CHEMICAL QUALITY OF SURFACE WATER AND MATHEMATICAL SIMULATION OF THE SURFACE-WATER SYSTEM, POWDER RIVER DRAINAGE BASIN, NORTHEASTERN WYOMING AND SOUTHEASTERN MONTANA

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per mile (acre-ft/mi)	766.3	cubic meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot squared per day (ft^2/d)	0.09294	meter squared per day
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton (short)	907.2	kilogram
ton per day (ton/d)	907.2	kilogram per day

Temperature in degrees Celsius ($^{\circ}C$) can be converted to degrees Fahrenheit ($^{\circ}F$) by the following equation:

$$^{\circ}F = 9/5\ (^{\circ}C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water-Quality Units

mg/L	milligrams per liter
μg/L	micrograms per liter

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ABSTRACT

The drainage area of the Powder River in northeastern Wyoming and southeastern Montana (approximately 13,500 square miles) comprises two contrasting hydrologic settings--mountains and plains. Dissolved-solids load in the tributary streams is not necessarily proportional to their stream discharge--two of the mountain streams, Clear Creek and Middle Fork Powder River, contributed more than one-half the average stream discharge at Locate, Mont. (near the mouth of the Powder River) during 1975-88, but less than one-fourth the average dissolved-solids load. Plains streams, although mostly intermittent or ephemeral, are the source of more than one-half of the average dissolved-solids load at Locate. An average of about 37 cubic feet per second of saline oil-production water is discharged to Salt Creek, increasing both the stream discharge and the dissolved-solids load in the main stem.

Dissolved-solids concentration in the main stem of the Powder River varies with location and stream discharge. The smallest dissolved-solids concentrations generally were detected at Kaycee, Wyo. and ranged from 300 to 1,300 milligrams per liter. The largest dissolved-solids concentrations, ranging from about 500 to nearly 5,000 milligrams per liter, generally were detected at Arvada, Wyo. Stream discharge and dissolved-solids concentrations generally are related inversely. On April 12, 1989, stream discharge at Locate was 304 cubic feet per second, and dissolved-solids concentration was 1,610 milligrams per liter. On September 15, 1988, discharge was only 1.1 cubic feet per second, and dissolved-solids concentration was 3,450 milligrams per liter.

Irrigation diversion and return flow, canal leakage, consumptive use, evaporation, interaction with the alluvial ground-water system, and local inflow are important pathways for water movement in the system. Leaching of salts in the soil zone, concentration of solutes by evaporation or transpiration, and dissolution of minerals can affect dissolved-solids concentration.

A monthly mass-accounting computer model of the basin was calibrated and tested. A baseline simulation, designed to be compared with the results of application simulations, was created to represent the surface-water system during 1975-88. Three application simulations are presented. The first illustrates the effect of removing 77 percent of the oil-production water that was discharged to Salt Creek. At all main-stem sites downstream from Salt Creek, the decreased discharge caused an overall decrease both in simulated stream discharges and in simulated dissolved-solids concentrations. Downstream from Arvada, the decrease in simulated dissolved-solids load in the Powder River was about 20 percent. The second example simulates the effect of increasing irrigated acreage in Montana on stream discharge and dissolved-

solids concentrations in the Powder River; the increase caused only a small change in simulated stream discharge and dissolved-solids concentrations at main-stem sites in Montana. The third example simulates dissolved-sodium concentrations at main-stem sites. Sodium concentrations are calculated using a regression equation relating dissolved-sodium concentrations to dissolved-solids concentrations. Both recorded and simulated mean sodium concentrations are smallest at Kaycee and largest at Sussex, Wyo.; concentrations decrease substantially downstream from Sussex.

INTRODUCTION

Demands for water in many parts of the semiarid Western United States are accompanied by interest in the suitability of the water for its intended uses. In some areas, concern about the quality of water may be as great as the concern about the quantity. One such area is the drainage basin of the Powder River. The Powder River originates in Wyoming and flows northward into Montana, where it joins the Yellowstone River near Terry, Mont. (fig. 1).

Water from the Powder River and its tributaries is used mainly for irrigation of forage crops. Generally, salinity is smaller in the mountain tributaries in Wyoming than in the plains tributaries and the Powder River in both States. Irrigators in the Montana part of the basin, where there are no mountain tributaries, are concerned that changes in use of surface water in the basin might increase salinity in the Powder River to concentrations unsuitable for irrigation.

During 1988-90, the Wyoming and Montana offices of the U.S. Geological Survey (USGS) jointly studied the water quality (salinity) of the Powder River and its principal tributaries. The investigation was done in cooperation with the Wyoming Water Development Commission, the Montana Department of Natural Resources and Conservation, and the Wyoming State Engineer. Objectives of the investigation were to (1) compile existing surface-water-quality data for the basin and collect additional data, (2) define water-quality characteristics of the Powder River and major tributaries, (3) develop and test a conceptual model of the hydrologic system that could be used to assess the hydrologic effects of water development on water quantity and quality.

Purpose and Scope

This report describes the chemical quality of surface water in the Powder River and its principal tributaries. A conceptual model of the surface-water system in the Powder River drainage basin, emphasizing the hydrologic processes that affect stream discharge and chemical quality of the water, also is described.

The investigation included collection and analysis of water samples at 24 sites to supplement the data base, and statistical analysis of water-quality data for long-term and miscellaneous-sampling sites throughout the basin to assess areal, seasonal and temporal variation in the chemical quality of water. A conceptual model of the system was developed to identify and evaluate the relative importance of several hydrologic processes affecting chemical quality of the river. A mathematical model of the drainage basin was developed, calibrated, and tested to evaluate the validity of the conceptual

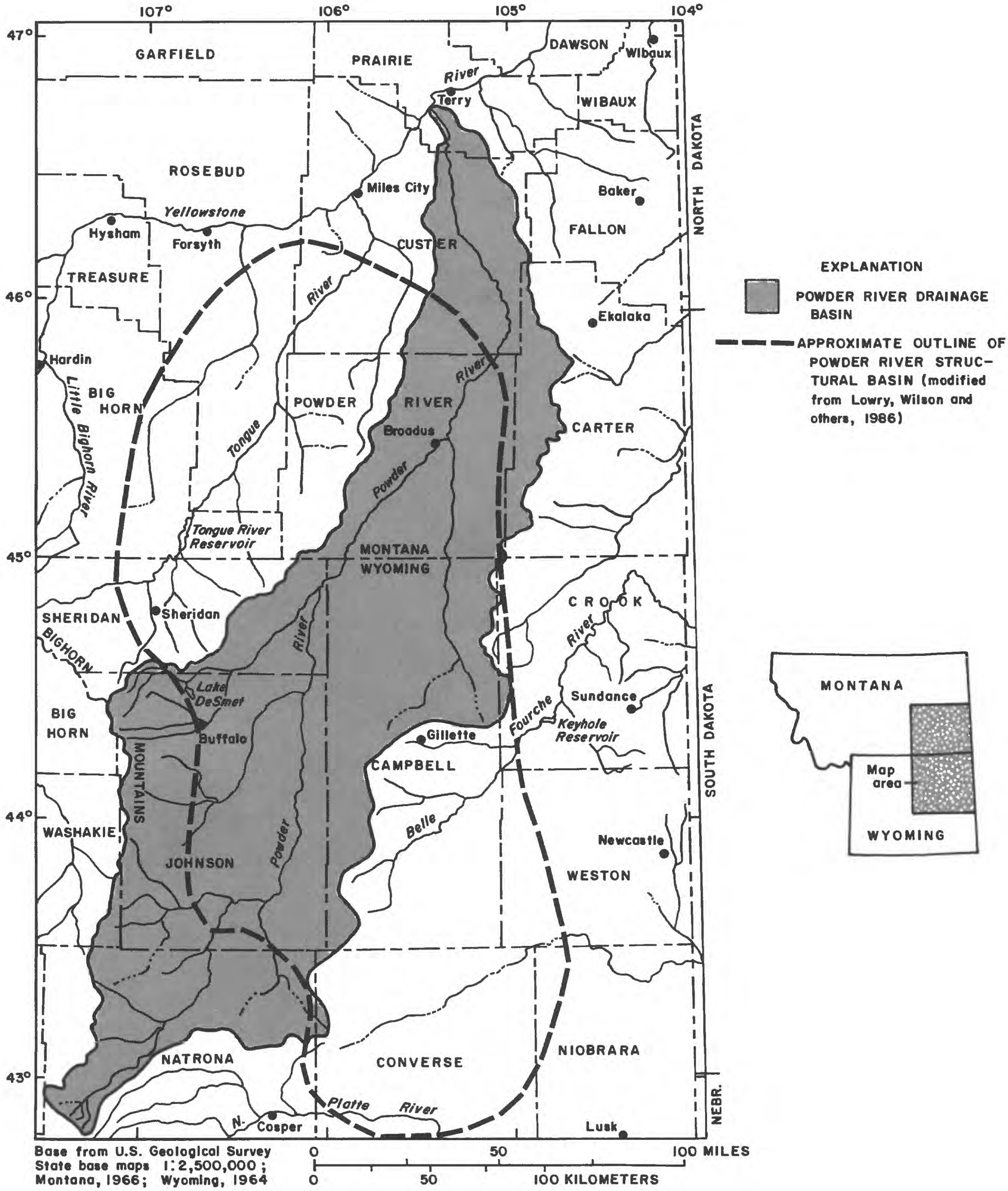


Figure 1.--Location of Powder River drainage basin and Powder River structural basin.

model. The model calculates stream discharge and water quality in the main stem of the Powder River. The use of the mathematical model to evaluate water-management alternatives is demonstrated by three application simulations.

The report includes the following:

- Description of the hydrologic system of the Powder River drainage basin, in relation to surface-water quality.
- Summary of results of trend analyses as reported by Cary (1991).
- Statistical characterization of the areal and seasonal variability of surface-water quality.
- Description of the conceptual model of the surface-water system.
- Description of the calibration, testing, and application of an interactive, mathematical-simulation model for water management; examples are included.
- Tabulation of analyses of the chemical quality of water samples collected during the investigation.

Analysis and discussion are limited to concentrations and loads of common dissolved constituents. The investigation did not consider dissolved trace elements, nutrients, or biological constituents. The large fluvial sediment loads transported by the Powder River, although a factor in water quality, also were not considered in the analysis.

Previously collected data for five sites on the Powder River main stem and for the farthest downstream sites on the major tributaries were used in the investigation. During the investigation, sampling continued at these sites, and supplemental sampling sites were established at the start of the investigation and discontinued at its conclusion.

Acknowledgments

The following State agency representatives provided information and advice during the investigation: Charles Dalby, Montana Department of Natural Resources and Conservation; Evan Green, Wyoming Water Development Commission; Sue Lowry, Wyoming State Engineer's Office; and Michael Whitaker, Superintendent of Water Division 2, Wyoming State Board of Control. Dr. James Bauder, Montana State University, provided valuable insight about the effects of salinity in irrigation water on alfalfa production and conducted a tour of some of the alfalfa fields in Montana irrigated with water from the Powder River.

Water-quality stations have been operated in the Powder River drainage basin at various times in cooperation with the Wyoming Department of Agriculture, Wyoming Department of Environmental Quality, Wyoming Water Development Commission, Montana Department of State Lands, U.S. Bureau of Land Management, and U.S. Environmental Protection Agency. Data collection is continuing at several of the stations, thus providing continuity of information essential for future evaluations of water quality.

POWDER RIVER DRAINAGE BASIN

The investigation area is the Powder River drainage (topographic) basin--an area of about 13,500 mi^2 (fig. 1). The areal extent of the drainage basin is not the same as that of the Powder River structural basin, an asymmetrical syncline now filled with sedimentary rock, which excludes parts of the drainage basin and includes large areas east and west of the drainage basin. Most hydrologic studies in northeastern Wyoming and southeastern Montana since the 1970s have been focused on the energy resources of the structural basin, rather than the surface-water resources of the drainage basin.

The information in the following sections on Hydrologic Setting and Land and Water Use, unless otherwise specified, is drawn from three reports. Hembree and others (1952) report on the first comprehensive evaluation of sedimentation and chemical quality of water in the Powder River basin. Wyoming Water Planning Program (1972) presents detailed information about the area and its mineral and water resources for planning economic development. Lowry, Wilson, and others (1986) summarize information about hydrology in relation to surface mining of coal.

Hydrologic Setting

The Powder River drainage basin comprises two contrasting hydrologic settings. Tributaries are classified according to the type of terrain in which they originate--mountain or plains. The tributaries on the west side of the Powder River that originate in the Bighorn Mountains are perennial and contribute nearly all the dependable flow to the river. The mountain area, however, is small in comparison with the plains area (fig. 2)--about one-sixth of the basin is in the mountain area. The tributaries that originate in the plains area are intermittent or ephemeral; most contribute little, if any, dependable flow to the Powder River. The hydrographs in figures 3A and 3B show the differences between streamflow in the two types of streams. Although entirely in the plains area, the main stem of the Powder River is perennial because of the flow from mountain tributaries. The long-term variation of discharge in the Powder River is shown in figure 3C.

Mountain Streams

The hydrologic setting for the headwaters of the mountain streams (fig. 2) includes mountains and foothills, with altitudes between 6,000 and 13,000 feet above sea level. Soils are coarse grained and acidic or alkaline with organic material. Vegetation consists mainly of pine, fir, and aspen. Annual precipitation on this part of the drainage basin ranges from about 14 to 25 inches; much of the precipitation is snow. Typically, streams are cascading, with steep slopes. Crazy Woman Creek and Clear Creek originate at the crest of the Bighorn Mountains, flowing over igneous and metamorphic rocks of Precambrian age and then over the eastward-dipping sandstones and limestones of Paleozoic age. The western headwater tributaries, North Fork and Middle Fork Powder River, originate in an area underlain by Paleozoic rocks. Streams may lose or gain flow at numerous sinkholes and springs in limestone outcrops. Channel erosion and suspended-sediment loads in these upstream reaches generally are smaller than elsewhere in the basin, and dissolved-solids concentrations in streamflow usually are less than 600 mg/L; major ions are calcium and bicarbonate, indicative of the limestones.

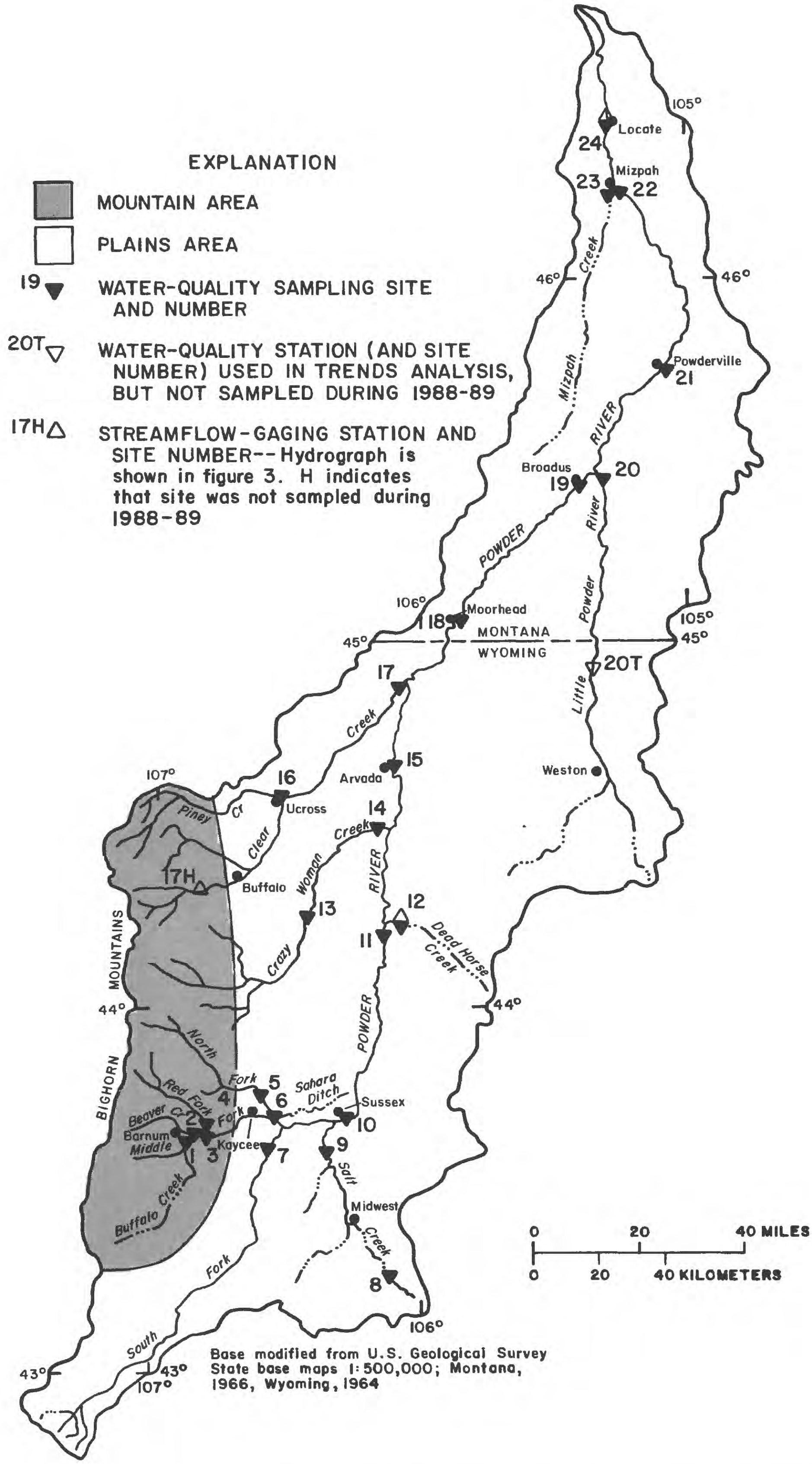


Figure 2.--The Powder River drainage basin, approximate areas of mountains and plains, and location of water-quality-sampling sites.

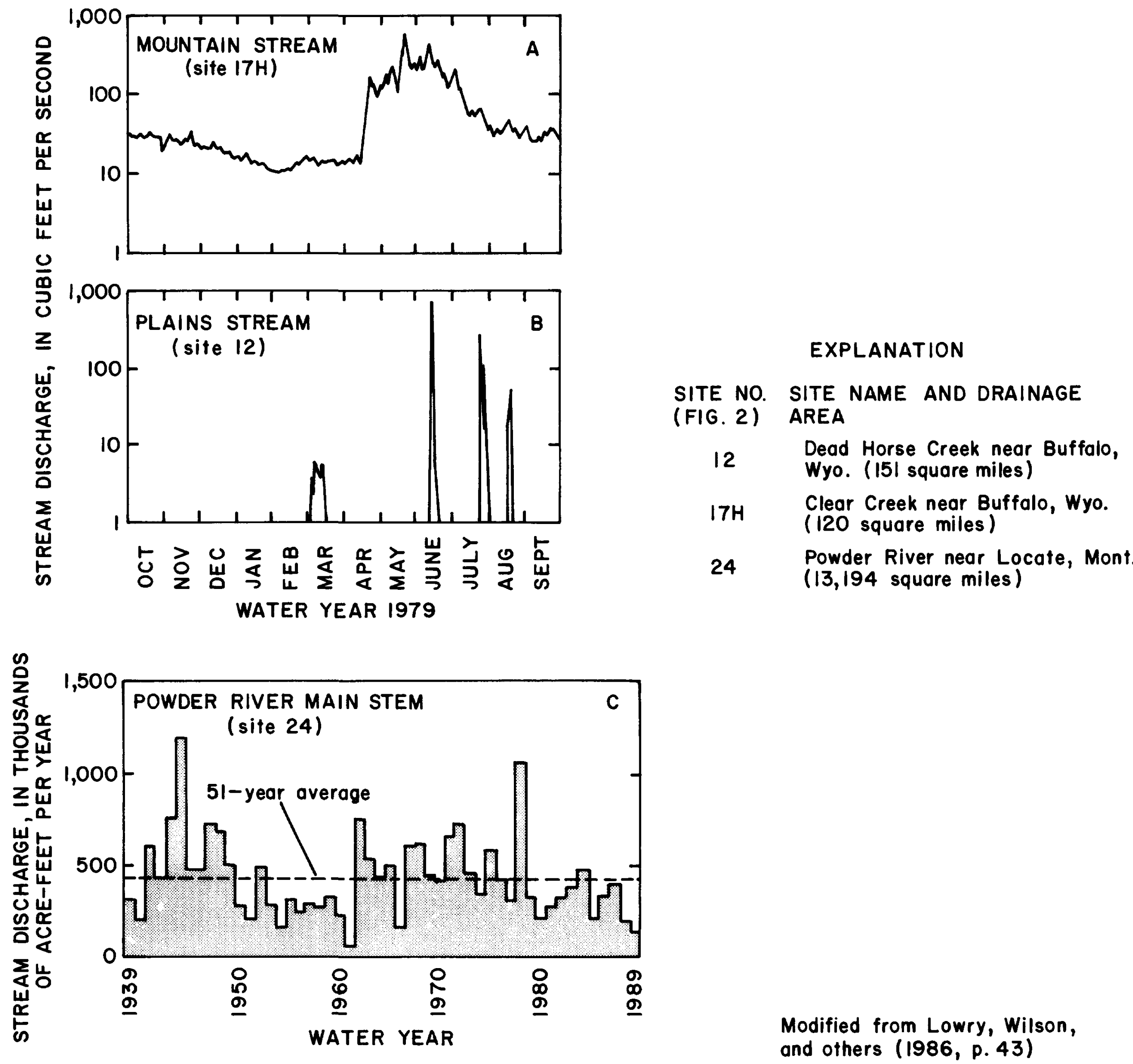


Figure 3.--Typical hydrographs showing seasonal variation in discharge in (A) a mountain stream and (B) a plains stream; and (C) long-term variation in discharge in the Powder River main stem.

Continuing through the foothills, the mountain streams cross marine sandstones and shales and gypsum-bearing rocks of Mesozoic age. Erosion and sedimentation increase, but remain small. Dissolved-solids concentrations in streamflow increase to 700 to 1,000 mg/L; where there is dissolution of gypsum, calcium and sulfate are the major ions. Buffalo Creek, the southernmost large tributary of Middle Fork Powder River, originates in the foothills and is ephemeral. Downstream from the foothills, the hydrologic characteristics of the mountain streams are modified to varying degrees by the plains environment.

The mountain streams rarely, if ever, go dry (Armentrout and Wilson, 1987, pl. 1). Even during dry years, streamflow is sustained by melting snowpacks or by discharge from ground water. Annual maximum streamflows usually occur during spring melting of the snowpack; when snowmelt is combined with warm air and rainfall, large floods of short duration may occur. The larger streamflows dilute dissolved-solids concentrations but have increased capacity for erosion and sediment transport.

Plains Streams

The hydrologic setting for the plains streams includes plains, tablelands, badlands, and open high hills, with altitudes between about 3,000 and 6,000 ft above sea level; fine-grained, alkaline soils with little or no organic material; and sparse vegetation--mainly grasses and sagebrush. This part of the Powder River drainage basin is semiarid; annual precipitation averages about 10 to 14 in. Streams are meandering with nearly flat slopes.

The Powder River and its southern and eastern tributaries, including South Fork Powder River, Salt Creek, and Little Powder River, as well as the downstream reaches of the mountain tributaries, flow through extensive areas underlain by nearly flat-lying marine and continental sandstones, siltstones, and shales of Cretaceous and Tertiary age. Erosion is much greater and suspended-sediment loads are much larger than in the mountain streams. Generally, dissolved-solids concentrations exceed 1,000 mg/L, and usually the dominant ions are sodium and sulfate, indicative of the shales. Sodium and chloride are the dominant ions in Salt Creek, however, indicative of the saline oil-production water discharged to the stream. Concentrations of dissolved trace elements in streams throughout the area generally are small, except for manganese and iron; selenium concentrations greater than 10 μg/L have been detected in water samples from South Fork Powder River (L.R. Larson, in Lowry, Wilson, and others, 1986, p. 68-69).

In contrast with mountain streams, the intermittent plains streams go dry for brief or extended periods during most years, and the ephemeral plains streams are nearly always dry (Armentrout and Wilson, 1987, p. 20 and pl. 1). Some ephemeral streams have interrupted reaches--reaches with discharge from ground water that causes the stream to be perennial for short distances, until the water is lost to infiltration, evaporation, and transpiration. Evaporation and transpiration in semiarid areas may cause a buildup of salts along stream channels and on hillsides. When runoff takes place in such areas, there may be an initial washoff of the salts, causing temporary increases in dissolved-solids concentrations, rather than dilution.

Flooding is less common in plains streams, but locally large floods occasionally are caused by intense thunderstorms. Severe flooding simultaneously on all major streams is rare, but such flooding occurred during May 1978 (Parrett and others, 1984). Large floods on plains streams cause extensive erosion of streambanks and transportation and deposition of large amounts of sediment. Generally, however, the tributaries are not the main source of the large sediment loads commonly transported by the Powder River main stem.

Powder River Main Stem

The Powder River is formed by the confluence of the Middle Fork and North Fork Powder River near Kaycee, Wyo., about 4 river miles upstream from the mouth of the South Fork, once considered the point where the main stem begins. The river flows about 350 river miles northeastward to the Yellowstone River. Principal tributaries are Crazy Woman Creek, Clear Creek, Little Powder River, Salt Creek, and Mizpah Creek (fig. 2). Hembree and others (1952, p. 12) stated:

> The Powder River, therefore, is from its inception a large river. However, it is merely an extension of the South Fork in that it has all the characteristics of that stream and practically none of the characteristics of the Middle Fork. The Powder River, then, begins as a wide, flat, meandering stream that flows on a sand-covered stream bed between predominantly low stream banks. Throughout most of its length, it is bordered by a wide, low flood plain and a series of terraces that blend into alluvial fans that extend down from the bordering hills. * * * At some points, where the river is cutting laterally into flood-plain deposits that predate the present flood plain, the low streambanks give way on one side to high banks.

Median monthly dissolved-solids concentrations in water samples from the river generally range from 1,000 to 2,000 mg/L, except at Kaycee (site 6, fig. 2), where concentrations are less than 1,000 mg/L. Sodium and sulfate generally are the major ions.

The alluvium of the floodplain and terraces is an important hydrologic component of the main stem. Ringen and Daddow (1990, p. 7-26) described the alluvium and its hydrologic function in the 155-river-mile reach between Sussex, Wyo. and Moorhead, Mont. Generally 10 to 30 ft thick and about one-half mile wide, the alluvium is recharged by the river during high flow and discharges water to the river in some reaches during low flow. The chemical quality of water in the alluvium is similar to that in the river.

The alluvium and underlying bedrock may not be hydraulically connected in many parts of the investigation area according to Ringen and Daddow (1990, p. 39). Between Sussex and Arvada, the bedrock is the Wasatch Formation of Eocene age, and downstream from Arvada it is the Fort Union Formation of Paleocene age. Dissolved-solids concentrations in water in the bedrock aquifers at Sussex (site 10), Arvada (site 15), and Moorhead (site 18) ranged from 340-1,340 mg/L (Ringen and Daddow, 1990, p. 36), and are smaller than concentrations in water in the alluvium and river; also, water in the bedrock is a sodium bicarbonate type, in contrast with the sodium sulfate water in the alluvium and river (Ringen and Daddow, 1990, p. 36 and 38).

Discharge in the Powder River is highly variable (fig. 3C). Although the river is considered to be perennial throughout its length, in about 7 out of 10 years the reach between Arvada, Wyo. and the mouth of Clear Creek goes dry during August or September (Armentrout and Wilson, 1987, p. 20). Low flows in the river nearly always are the result of lower than average flows in the major tributaries. Similarly, high flows usually are the result of high flows in the mountain tributaries, although at times the discharge in the river locally may be increased substantially by intense thunderstorms.

Suspended-sediment discharges from the tributaries generally are small, but the Powder River typically transports large quantities of sediment. The average annual suspended-sediment load (24 years) is about 4.7 million tons at Arvada (site 15). During water year 1978, about 16.3 million tons passed Arvada (B.H. Ringen, in Lowry, Wilson, and others, 1986, p. 72-73). Most of the sediment originates in the river itself: Loads increase between Sussex (1979-80 average 0.5 million tons) and Arvada (1.8 million tons), indicating a degrading channel, and decrease between Arvada and Locate (1.0 million tons), indicating an aggrading channel. The effect of erosion and deposition of sediment on chemical quality of water in the Powder River has not been documented, but the sediment probably serves as both a source and a sink for chemical constituents--particularly trace elements such as manganese, iron, and selenium.

Land and Water Use

The physical characteristics and limited water resources of the Powder River drainage basin limit human uses of land and water in the basin and the population of the area. Primary land uses are livestock grazing, irrigation of forage crops along some streams, oil-field operations, bentonite mining, and recreational activities such as hunting, hiking, and snowmobiling. Coal and uranium deposits are present but not mined. The largest community is Buffalo, Wyo., with a population smaller than 4,000 in 1989 (Wyoming Highway Department, written commun., 1990). Only five other towns have more than 100 residents.

The major water use is irrigation of forage crops (about 98 percent of all surface water used). Other water uses include municipal supplies (Buffalo, Wyo., uses water from Clear Creek; all other communities use ground water); rural domestic and stock watering--there are many small stock ponds in the area; and minor industrial supplies. Eight storage reservoirs with capacities greater than 1,000 acre-ft are located in the drainage basin; only one, Lake DeSmet, has a capacity greater than 10,000 acre-ft (Wyoming Water Planning Program, 1972, p. 108). Fishing is the most popular nonconsumptive recreational use of surface water.

Most of the irrigation in the Wyoming part of the drainage basin takes place in the headwater and tributary drainage basins. In the Montana part of the basin, nearly all irrigation water is diverted from the main stem. There is land along the tributaries in Montana, of comparable acreage to that along the main stem, that could be irrigated. However, most of the tributaries are ephemeral and provide an undependable water supply for irrigation, so this acreage was not considered to be irrigated in the model described later in this report. Approximate irrigated acreages (Wyoming Water Planning Program, 1971, p. 8-9; Charles Dalby, Montana Department of Natural Resources and Conservation, written commun., 1990) are as follows:

Drainage basin	Approximate irrigated area (acres)
Headwater	12,500
Crazy Woman Creek	12,100
Clear Creek	35,300
Little Powder River (Wyoming)	3,200
Powder River main stem (Wyoming)	6,100
Powder River main stem (Montana)	15,900

CHEMICAL QUALITY OF SURFACE WATER

Several reports of investigations include descriptive or statistical characterizations of the chemical quality of water in the Powder River drainage basin. The earliest of these is Hembree and others (1952), discussed briefly in the Hydrologic Setting section of this report. Druse and others (1981) synoptically collected water-quality samples during periods of base flow in 1978 and 1979 at about 70 sites throughout the drainage basin. Statistical data from selected long-term water-quality stations were evaluated by Rucker and DeLong (1987) for Wyoming and by Knapton and Ferreira (1980) for Montana. Summaries of various water-quality topics were prepared by L.R. Larson (Lowry, Wilson, and others, 1986, p. 56-69). Peterson (1988a) summarized water-quality statistics for water years 1975-81 at 14 hydrologic-network stations in the Wyoming part of the drainage basin and evaluated adequacy of the data for future information needs in relation to coal mining. Peterson (1988b) summarized annual, monthly, low-flow, and high-flow statistics of stream discharge for the period of record through water year 1984 at 28 hydrologic-network stations in the Wyoming part of the basin. Cary (1989) made a preliminary evaluation of trends in selected water-quality characteristics at two long-term stations: Powder River near Sussex, Wyo., and Powder River near Locate, Mont. As a part of this investigation, Cary (1991) evaluated long-term trends at 10 sites in the drainage basin; the findings are discussed in the Trends Analysis section of this report.

Data from previous investigations, supplemented with new data, were used in this investigation to characterize the chemical quality of water in the Powder River and its major tributaries. Trends in selected dissolved constituents were evaluated statistically, and the areal and seasonal variations in major dissolved constituents were described.

Data Available

The long-term data needed for parts of this investigation had been accumulated over several decades of operation of the hydrologic-data network in both States. These data were used to describe the general quality of water, to evaluate statistical trends in selected water-quality characteristics, and to calibrate and test the mathematical-simulation model of discharge and water quality. The periods for which data are available at these stations are indicated in figure 4. Site numbers used in this report also are indicated in figure 4; the location of the network stations can be determined in figure 2 by the site numbers. Records for several active and discontinued network stations were not used in this investigation; where more than one station had been operated on a tributary to the Powder River, the station farthest downstream was used.

A short-term data-collection program was carried out during this investigation to supplement the long-term data shown in figure 4 and to develop mass balances of stream discharge and dissolved-solids load at sites on the Powder River main stem prior to calibration of the simulation model. The program was designed to obtain concurrent data at intervals of about 6 weeks at 19 sites. Twelve of the sites were at active hydrologic-network stations, one was at the site of a discontinued network station, and six were established for this investigation. Five additional miscellaneous sites were sampled one to three times. All sites sampled during the investigation--network stations, sites established for the investigation, and miscellaneous sites--are listed in table 1, and their location is shown in figure 2. Sequential numbers are used throughout this report to identify sites, instead of the permanent but longer U.S. Geological Survey station numbers (table 1). The chemical analyses of all samples collected during June 1988 through December 1989 that passed laboratory quality-assurance tests are listed in table 12 at the back of this report.

Trends Analysis

Data for dissolved-solids concentration, major ion concentration, and adjusted sodium-adsorption ratio in water samples from the Powder River and its tributaries in Wyoming and Montana were analyzed for trends. In a separate report, Cary (1991) described the methods of analysis and the trends detected in the chemical quality of surface water at 10 sites. This section summarizes the findings reported by Cary (1991).

The data analyzed were collected during water years 1968-88 at seven stations and during water years 1975-88 at nine stations. Six stations had data for both periods. The seasonal Kendall test with correction for serial correlation (Hirsch and others, 1982; Hirsch and Slack, 1984) was applied to flow-adjusted data for some chemical-quality characteristics and to unadjusted data for the remaining characteristics. The trend test used is an exploratory statistical technique. No inferences can be made regarding the continuation of a trend into the future. Also, a trend in the value or concentration of a characteristic might be statistically significant but not have a readily identifiable physical, biological, or chemical cause. Estimates of the percentage change per year in the value or concentration of a characteristic during the period analyzed were reported for the characteristics that had statistically significant trends at the 90-percent confidence level.

The results of the trend tests and estimates of the percentage change per year for those characteristics with statistically significant trends are summarized in table 2. The results are for flow-adjusted data, except for magnesium and sulfate at Salt Creek (site 9) for water years 1968-88. The relation between the concentration of these two water-quality characteristics and discharge was not statistically significant; therefore, these data were not flow-adjusted, and the unadjusted data for these two characteristics were tested for trends.

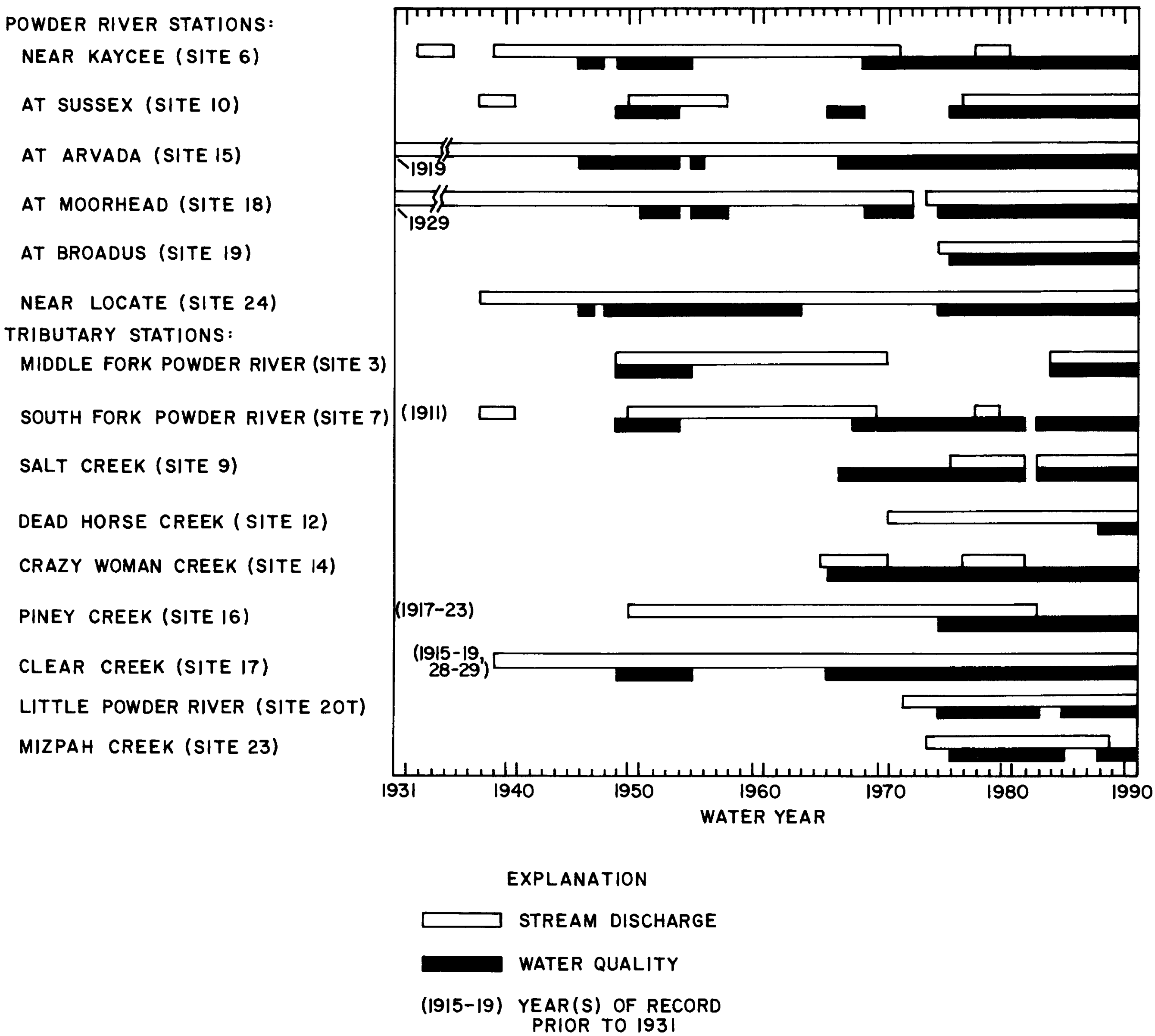


Figure 4.--Periods for which stream-discharge and water-quality (salinity) data are available for selected hydrologic-network stations.

Table 1.--Sampling sites and frequency of sampling, June 1988 through December 1989

[Site type: A, active network station; R, discontinued network station reactivated for this study; S, sampling site established for this study; M, miscellaneous-sampling site for this study; --, not determined]

Site No.	Site name	U.S. Geological Survey station No.	Site type	Drainage area (square miles)	Number of site visits	Number of discharge measurements[1]	Number of chemical-quality samples[1,2]
1	Middle Fork Powder River above Beaver Creek, near Barnum, Wyo.	433901106505001	M	--	1	1	1
2	Middle Fork Powder River below Beaver Creek, near Barnum, Wyo.	433905106504801	M	--	1	1	1
3	Middle Fork Powder River above Kaycee, Wyo.	06309500	A	450	16	16	16
4	Red Fork near Barnum, Wyo.	06310000	S	--	12	12	12
5	North Fork Powder River near Kaycee, Wyo.	06312000	S	106	12	12	12
6	Powder River near Kaycee, Wyo.[3]	06312500	A	980	16	16	16
7	South Fork Powder River near Kaycee, Wyo.	06313000	A	1,150	14	10	8
8	Salt Creek near Midwest, Wyo.	431410106061101	M	--	1	1	1
9	Salt Creek near Sussex, Wyo.	06313400	A	769	15	15	15
10	Powder River at Sussex, Wyo.	06313500	A	3,090	16	16	16
11	Powder River above Dead Horse Creek, near Buffalo, Wyo.	441252106090801	S	--	12	12	12
12	Dead Horse Creek near Buffalo, Wyo.	06313700	S	151	10	1	1
13	Crazy Woman Creek below Timber Draw, near Buffalo, Wyo.	441500106254601	M	--	1	1	1
14	Crazy Woman Creek at upper station, near Arvada, Wyo.	06316400	A	945	16	16	12
15	Powder River at Arvada, Wyo.	06317000	A	6,050	15	14	14
16	Piney Creek at Ucross, Wyo.	06323500	A	267	15	15	11
17	Clear Creek near Arvada, Wyo.	06324000	A	1,110	15	15	12
18	Powder River at Moorhead, Mont.	06324500	A	8,088	16	16	13

Table 1.--Sampling sites and frequency of sampling, June 1988 through December 1989--Continued

Site No.	Site name	U.S. Geological Survey station No.	Site type	Drainage area (square miles)	Number of site visits	Number of discharge measurements[1]	Number of chemical-quality samples[1,2]
19	Powder River at Broadus, Mont.	06324710	A	8,748	14	14	12
20	Little Powder River at mouth, near Broadus, Mont.	06325550	S	1,974	12	12	12
21	Powder River near Powderville, Mont.	06325650	S	--	12	12	12
22	Powder River near Mizpah, Mont.	06326000	M	--	3	3	3
23	Mizpah Creek near Mizpah, Mont.	06326300	R	797	7	7	7
24	Powder River near Locate, Mont.	06326500	A	13,194	16	16	13

[1] No discharge measurements or water-quality samples for visits when there was no flow at site.

[2] Some analyses rejected on basis of laboratory quality-control procedures.

[3] Gage is located downstream of diversion for Sussex Irrigation Canal (Sahara Ditch).

Table 2.--Statistically significant trends in chemical-quality characteristics at selected water-quality-sampling stations, water years 1968-88 and 1975-88

[Characteristic is dissolved concentration of constituent, except for sodium-adsorption ratio; --, trend not significant and change in concentration not computed. Source: Cary, 1991]

Site No.	Sampling station and periods, in water years	Change in value or concentration for indicated characteristic, in percent per year							
		Calcium	Magnesium	Sodium	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate	Chloride	Dissolved solids, sum of constituents
6	Powder River near Kaycee, Wyo.								
	1968-88	--	--	--	--	--	-0.4	--	--
	1975-88	--	--	--	--	--	--	1.3	--
7	South Fork Powder River near Kaycee, Wyo.								
	1968-88	--	--	2.9	2.8	--	1.3	--	1.2
	1975-88	--	--	--	4.3	--	--	--	--
9	Salt Creek near Sussex, Wyo.								
	1968-88	-3.8	-2.5	--	1.9	2.0	-2.6	--	- .9
	1975-88	-3.8	-1.6	--	1.6	1.4	-2.3	--	--
10	Powder River at Sussex, Wyo.								
	1975-88	-2.8	-1.3	1.8	2.8	--	--	1.5	1.3
14	Crazy Woman Creek at upper station, near Arvada, Wyo.								
	1968-88	--	--	--	1.3	.7	--	--	--
15	Powder River at Arvada, Wyo.								
	1968-88	-1.3	--	1.7	2.2	1.3	--	1.5	.6
	1975-88	--	--	1.6	2.1	--	--	1.6	.9
17	Clear Creek near Arvada, Wyo.								
	1968-88	.9	--	--	--	--	--	--	--
	1975-88	1.2	--	--	--	--	--	--	--

Table 2.--Statistically significant trends in chemical-quality characteristics at selected water-quality-sampling stations, water years 1968-88 and 1975-88--Continued

Site No.	Sampling station and periods, in water years	Change in value or concentration for indicated characteristic, in percent per year							
		Calcium	Magnesium	Sodium	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate	Chloride	Dissolved solids, sum of constituents
18	Powder River at Moorhead, Mont.								
	1968-88	--	--	1.2	--	--	--	.9	--
	1975-88	-1.3	--	--	--	--	--	--	--
20T[1]	Little Powder River above Dry Creek, near Weston, Wyo.								
	1975-88	--	--	--	--	--	--	6.4	--
24	Powder River near Locate, Mont.								
	1975-88	--	--	1.4	1.2	--	--	2.5	.9

[1] This site was used for trends analysis only; not sampled during this investigation (see site 20, table 1).

For water years 1968-88, there were 22 significant trends out of 56 trend tests. Increasing trends were detected in 16 of the tests, and decreasing trends were detected in 6 of the tests. Increasing trends ranged from 0.6 percent per year for concentrations of dissolved solids at Powder River at Arvada (site 15; mean concentration, 1,950 mg/L) to 2.9 percent per year for concentrations of sodium at South Fork Powder River (site 7; mean concentration, 450 mg/L). The test that yielded the largest decreasing trend was for concentrations of calcium at Salt Creek (site 9). Concentrations of calcium decreased 3.8 percent per year; the mean concentration of calcium was 79 mg/L. The test that yielded the smallest statistically significant decreasing trend was for concentrations of sulfate at Powder River near Kaycee (site 6), which decreased 0.4 percent per year (mean concentration, 380 mg/L).

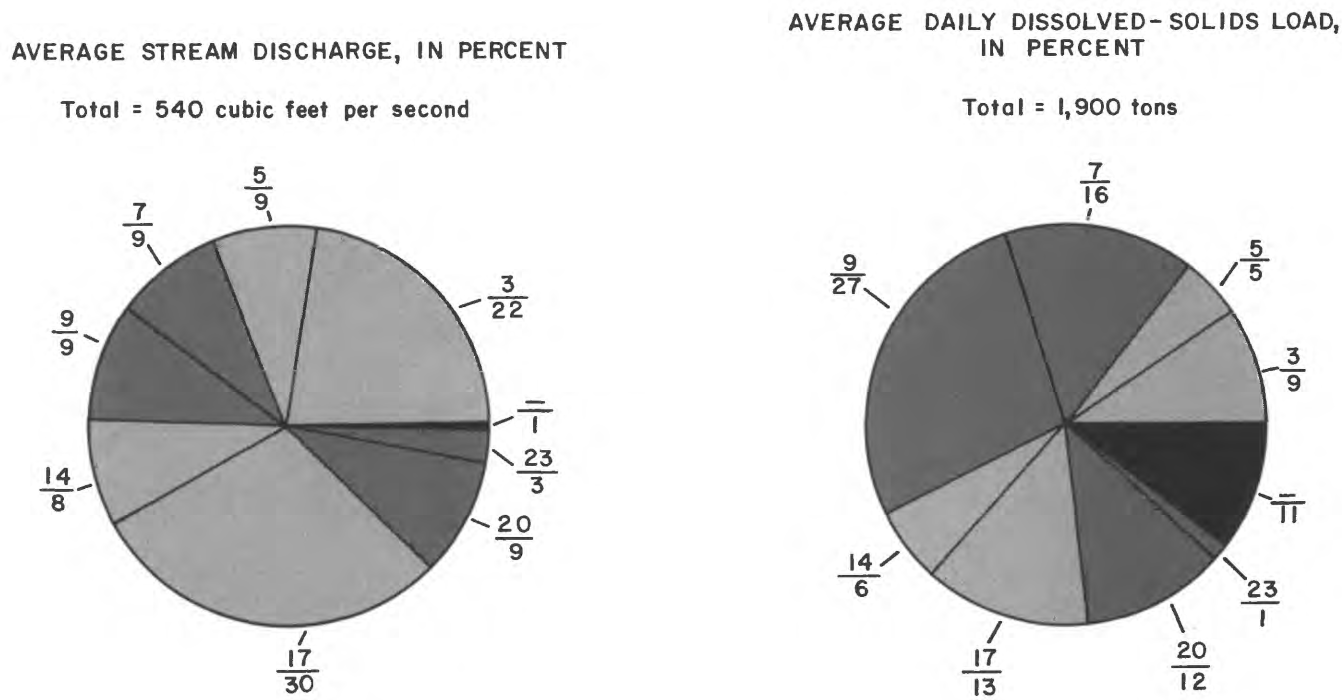
None of the chemical-quality characteristics tested had statistically significant trends at all stations for water years 1975-88. Significant trends were detected in 24 of the 72 trend tests. Increasing trends were detected in 18 of the tests, and decreasing trends were detected in 6 of the tests. The test that yielded the largest increasing trend was for concentrations of chloride at Little Powder River (site 20T, fig. 2; table 2) (mean concentration, 20 mg/L), which increased 6.4 percent per year. The tests that yielded the smallest statistically significant increasing trend were for concentrations of dissolved solids at Powder River at Arvada (site 15; mean concentration, 1,980 mg/L) and at Powder River near Locate (site 24; mean concentration, 1,540 mg/L), which both increased 0.9 percent per year. The test that yielded the largest decreasing trend was for concentrations of calcium at Salt Creek (site 9; mean concentration, 69 mg/L), which decreased 3.8 percent per year. The tests that yielded the smallest decreasing trends were for concentrations of calcium at Powder River at Moorhead (site 18; mean concentration, 130 mg/L), which decreased by 1.3 percent per year, and concentrations of magnesium at Powder River at Sussex (site 10), which decreased 1.3 percent per year (mean concentration, 48 mg/L).

Areal and Seasonal Variation

The trends of values or concentrations of chemical-quality characteristics were analyzed to detect long-term changes at sampling sites; in this section the areal and seasonal variations of stream discharge and dissolved-solids concentration (salinity) are discussed. Comparison of areal variation of data at sites on the Powder River main stem illustrates the effect of tributary and upstream water quality on downstream water quality. Seasonal variation is indicated by comparison of data collected at two or more times during the year and by long-term statistics of monthly values.

The long-term areal variation of stream discharge and dissolved-solids load in various tributaries to the Powder River is shown in figure 5 and is based on data collected during water years 1975-88. Some of the stations had incomplete records during this period. For those stations, the record was extended using the method of Alley and Burns (1983) and regression equations developed by Cary (1991). This record became the initial data for the mathematical model described in the following section of this report.

Data collected during July 25-27, 1988; October 17-21, 1988; and April 10-12, 1989 were selected for illustrating areal and seasonal variation (fig. 6). During July--the middle of the irrigation season--stream discharges



EXPLANATION

SOURCE OF CONTRIBUTION TO STREAM DISCHARGE OR DISSOLVED-SOLIDS LOAD IN POWDER RIVER

- Mountain Stream
- Plains Stream
- Unaccounted for

17 TRIBUTARY SITE NUMBER
30 CONTRIBUTION FROM TRIBUTARY TO STREAM DISCHARGE OR DISSOLVED-SOLIDS LOAD IN POWDER RIVER, IN PERCENT

SITE NUMBER AND STREAM NAME

3 Middle Fork Powder River
5 North Fork Powder River
7 South Fork Powder River
9 Salt Creek
14 Crazy Woman Creek
17 Clear Creek
20 Little Powder River
23 Mizpah Creek

Figure 5.--Contribution from tributaries to the average stream discharge and dissolved-solids load in the Powder River near Locate, Mont., water years 1975-88.

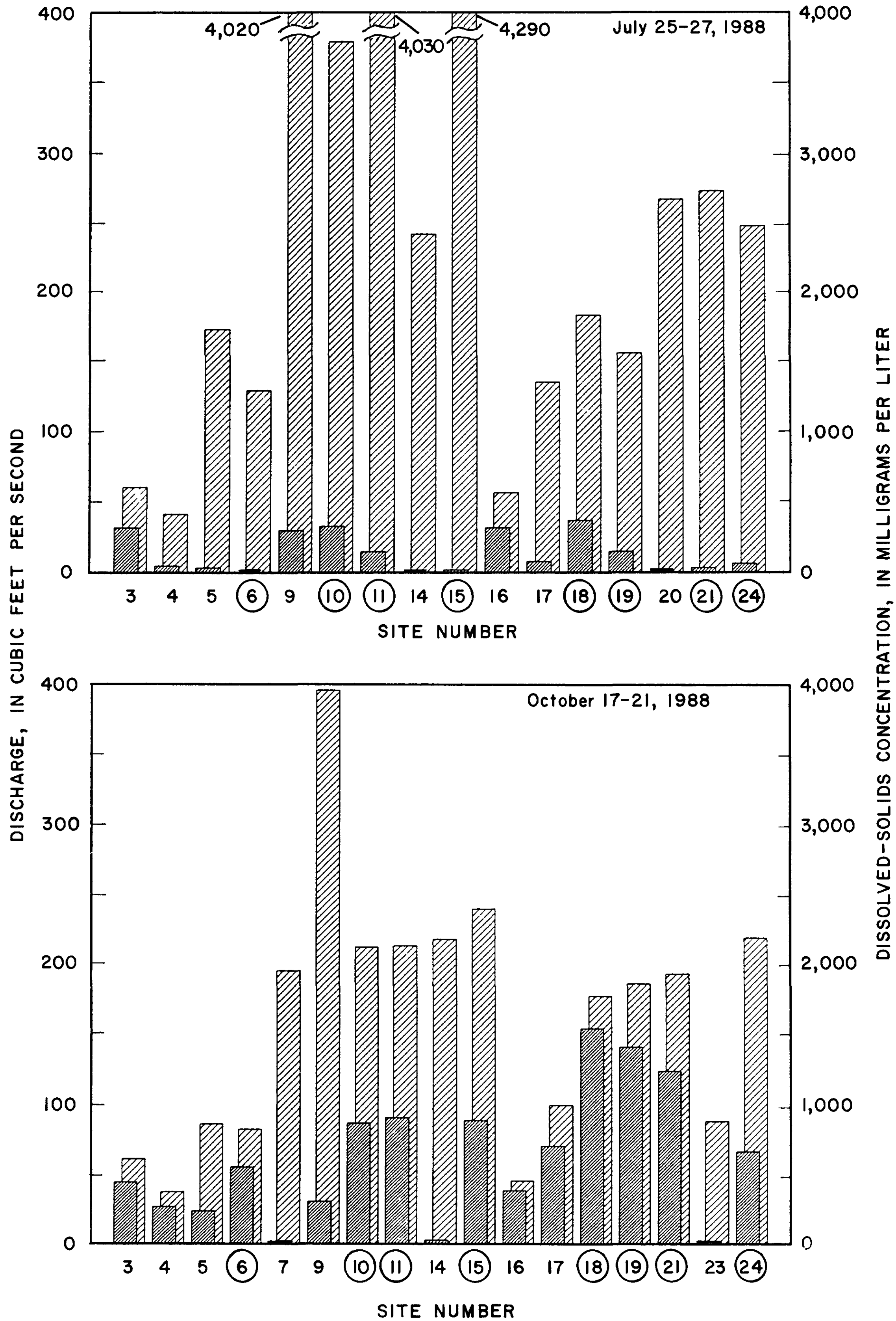
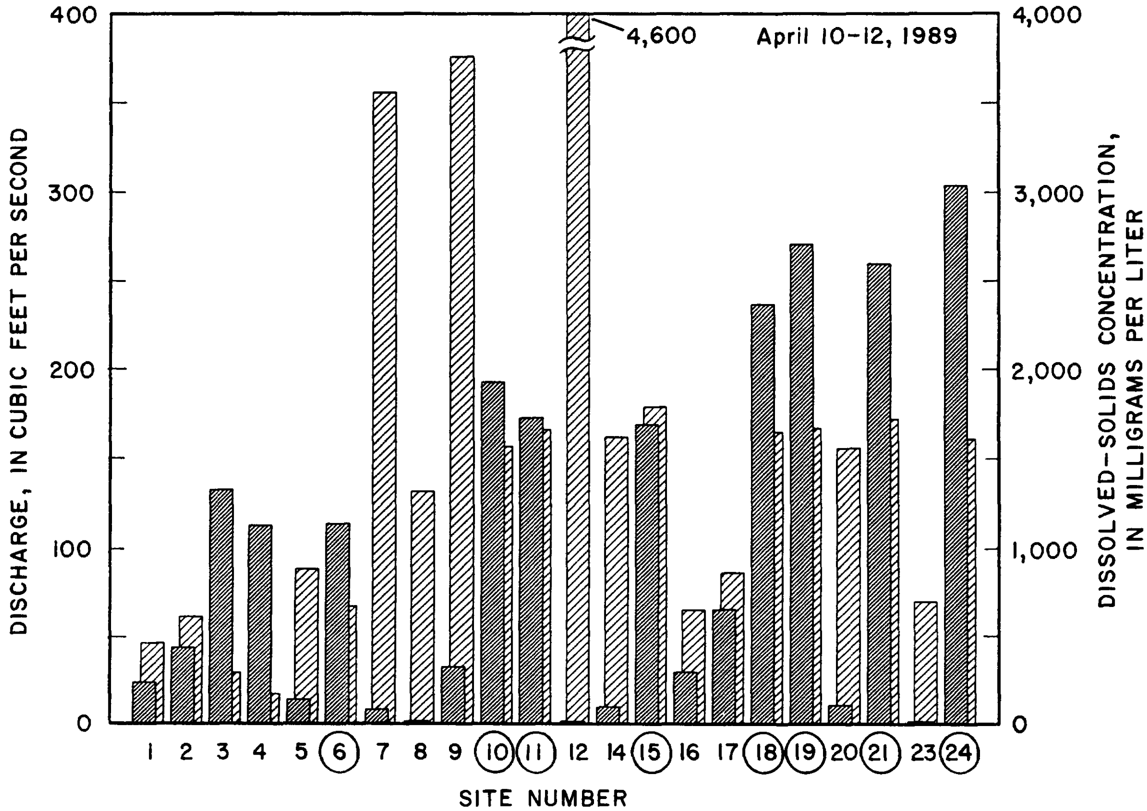


Figure 6.--Instantaneous stream discharges and dissolved-solids concentrations for three sets of water samples collected at sites in the Powder River drainage basin during 1988 and 1989. Data are listed in table 12.



EXPLANATION

STREAM DISCHARGE

DISSOLVED-SOLIDS CONCENTRATION

SITE NUMBER AND STREAM NAME

(Site numbers for Powder River main stem are circled)

1 Middle Fork Powder River (above Beaver Creek)

2 Middle Fork Powder River (below Beaver Creek)

3 Middle Fork Powder River (above Kaycee)

4 Red Fork

5 North Fork Powder River

6 Powder River (near Kaycee)

7 South Fork Powder River

8 Salt Creek (near Midwest)

9 Salt Creek (near Sussex)

10 Powder River (at Sussex)

11 Powder River (above Dead Horse Creek)

12 Dead Horse Creek

14 Crazy Woman Creek (at upper station)

15 Powder River (at Arvada)

16 Piney Creek

17 Clear Creek

18 Powder River (at Moorhead)

19 Powder River (at Broadus)

20 Little Powder River (at mouth)

21 Powder River (near Powderville)

23 Mizpah Creek

24 Powder River (near Locate)

typically are near the annual minimums, and dissolved-solids concentrations typically are near the annual maximums. By October, irrigation has ceased and evapotranspiration has decreased substantially; generally, discharges are larger than during the summer months, and dissolved-solids concentrations are smaller. In the spring, represented by April in this analysis, irrigation has not started, and runoff from snowmelt or spring rainfall typically causes larger stream discharges and smaller dissolved-solids concentrations than during July or October.

Both areal and seasonal variation of instantaneous stream discharge and dissolved-solids concentration throughout the drainage basin are shown in figure 6. Data for tributaries and the main stem are given in downstream order for the three sampling periods. The data for each period were collected during a few days, without regard to traveltime of the water between successive sites on the main stem; the downstream variation probably would be somewhat different had sampling corresponded with the traveltimes. Because of the long traveltimes, changes in hydrologic conditions affecting stream discharge and dissolved-solids concentrations or loads at sites sampled at the upstream end of the basin had not had time to affect these variables sampled at the downstream sites when the samples were taken. Traveltimes from Kaycee (site 6) to Locate (site 24), which vary inversely with stream discharge, range from about 7 days during the spring to as much as 30 days during late summer, and are discussed more fully in the Conceptual Model section.

The graphs in figure 6 indicate that, regardless of season, substantial increases in dissolved-solids concentrations in the Powder River occur between Kaycee (site 6) and Sussex (site 10), mainly because of contributions of salts from South Fork Powder River (site 7) and Salt Creek (site 9). Downstream from Sussex, dissolved-solids concentrations in the main stem generally vary little, ranging from about 1,600 to about 2,700 mg/L, regardless of discharge, in the three sets of samples. The exception to this pattern is at I-90 (site 11) and Arvada (site 15) during July 1988, when dissolved-solids concentrations were 4,030 and 4,290 mg/L. The largest concentrations (greater than 2,500 mg/L) in the tributary streams occur at sites where the discharge is extremely small (fig. 6); therefore, dissolved-solids loads contributed to the Powder River by these streams also are small.

The results of mass-balance computations are shown in figure 7. Stream discharges and dissolved-solids concentrations at five principal sampling sites on the main stem of the Powder River are computed from values for the contributing sites upstream. The computed values are compared with measured values for the sites for the same three periods described in figure 6. For example, the computed discharge for Powder River at Moorhead (site 18) is the sum of the discharges for the Powder River at Arvada (site 15) and Clear Creek (site 17). The dissolved-solids concentration was computed as the sum of the instantaneous dissolved-solids loads calculated from the instantaneous dissolved-solids concentration and stream discharge, divided by the sum of instantaneous discharges from the contributing upstream site and tributaries (sites 15 and 17 for this example). Discrepancies between measured and computed values are most pronounced in July (when velocities of water in the river are lowest and diversions for irrigation are greatest) because of increased traveltimes, and the effects of irrigation withdrawals and return flows. None of these factors is accounted for in figure 7.

The downstream and seasonal variation of the six major ions also are shown in figure 7. The figure shows the proportion of dissolved-solids concentration contributed by each of the major ions, termed "relative concentration." Because of inflow from Salt Creek, relative sodium-plus-potassium and chloride concentrations increased substantially and relative sulfate concentrations decreased substantially between Kaycee (site 6) and Sussex (site 10) in all three sets of samples. Downstream from Sussex, relative sodium-plus-potassium concentrations gradually decreased, and relative sulfate concentrations gradually increased; these were the dominant ions in all three sets of samples at sites on the main stem downstream from Sussex.

The statistics of monthly variation of stream discharge and dissolved-solids concentration during 1975-88 are shown in figure 8 for the five principal sites on the Powder River. Variation downstream, as well as seasonal variation at each of the main-stem sites, is shown in figure 8. The seasonal variation previously discussed, with generally smaller discharges and larger dissolved-solids concentrations in summer and fall, and larger discharges and smaller concentrations during the spring, is evident for all five sites. Dissolved-solids concentrations generally increase downstream along the Powder River, although this pattern is masked at some sites by inflow from tributaries. Because of the cyclical nature of the variations, Rucker and DeLong (1987, p. 13) used a season-related variable for regression analysis of annual dissolved-solids data.

To provide perspective about how well the samples of July 1988, October 1988, and April 1989 represent the long-term dissolved-solids concentrations in the Powder River, the instantaneous dissolved-solids concentrations (table 12 at the back of this report) are plotted on the diagrams in figure 8. Most of the dissolved-solids concentrations in water samples collected in July and October 1988 plot substantially above the median of the 1975-88 mean monthly dissolved-solids concentrations, and most of the April 1989 dissolved-solids concentrations plot near the 1975-88 median concentrations for April; therefore, the frequency of occurrence of dissolved-solids concentrations in samples at most sites for July and October 1988 is not comparable to that for April 1989.

The effect of tributaries on chemical quality of water in the main stem also is evident in an analysis of time trends in chemical-quality characteristics (table 2). Trends in calcium, sodium, adjusted sodium-adsorption ratio, and alkalinity seemed to affect chemical quality of water downstream. Trends detected in other constituents seemed to have only a more localized effect, or to be caused by factors other than changes in upstream chemical quality of water. A more detailed discussion can be found in Cary (1991).

CONCEPTUAL MODEL

Understanding the hydrology of the surface-water system of the Powder River and its tributaries began with the development of a conceptual model. Important pathways for water movement in the system were identified and included explicitly in the conceptual model. Simplifying assumptions were made so that the effects of processes occurring along these important pathways on water quantity and quality could be described mathematically. Effects on water quantity or quality from pathways and processes that were less

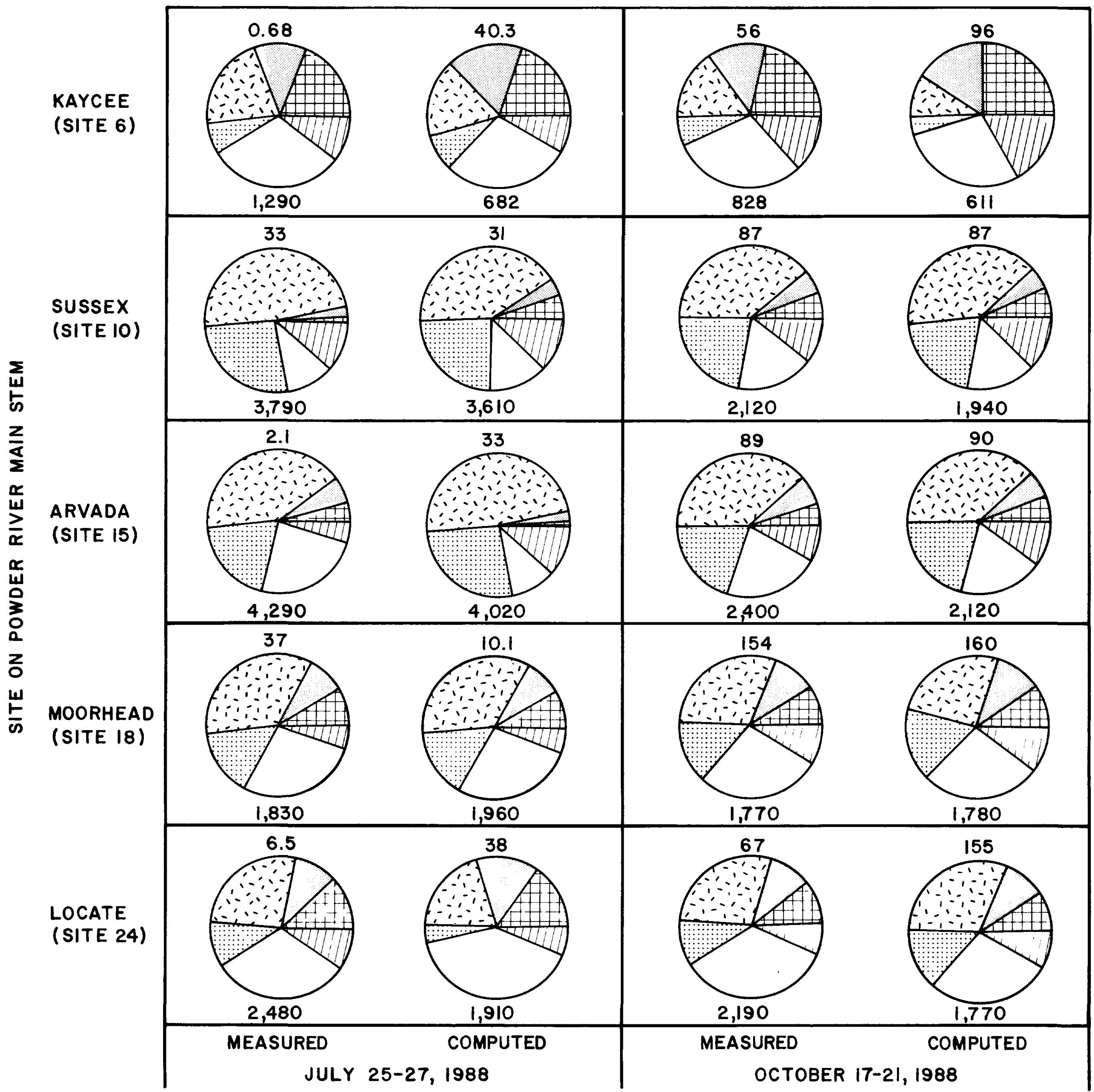
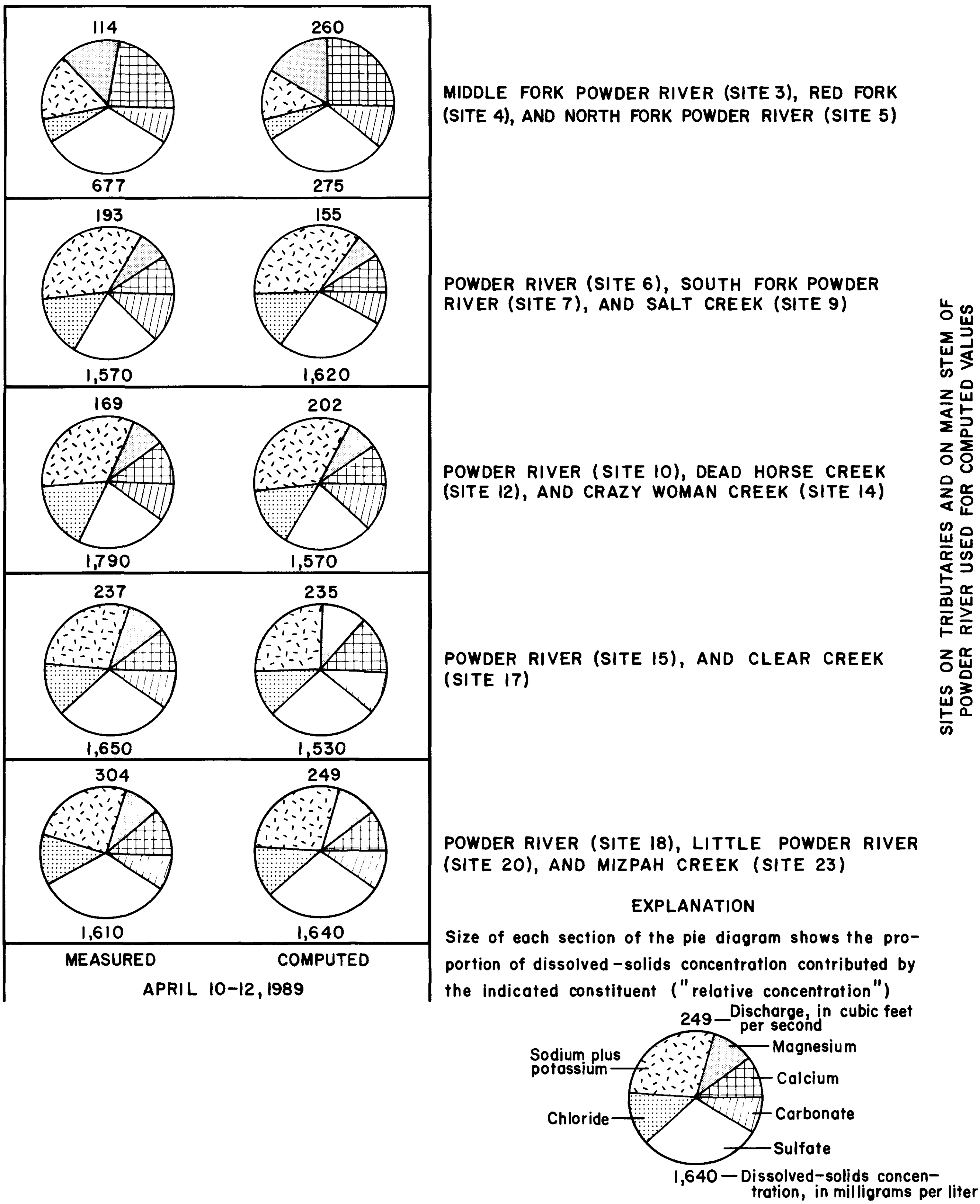


Figure 7.--Measured and computed instantaneous stream discharges and dissolved-solids concentrations for three sets of water samples collected at selected sites on the Powder River during 1988 and 1989.



114
677
260
275
MIDDLE FORK POWDER RIVER (SITE 3), RED FORK (SITE 4), AND NORTH FORK POWDER RIVER (SITE 5)
193
1,570
155
1,620
POWDER RIVER (SITE 6), SOUTH FORK POWDER RIVER (SITE 7), AND SALT CREEK (SITE 9)
169
1,790
202
1,570
POWDER RIVER (SITE 10), DEAD HORSE CREEK (SITE 12), AND CRAZY WOMAN CREEK (SITE 14)
237
1,650
235
1,530
POWDER RIVER (SITE 15), AND CLEAR CREEK (SITE 17)
304
1,610
249
1,640
POWDER RIVER (SITE 18), LITTLE POWDER RIVER (SITE 20), AND MIZPAH CREEK (SITE 23)
MEASURED
COMPUTED
APRIL 10-12, 1989
SITES ON TRIBUTARIES AND ON MAIN STEM OF POWDER RIVER USED FOR COMPUTED VALUES
EXPLANATION
Size of each section of the pie diagram shows the proportion of dissolved-solids concentration contributed by the indicated constituent ("relative concentration")
249—Discharge, in cubic feet per second
Sodium plus potassium
Magnesium
Calcium
Chloride
Carbonate
Sulfate
1,640—Dissolved-solids concentration, in milligrams per liter

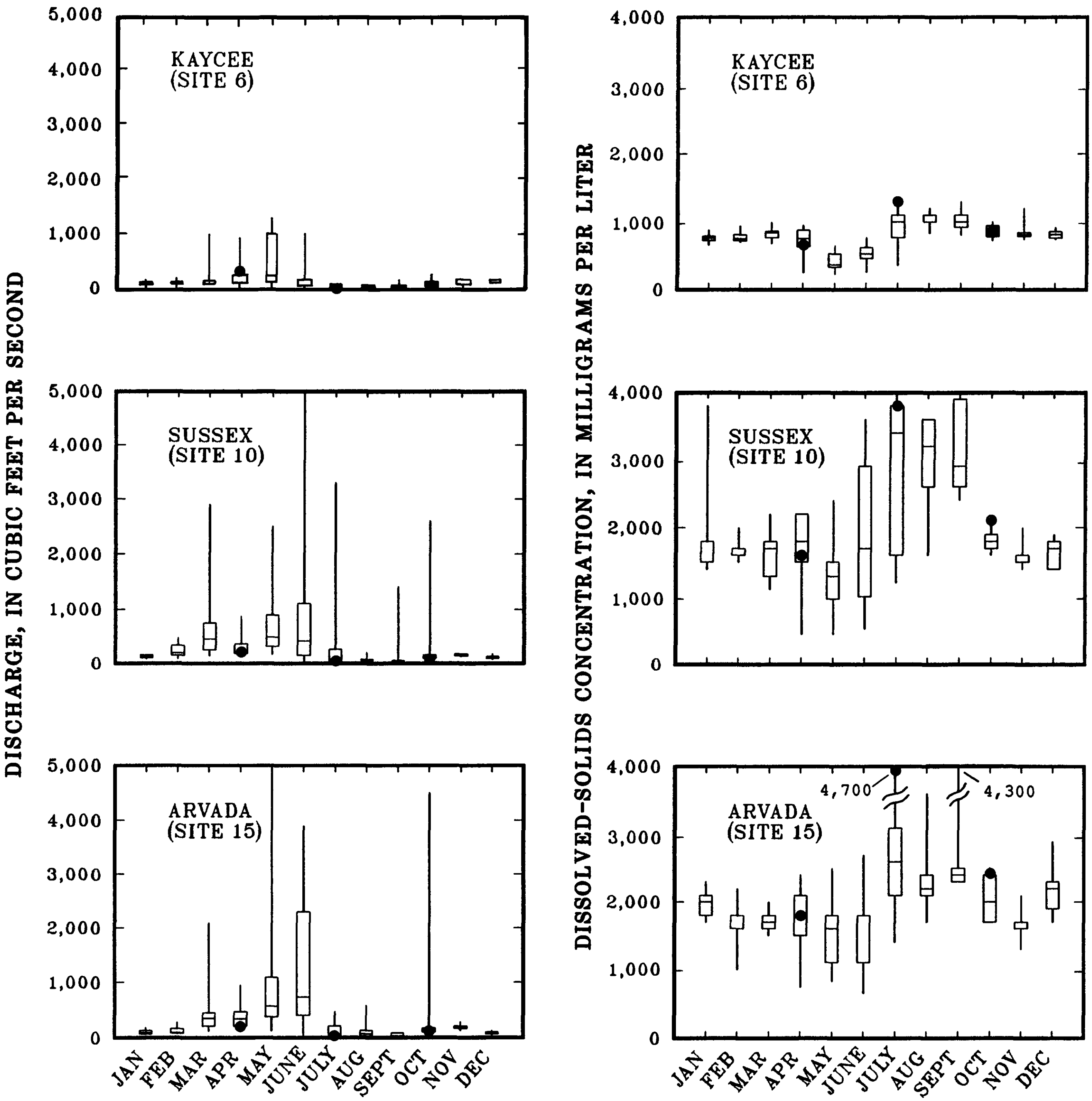
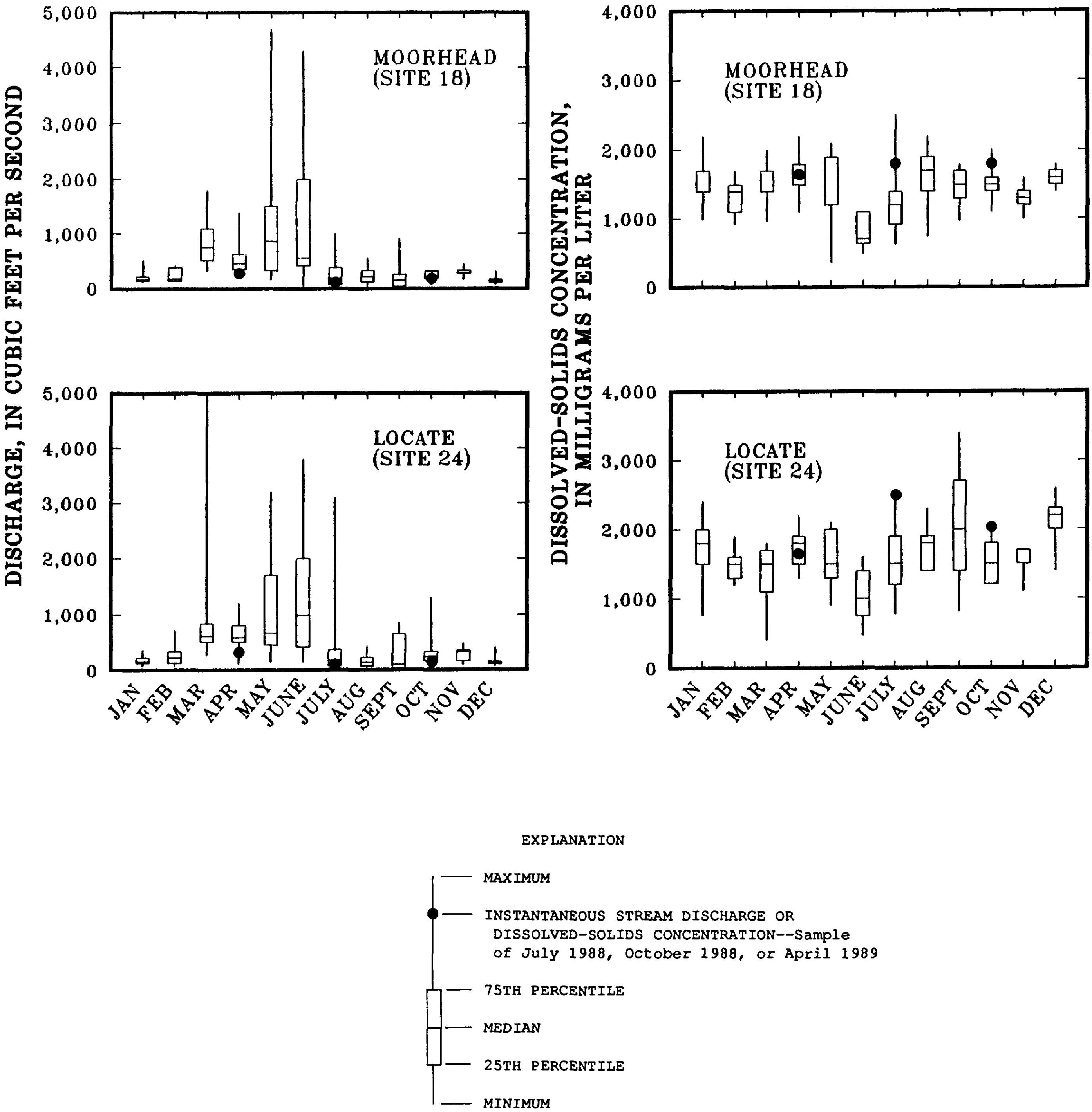


Figure 8.--Monthly variation in stream discharge and dissolved-solids concentrations in the Powder River at five sites, water years 1975-88.


DISCHARGE, IN CUBIC FEET PER SECOND
DISSOLVED-SOLIDS CONCENTRATION, IN MILLIGRAMS PER LITER
MOORHEAD (SITE 18)
LOCATE (SITE 24)
0
1,000
2,000
3,000
4,000
5,000
JAN
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
EXPLANATION
MAXIMUM
INSTANTANEOUS STREAM DISCHARGE OR DISSOLVED-SOLIDS CONCENTRATION--Sample of July 1988, October 1988, or April 1989
75TH PERCENTILE
MEDIAN
25TH PERCENTILE
MINIMUM

important, or less readily quantifiable, were grouped into one empirically determined factor for each reach of the river. The mathematical expression of the conceptual model became the mathematical model (described in the next section).

Pathways and processes affecting surface water quantity and quality in the Powder River drainage basin can be described as follows. Water with low dissolved-solids concentration (generally less than 1,000 mg/L) is present in the upper Powder River tributaries, but after it flows from the mountainous parts of the basin, it mixes in the Powder River with water with larger dissolved-solids concentration from the plains tributaries. Some of the water is diverted for irrigation. Canal leakage, application of irrigation water in excess of plant requirements, and high flow in the river recharge the alluvial aquifer adjacent to the river. Some of this ground water eventually returns to the river; however, the return flow generally has a larger concentration of dissolved solids than the water that was diverted. Crops use some of the water applied to them, but most of the dissolved solids remain behind as salts in the root zone. Leaching of salts and dissolution of minerals in the soil as the water drains to, and through, the alluvial aquifer also contribute to a degradation of water quality of return flow.

Discharge in the main stem of the Powder River is substantially affected by water movement along several pathways, including irrigation diversion, canal leakage, consumptive use, irrigation return flow, movement into and out of the alluvium, local inflow such as overland runoff, and a minimal quantity of precipitation on, and evaporation from, the water surfaces. Processes occurring along those pathways include concentration of solutes by evaporation and transpiration, and gain of solutes by leaching or dissolution of minerals. The effects of these processes are combined with the fundamental principle that the system is conservative to describe discharge and water quality. Discharge at any point on the main stem is assumed to be the sum of the discharge at an upstream main-stem site, plus discharge contributed by any tributaries in the intervening reach, plus or minus gains or losses along the pathways. Dissolved-solids loads also are assumed to be conservative; that is, they are not affected by geochemical, physical, or biological processes in the natural environment, although dissolved solids can be concentrated by evaporation and transpiration.

Some simplifying assumptions were made regarding time. It was assumed that short-term variations (several days) were small compared to seasonal variations, and therefore mean monthly values of stream discharge, dissolved-solids concentration, and dissolved-solids load could be used to describe the system adequately. Also, no hydraulic-flow routing is incorporated--traveltime is not accounted for. Thus, the average stream discharge or dissolved-solids load at the upstream end of the basin in a given month will affect the discharge or load at the downstream end of the basin for that month but not for the following month. Calculations using the method of Boning (1974) indicate that during August, the month of smallest stream discharges, it could take 20 to 30 days for water to travel from Kaycee to Locate, a distance of about 350 river miles. Average traveltime, however, is in the range 9 to 13 days (on the basis of average discharge for 14 years).

Irrigation diversion is one major pathway that could be incorporated explicitly. However, records on actual amounts of irrigation diversion were not available for most of the basin. The amount of water expected to be diverted can be calculated on the basis of irrigated acreage and crop demand (the quantity of water needed by crops for full growth). Crop demand depends on crop type and time of year. It was assumed that part of this demand was satisfied by precipitation, and if precipitation was insufficient in any month, the rest of the demand would be satisfied by applied irrigation water. However, more water must be diverted from the stream than is applied to crops, because of losses en route and inefficiencies in application.

The fate of water diverted for irrigation is complex. Some water leaks from unlined canals and recharges the ground-water system. Some water is lost by evaporation in transit. In many instances, more water is applied to crops than the crop needs. Of that applied to crops, some water is used consumptively by the crop, some runs off the fields (tailwater), and some recharges the ground-water system. Tailwater and ground-water recharge ultimately may return to the river.

Other nonpoint sources, such as overland runoff and gain from or loss to alluvium, are not considered explicitly because they are difficult or impossible to quantify on the basis of existing data. Gains in stream discharge by precipitation on the water surface, and losses by evaporation from the water surface, also are not considered explicitly because they probably are very small compared to other processes occurring in the basin. Instead, all these gains and losses are lumped into a factor called incremental discharge. Incremental discharge could represent gains due to inflow from minor tributaries, overland runoff, or irrigation return flow not considered explicitly, or losses due to diversions, bank storage, or evapotranspiration, or a combination of several of these factors. It is different for each river reach and can vary by month. Because it is harder to measure than any of the other factors, it is determined empirically--it is the difference in discharge between an upstream and downstream site when all other contributions to discharge from pathways that are explicitly considered have been accounted for.

Once discharge is known, dissolved-solids concentration and load can be calculated. Chemical quality of water (dissolved-solids concentration) at a site is assumed to be a function of stream discharge at that site. The relation is inverse--larger discharges have smaller dissolved-solids concentrations, smaller discharges have larger dissolved-solids concentrations. This relation reflects the fact that dissolved solids in the stream are diluted by runoff during the spring and might be concentrated during low-flow months in the summer and fall. Mixing of tributary water with main-stem water, or ground water with surface water, is assumed to be complete and instantaneous. Dissolved solids in incremental discharge might or might not move conservatively--either the water could be lost with its solids (conservative, as in a diversion for irrigation) or the water could be lost but the solids left behind (nonconservative, as in consumptive use by phreatophytes). Dissolved solids also could be gained by the leaching of salts and the dissolution of minerals, as described earlier in this section. However, insufficient data exist to quantify these processes.

Water movement along all the pathways described above also occurs along the tributaries. In translating this conceptual model into mathematical terms, it is not necessary to calculate the quantities of water and dissolved solids moving along these pathways because data for discharge and water quality at the mouths of major tributaries are available.

MATHEMATICAL SIMULATION OF SURFACE-WATER SYSTEM

The conceptual model of pathways and processes affecting water quantity and quality in the Powder River and its tributaries described in the previous section of this report was translated into mathematical terms using an existing computer code. A baseline model was calibrated and tested. This baseline represented the existing surface-water system. Finally, the initial data used in the baseline model were changed to represent the water-management alternatives being considered. Each application simulation was compared to the baseline simulation to estimate effects of the water-management alternatives on the simulated system.

Description of Mathematical Model

A stream-discharge and water-quality accounting model developed by Burns (1988a) was used to simulate the surface-water system of the Powder River basin. In this model, mean monthly values of discharge and constituent loads are accumulated at various nodes in the stream system.

First, the model calculates discharge and water quality at a node without accounting for irrigation diversion and return flow. The discharge at any main-stem node is the sum of the discharge at the next main-stem node upstream plus the discharge from any principal tributary and the estimated incremental discharge in the reach between the node and the next main-stem node upstream. The first (farthest upstream) node at the headwaters and on each tributary are special cases. The node representing the start of the Powder River at the confluence of North and Middle Forks has no upstream main-stem node, but contributions from two principal tributaries and incremental discharge must be accounted for. The first node on each tributary also has no contribution from upstream nodes--the incremental discharge is the only source of water. Likewise, the load of any constituent at any node is the sum of the chemical-constituent loads at the next upstream node and any principal tributary in the reach, plus the estimated load of the incremental stream discharge in the reach. If water-use diversions occur in the reach, the reduction in stream discharge, decrease in ground water in storage, possible gain in irrigation return flow, and resulting surface-water/ground-water interaction are then calculated and added to or subtracted from the discharge and load. The mathematical representation of these steps is described in the following paragraphs.

At all nodes, the incremental stream discharge is calculated from regression equations. The relations are developed for each node independently, then the values estimated for the regression parameters are used in the model. For discharge, three different types of regression equations are available in the model:

$$Q = a + b X; \tag{1}$$

$$\log Q = \log a + b \log X; \text{ and} \tag{2}$$

$$Q = a + b U; \tag{3}$$

where Q is the incremental stream discharge;
a is the regression constant;
b is the regression coefficient;
X is the independent variable; and
U is the stream discharge at the upstream node (calculated by the model).

For nodes where recorded stream discharges are used in the model (input nodes), the first type of regression equation (eq. 1) is specified with a regression constant of 0, a regression coefficient of 1, and the independent variable set equal to the recorded values of monthly discharge. For other nodes (output nodes), differing patterns of monthly discharge can be accommodated by specifying different constants and coefficients for each month. The independent variable used to calculate incremental stream discharge can be some climatological variable, such as monthly precipitation, or monthly discharge at some nearby, hydrologically similar site.

Chemical-constituent concentrations also are calculated from regression equations. The model has provisions for a two-step regression analysis. First, the selected chemical-constituent concentration can be calculated as a function of the stream discharge at the node as follows:

$$C = c\ Q^{d} \qquad (4)$$

where C is the estimated mean monthly concentration of the selected chemical constituent;
c is the regression constant;
Q is the monthly mean or incremental stream discharge at the node; and
d is the regression coefficient.

Second, the concentration of some other chemical constituent can be calculated as a function of the calculated chemical constituent as follows:

$$C_2 = e + f\ C \qquad (5)$$

where C_2 is the concentration of the second chemical constituent;
e is the linear-regression constant;
f is the linear-regression coefficient; and
C is the concentration of the selected constituent.

The two-step provision of the model is especially useful where sufficient data exist to develop regression equations for one constituent (for example, dissolved-solids concentration), but little or no data exist for some other constituent of interest (such as dissolved-sodium concentration).

After discharge and dissolved-solids concentration or load are calculated on the basis of a conservative accounting of discharge from upstream nodes, tributary inflow, and incremental discharge, the values are modified to account for irrigation diversion and return flow. Irrigation diversion is dependent on the same factors in the mathematical model as in the conceptual model. Return flow is composed of excess irrigation water and canal seepage.

The quantity of water needed for irrigation in any month depends on precipitation, crop demand, irrigated acreage, and water-use efficiency, as in the conceptual model. The mathematical model, however, includes the assumption that not all precipitation that falls in a given month can be used by the crop. Instead, it includes a parameter called effective precipitation. Effective precipitation is the maximum amount of monthly precipitation that contributes to consumptive use by plants. Monthly precipitation less than effective precipitation is used toward satisfying crop demand; monthly precipitation greater than effective precipitation is not used in the model. It is assumed that crop demand will be met if water is available. After the contribution from precipitation is accounted for, enough water must be diverted from the stream to meet the remainder of crop demand, plus losses by evaporation and seepage through unlined canals. The model can account for irrigation water supplied by either surface-water diversion or ground-water pumpage; however, ground-water pumpage is insignificant in the Powder River basin. If more water is applied than the crops need, the excess water applied can become return flow or infiltrate to recharge the ground-water system. Return flow, as used in the model, can return to the river by two pathways--it may be tailwater, which returns to the river in the month after being delivered; deep percolation, which returns to the river in a time-delayed manner described by ground-water response functions; or a combination of both distributed between the two pathways by a percentage factor. Canal leakage also is return flow; it is distributed as tailwater and deep percolation to ground water by the same percentage factor.

Ground-water response functions (Jenkins, 1970) are used to compute the time-delayed effects of changes in ground-water levels on the leakage to and from streams. These changes could be caused by evapotranspiration or infiltration of applied irrigation water, and are assumed to affect ground-water storage instantly. Soil moisture is not simulated in the model; therefore, all land-surface activities, such as infiltration of excess irrigation-water applications to ground water and canal leakage, are also assumed to affect ground-water storage instantly. The magnitude and timing of the effects of those stresses that are transmitted through the aquifer to the river are functions of aquifer and streambed properties (transmissivity and storage coefficient) and distance to the stream.

Application of Mathematical Model

Eighteen nodes were used to simulate stream discharge and chemical quality of water in the Powder River drainage basin. Fifteen of the nodes were at or near streamflow-gaging stations where recorded data were available. Nine were input nodes where recorded monthly discharges and calculated dissolved-solids concentrations were input to the model. The other nine were output nodes where stream discharge and chemical-constituent concentrations were calculated in the model. A schematic of the stream network with nodes and node numbers is shown in figure 9, and the node and site numbers, type, names, and availability of recorded data are shown in table 3.

Because stream discharge accumulates downstream, calculations in the model begin at the farthest upstream input nodes (nodes 100 and 200) and proceed downstream. At output nodes where recorded discharge data are available, comparisons can be made between recorded monthly discharges and simulated monthly discharges. Comparisons also could be made between recorded dissolved-solids concentrations and simulated concentrations if monthly mean

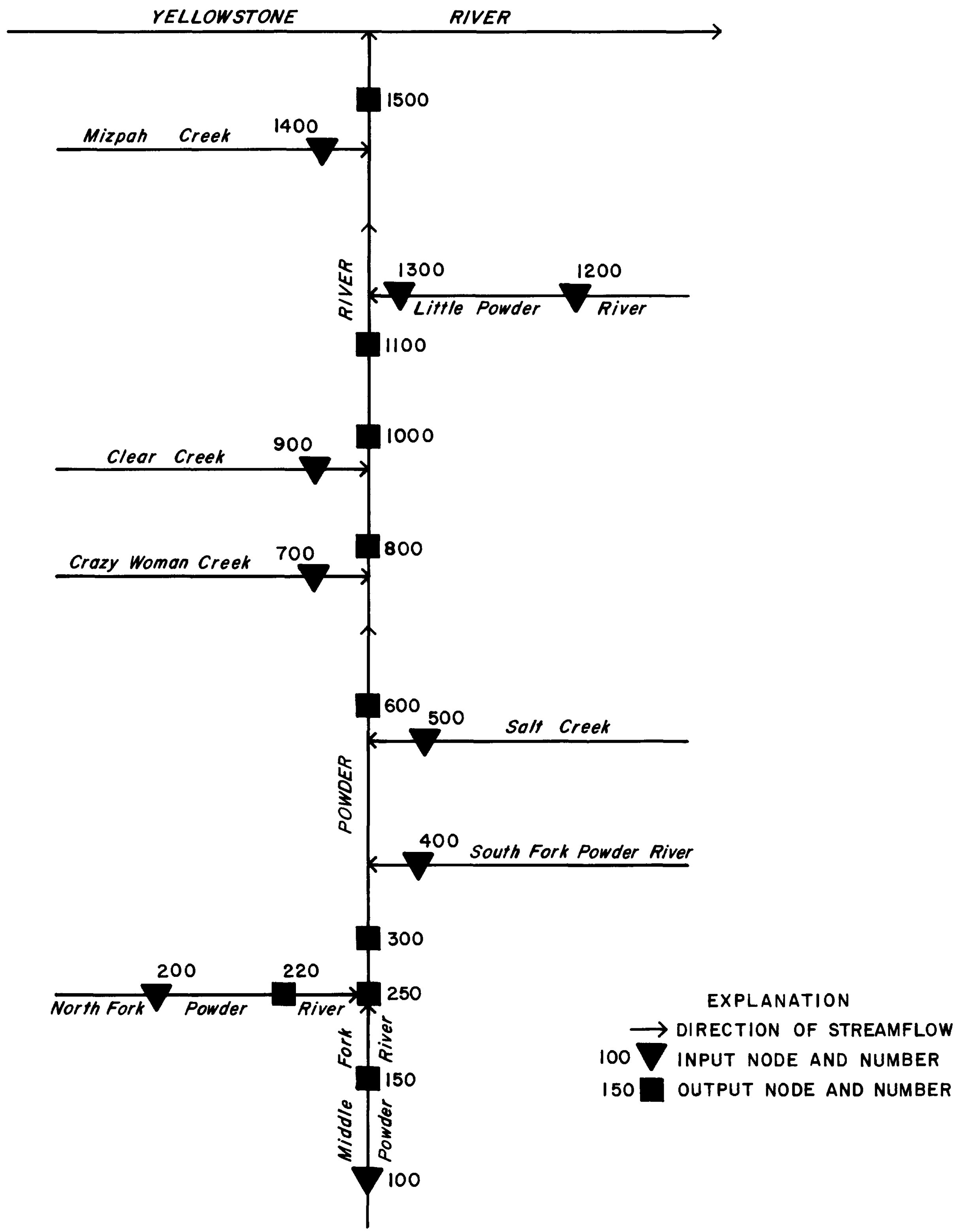


Figure 9.--Schematic of stream network showing the relative location of input and output nodes used in the mathematical-simulation model.

Table 3.--Model node and site numbers, node type and name, and availability of recorded data

[--, not a sampling site]

Node No.	Site No.	Node type	Node name	Data available
100	3	Input	Middle Fork Powder River above Kaycee	Yes
150	--	Output	Middle Fork, Routed	No
200	5	Input	North Fork Powder River near Kaycee	Yes
220	--	Output	North Fork, Routed	No
250	--	Output	Sum of Middle Fork and North Fork	No
300	6	Output	Powder River near Kaycee	Yes
400	7	Input	South Fork Powder River near Kaycee	Yes
500	9	Input	Salt Creek near Sussex	Yes
600	10	Output	Powder River at Sussex	Yes
700	14	Input	Crazy Woman Creek at upper station, near Arvada	Yes
800	15	Output	Powder River at Arvada	Yes
900	17	Input	Clear Creek near Arvada	Yes
1000	18	Output	Powder River at Moorhead	Yes
1100	19	Output	Powder River at Broadus	Yes
1200	20T	Input	Little Powder River above Dry Creek	Yes
1300	20	Input	Little Powder River at mouth, near Broadus	Yes
1400	23	Input	Mizpah Creek near Mizpah	Yes
1500	24	Output	Powder River near Locate	Yes

concentration data were available. Water-quality data most commonly are collected at discrete time periods, rather than on a daily basis, so monthly mean values commonly are estimated from the discrete values. The only daily data available for this investigation were specific conductance for Powder River near Locate (site 24, node 1500); monthly mean values of dissolved-solids concentrations for this site were calculated from a regression equation relating dissolved-solids concentrations to specific conductance. Thus, only at this node could comparisons be made between estimated dissolved-solids concentrations and dissolved-solids concentrations simulated by the model. At all other output nodes, comparisons could be made only between dissolved-solids concentrations simulated by the model and dissolved-solids concentrations calculated using monthly mean discharges and discrete water-quality data.

The ability to make comparisons between recorded and simulated data is particularly useful to calibrate and to test the model. To calibrate the model, the initial values of regression parameters are modified systematically to reduce the differences between recorded and simulated data in successive runs. The strategies used to accomplish this for the Powder River drainage basin are described in detail in the Calibration and Testing section of this report.

Regression Equations

For this investigation, incremental stream discharge at each output node was calculated using regression equation 1 with recorded discharge at the closest upstream node as the independent variable. The regression equations were developed using data from 1975-88. A single regression equation for each node using data for all months was tried initially, but the fit was poor at some of the nodes. Accordingly, at each node where the fit was poor, a regression using an index variable as a second independent variable was used. The index variable accounts for seasonality (Chatterjee and Price, 1977, p. 139-142) and was given a value of 0 for some months and a value of 1 for the rest of the months. A trial-and-error procedure was used to determine the index variable for each month. Generally, the index variable was 0 for October through May and 1 for June through September. This regression analysis resulted in a regression equation at each node with the same regression coefficient for each month, but with different regression constants for months with different index variables. The coefficients of determination (R^2) for the regression equations for incremental discharge ranged from 12 percent at node 1100 to 69 percent at node 600. The regression constants and coefficients derived for incremental discharge at each output node are shown in table 4. The regression constants subsequently were adjusted during model calibration and testing, as explained in a later section of this report.

The regression equations relating instantaneous stream discharge to mean monthly dissolved-solids concentration at each input node also were developed outside the model using equation 4. Because of the limited amount of sample data available, however, all available discrete samples, not just data from 1975-88, were used in the regressions. The relations between instantaneous discharge and dissolved-solids concentration for all samples at each node were assumed to be equivalent to the relations between mean monthly discharge and mean monthly dissolved-solids concentration. The regression equations were developed on a monthly basis to ensure accounting for all monthly variations in sampled values. Finally, the regressions developed for the input nodes were assumed to be applicable to incremental stream discharge at output nodes having similar runoff characteristics. For example, the regressions developed for the South Fork Powder River (site 7, node 400) also were used for the calculation of dissolved-solids concentration for the incremental discharge at Powder River at Sussex (site 10, node 600). The coefficients of determination (R^2) for the regression equations relating mean monthly discharge to mean monthly dissolved-solids concentration ranged from less than 1 percent for winter months to greater than 90 percent for spring and summer months. Although the regressions may not have been statistically significant for some months at some sites, they provided the best obtainable relations between discharge and dissolved-solids concentrations. The regression constants and coefficients initially used for the calculation of dissolved-solids concentration at each node are shown in table 5. The regression constants for the calculation of dissolved-solids concentration subsequently were modified during the model-calibration phase, as were the constants for the calculation of incremental discharge.

Because the model was used to simulate dissolved-sodium concentrations as well as dissolved-solids concentrations, equation 5 was used to develop relations between dissolved-sodium concentration and dissolved-solids concentration at all nodes where data for both constituents were available. These regressions were based on data from 1975-88 for all nodes with data except

Table 4.--Regression parameters for equations for estimating incremental stream discharge

[Equations are of the form Q = a + b X, where Q is incremental stream discharge, in cubic feet per second; a is the regression constant; b is the regression coefficient; and X is mean monthly stream discharge at the next node upstream, in cubic feet per second. For model input nodes, a = 0 and b = 1, and stream discharge is available from recorded data.]

Node	October		November		December		January		February		March	
No.	a	b	a	b	a	b	a	b	a	b	a	b
100	0	1	0	1	0	1	0	1	0	1	0	1
150	-14.7	.73	-14.7	.73	-14.7	.73	-14.7	.73	-14.7	.73	-14.7	.73
200	0	1	0	1	0	1	0	1	0	1	0	1
220	-4.6	.23	-4.6	.23	-4.6	.23	-4.6	.23	-4.6	.23	-4.6	.23
250	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0
400	0	1	0	1	0	1	0	1	0	1	0	1
500	0	1	0	1	0	1	0	1	0	1	0	1
600	30.2	-.80	30.2	-.80	30.2	-.80	30.2	-.80	30.2	-.80	30.2	-.80
700	0	1	0	1	0	1	0	1	0	1	0	1
800	-58.2	1.21	-58.2	1.21	-58.2	1.21	-58.2	1.21	-58.2	1.21	-58.2	1.21
900	0	1	0	1	0	1	0	1	0	1	0	1
1000	-19.8	.37	-19.8	.37	-19.8	.37	-19.8	.37	-19.8	.37	-19.8	.37
1100	6.9	.214	6.9	.214	6.9	.214	6.9	.214	6.9	.214	6.9	.214
1200	0	1	0	1	0	1	0	1	0	1	0	1
1300	0	1	0	1	0	1	0	1	0	1	0	1
1400	0	1	0	1	0	1	0	1	0	1	0	1
1500	18.5	.88	18.5	.88	18.5	.88	18.5	.88	18.5	.88	18.5	.88

Node	April		May		June		July		August		September	
No.	a	b	a	b	a	b	a	b	a	b	a	b
100	0	1	0	1	0	1	0	1	0	1	0	1
150	-14.7	.73	-14.7	.73	-59.1	.73	-59.1	.73	-59.1	.73	-59.1	.73
200	0	1	0	1	0	1	0	1	0	1	0	1
220	-4.6	.23	-4.6	.23	-18.8	.23	-18.8	.23	-18.8	.23	-18.8	.23
250	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0
400	0	1	0	1	0	1	0	1	0	1	0	1
500	0	1	0	1	0	1	0	1	0	1	0	1
600	30.2	-.80	30.2	-.80	27.4	-.80	27.4	-.80	27.4	-.80	27.4	-.80
700	0	1	0	1	0	1	0	1	0	1	0	1
800	-58.2	1.21	-58.2	1.21	-0.4	1.21	-0.4	1.21	-0.4	1.21	-0.4	1.21
900	0	1	0	1	0	1	0	1	0	1	0	1
1000	-19.8	.37	-19.8	.37	26.2	.37	26.2	.37	26.2	.37	26.2	.37
1100	6.9	.214	6.9	.214	-16.8	.214	-16.8	.214	-16.8	.214	-16.8	.214
1200	0	1	0	1	0	1	0	1	0	1	0	1
1300	0	1	0	1	0	1	0	1	0	1	0	1
1400	0	1	0	1	0	1	0	1	0	1	0	1
1500	18.5	.88	18.5	.88	11.2	.88	11.2	.88	11.2	.88	11.2	.88

Table 5.--Regression parameters for equations for estimating dissolved-solids concentration

[Equations are of the form $C = c\,Q^{d}$, where C is mean monthly dissolved-solids concentration, in milligrams per liter; c is the regression constant; Q is mean monthly incremental discharge, in cubic feet per second; and d is the regression coefficient]

Node	October		November		December		January		February		March	
No.	c	d	c	d	c	d	c	d	c	d	c	d
100	3,294	-.430	13,360	-.780	1,480	-.210	1,339	-.160	1,636	-.250	1,808	-.240
150	3,294	-.430	13,360	-.780	1,480	-.210	1,339	-.160	1,636	-.250	1,808	-.240
200	3,294	-.430	13,360	-.780	1,480	-.210	1,339	-.160	1,636	-.250	1,808	-.240
220	3,294	-.430	13,360	-.780	1,480	-.210	1,339	-.160	1,636	-.250	1,808	-.240
250	1,120	-.068	832	-.003	2,040	-.197	851	-.020	676	.030	1,290	-.090
300	1,120	-.068	832	-.003	2,040	-.197	851	-.020	676	.030	1,290	-.090
400	3,240	-.095	3,090	-.088	3,090	-.065	2,950	-.013	2,690	-.086	2,880	-.097
500	13,800	-.355	8,130	-.182	6,760	-.129	10,000	-.263	7,760	-.204	16,980	-.371
600	2,750	-.258	1,950	-.156	2,630	-.238	3,980	-.472	2,690	-.326	1,860	-.148
700	2,750	-.258	1,950	-.156	2,630	-.238	3,980	-.472	2,690	-.326	1,860	-.148
800	2,750	-.258	1,950	-.156	2,630	-.238	3,980	-.472	2,690	-.326	1,860	-.148
900	4,370	-.353	3,160	-.285	5,620	-.418	4,790	-.404	3,240	-.317	2,240	-.212
1000	2,040	-.101	2,400	.053	3,310	-.026	2,880	-.066	3,090	-.222	2,510	-.213
1100	2,040	-.101	2,400	.053	3,310	-.026	2,880	-.066	3,090	-.222	2,510	-.213
1200	2,040	-.101	2,400	.053	3,310	-.026	2,880	-.066	3,090	-.222	2,510	-.213
1300	2,040	-.101	2,400	.053	3,310	-.026	2,880	-.066	3,090	-.222	2,510	-.213
1400	812	-.260	1,212	-.210	992	-.270	735	-.440	1,097	-.340	992	-.270
1500	2,040	-.101	2,400	.053	3,310	-.026	2,880	-.066	3,090	-.222	2,510	-.213

Node	April		May		June		July		August		September	
No.	c	d	c	d	c	d	c	d	c	d	c	d
100	8,103	-.660	2,697	-.460	1,808	-.390	1,636	-.310	992	-.150	812	-.050
150	8,103	-.660	2,697	-.460	1,808	-.390	1,636	-.310	992	-.150	812	-.050
200	8,103	-.660	2,697	-.460	1,808	-.390	1,636	-.310	992	-.150	812	-.050
220	8,103	-.660	2,697	-.460	1,808	-.390	1,636	-.310	992	-.150	812	-.050
250	7,590	-.473	1,350	-.229	1,170	-.180	1,120	-.149	1,120	-.025	1,170	-.067
300	7,590	-.473	1,350	-.229	1,170	-.180	1,120	-.149	1,120	-.025	1,170	-.067
400	3,470	-.095	3,630	-.115	3,310	-.087	2,880	-.031	3,020	-.053	3,020	-.056
500	8,130	-.176	12,600	-.287	8,710	-.203	7,590	-.171	21,900	-.518	14,100	-.380
600	6,460	-.482	4,370	-.365	2,290	-.275	2,140	-.185	2,090	-.189	1,950	-.163
700	6,460	-.482	4,370	-.365	2,290	-.275	2,140	-.185	2,090	-.189	1,950	-.163
800	6,460	-.482	4,370	-.365	2,290	-.275	2,140	-.185	2,090	-.189	1,950	-.163
900	22,900	-.683	2,630	-.290	1,900	-.305	2,920	-.337	2,190	-.222	1,950	-.200
1000	2,190	.023	2,690	-.188	2,290	-.093	1,580	-.167	1,480	-.142	2,290	.066
1100	2,190	.023	2,690	-.188	2,290	-.093	1,580	-.167	1,480	-.142	2,290	.066
1200	2,190	.023	2,690	-.188	2,290	-.093	1,580	-.167	1,480	-.142	2,290	.066
1300	2,190	.023	2,690	-.188	2,290	-.093	1,580	-.167	1,480	-.142	2,290	.066
1400	1,339	-.170	1,480	-.160	1,212	-.130	1,212	-.150	1,339	-.180	812	-.260
1500	2,190	.023	2,690	-.188	2,290	-.093	1,580	-.167	1,480	-.142	2,290	.066

Crazy Woman Creek (site 14, node 700), where data from an upstream site with a period of record of 1968-88 were used (L.E. Cary, U.S. Geological Survey, written commun., 1990). The relation between dissolved-sodium concentration and dissolved-solids concentration at each node was considered to be constant throughout the year; therefore, a single regression equation was developed for each site. Figure 7 shows that the relative sodium concentration at any one site has a small seasonal variation compared to the difference between sites, implying that the use of a single regression equation for each site is appropriate. The regression constants and coefficients developed for the calculation of dissolved-sodium concentration are shown in table 6.

Table 6.--Regression parameters for equations for estimating dissolved-sodium concentration

[Form of equation is $C_2 = e + f\ C$, where C_2 is dissolved-sodium concentration, in milligrams per liter; e is the regression constant; f is the regression coefficient; and C is dissolved-solids concentration, in milligrams per liter]

Site No.	Site name	Parameter e	Parameter f	Coefficient of determination, R^2 (percent)
3	Middle Fork Powder River above Kaycee	-24.0	0.29	90
6	Powder River near Kaycee	-25.0	.15	88
7	South Fork Powder River near Kaycee	1.0	.17	87
9	Salt Creek near Sussex	-230.0	.39	89
10	Powder River at Sussex	-210.0	.37	92
14	Crazy Woman Creek at upper station, near Arvada	-12.0	.11	88
15	Powder River near Arvada	-130.0	.29	91
17	Clear Creek near Arvada	-13.0	.11	92
18	Powder River at Moorhead	-37.0	.21	87
19	Powder River at Broadus	-47.0	.22	87
20	Little Powder River at mouth, near Broadus	2.8	.18	86
23	Mizpah Creek near Mizpah	-19.0	.29	91
24	Powder River near Locate	-22.0	.20	94

Because the model has no provision for changing regression constants and coefficients over time, trends in chemical-quality data cannot be simulated. This restriction affects the accuracy of model calibration; however, all trends described by Cary (1991) are small compared to the monthly fluctuations in concentration. Also, the model was used to compare various simulations with each other rather than to predict future chemical-quality concentrations.

Inaccuracies due to trends would be present in both runs being compared and would cancel each other out. Therefore, the detected trends in sampled data probably do not affect model reliability adversely.

Information Required

The primary data used in the model are monthly mean discharges for the selected simulation period for all input nodes and for output nodes where comparisons are required. The water years 1975-88 were selected for the simulation period because there were nearly complete discharge records for many nodes. Where monthly discharge records for 1975-88 were incomplete, a streamflow record-extension program developed by Alley and Burns (1983) was used to estimate missing monthly discharges.

Monthly mean dissolved-solids concentration was calculated from recorded discharge by using the regression equations described in the previous section. Monthly mean dissolved-solids load (in tons) is calculated by multiplying monthly mean discharge (in ft^3/s) by dissolved-solids concentration (in mg/L), and multiplying the result by a conversion factor of 0.002695 times the number of days in the month.

In addition to monthly mean discharge and dissolved-solids regression equations, several model parameters are needed. These parameters account for the effects of each pathway and process (described in the section on the Conceptual Model) on discharge and water quality. Calculation of the amount of irrigation diversion requires estimates of mean monthly precipitation, irrigated acreage, effective precipitation factor, potential evapotranspiration, and irrigation demand factor. Interaction with the alluvial ground-water system is complex--it includes natural gains and losses (accounted for in incremental discharge) and irrigation return flow (calculated explicitly). The amount and timing of irrigation return flow is calculated using canal seepage factor, disposition of irrigation return flow, and aquifer properties including transmissivity, storage coefficient, and initial ground-water storage and quality. The sources of this additional information are described in the following paragraphs.

Mean monthly precipitation is used to calculate monthly irrigation requirements. Data from National Weather Service precipitation stations at Sheridan, Wyo., and Miles City, Mont., were used for this purpose (Earth Info Inc., 1989).

Information about irrigated acreage quantities and locations was obtained from the Wyoming State Engineer's Office (Sue Lowry, written commun., 1990) and the Montana Department of Natural Resources and Conservation (Charles Dalby, written commun., 1990). Irrigated acreage upstream from nodes on tributaries was not included in model simulations because these tributary nodes were input nodes, where the recorded stream discharges reflect upstream water uses.

The effective-precipitation factor was set arbitrarily at 6 in.; all monthly precipitation less than this amount was considered to be available for crop use. Although this figure was chosen arbitrarily and may be conservatively large for many applications, a sensitivity analysis (described in the next section) indicated that the effective-precipitation factor has only a minor effect on simulated stream discharge.

Crop demand is represented by potential evapotranspiration. Potential evapotranspiration was estimated for alfalfa (the most common crop grown in the basin) using data from the U.S. Soil Conservation Service (1970). Because the model requires only one value of potential evapotranspiration for each month representing the average for the entire basin, calculated values for Miles City, Mont., and Kaycee, Wyo., were averaged to provide the initial values used in the model. They ranged from a low of 0 ft for October through April to a high of 0.66 ft for July.

Irrigation-demand factor accounts for losses in transit and inefficient application; it is defined as the ratio between the quantity of water diverted and the quantity required by crops. Irrigation-demand factor was estimated for Wyoming for Sahara Ditch for water year 1975, the only year and location for which sufficiently detailed data were available. Total diversions for the Sahara Ditch that year were 19,900 acre-ft (Sue Lowry, Wyoming State Engineer's Office, written commun., 1989). That water was used to irrigate 5,600 acres. Calculations based on the method recommended by U.S. Soil Conservation Service (1970) indicated that the water need for alfalfa grown on that acreage was approximately 11,400 acre-ft. Irrigation-demand factor, therefore, was calculated to be about 1.8 (19,900 acre-ft divided by 11,400 acre-ft) for Wyoming. In Montana, flood irrigation--less efficient than the sprinkler and border-dike irrigation methods used in Wyoming--commonly is used. The irrigation-demand factor for Montana, therefore, was assumed to be larger than the 1.8 used for Wyoming. An initial estimate of 2.0 for Montana was refined during calibration to a final value of 2.5.

Seepage loss, represented in the model by a parameter called canal-seepage factor, was estimated to be 200 acre-ft/mi by applying a generalized loss rate of 1 percent of total water diverted, per mile, which is used by the Wyoming State Engineer's Office (Michael Whitaker, Wyoming State Board of Control, oral commun., 1989). This loss rate was applied to the 1975 diversions for Sahara Ditch (19,900 acre-ft) to obtain the value of about 200 acre-ft/mi.

Disposition of irrigation return flow describes the fate of excess applied irrigation water--whether it runs off as tailwater or infiltrates the ground-water system, or a combination of both. Because there are no indentified irrigation-water wasteways (Michael Whitaker, Wyoming State Board of Control, oral commun., 1989), it was assumed that all excess irrigation water recharged the shallow ground-water system. The same assumptions for seepage loss and irrigation return flow were used for Montana.

Estimates of aquifer transmissivity and storage coefficient obtained from Ringen and Daddow (1990, p. 24-26) for a site near site 11, Powder River above Dead Horse Creek, were assumed to be applicable to the entire Powder River drainage basin for this investigation. Calculation of the quantity of ground water in storage also was based on their work; they described an average width of alluvium of 900 ft along each side of the main stem of the Powder River above Dead Horse Creek (site 11), and an average saturated thickness of 21.5 ft. These values also were used for the main stem in Montana. Along North Fork, Middle Fork, and South Fork Powder River, an average width of 300 ft and an average thickness of 21.5 ft were assumed. Ground-water storage along Crazy Woman Creek, Clear Creek, Little Powder River, and Mizpah Creek was not included in the model because ground-water/surface-water interactions are included in the data for the input nodes for these streams.

Several parameters such as average river sinuosity and pan evaporation were not required to translate the conceptual model into mathematical terms. However, because the computer code was developed for a general river basin, these parameters were required input. An effort was made to use realistic values so simulations of water-management alternatives requiring these parameters would be possible. Because they had little or no effect on the baseline simulation, these parameters are not reported in the sensitivity analysis.

Average river sinuosity (sinuosity factor) is used to calculate the number of river miles between two points from the straight-line distance between those same two points. An average value was calculated by dividing river miles by straight-line distance for a measured total of 15 reaches on the USGS 1:100,000 topographic maps of Kaycee, Buffalo, Sheridan, Powderville, Broadus, and Miles City.

Water loss by evaporation from the surface of lakes and reservoirs is another example of a parameter required by the mathematical model that is not used in the conceptual model. Only one value for lake evaporation each month for the entire basin could be used in the model. The values of pan evaporation reported by Farnsworth and Thompson (1982) for Terry, Mont., and Sheridan, Wyo., were averaged to arrive at the final values that ranged from a low of 0.30 ft for October to a high of 0.86 ft for July.

Calibration and Testing

The general calibration strategy was to use the best available estimates for all initial data used in the model and to calibrate the model by adjusting the regression constants for incremental stream discharge and for dissolved-solids concentration. The decision to adjust only the regression constants and not the regression coefficients was based on procedures developed in the application of the model in the Arkansas River basin in Colorado (Burns, 1988b). Simulated monthly stream discharge and dissolved-solids concentration at each output node where recorded data were available were compared to the means of the recorded values for discharge and calculated values for dissolved-solids concentration for each month to judge the success of the calibration. (Calculated values of dissolved-solids concentration at a given site are values calculated from a regression equation developed from discharge measurements and chemical analysis of water samples at that site.) The first half of the period of record (water years 1975-81) was used for calibration purposes. The second half of the period of record (water years 1982-88) then was used to test the calibrated model.

Because the model calculates dissolved-solids concentration as a function of stream discharge, and because more discharge than dissolved-solids concentration data were available for the simulation period, the model first was calibrated and tested for discharge. The model then was calibrated and tested for dissolved-solids concentration.

The primary test statistic for the calibration and testing comparisons, called the coefficient of determination by Burns (1988a), is expressed as:

$$R^2 = 1 - \frac{(MR)^2 + (SDR)^2}{(SDY)^2} \qquad (6)$$

where R^2 is the test statistic;
MR is the arithmetic average of the residuals (differences between simulated and recorded values) for all months being considered;
SDR is the standard deviation of the residuals; and
SDY is the standard deviation of the calculated values.

The goal of the calibration was to maximize R^2 at all output nodes where comparisons were made. MR also was calculated for individual months at each node, and the monthly values of MR also were used as test statistics for calibration and testing. Although the form of the test statistic places more weight on large values of discharge than on small values, model results generally matched small values more closely than large values. Because the primary concern of most Powder River water users and water managers is irrigation rather than flood control, the bias toward accurately matching low and mid-range discharges, at the expense of large peak discharges such as those of May 1978, is appropriate.

For the calibration of the model using stream discharge, each main-stem output node with discharge data was examined in turn, in downstream order, beginning with the Powder River near Kaycee (site 6, node 300). For calibration, discharge for 1975-81 was simulated, and the test statistic R^2 was calculated at the Kaycee node. R^2 was examined, as well as the MR for each month. If the MR for any month was substantially different from zero, the regression constant for incremental discharge for that month (table 4) was adjusted. Discharge for 1975-81 was simulated again, and the new R^2 and MR for each month were compared with the previously simulated values. If the R^2 and MR for each month had improved (that is, R^2 increased and MR decreased), discharge run for the testing period 1982-88 was simulated. If the R^2 and MR for the testing run also showed improvement, further adjustments to the regression constants were made in an attempt to make the MR for all months as close to zero as possible. If an adjustment resulted in a smaller MR for some month for the calibration period, but a larger MR for that month for the testing period, no further adjustments to the regression constant for that month were attempted. When no further improvements could be made for any month, the model was considered calibrated and tested for that node, and the procedure was repeated for the next downstream node. When the regression constants for incremental discharge for all main-stem nodes had been adjusted, the model was considered to be calibrated and tested for discharge. Final calibrated values of regression parameters are shown in table 7.

After the calibration and testing for stream discharge, the model was calibrated for dissolved-solids concentration. In this calibration, however, Powder River near Locate (site 24, node 1500) was the only node where simulated dissolved-solids concentrations could be compared to estimated dissolved-solids concentrations. As described earlier, monthly mean dissolved-solids concentrations at Locate were derived from daily mean concentrations. The daily mean dissolved-solids concentrations, in turn, were calculated from daily mean values of specific conductance. At all other main-stem nodes, the calculated values were derived from regression equations

Table 7.--Final values of regression parameters for equations for estimating incremental stream discharge

[Equations are of the form Q = a + b X, where Q is mean monthly incremental stream discharge, in cubic feet per second; a is the regression constant; b is the regression coefficient; and X is mean monthly stream discharge at the next node upstream, in cubic feet per second. For model input nodes, a = 0 and b = 1, and stream discharge is available from recorded data]

Node	October		November		December		January		February		March	
No.	a	b	a	b	a	b	a	b	a	b	a	b
100	0	1	0	1	0	1	0	1	0	1	0	1
150	-13.2	.73	-28.5	.73	-28.0	.73	-28.2	.73	-5.2	.73	-2.2	.73
200	0	1	0	1	0	1	0	1	0	1	0	1
220	-4.1	.23	-9.1	.23	-8.6	.23	-9.1	.23	-2.1	.23	- .1	.23
250	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0
400	0	1	0	1	0	1	0	1	0	1	0	1
500	0	1	0	1	0	1	0	1	0	1	0	1
600	-70.0	-.80	-25.0	-.80	-20.0	-.80	-5.0	-.80	30.2	-.80	100.0	-.80
700	0	1	0	1	0	1	0	1	0	1	0	1
800	-36.0	1.21	-63.0	1.21	-66.0	1.21	-53.0	1.21	-68.0	1.21	-18.0	1.21
900	0	1	0	1	0	1	0	1	0	1	0	1
1000	-12.0	.37	-30.0	.37	-45.0	.37	-10.0	.37	0.0	.37	15.0	.37
1100	-68.0	.214	-58.0	.214	-38.0	.214	-33.0	.214	-23.0	.214	57.0	.214
1200	0	1	0	1	0	1	0	1	0	1	0	1
1300	0	1	0	1	0	1	0	1	0	1	0	1
1400	0	1	0	1	0	1	0	1	0	1	0	1
1500	-115.0	.88	-106.0	.88	-90.0	.88	-75.0	.88	-52.0	.88	43.0	.88

Node	April		May		June		July		August		September	
No.	a	b	a	b	a	b	a	b	a	b	a	b
100	0	1	0	1	0	1	0	1	0	1	0	1
150	-37.7	.73	23.3	.73	39.9	.73	44.0	.73	22.0	.73	28.0	.73
200	0	1	0	1	0	1	0	1	0	1	0	1
220	-11.6	.23	7.4	.23	12.2	.23	13.2	.23	5.0	.23	9.2	.23
250	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0
400	0	1	0	1	0	1	0	1	0	1	0	1
500	0	1	0	1	0	1	0	1	0	1	0	1
600	55.0	-.80	50.0	-.80	47.0	-.80	-8.0	-.80	-23.0	-.80	-48.0	-.80
700	0	1	0	1	0	1	0	1	0	1	0	1
800	-58.0	1.21	-93.0	1.21	20.0	1.21	30.0	1.21	-12.0	1.21	-33.0	1.21
900	0	1	0	1	0	1	0	1	0	1	0	1
1000	-50.0	.37	-40.0	.37	65.0	.37	30.0	.37	5.0	.37	10.0	.37
1100	7.0	.214	7.0	.214	13.0	.214	103.0	.214	68.0	.214	3.0	.214
1200	0	1	0	1	0	1	0	1	0	1	0	1
1300	0	1	0	1	0	1	0	1	0	1	0	1
1400	0	1	0	1	0	1	0	1	0	1	0	1
1500	15.0	.88	-18.0	.88	183.0	.88	154.0	.88	81.0	.88	-12.0	.88

relating discretely sampled dissolved-solids concentration to measured stream discharge. Thus, comparisons at all nodes except Locate were comparisons of simulated concentrations to calculated concentrations; these comparisons, consequently, were given less weight in calibration.

The calibration and testing procedure used for dissolved-solids concentration generally was the same as that used for stream discharge. The procedure began at the node for Powder River near Kaycee (node 300), and adjustments were made to the regression constants for the dissolved-solids concentration of the incremental stream discharge (table 5) in the same manner as was done for discharge. In this calibration, however, changes were made to the regression constant for a particular month only if the R^2 improved at the Locate node as well as at the node under consideration. Thus, if MR for a particular month for the calibration period indicated that the regression constant needed adjustment, that adjustment was made only if MR improved for both the calibration and the testing periods, and if the R^2 improved at the Locate node for both the calibration and testing periods. This more restrictive test on adjustment of the regression constant ensured that changes in constants would improve results at the only node where daily dissolved-solids concentrations were available.

Changing only the regression constants for the dissolved-solids concentration of the incremental stream discharge often did not result in substantial changes to the simulated dissolved-solids concentration at most nodes on the main stem of the Powder River. Accordingly, when adjustments to those regression constants were indicated, 20 percent of the indicated adjustment also was applied to the regression constants for the dissolved-solids concentration of the discharge at the upstream input nodes. The rationale for this additional adjustment at input nodes was that the relation between stream discharge and dissolved-solids concentration at the input nodes, while more reliable than the assumed relation for incremental stream discharge, nevertheless was relatively unreliable because it was based on discrete samples at the input nodes. The selection of a 20-percent adjustment for the input nodes was arbitrary; 10- and 30-percent adjustments also were tried but did not result in substantially different calibration results. Final calibrated values for regression parameters are shown in table 8.

The final values of the R^2 test statistic for the calibration and testing periods for both stream discharge and dissolved-solids concentration are shown in table 9. Values of R^2 for dissolved-solids concentration are shown only for the node at Locate because that was the node where recorded values were most accurate. (Comparisons of simulated with recorded or calculated results also can be made from figures 10 and 11.)

Sensitivity Analysis

A sensitivity analysis describes how changes in selected parameters affect model results, and identifies which parameters have the greatest effects on modeling results. Judgments about the overall reliability of the model can be made based on the reliability of the estimates of the parameters to which the model is more sensitive.

Table 8.--Final values of regression parameters for equations for estimating dissolved-solids concentration

[Equations are of the form $C = c\ Q^{d}$, where C is mean monthly dissolved-solids concentration, in milligrams per liter; c is the regression constant; Q is mean monthly incremental stream discharge, in cubic feet per second; and d is the regression coefficient]

Node	October		November		December		January		February		March	
No.	c	d	c	d	c	d	c	d	c	d	c	d
100	2793	-0.430	11292	-0.780	1630	-0.210	1421	-0.160	1749	-0.250	1950	-0.240
150	1265	-.430	4329	-.780	2279	-.210	1768	-.160	2164	-.250	2430	-.240
200	2793	-.430	11292	-.780	1630	-.210	1421	-.160	1749	-.250	1950	-.240
220	1265	-.430	4329	-.780	2279	-.210	1768	-.160	2164	-.250	2430	-.240
250	1244	-.095	1001	-.088	4759	-.065	3894	-.013	3558	-.086	3871	-.097
300	1244	-.095	1001	-.088	4759	-.065	3894	-.013	3916	-.086	3871	-.097
400	4009	-.095	2850	-.088	2624	-.065	2950	-.013	2959	-.086	3053	-.097
500	17075	-.355	7499	-.182	5742	-.129	10000	-.263	8536	-.204	17999	-.371
600	7128	-.258	1280	-.156	1077	-.238	3980	-.472	4035	-.326	2418	-.148
700	3632	-.258	2483	-.156	4289	-.238	6149	-.472	2690	-.326	1860	-.148
800	7885	-.258	4915	-.156	19458	-.238	24358	-.472	2690	-.326	1860	-.148
900	3186	-.353	2560	-.285	7339	-.418	6491	-.404	3753	-.317	2410	-.212
1000	255	-.101	600	.053	10328	-.026	10368	-.066	5192	-.222	3253	-.213
1100	571	-.101	2400	.053	7448	-.026	7373	-.066	3090	-.222	2510	-.213
1200	1850	-.101	2177	.053	3376	-.026	3365	-.066	3747	-.222	2411	-.213
1300	1850	-.101	2177	.053	3376	-.026	3365	-.066	3747	-.222	2411	-.213
1400	737	-.260	1100	-.210	1012	-.270	859	-.440	1330	-.340	953	-.270
1500	816	-.101	960	.053	3641	-.026	5841	-.066	7231	-.222	2033	-.213

Node	April		May		June		July		August		September	
No.	c	d	c	d	c	d	c	d	c	d	c	d
100	8754	-0.660	3091	-0.460	2191	-0.390	2134	-0.310	1169	-0.150	789	-0.050
150	11377	-.660	4984	-.460	4177	-.390	5027	-.310	1770	-.150	597	-.050
200	8754	-.660	3091	-.460	2191	-.390	2134	-.310	1169	-.150	789	-.050
220	11377	-.660	4984	-.460	4177	-.390	5027	-.310	1770	-.150	597	-.050
250	4872	-.095	6708	-.115	7646	-.087	8848	-.031	5391	-.053	2220	-.056
300	4872	-.095	6708	-.115	7646	-.087	8848	-.031	5391	-.053	2220	-.056
400	3263	-.095	4477	-.115	4150	-.087	3166	-.031	4752	-.053	4752	-.056
500	7646	-.176	15539	-.287	10922	-.203	8346	-.171	34460	-.518	22186	-.380
600	4605	-.482	10620	-.365	5803	-.275	3178	-.185	13696	-.189	12779	-.163
700	8914	-.482	6507	-.365	2477	-.275	2054	-.185	1700	-.189	1950	-.163
800	24806	-.482	23269	-.365	3298	-.275	1712	-.185	615	-.189	1950	-.163
900	27236	-.683	3046	-.290	1750	-.305	3491	-.337	2619	-.222	1860	-.200
1000	4698	.023	4520	-.188	1443	-.093	2740	-.167	2567	-.142	1489	.066
1100	4928	.023	3497	-.188	2290	-.093	4045	-.167	4026	-.142	2290	.066
1200	2234	.023	3449	-.188	2334	-.093	1838	-.167	1750	-.142	1783	.066
1300	2234	.023	3449	-.188	2334	-.093	1838	-.167	1750	-.142	1783	.066
1400	1366	-.170	1897	-.160	1236	-.130	1410	-.150	1584	-.180	632	-.260
1500	2409	.023	7834	-.188	2473	-.093	2957	-.167	2842	-.142	494	.066

Table 9.--Final values of test statistic (R^2) at output nodes

[--, not calculated]

Node name and number (fig. 9)	Final value of test statistic (R^2)			
	Stream discharge		Dissolved-solids concentration	
	Calibrated	Tested	Calibrated	Tested
Powder River near Kaycee (300)	0.71	0.88	--	--
Powder River at Sussex (600)	.85	.95	--	--
Powder River at Arvada (800)	.93	.98	--	--
Powder River at Moorhead (1000)	.96	.99	--	--
Powder River at Broadus (1100)	.96	.99	--	--
Powder River near Locate (1500)	.97	.98	0.50	0.41

To determine the sensitivity of the model to the parameters used in this investigation, the calibrated and tested model was used to simulate 1975-88 with selected parameters being varied, in turn, by −20 and +20 percent. This type of analysis does not consider the effect of interactions between two or more parameters on model results--it assumes all parameters are independent. One parameter, irrigation return-flow percentage, was varied by only −20 percent because the value used in the model simulations was 100 percent. If a ±20-percent change in any parameter resulted in a change of more than ±5 percent in simulated stream discharge or dissolved-solids concentration at Powder River near Locate (site 24, node 1500), the model was considered to be very sensitive to that parameter. If a ±20-percent change in any parameter resulted in a change of ±1 to ±5 percent in simulated stream discharge or dissolved-solids concentration at node 1500, the model was considered moderately sensitive to that parameter. If a ±20-percent change in any parameter resulted in a change of less than ±1 percent in simulated stream discharge or dissolved-solids concentration at node 1500, the model was considered insensitive to that parameter.

The model was tested for sensitivity to irrigated acreage, effective-precipitation factor, potential evapotranspiration, sinuosity factor, irrigation-demand factor, canal-seepage factor, irrigation return flow, transmissivity, and specific yield. The values of the parameters used and the results of the sensitivity analysis for each parameter are shown in table 10. As the results in table 10 indicate, neither stream discharge nor dissolved-solids concentration was very sensitive to the tested parameters. Either discharge or dissolved-solids concentration was moderately sensitive to six parameters. The parameter to which discharge was most sensitive was irrigated acreage; a −20-percent change produced a +4.3-percent change in simulated

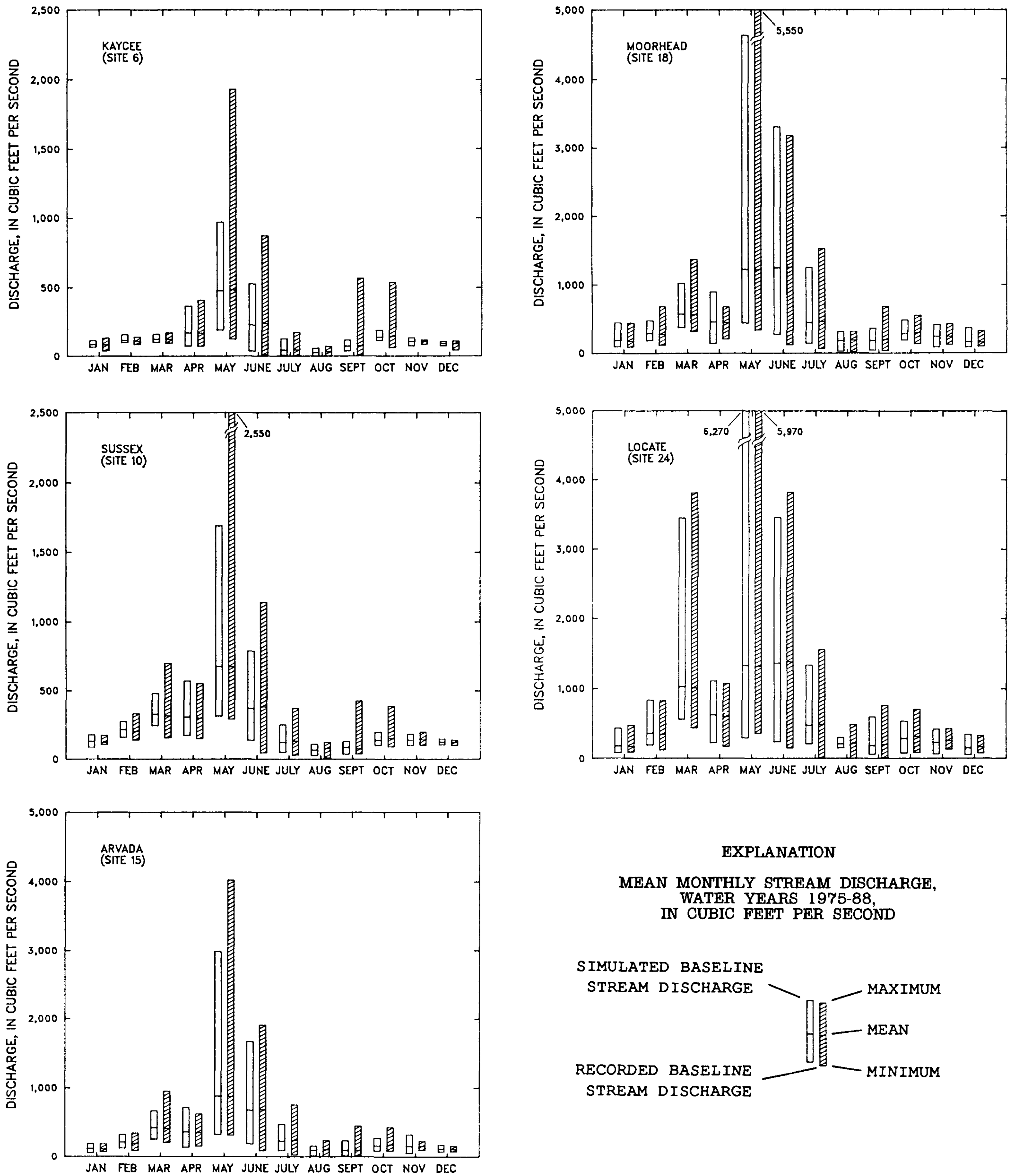


Figure 10.--Mean monthly stream discharge for simulated and recorded baseline conditions at selected sites in the Powder River.

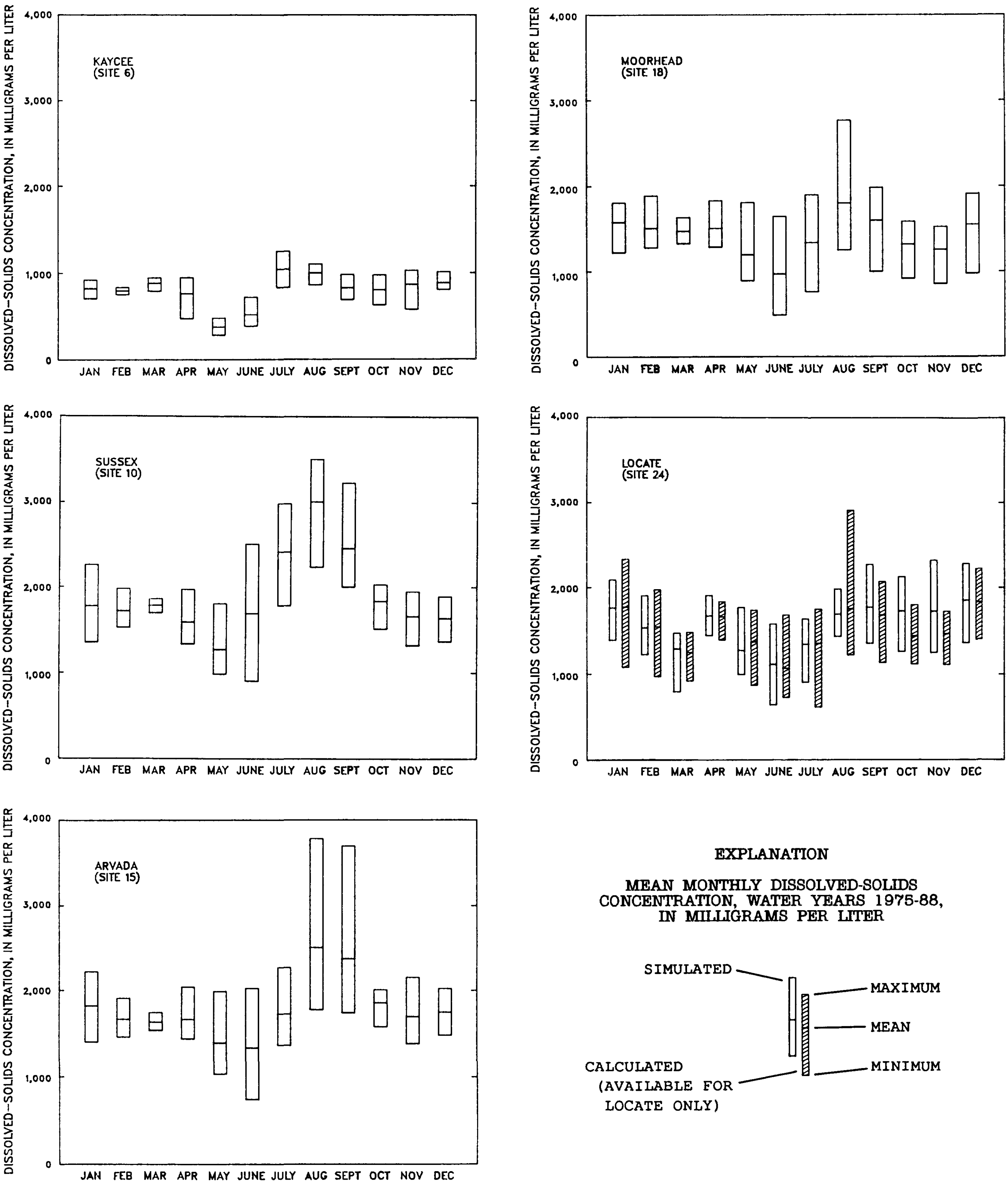


Figure 11.--Mean monthly dissolved-solids concentrations for simulated and calculated baseline conditions at selected sites on the Powder River.

Table 10.--Final values of parameters and sensitivity of model results

[Sensitivity: M, moderately sensitive--a 20-percent change in the parameter resulted in a change in simulated discharge or dissolved-solids concentration of between 1 and 5 percent at Locate; I, insensitive--a 20-percent change in the parameter resulted in less than a 1-percent change in simulated discharge or dissolved-solids concentration at Locate]

Parameter	Parameter value		Sensitivity	
	Wyoming	Montana	Stream discharge	Dissolved-solids concentration
Irrigated acreage (acres)	15,600	15,000	M	M
Effective-precipitation factor (in.)	6.0	6.0	I	I
Potential evapotranspiration (in.)	(varies by month)		M	M
Sinuosity factor (unitless)	1.75	1.75	M	M
Irrigation-demand factor (unitless)	1.8	2.5	M	M
Canal-seepage factor (acre-ft/mi)	200	200	M	M
Irrigation return flow (percent)	100	100	M	I
Transmissivity (ft^2/d)	2,040	2,040	I	I
Specific yield (unitless)	.20	.20	I	I

discharge at Locate. The parameter to which dissolved-solids concentration was most sensitive was potential evapotranspiration; a −20-percent change produced a −3-percent change in simulated dissolved-solids concentration at Locate. Perhaps most importantly, discharge and dissolved-solids concentration were insensitive or only moderately sensitive to the parameters that were most subjectively determined or had the least amount of data available (irrigation-demand factor, effective-precipitation factor, and irrigation return flow). Efforts to improve estimates of these parameters, therefore, probably are not warranted.

Baseline Simulation

The baseline simulation uses the calibrated and tested model parameters for the simulation period and represents the hydrologic conditions in the Powder River drainage basin during water years 1975-88. The baseline simulation is used for comparison with application simulations presented later in this report. As shown in table 9, the test statistic R^2 for the baseline simulation, when compared with recorded data, was 90 percent or greater for stream discharge at most sites, and 41 to 50 percent for dissolved-solids concentration at node 1500 (Powder River near Locate). Figure 10 shows the mean monthly simulated and recorded minimum, mean, and maximum stream discharge during the baseline-simulation period; figure 11 shows simulated and calculated dissolved-solids concentration for the same period.

Application Simulations

The model can be used to simulate the effects of various changes in water use, land use, and water management on stream discharge and dissolved-solids concentrations at any output node downstream from the change. Because many simplifying assumptions are required in any mathematical representation of a hydrologic system, use of the model to make specific predictions of the discharge and dissolved-solids concentrations that would occur at any node in the Powder River basin under a specified set of conditions probably is not warranted. However, differences resulting from alternate sets of conditions probably can be compared reliably.

Three types of application simulations are presented in this report. The primary purpose in presenting them is to demonstrate the way in which the model could be used, rather than to present them as specific management alternatives. The first two applications show how the model could be used to examine the effects of specific changes in water use and management in the basin on the hydrologic system. Decreasing discharge of oil-production water to Salt Creek and increasing irrigated acreage in Montana are simulated, and the results of the simulations are compared to the results of the baseline simulation. The third application demonstrates the use of the two-stage regression equations to estimate the concentration of a specific constituent of concern--in this case dissolved sodium--based on simulated dissolved-solids concentrations. Simulated hydrologic conditions are compared with simulated baseline conditions at output nodes representing sites along the main stem. The results of the simulations are presented in two formats: Comparison of the minimum, mean, and maximum stream discharge or dissolved-solids concentration for each month during the simulated hydrologic conditions with corresponding values for the simulated baseline period; and comparison of the percentage of time a given discharge or concentration was equaled or exceeded during the simulated hydrologic conditions and the simulated baseline period.

Change in Discharge in Salt Creek

Salt Creek, an upstream tributary of the Powder River, flows through a major oil and gas field; saline ground water is brought to the surface with the oil and gas. Under natural conditions, Salt Creek was ephemeral, flowing only in direct response to precipitation. For decades, however, the saline oil-production water has been discharged into Salt Creek, changing it to a perennial stream. Except for peak flows resulting from precipitation, stream discharge has averaged 50 ft^3/s during water years 1975-88. Dissolved-solids concentrations generally ranged from about 2,300 to 4,800 mg/L, representing a combination of the natural water and the oil-production water.

For at least 3 years prior to February 1990, the oil producers in the area discharged an average of 36.7 ft^3/s of saline oil-production water into Salt Creek. One oil producer in the area was discharging 91 percent of all saline oil-production water discharged into Salt Creek, an average of 33 ft^3/s with an average dissolved-solids concentration of 3,430 mg/L (311 tons/d) (Data on file, Wyoming Department of Environmental Quality). In February 1990, that producer began reinjecting to ground water about 85 percent of the oil-production water it had previously discharged to Salt Creek (77 percent of all the oil-production water discharged to the creek), thus reducing the average stream discharge of Salt Creek by 28 ft^3/s.

The model was used to simulate changes in stream discharge and dissolved-solids load in Salt Creek (site 9, node 500) and the subsequent effects of those changes at downstream sites on the Powder River main stem, and these changes were compared with the baseline simulation. To simulate the changes in Salt Creek, monthly stream discharges greater than 28 ft^3/s in Salt Creek during water years 1975-88 were decreased by 28 ft^3/s, and monthly stream discharges of 28 ft^3/s or less were decreased to 0.0001. The new simulation indicated that had 1975-88 conditions been identical except that 28 ft^3/s of oil-production water was not discharged to Salt Creek, the stream at site 9 would have been dry 29 of 168 months, or 17 percent of the time.

The dissolved-solids concentrations were recomputed in the model using the regression equation given in table 8 (node 500), but the results were not realistic, because the decreased stream discharges were outside the range of data used to develop the regression equation. Therefore, the regression equation for the neighboring, hydrologically similar South Fork Powder River (site 7, node 400) was substituted for the Salt Creek regression equation in the model.

The validity of substituting the regression equation for South Fork Powder River for the equation for Salt Creek was checked as follows. The average dissolved-solids load in Salt Creek under baseline conditions was calculated from the regression equation for Salt Creek (table 8, node 500) to be 520 tons/d. Of this amount, one oil producer now reinjects an estimated average of 259 tons/d in 28 ft^3/s of oil-production water and discharges only 52 tons/d to Salt Creek, as previously described. The remainder, 209 tons/d, is attributed to a combination of natural conditions and other oil-production water. The dissolved-solids load in Salt Creek, after the average stream discharge is reduced by 28 ft^3/s, was calculated from the regression equation for South Fork Powder River (table 8, node 400) to be 149 tons/d. Oil-production water still being discharged to Salt Creek could account for the difference, 60 tons/d, or 11 percent of the original total. Therefore, the substitution of the regression equation for South Fork Powder River to simulate the behavior of Salt Creek under near-natural conditions is a reasonable assumption, until sufficient data have been collected to revise the regression equation for Salt Creek.

When the simulation with decreased oil-production water discharge to Salt Creek is compared with the baseline simulation, the most dramatic differences appear at Salt Creek (site 9) (figs. 12 and 13). The range in mean monthly dissolved-solids concentrations under the two sets of conditions is shown in figure 12. The percentage of months a dissolved-solids concentration was equaled or exceeded is shown in figure 13. The simulated dissolved-solids concentrations for decreased oil-production water discharge to Salt Creek indicate an overall decrease in comparison with the baseline simulation; however, there were a few exceptions. At low flows, simulated dissolved-solids concentrations for decreased oil-production water discharge were larger than baseline, because of the inverse relation between stream discharge and dissolved-solids concentration. In figure 13, the extremely large dissolved-solids concentrations for the decreased oil-production-water-discharge alternative on the upper right-hand side of the graph for Salt Creek represent dry conditions; the dissolved-solids load contributed by the stream to the Powder River main stem is zero. Overall, dissolved-solids loads decreased from baseline values.

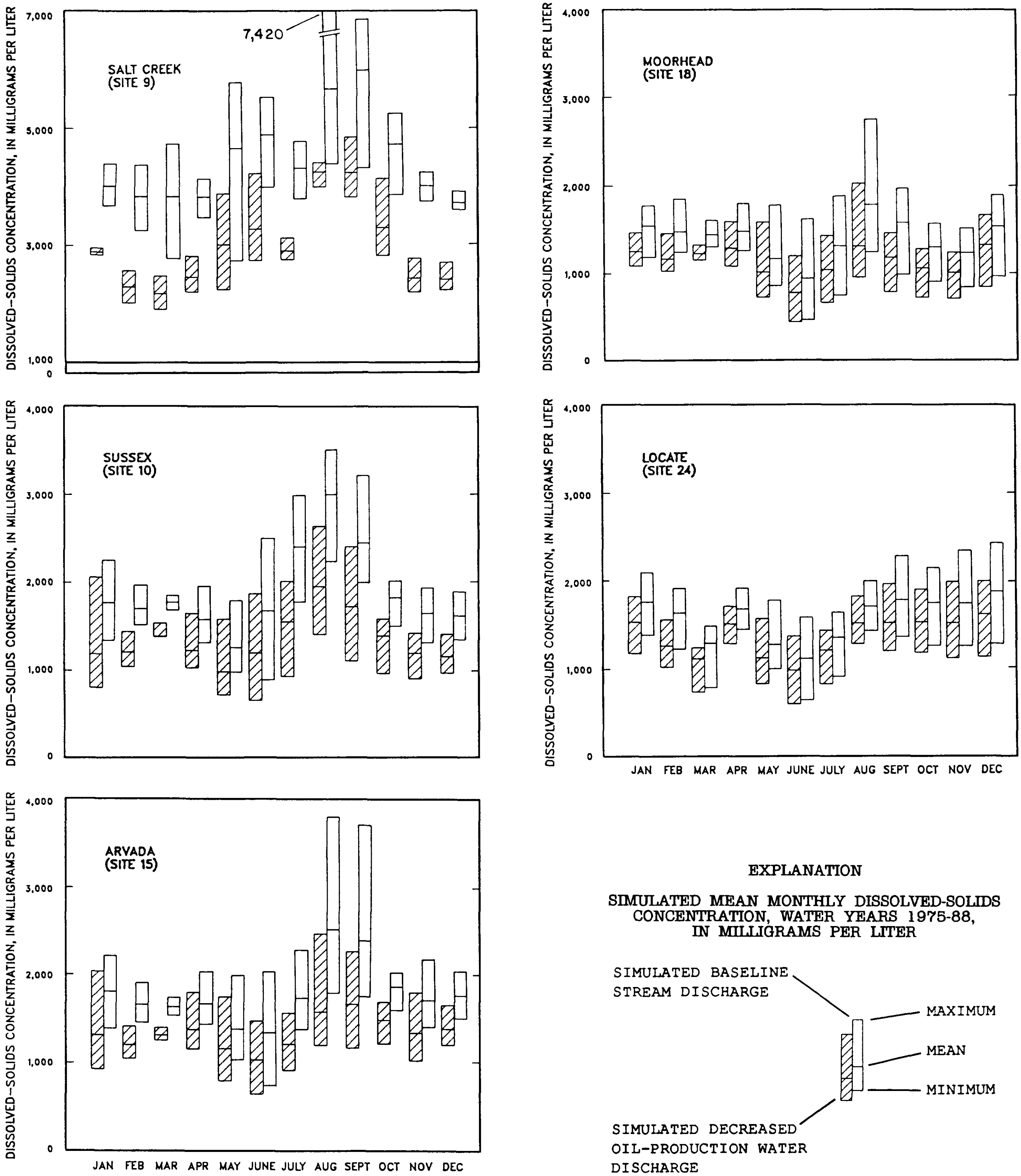


Figure 12.--Mean monthly dissolved-solids concentrations at selected sites on the Powder River and Salt Creek for simulated decreased oil-production water discharge to Salt Creek and for simulated baseline stream discharge.

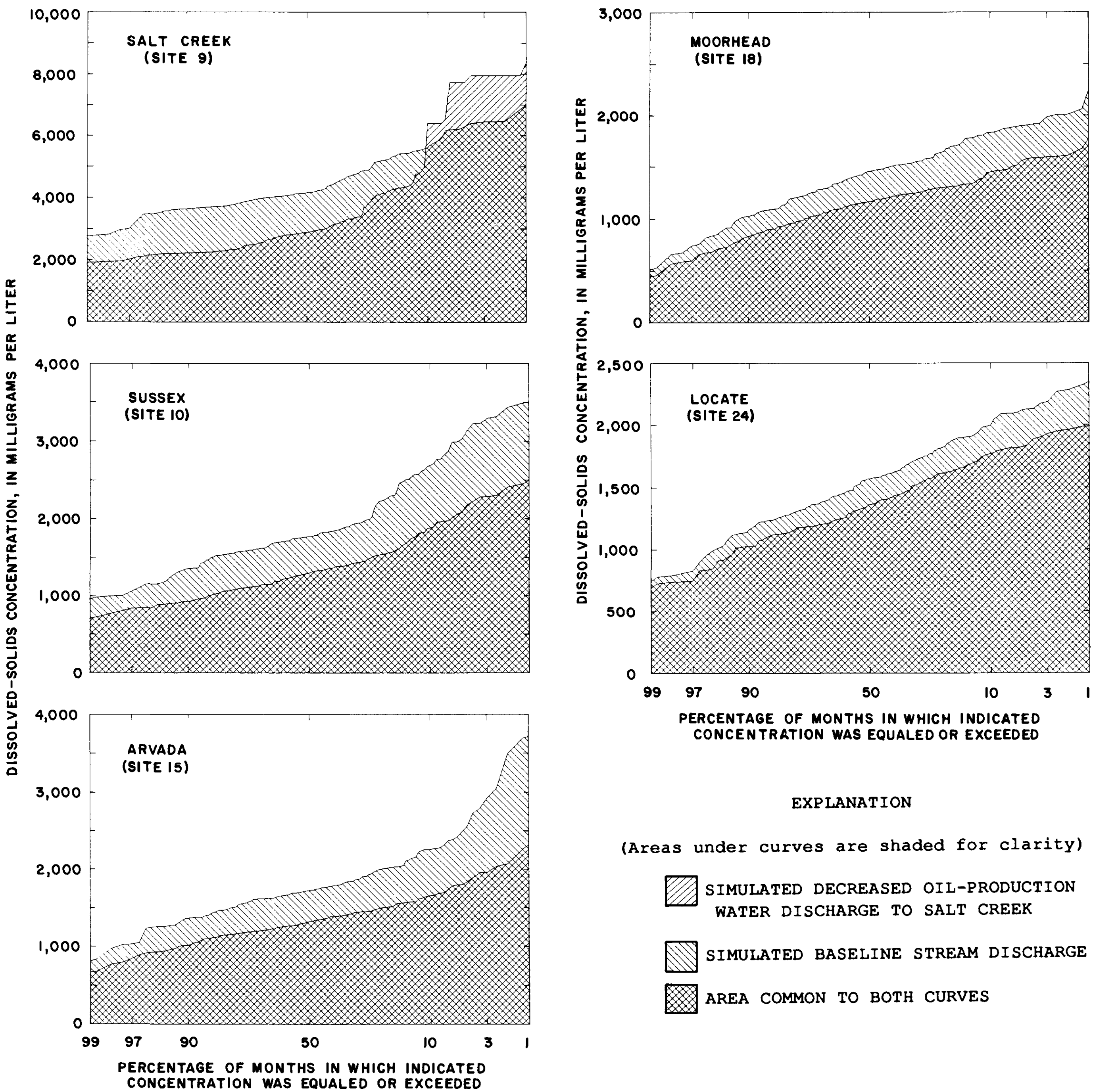


Figure 13.--Percentage of months in which mean monthly dissolved-solids concentrations were equaled or exceeded at selected sites on the Powder River and Salt Creek for simulated decreased oil-production water discharge to Salt Creek and for simulated baseline stream discharge.

The changes at Salt Creek also affect stream discharge and dissolved-solids concentration at sites on the Powder River downstream from Salt Creek. The results of the simulation with decreased oil-production water discharge to Salt Creek and the baseline simulation were compared for selected main-stem sites (figs. 12 and 13). At all sites downstream from Salt Creek, the decreased oil-production water discharge caused an overall decrease both in simulated stream discharges and in simulated dissolved-solids concentrations. The differences were greatest at sites that had the smallest discharges. However, at each successive node downstream, the proportional effect of the decreased oil-production water discharge from Salt Creek was dampened. At the node representing Powder River at Sussex (site 10, node 600), the average dissolved-solids load for water years 1975-88 was decreased 35 percent compared with the baseline simulation. At nodes representing Arvada (site 15, node 800), Moorhead (site 18, node 1000), Broadus (site 19, node 1100; not depicted in figs. 12 and 13), and Locate (site 24, node 1500), the average dissolved-solids load decreased about 20 percent, indicating that removal of oil-production water discharge to Salt Creek has a moderate effect on the quantity and chemical quality of water in the Powder River.

Hypothetical Change in Irrigated Acreage

The model is an exploratory tool that planners could use to evaluate the effects on the hydrologic system if a particular water use were implemented. To illustrate the use of the model for this purpose, the effects of increasing irrigated acreage in Montana by 20 percent were simulated. Thirty-five percent of the irrigated acreage simulated in Montana is located upstream of Powder River at Broadus (site 19); the remaining 65 percent is between site 19 and Powder River near Locate (site 24). The use of a 20-percent increase is for demonstration purposes only and is not meant to imply that such a change in water use is being considered. The simulation assumes that factors such as water-use efficiencies, crop demand, canal-seepage losses, leaching, and the concentrating effects of consumptive use are the same as in the baseline simulation.

The ranges of mean monthly stream discharges for the simulation for increased irrigated acreage and for the baseline simulation are shown in figure 14. The percentage of months in which a given stream discharge was equaled or exceeded for the two simulations is shown in figure 15. Similar information for mean monthly dissolved-solids concentrations is shown in figures 16 and 17.

Increasing irrigated acreage in Montana would have almost no effect on simulated stream discharge and dissolved-solids concentration for Powder River at Broadus (site 19) (figs. 14-17). At Powder River near Locate (site 24), mean monthly stream discharge for July through September is slightly less for the increased irrigation simulation than for the baseline simulation. Mean dissolved-solids concentration for August and September is slightly greater for the increased irrigation simulation than for the baseline simulation. Slight variations between baseline and increased irrigation simulation results during October through April are probably caused by effects of irrigation return flow.

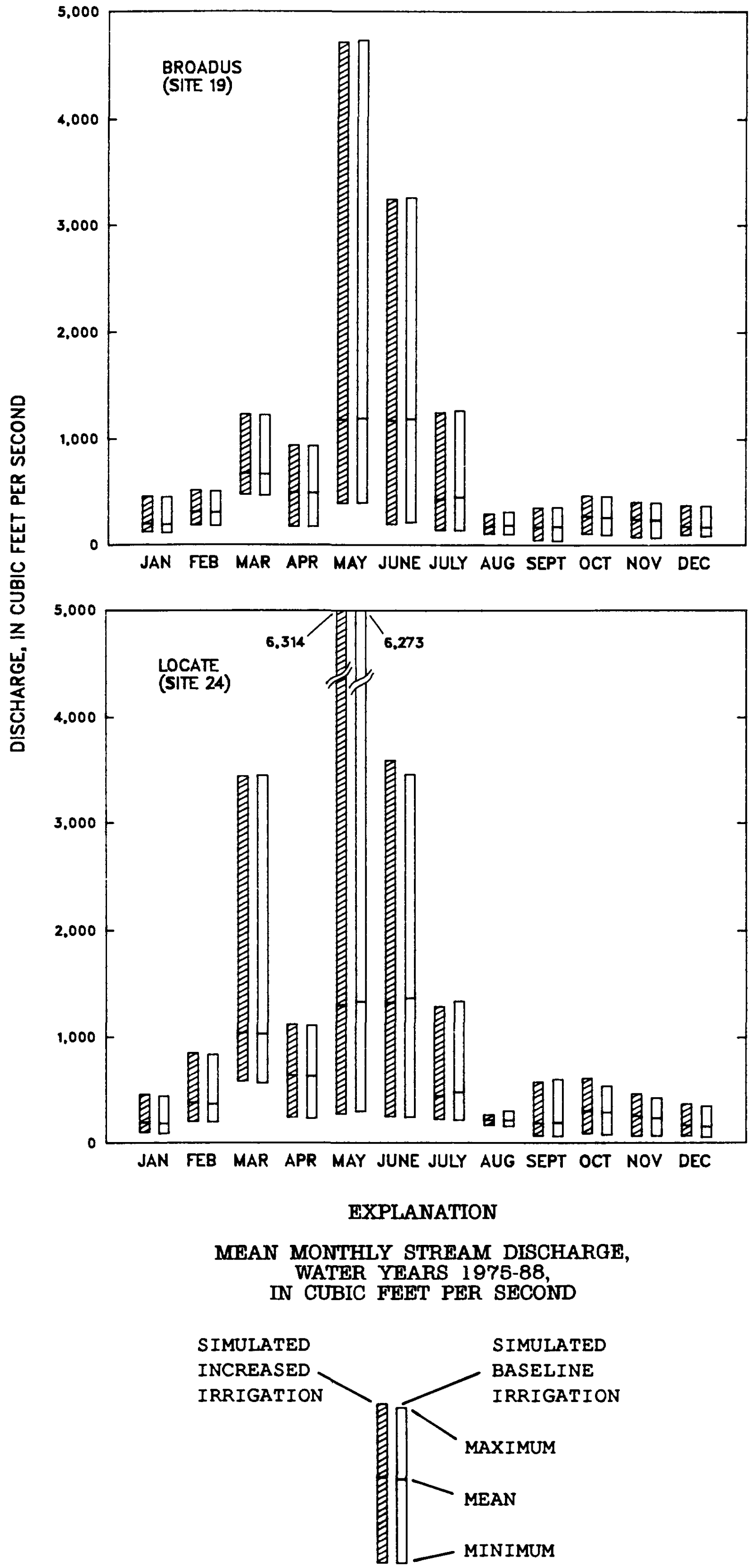


Figure 14.--Mean monthly stream discharges at selected sites on the Powder River for simulated increased irrigation in Montana and for simulated baseline irrigation.

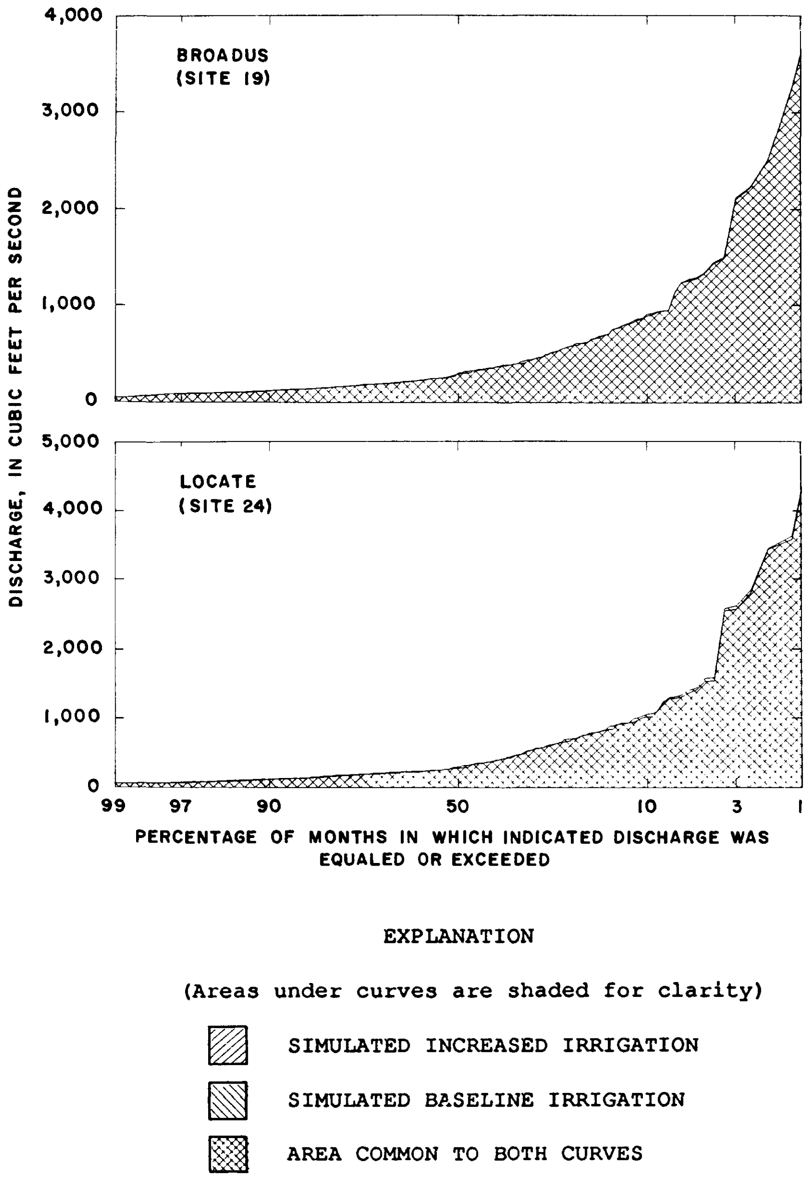


Figure 15.--Percentage of months in which mean monthly stream discharges were equaled or exceeded at selected sites on the Powder River for simulated increased irrigation in Montana and for simulated baseline irrigation.

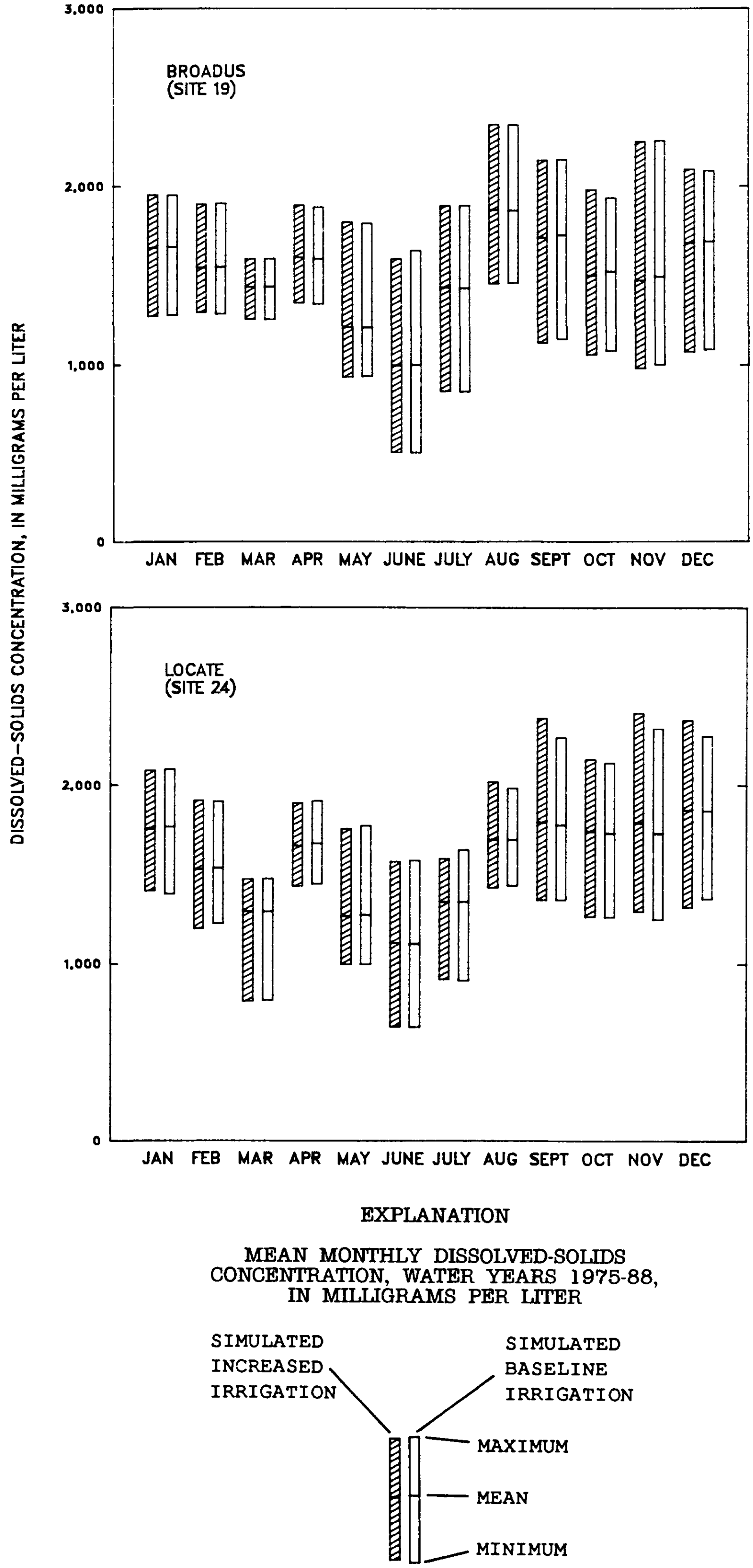


Figure 16.--Mean monthly dissolved-solids concentrations at selected sites on the Powder River for simulated increased irrigation in Montana and for simulated baseline irrigation.

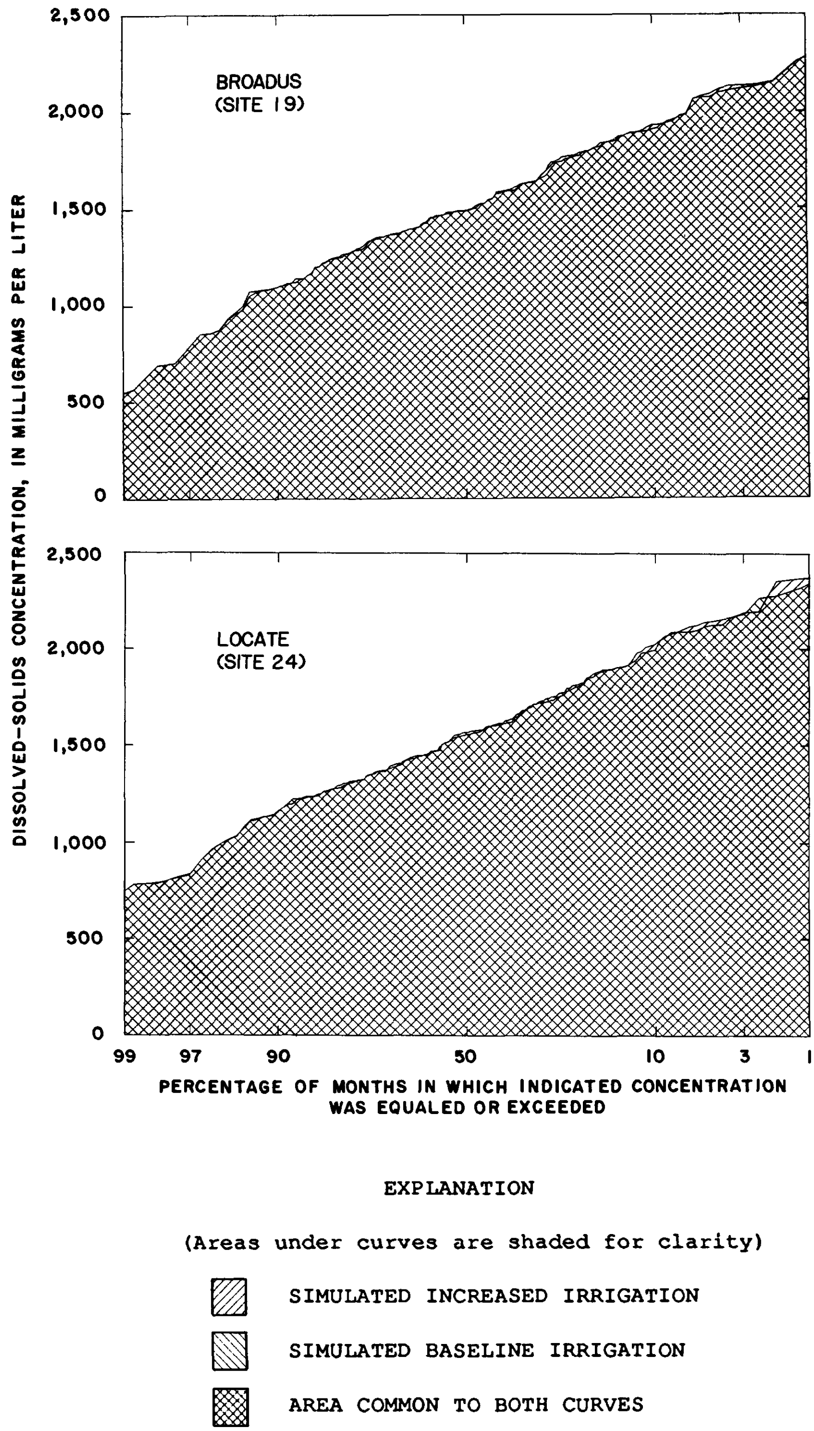


Figure 17.--Percentage of months in which mean monthly dissolved-solids concentrations were equaled or exceeded at selected sites on the Powder River for simulated increased irrigation in Montana and for simulated baseline irrigation.

Dissolved Sodium

In addition to dissolved-solids concentration, irrigators in the Powder River drainage basin are concerned about the dissolved-sodium concentration in the water. Sodium is of particular concern because it can interact with soils, particularly clayey soils, decreasing the soil's ability to transmit water and degrading its texture. Moreover, some crops are sensitive to the concentration of dissolved sodium in irrigation water.

The equations presented in table 6 to relate dissolved-solids concentration to dissolved-sodium concentration in the Powder River and its tributaries were incorporated into the model. Recorded mean dissolved-sodium concentrations during 1975-88 at five main-stem sites and simulated mean-sodium concentrations for the same period is shown in table 11. The baseline range in monthly dissolved-sodium concentrations at the five main-stem sites is shown in figure 18.

Table 11.--Recorded and simulated mean dissolved-sodium concentrations

Powder River site and No. (fig. 2)	Recorded mean dissolved-sodium concentration (milligrams per liter)	Number of discrete water samples	Simulated mean dissolved-sodium concentration (milligrams per liter)
Kaycee (6)	91	127	205
Sussex (10)	522	110	533
Arvada (15)	443	131	461
Moorhead (18)	255	133	315
Locate (24)	292	124	329

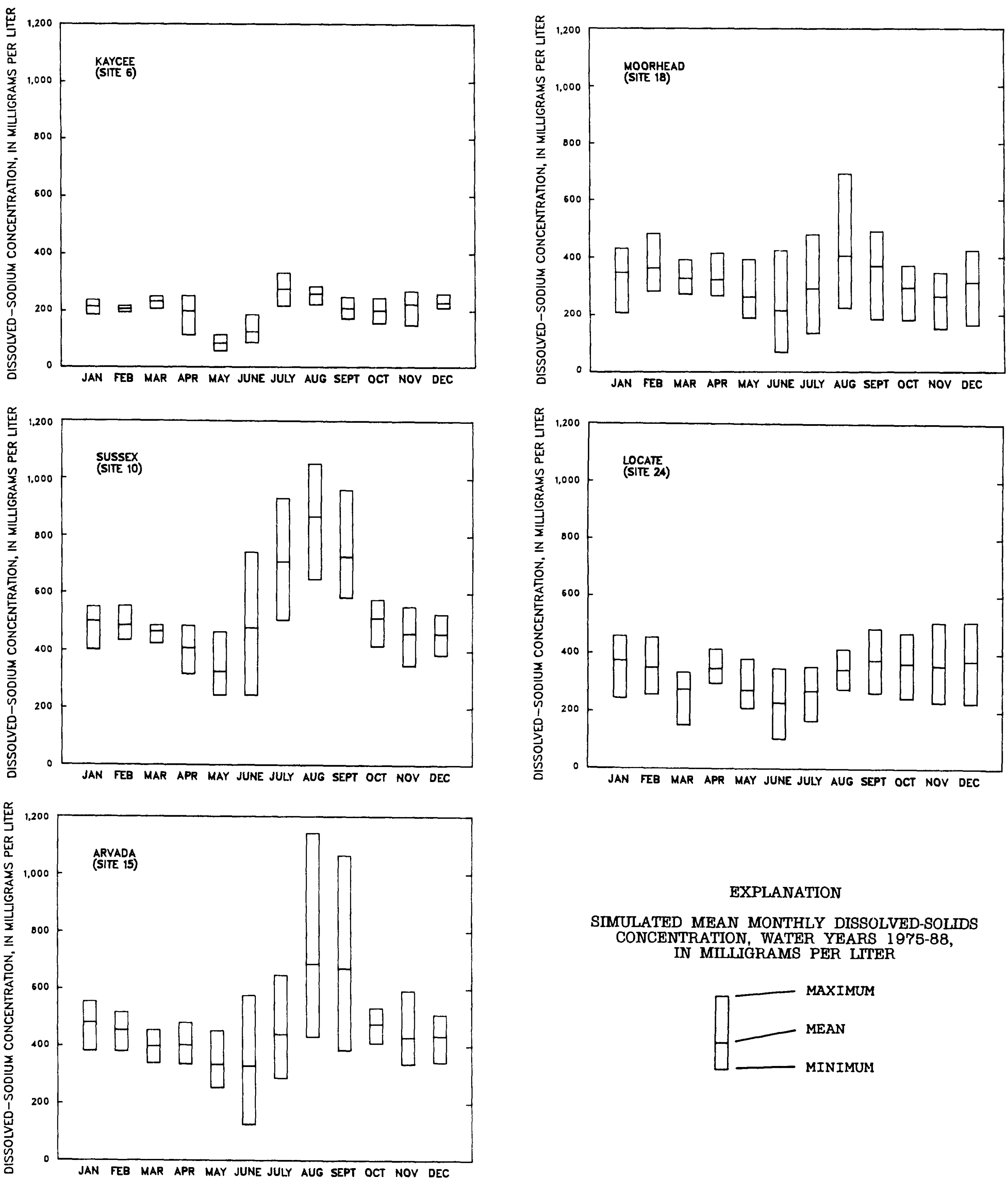


Figure 18.--Mean monthly dissolved-sodium concentrations for simulated baseline conditions at selected sites on the Powder River.

SUMMARY

The Powder River drains an area of about 13,500 mi^2 in northeastern Wyoming and southeastern Montana. The drainage area of the Powder River comprises two contrasting hydrologic settings--mountains and plains. Most of the dependable flow in the river originates in the mountains. Dissolved-solids load in the tributary streams is not necessarily proportional to their stream discharge--two of the mountain streams, Clear Creek and Middle Fork Powder River, contributed more than one-half the average discharge at Locate (site 24, near the mouth of the Powder River) during 1975-88, but less than one-fourth the total dissolved-solids load. By contrast, the plains streams, although mostly intermittent or ephemeral, are the source of more than one-half the average dissolved-solids load at Locate. An average of about 37 ft^3/s of saline oil-production water is discharged to Salt Creek, increasing both the discharge and the dissolved solids in the main stem.

Long-term data from stations in the hydrologic-data network in Wyoming and Montana were used to evaluate trends in selected water-quality characteristics, to generally describe the water quality, and to calibrate and test a mathematical model of discharge and water quality. The long-term data were supplemented for this investigation by a short-term (June 1988 through December 1989) program to collect discharge and water-quality data concurrently at 19 sites on the Powder River and its major tributaries; 12 of these sites were at active network stations.

Dissolved-solids concentration in the Powder River varies with location and stream discharge. The smallest dissolved-solids concentrations in the main stem generally were detected at Kaycee (site 6), and ranged from about 300 to 1,300 mg/L. Water was a calcium-sodium-sulfate type. Inflow from Salt Creek, mixing with main-stem water, caused sodium and chloride concentrations to increase substantially and relative sulfate concentrations to decrease substantially in the Powder River at Sussex (site 10). Downstream from Sussex, relative sodium concentrations gradually decreased, and relative sulfate concentrations gradually increased. The largest dissolved-solids concentrations in the Powder River, ranging from about 500 to nearly 5,000 mg/L, generally were detected at Arvada (site 15). Water was a sodium-sulfate type.

Discharge and dissolved-solids concentrations generally are related inversely. For example, on April 12, 1989, discharge in the Powder River at Locate (site 24) was 304 ft^3/s, and dissolved-solids concentration was 1,610 mg/L. On September 15, 1988, however, discharge was only 1.1 ft^3/s, and dissolved-solids concentration was 3,450 mg/L. Water was a sodium-sulfate type on both days.

In a separate but related study, trends in water-quality characteristics at seven hydrologic-network stations during water years 1968-88 and at nine stations during water years 1975-88 were investigated using a seasonal Kendall test with correction for serial correlation. Increasing trends in concentrations of sodium, chloride, and adjusted sodium-adsorption ratio were detected at five or more stations, including Powder River near Sussex (site 9), at Arvada (site 15), and near Locate (site 24). A decreasing trend in concentration of calcium was detected at four stations. Although the increasing trend in chloride was 6.4 percent per year at a station on the Little Powder River, most increasing trends that were statistically significant (90-percent confidence level) were from 1 to 2.8 percent per year.

A conceptual model of the hydrologic system in the basin was developed by identifying pathways for water movement and processes occurring along those pathways which substantially affected discharge and dissolved-solids concentrations and loads. Irrigation diversion and return flow, canal leakage, consumptive use, evaporation, movement into and out of the alluvium, and local inflow such as overland runoff are important pathways for water movement in the system. Dissolved-solids concentration in water moving along these pathways is affected by processes such as concentration by evaporation and transpiration, and gain of solutes by leaching or dissolution of minerals. The conceptual model was translated into mathematical terms to develop the numerical model.

To aid in estimating the effects of implementing water-management alternatives on surface-water quantity and quality in the basin, a computer model was calibrated, tested, and used for application simulations. The model is a conservative monthly mass-accounting model. Records for water years 1975-81 were used to calibrate the model, and records for water years 1982-88 were used to test the model. The model was calibrated and tested for stream discharge by comparing simulated values to recorded values at six main-stem sites, and for dissolved-solids concentration by comparing simulated values to estimated values at one main-stem site. A baseline was simulated to represent the surface-water system during water years 1975-88. Values of the test statistic for the simulation of discharge were better than 90 percent for most sites. The baseline model was used for comparison with the results of application simulations.

Three application simulations are presented. The first application simulates the effect of removing 77 percent (28 ft^3/s) of all the oil-production water that was discharged to Salt Creek during water years 1975-88. At all sites on the Powder River downstream from Salt Creek (site 9), the decreased oil-production water discharge caused an overall decrease both in simulated stream discharges and in simulated dissolved-solids concentrations. However, downstream from Arvada (site 15), the change in dissolved-solids load was about 20 percent, indicating that the removal of 77 percent of the discharge of oil-production water to Salt Creek has a moderate effect on the water quantity and dissolved-solids concentrations of the Powder River. The second application simulates the effect of increasing irrigated acreage in Montana on discharge and dissolved-solids concentrations in the Powder River; the increase caused only a small change in simulated discharge and dissolved-solids concentrations at main-stem sites in Montana. The third application simulates dissolved-sodium concentrations at sites on the Powder River, using regression equations relating dissolved-sodium concentration to dissolved-solids concentration. Both recorded and simulated mean-sodium concentrations are smallest at Kaycee and largest at Sussex.

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WATER-QUALITY DATA

Table 12.--Analyses of water samples from the Powder River

[°C, degrees Celsius; ft^3/s, cubic feet per second; μS/cm, microsiemens per centimeter at 25
estimated

Date	Discharge (ft^3/s)	Specific conductance (μS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
Site 1, Middle Fork Powder River above Beaver Creek,									
4-11-89	24	720	8.4	8.0	11.0	360	93	30	20
Site 2, Middle Fork Powder River below Beaver Creek,									
4-11-89	44	890	8.4	10.0	10.0	500	130	42	21
Site 3, Middle Fork Powder River above									
6-02-88	140	410	8.4	13.0	10.4	200	52	17	9.0
7-05-88	41	950	7.9	20.0	7.8	450	120	35	22
7-25-88	32	890	8.3	24.0	7.8	490	130	39	27
9-06-88	24	980	8.2	14.0	9.2	490	130	41	26
10-17-88	45	895	8.2	8.0	9.8	450	110	42	26
11-28-88	53	950	8.3	0	10.4	490	130	39	21
1-12-89	35	950	8.2	0.5	10.6	530	140	43	22
2-28-89	37	1,010	8.4	0	11.6	490	130	40	27
4-11-89	53	900	8.4	4.5	11.4	490	130	41	21
4-27-89	133	462	8.4	7.0	9.6	230	60	19	9.9
5-24-89	77	482	8.0	11.5	9.0	240	60	22	16
6-26-89	39	775	8.6	21.5	7.8	380	98	33	26
8-07-89	20	980	8.3	20.5	8.5	490	130	40	30
9-19-89	32	900	8.1	13.0	9.7	440	110	39	21
10-31-89	45	930	8.2	2.0	11.9	460	120	39	20
12-05-89	42	960	8.2	6.0	10.4	460	120	39	18
Site 4, Red Fork near Barnum,									
7-25-88	4.7	730	8.4	27.0	8.0	340	82	32	29
9-06-88	8.2	645	8.2	20.5	9.2	320	80	30	19
10-17-88	27	615	8.3	9.5	10.0	310	74	30	20
11-28-88	20	690	8.2	.5	12.0	340	85	30	19
1-12-89	18	670	8.2	0	11.3	350	87	32	20
3-01-89	22	695	8.4	.5	12.3	330	82	30	21
4-11-89	43	670	8.3	4.0	11.2	320	79	29	16
4-27-89	113	295	8.2	7.0	9.4	150	38	13	4.4
6-26-89	26	625	8.6	20.0	10.3	320	84	27	19
8-07-89	3.1	740	8.3	19.0	8.7	330	83	31	27
9-23-89	28	640	--	11.0	--	310	77	29	16
10-31-89	27	650	7.9	3.0	11.4	310	75	29	17

degrees Celsius; mg/L, milligrams per liter; lab, laboratory; <, less than; --, no data; E, discharge]

Sodium-adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dissolved (mg/L)	Nitrogen, NO_2+ NO_3, dissolved (mg/L as N)	Phosphorus, total (mg/L as P)
near Barnum, Wyo. (station 433901106505001)									
0.5	1.8	150	210	14	0.2	8.3	468	0.1	0.03
near Barnum, Wyo. (station 433905106504801)									
.4	2.1	170	300	11	.2	9.0	619	.3	.03
Kaycee, Wyo. (station 06309500)									
.3	1.3	110	80	5.2	.2	7.7	238	< .1	.04
.4	2.3	120	290	8.7	.2	9.9	564	.1	.03
.5	2.3	110	320	11	.3	7.9	603	< .1	.04
.5	2.3	150	360	14	.3	8.9	673	.1	.01
.5	2.0	160	320	10	.3	8.2	616	.3	.02
.4	2.2	91	300	13	.3	11	574	.6	.03
.4	2.1	--	300	10	< .1	11	--	.8	.04
.5	2.2	160	320	13	.3	9.0	640	.6	.08
.4	2.7	--	--	9.0	.3	7.9	--	.1	.20
.3	1.4	100	130	4.7	.2	7.9	295	.4	.05
.4	1.4	110	130	6.5	.2	6.3	308	< .1	.03
.6	2.2	150	250	8.0	.3	7.9	515	< .1	.04
.6	2.3	150	320	13	.3	10	636	< .1	.03
.4	2.4	160	390	70	.5	4.8	734	< .1	.03
.4	3.2	120	300	11	.4	8.9	575	.2	.06
.4	2.6	180	300	12	.3	9.9	612	.5	.12
Wyo. (station 06310000)									
.7	2.7	85	170	38	.3	7.6	413	< .1	< .10
.5	2.3	180	130	23	.3	9.5	403	.2	.01
.5	2.3	170	120	22	.3	7.6	379	.2	< .03
.5	2.3	140	130	25	.3	9.7	387	.5	< .03
.5	2.2	--	110	22	.3	10	--	.6	< .03
.5	2.0	--	120	23	.3	9.4	--	.4	< .03
.4	2.7	--	--	18	.3	7.3	--	.4	< .03
.2	1.4	110	37	4.7	.1	7.4	175	.7	.05
.5	2.1	180	130	16	.3	7.1	393	< .1	.05
.6	2.5	180	160	26	.4	8.2	446	< .1	< .03
.4	2.1	190	110	19	.4	9.4	378	.2	< .03
.4	3.2	190	110	20	.3	8.3	378	.3	.03

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 5, North Fork Powder River near			
7-25-88	3.6	2,450	8.3	22.5	8.7	710	160	75	310
9-06-88	13	1,480	8.3	20.5	8.6	460	100	50	140
10-17-88	24	1,350	8.3	11.0	9.9	430	94	48	130
11-28-88	14	1,460	8.1	.5	8.1	510	120	50	130
1-11-89	12	1,630	8.0	1.0	10.0	480	95	60	180
2-27-89	25	1,320	8.1	0	--	410	98	41	110
4-10-89	14	1,340	8.6	9.0	10.6	440	100	46	120
4-27-89	30	1,150	8.3	9.5	--	380	88	40	120
6-26-89	48	990	8.4	17.0	8.1	320	75	33	95
8-07-89	9.3	1,800	8.2	18.5	8.2	510	120	52	200
9-23-89	20	1,590	--	12.0	--	520	120	53	150
10-31-89	25	1,280	8.2	2.0	10.6	430	100	44	110
						Site 6, Powder River near Kaycee,			
6-02-88	71	--	--	18.0	--	280	70	25	53
7-05-88	.41	1,600	7.8	20.0	8.1	630	170	50	150
7-25-88	.68	1,850	8.0	21.5	7.7	650	160	60	200
9-07-88	.50	1,750	8.1	22.5	9.1	710	180	64	190
10-17-88	56	1,220	8.5	11.5	9.2	490	120	47	97
11-28-88	68	1,500	8.1	0	8.2	560	140	52	110
1-11-89	37	1,470	8.2	.5	12.4	590	150	52	110
2-27-89	102	1,220	8.3	0	--	460	120	39	79
4-10-89	114	1,120	8.4	4.0	11.4	410	100	40	81
4-27-89	290	550	8.4	9.5	--	250	68	20	40
5-24-89	26	860	8.1	16.0	8.4	300	74	29	55
6-26-89	35	1,120	8.4	15.0	8.3	410	100	39	93
8-10-89	.72	1,000	8.2	26.0	9.9	630	150	62	230
9-19-89	41	1,330	8.2	17.0	8.9	480	110	49	110
11-01-89	72	1,290	8.1	2.0	11.6	480	120	43	77
12-04-89	94	--	--	3.0	--	440	110	41	77

its tributaries, June 1988 through December 1989--Continued

Sodium-adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, dsoslved (mg/L)	Nitrogen, NO_2 + NO_3, dissolved (mg/L as N)	Phosphorus, total (mg/L as P)
Kaycee, Wyo. (station 06312000)									
5	13	180	850	210	0.60	7.1	1,730	<0.1	<0.03
3	5.8	190	460	72	.40	7.5	950	.1	.01
3	5.6	170	400	78	.40	5.5	864	.1	< .03
3	6.0	130	400	89	.40	12	887	.4	< .03
4	7.1	81	540	130	.40	15	1,080	.5	< .03
2	4.3	190	360	65	.30	10	806	.8	.05
2	5.4	93	480	70	.40	7.1	888	.7	< .03
3	4.1	180	300	54	.30	8.1	735	2.9	.03
2	3.6	160	280	37	.30	7.1	627	< .1	.05
4	10	170	500	170	.70	9.2	1,160	< .1	.04
3	6.7	190	440	91	.50	7.7	983	< .1	< .03
2	5.7	190	350	68	.40	9.7	803	.4	.03
Wyo. (station 06312500)									
1	2.3	140	190	34	.2	8.6	467	.1	.04
3	4.6	73	540	82	.3	8.2	1,050	.1	.02
3	4.7	210	630	100	.4	6.7	1,290	< .1	< .03
3	4.8	190	660	100	.4	6.7	1,320	.1	.01
2	3.7	160	400	59	.3	5.4	828	< .1	.05
2	3.9	83	460	76	.4	11	905	.5	< .03
2	4.0	--	370	82	.3	11	--	.7	.06
2	3.0	160	350	55	.3	8.1	753	.7	.04
2	3.3	89	350	44	.3	4.8	677	< .1	.25
1	2.8	--	140	18	.2	7.5	--	.5	.05
1	2.2	140	210	32	.2	7.0	493	< .1	.04
2	3.4	180	330	45	.3	7.6	726	< .1	.04
4	5.4	180	620	160	.5	5.6	1,340	< .1	.03
2	4.3	170	320	10	.4	8.1	714	.1	< .03
2	4.1	180	320	52	.4	8.5	734	.3	< .03
2	3.4	180	280	53	.3	9.3	684	.5	.03

Table 12.--Analyses of water samples from the Powder River and

Date	Dis-charge (ft^3/s)	Spe-ific con-duct-ance (µS/cm)	pH	Temper-ature (°C)	Oxygen, dis-solved (mg/L)	Hard-ness, total (mg/L as $CaCO_3$)	Calcium, dis-solved (mg/L as Ca)	Magne-sium, dis-solved (mg/L as Mg)	Sodium, dis-solved (mg/L as Na)
						Site 7, South Fork Powder River near			
7-05-88	0.85	--	--	31.0	--	--	--	--	--
7-25-88	0	--	--	--	--	--	--	--	--
9-07-88	0	--	--	--	--	--	--	--	--
10-18-88	.08	2,720	7.9	19.0	7.6	310	81	25	530
11-28-88	0	--	--	--	--	--	--	--	--
1-12-89	0	--	--	--	--	--	--	--	--
2-28-89	4.8	3,770	8.3	1.0	11.3	1,200	360	84	440
4-10-89	8.3	4,150	8.2	0	12.2	1,200	320	98	670
4-27-89	9.0	3,500	8.3	9.5	12.2	910	250	70	530
6-26-89	9.9	4,550	8.4	24.0	6.6	1,300	340	100	760
8-10-89	E .24	6,000	8.2	30.0	6.5	1,900	480	160	970
9-22-89	139	2,500	7.8	9.5	9.8	740	210	52	300
11-01-89	10	3,800	8.3	2.0	11.1	1,000	280	80	490
12-04-89	4.9	--	--	3.5	--	--	--	--	--
						Site 8, Salt Creek near Midwest,			
4-10-89	.03	1,500	8.0	1.0	7.8	780	180	80	180
						Site 9, Salt Creek near Sussex,			
6-20-88	31	--	--	24.0	--	240	40	35	1,600
7-26-88	30	6,330	8.5	21.5	7.8	170	26	25	1,500
9-07-88	25	6,150	8.3	17.5	8.3	220	39	30	1,400
10-17-88	31	6,000	8.5	9.5	7.8	200	30	31	1,500
11-28-88	19	7,350	8.6	0	12.4	260	44	36	1,500
1-11-89	36	6,100	8.4	0	11.6	230	38	32	1,300
2-27-89	51	4,400	8.3	0	9.6	400	69	55	1,300
4-10-89	33	5,700	8.7	3.0	11.0	330	54	47	1,300
4-27-89	38	6,000	8.6	11.5	9.2	210	33	32	1,300
5-25-89	29	6,500	8.7	12.0	--	250	35	40	1,600
6-26-89	32	5,300	8.2	18.0	5.4	320	58	42	1,200
8-10-89	23	5,400	8.2	18.5	7.8	190	36	25	1,100
9-20-89	501	2,400	8.2	9.5	8.0	320	80	30	370
10-31-89	39	6,000	8.5	2.0	11.3	240	44	31	1,200
12-04-89	28	--	--	3.0	--	310	62	37	1,300

Sodium-adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, disolved (mg/L)	Nitrogen, NO_2+ NO_3, dissolved (mg/L as N)	Phosphorus, total (mg/L as P)
Kaycee, Wyo. (station 06313000)									
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13	12	92	830	400	1.1	6.0	1,950	1.5	0.04
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5	8.5	150	1,700	78	.7	5.9	2,810	9.0	.09
8	12	150	2,200	94	.9	4.8	3,560	16.0	< .03
8	15	140	1,500	100	.7	3.9	2,570	3.5	.05
9	14	140	2,400	110	.8	5.2	3,820	.5	.06
10	20	140	3,200	89	.8	8.4	5,010	.3	.05
5	10	160	1,300	24	.6	5.3	2,000	1.1	.03
7	12	140	1,700	110	.7	6.2	2,770	1.5	.12
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Wyo. (station 431410106061101)									
3	6.1	320	660	11	.2	7.5	1,320	< .1	.04
Wyo. (station 06313400)									
45	16	790	770	1,000	2.6	24	3,960	< .1	.02
50	15	830	530	1,400	2.5	27	4,020	.1	< .03
41	18	690	750	1,300	2.3	29	3,980	.1	.01
46	15	840	650	1,200	2.3	24	3,960	.1	< .03
41	21	900	690	1,300	2.4	29	4,160	< .1	.26
38	16	--	610	470	2.5	25	--	.7	< .03
28	17	650	1,000	960	1.9	18	3,810	.8	.04
31	16	720	790	1,100	2.0	18	3,760	< .1	.04
39	12	--	540	750	2.1	21	--	< .1	< .03
44	16	860	710	1,300	2.4	17	4,240	< .1	.06
29	15	580	900	910	1.6	13	3,490	.4	.06
34	13	650	460	1,000	2.0	22	3,050	< .1	.04
9	8	230	770.3	180	.6	5.3	1,590	.7	.03
34	16	660	660	920	1.9	22	3,290	< .1	< .03
32	21	670	650	1,000	2.1	29	3,500	.1	.03

Table 12.--Analses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 10, Powder River at Sussex,			
6-20-88	42	--	--	22.0	--	400	75	52	1,300
7-26-88	33	6,000	8.4	26.5	7.7	230	32	36	1,400
9-07-88	27	6,200	8.5	21.5	7.7	230	35	34	1,400
10-17-88	87	3,250	8.3	10.0	9.6	390	81	46	620
11-28-88	110	3,050	8.5	0	12.8	520	120	54	470
1-11-89	79	3,300	8.3	0	12.0	540	130	52	520
2-27-89	170	2,700	8.0	0	11.2	520	130	47	410
4-10-89	193	2,500	8.3	10.0	9.3	430	100	44	420
4-27-89	335	1,340	8.4	9.5	9.6	240	57	23	190
5-25-89	68	3,800	8.4	15.5	--	400	84	45	760
6-26-89	99	2,650	8.1	24.5	6.1	520	130	47	610
8-10-89	27	3,800	8.3	22.0	7.6	330	69	38	750
9-20-89	93	3,190	8.2	11.5	8.9	340	70	40	590
9-22-89	378	2,580	7.9	12.5	8.3	600	160	49	360
10-31-89	127	2,900	8.2	2.0	12.0	430	100	43	430
12-04-89	151	--	--	3.0	--	460	110	44	320
						Site 11, Powder River above Dead Horse Creek,			
7-26-88	15	6,350	8.7	23.5	7.8	340	39	60	1,300
9-06-88	13	6,900	8.8	18.0	9.0	350	34	64	1,500
10-18-88	91	3,200	8.4	6.0	10.2	420	76	57	600
11-28-88	21	3,250	8.3	0	10.0	590	130	65	530
1-11-89	63	2,950	8.0	0	4.0	540	130	52	460
3-02-89	125	3,000	8.1	0	8.6	530	130	49	550
4-10-89	173	2,660	8.1	7.5	10.8	460	100	50	490
4-27-89	232	1,500	8.3	9.0	--	260	61	27	220
6-27-89	157	3,320	8.2	18.5	7.1	410	88	45	620
8-08-89	11	6,100	8.5	22.0	8.0	420	57	68	1,300
9-22-89	623	3,390	8.0	14.0	7.7	350	74	40	570
11-02-89	146	2,680	8.2	0	14.7	450	100	48	430

its tributaries, June 1988 through December 1989--Continued

Sodium-ad-sorp-tion ratio	Potas-sium, dis-solved (mg/L as K)	Alka-linity, lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, disolved (mg/L)	Nitrogen, NO_2+ NO_3, dis-solved (mg/L as N)	Phos-phorus, total (mg/L as P)
Wyo. (station 06313500)									
28	14	260	970	880	1.8	19	3,470	0.1	0.02
40	15	710	660	1,200	2.0	20	3,790	.1	< .03
40	18	670	800	1,200	2.3	25	3,920	.1	.01
14	8.1	350	610	530	1.0	11	2,120	.1	.03
9	7.2	330	480	400	1.0	12	1,740	.4	< .03
10	8.3	--	500	230	.9	15	--	.6	< .03
8	6.9	150	750	280	.6	9.9	1,730	.5	.03
9	7.2	300	540	270	.8	8.5	1,570	.0	.05
5	3.8	190	250	150	.4	10	800	.4	.04
17	9.7	450	660	620	1.2	12	2,460	< .1	.04
12	10	280	930	290	.8	7.1	2,200	.6	.07
18	12	400	660	570	1.4	12	2,350	.2	.05
14	8.8	330	520	480	1.0	10	1,920	.1	.03
6	10	180	1,000	100	.7	5.7	1,800	.8	.03
9	8.0	310	570	350	.8	9.8	1,700	.2	.03
7	7.5	260	470	270	.7	13	1,390	.4	.07
near Buffalo, Wyo. (station 441252106090801)									
30	15	510	1,100	1,200	1.6	11	4,030	<0.1	<0.03
35	< .2	610	1,200	1,100	.2	9.7	--	< .1	< .03
13	9.2	290	710	490	.9	8.9	2,130	.1	.03
9	8.7	270	690	460	.8	13	2,060	.5	< .03
9	7.4	--	480	280	.6	14	--	.5	< .03
10	8.2	--	830	340	.8	11	--	.6	< .03
10	11	200	660	320	.7	8.7	1,760	< .1	< .03
6	4.5	200	290	170	.6	9.7	905	.5	.05
13	10	280	720	490	1.0	7.5	2,150	.5	.06
28	17	360	1,200	1,100	1.4	13	3,970	< .1	.04
13	13	350	770	460	1.0	8.1	2,150	.4	.03
9	7.6	270	640	310	.9	7.9	1,710	.3	< .03

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
					Site 12, Dead Horse Creek near				
7-26-88	0	--	--	--	--	--	--	--	--
9-06-88	0	--	--	--	--	--	--	--	--
10-18-88	0	--	--	--	--	--	--	--	--
11-28-89	0	--	--	--	--	--	--	--	--
1-11-89	0	--	--	--	--	--	--	--	--
3-02-89	0	--	--	--	--	--	--	--	--
4-10-89	.04	5,020	7.8	13.0	--	2,500	520	280	590
6-27-89	0	--	--	--	--	--	--	--	--
9-22-89	0	--	--	--	--	--	--	--	--
11-01-89	0	--	--	--	--	--	--	--	--
					Site 13, Crazy Woman Creek below Timber Draw				
4-10-89	7.3	2,410	8.1	3.0	11.5	1,100	210	140	190
					Site 14, Crazy Woman Creek at upper station,				
6-07-88	8.2	--	--	26.0	--	--	--	--	--
7-06-88	3.6	--	--	23.0	--	--	--	--	--
7-26-88	.08	2,980	8.0	28.0	8.5	1,200	280	130	300
9-06-88	.03	3,100	7.9	24.5	7.2	1,300	280	140	350
9-25-88	3.1	--	--	18.0	--	--	--	--	--
10-18-88	2.9	2,630	7.9	8.0	8.4	1,200	230	150	230
11-29-88	5.0	3,130	8.1	0	12.8	1,100	170	170	230
1-12-89	3.9	2,340	7.7	0	13.3	1,100	230	130	170
2-27-89	9.4	1,830	7.9	0	10.6	800	180	86	120
4-11-89	9.8	1,980	8.3	11.0	8.8	1,000	220	110	180
4-27-89	8.7	2,650	8.2	9.0	--	1,300	240	160	220
6-26-89	42	1,400	8.2	21.0	7.8	560	130	58	67
8-08-89	.05	2,750	7.9	26.0	8.8	1,200	250	130	290
9-13-89	.04	--	--	12.0	--	--	--	--	--
9-22-89	12	2,860	7.8	15.0	9.0	1,100	260	120	300
11-02-89	15	1,550	8.1	1.5	12.2	660	140	75	96

its tributaries, June 1988 through December 1989--Continued

Sodium-ad-sorp-tion ratio	Potas-sium, dis-solved (mg/L as K)	Alka-linity, lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, disolved (mg/L)	Nitrogen, NO_2+ NO_3, dis-solved (mg/L as N)	Phos-phorus, total (mg/L as P)
Buffalo, Wyo. (station 06313700)									
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5	19	280	3,000	21	0.4	0.9	4,600	<0.1	<0.03
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--	--	--	--	--	--	--	--	--	--
near Buffalo, Wyo. (station 441500106254601)									
2	10	210	1,100	13	.3	4.0	1,790	< .1	< .03
near Arvada, Wyo. (station 06316400)									
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4	9.9	130	1,600	16	.4	3.8	2,420	< .1	< .03
4	9.1	300	1,600	14	.4	6.3	2,580	< .1	< .03
--	--	--	--	--	--	--	--	--	--
3	9.1	230	1,400	16	.4	3.7	2,180	.1	< .03
3	6.3	190	1,400	16	.3	7.8	2,110	< .1	< .03
2	4.6	--	920	9.8	.3	11	--	.4	.04
2	4.4	180	750	8.0	.3	8.2	1,270	.3	.03
2	9.4	150	1,000	10	.3	3.3	1,620	.1	< .03
3	6.2	--	1,100	15	.3	3.2	--	< .1	< .03
1	4.6	180	480	6.8	.3	9.5	864	< .1	.03
4	9.0	260	1,500	13	.5	7.0	2,360	< .1	< .03
--	--	--	--	--	--	--	--	--	--
4	9.3	290	1,500	13	.5	6.2	2,380	< .1	< .03
2	3.6	180	630	8.5	.3	5.2	1,070	< .1	< .03

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 15, Powder River at Arvada,			
6-22-88	55	--	--	25.0	--	750	170	78	630
7-27-88	2.1	6,200	8.5	22.5	8.7	710	120	100	1,300
9-06-88	0	--	--	--	--	--	--	--	--
10-18-88	89	3,600	8.6	7.0	11.2	450	77	62	690
11-29-88	32	4,300	8.2	0	12.6	610	100	88	620
1-12-89	96	3,280	7.8	0	4.6	580	130	61	470
2-27-89	97	2,650	8.1	0	11.6	430	100	44	420
4-11-89	169	2,900	8.3	12.0	7.6	560	130	58	440
4-27-89	352	2,100	8.3	8.5	--	350	77	39	320
6-07-89	260	2,210	8.2	17.5	8.0	440	100	46	260
6-26-89	113	2,790	8.3	24.0	7.4	530	120	57	440
8-07-89	5.0	6,030	8.3	30.0	7.7	770	160	89	980
9-13-89	113	5,400	--	14.5	--	480	95	60	1,000
9-22-89	63	3,260	8.4	13.5	9.2	400	81	48	620
11-02-89	148	3,200	8.3	2.5	11.9	580	130	61	490
						Site 16, Piney Creek at Ucross,			
6-23-88	77	--	--	21.0	--	--	--	--	--
7-26-88	32	940	8.2	26.0	8.9	390	98	35	42
9-07-88	37	870	8.1	16.0	7.8	400	94	41	42
9-28-88	23	--	--	8.5	--	--	--	--	--
10-08-88	22	--	--	6.0	--	--	--	--	--
10-18-88	39	690	8.3	10.0	12.0	320	83	28	28
11-30-88	14	920	8.2	0	12.6	400	98	38	41
1-11-89	13	850	7.8	0	12.9	360	87	35	36
2-28-89	24	710	7.8	0	12.8	320	80	29	31
4-11-89	30	780	8.3	2.0	10.8	440	99	46	62
6-26-89	38	765	8.1	13.0	9.8	290	69	28	31
8-07-89	61	720	8.2	17.5	8.7	320	84	26	29
9-15-89	42	--	--	11.5	--	--	--	--	--
9-23-89	17	770	--	15.0	--	340	81	33	35
11-01-89	12	845	7.8	.5	12.4	350	81	35	43

Sodium-adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, disolved (mg/L)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, total (mg/L as P)
Wyo. (station 06317000)									
10	2.7	230	1,400	300	0.9	8.7	2,730	0.9	0.05
21	17	330	1,600	950	1.1	6.9	4,290	< .1	< .03
--	--	--	--	--	--	--	--	--	--
14	9.6	310	830	540	.9	6.5	2,400	.1	.05
11	9.0	300	910	490	.8	9.8	2,410	.6	< .03
9	7.8	--	560	280	.7	14	--	.5	< .03
9	6.7	290	480	340	.6	8.4	1,570	.3	.03
8	7.8	260	650	340	.7	6.4	1,790	.5	.04
7	5.7	240	390	240	.7	13	1,230	.4	.04
5	6.8	180	650	92	.7	6.8	1,270	.7	.04
8	8.5	200	810	300	.7	9.1	1,870	< .1	.04
15	17	190	1,400	690	1.0	7.2	3,460	< .1	.06
20	15	390	1,000	860	1.4	7.2	3,280	.4	.05
13	12	240	800	470	1.1	8.8	2,180	< .1	.04
9	8.1	250	840	320	.7	7.0	2,010	.7	< .03
Wyo. (station 06323500)									
--	--	--	--	--	--	--	--	--	--
.9	5.4	110	310	2.5	.3	4.2	563	< .1	< .03
.9	5.6	150	330	3.0	.3	5.2	611	< .1	.12
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.7	5.2	160	210	2.3	.2	7.8	460	< .1	.06
.9	5.0	180	250	2.4	.3	11	554	< .1	< .03
.8	4.8	--	220	1.9	.2	13	--	< .1	< .03
.8	4.9	150	210	2.1	.2	8.4	456	< .1	< .03
1	5.9	210	310	3.9	.2	5.0	658	< .1	.03
.8	3.7	150	200	1.2	.2	6.1	429	< .1	< .03
.7	4.0	130	250	2.1	.3	4.5	478	< .1	.03
--	--	--	--	--	--	--	--	--	--
.8	4.8	180	210	2.1	.3	8.5	483	< .1	< .03
1	4.2	190	230	2.5	.2	11	521	< .1	< .03

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
Site 17, Clear Creek near Arvada,									
6-22-88	2.1	--	--	30.0	--	--	--	--	--
7-27-88	8.0	1,690	8.0	25.0	7.6	850	190	91	130
9-06-88	3.0	2,050	8.1	26.0	9.1	950	200	110	150
9-25-88	54	--	--	16.0	--	--	--	--	--
10-18-88	71	1,300	8.4	10.0	10.1	610	130	69	95
11-29-88	51	1,720	8.3	0	12.8	720	160	78	95
1-12-89	34	1,650	7.7	0	9.5	740	170	77	89
2-27-89	60	1,320	8.1	0	12.6	560	130	56	71
4-11-89	66	1,050	8.3	10.0	9.4	530	120	56	70
4-27-89	117	980	8.5	8.0	--	440	100	47	58
6-26-89	80	1,200	8.3	19.5	8.6	570	110	71	90
8-07-89	44	1,280	8.2	27.0	8.6	580	130	61	72
9-13-89	91	--	--	16.0	--	--	--	--	--
9-22-89	43	1,550	8.1	14.5	9.7	680	150	75	91
11-02-89	86	1,380	8.0	2.5	11.8	580	140	57	68
Site 18, Powder River at Moorhead,									
6-07-88	441	1,140	8.1	20.5	7.2	280	66	29	130
6-22-88	79	--	--	29.0	--	--	--	--	--
7-26-88	37	2,350	8.1	19.5	7.8	840	170	100	250
9-14-88	28	2,170	8.1	15.5	9.7	790	150	100	180
9-25-88	66	--	--	19.0	--	--	--	--	--
10-19-88	154	2,880	8.3	7.5	9.6	520	100	66	390
12-06-88	105	2,800	8.7	0	13.0	690	150	76	320
1-24-89	138	2,520	7.8	0	5.0	630	140	67	340
2-28-89	65	2,120	8.6	0	12.0	510	110	57	280
4-11-89	235	2,440	8.4	4.0	11.0	530	110	62	340
5-16-89	525	2,040	8.3	20.0	7.0	400	86	44	310
6-28-89	178	2,240	8.4	26.5	6.9	530	120	56	300
8-10-89	47	1,620	8.6	24.5	7.6	610	130	69	140
8-23-89	60	--	--	25.0	--	--	--	--	--
9-26-89	217	2,620	8.3	18.0	--	430	94	48	380
11-08-89	263	2,150	8.5	2.0	11.3	500	110	54	300

its tributaries, June 1988 through December 1989--Continued

Sodium-ad-sorp-tion ratio	Potas-sium, dis-solved (mg/L as K)	Alka-linity, lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, disolved (mg/L)	Nitrogen, NO_2+NO_3, dis-solved (mg/L as N)	Phos-phorus, total (mg/L as P)
Wyo. (station 06324000)									
--	--	--	--	--	--	--	--	--	<0.01
2	7.7	180	800	16	0.3	5.0	1,350	<0.1	< .03
2	8.5	230	980	5.9	.3	7.4	1,600	.1	.10
--	--	--	--	--	--	--	--	--	--
2	5.9	220	560	5.9	.2	6.0	1,000	.1	.06
2	5.4	140	600	16	.3	11	1,050	.2	< .03
1	5.6	--	530	3.9	.2	11	--	.5	< .03
1	5.9	200	490	4.4	.2	7.3	886	.4	< .03
1	8.0	180	500	3.4	.2	.9	866	< .1	< .03
1	3.8	180	330	2.7	.2	7.6	657	< .1	< .03
2	4.8	180	470	1.8	.2	3.9	860	< .1	.03
1	6.1	170	510	2.8	.3	5.8	890	< .1	.03
--	--	--	--	--	--	--	--	--	--
2	6.7	200	690	4.2	.3	6.8	1,140	> .1	< .03
1	4.3	140	490	3.8	.2	10	859	.3	< .03
Mont. (station 06324500)									
3	3.9	155	300	82	.3	7.2	711	< .10	--
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4	9.7	187	1,100	80	.3	5.8	1,830	< .10	0.06
3	8.8	210	1,100	18	.2	5.8	1,690	< .10	--
--	--	--	--	--	--	--	--	--	--
7	9.2	245	770	280	.5	6.1	1,770	< .10	.02
5	6.9	309	820	200	.4	9.5	1,770	.25	.01
6	6.6	377	660	160	.4	8.0	1,610	.27	.19
5	6.8	292	530	190	.5	12	1,360	.40	.06
6	6.7	243	740	240	.5	7.3	1,650	.17	.02
7	5.6	227	530	200	.6	8.3	1,320	.28	2.90
6	7.3	197	730	190	.5	7.1	1,530	< .10	.36
2	7.9	172	730	37	.3	5.6	1,220	< .10	< .01
--	--	--	--	--	--	--	--	--	--
8	9.3	223	860	150	.6	4.0	1,680	.61	.30
6	6.2	242	630	220	.5	8.0	1,470	.23	2.20

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 19, Powder River at Broadus,			
7-07-88	338	--	--	26.0	--	--	--	--	--
7-25-88	15	--	8.1	27.0	7.5	180	27	28	470
9-13-88	11	3,230	8.2	13.0	10.7	1,000	220	120	410
10-19-89	141	2,960	8.2	10.5	9.2	570	100	78	390
12-06-89	152	2,650	8.7	0	12.6	660	130	82	290
1-24-89	109	2,910	7.8	0	4.4	450	100	48	260
2-28-89	E65	2,370	8.4	0	11.0	560	120	63	330
4-10-89	271	2,480	8.3	7.0	10.9	570	120	65	340
5-17-89	221	2,310	8.4	16.0	8.5	470	100	53	340
6-29-89	177	2,260	8.3	19.5	7.4	490	110	52	300
8-11-89	18	2,420	8.4	22.0	7.5	800	170	90	290
8-23-89	35	--	--	26.5	--	--	--	--	--
9-28-89	183	2,700	8.3	16.0	--	450	99	50	440
11-08-89	240	2,050	8.6	2.0	11.4	510	110	57	280
						Site 20, Little Powder River at mouth,			
7-26-88	0.90	--	8.4	27.0	8.0	1,000	210	120	480
9-14-88	1.4	2,030	8.6	13.5	7.8	160	28	22	410
10-18-88	1.7	2,100	8.3	10.0	9.7	190	40	21	400
12-05-88	2.8	2,120	8.8	0	12.8	190	45	20	390
1-23-89	4.9	--	8.0	0	10.9	270	57	32	380
2-27-89	.39	1,880	8.7	0	11.6	240	53	27	350
4-11-89	11	2,190	8.3	10.0	10.6	370	72	45	380
5-17-89	69	1,560	8.2	17.0	7.2	280	58	33	240
6-30-89	22	3,240	8.4	22.0	6.6	660	120	87	510
8-09-89	.22	2,480	8.2	18.0	5.9	310	61	39	440
9-29-89	.72	2,000	8.6	14.0	7.1	160	29	21	410
11-09-89	3.5	1,440	8.6	3.5	10.4	110	27	9.5	290

its tributaries, June 1988 through December 1989--Continued

Sodium-ad-sorp-tion ratio	Potas-sium, dis-solved (mg/L as K)	Alka-linity, lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, disolved (mg/L)	Nitrogen, NO_2+ NO_3, dis-solved (mg/L as N)	Phos-phorus, total (mg/L as P)
Mont. (station 06324710)									
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15	7.2	417	770	7.5	0.3	3.5	1,560	<0.10	0.07
6	10	213	1,500	140	.3	5.5	2,530	< .10	--
7	3.0	233	880	260	.5	6.0	1,860	< .10	.02
5	7.0	295	820	170	.4	9.6	1,690	.28	.01
5	4.6	357	750	7.7	.2	6.8	1,390	< .10	.02
6	7.0	319	620	240	.7	13	1,590	.35	.14
6	7.0	244	780	200	.5	7.9	1,670	.24	.02
7	6.2	235	650	220	.6	9.3	1,520	.22	.66
6	7.6	189	740	190	.5	8.2	1,520	.13	.21
4	11	192	1,000	120	.4	10	1,810	< .10	< .01
--	--	--	--	--	--	--	--	--	--
9	10	236	970	180	.8	5.0	1,900	.85	5.70
5	6.3	245	670	180	.5	8.0	1,460	.21	2.00
near Broadus, Mont. (station 06325550)									
7	10	236	1,500	200	.4	12	2,670	< .10	.03
14	5.0	--	660	4.7	.3	4.5	--	< .10	.02
13	9.5	428	600	6.1	.3	2.9	1,340	< .10	.02
12	3.6	454	590	5.7	.2	12	1,340	< .10	.03
10	5.0	319	800	--	.5	14	--	.41	.13
10	5.2	391	640	8.2	.3	10	1,330	.14	.03
9	8.0	366	810	14	.3	10	1,560	< .10	.02
6	8.8	208	520	19	.4	8.7	1,010	.34	--
9	13	289	1,400	32	.4	5.3	2,340	< .10	.49
11	10	448	910	8.8	.4	13	1,750	< .10	.02
14	5.6	421	630	5.4	.3	3.0	1,360	< .10	.08
12	3.9	359	420	5.5	.2	10	982	.25	.07

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 21, Powder River near Powderville,			
7-27-88	3.7	3,520	8.1	18.5	8.0	820	170	96	550
9-15-88	2.8	3,640	8.1	11.0	9.3	720	150	85	630
10-20-88	124	2,950	8.2	8.0	10.0	610	110	81	390
12-07-88	121	2,910	8.6	0	13.0	630	120	80	360
1-25-89	110	2,800	7.7	0	4.6	700	150	80	400
3-01-89	66	2,750	8.4	0	13.0	610	130	70	380
4-12-89	260	2,510	8.3	5.5	10.6	570	120	65	350
5-18-89	276	2,370	8.4	18.0	8.2	480	100	57	370
6-29-89	178	2,210	8.4	25.5	7.5	530	120	56	320
8-09-89	22	3,450	8.4	22.5	8.1	770	170	85	500
9-27-89	231	3,850	8.3	14.5	--	630	130	74	630
11-07-89	255	2,350	8.6	3.0	10.6	510	110	58	330
						Site 22, Powder River near Mizpah,			
5-16-89	311	2,060	8.1	16.5	8.6	460	92	55	370
7-27-89	236	1,820	8.5	18.0	8.3	520	120	54	260
9-28-89	208	3,300	8.3	14.5	8.6	710	150	82	440
						Site 23, Mizpah Creek near Mizpah,			
10-20-88	.50	1,240	8.3	8.5	8.8	80	19	8.0	250
12-08-88	.30	4,200	8.6	0	12.4	300	54	39	770
1-25-89	.05	3,200	8.1	0	8.8	250	46	33	660
4-12-89	.53	1,120	8.5	6.5	9.4	99	24	9.6	190
5-16-89	5.8	831	8.6	15.5	8.0	70	17	6.7	180
6-27-89	2.1	--	8.1	19.5	6.2	170	40	17	330
11-07-89	5.6	940	8.4	3.0	12.0	63	15	6.3	180

its tributaries, June 1988 through December 1989--Continued

Sodium-ad-sorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, sum of constituents, disolved (mg/L)	Nitrogen, NO_2+ NO_3, dissolved (mg/L as N)	Phosphorus, total (mg/L as P)
Mont. (station 06325650)									
8	10	203	1,600	170	0.3	12	2,730	<0.10	0.02
10	10	202	1,700	130	.2	5.1	2,830	< .10	--
7	8.4	234	950	240	.4	6.0	1,930	< .10	.02
6	7.5	308	870	210	.4	9.9	1,840	.26	.09
7	7.6	382	850	280	.5	14	2,010	.41	.14
7	7.3	371	720	260	.6	14	1,810	.35	.05
6	7.4	248	820	200	.5	8.6	1,720	.24	.02
7	7.8	245	800	160	.6	9.1	1,650	.22	.69
6	8.0	206	790	170	.5	9.4	1,600	< .10	.46
8	13	211	1,300	300	.5	10	2,510	< .10	< .01
11	12	285	1,100	500	.7	5.0	2,620	.49	.28
6	6.7	239	770	190	.5	7.0	1,620	.27	2.90
Mont. (station 06326000)									
8	7.3	213	890	120	.5	11	1,670	.29	.10
5	7.8	200	750	120	.5	9.2	1,440	.14	.95
7	11	227	1,100	270	.5	6.0	2,200	.34	7.10
Mont. (station 06326300)									
12	5.1	248	410	11	.6	23	885	2.20	.29
19	8.8	807	1,300	13	.6	13	2,680	.19	.04
18	8.9	657	1,100	14	.4	12	2,270	.25	.08
8	4.1	198	340	4.0	.4	7.2	705	1.50	.13
9	3.8	181	320	11	.5	8.9	664	1.70	.23
11	6.3	343	560	4.1	.6	4.5	1,170	< .10	.12
10	6.0	180	290	11	.5	15	641	2.00	3.70

Table 12.--Analyses of water samples from the Powder River and

Date	Discharge (ft^3/s)	Specific conductance (μS/cm)	pH	Temperature (°C)	Oxygen, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
						Site 24, Powder River near Locate,			
6-21-88	246	2,050	8.2	23.5	7.2	490	110	51	270
7-27-88	6.5	3,400	8.2	31.0	7.3	670	130	85	540
8-05-88	2.8	3,550	--	15.5	--	--	--	--	--
9-15-88	1.1	4,330	8.2	20.0	10.0	810	160	100	760
10-05-88	30	3,100	--	6.0	--	--	--	--	--
10-21-88	67	3,200	8.2	5.0	10.2	660	130	82	430
12-07-88	93	3,460	8.7	0	12.8	760	160	88	440
1-26-89	95	2,870	7.9	0	4.4	670	140	77	400
3-02-89	66	2,920	8.2	0	8.6	650	140	73	420
4-12-89	304	2,470	8.4	9.0	10.2	480	110	51	290
5-17-89	304	2,090	8.2	15.0	8.8	460	96	54	350
6-28-89	201	1,900	8.8	20.0	7.5	510	120	50	280
8-08-89	7.4	2,690	8.4	18.5	8.0	610	110	80	500
9-28-89	202	3,490	8.2	15.5	8.0	720	150	85	450
11-07-89	275	2,360	8.3	2.5	11.2	430	92	48	330
12-27-89	107	2,600	8.5	0	13.0	540	110	65	350

Sodium-ad-sorp-tion ratio	Potas-sium, dis-solved (mg/L as K)	Alka-linity, lab (mg/L as $CaCO_3$)	Sulfate, dis-solved (mg/L as SO_4)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, disolved (mg/L)	Nitrogen, $NO_2 + NO_3$, dis-solved (mg/L as N)	Phos-phorus, total (mg/L as P)
Mont. (station 06326500)									
5	6.7	210	680	160	0.3	20	1,430	--	0.09
9	11	210	1,400	180	.3	12	2,480	<0.10	< .01
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12	12	282	2,000	220	.3	5.2	3,450	< .10	< .01
--	--	--	--	--	--	--	--	--	--
7	9.2	245	1,100	240	.4	6.0	2,190	< .10	.02
7	8.6	330	1,100	270	.4	11	2,280	.27	.04
7	7.7	375	880	260	.3	13	2,030	.38	.04
7	7.8	324	840	280	.5	14	2,010	.27	.05
6	7.9	210	800	210	.5	9.0	1,610	.19	.20
7	8.1	216	830	140	.5	11	1,620	.33	.03
5	7.6	197	790	140	.1	9.6	1,550	.16	.03
9	11	248	1,300	190	.4	14	2,350	< .10	.01
7	12	228	1,300	230	.5	6.0	2,370	.29	5.70
7	6.5	243	650	210	.5	7.7	1,470	.50	3.90
7	6.6	295	810	170	.4	11	1,690	.41	.14

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