SUMMARY OF HYDROLOGIC INFORMATION FOR THE DENVER COAL REGION, COLORADO

By J. Michael Norris, S. G. Robson, and Randolph S. Parker

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[Plates are in pocket]

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METRIC CONVERSION FACTORS

Inch-pound units used in this report may be converted to metric units by use of the following conversion factors:

Multiply	*By*	*To obtain*
acre-foot	1,233	cubic meter
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton (short)	0.907	megagram

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

$$°C = 5/9(°F-32)$$

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

$$°F = 9/5°C+32$$

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ABSTRACT

Available hydrologic data for the Denver coal region are summarized, and references providing important data and interpretations are cited, in order to provide a comprehensive review of the existing hydrologic information of the area. This report, prepared in cooperation with the U.S. Bureau of Land Management, will be useful to potential developers of the coal resources in the region and to State and Federal agencies responsible for monitoring the effects of coal mining on the hydrologic system.

Selected data from 35 streamflow-gaging stations in the area were used to construct relative flood-histograms and flow-duration curves. Surface-water chemistry data were used to develop empirical relations between specific conductance and (1) dissolved solids, (2) the major cation concentrations, and (3) the major anion concentrations.

Ground water occurs in alluvial and bedrock aquifers. Alluvial aquifers consisting of sand and gravel occur along the channels of the principal streams. The alluvial aquifers normally are less than 200 feet thick with a transmissivity between 1,300 and 67,000 ft squared per day. The water contains from 100 to 2,500 milligrams per liter dissolved solids, is hard to very hard, and is a calcium bicarbonate or calcium sulfate type.

The four principal bedrock aquifers are the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers. Depths to water range from near zero in some low-lying undeveloped areas to more than 1,000 feet in other areas. The aquifers are as much as 1,000 feet thick with transmissivities of as much as 1,200 feet squared per day in the Dawson, 400 feet squared per day in the Denver, 2,700 feet squared per day in the Arapahoe, and 1,000 feet squared per day in the Laramie-Fox Hills. The chemical quality of the water generally is suitable for most uses; dissolved-solids concentrations range from 20 to 2,000 milligrams per liter. The water is a calcium bicarbonate type in the Dawson aquifer, becoming a mixed calcium bicarbonate to sodium bicarbonate or sodium sulfate type near the margins of the underlying aquifers.

INTRODUCTION

This report, prepared in cooperation with the U.S. Bureau of Land Management, summarizes existing information and data on the hydrology of the Denver coal region. The report, based on a literature search of hydrologic information, describes surface-water and ground-water quantity and quality. Data used in these summaries were obtained primarily from the WATSTORE data base of the U.S. Geological Survey. The report will be useful to potential developers of the coal resources in the region and to State and Federal agencies responsible for monitoring the effects of coal mining on the hydrologic system.

Description of Study Area

The Denver coal region extends along the Front Range from Colorado Springs to just north of the South Platte River, and from the foothills east to near Limon (fig. 1). The area is a broad, rolling plain with wide flood plains. Altitudes range from about 4,550 ft above sea level at Fort Morgan to about 7,600 ft above sea level in the Black Forest area north of Colorado Springs.

The climate is continental, characterized by light precipitation, low humidity, large daily temperature ranges, and moderately high wind. Annual mean temperature is about 50°F, with summer temperatures often in the 95° to 100°F range. Minimum winter temperatures can be -45°F. Mean annual precipitation ranges from 12 to 19 in., increasing with altitude. Most precipitation occurs as rain, but 2 to 6 ft of total winter snowfall is not uncommon (Hansen and others, 1978).

Coal Resources

Strippable coal deposits of the Denver coal region are shown in figure 2. Strippable coal deposits are defined as those containing at least 2 ft of coal within 150 ft of the land surface (Speltz, 1974). Assuming an average of 1,700 tons of coal per acre-foot, the basin is estimated to contain about 13 billion tons of coal that could be mined by surface-mining methods.

SURFACE WATER

The major river in the area is the South Platte River, which originates outside the area in the Rocky Mountains. The major tributaries to the South Platte River--the Cache la Poudre River, Big Thompson River, and St. Vrain Creek--also originate outside the area in the mountains to the west. Most other tributaries discussed in this report originate in the study area in the Black Forest area.

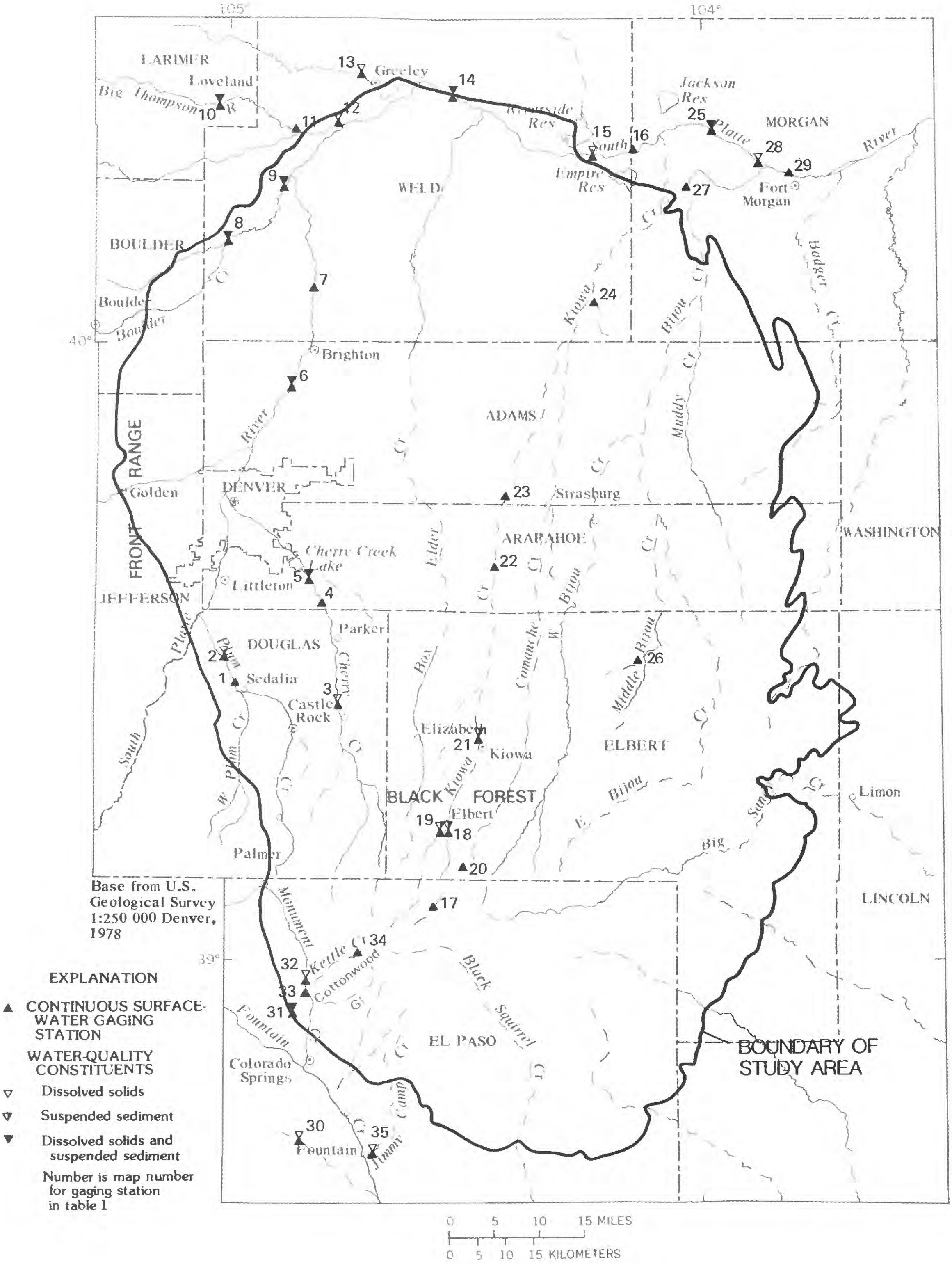


Figure 1.--U.S. Geological Survey streamflow-gaging and water-quality stations.

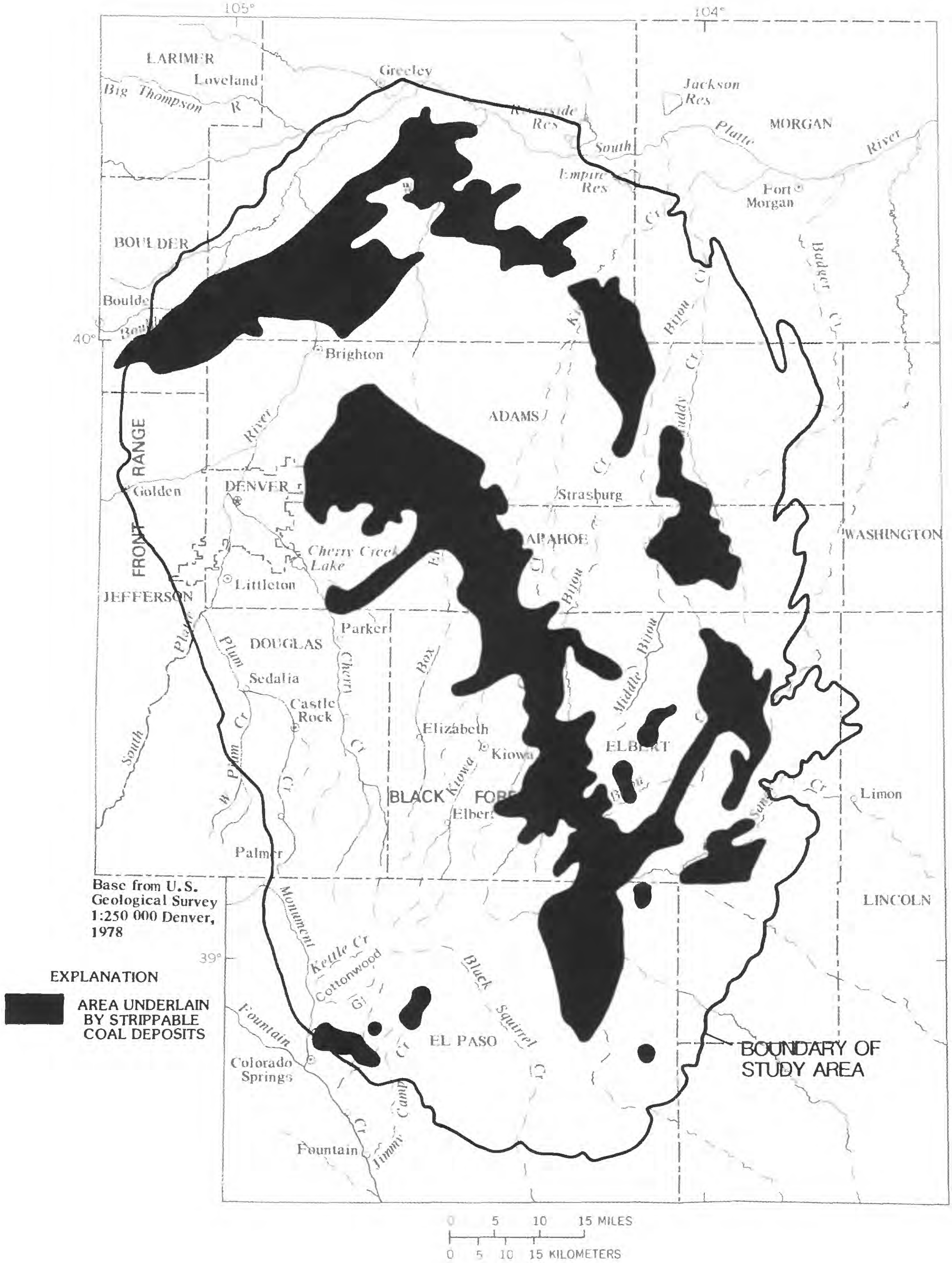


Figure 2.--Strippable coal deposits (From Speltz, 1974).

Streamflow-Gaging and Water-Quality Network

The U.S. Geological Survey streamflow-gaging stations located in the study area (fig. 1) are listed in table 1. Stations without continuous records are designated in table 1 by * and were not used in the hydrologic analysis. A continuous-record station is one with daily flow data available. A partial-record station, in contrast, is one with some flow data, but data is not collected daily, and often there are long periods of no data. Most commonly, flow measurements made at these stations were made in conjunction with some other type of data collection, such as water quality.

Stations where water-quality data have been collected and the type of data available also are shown in figure 1. Water-quality stations shown in figure 1 were divided into three categories--those with dissolved-solids data, those with suspended-sediment data, and those with both types of data.

As indicated in figure 1, streamflow-gaging and water-quality stations are sparse for much of the area. Stations with less than 10 years of continuous surface-flow records were eliminated from the surface-water analysis, and water-quality stations with less than five samples were eliminated from the water-quality analysis. Additional stations eliminated from study include those where it was believed urbanization substantially affected discharge and water quality, such as those located in the city of Denver and its suburbs. Stations affected by urbanization are not included in figure 1 or in table 1.

Stations used in the study were divided into three hydrologically similar categories: The South Platte River, major tributaries to the South Platte River, and plains tributaries to the South Platte River. Four stations on the South Platte River were used: The South Platte River at Henderson (station 6), South Platte River near Kersey (station 14), South Platte River near Weldona (station 25), and the South Platte River at Fort Morgan (station 29). Stations on the major tributaries were St. Vrain Creek at mouth near Platteville (station 9), Big Thompson River at mouth near LaSalle (station 12), and Cache la Poudre River near Greeley (station 13).

The South Platte River stations were placed in a separate category because the South Platte is the major river draining the study area, and most of the hydrologic data in the area are from the South Platte River. The headwaters of the South Platte River are in the mountains, and most of the stream discharge upstream from Denver is from snowmelt. The effect of man on the streamflow of the South Platte River is substantial, with such works as dams, irrigation diversions, transmountain diversions, and transbasin diversions.

All major tributaries also have headwaters in mountainous areas, and most of the discharge is from snowmelt. The effect of man on the stream discharge is substantial, ranging from diversions for irrigation to the addition of water imported from the wetern slope of the Rockies.

Plains tributaries are mostly ephemeral streams with headwaters in the plains area of the study area. Plains tributaries flow in spring from snowmelt runoff, but in late summer usually only as a result of rainfall runoff or irrigation-return flow.

Table 1.--*Streamflow-gaging and water-quality stations*

[* indicates stations without continuous records; NA=not available]

Report station number	Station number	Partial record station	Station name	Location		Sequence number	Drainage area (square miles)	Period of record (water years)
				Latitude	Longitude			
1	06709000	--	Plum Creek near Sedalia	39°26'19"	104°58'56"	00	274	1942-47
2	06709500	--	Plum Creek near Louviers	39°29'04"	105°00'07"	00	302	1947-
3	06712000	--	Cherry Creek near Franktown	39°21'21"	104°45'46"	00	169	1939-
4	06712500	--	Cherry Creek near Melvin	39°35'42"	104°48'44"	00	336	1939-69
5	06712850	*	Cherry Creek above Cherry Creek Lake	39°37'29"	104°50'01"	00	NA	1977-
6	06720500	--	South Platte River at Henderson	39°55'19"	104°52'00"	00	4,710	1926-
7	06721000	--	South Platte River at Fort Lupton	40°04'50"	104°49'18"	00	5,010	1929-57
8	06725450	--	St. Vrain Creek below Longmont	40°09'29"	105°00'53"	00	424	1976-
9	06731000	--	St. Vrain Creek at mouth, near Platteville	40°15'29"	104°52'45"	00	976	1927-
10	06741520	*	Big Thompson River below Loveland	40°23'00"	105°01'45"	00	543	1979-
11	06743500	--	Little Thompson River at Milliken	40°20'07"	104°51'53"	00	199	1951-55
12	06744000	--	Big Thompson River at mouth, near LaSalle	40°21'00"	104°47'04"	00	830	1927-
13	06752500	--	Cache La Poudre River near Greeley	40°25'04"	104°38'22"	00	1,880	1924-
14	06754000	--	South Platte River near Kersey	40°24'44"	104°33'46"	00	9,600	1905-
15	06756995	--	South Platte River at Masters	40°08'21"	104°14'40"	00	12,100	1976-
16	06757000	--	South Platte River at Sublette	40°18'14"	104°10'43"	00	12,200	1926-42, 1943-55
17	06757600	*	Kiowa Creek at K-79 Reservoir near Eastonville.	39°04'00"	104°34'55"	00	3.20	1955-65
18	06758000	--	Kiowa Creek at Elbert	39°12'35"	104°32'00"	00	28.6	1955-65
19	06758100	--	West Kiowa Creek at Elbert	39°12'38"	104°32'16"	00	35.9	1962-65
20	06758150	*	Kiowa Creek tributary near Elbert	39°12'06"	104°30'14"	00	1.22	1970-79
21	06758200	--	Kiowa Creek at Kiowa	39°20'14"	104°28'30"	00	111	1955-65
22	06758250	*	Kiowa Creek tributary near Bennett	39°36'47"	104°27'01"	00	6.40	1970-79
23	06758300	--	Kiowa Creek at Bennett	39°44'54"	104°24'46"	00	236	1960-65
24	06758400	*	Goose Creek near Hoyt	40°02'10"	104°13'06"	00	3.79	1970-79
25	06758500	--	South Platte River near Weldona	40°19'19"	103°55'17"	00	13,200	1952-
26	06758700	*	Middle Bijou Creek tributary near Deer Trail	39°29'33"	104°09'46"	00	1.74	1970-79
27	06759000	--	Bijou Creek near Wiggins	40°14'53"	104°02'08"	00	1,310	1950-56
28	06759100	--	Bijou Creek near Fort Morgan	40°15'58"	103°52'30"	00	1,500	1976-
29	06759500	--	South Platte River at Fort Morgan	40°16'08"	103°48'02"	00	14,800	1943-58
30	07099215	--	Turkey Creek near Fountain	38°36'42"	104°53'39"	01	13.0	1978-
31	07103700	--	Fountain Creek near Colorado Springs	38°51'17"	104°52'39"	00	103	1958-
32	07103800	--	West Monument Creek at Air Force Academy	38°58'14"	104°54'08"	00	14.9	1970-
33	07103900	--	West Monument Creek near Pikeview	38°58'17"	104°53'56"	00	15.4	1957-70
34	07108950	--	Kettle Creek near Black Forest	39°00'14"	104°44'21"	00	9.01	1976-
35	07105900	--	Jimmy Camp Creek at Fountain	38°41'04"	104°41'17"	00	65.6	1976-

More information on the preceding material can be found in Bluestein and Hendricks, 1975; Hem, 1970; Hurr and others, 1975; Livingston and others, 1975, 1976; Mundoroff, 1968; Speltz, 1974; and U.S. Department of the Army, Corps of Engineers, 1977.

Flow Characteristics

Factors describing surface-water flow characteristics are discussed in the following sections. These include relative flood frequency, equations for estimating flood-peak discharge, flood history, flow-duration curves, and mean and low flows. This type of information is needed for planning and design purposes.

Relative Flood-Discharge Frequency, South Platte River

Relative annual flood-frequency histograms for the streamflow-gaging stations along the South Platte River are shown in figures 3 to 6. Most peak discharges on the South Platte River occur in May and June as a result of snowmelt; however, many yearly peak discharges occur as a result of localized intense rainfall in July and August. Flood-frequency curves developed from existing data would be of little use due to the changing effects of man on the flow through time. Any meaningful flood-frequency curves would need to account for man's regulation of the streamflow. Readers are referred to U.S. Department of the Army, Corps of Engineers, 1977, v. V, appendix H, where a computer model is used to predict flood-frequency curves while attempting to account for man's effects on the discharge along the South Platte River.

Relative Flood-Discharge Frequency, Major Tributaries

Relative flood-frequency histograms for the three major tributaries to the South Platte River are shown in figures 7 to 9. Most peak discharges for these stations also occur in May and June. Again, flood-frequency curves developed for these stations would need to account for man's effects on the discharge to be of any use in estimating flood discharge.

Relative Flood-Discharge Frequency, Plains Tributaries

Relative flood-frequency histograms for the plains tributaries are shown in figures 10 to 17. Most peak flows for these stations occur in July and August as a result of rainfall runoff. Few of these stations monitor discharges greatly affected by man, but many of them have periods of record so short as to make flood-frequency curves unreliable.

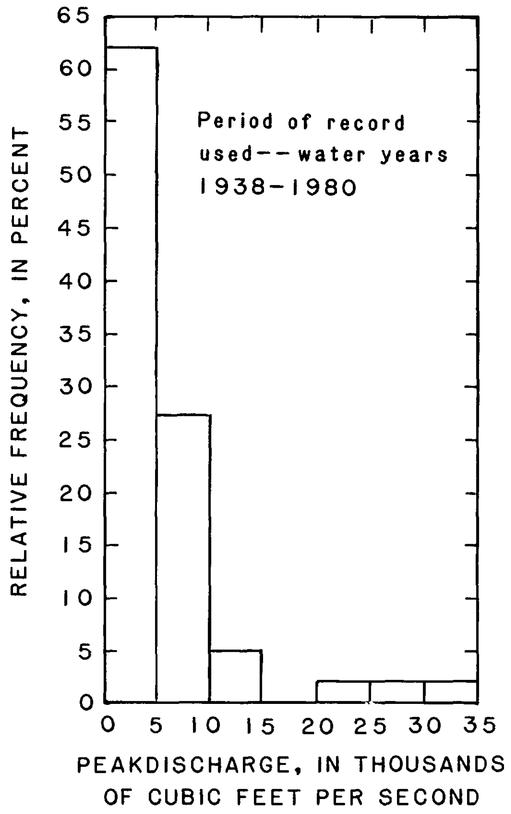


Figure 3.--Relative frequency of annual peak discharge for South Platte River at Henderson (station 6).

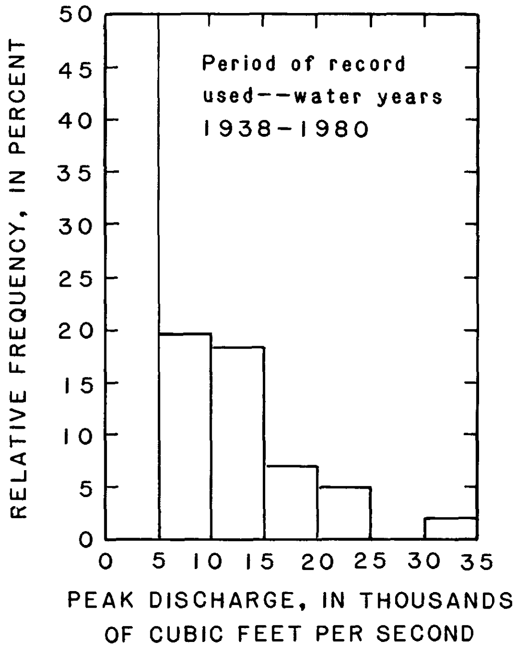


Figure 4.--Relative frequency of annual peak discharge for South Platte River near Kersey (station 14).

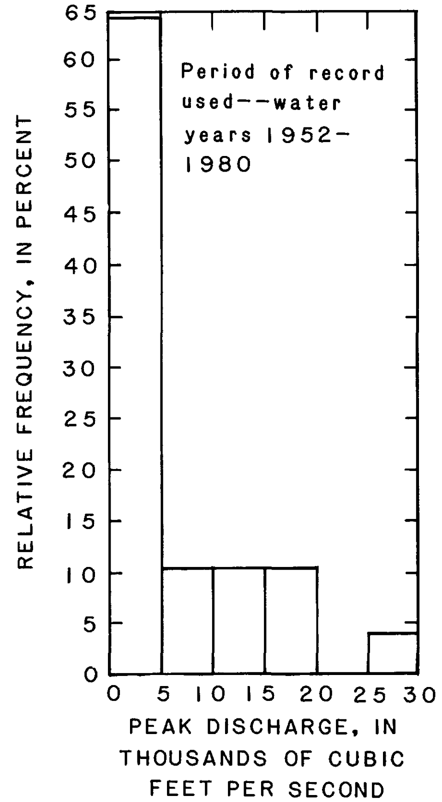


Figure 5.--Relative frequency of annual peak discharge for South Platte River near Weldona (station 25).

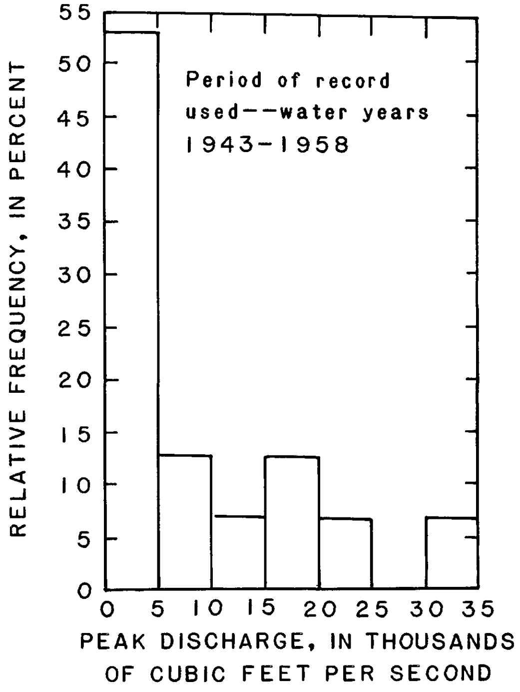


Figure 6.--Relative frequency of annual peak discharge for South Platte River at Fort Morgan (station 29).

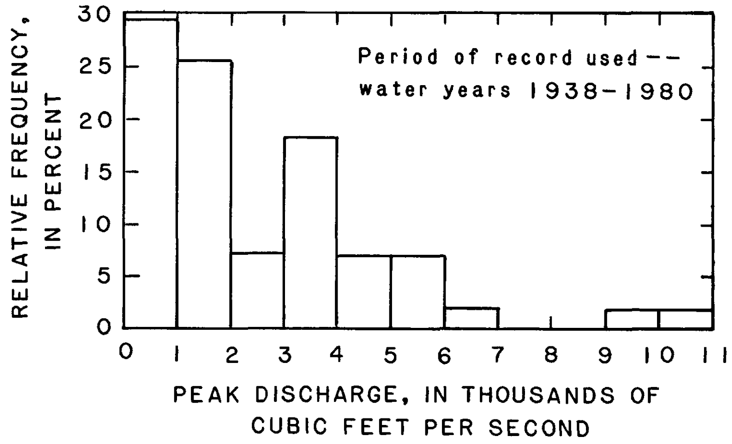


Figure 7.--Relative frequency of annual peak discharge for St. Vrain Creek at mouth, near Platteville (station 9).

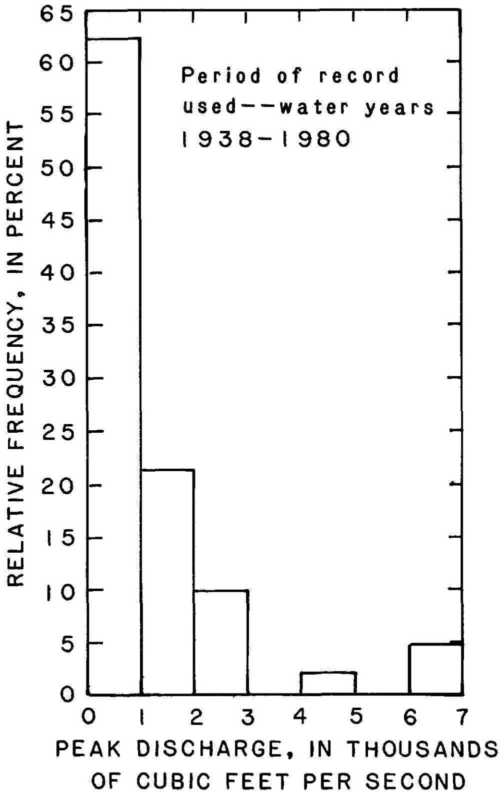


Figure 8.--Relative frequency of annual peak discharge for Big Thompson River at mouth, near LaSalle (station 12).

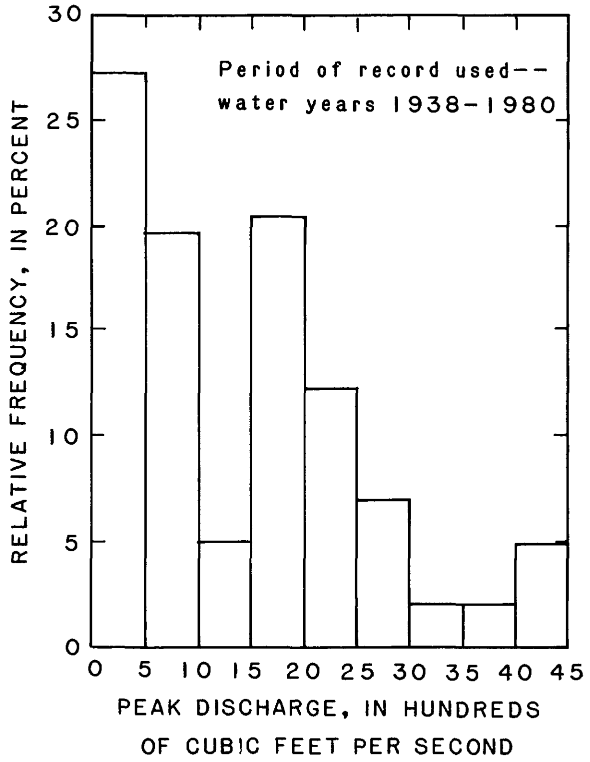


Figure 9.--Relative frequency of annual peak discharge for Cache la Poudre River near Greeley (station 13).

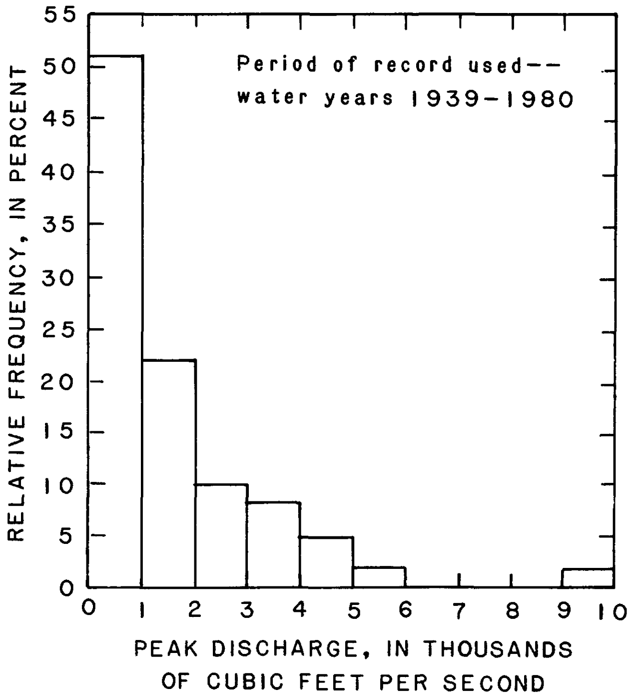


Figure 10.--Relative frequency of annual peak discharge for Cherry Creek near Franktown (station 3).

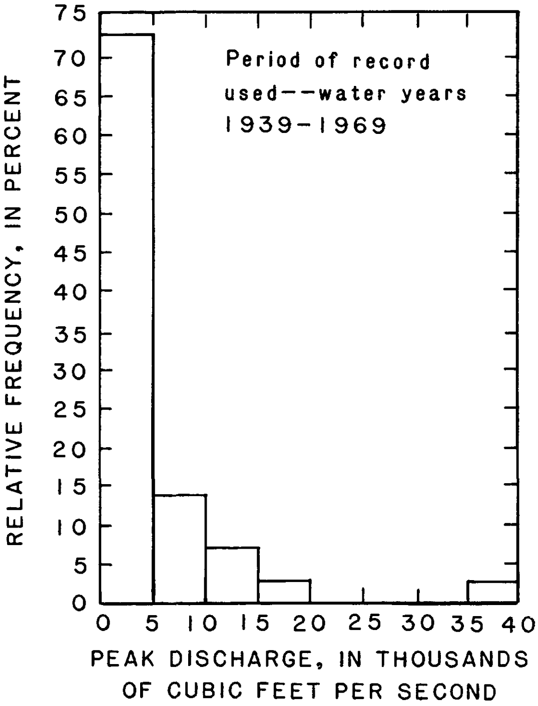


Figure 11.--Relative frequency of annual peak discharge for Cherry Creek near Melvin (station 4).

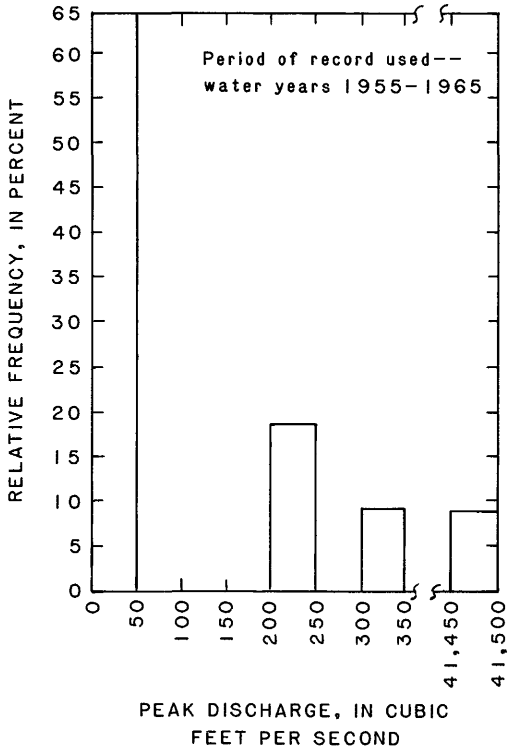


Figure 12.--Relative frequency of annual peak discharge for Kiowa Creek at Elbert (station 18).

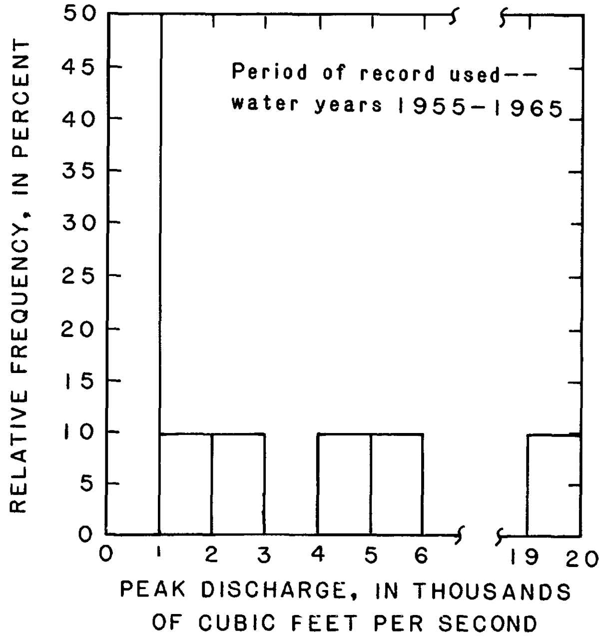


Figure 13.--Relative frequency of annual peak discharge for Kiowa Creek at Kiowa (station 21).

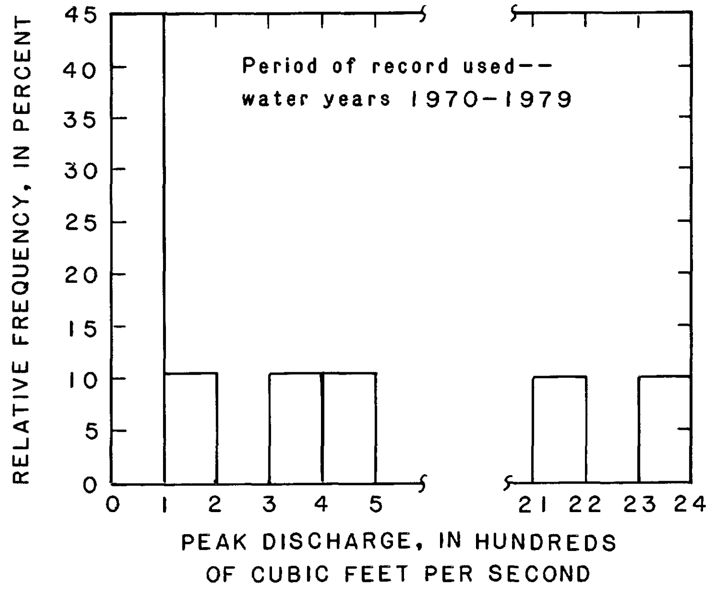


Figure 14.--Relative frequency of annual peak discharge for Kiowa Creek tributary near Bennett (station 22).

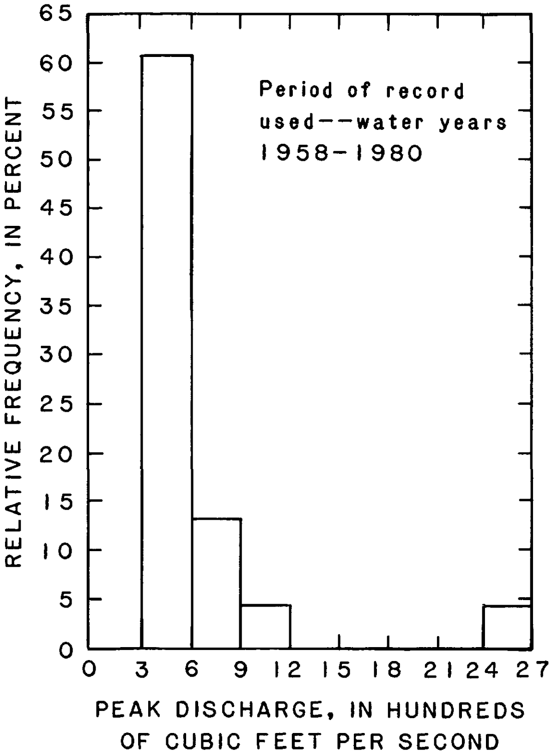


Figure 15.--Relative frequency of annual peak discharge for Fountain Creek near Colorado Springs (station 31).

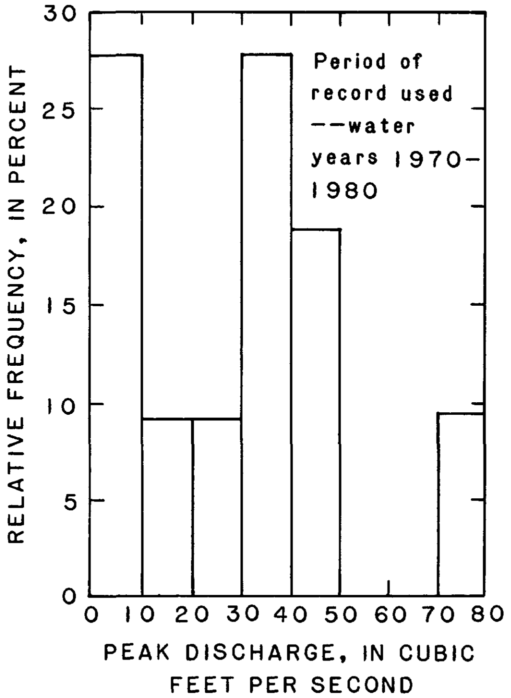


Figure 16.--Relative frequency of annual peak discharge for West Monument Creek at U.S. Air Force Academy (station 32).

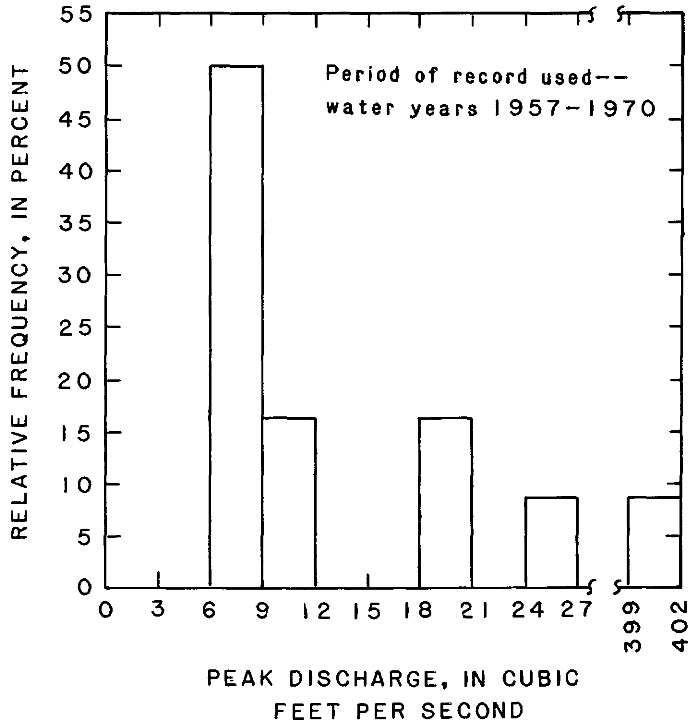


Figure 17.--Relative frequency of annual peak discharge for West Monument Creek near Pikeview (station 33).

Flood-Peak Estimation Equations

Equations are available to estimate peak flood discharges for areas with no discharge data. Two sets of these equations (McCain and Jarrett, 1976; Livingston, 1981) are shown in table 2. McCain's and Jarrett's (1976) equations were developed from flood-frequency analysis and multiple-regression analysis of flood characteristics, basin characteristics, and climatic variables of 258 gaged basins in Colorado and adjacent States.

The limitations of the McCain-Jarrett (1976) equations are as follows: (1) They are not applicable to urban areas unless the effects of urbanization on the discharge are insignificant; (2) they are not applicable to streams where manmade works, such as dams or diversion structures have significant effect on streamflow; (3) they are least reliable for stream sites in mixed-population flood areas (areas where floods are caused by rainfall, snowmelt, or a combination of both); and (4) the results from using the equations on basins outside given basin and climatic factors are unknown (McCain and Jarrett, 1976).

Limitations of Livingston's (1981) equations are that they: (1) Are based on data from watersheds with areas ranging from 0.5 to 15.0 mi^2; (2) were developed for basins only in the Arkansas River basin, though initial results indicate they are applicable to streams in the South Platte River basin; and (3) the effects of urbanization are unknown, though with effective impervious area of less than 30 percent, the results of urbanization seem to be minor (Livingston, 1981).

Table 2.--*Flood-peak estimation equations*

[A=total area of basin contributing to flood discharges, in square miles; S_B=(channel) slope, measured between two points, one at 10 percent of the channel length, the other at 85 percent of the channel length, measured upstream along water course from the site to the basin divide, in feet per mile; A_E=effective drainage, in square miles, in total area minus drainage areas for all flood-detention reservoirs in basin; Q_{10}, Q_{25}, Q_{50}, Q_{100}, and Q_{500}=flood discharge with probability of occurring once every 10 years, 25 years, 50 years, 100 years, and 500 years, respectively]

Source	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Q_{500}
McCain and Jarrett (1976)----------	$144A^{0.528}S_B^{0.336}$	-----------	$891A^{0.482}S_B^{0.154}$	$1{,}770A^{0.463}S_B^{0.086}$	$5{,}770A^{0.432}$
Livingston (1981) (for basins with areas ranging from 0.5 to 3.0 square miles.	$500A_E^{0.89}$	$840A_E^{0.97}$	$1{,}140A_E^{1.01}$	$1{,}500A_E^{1.07}$	-----------
Livingston (1981) (for basins with areas ranging from 3.0 to 15 square miles.	$830A_E^{0.41}$	$1{,}560A_E^{0.44}$	$2{,}280A_E^{0.47}$	$2{,}930A_E^{0.50}$	-----------

In work similar to Livingston's (1981), equations were developed (D. R. Minges, U.S. Geological Survey, oral commun., 1981) to estimate flood peaks in the South Platte River basin. In addition to using the same effective drainage-area parameter as Livingston (1981), altitude, relief, and basin slope also were used. These equations appear to adequately predict flood peaks in the South Platte River basin, with statistical R-values ranging from 0.8 to 0.9.

A general graphical procedure was developed in Matthai (1968) to estimate peak discharges for the Missouri River basin. Because the graphical procedure is applicable chiefly to a much larger area than the South Platte River basin, the procedure probably is less accurate than the procedures used by Minges (D. R. Minges, U.S. Geological Survey oral commun., 1981) and Livingston (1981). Additional peak flood-discharge information may be found in Livingston and others (1975 and 1976).

Flood History

The maximum instantaneous discharges measured since 1940 at selected stations in the study area are shown in table 3. The flood of 1973 on the South Platte River occurred the week of May 6 to May 11 and was caused by a rapidly melting snowpack in the mountains and rainfall runoff at the lower altitudes. The result was flooding throughout the South Platte River basin, characterized by high, abrupt hydrograph peaks from the rainfall runoff and slow recessions because of the melting snowpack.

Many of the tributaries to the South Platte River had the highest measured discharge from the 1965 flood. This flood, in June 1965, did extensive damage in Denver and in other areas downstream from a storm centered over the Cherry Creek and Plum Creek basins. Near Fort Morgan, another storm center over Bijou Creek caused more flooding. Near the mouth of Bijou Creek, flow was estimated to be about 466,000 ft^3/s from a drainage area of 1,314 mi^2.

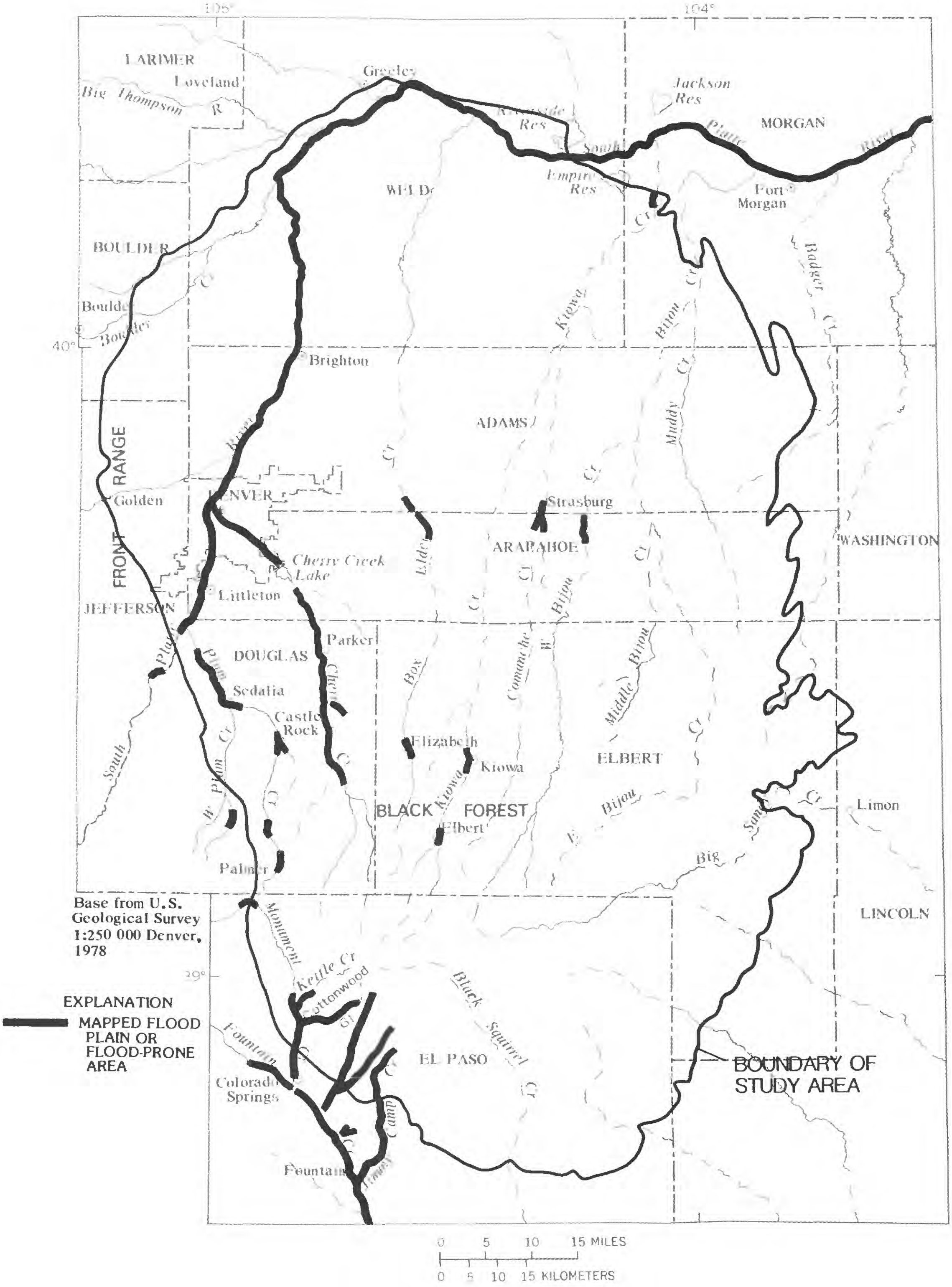
As an example of the magnitude of floods that can occur in the area, in May 1878, a flood of unknown discharge occurred in the Kiowa Creek basin (U.S. Department of the Army, Corps of Engineers, 1977, v. V, appendixes D and H). A wooden railroad bridge that crossed the usually dry channel was destroyed shortly before a standard gage Kansas Pacific (now Union Pacific) freight train was due. The engine and most of the cars went into the channel, along with the engineer, fireman, and brakeman, and were completely buried in the sediment. A search was begun a few days later for the engine. Metal rods were driven into the sand and pits were dug, but it appeared hopeless, as it was estimated that bedrock was at least 50 ft below the channel. The engine has never been found. Additional information on floods in this area can be found in a report by the U.S. Department of the Army, Corps of Engineers (1977, v. V, appendixes D and H).

Flood-Plain and Flood-Prone Mapping

Areas in the Denver coal region in which flood-plain or flood-prone mapping has been completed are shown in figure 18. Most flood plains in the Denver metropolitan area have been mapped (Colorado Water Conservation Board,

Table 3.--*Maximum measured discharge since 1940 at selected sites*

Streamflow-gaging station	Year	Measured discharge (cubic feet per second)	Drainage area (square miles)	Discharge (cubic feet per second per square mile)
Plum Creek near Louviers (06709500)-------------------	1965	154,000	302	510
Cherry Creek near Franktown (06712000)----------------	1945	9,170	169	54
Cherry Creek near Melvin (06712500)-------------------	1965	39,900	336	119
South Platte River at Henderson (06720500)------------	1973	33,000	4,710	7
St. Vrain Creek at mouth, near Plattesville (06731000)	1969	110,300	976	113
Big Thompson River at mouth, near LaSalle (06744000)--	1980	6,220	830	7
Cache la Poudre River near Greeley (06752500)---------	1947	4,050	1,877	2
South Platte River near Kersey (06754000)-------------	1973	31,500	9,598	3
Kiowa Creek at Elbert (06758000)----------------------	1965	41,500	28.6	1,451
Kiowa Creek at Kiowa (06758200)-----------------------	1965	19,700	111	177
Kiowa Creek tributary near Bennett (06758250)---------	1978	2,400	6.4	375
South Platte River near Weldona (06758500)------------	1973	26,800	13,245	2
South Platte River at Fort Morgan (06759500)----------	1951	33,800	14,810	2
Fountain Creek near Colorado Springs (07103700)-------	1964	2,630	103	25
West Monument Creek at Air Force Academy (07103800)---	1980	80	14.9	5
West Monument Creek near Pikeview (07103900)----------	1965	400	15.4	26



Base from U.S. Geological Survey 1:250 000 Denver, 1978

Figure 18.--Location of flood-plain and flood-prone mapping.

1981) and are not shown in figure 18. Little flood-plain or flood-prone mapping has been done in the rural areas. However, flood-prone mapping of the western one-third of Elbert County recently has been completed by Dosch (1981) but is not shown in figure 18.

Flow-Duration Curves

Flow-duration curves for the stations on the South Platte River are shown in figure 19. Two sets of curves are shown, one prior to the date Chatfield Reservoir was completed (May 29, 1975) and one after Chatfield Reservoir began affecting the discharge of the South Platte River. From this figure, Chatfield Reservoir's major effects are on the higher and lower discharges. Flow-duration curves for the major tributaries are shown in figure 20. The Big Thompson River and Cache la Poudre River flow-duration curves are similar, but the St. Vrain Creek flow-duration curve shows higher minimum flows. Again, the effects of man on the measured discharge may be a factor. These curves are from streamflow data from water years 1970-80. These 11 years were used because it was assumed no major works were constructed during that time and all of the effects of man on the flow would be nearly constant. The shape of these curves indicates most higher discharges are from melting snow.

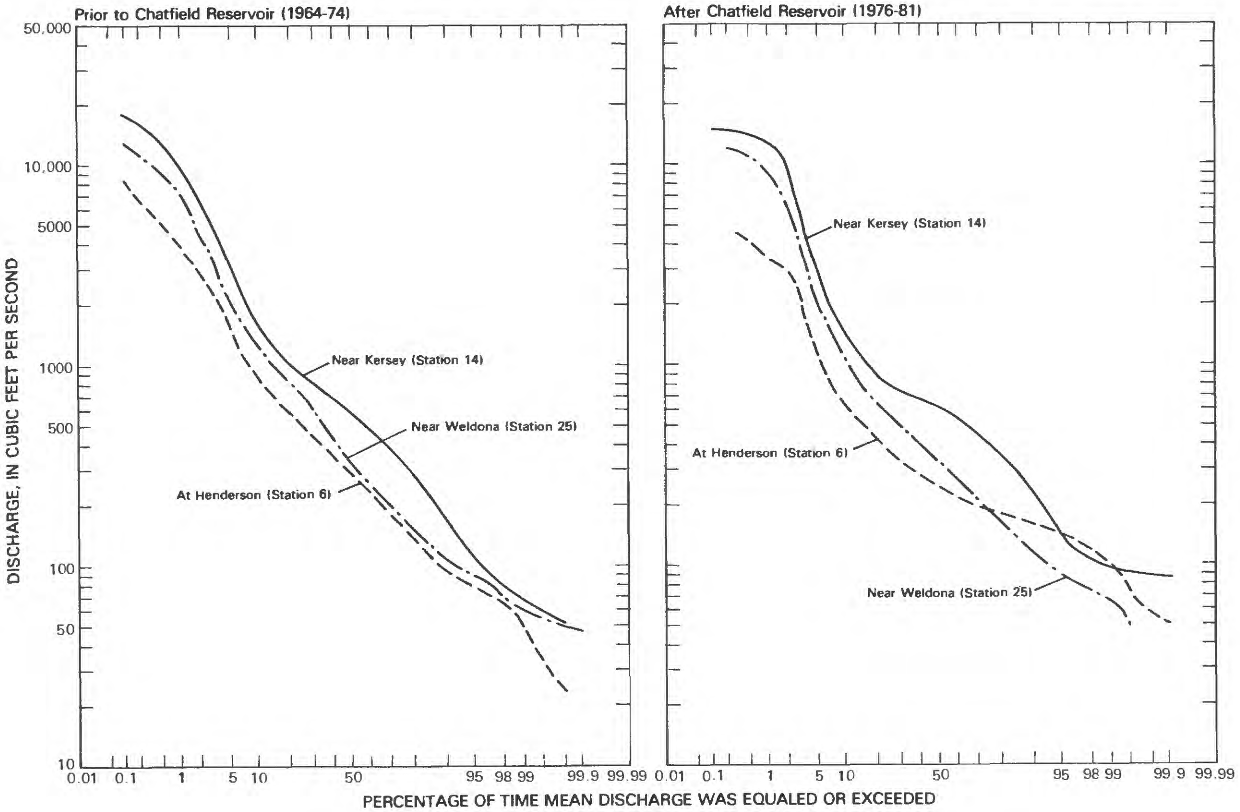


Figure 19--Flow-duration curves for stations on the South Platte River, water years 1964-74 and 1976-81.

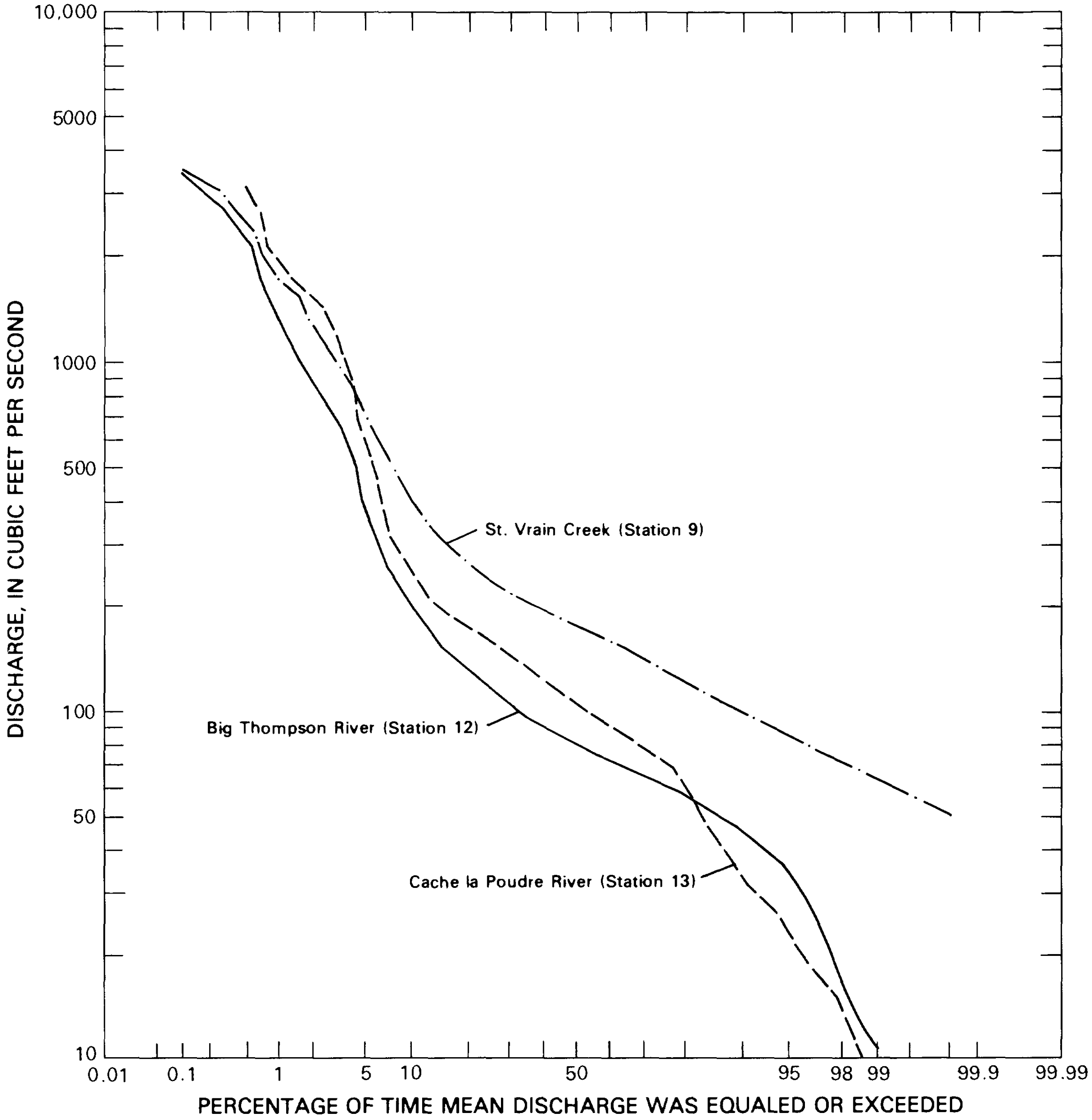


Figure 20.--Flow-duration curves for major tributaries to South Platte River, water years 1970-80.

Only eight stations on plains tributaries have at least 10 years of data from which to obtain flow-duration curves. Four curves that were considered representative are shown in figure 21. Plum Creek and Cherry Creek have headwaters at somewhat higher altitudes than do streams farther east. The curves of both creeks show steep slopes, indicating that most higher discharges are from rainstorms. Both also flow most of the time. Kiowa Creek is in the eastern part of the area, and though it was the only stream with enough data to derive a flow-duration curve in the area, it is considered representative. The curve shows that most higher discharges are from rainfall runoff; however, Kiowa Creek has no flow 40 percent of the year.

Fountain Creek is in the southern edge of the study area near Colorado Springs. This creek is not in the South Platte River drainage area but is in the Arkansas River basin. Fountain Creek is representative of the streams in that area which have headwaters at higher altitudes. The slope of the curve for Fountain Creek is less steep than the slopes of the curves for the other creeks, indicating much of the higher discharge is from a melting snowpack.

Mean and Low Flow

The mean annual flow, low-flow statistics, and years of record used in the evaluations of the South Platte River stations are listed in table 4. Three values are given for mean annual flow and the low-flow statistics; one for the entire period of record, one for the 10 years prior to Chatfield Reservoir construction (water years 1964-74), and one for the period after Chatfield began altering the discharge of the South Platte River (water years 1977-81). The streamflow-gaging stations listed in table 4 are in downstream order. From the variations in mean annual flow at these stations, it is seen that this is a fairly complex stream system, and an in-depth study would be required to determine how much effect man has on the discharge and how much of the changes in flow are natural. However, it is known that these flows are not representative of natural conditions. During periods of low flow, Denver's sewage effluent is the major component of the flow downstream from Denver, until irrigation-return flows enter the river during the irrigation season.

Similar information for the major tributaries to the South Platte River is presented in table 5 and for the plains tributaries to the South Platte River in table 6. Mean annual flows for the water years 1970-80 are not shown for plains tributaries in table 6. As low-flow values for the plains tributaries (table 6) and the duration curves indicate, many of the smaller streams in the area often are dry.

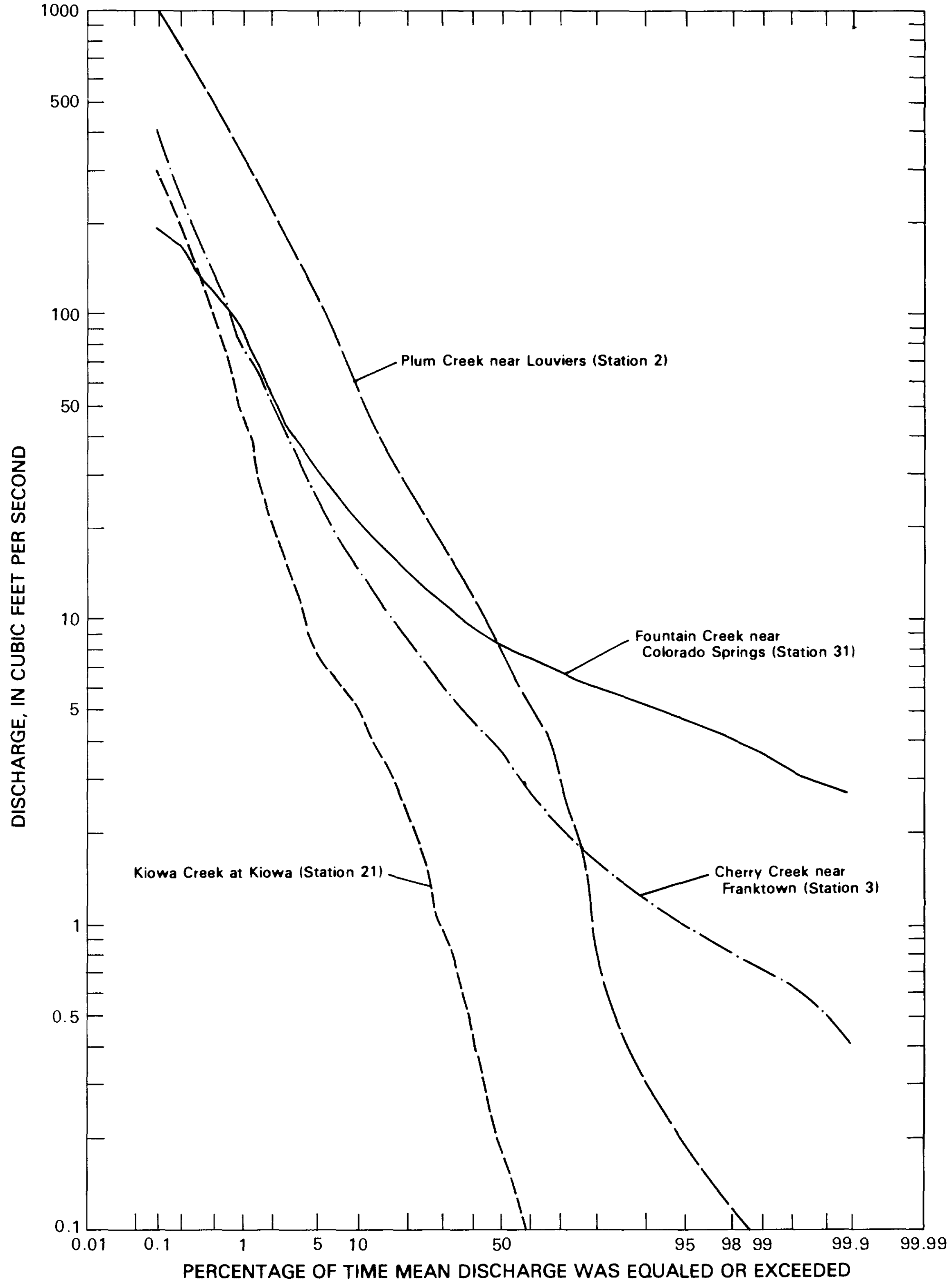


Figure 21.--Flow-duration curves for plains tributaries to South Platte River.

Table 4.--*Mean and low flows at stations on the South Platte River*

[$7Q_{10}$=lowest flow expected for 7 consecutive days with a return period of 10 years]

Streamflow-gaging station and number	Water years of record used	Mean annual flow (cubic feet per second)			$7Q_{10}$ (cubic feet per second)		
		Period of record	water years 1964-74	water years 1977-81	Period of record	water years 1964-74	water years 1977-81
At Henderson (station 6)----	41	405	524	447	12.2	35.6	51.3
Near Kersey (station 14)---	41	850	1,050	1,132	45.2	45.4	79.4
Near Weldona (station 25)---	28	603	733	752	57.8	57.1	31.6

Table 5.--*Mean and low flows at stations on major tributaries to the South Platte River*

[ft^3/s=cubic feet per second, $(ft^3/s)/mi^2$=cubic feet per second per square mile, $7Q_{10}$=lowest flow expected for 7 consecutive days with a return period of 10 years]

Streamflow-gaging station and number	Water years of record used	Mean annual flow				$7Q_{10}$ (ft^3/s)
		Period of record		water years 1970-80		
		ft^3/s	$(ft^3/s)/mi^2$	ft^3/s	$(ft^3/s)/mi^2$	
St. Vrain Creek at mouth, near Platteville (station 9)---	41	222.9	0.23	259.8	0.27	27.1
Big Thompson River at mouth, near La Salle (station 12)--	41	92.4	.11	143.1	.17	1.7
Cache la Poudre River near Greeley (station 13)--------	41	122.2	.07	196.3	.10	4.4

Table 6.--*Mean and low flows at stations on plains tributaries to the South Platte River*

[ft^3/s=cubic feet per second, $(ft^3/s)/mi^2$=cubic feet per second per square mile, $7Q_{10}$=lowest flow expected for 7 consecutive days with a return period of 10 years]

Streamflow-gaging stations and numbers	Water years of record used	Mean annual flow		$7Q_{10}$ (ft^3/s)
		ft^3/s	$(ft^3/s)/mi^2$	
Plum Creek near Louviers (station 2)	33	28.7	0.10	0.0
Cherry Creek near Franktown (station 3)----------------------	40	8.6	.05	.5
Cherry Creek near Melvin (station 4)-	30	11.8	.04	.0
Kiowa Creek at Elbert (station 18)---	10	.9	.03	.0
Kiowa Creek at Kiowa (station 21)----	10	3.8	.03	.0
Fountain Creek near Colorado Springs (station 31)----------------------	22	12.6	.12	3.13
West Monument Creek at U.S. Air Force Academy (station 32)--------------	10	2.5	.17	.0
West Monument Creek near Pikeview (station 33)----------------------	12	.8	.05	.0

Water Quality

The following sections on water quality are divided into dissolved and suspended constituents. Little water-quality information is available for the plains tributaries in general, and little information is available for trace metals throughout the area.

Dissolved Solids

The specific conductance of a water sample can be directly related to the dissolved-solids concentration. Using the data available from the South Platte River system, a least-squares fit of specific conductance and dissolved solids has the form of:

$$DS=bSc \qquad (1)$$

where DS=dissolved solids, in milligrams per liter;
Sc=specific conductance, in micromhos per centimeter at 25° Celsius; and
b=least-squares parameter estimate.

This form of the regression equation is suggested in Hem (1970, p. 99); the coefficient b in the equation generally ranges between 0.55 and 0.75 for natural waters. The equations for dissolved solids at the stations in the Denver coal region with sufficient data are given in table 7.

Table 7.--*Relation between dissolved solids and specific conductance in flow at selected streamflow-gaging stations*

[DS=dissolved solids, in milligrams per liter; Sc=specific conductance, in micromhos per centimeter at 25° Celsius]

Streamflow-gaging station name and number	Regression equation	Coefficient of determination, r^2
South Platte River at Henderson (station 6)	DS=0.64 Sc	0.99
St. Vrain Creek at mouth, near Platteville (station 9)	DS=0.71 Sc	.99
Big Thompson River at mouth, near LaSalle (station 12)	DS=0.77 Sc	.99
Cache la Poudre River near Greeley (station 13)	DS=0.73 Sc	.99
South Platte River near Weldona (station 25)	DS=0.73 Sc	.99

The major ions that comprise the dissolved-solids concentration are those mineral constituents selectively dissolved from soils or rocks in relatively large quantities. Concentrations of major ions in water are reported in milligrams per liter (mg/L); (1 mg/L is virtually equal to 1 part in 1 million by weight at concentrations less than 7,000 mg/L). The most common major ions are listed below:

Cations (positive charge)	Anions (negative charge)
Calcium (ca)	Bicarbonate (HCO_3)
Magnesium (Mg)	Chloride (Cl)
Potassium (K)	Sulfate (SO_4)
Sodium (Na)	

Regression equations for the individual dissolved ions versus specific conductance are given in table 8. These equations have the form of:

$$DC=a+bSc, \qquad (2)$$

where DC=concentration of major ion, in milligrams per liter;
Sc=specific conductance, in micromhos per centimeter at 25° Celsius; and
a and b=least-squares parameter estimates.

Scatter diagrams of the relation between major dissolved constituents and specific conductance in flow at five selected streamflow-gaging stations are presented in figures 22 to 26.

The dominant anions are bicarbonate and sulfate in streamflow at all five stations. The dominant cations are calcium and sodium, although the cation magnesium also is dominant in the major tributaries (stations 9, 12, and 13). Similar regression equations are given for additional gaging stations in Gaydos (1980).

Table 8.--*Relations between concentrations of major dissolved ions and specific conductance in flow at selected streamflow-gaging stations*

[Brackets indicate concentration of constituent, in milligram per liter; Sc, specific conductance, in micromho per centimeter at 25° Celsius]

Regression equation	Coefficient of determination, r^2
South Platte River at Henderson (station 6)	
Calcium (Ca)=6.9+0.07Sc	0.82
Magnesium (Mg)=1.7+0.02Sc	.73
Potassium (K)=0.8+0.007Sc	.64
Sodium (Na)=-13.5+0.12Sc	.96
Bicarbonate (HCO_3)=-12.0+0.25Sc	.75
Chloride (Cl)=-16.0+0.10Sc	.79
Sulfate (SO_4)=7.1+0.16Sc	.70
St. Vrain Creek at mouth, near Platteville (station 9)	
Calcium (Ca)=4.5+0.07Sc	0.85
Magnesium (Mg)=-10.9+0.06Sc	.92
Potassium (K)=2.1+0.002Sc	.20
Sodium (Na)=-19.1+0.10Sc	.94
Bicarbonate (HCO_3)=54.8+0.16Sc	.69
Chloride (Cl)=3.0+0.02Sc	.50
Sulfate (SO_4)=-120+0.45Sc	.92
Big Thompson River at mouth, near LaSalle (station 12)	
Calcium (Ca)=3.5+0.08Sc	0.90
Magnesium (Mg)=-15.6+0.06Sc	.91
Potassium (K)=0.31+0.003Sc	.40
Sodium (Na)=-14.8+0.08Sc	.91
Bicarbonate (HCO_3)=41.4+0.15Sc	.68
Chloride (Cl)=0.63+0.01Sc	.51
Sulfate (SO_4)=-129.6+0.51Sc	.92
Cache la Poudre River near Greeley (station 13)	
Calcium (Ca)=0.09+0.09Sc	0.85
Magnesium (Mg)=-9.7+0.05Sc	.86
Potassium (K)=0.8+0.004Sc	.35
Sodium (Na)=-16.4+0.08Sc	.87
Bicarbonate (HCO_3)=-31.9+0.22Sc	.43
Chloride (Cl)=-12.8+0.03Sc	.31
Sulfate (SO_4)=-61.3+0.41Sc	.80
South Platte River near Weldona (station 25)	
Calcium (Ca)=-13.7+0.10Sc	0.79
Magnesium (Mg)=-13.0+0.05Sc	.77
Potassium (K)=2.7+0.003Sc	.55
Sodium (Na)=-4.6+0.09Sc	.84
Bicarbonate (HCO_3)=105.2+0.12Sc	.60
Chloride (Cl)=17.1+0.03Sc	.61
Sulfate (SO_4)=-170.5+0.46Sc	.85

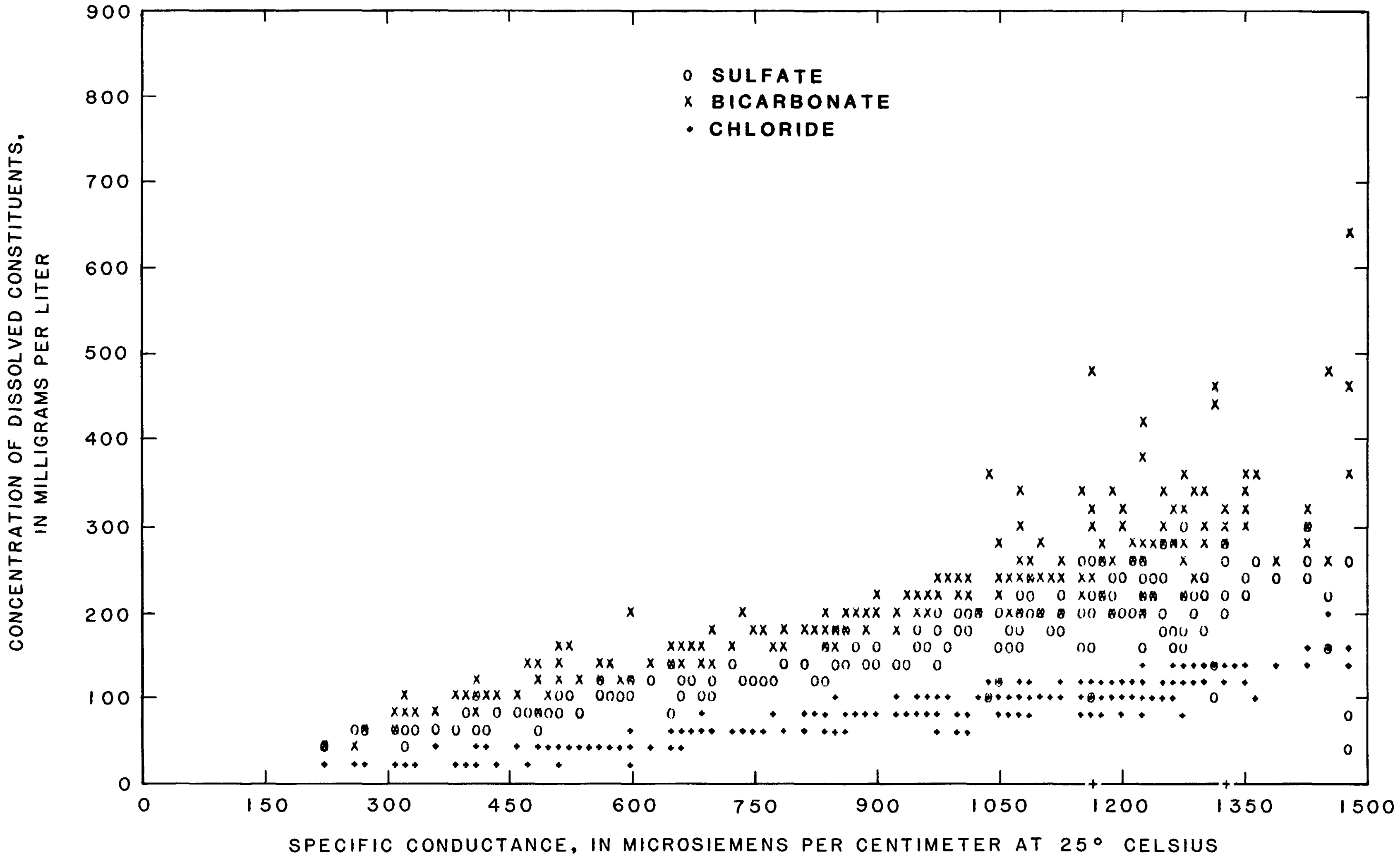


Figure 22.--Relation between major dissolved constituents and specific conductance in streamflow at South Platte River at Henderson (station 6).

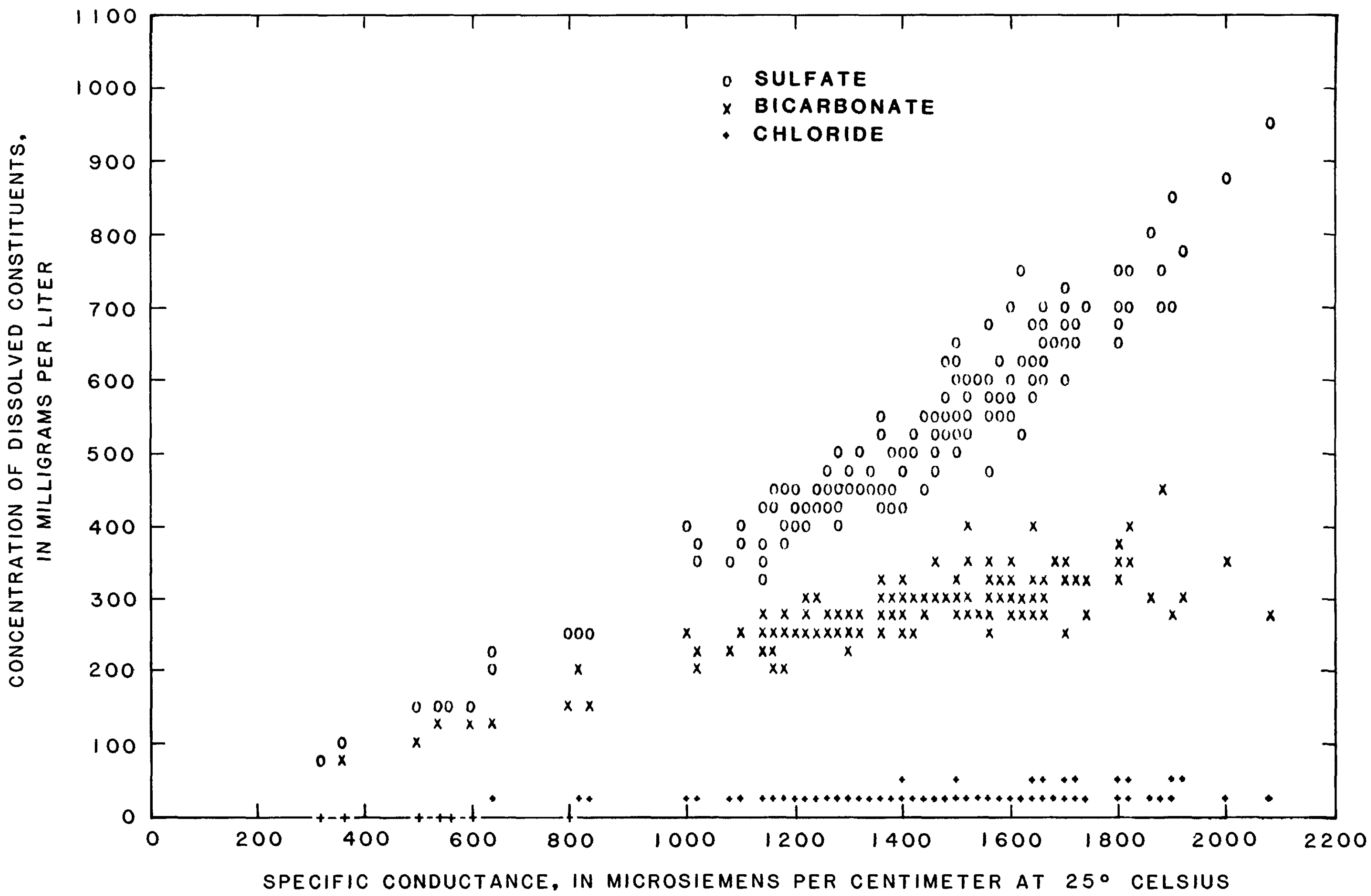


Figure 23.--Relation between major dissolved constituents and specific conductance in streamflow at St. Vrain Creek at mouth, near Platteville (station 9).

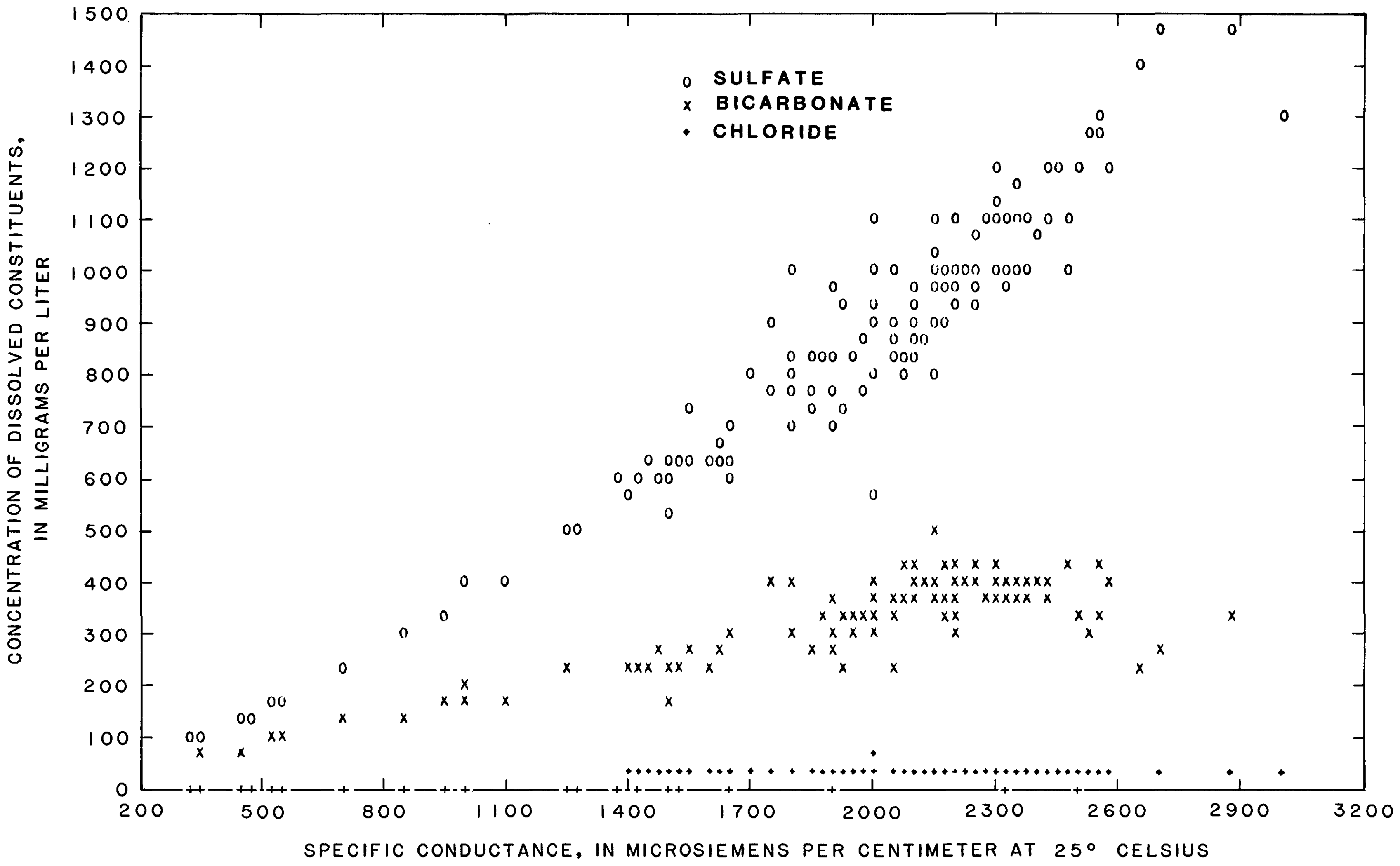


Figure 24.--Relation between major dissolved constituents and specific conductance in streamflow at Big Thompson River at mouth, near LaSalle (station 12).

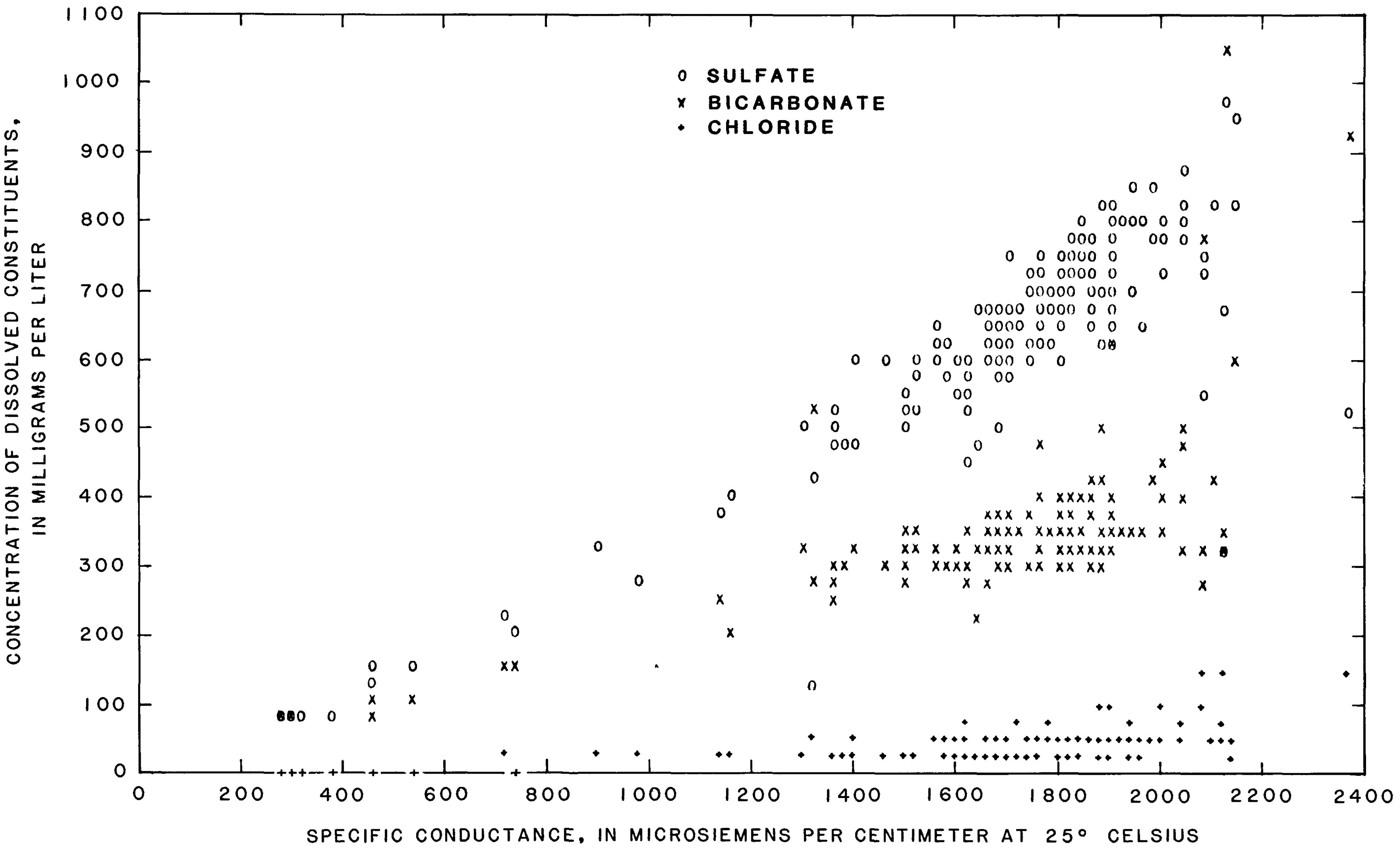


Figure 25.--Relation between major dissolved constituents and specific conductance in streamflow at Cache la Poudre River near Greeley (station 13).

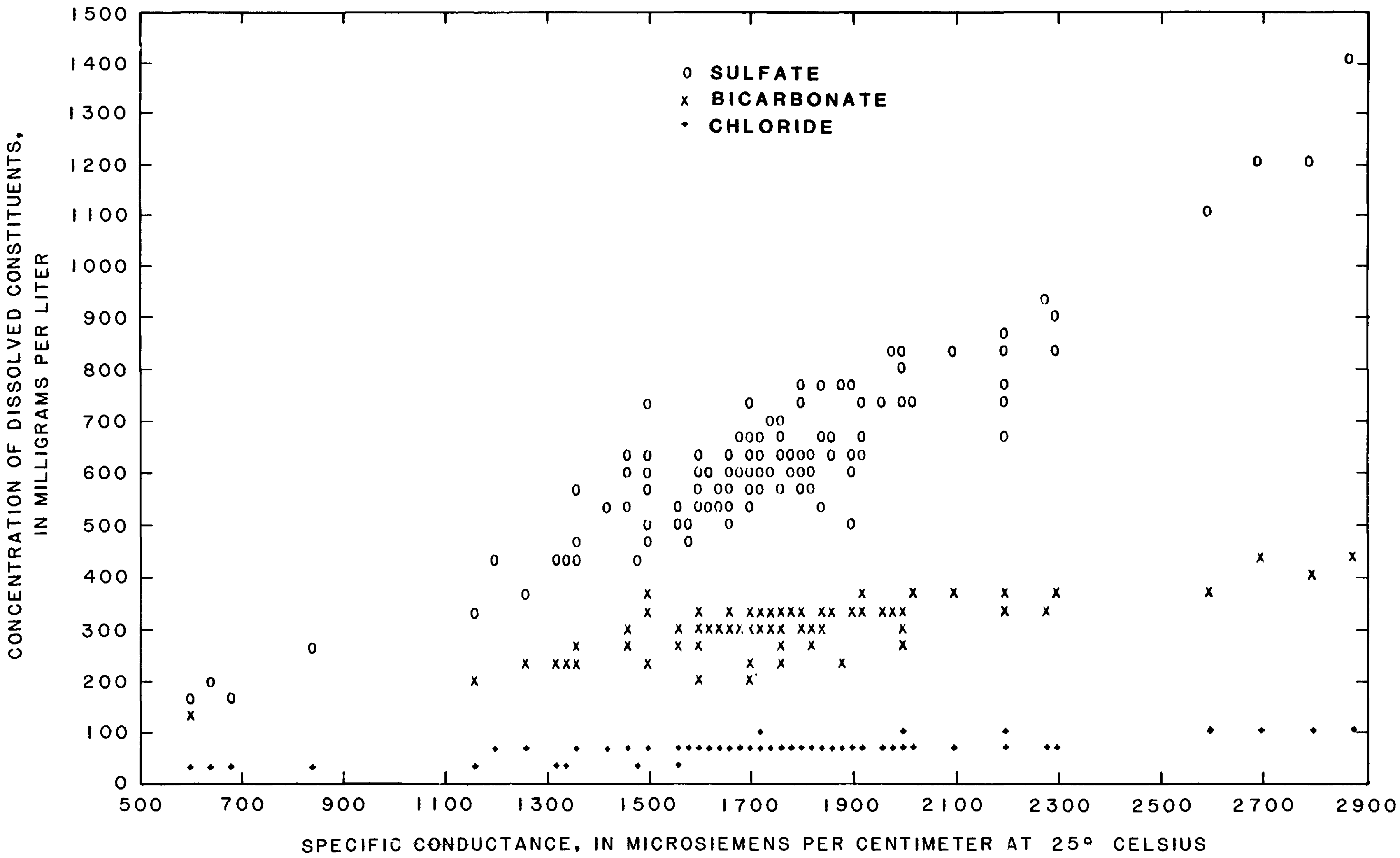


Figure 26.--Relation between major dissolved constituents and specific conductance in streamflow at South Platte River near Weldona (station 25).

The cause of the dominance of these ions in the South Platte River and its major tributaries is difficult to determine because of the large effect of diversions and introduction of imported water from other basins. However, the basic factors probably are irrigation and the reuse of water and the concentration of constituents resulting from evapotranspiration losses. As water is evapotranspired, those ions that are more soluble continue to gain in dominance, and, therefore, the more soluble ions become the major components of the dissolved solids.

Few water-quality data are available for those streams draining the plains area south of the South Platte River. In fact, of those stations shown in figure 1, only one station, Bijou Creek near Fort Morgan (station 28), has sufficient data for analysis. Unfortunately, the data available for this station are from samples collected within a narrow range of discharge. Of the 50 water-quality samples collected, 46 of these samples were collected when discharge was between 10 and 30 ft^3/s. Therefore, 82 percent of the specific-conductance values range between 1,520 and 1,840 micromhos. For this reason, appropriate regression equations cannot be derived between individual dissolved ions and specific conductance. Histograms for the major dissolved ions are shown in figure 27. The major cations are calcium and sodium. The major dissolved anions are bicarbonate and sulfate. These were the dominant ions in water at the streamflow-gaging stations on the South Platte River and its major tributaries. Unfortunately, with water-quality data available for only a small range of discharge and for only one station in the plains area, it is not possible to establish the similarity to the South Platte River and its major tributaries.

These water-quality data on dissolved constituents represent low streamflow conditions and were affected by ground-water discharge. Therefore, these water-quality data for the stream reflect the ground-water quality in the area.

Further information on dissolved solids in the study area may be found in Gaydos (1980) and Livingston and others (1976). Data collected by the U.S. Geological Survey can be accessed from the U.S. Geological Survey WATSTORE computer files, and beginning in 1971, selected data are published annually in a series of U.S. Geological Survey water-data reports entitled, "Water Resources Data for Colorado."

Suspended Sediment

The suspended-sediment load of a stream consists of material (sand, silt, and clay) that are swept into the main body of flow by the upward components of the turbulence and retained in suspension for an appreciable time. In addition, this system includes suspended trace metals that are sorbed to the fine-grained suspended sediment. Each metal can be analyzed as to dissolved, suspended, or total concentration in the water-sediment mixture. These three types of analysis have the following relation:

$$\text{Total} = \text{suspended} + \text{dissolved}.$$

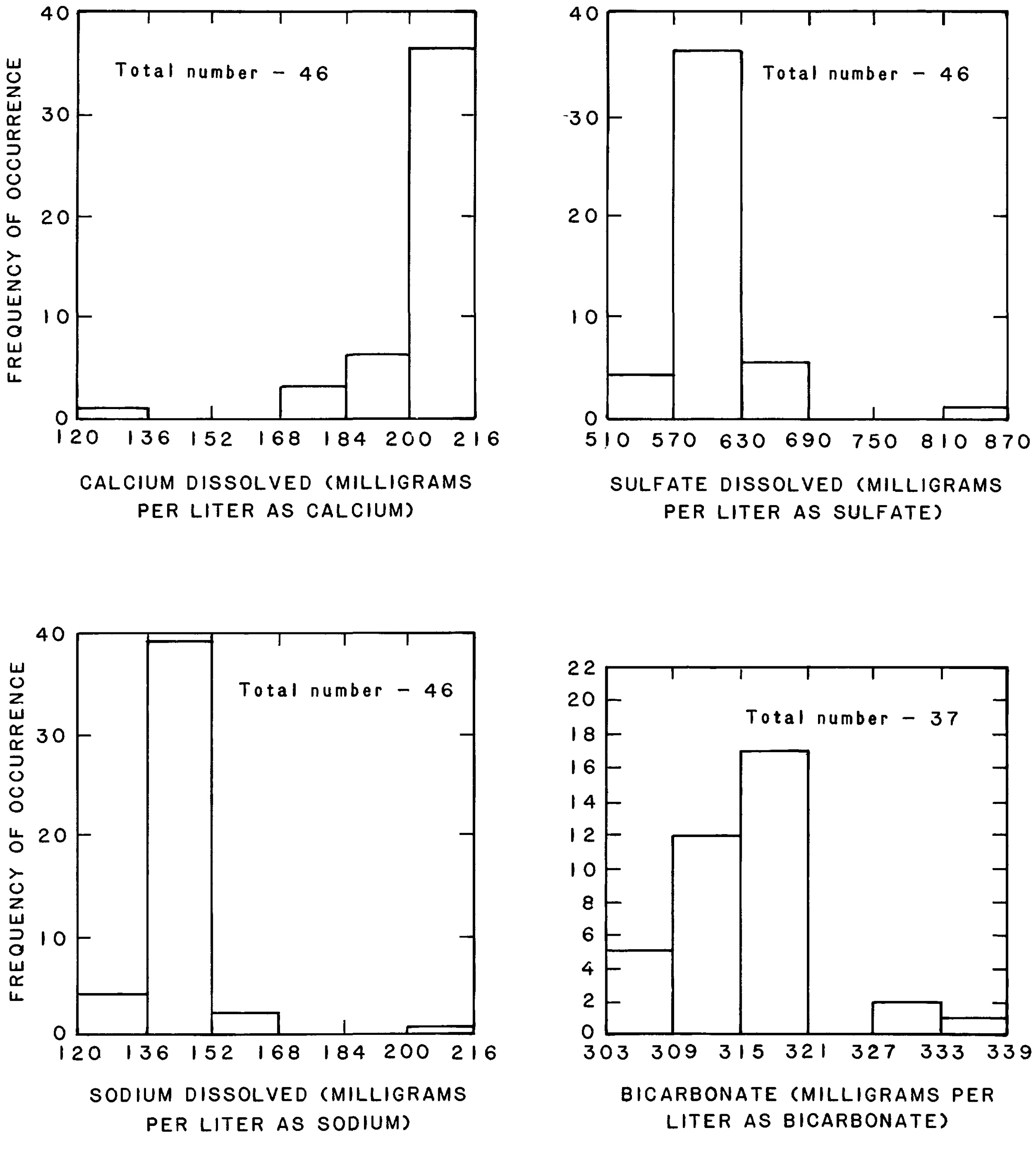


Figure 27.--Major dissolved constituents, Bijou Creek near Fort Morgan (station 28).

The number of samples collected at each station and the mean, standard deviation, and range of the sampled trace metals are shown in table 9. Few data are available at the individual stations, but at those stations for which analyses of both dissolved and suspended metals are available, the suspended fraction is 90 percent or more of the total metal concentration. For example, the ratio of suspended to total iron concentration in the samples collected at the South Platte River at Henderson (station 6) is 91 percent. This is to be expected because the pH of the water ranges from 7.0 to 8.0. Because of the near neutral system, most of the metals present would be expected to be sorbed onto the sediment rather than dissolved.

To better understand the range of trace-metal concentrations and to determine the annual loads of trace metals, additional sampling would be needed to cover a broad range of discharge. This sampling would need to be done on both the large and small tributaries and the South Platte River main stem. Included in this data-collection program would be the sampling of suspended-sediment concentration in conjunction with the trace metals, because suspended sediment is the transport medium for the majority of trace metals.

Few suspended-sediment data have been collected in the South Platte River drainage. On the main stem of the South Platte River, the South Platte River near Kersey (station 14) has 87 samples, and the South Platte River near Weldona (station 25) has 139 samples. Suspended-sediment samples from the South Platte River near Weldona (station 25) have not been collected at discharges greater than 2,000 ft^3/s. This is equal to the return period of a 1-year flood. Thus, no high flows have been sampled. The peak suspended-sediment concentration sampled was 7,160 mg/L at a discharge of 1,360 ft^3/s. The sample concentrations generally range from 200 to 500 mg/L. Without flood sampling, further analysis is not warranted.

None of the major tributaries has a sufficient number of sediment samples to allow meaningful analysis.

Suspended-sediment data have been collected at three stations on plains tributaries. These stations are: (1) Kiowa Creek at Elbert (station 18), (2) West Kiowa Creek at Elbert (station 19), and (3) Kiowa Creek at Kiowa (station 21). Even for these stations, little information is known about sediment concentration or loads. However, from the data available a plot of suspended-sediment concentration versus discharge at the three stations (fig. 28) give some information. The least-squares equation used for each station is in the form:

$$C_s=aQ^b, \qquad (3)$$

where C_s=suspended-sediment concentration, in milligrams per liter;

Q=instantaneous discharge, in cubic feet per second; and

a and b=regression coefficients.

The equations for each station are given in table 10. The percent standard error for these three stations (table 10) are an estimate of the strength of the prediction of these equations. Based on these standard-error percentages, the predictive capabilities of these equations are poor. However, an indication of the suspended-sediment concentration for Kiowa Creek can be given by

Table 9.--*Trace metals in water-sediment mixture at selected streamflow-gaging stations*

[N, number of samples; µg/L, micrograms per liter]

Trace metal	N	Mean	Standard deviation	Minimum	Maximum	Standard error of mean
Station 5--Cherry Creek above Cherry Creek Lake						
Cadmium, dissolved (µg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, suspended, recoverable (µg/L as C	0	--------	--------	------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	5	2.20	1.48	0.00	4.00	0.66
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (µg/L as Cr)	5	5.00	3.08	.00	7.00	1.38
Cobalt, dissolved (µg/L as Co)	0	--------	--------	-------	---------	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	-------	---------	--------
Cobalt, total recoverable (µg/L as Co)	1	7.00	--------	7.00	7.00	--------
Copper, total recoverable (µg/L as Cu)	4	2.75	3.77	.00	8.00	1.89
Iron, total recoverable (µg/L as Fe)	2	143.50	37.48	117.00	170.00	26.50
Iron, dissolved (µg/L as Fe)	0	--------	--------	-------	---------	--------
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	-------	---------	--------
Lead, total recoverable (µg/L as Pb)	5	24.20	15.83	.00	43.00	7.08
Nickel, total recoverable (µg/L as Ni)	5	11.60	6.54	.00	16.00	2.93
Zinc, total recoverable (µg/L as Zn)	5	6.80	5.93	.00	14.00	2.65
Aluminum, total recoverable (µg/L as Al)	4	70.75	25.26	40.00	100.00	12.63
Aluminum, dissolved (µg/L as Al)	0	--------	--------	-------	---------	--------
Boron, dissolved (µg/L as B)	0	--------	--------	-------	---------	--------
Manganese, suspended, recoverable (µg/L as Mn)	0	--------	--------	-------	---------	--------
Manganese, total recoverable (µg/L as Mn)	2	110.50	.71	110.00	111.00	.50
Manganese, dissolved (µg/L as Mn)	0	--------	--------	-------	---------	--------
Silver, total recoverable (µg/L as Ag)	2	1.00	1.41	0.00	2.00	1.00
Selenium, total (µg/L as Se)	1	12.00	--------	12.00	12.00	--------
Station 6--South Platte River at Henderson						
Cadmium, dissolved (µg/L as Cd)	9	0.67	0.86	0.00	2.00	0.29
Cadmium, suspended, recoverable (µg/L as Cd)	0	--------	--------	-------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	0	--------	--------	-------	---------	--------
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	1	.00	--------	.00	.00	--------
Chromium, total recoverable (µg/L as Cr)	1	.00	--------	.00	.00	--------
Cobalt, dissolved (µg/L as Co)	1	.00	--------	.00	.00	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	-------	---------	--------
Cobalt, total recoverable (µg/L as Co)	0	--------	--------	-------	---------	--------
Copper, total recoverable (µg/L as Cu)	0	--------	--------	-------	---------	--------
Iron, total recoverable (µg/L as Fe)	41	82.38	154.13	.03	760.00	24.07
Iron, dissolved (µg/L as Fe)	76	7.53	47.64	.00	400.00	5.46
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	-------	---------	--------
Lead, total recoverable (µg/L as Pb)	0	--------	--------	-------	---------	--------
Nickel, total recoverable (µg/L as Ni)	0	--------	--------	-------	---------	--------
Zinc, total recoverable (µg/L as Zn)	0	--------	--------	-------	---------	--------
Aluminum, total recoverable (µg/L as Al)	0	--------	--------	-------	---------	--------
Aluminum, dissolved (µg/L as Al)	48	.13	.06	.00	.30	.01
Boron, dissolved (µg/L as B)	126	202.14	174.22	.06	560.00	15.52
Manganese, suspended, recoverable (µg/L as Mn)	0	--------	--------	-------	---------	--------
Manganese, total recoverable (µg/L as Mn)	0	--------	--------	-------	---------	--------
Manganese, dissolved (µg/L as mn)	52	28.81	135.48	.00	900.00	18.79
Silver, total recoverable (µg/L as Ag)	0	--------	--------	-------	---------	--------
Selenium, total (µg/L as Se)	0	--------	--------	-------	---------	--------

Table 9.--*Trace metals in water-sediment mixture at selected streamflow-gaging stations*--Continued

Trace metal	N	Mean	Standard deviation	Minimum	Maximum	Standard error of mean
Station 8--St. Vrain Creek below Longmont						
Cadmium, dissolved (µg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, suspended, recoverable (µg/L as C	0	--------	--------	------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	0	--------	--------	------	---------	--------
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Cobalt, dissolved (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, total recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Copper, total recoverable (µg/L as Cu)	0	--------	--------	------	---------	--------
Iron, total recoverable (µg/L as Fe)	0	--------	--------	------	---------	--------
Iron, dissolved (µg/L as Fe)	36	63.06	116.22	10.00	720.00	19.37
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Lead, total recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Nickel, total recoverable (µg/L as Ni)	0	--------	--------	------	---------	--------
Zinc, total recoverable (µg/L as Zn)	0	--------	--------	------	---------	--------
Aluminum, total recoverable (µg/L as Al)	0	--------	--------	------	---------	--------
Aluminum, dissolved (µg/L as Al)	0	--------	--------	------	---------	--------
Boron, dissolved (µg/L as B)	0	--------	--------	------	---------	--------
Manganese, suspended, recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, total recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, dissolved (µg/L as Mn)	36	75.56	41.91	10.00	200.00	6.99
Silver, total recoverable (µg/L as Ag)	0	--------	--------	------	---------	--------
Selenium, total (µg/L as Se)	0	--------	--------	------	---------	--------
Station 9--St. Vrain Creek at mouth, near Platteville						
Cadmium, dissolved (µg/L as Cd)	1	0.00	--------	0.00	0.00	--------
Cadmium, suspended, recoverable (µg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	0	--------	--------	------	---------	--------
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Cobalt, dissolved (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, total recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Copper, total recoverable (µg/L as Cu)	0	--------	--------	------	---------	--------
Iron, total recoverable (µg/L as Fe)	4	25.00	10.00	20.00	40.00	5.00
Iron, dissolved (µg/L as Fe)	133	68.05	133.38	10.00	970.00	11.57
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Lead, total recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Nickel, total recoverable (µg/L as Ni)	0	--------	--------	------	---------	--------
Zinc, total recoverable (µg/L as Zn)	0	--------	--------	------	---------	--------
Aluminum, total recoverable (µg/L as Al)	0	--------	--------	------	---------	--------
Aluminum, dissolved (µg/L as Al)	0	--------	--------	------	---------	--------
Boron, dissolved (µg/L as B)	43	270.01	74.90	.31	420.00	11.42
Manganese, suspended, recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, total recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, dissolved (µg/L as mn)	126	141.64	113.63	.00	780.00	10.12
Silver, total recoverable (µg/L as Ag)	0	--------	--------	------	---------	--------
Selenium, total (µg/L as Se)	0	--------	--------	------	---------	--------

Table 9.--*Trace metals in water-sediment mixture at selected streamflow-gaging stations*--Continued

Trace metal	N	Mean	Standard deviation	Minimum	Maximum	Standard error of mean
Station 10--Big Thompson River below Loveland						
Cadmium, dissolved (µg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, suspended, recoverable (µg/L as C	0	--------	--------	------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	24	0.46	1.28	0.00	6.00	0.26
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (µg/L as Cr)	24	4.83	3.62	.00	10.00	.74
Cobalt, dissolved (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, total recoverable (µg/L as Co)	7	1.57	2.07	.00	5.00	.78
Copper, total recoverable (µg/L as Cu)	24	6.63	4.18	.00	17.00	.85
Iron, total recoverable (µg/L as Fe)	7	1,500.00	2,875.21	180.00	8,000.00	1,086.73
Iron, dissolved (µg/L as Fe)	25	31.20	25.22	10.00	100.00	5.04
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Lead, total recoverable (µg/L as Pb)	24	10.58	21.18	.00	100.00	4.32
Nickel, total recoverable (µg/L as Ni)	7	7.29	8.01	.00	24.00	3.03
Zinc, total recoverable (µg/L as Zn)	24	25.83	10.60	10.00	50.00	2.16
Aluminum, total recoverable (µg/L as Al)	19	367.89	455.76	.00	2,000.00	104.56
Aluminum, dissolved (µg/L as Al)	0	--------	--------	------	---------	--------
Boron, dissolved (µg/L as B)	0	--------	--------	------	---------	--------
Manganese, suspended, recoverable (µg/L as Mn)	7	38.57	54.29	.00	160.00	20.52
Manganese, total recoverable (µg/L as Mn)	7	78.57	48.11	40.00	170.00	18.18
Manganese, dissolved (µg/L as Mn)	25	46.36	30.86	9.00	120.00	6.17
Silver, total recoverable (µg/L as Ag)	24	0.08	0.28	.00	1.00	.06
Selenium, total (µg/L as Se)	6	5.50	3.02	2.00	9.00	1.23
Station 14--South Platte River near Kersey						
Cadmium, dissolved (µg/L as Cd)	1	0.00	--------	0.00	0.00	--------
Cadmium, suspended, recoverable (µg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, total recoverable (µg/L as Cd)	0	--------	--------	------	---------	--------
Chromium, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (µg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (µg/L as Cr)	0	--------	--------	------	---------	--------
Cobalt, dissolved (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, suspended, recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, total recoverable (µg/L as Co)	0	--------	--------	------	---------	--------
Copper, total recoverable (µg/L as Cu)	0	--------	--------	------	---------	--------
Iron, total recoverable (µg/L as Fe)	51	81.14	223.70	.00	1,500.00	31.32
Iron, dissolved (µg/L as Fe)	77	32.08	21.23	10.00	90.00	2.42
Lead, suspended, recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Lead, total recoverable (µg/L as Pb)	0	--------	--------	------	---------	--------
Nickel, total recoverable (µg/L as Ni)	0	--------	--------	------	---------	--------
Zinc, total recoverable (µg/L as Zn)	0	--------	--------	------	---------	--------
Aluminum, total recoverable (µg/L as Al)	0	--------	--------	------	---------	--------
Aluminum, dissolved (µg/L as Al)	0	--------	--------	------	---------	--------
Boron, dissolved (µg/L as B)	110	233.61	105.85	.09	560.00	10.43
Manganese, suspended, recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, total recoverable (µg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, dissolved (µg/L as mn)	60	122.78	80.81	7.00	340.00	10.43
Silver, total recoverable (µg/L as Ag)	0	--------	--------	------	---------	--------
Selenium, total (µg/L as Se)	0	--------	--------	------	---------	--------

Table 9.--*Trace metals in water-sediment mixture at selected streamflow-gaging stations*--Continued

Trace metal	N	Mean	Standard deviation	Minimum	Maximum	Standard error of mean
Station 25--South Platte River Near Weldona						
Cadmium, dissolved (μg/L as Cd)	0	--------	--------	------	---------	--------
Cadmium, suspended, recoverable (μg/L as C	0	--------	--------	------	---------	--------
Cadmium, total recoverable (μg/L as Cd)	0	--------	--------	------	---------	--------
Chromium, dissolved (μg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, suspended, recoverable (μg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, hexavalent, dissolved (μg/L as Cr)	0	--------	--------	------	---------	--------
Chromium, total recoverable (μg/L as Cr)	0	--------	--------	------	---------	--------
Cobalt, dissolved (μg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, suspended, recoverable (μg/L as Co)	0	--------	--------	------	---------	--------
Cobalt, total recoverable (μg/L as Co)	0	--------	--------	------	---------	--------
Copper, total recoverable (μg/L as Cu)	0	--------	--------	------	---------	--------
Iron, total recoverable (μg/L as Fe)	0	--------	--------	------	---------	--------
Iron, dissolved (μg/L as Fe)	128	35.47	38.29	10.00	260.00	3.38
Lead, suspended, recoverable (μg/L as Pb)	0	--------	--------	------	---------	--------
Lead, total recoverable (μg/L as Pb)	0	--------	--------	------	---------	--------
Nickel, total recoverable (μg/L as Ni)	0	--------	--------	------	---------	--------
Zinc, total recoverable (μg/L as Zn)	0	--------	--------	------	---------	--------
Aluminum, total recoverable (μg/L as Al)	0	--------	--------	------	---------	--------
Aluminum, dissolved (μg/L as Al)	0	--------	--------	------	---------	--------
Boron, dissolved (μg/L as B)	0	--------	--------	------	---------	--------
Manganese, suspended, recoverable (μg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, total recoverable (μg/L as Mn)	0	--------	--------	------	---------	--------
Manganese, dissolved (μg/L as Mn)	127	40.80	30.81	.00	200.00	2.73
Silver, total recoverable (μg/L as Ag)	0	--------	--------	------	---------	--------
Selenium, total (μg/L as Se)	0	--------	--------	------	---------	--------
Station 31--Fountain Creek near Colorado Springs						
Cadmium, dissolved (μg/L as Cd)	6	0.00	0.00	0.00	0.00	0.00
Cadmium, suspended, recoverable (μg/L as Cd)	6	10.00	.00	10.00	10.00	.00
Cadmium, total recoverable (μg/L as Cd)	26	8.73	9.86	.00	20.00	1.93
Chromium, dissolved (μg/L as Cr)	12	1.67	3.89	.00	10.00	1.12
Chromium, suspended, recoverable (μg/L as Cr)	6	.00	.00	.00	.00	.00
Chromium, hexavalent, dissolved (μg/L as Cr)	22	.14	.47	.00	2.00	.10
Chromium, total recoverable (μg/L as Cr)	18	3.33	7.67	.00	20.00	1.81
Cobalt, dissolved (μg/L as Co)	6	1.33	1.03	.00	2.00	.42
Cobalt, suspended, recoverable (μg/L as Co)	6	42.67	16.50	9.00	50.00	6.74
Cobalt, total recoverable (μg/L as Co)	6	85.00	36.74	10.00	100.00	15.00
Copper, total recoverable (μg/L as Cu)	26	12.31	9.23	.00	39.00	1.81
Iron, total recoverable (μg/L as Fe)	26	1,249.62	2,144.12	90.00	11,000.00	420.50
Iron, dissolved (μg/L as Fe)	39	46.15	39.64	10.00	220.00	6.35
Lead, suspended, recoverable (μg/L as Pb)	6	82.33	40.35	.00	100.00	16.47
Lead, total recoverable (μg/L as Pb)	26	82.08	95.21	.00	200.00	18.67
Nickel, total recoverable (μg/L as Ni)	7	2.71	1.50	.00	4.00	.57
Zinc, total recoverable (μg/L as Zn)	26	41.15	56.94	.00	300.00	11.17
Aluminum, total recoverable (μg/L as Al)	0	--------	--------	------	---------	--------
Aluminum, dissolved (μg/L as Al)	7	51.43	36.71	10.00	100.00	13.88
Boron, dissolved (μg/L as B)	0	--------	--------	------	---------	--------
Manganese, suspended, recoverable (μg/L as Mn)	13	57.69	53.88	20.00	220.00	14.94
Manganese, total recoverable (μg/L as Mn)	26	102.81	52.18	40.00	270.00	10.23
Manganese, dissolved (μg/L as mn)	40	32.32	17.27	.00	80.00	2.73
Silver, total recoverable (μg/L as Ag)	9	.08	.01	.00	.05	.00
Selenium, total (μg/L as Se)	18	.85	.80	.00	3.00	.22

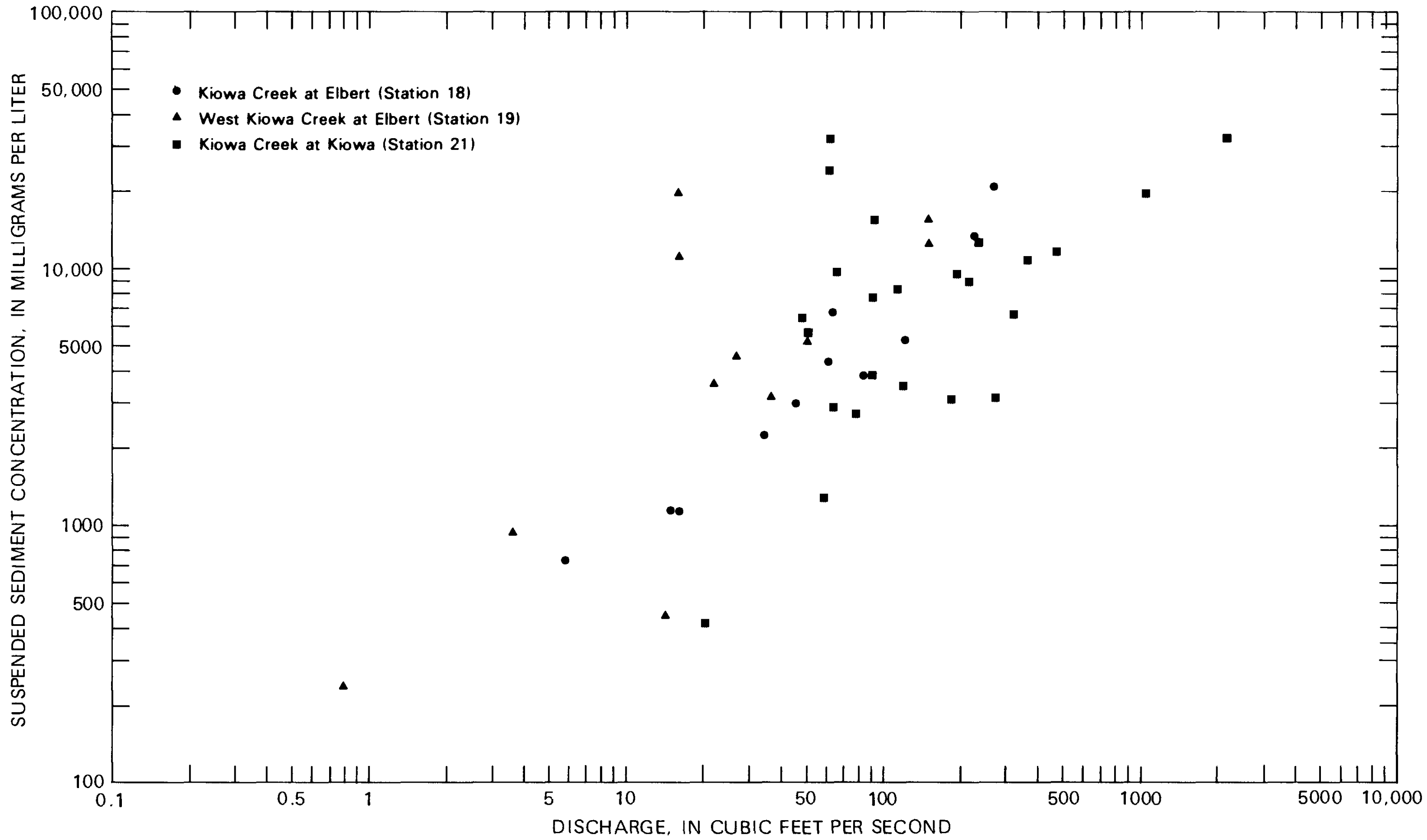


Figure 28.--Sediment-concentration rating curve for plains tributaries.

Table 10.--*Sediment-concentration-rating equations derived by least squares for plains tributaries*

[C_s=suspended-sediment concentration, in milligrams per liter, and Q=instantaneous discharge, in cubic feet per second]

Station name and number	Number of samples	Regression equation	Standard error (average percent)
Kiowa Creek at Elbert (station 18)-----	11	$C_s=122.7Q^{0.856}$	28
West Kiowa Creek at Elbert (station 19)	11	$C_s 383.75Q^{0.738}$	118
Kiowa Creek at Kiowa (station 21)------	24	$C_s=699.2Q^{0.457}$	100

use of the equations. These equations predict a concentration of suspended sediment between 6,300 and 11,000 mg/L at a discharge of only 100 ft^3/s. A suspended-sediment concentration of 16,000 mg/L at a discharge of 1,000 ft^3/s has been measured at Kiowa Creek at Kiowa (station 21). These values indicate that these plains tributaries transport large concentrations of suspended material. An additional, qualitative indicator of the large sediment concentrations and loads transported by these streams is from geomorphic evidence. Channels, such as Kiowa Creek, characteristically have a large width to depth ratio and a sand bed. These are indicators of channels capable of transporting large sediment loads. An example of the mobility of the stream beds of these channels is illustrated by the train engine buried in the bed of Kiowa Creek already discussed.

In part, the large values of the percent standard error are to be expected from sediment-concentration-discharge relations, but the variability of the data probably is greatly affected by suspended sediment derived from gully migration and associated bank caving. The effect of gully migration on sediment concentration is characterized by a very random component in which cause and effect, and therefore, predictability, is weak. Probably little of the sediment is derived from actual material migration from upland slopes.

Further information on sediment for the South Platte River basin may be found in Kircher (1981) and Mundoroff (1968). Suspended-sediment data collected by the U.S. Geological Survey are accessible from the U.S. Geological Survey WATSTORE computer files, and beginning in 1971, some may be found in an annual series of U.S. Geological Survey water-resources data reports entitled "Water Resources Data for Colorado."

Adequacy of Data-Collection Network

The preceding sections on surface water and surface-water quality are divided into the South Platte River main stem, major tributaries, and plains tributaries. Coal-mining potential is primarily in the plains area, and it is here that effects on the hydrologic regime could be most pronounced. Effects on downstream areas also would be of concern, which suggests a continuing hydrologic interest in the South Platte River main stem and the major tributaries.

At the present time, the South Platte River main stem and the major tributaries appear adequately monitored by surface-water gaging stations. These areas represent a complex hydrologic regime because of intense water use and diversions.

Knowledge of flood hydrology in the plains area probably is adequate. Certainly, more information on flood frequencies would be beneficial, but data-collection programs in this area of predominately rainfall runoff is extremely expensive and time-consuming. It is doubtful whether any long-term data-collection effort would be cost effective in improving flood-frequency predictions.

Less is known about low flow and flow duration of streams in the plains area. Most of the previous data on the streams in this area were collected using partial-record stations. This type station records only higher flows. Additional stations collecting continuous surface-water data are needed to better estimate low flow and flow-duration statistics.

Water-quality data for main-stem and major tributary stations generally is adequate and data collection is continuing. The one inadequacy in this data-collection program is the lack of concentration data for suspended trace metals and associated suspended sediment. Additional sampling for trace-metal and suspended-sediment concentrations is needed during high flows at several stations on the South Platte River main stem.

There is little information on water quality for the plains streams. The only data available are for Bijou Creek near Fort Morgan (station 28) where data represent nearly the same discharge. A sampling program for major constituents, trace metals, and suspended sediment is needed for the small streams in the area. The program needs to acquire data during high, medium, and low flows.

It may be well to combine the needed water-quantity and water-quality networks by collecting both types of data at the same stations. These stations need to be in small drainage basins and preferably near areas of potential coal mining in order to monitor the hydrologic system prior to, during, and after any future mining.

Additional reconnaissance sites need to be established on major streams in the area that empty into the South Platte River. Sampling at these sites needs to be routinely done at various discharges in order to provide background data to compare with cumulative effects from multiple mines upstream.

GROUND WATER

Ground water occurs throughout the study area, but the depth to an aquifer and the yield of a well may vary considerably from one area to another. In areas underlain by significant alluvial aquifers, comparatively shallow wells can be expected to yield large quantities of water, whereas in other areas bedrock formations are relied on for water, and deeper wells and lower yields are to be expected. The differences in well yield and water quality between alluvial and bedrock wells affect the water use. Wells completed in alluvial aquifers that yield large volumes of water commonly are used to supply water for irrigation of commercial crops. The lower yielding wells completed in bedrock, which generally supply water of better chemical quality, commonly are used as municipal, domestic, and stock supplies. The marked differences between the hydrologic characteristics of the alluvial and bedrock aquifers require a separate discussion of these two sources of ground water.

The geology and hydrology of both aquifer systems have been described in varying detail in selected areas. Anna (1975), Chronic and Chronic (1974), Hampton (1975), and Hampton and others (1974) provide indexes to more than 1,800 reports dealing with the geology and hydrology of the western part of the study area. The following discussion of the ground-water system references only those reports that, in the opinion of the authors, provide the best sources of information on a given subject.

Alluvial Aquifers

Alluvial aquifers occur along most of the channels of the principal streams. They range in width from a few tens of feet near the headwaters of the smaller streams draining the central part of the study area, to as much as 15 mi in width in Weld County, along the downstream reaches of these streams. Aquifer thickness commonly ranges from a few feet in the upstream reaches of the smaller streams to about 100 ft in the area to the south of the South Platte River in Weld County. The alluvial aquifer along the South Platte River generally increases in thickness with distance downstream. The aquifer is as much as 20 ft thick near Denver and increases to as much as 200 ft thick northeast of Wiggins. The approximate location and extent of major alluvial aquifers are shown in plate 1. More detailed descriptions of the location, extent, and thickness of the alluvial aquifers are contained in Bjorklund and Brown (1957), Code (1945), Duke and Longenbaugh (1966), Erker and Romero (1967), Hurr and Schneider (1972a, 1972b), Hurr, Schneider, and others (1972), Konikow (1975), Livingston and others (1976), Maberry and Hampton (1972), McGovern and Jenkins (1966), McLaughlin (1946), Owens (1967), Robson (1977), and Smith and others (1964).

The alluvial aquifers occur in layers of unconsolidated sediment ranging in grain size from clay to boulders. These valley-fill deposits are of Quaternary age and primarily consist of sand and gravel, but contain lenses and beds of silt and clay and, in some areas, a lower bed of cobbles and boulders. Sand and gravel generally are well rounded to subrounded and are crossbedded. In some areas, layers of clay are thick and extensive. Unconsolidated deposits consisting of dune sand, slope wash, and terrace and upland deposits form a permeable layer over much of the valley-fill deposits and bedrock formations. These deposits are not important sources of ground water, although they are a medium for recharge. The generalized distribution of unconsolidated deposits in the study area is shown on the geologic map of Colorado (Tweto, 1979). More detailed mapping of localized areas is contained in Bjorklund and Brown (1957), Bryant and others (1978), Chase and McConaghy (1972), Colton (1978), Hurr (1976), Lindvall (1972), Maberry and Lindvall (1972, 1974), Machette (1978), Scott (1962, 1963), Scott and others (1978), Scott and Wobus (1973), Sharps (1980), Smith (1964), Smith and others (1964), Soister (1965a, 1965b, 1965c, 1968a, 1968b), Trimble (1975), Trimble and Machette (1979a, 1979b), Tweto (1979), Van Horn (1957), and Varnes and Scott (1967).

Water Levels

Ground water in the alluvial aquifers generally occurs under unconfined (water-table) conditions. Depths to water ranging from 0 to 50 ft are common, with the greater depths occurring at points more distant from the strean channel. Maps showing depth to water in selected areas are found in Bjorklund and Brown (1957), Hillier and Hutchinson (1980b), Hillier and Schneider (1979b), and Smith and others (1964). This information is based on water-level measurements in wells. Thousands of water-level measurements are available from the files of the U.S. Geological Survey, or are published in various U.S. Geological Survey publications. Principal among those publications containing water-level data are Bjorklund and Brown (1957), Borman (1981), Brookman (1969, 1970, 1971, and 1973), Code (1945), Gregg and others (1961), Hillier and others (1979), Hutchinson and Hillier (1979), Jenkins (1961a, 1961b), Major and others (1974), Major and others (1975), McConaghy and others (1964), McLaughlin (1946), Robson (1977), Schneider (1962), Schneider and Hillier (1978), Skinner (1962 and 1963), Skinner and others (1965), Skinner and Thomas (1964), and Wilson (1965). Records of water levels and artesian pressures in observation wells also are published in the Water-Supply Papers of the U.S. Geological Survey and beginning in 1971 in an annual series of U.S. Geological Survey Water-Data Reports entitled, "Water Resources Data for Colorado." When water-level measurements are used to define the altitude of a water table, a water-table contour map may be constructed. Such a map is shown as plate 1. The water-table altitude is shown to decrease from 7,000 ft to less than 4,500 ft with the direction of ground-water movement generally corresponding to the direction of surface-water flow. More detailed water-level mapping is contained in Bjorklund and Brown (1957), Code (1945), Duke and Longenbaugh (1966), Erker and Romero (1967), Hurr (1976), Hurr and Schneider (1972a and 1972b), Hurr, Schneider, and others (1972), Konikow (1975), Livingston and others (1976), McGovern and Jenkins (1966), Owens (1967), Robson (1977), and Smith and others (1964).

Water levels in the alluvial aquifers rise and decline in response to periods of recharge or discharge. The duration of these periods can vary from a few minutes or hours, as might occur when water-level changes are due to the effects of a nearby pumping well, to months or years. Changes during longer periods generally are due to climatic factors, such as greater-than-normal or less-than-normal annual precipitation, or the length of the growing season of irrigated crops. The shallow depth to the alluvial aquifers allows surface-water recharge to occur much more rapidly than is the case for the deeper bedrock aquifers. The availability of surface runoff in streams and the widespread use of surface water for irrigation generally has moderated the effects of pumpage. In addition, pumpage is strictly controlled by Colorado statutes. As a result, water levels in the alluvial aquifers generally have not declined to any significant degree. The water-level data in the above cited references indicate the extent and magnitude of water-level changes in some areas, as do water-level hydrographs and water-level change maps published in Bjorklund and Brown (1957), Brookman (1969, 1970, 1971, and 1973), Duke and Longenbaugh (1966), Erker and Romero (1967), Hurr (1976), Jenkins (1964), Livingston and others (1976), Major and others (1975), McGovern and Jenkins (1966), McLaughlin (1946), and Smith and others (1964).

Water-Yielding Characteristics

Transmissivity of the alluvial aquifers as described in Bjorklund and Brown (1957), Borman (1981), Hurr and others (1972), Hurr and Schneider (1972a and 1972b), Jenkins (1964), Konikow (1975), McConaghy and others (1964), McGovern and Jenkins (1966), McLaughlin (1946), Owens (1967), Smith and others (1964), and Wilson (1965) ranges from about 1,300 ft^2/d to as much as 67,000 ft^2/d. The large transmissivity values commonly occur in the thicker part of the aquifers where the sediments are well-sorted coarse sand and gravel. The smaller saturated thickness and less well-sorted materials near the margins of the aquifers account for the smaller transmissivity values in these areas. Well yields generally correspond to the zones of differing transmissivity. For equal drawdown, a well completed in a very transmissive zone can yield more water than a similar well completed in a lesser transmissive zone. Yields of 50 to 1,000 gal/min are common in the central parts of the principal alluvial aquifers. Yields for selected wells are shown in Bjorklund and Brown (1957), Borman (1981), Gregg and others (1961), Hillier and Hutchinson (1980a), Hillier and Schneider (1979a), Jenkins (1961a, 1961b), McConaghy and others (1964), McGovern and Jenkins (1966), McLaughlin (1946), Owens (1967), Schneider (1962), Smith and others (1964), and Wilson (1965).

The specific yield of the alluvial aquifers has been estimated to range from about 0.1 to 0.3. These estimates are documented in Bjorklund and Brown (1957), Code (1945), Jenkins (1964), McConaghy and others (1964), and Smith and others (1964), and are based on either laboratory analysis or field techniques. Large values of specific yield commonly are associated with the more coarse-grained aquifer materials, which also are more permeable. In fine sand, silt, or clay, specific yield and permeability generally are less. The well logs shown in Borman (1981), Jenkins (1961a, 1961b), McConaghy and others (1964), McLaughlin (1946), and Schneider (1962) provide a general description of the type material penetrated during drilling of wells in alluvial aquifers and provide a means of judging the relative permeability and specific yield of the aquifer.

Recharge and Discharge

Recharge to the alluvial aquifers primarily occurs from surface sources, because the rate of recharge from the underlying bedrock aquifers is limited by low potentiometric gradient and lesser transmissivity of these aquifers.

Principal surface-recharge sources include infiltration of precipitation and applied irrigation water, and leakage from the channels of flowing streams, irrigation canals, and lakes. Aquifers that extend beyond the limit of the study area also may either receive recharge from, or discharge to, adjacent alluvial aquifers outside the study area by means of underflow.

Pumpage and ground-water discharge to gaining streams such as the South Platte River are the principal means of discharge for the aquifers. The number of wells currently producing water from the alluvial aquifers in the area is not known. Smith and others (1964) state that about 1,700 large-capacity irrigation, municipal, and industrial wells were located in the South Platte River valley between Denver and Kuner in 1958. More recent tabulations of the number of registered wells in the study area indicate that about 5,000 wells of all sizes may be located in the area. Other sources of ground-water discharge include evapotranspiration in areas of shallow water table and intermittent discharge to stream channels and ponds.

Water budgets have been calculated for various parts of the alluvial-aquifer system. These budgets generally show the quantity, and in some cases distribution, of recharge and discharge for the aquifer segment. References containing these partial water budgets include Bjorklund and Brown (1957), Code (1945), Duke and Longenbaugh (1966), Erker and Romero (1967), Jenkins (1964), Owens (1967), and Smith and others (1964).

Water Quality

Water with the smallest dissolved-solids concentrations most commonly occurs in the upstream reaches of the alluvial aquifers near sources of natural recharge. As the water moves downgradient, recharge from pumped water applied to irrigated fields introduces additional dissolved minerals into the aquifer, and the chemical quality of the ground water is degraded. Dissolved-solids concentrations commonly range from 100 to 500 mg/L in the upstream reaches of the aquifers to more than 2,500 mg/L in the downstream reaches in Weld and Morgan Counties. The irrigation pumpage and recharge cycle, combined with recharge of better quality water from canals and streams, produces substantial differences in water quality in local areas in the downvalley parts of the aquifers. Water in the alluvial aquifer normally is either a calcium bicarbonate or calcium sulfate type and ranges from hard to very hard.

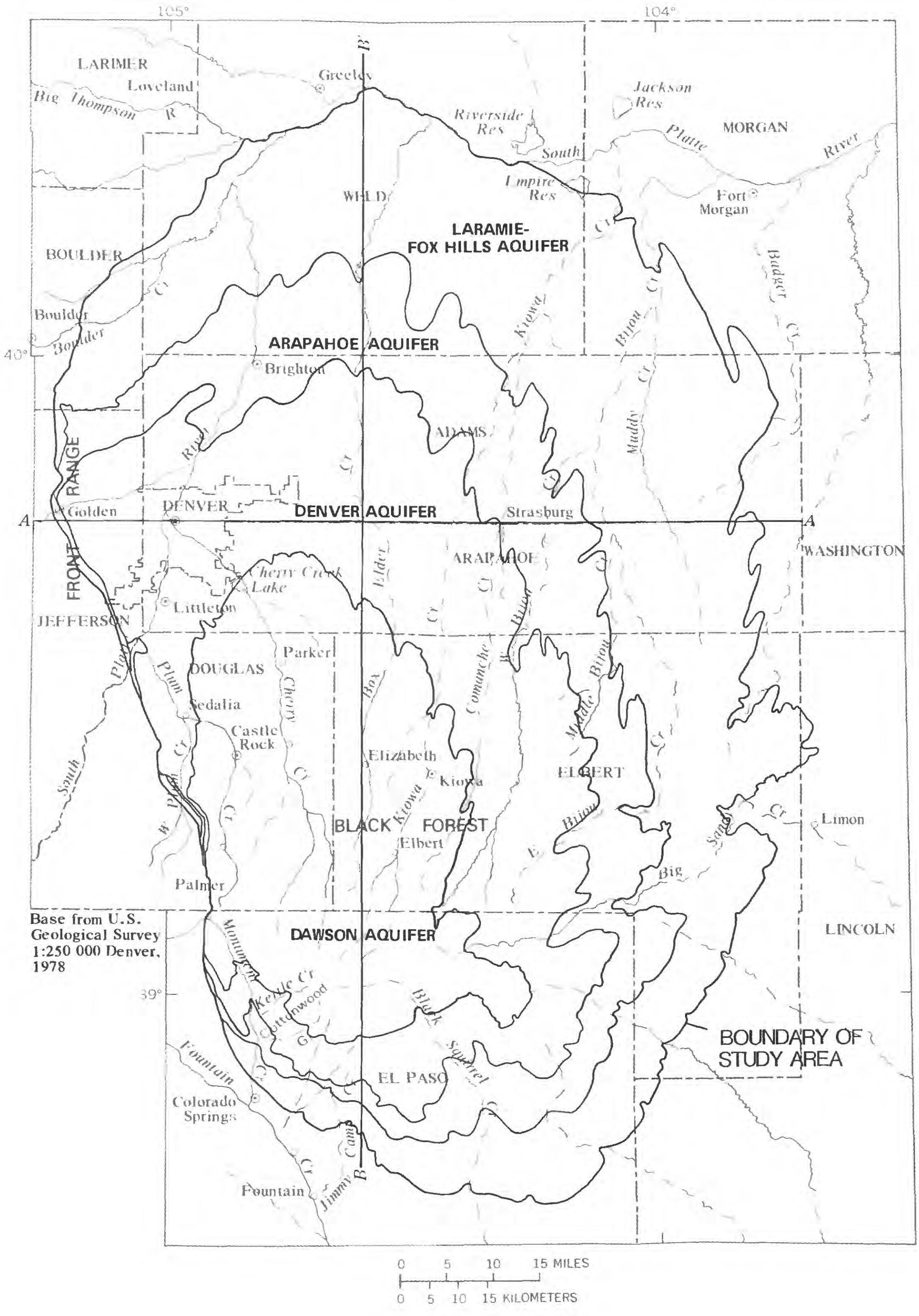
Borman (1981), Hillier and Hutchinson (1980a), Hillier and Schneider (1979a), Livingston and others (1976), Smith and others (1964), and U.S. Department of the Interior, Federal Water Pollution Control Administration (1967) contain maps or hydrographs of dissolved-solids concentrations for some parts of the aquifers. These reports combined with the chemical analyses presented in Bjorklund and Brown (1957), Borman (1981), Gregg and others (1961), Hall and others (1979), Hillier and Hutchinson (1980a), Hillier and others (1979), Hillier and Schneider (1979a), Hutchinson and Hillier (1979), Jenkins (1961a and 1961b), Jenkins (1964), McConaghy and others (1964), McGovern and Jenkins (1966), McLaughlin (1946), Robson (1977), Schneider (1962), Schneider and Hillier (1978), Smith and others (1964), and U.S. Department of the Interior (1967) provide the basis for water-chemistry evaluation. Studies involving more extensive interpretation of the geochemistry of the alluvial aquifers are documented in Bjorklund and Brown (1957), Borman (1981), Jenkins (1964), Livingston and others (1976), McLaughlin (1946), Robson (1977), Smith and others (1964), and U.S. Department of the Interior, Federal Water Polution Control Administration (1967).

Bedrock Aquifers

The four major bedrock aquifers occurring in the study area are the Laramie-Fox Hills aquifer (the deepest aquifer), the Arapahoe aquifer, the Denver aquifer, and the Dawson aquifer (fig. 29). The Dawson aquifer is the least extensive of the four, underlying an area of about 1,200 mi^2 between Denver and Colorado Springs. The Laramie-Fox Hills aquifer is the most extensive in the Denver ground-water basin, underlying an area of about 6,700 mi^2 extending from Greeley in the north to Colorado Springs in the south, and from the Front Range in the west to near Limon in the east (fig. 29). These aquifers are the primary source of water for rural residents in the study area. Most of the estimated 12,000 wells completed in these aquifers supply water to residents and livestock. Little water for irrigation of commercial crops is supplied from the bedrock aquifers.

The geologic formations containing the four aquifers are the Fox Hills Sandstone, the Laramie and Arapahoe Formations of Late Cretaceous age, the Denver Formation of Late Cretaceous and Early Tertiary age, and the Dawson Arkose of Tertiary age. These formations occur in a sequence of layers as shown by the generalized geologic sections drawn from west to east and from south to north through the region (fig. 30). The northern, eastern, and southern parts of the region form a shallow bowl, the sides of which dip gently toward the west-central part of the region. Along the western edge of the region, sedimentary formations are upturned along the Precambrian crystalline rocks of the Front Range and dip steeply to the east as a result of faulting and folding produced by the gradual upward movement of the Rocky Mountains. The Pierre Shale of Late Cretaceous age underlies the Fox Hills Sandstone and is considered to be the base of the bedrock-aquifer system. Two principal coal-bearing zones occur, one in the upper part of the Laramie Formation and the other in the upper part of the Denver Formation.

The sediments that form the Dawson aquifer primarily consist of conglomerate, sandstone, and shale varying from light gray to yellowish brown, with beds of pale green shale in some areas. The conglomerates and sandstones generally are coarse grained and poorly to moderately well consolidated. In most of the aquifer in Arapahoe, Douglas, and Elbert Counties, a layer of shale 100 to 250 ft thick separates an upper and lower sequence of conglomerate, sandstone, and minor beds of shale. In the southern part of the aquifer, the intervening shale is absent and conglomerate, sandstone, and minor beds of shale occur in a continuous sequence 600 ft or more thick. Individual conglomerate and sandstone beds are commonly lens shaped and range in thickness from a few inches to as much as 200 ft. Conglomerate and sandstone beds that are penetrated by one well may be of a different thickness or absent in an adjacent well because of this lens-shaped layering.



Base from U.S. Geological Survey 1:250 000 Denver, 1978

Figure 29.--Approximate location and extent of bedrock aquifers. (Sections presented in figure 30.)

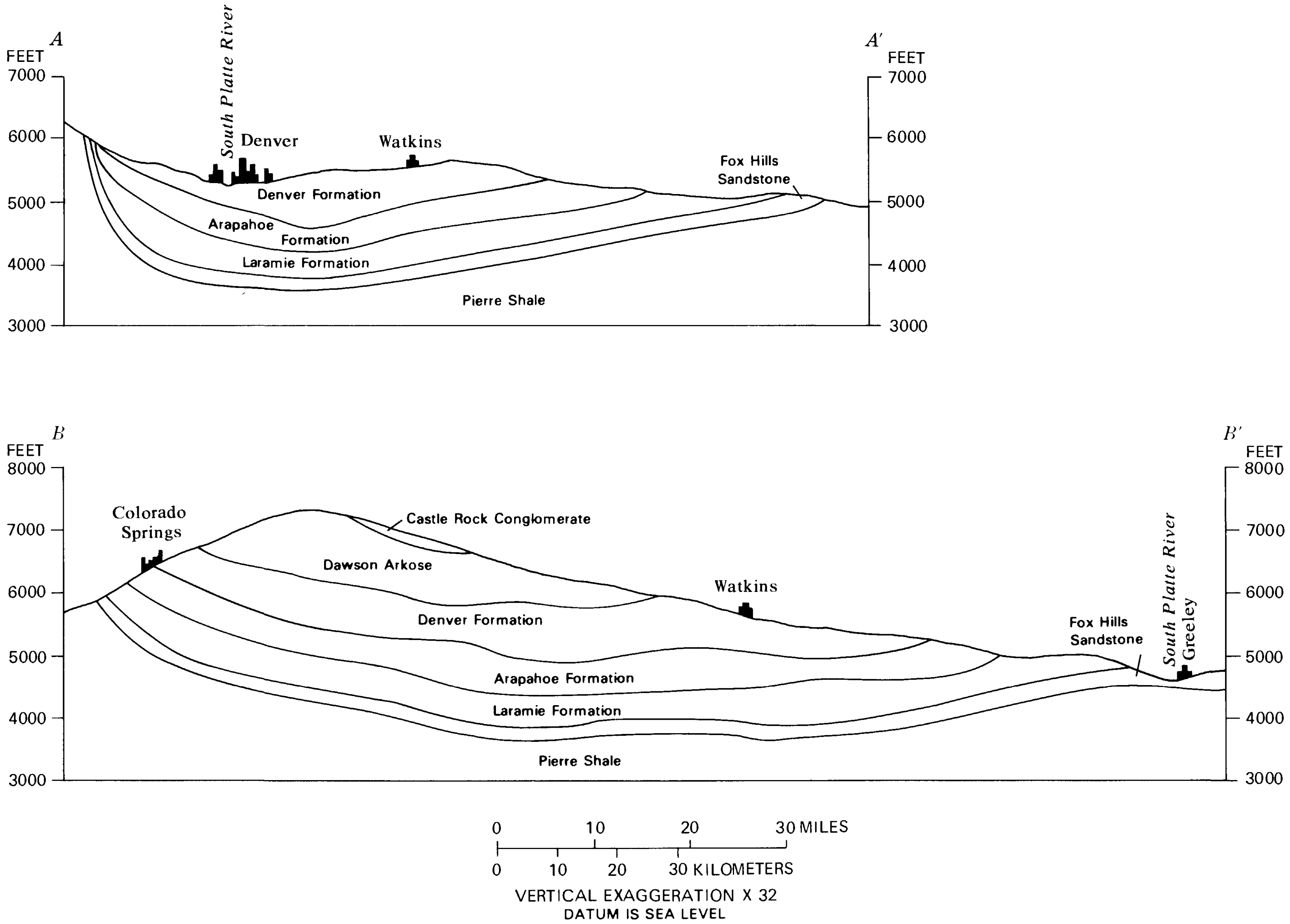


Figure 30.--Generalized geologic sections. (Line of sections located in figure 29.)

The Denver Formation consists of a 600- to 1,000-ft thick series of interbedded shale, claystone, siltstone, and sandstone in which coal and fossilized plant remains are common. Distinguishing characteristics of the formation are its olive, green-gray, brown, and tan colors; the presence of coal; and the preponderance of shale and claystone with respect to other rock types. The predominant olive and green-gray colors in the formation are due to the presence of iron-rich sediments derived from erosion of basaltic and andesitic lavas and distinguish Denver rocks from the generally lighter colored rocks found in the overlying Dawson Arkose and the underlying Arapahoe Formation. Water-yielding layers of sandstone and siltstone occur in poorly defined, irregular beds that are dispersed through relatively thick sequences of claystone and shale. Individual sandstone and siltstone layers commonly are lens shaped and range in thickness from a few inches to as much as 50 ft.

The Arapahoe Formation consists of a 400- to 700-ft thick series of interbedded conglomerate, sandstone, siltstone, and shale. Shale is more prevalent in the northern one-third of the formation. In some areas, the formation can be subdivided into an upper and lower part. The upper part commonly consists of 200 to 300 ft of shale with some conglomerate and sandstone beds, whereas the lower part consists of 200 to 300 ft of sandstone and conglomerate with less prevalent beds of shale. The conglomerate, sandstone, and siltstone normally are light to medium gray with local very light gray and grayish-green beds. These colors generally are darker in the upper 100 to 200 ft of the formation near its boundary with the overlying Denver Formation. Shales normally are medium gray and silty. The larger proportion of conglomerate and sandstone with respect to shale, the absence of significant carbonaceous beds, and a generally lighter color distinguish the Arapahoe Formation from the underlying Laramie Formation and the overlying Denver Formation. Individual conglomerate and sandstone beds in the Arapahoe Formation commonly are lens-shaped, moderately consolidated, and range in thickness from a few inches to 30 or 40 ft. The beds may be so closely spaced that they form a single hydrologic unit that is 200 to 300 ft thick in some areas.

The Laramie-Fox Hills aquifer occurs in the lower sandstone units of the Laramie Formation and the upper sandstone and siltstone units of the underlying Fox Hills Sandstone. The thickness of the Laramie-Fox Hills aquifer varies from zero near the aquifer boundary to between 200 and 300 ft in the central part of the aquifer. In the northwest part of the basin near Boulder County, numerous local faults have offset the strata in the Fox Hills Sandstone and Laramie Formation. Faulting may have occurred in part during deposition of these formations, for marked changes in bedding thickness have been observed across some fault zones. In some cases, marked differences in hydrologic characteristics occur over short distances near these faults. Results presented in Robson and others (1981a and 1981b) and Romero (1976) describe the general geologic and hydrologic conditions in this area but do not show details of local conditions. Colton and Lowrie (1973) and Weimer (1973) provide better definition of the location and extent of the faulting in this area.

The part of the Laramie-Fox Hills aquifer within the Fox Hills Sandstone generally is 150 to 200 ft thick and is composed of an overlying bed of very fine grained silty sandstone 40 to 50 ft thick underlain by 100 to 150 ft of shaly siltstone and interbedded shale. The part of the Laramie-Fox Hills aquifer within the Laramie Formation generally is 50 to 100 ft thick and is composed of very fine to medium-grained sandstone with interstitial siltstone and clay. Locally, the sandstone is separated into upper and lower members by interceding shale beds 10 to 20 ft thick. A shale bed 5 to 20 ft thick commonly separates the Laramie part of the aquifer from the Fox Hills part.

The 400 to 500 ft of Laramie Formation overlying the Laramie-Fox Hills aquifer form an upper boundary layer for the aquifer. Laramie strata above the aquifer are composed of gray through black shale, coal seams, and minor gray siltstone and sandstone. The lowermost coal seams are useful in identifying the upper limit of the aquifer. The subbituminous to lignitic coal seams range in thickness from a few inches to about 10 ft and are present in several stratigraphic horizons. These seams have been extensively mined along the northwest and southwest margin of the Laramie Formation. The locations of about 300 abandoned or inactive coal mines in these two areas are shown in Colton and Lowrie (1973) and Kirkham (1978). The Pierre Shale underlies the Fox Hills Sandstone and consists of 5,000 to 8,000 ft of shale with minor layers of siltstone and sandstone. The Pierre Shale forms the base of the Laramie-Fox Hills aquifer.

The geologic structure of the top and the bottom of the aquifers, the depth to the base of the aquifer, and the aggregate thickness of water-yielding materials in the aquifers are mapped throughout the Denver basin by Robson and Romero (1981a and 1981b) and Robson and others (1981a and 1981b). Additional or more detailed discussion of the thickness, location, and extent of the aquifers may be found in Erker and Romero (1967), Hillier and others (1978), Hurr (1976), Livingston and others (1975 and 1976), Romero (1976), Romero and Hampton (1972), Schneider (1980), and Varnes and Scott (1967).

Water Levels

Water in the bedrock aquifers generally is confined by overlying and underlying shale and clay strata of low permeability. As a result, the water level in a well may be considerably above the level of the water-yielding strata. Near Aurora, for example, the top of the Laramie-Fox Hills aquifer occurs at a depth of 1,500 ft, but the depth to water in nearby wells completed in the aquifer is only about 250 ft. Depths to water in the bedrock aquifers thus reflect the varying pressure (heads) encountered in strata of different depths at different times. Prior to about 1885, heads in the Denver Arapahoe, and Laramie-Fox Hills aquifers were large enough to cause wells completed in bedrock underlying the valley of the South Platte River near Denver to flow with considerable pressure at the land surface (Emmons and others, 1896). The rapid decline in water level in one of these wells completed in the Arapahoe aquifer is shown in figure 31. The water level in this well has ranged from about 60 ft above land surface in 1883 (a flowing well) to as much as 340 ft below land surface in 1960. Depths to water in the bedrock aquifers currently range from near zero in some low-lying undeveloped areas to more than 1,000 ft in other areas. Principal sources for water-level data for bedrock wells include the files of the U.S. Geological Survey, Gregg and others (1961), Jenkins (1961b), Major and others (1983), McConaghy and others (1964), Schneider (1980), and Varnes and Scott (1967).

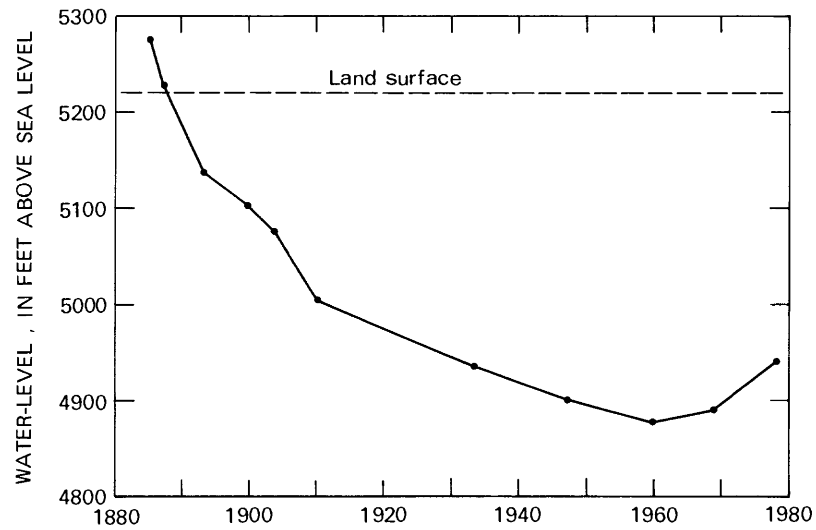


Figure 31.--Water level in a well completed in the Arapahoe aquifer near the State Capitol building.

In 1978 the altitude of the potentiometric surface in the Dawson aquifer ranged from a high of 7,500 ft in the area near Black Forest to a low of 5,500 ft near Englewood. A ridge in the potentiometric surface is located near a line from Palmer Lake to Rattlesnake Butte and forms a ground-water divide. Ground water north of the divide moves in a northerly direction, whereas ground water south of the divide moves in a southerly direction. The altitude of the potentiometric surface and the direction of water movement are controlled primarily by the altitude of the stream channels in the area, the hydrologic properties of the aquifer, and the magnitude and disribution of precipitation. This occurs because the rate of precipitation recharge to the Dawson aquifer generally exceeds the ability of the aquifer to transmit water long distances. The excess ground water is discharged to nearby streams, allowing the altitude of the stream channels to affect the altitude of the potentiometric surface and the direction of the ground-water movement. As a result, the areas with the highest land-surface altitude (near the Black Forest, for example) also have the highest potentiometric-surface altitude. In addition, more water is available for recharge in these high areas because more precipitation generally occurs at the higher altitudes.

In most of the northwestern part of the Dawson aquifer, water-level changes have ranged from 50 ft of rise to 50 ft of decline from 1958 to 1978. However, water-level declines near Castle Rock and Parker have exceeded 100 ft, and near Cherry Creek Reservoir declines have exceeded 200 ft. The 1958-78 water-level-change data from wells at a few scattered locations in other parts of the Dawson aquifer generally show water-level rises or declines of less than 30 ft with no consistent pattern in these areas. Erker and Romero (1967), Livingston and others (1975 and 1976), Robson and Romero (1981a), and Romero (1976) provide additional descriptions and mapping of the potentiometric surface in the Dawson aquifer. It should be noted that various authors have used the term "Dawson Formation" or "Dawson aquifer" to refer to different bedrock strata. In older usage, the strata above the Laramie Formation were called the Dawson Formation. More recent usage recognizes these strata as the Dawson Arkose, the Denver Formation, and the Arapahoe Formation.

In 1978, the measured part of the potentiometric surface in the Denver aquifer ranged in altitude from a high of 6,800 ft in the southern part of the aquifer to a low of 5,000 ft near Commerce City (pl. 2). In the northern, eastern, and southern parts of the aquifer, water generally is moving from the south-central part of the area toward the margins of the aquifer. Relatively sharp bends in the potentiometric contours occur near some small streams as a result of water moving from the aquifer into the stream valleys. Near the western edge of the aquifer, water is moving either approximately parallel to the aquifer limit or is moving east from the aquifer limit toward the South Platte River. Ground water flows into a major trough in the potentiometric surface extending along Plum Creek and the South Platte River to the area northeast of Commerce City (pl. 2). The trough originally was shallower, being formed by the natural discharge of ground water into the South Platte River and its tributaries, but it has been deepened during the past 100 years by the pumpage in the Denver metropolitan area.

Between 1958 and 1978, water-level decline in the Denver aquifer exceeded 200 ft in a 40-mi^2 area east of Denver, and declines exceeding 50 ft have occurred in large areas along the eastern and southern edge of the metropolitan area. Water-level rises of as much as 100 ft have occurred in the central part of the metropolitan area and are due to a decrease in pumping in this area since 1958. Near Cherry Creek Reservoir the water level in the Denver aquifer rose more than 50 ft between 1958 and 1978, probably as a result of recharge from the reservoir. The water-level-change data from wells at a few scattered locations in other parts of the Denver aquifer generally show water-level rises or declines of less than 50 ft with no consistent pattern in these areas. Robson and Romero (1981b), Romero (1976), and Varnes and Scott (1967) provide additional information pertaining to the potentiometric surface in the Denver aquifer.

In the Arapahoe aquifer, the measured part of the 1978 potentiometric surface ranged in altitude from a high of 6,500 ft in the southern part of the aquifer to a low of 4,900 ft near Brighton. In the central part of the aquifer, reliable water-level data for the Arapahoe aquifer are unavailable and the potentiometric surface cannot be accurately defined in this area. In the northern, eastern, and southern parts of the aquifer, water generally is moving from the south-central part of the area toward the margins of the aquifer. Near the western edge of the aquifer, water is moving either approximately parallel to the aquifer limit or is moving east from the aquifer limit toward the South Platte River. Ground water flows from the west, northwest, and southeast into a major trough in the potentiometric surface extending along the South Platte River to an area northeast of Brighton. The trough was originally shallower prior to extensive pumping in the area and has been deepened and expanded by pumping during the past 100 years.

Water-level declines in the Arapahoe aquifer have exceeded 200 ft in the 135-mi^2 area southeast of Denver and have exceeded 50 ft in a much larger but less well defined area. Water-level rises have exceeded 100 ft in a 60-mi^2 area under the north-central part of the Denver metropolitan area, whereas in other parts of this area only moderate water-level changes have occurred. This pattern of water-level change is the likely result of a decrease in the rate of pumping in the metropolitan area coupled with an increase in pumping in the surrounding suburban areas. The 1958 to 1978 water-level-change data for wells at a few scattered locations and other parts of the Arapahoe aquifer generally show water-level rises or decines of less than 50 ft with no consistent pattern in these areas. Other sources of mapping and discussion of the potentiometric surface in the Arapahoe aquifer include Hillier and others (1978), Hurr (1976), Robson and others (1981a), Romero (1976), and Varnes and Scott (1967).

The 1978 altitude of the measured potentiometric surface in the Laramie-Fox Hills aquifer is highest (6,300 ft) in the southern part of the aquifer and lowest (4,700 ft) in the area extending from Brighton to Wiggins. In the central part of the aquifer, reliable water-level data for the Laramie-Fox Hills aquifer are unavailable, and the potentiometric surface cannot be accurately defined. North of El Paso County water generally is moving to the north or northeast, whereas south of the northern El Paso County line water generally is moving to the south or southeast. In and near Boulder County, local faulting appears to have segmented the aquifer and allowed markedly different water levels to occur in adjacent segments. The resulting potentiometric surface is distorted near these segments, and the direction of water movement in this area is complex. More detailed maps of the potentiometric surface and additional discussion of the hydrology in this area are contained in Schneider (1980). In the northwestern part of the Denver basin, ground water in the Laramie-Fox Hills aquifer moves toward a major trough in the potentiometric surface. This trough extends from Littleton through Northglenn and Brighton and northeast toward Masters. A similar, but less extensive trough is shown (Romero, 1976) to be present in this area in 1970. The trough has been formed by pumpage from wells in the area and has expanded and deepened as withdrawals have increased.

Water-level declines have occurred in the Laramie-Fox Hills aquifer between 1958 and 1978. In an 80-mi^2 area near Brighton, water levels declined more than 200 ft with more than 300 ft of decline in part of this area. Declines in excess of 100 ft have occurred in an area extending from Westminster to Superior to Hudson, and in the area near Littleton and Aurora. Water-level-change data from wells at a few scattered locations in other parts of the aquifer generally showed water-level rises or declines of less than 50 ft with no consistent pattern in these areas. Potentiometric-surface maps and additional discussion of the hydrology of the aquifer are contained in Hurr (1976), Robson and others (1981b), Romero (1976), Schneider (1980), and Varnes and Scott (1967).

Water-Yielding Characteristics

The hydraulic conductivity of the bedrock aquifers ranges from about 0.05 to 15 ft/d with variations due to the depth and location of the wells. In the Dawson aquifer, hydraulic conductivity commonly ranges from 0.2 to 3.0 ft/d. In the Denver aquifer, values between 0.5 and 1.5 ft/d are common. The Arapahoe aquifer contains the most permeable water-yielding material in the basin with hydraulic conductivity commonly ranging from 0.5 to 7 ft/d. The largest values of hydraulic conductivity occur in a 600-mi^2 area of the Arapahoe aquifer extending from Castle Rock to Brighton. Hydraulic conductivity for the Laramie-Fox Hills aquifer commonly ranges from 0.5 to 2.0 ft/d. However, the aquifer is much less permeable in an area extending from Platteville to Lakewood. In this area, hydraulic-conductivity values between 0.05 and 0.3 ft/d are common.

Transmissivity of the aquifers varies in a pattern similar to that for hydraulic conductivity. Transmissivity values range from zero at the edge of the aquifers to as much as 1,200 ft^2/d in the Dawson aquifer, 400 ft^2/s in the Denver aquifer, 2,100 ft^2/s in the Arapahoe aquifer, and 1,000 ft^2/d in the Laramie-Fox Hills aquifer. Aquifer-test data used to evaluate water-yielding characteristics primarily are contained in the files of the U.S. Geological Survey and in Hillier and others (1978), Livingston and others (1975), Major and others (1983), McConaghy and others (1964), Robson (1982), Romero (1976), Varnes and Scott (1967), and Wilson (1965). Mapping of hydraulic conductivity or transmissivity, or additional discussion of these characteristics, is contained in Robson (1982), Romero (1976), and Varnes and Scott (1967).

The storage coefficient and specific yield of the aquifers are less well defined than are the hydraulic conductivity and transmissivity. Storage coefficients in the confined parts of the aquifers are estimated to range from about $2\mathrm{x}10^{-4}$ to $8\mathrm{x}10^{-4}$. Specific yield of the unconfined parts of the aquifers are estimated to range from about 0.1 to 0.2. McConaghy and others (1964), Robson (1982), Romero (1976), Varnes and Scott (1967), and Wilson (1965) contain estimates of specific yield and storage coefficient with storage-coefficient mapping shown in Robson (1982).

Recharge and Discharge

Part of the precipitation that falls in the study area percolates to depth and recharges the bedrock aquifers. In the outcrop area of the formations, recharge occurs as deep infiltration of precipitation in the highland areas between stream channels or as infiltration of water from alluvial aquifers located above the water level in the bedrock aquifers. In the central part of the basin, downward movement of water from overlying bedrock aquifers probably is an important source of recharge to underlying aquifers. The rate of vertical movement is thought to be small in comparison to the rate of lateral movement, and in the case of the Laramie-Fox Hills aquifer, vertical movement through the thick shales of the Laramie Formation may be insignificant. Most water moves laterally through the permeable sandstone strata from areas of recharge towards areas of discharge. This occurs on both a local and regional scale. On a local scale, water moves from the highland recharge areas in the outcrop through the upper (near-surface) part of the aquifer, or through perched aquifers, to the discharge areas in nearby stream valleys. On a regional scale, water moves from outcrop recharge areas, or the central part of the study area, into the aquifer and ultimately discharges in more remote stream valleys. In the stream valleys, water from the bedrock discharges into the streams, into the alluvial aquifers along the stream channels, or is consumed by vegetation growing in the valleys.

In addition to the above long-standing processes of natural recharge and discharge, relatively recent discharge is occurring from pumping wells. In areas where pumping has caused significant water-level declines, natural discharge no longer may occur and pumpage may be the only form of ground-water discharge. In these areas, the interaquifer movement of water may be enhanced, halted, or reversed, depending on the relation of the hydrostatic heads in adjacent aquifers. Yield from bedrock wells is quite variable. Yields of a few gallons per minute can be expected from domestic or stock wells, or from municipal and industrial wells located in areas of lesser transmissivity. Yields of 800 gal/min may be obtained from large municipal or industrial wells in areas of greater transmissivity.

In 1981, the U.S. Geological Survey began construction of several ground-water-flow models of the bedrock aquifers in the Denver basin. A water budget based on the three-dimensional, steady-state model of the aquifer system indicates that total recharge and discharge for the system was 54.7 ft^3/s (Robson, 1984). The steady-state model simulates long-term average flow conditions and does not consider temporal changes in hydrologic conditions, such as pumpage or annual variations in precipitation. The regional-scale recharge and discharge from the four principal bedrock aquifers are shown in table 11. Local scale recharge and discharge is not considered in the model, for its inclusion would not be representative of the effective recharge to the aquifers. Additional information pertaining to recharge and discharge for the bedrock aquifers may be found in Livingston and others (1975 and 1976) and Romero (1976).

Water Quality

Water-quality analyses have been performed on samples from a large number of bedrock wells in the Denver coal region. Some of these analyses are available from the files of the U.S. Geological Survey or are published in Bjorklund and Brown (1957), Gregg and others (1961), Hillier and others (1978), Jenkins (1961b), Major and others (1983), McConaghy and others (1964), McLaughlin (1946), Romero (1976), Schneider (1962), Schneider (1980), Smith and others (1964), U.S. Department of the Interior, Federal Water Pollution Control Administration (1967), and Varnes and Scott (1967). Interpretive reports containing water-quality maps or discussion of water-quality conditions are available. Among these reports are Bjorklund and Brown (1957), Hillier and others (1978), Livingston and others (1975), Livingston and others (1976), McLaughlin (1946), Robson and others (1981a and 1981b), Robson and Romero (1981a and 1981b), Romero (1976), Schneider (1980), Smith and others (1964), U.S. Department of the Interior, Federal Water Pollution Control Administration (1967), and Varnes and Scott (1967). The following discussion is based primarily on the information in Robson and Romero (1981a and 1981b) and Robson and others (1981a and 1981b).

Table 11.--*Regional water budget for the bedrock aquifers*

[All values in cubic feet per second]

Source	Aquifer				Total
	Dawson	Denver	Arapahoe	Laramie-Fox Hills	
Precipitation recharge	40.6	5.5	2.8	5.8	54.7
Discharge to principal drainage area					
Plum Creek	6.1	1.1	0.3	---	7.5
Cherry Creek	10.3	.2	---	---	10.5
South Platte River	.3	2.2	2.4	0.5	5.4
Box Elder Creek	2.6	.2	.9	.1	3.8
Lost Creek	----	.1	.6	.2	.9
Kiowa Creek	5.9	.2	.2	.7	7.0
Bijou Creek	.6	2.1	2.1	2.1	6.9
San Arroyo and Badger Creeks	----	---	---	1.1	1.1
Big Sandy Creek	.2	.3	.5	.2	1.2
Rush and Steel Fork Creeks	----	---	.1	.5	.6
Black Squirrel Creek	.4	.7	.5	.2	1.8
Monument and Fountain Creeks	7.0	.3	.5	.2	8.0
Total Discharge	33.4	7.4	8.1	5.8	54.7

Water in the Dawson aquifer generally is suitable for all uses, meeting drinking-water standards (U.S. Environmental Protection Agency, 1976 and 1977; and Colorado Department of Health, 1978) for public water supplies in most of the area. The water generally contains a preponderance of dissolved calcium and bicarbonate ions and thus is classified as a calcium bicarbonate type water. Sodium bicarbonate or sodium sulfate type water occurs in a few isolated areas. Dissolved-solids concentrations range from less than 100 mg/L in the south-central part of the aquifer to more than 1,500 mg/L near the northern edge of the aquifer. Dissolved-solids concentrations and the pH of the water are least near the ground-water divide in the area between Palmer Lake and Rattlesnake Butte. Dissolved-iron concentrations generally range from 20 to 100 μg/L (micrograms per liter), which is less than the limit of 300 μg/L recommended for public water supplies (U.S. Environmental Protection Agency, 1977). Dissolved-iron concentrations between 8,000 and 85,000 μg/L occur in water from a few scattered wells. Dissolved-sulfate concentrations commonly range from 4 to 10 mg/L in the central part of the aquifer to more than 700 mg/L in an isolated area at the northern margin of the aquifer.

Water in the Denver aquifer also generally is suitable for all uses, meeting drinking-water standards (U.S. Environmental Protection Agency, 1976 and 1977; and Colorado Department of Health, 1978) for public water supplies in most of the area. Water in the central part of the aquifer is classified as a calcium bicarbonate type. Near the margins of the aquifer, a sodium bicarbonate or sodium sulfate type water is more common. The calcium bicarbonate water occurs as a result of the calcium bicarbonate water in the overlying Dawson aquifer moving down into the Denver aquifer. As the calcium bicarbonate water moves laterally through the Denver aquifer, the water is naturally softened by cation exchange on the clay minerals that abound in this predominantly silty and clayey formation. This process increases the dissolved-sodium concentration in the water while decreasing the dissolved-calcium concentration. As the water in the Denver aquifer moves beyond the limit of the overlying Dawson aquifer, other factors affect the chemical composition of the water. In the outcrop areas, the availability of oxygen in the soil and in the shallow bedrock can cause the formation of soluble minerals in these sediments and in the coal and other organic material that commonly occur in the formation. Part of the precipitation that falls on the outcrop area percolates to depth, transporting some of these soluble minerals from the soil, rock, and coal into the aquifer. This process, coupled with the cation exchange, produces the sodium bicarbonate or sodium sulfate type water found near the margins of the aquifer. Dissolved-solids concentrations are less in the central part of the aquifer, near the source of recharge from the overlying Dawson aquifer. The concentrations of dissolved solids increase as much as 1,000 mg/L as the water moves toward the north, east, and south margins of the aquifer (pl. 3). Dissolved-iron concentrations generally range from 10 to 150 µg/L; however, concentrations as much as 6,600 µg/L occur in water from a few widely scattered wells. Measured concentrations of dissolved sulfate range from 2 mg/L in the central part of the aquifer to as much as 2,700 mg/L in the northern part of the aquifer. Concentrations in excess of 250 mg/L occur in a 300-mi^2 area along the northern margin of the aquifer and in a few isolated areas in the southern part of the aquifer.

Water in the Arapahoe aquifer generally is suitable for all uses, meeting drinking-water standards (U.S. Environmental Protection Agency, 1976 and 1977; and Colorado Department of Health, 1978) for public water supplies in most of the area. The water is classified as a sodium bicarbonate type. Calcium bicarbonate type water also occurs in the aquifer at scattered locations and in the area between Sedalia and Colorado Springs. Water in the Arapahoe aquifer generally is similar in type to that found in the overlying Denver aquifer, possibly due to the downward movement of water from the Denver aquifer to the Arapahoe aquifer. Dissolved-solids concentrations of water are less in the central part of the aquifer, near the source of recharge from the overlying Denver aquifer. The concentrations increase to more than 2,000 mg/L in some areas as the water moves toward the margins of the aquifer. This occurs as the result of soluble minerals being transported into the aquifer from near-surface sources. Dissolved-iron concentrations generally range from 20 to 200 µg/L, with concentrations as much as 6,500 µg/L in a few widely scattered wells. In areas of significant reducing conditions in the aquifer, sulfate minerals and organic material may be reduced to hydrogen sulfide and methane gases. When these gases are present in large concentrations, water pumped from the aquifer may effervesce, have a putrid odor, and be of marginal value for many uses. Dissolved-sulfate concentrations in excess of 250 mg/L occur in a 500-mi^2 area along the east margin of the aquifer and in a 350-mi^2 area along the northwest margin of the aquifer. Measured concentrations of dissolved sulfate range from 5 mg/L in the southeastern part of the aquifer to as much as 1,500 mg/L near the northern margin of the aquifer.

Water in the Laramie-Fox Hills aquifer generally is classified as a sodium bicarbonate type with sodium sulfate type water found along the northern and eastern margins of the aquifer. Dissolved-solids concentrations seem to be less in the central part of the aquifer and increase to more than 1,200 mg/L in four areas near the northern and eastern margins of the aquifer. In each of these areas, the Laramie-Fox Hills aquifer is overlain by the shaly upper part of the Laramie Formation and is beyond the edge of the overlying Arapahoe aquifer. When the direction of ground-water movement is considered, it appears that poor-quality water in these areas occurs as a result of soluble minerals being transported into the aquifer from surface sources or from sources within the upper part of the Laramie Formation. Dissolved-iron concentraions generally range from 20 to 200 μg/L with concentrations of 42,000 and 79,000 μg/L in two wells near Colorado Springs. Concentrations of about 1,000 μg/L have been found at a few other widely scattered wells. In areas of significant reducing conditions in the aquifer, sulfate minerals and organic material may be reduced to hydrogen sulfide and methane gases. When these gases are present in large concentrations, water pumped from the aquifer may effervesce, have a putrid odor, and be of marginal value for most uses. Dissolved-sulfate concentrations in excess of 250 mg/L occur in five areas located near the northern, eastern, and southern margins of the aquifer. Concentrations range from less than 2 mg/L south of Denver to more than 1,200 mg/L near Frederick.

SUMMARY

Available hydrologic and geologic information for the Denver coal region are tabulated and discussed, and references providing important sources of data and interpretations are cited in order to provide a comprehensive review of the existing hydrologic information of the study area.

A continental climate occurs in the area and is characterized by 12 to 19 in. of mean annual precipitation, large daily temperature fluctuations, low humidity, and moderately high winds.

There are 35 streamflow-gaging stations located in the area. Data from these stations were used to construct 15 flood-probability curves for: (1) The South Platte River main stem, (2) major tributaries to the South Platte River, and (3) plains tributaries to the South Platte River. Flow at some of these stations may be substantially altered by manmade factors; as a result, some of the flood-probability curves probably do not show natural-flow conditions in the streams. Maximum instantaneous discharge measured at selected stations ranges from 2 to 1,451 $(ft^3/s)/mi^2$ of drainage area. The larger values occur in the streams with relatively small drainage areas in the plains part of the study area, and the smaller values occur along the South Platte River. A maximum instantaneous discharge of 154,000 ft^3/s occurred on Plum Creek near Louviers in 1965. Low flows at the stations range from zero at many of the plains-tributary stations to 57.8 ft^3/s at the South Plate River near Weldona.

Selected water-chemistry data have been analyzed at seven stations in the study area. Empirical relations developed between specific conductance and dissolved-solids concentration, the major cation concentrations, and the major anion concentrations indicate that specific conductance can be used as an easily measured indicator of the concentrations of the principal dissolved constituents. Water-quality data are unavailable at many of the plains tributary stations. Analysis of suspended sediment from seven stations indicates that as much as 90 percent of the heavy metals are transported in the suspended phase rather than in the dissolved phase.

Adequate sediment-concentration data are unavailable for most stations. Existing fragmentary data indicate that the plains tributaries transport a much larger sediment load than does the South Platte River or the major tributaries.

Ground water occurs throughout the study area in either alluvial or bedrock aquifers. Alluvial aquifers consisting of layers of gravel, sand, and clay occur along the channels of the principal streams and commonly range in thickness from a few feet to about 200 ft. Water in the alluvial aquifers occurs under water-table conditions. The water-table altitude decreases from 7,000 ft to less than 4,500 ft with the direction of ground-water movement generally corresponding to the direction of surface-water flow. Transmissivity of the aquifers commonly ranges from 1,300 to 67,000 ft^2/d, and specific yield ranges from 0.1 to 0.3. Alluvial aquifers are readily recharged from precipitation and surface water. As a result, only minimal water-level declines have occurred in the aquifer. Pumpage and ground-water discharge to gaining streams are the principal means of discharge.

Dissolved-solids concentrations of water in the alluvial aquifers usually range from 100 to 500 mg/L in upstream areas to more than 2,500 mg/L in downstream areas. The water normally is either a calcium bicarbonate or calcium sulfate type and ranges from hard to very hard.

The four principal bedrock aquifers in the area are the Laramie-Fox Hills aquifer, the Arapahoe aquifer, the Denver aquifer, and the Dawson aquifer. The Laramie-Fox Hills aquifer is the deepest and most extensive of the four, underlying an area of 6,700 mi^2. The aquifers consist of interbedded layers of conglomerate, sandstone, siltstone, claystone, and shale, ranging in thickness from near zero to as much as 1,000 ft. Water moves through the more permeable conglomerate, sandstone, and siltstone units and is confined by overlying and underlying shale and claystone strata of low permeability. Water-level declines (1958 to 1978) have occurred in parts of each of the aquifers, with maximum declines occurring in the Arapahoe aquifer and the Laramie-Fox Hills aquifer. Minimal declines have occurred in most rural areas. Depths to water range from near zero in some low-lying, undeveloped areas to more than 1,000 ft in other areas. The 1978 potentiometric-surface altitude was about 7,500 ft near Black Forest, decreasing to about 4,600 ft near Masters. A trough in the potentiometric surface near Denver is due to the effects of pumpage and the historical discharge of water into the South Platte River.

Transmissivity of the aquifers ranges from zero at the basin edge to as much as 1,200 ft^2/d in the Dawson aquifer, 400 ft^2/d in the Denver aquifer, 2,100 ft^2/d in the Arapahoe aquifer, and 1,000 ft^2d in the Laramie-Fox Hills aquifer. Confined storage coefficients range from $2x10^{-4}$ to $8x10^{-4}$ and specific yield ranges from 0.1 to 0.2.

Recharge is from precipiataion or leakage from overlying alluvial aquifers and streams in the bedrock outcrop areas and from downward movement of water from overlying bedrock aquifers in the central part of the region. Under steady-state conditions 54.7 ft^3/s of recharge and discharge occurred.

Water in the bedrock aquifers generally is suitable for all uses with dissolved-solids concentrations ranging from 20 to 2,000 mg/L. The water is a calcium bicarbonate type in the Dawson aquifer, becoming a mixed calcium bicarbonate to sodium bicarbonate or sodium sulfate type near the margins of the underlying aquifers. Dissolved-iron concentrations ranging from 20 to 200 µg/L are common, but concentrations of as much as 85,000 µg/L have been measured.

In reviewing and synthesizing the available hydrologic data for the area, the lack of data for parts of the hydrologic environment was noted. Although information on surface-water flood hydrology is adequate, information on low flow and flow duration is lacking.

The greatest deficiency in hydrologic data is on surface-water quality. Almost none is available for the dissolved or suspended chemistry of the streams draining the plains area. Additional data collection in this area is needed.

Considerable ground-water information is available for the area. This information should be suitable for most environmental assessments. However, effects from mining on small areas and the interaction between mining and perched or alluvial ground-water systems in local areas may need further data and analysis.

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