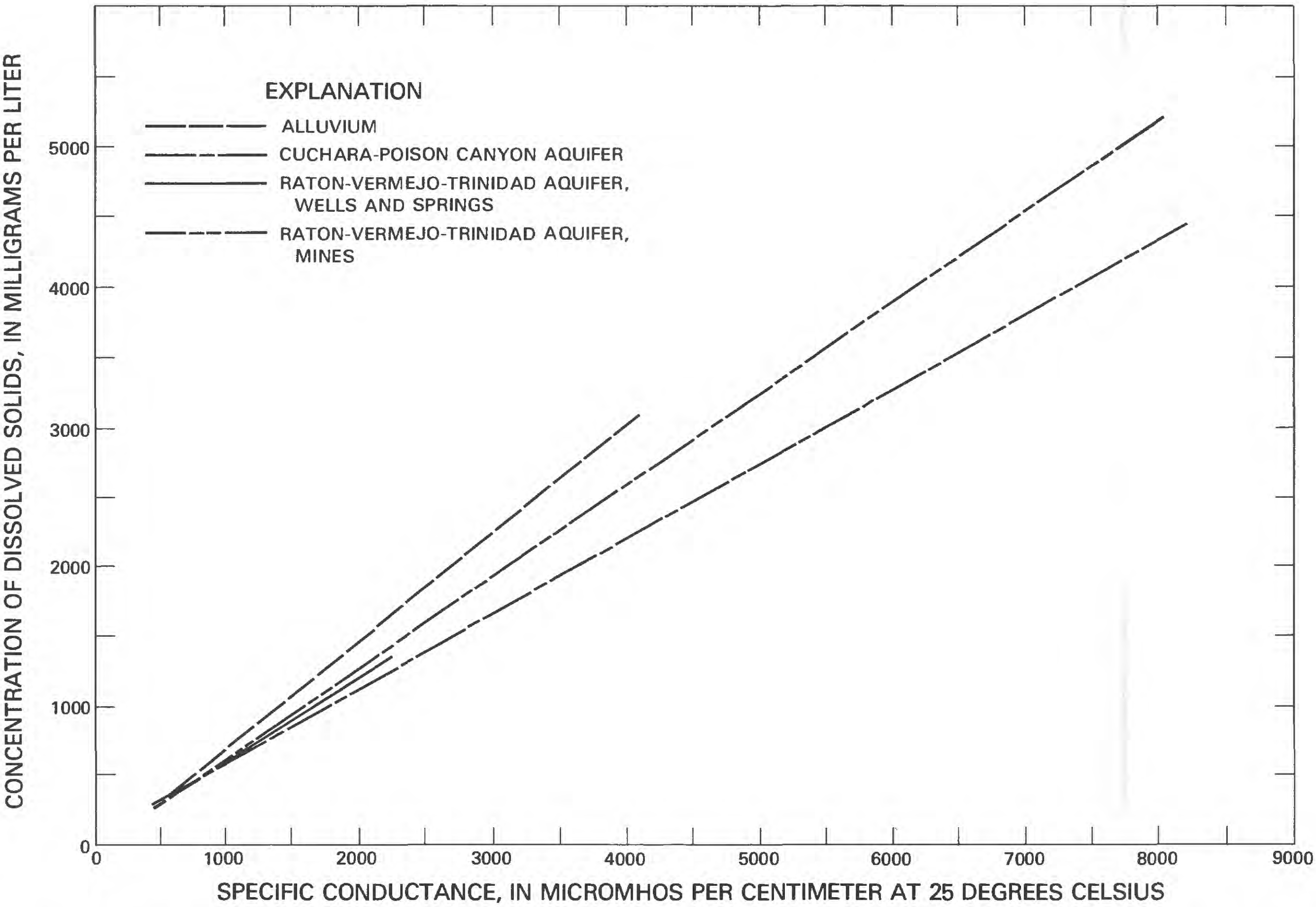


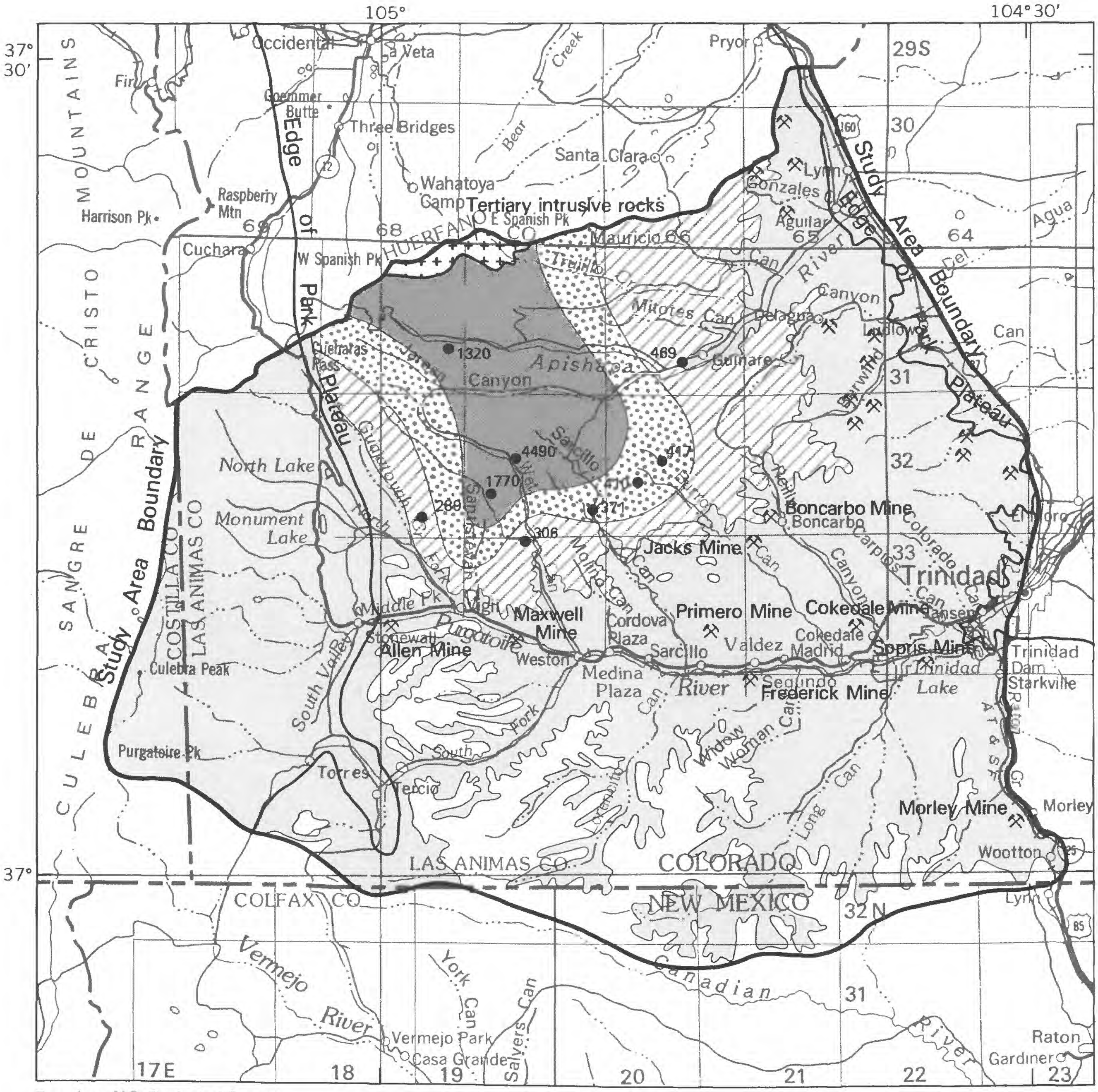
Figure 51. Relation of specific conductance to concentration of dissolved solids in ground water in the central Raton Basin.

households, well yields are so low that people take showers knowing the water may be gone before the suds. In an area where water is more abundant, most of the formations considered to be aquifers in the study area would be overlooked as a water supply.

Of all the aquifers in the area, the alluvium in the flood plains of the Purgatoire and Apishapa Rivers and in canyons that are tributary to them is the most productive. The oldest wells in the Raton Basin, hand dug by settlers in the 19th and early 20th centuries, draw water from this aquifer. Yields from wells range from 8 to 290 gal/min per 10 ft of drawdown but are highly susceptible to climatic variation. In dry years, some wells may go dry. Many of these old wells no longer are being used, and modern water laws effectively prevent new wells from being completed in the alluvium, because alluvial water is considered tributary to stream water, and stream-water use is restricted by prior appropriation rights. Not being able to use the water in the alluvium, some farmers along the Purgatoire River must irrigate their crops with water transported by the city of Trinidad from the Sangre de Cristo Mountains, as much as 25 mi away.

Most new wells are drilled into bedrock aquifers that yield less water than the alluvium but have a greater distribution and are less dependent on local precipitation for recharge. These new wells are much deeper than the old hand-dug ones and much more expensive to install, but the use of bedrock ground water is not restricted by the same laws that govern the appropriation of surface water.

In bedrock aquifers, sandstone layers are the best sources of water. The Cuchara–Poison Canyon aquifer is mostly sandstone, but the aquifer is drained by springs and percolation to alluvium and the Raton Formation over much of the area, and it generally yields small nonsustainable supplies of water to wells. In the Raton–Vermejo–Trinidad aquifer, sandstone layers at the top and bottom of the Raton Formation, lenses of sandstone and coal in the Raton and Vermejo Formations, and the Trinidad Sandstone produce water. The lenticular sandstone bodies terminate so abruptly that two closely spaced wells cannot be drilled with any certainty of successfully producing water at the same depth. Well yields typically are 0.07–1.4 gal/min per 10 ft of draw-



Base from U.S. Geological Survey State base maps, 1:500 000 Colorado, 1969, and New Mexico, 1984

0 5 10 15 MILES
0 5 10 15 KILOMETERS

EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION, IN MILLIGRAMS PER LITER		WATER TYPE
(dark shading)	1,000 to 5,000	Sodium chloride
(dot pattern)	250 to 500	Sodium bicarbonate
(diagonal lines)	250 to 500	Calcium bicarbonate
(blank)	No information	No information

(light shading) AREA WHERE POISON CANYON AND CUCHARA FORMATIONS ARE MISSING BECAUSE OF EROSION OR NONDEPOSITION

●417 WELL OR SPRING WITH CHEMICAL ANALYSIS OF WATER—Number is dissolved-solids concentration of water in milligrams per liter

⚒ MINE

Figure 52. Water chemistry in the Cuchara–Poison Canyon aquifer at depths of 60 to 450 feet in the central Raton Basin.

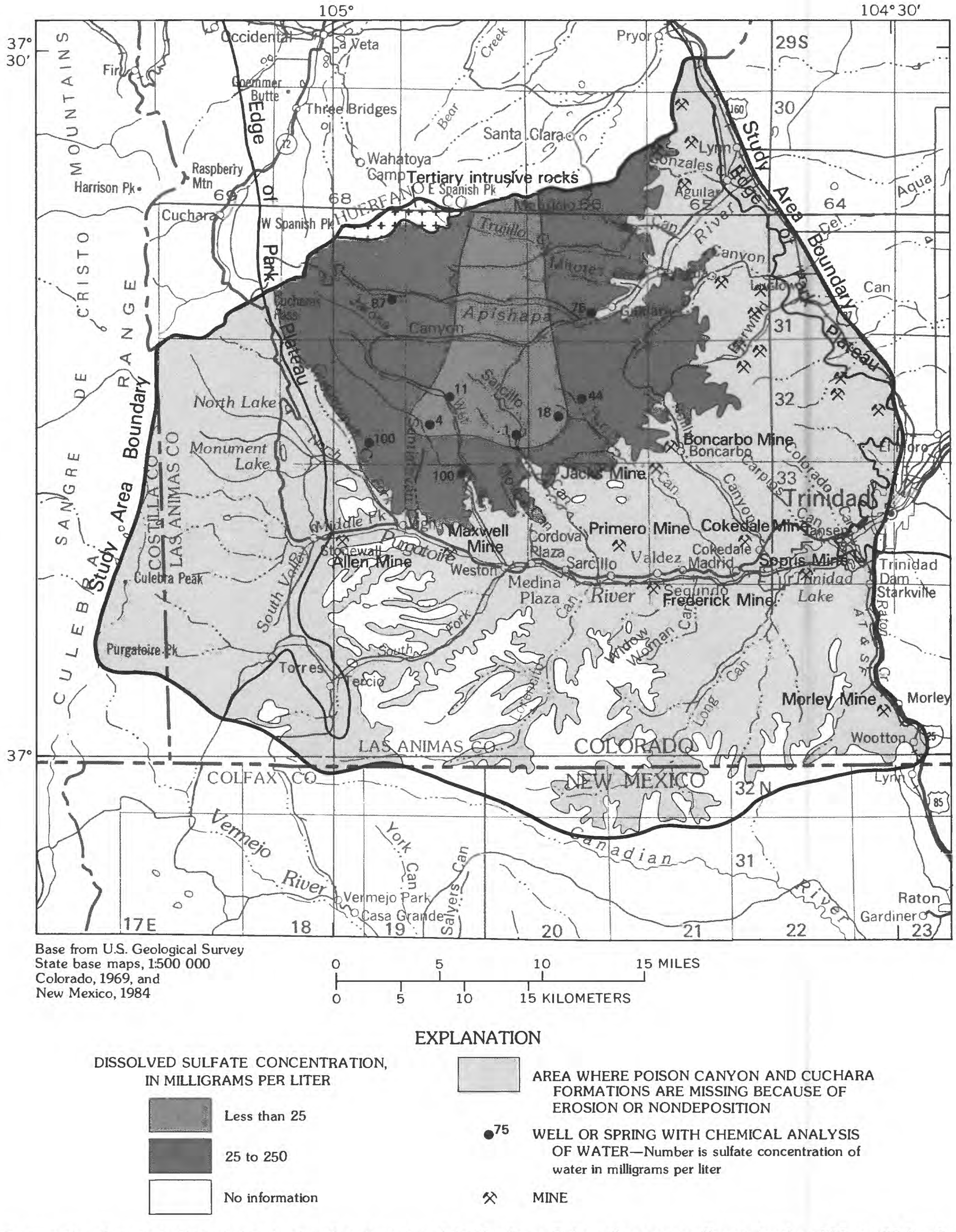


Figure 53. Concentration of dissolved sulfate in water of the Cuchara–Poison Canyon aquifer at depths of 60 to 450 feet in the central Raton Basin.

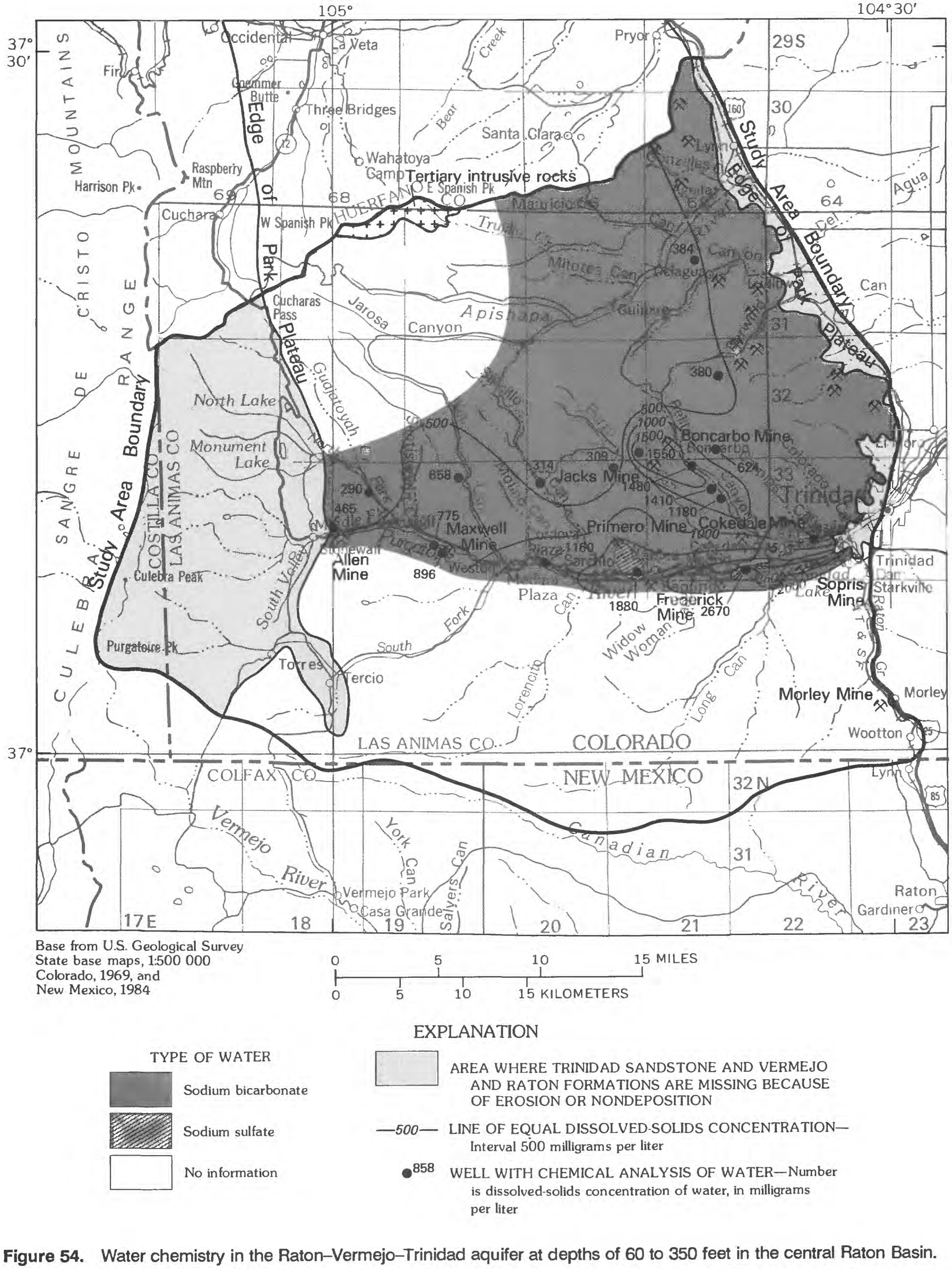


Figure 54. Water chemistry in the Raton–Vermejo–Trinidad aquifer at depths of 60 to 350 feet in the central Raton Basin.

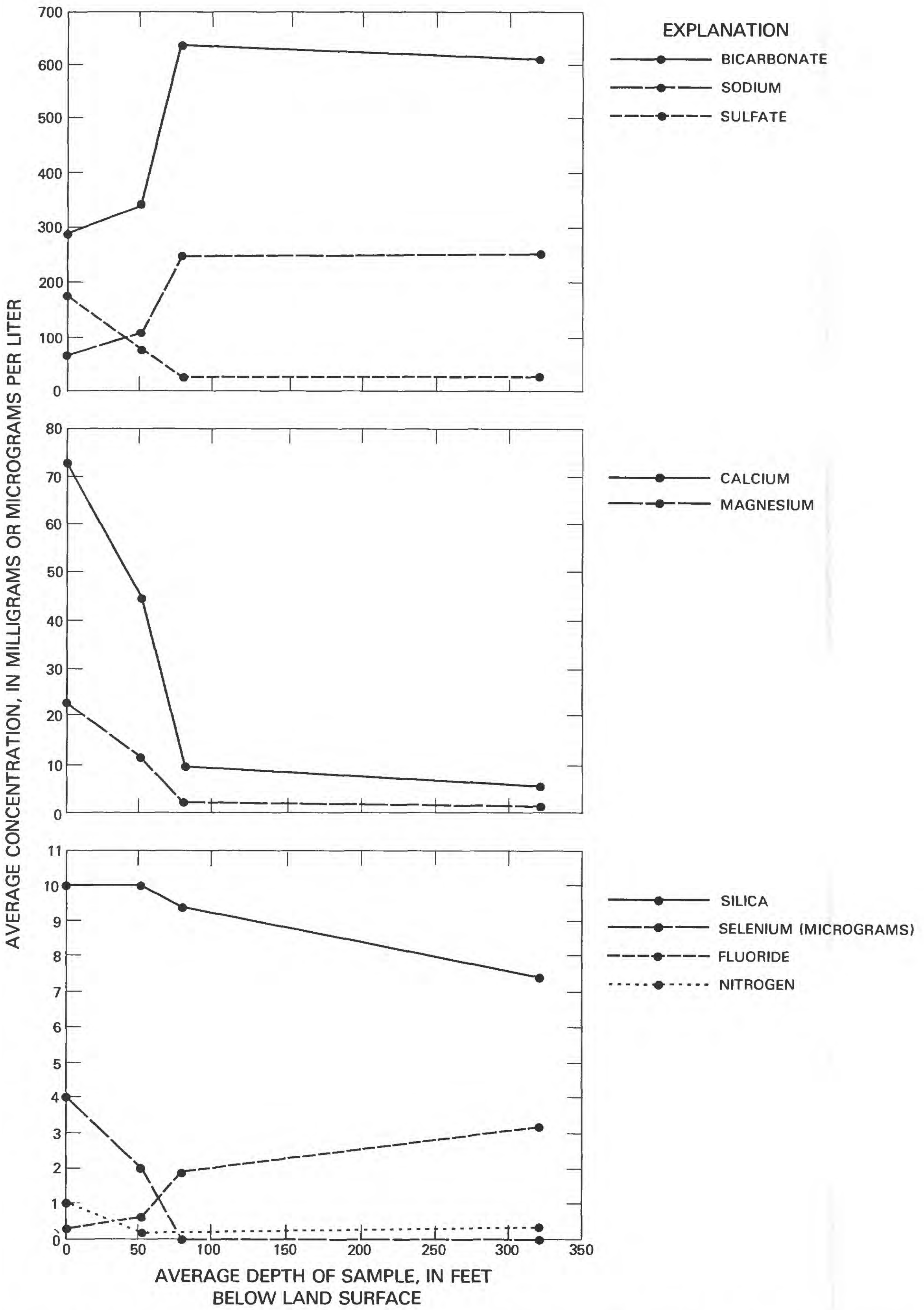


Figure 55. Influence of depth on concentration of dissolved constituents in the Raton–Vermejo–Trinidad aquifer in the central Raton Basin.

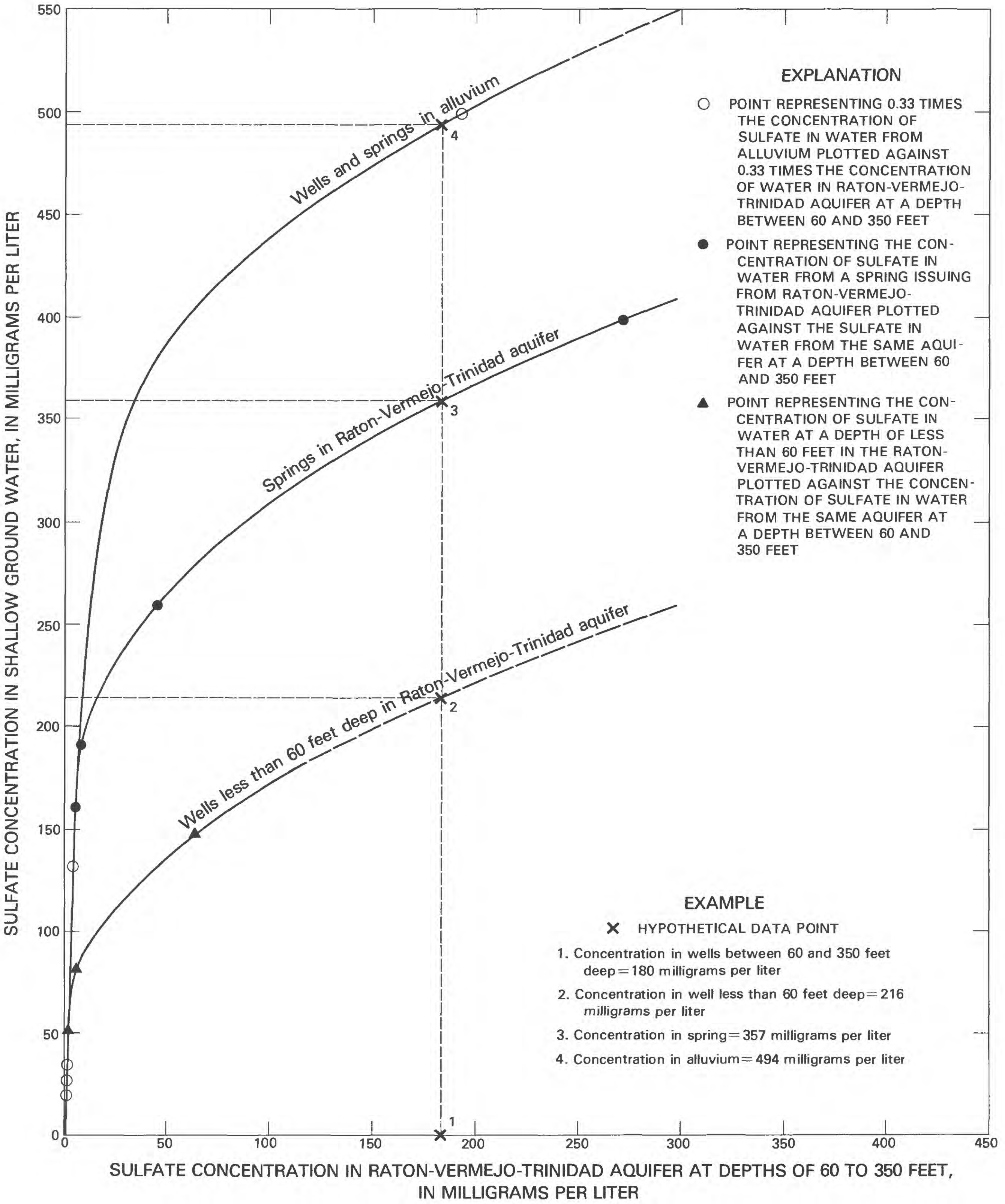


Figure 56. Effect of depth on concentration of dissolved sulfate in paired samples of water from the Raton–Vermejo–Trinidad aquifer and overlying alluvium in the central Raton Basin.

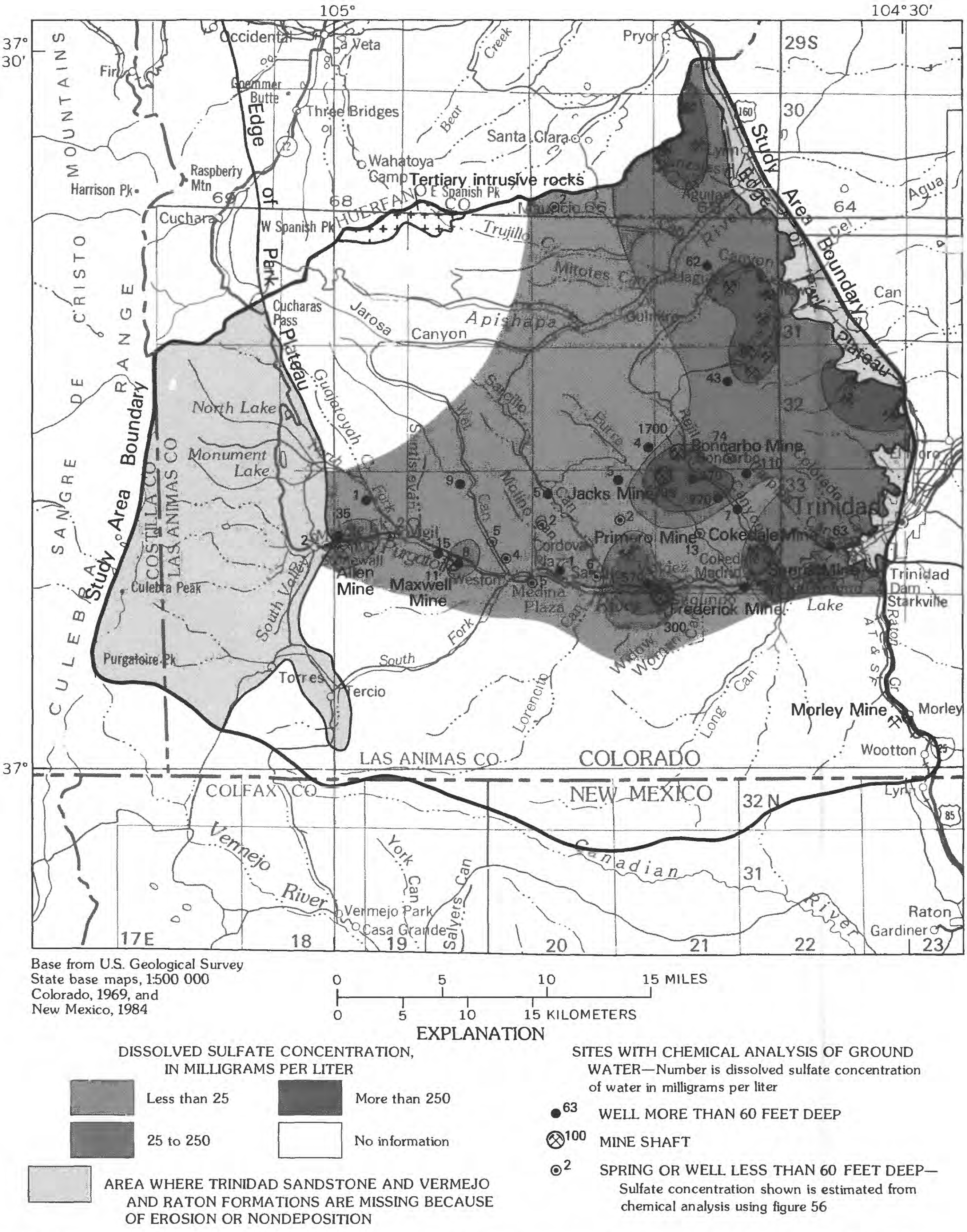


Figure 57. Concentration of dissolved sulfate in water of the Raton–Vermejo–Trinidad aquifer at depths of 60 to 350 feet in the central Raton Basin.

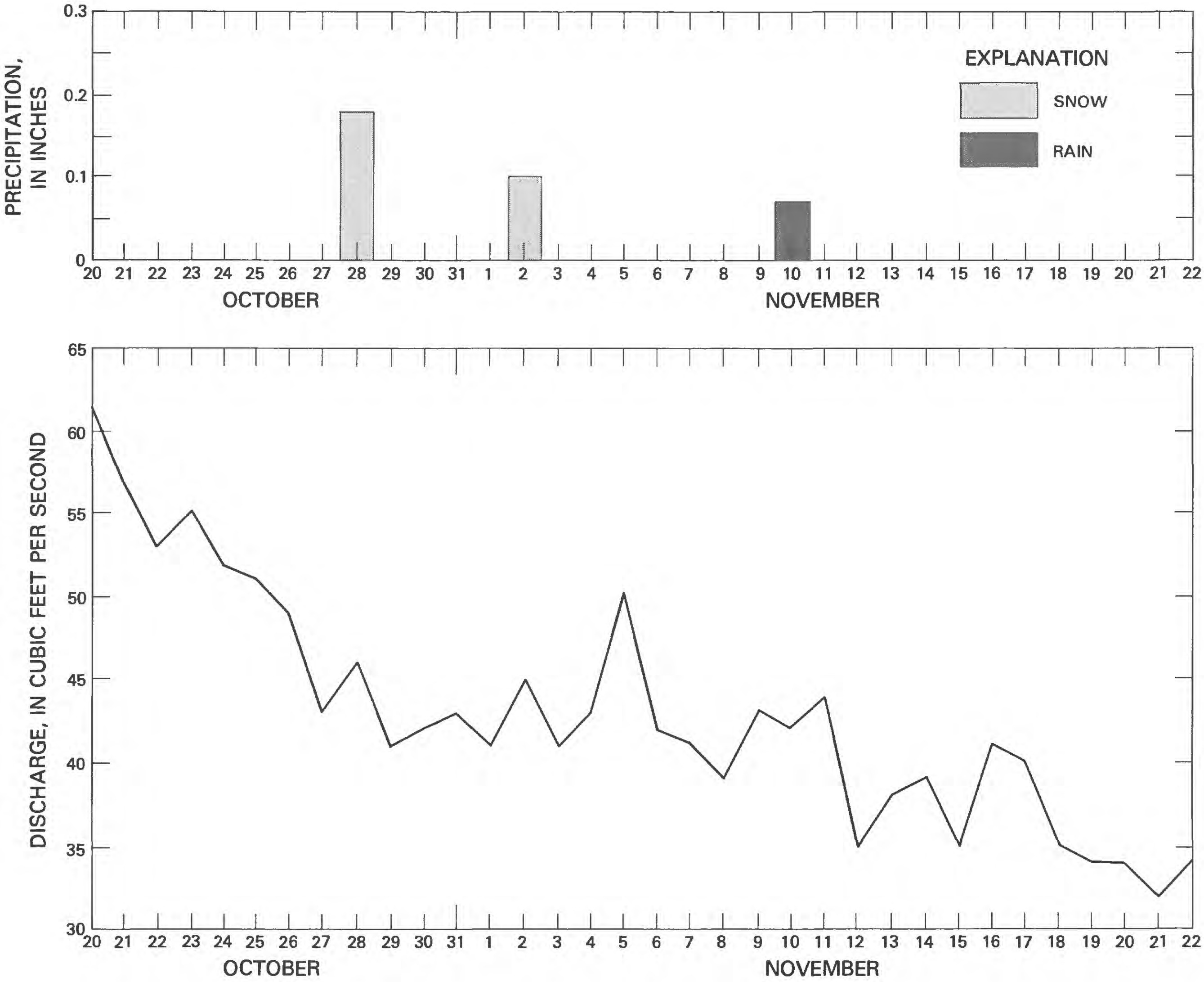
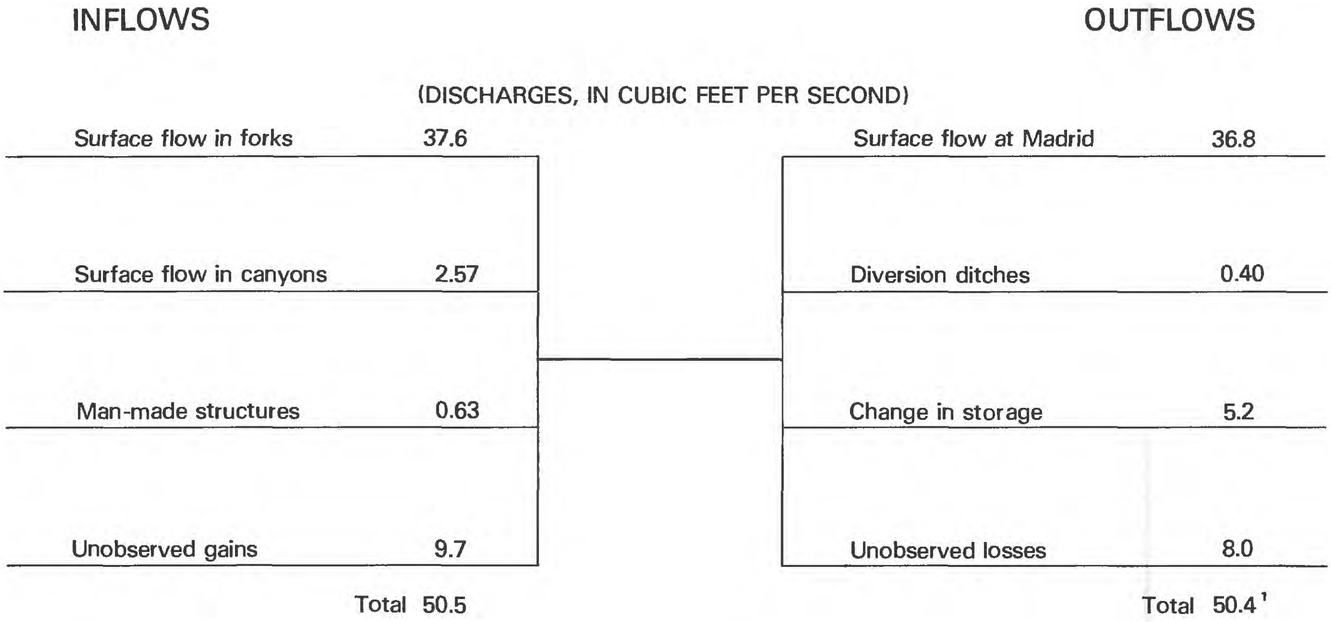


Figure 58. Precipitation at Trinidad, Colo., and discharge in the Purgatoire River at Madrid, Colo., during October and November 1982.

down in the Cuchara-Poison Canyon aquifer and 0.04–16 gal/min per 10 ft of drawdown in the Raton–Vermejo–Trinidad aquifer. The Dakota–Purgatoire aquifer, with estimated well yields of 10–100 gal/min per 10 ft of drawdown, generally is too deep to be utilized economically.

Even where supplies are adequate, the quality of ground water may not meet standards set for domestic consumption. Although much of the water is potable, dissolved-solids concentrations of 1,000–2,000 mg/L (two to four times more than the U.S. Environmental Protection Agency recommended limit) commonly are tolerated. Dissolved-solids concentrations typically are 200–1,000 mg/L in water from the alluvium, 250–4,500 mg/L in water from the Cuchara–Poison Canyon aquifer, and 300–1,500 mg/L in water from the Raton–Vermejo–Trinidad aquifer. The ground water usually is a calcium bicarbonate or sodium bicarbonate type, but sodium chloride water occurs in the Cuchara–Poison Canyon aquifer and Pierre Shale. In the vicinity of coal mines, the Raton–Vermejo–Trinidad and alluvial aquifers contain calcium or sodium sulfate water with dissolved-solids concentrations of more than 1,500 mg/L and concentrations of selenium and boron that may exceed drinking-water standards. Locally, concentrations of dissolved iron, manganese, zinc, fluoride, or nitrogen also may exceed drinking-water standards. In one household, the cooking water turns the pots black, and in many wells, the water smells sulfurous. In a region where water is scarce, people use whatever is available, even if it is marginally acceptable.

Ground water flows regionally eastward and locally from stream divides to valleys. The Purgatoire River and its tributaries predominantly are gaining streams, but



[1] Difference between total inflow and total outflow is due to rounding errors.

Figure 59. Inflows and outflows to the Purgatoire River between Stonewall and Madrid, Colo., on November 17 and 18, 1982.

losing reaches occur. Seepage rates into tributaries of the Purgatoire River range from 0.007 to 0.04 ft^3/s/mi.

Much of the ground water in circulation discharges as springs on valley floors or seeps into stream alluvium. Because ground water flows toward stream valleys, depths to water in valleys tend to be shallower than in areas between stream valleys. Wells in valleys typically produce water at depths of 100 ft or less, whereas wells near stream divides may be 200–500 ft deep.

Ground-water quality deteriorates along flow paths. Consequently, some of the ground water on the eastern side of the area that has been in prolonged regional circulation has concentrations of chloride and dissolved solids so large that even livestock cannot drink it.

The following conclusions pertain to future development of ground-water resources:

1. Ground water is scarce but sufficient to meet existing demands. Ground-water supplies may not sustain much additional coal mining or a large population influx.
2. Water quality is acceptable to marginally acceptable for human consumption in most places. Deterioration in ground-water quality has occurred locally on the western side of the area and nearly everywhere on the eastern side of the area because of coal mining. Mining effluent and tailings have altered stream quality, but no acid mine drainage was observed. Additional coal mining in the area may cause further deterioration in ground-water and surface-water quality.
3. Ground water is most abundant and has the best quality on the western side of the area. Flowing from west to east, much of the ground water is intercepted by stream valleys, and the remainder becomes highly mineralized by prolonged contact with shale and coal. Water supplies to meet future demands are more likely to be developed successfully on the western side of the area.

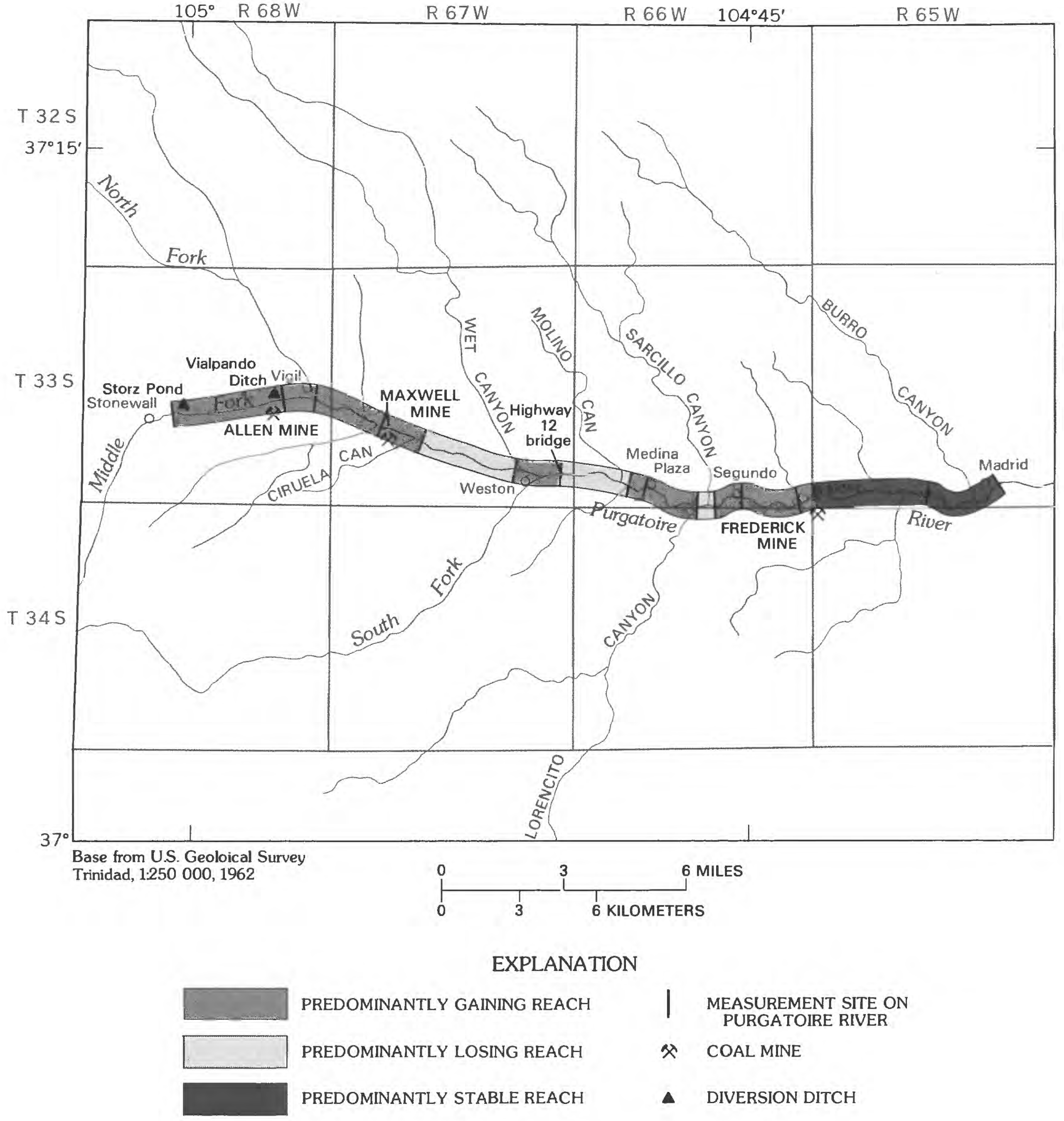


Figure 60. Gaining and losing reaches of the Purgatoire River between Stonewall and Madrid, Colo., on November 17 and 18, 1982.

Figure 61. Allen Mine tailings in the flood plain of the Purgatoire River near Weston, Colo. The tailings (partly covered by snow) extend along both sides of the river for 1 mi and are being eroded by it.

Figure 62. Seepage from a shaft of the abandoned Frederick Mine at Valdez, Colo. The shaft was backfilled with debris, but a hole has opened above and to the right of the seep. The shaft was discharging at the rate of 31 gal/min when photographed in November 1982.

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