TRENDS IN SELECTED WATER-QUALITY CHARACTERISTICS, POWDER RIVER AND TRIBUTARIES, MONTANA AND WYOMING, WATER YEARS 1968-88 AND 1975-88

by Lawrence E. Cary

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CONVERSION FACTOR AND ABBREVIATED WATER-QUALITY UNIT

Multiply	By	To obtain
mile (mi)	1.609	kilometer

Abbreviated water-quality unit used in report:

mg/L, milligrams per liter

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ABSTRACT

Relative sodium concentration and salinity are used in evaluating the suitability of water for irrigation. Data for selected water-quality characteristics that contributed most to relative sodium concentration and salinity in the Powder River and its major tributaries in southeastern Montana and north-central Wyoming were analyzed for trends. Those characteristics were of primary interest, owing to the effects of those characteristics on the suitability of the water for irrigation. This report describes the methods of analysis and the trends detected in the water quality of streamflow at combination streamflow-gaging and water-quality stations.

The methods of analysis consisted of review of data, computation of water-quality properties, statistical analysis, adjustment for stream discharge, and selection of the trend test for use. The data analyzed were collected at seven stations during water years 1968-88 and at nine stations during water years 1975-88. Six stations had sufficient data for analysis during both periods.

The seasonal Kendall test with correction for serial correlation was applied to flow-adjusted data for some characteristics and to unadjusted data for the remaining characteristics for water years 1968-88. Slope estimates were determined for the characteristics that had significant trends. Increases in adjusted sodium-adsorption ratio data were detected at four stations: South Fork Powder River near Kaycee, Wyoming (2.8 percent per year); Salt Creek near Sussex, Wyoming (1.9 percent per year); Crazy Woman Creek at upper station, near Arvada, Wyoming (1.3 percent per year); and Powder River at Arvada, Wyoming (2.2 percent per year). Trends also were detected in dissolved-solids data at three stations. Dissolved-solids concentration increased in the South Fork Powder River near Kaycee (1.2 percent per year) and in the Powder River at Arvada (0.6 percent per year). The dissolved-solids concentration decreased in Salt Creek near Sussex (0.9 percent per year).

The seasonal Kendall test with correction for serial correlation was applied to flow-adjusted data for water years 1975-88. The adjusted sodium-adsorption ratio increased at five stations: South Fork Powder River near Kaycee (4.3 percent per year); Salt Creek near Sussex (1.6 percent per year); Powder River at Sussex, Wyoming (2.8 percent per year); Powder River at Arvada (2.1 percent per year); and Powder River near Locate, Montana (1.2 percent per year). Trends were detected in dissolved-solids concentration at three stations. Dissolved-solids concentration increased in the Powder River at Sussex (1.3 percent per year), Powder River at Arvada (0.9 percent per year), and Powder River near Locate (0.9 percent per year).

Concurrent data for six stations for water years 1968-88 and 1975-88 were compared. The results differed between periods for some characteristics, but not for others. Adjusted sodium-adsorption ratio increased during both periods in the South Fork Powder River near Kaycee, Salt Creek near Sussex, and Powder River at Arvada. Dissolved-solids concentration increased during both periods in the Powder River at Arvada.

Increases in adjusted sodium-adsorption ratio and dissolved solids can result in the degradation of water's usefulness for irrigation. However, no inferences can be made about a trend continuing in the future.

INTRODUCTION

The Powder River originates in north-central Wyoming and flows northward, joining the Yellowstone River near Terry, Mont. (fig. 1). In Wyoming, most of the tributaries joining the Powder River from the west originate in the plains or foothills. However, Clear Creek and the uppermost headwaters of the mainstem Powder River originate in the mountains. All tributaries joining the Powder River in Montana originate in the plains or foothills.

Water from the Powder River and its tributaries is used for irrigation, industry, and domestic and livestock supply. Withdrawals for irrigation, the major use of water, constitute more than 98 percent of total water withdrawals. Of the withdrawals for irrigation, 90 percent are from surface-water sources (Lowry and others, 1986, p. 32, 33).

The quality of the water in the Powder River and the suitability of the water for irrigation vary seasonally. Two measures of the suitability of water for irrigation are the sodium-adsorption ratio, which indicates the relative sodium concentration, and the dissolved-solids concentration, which indicates the salinity. Small values of sodium-adsorption ratio and dissolved-solids concentration are generally associated with snowmelt runoff, mostly in April, May, and June, whereas large values are generally associated with periods of low flow, when ground-water discharge contributes a significant part of streamflow.

The ranges in values of sodium-adsorption ratio and dissolved-solids concentration determined during previous studies at three combination streamflow-gaging and water-quality stations on the Powder River reflect the variations in the suitability of the water for irrigation. Near Kaycee (fig. 1, station 1), which is upstream from most of the effects of streams that originate in the plains and foothills, the sodium-adsorption ratio ranges from about 0.5 to 3.5, and the dissolved-solids concentration ranges from 300 to 1,300 mg/L (Peterson, 1988, p. 35). At Sussex (station 4), which is downstream from the South Fork Powder River and from Salt Creek, the sodium-adsorption ratio ranges from about 3.5 to 28, and the dissolved-solids concentration ranges from 530 to 4,030 mg/L (Peterson, 1988, p. 38). About 28 mi upstream from the mouth near Locate (station 10), and downstream from the mountain stream Clear Creek, the sodium-adsorption ratio ranges from about 2.0 to 6.9, and the dissolved-solids concentration ranges from 408 to 2,130 mg/L (Knapton and Ferreira, 1980, p. 120).

The U.S. Salinity Laboratory Staff (1954, p. 75-81) classified the suitability of water for irrigation using the sodium-adsorption ratio and specific conductance (salinity). Specific conductance, a surrogate of dissolved solids, is used as a measure of salinity, because it is easily measured and values are commonly available. The staff defined four classes of hazard owing to relative sodium concentration and four owing to salinity as measured by specific conductance. The classes range from low to very high hazard. On the basis of this classification, water in the Powder River near Kaycee generally has a low sodium hazard and a medium to high salinity hazard. Water in the Powder River at Sussex has a low to very high sodium hazard and a high to very high salinity hazard. Water in the Powder River near Locate has a low to medium sodium hazard and a medium to very high salinity hazard.

Because of the marginal quality of the water for irrigation, increases in relative sodium concentration and salinity could result in the water being unsuitable for irrigation. Ranchers along the Powder River have expressed concern that activities in the Powder River basin and possible future development might result in increasing relative sodium concentration and salinity. As a result, the U.S. Geological Survey, in cooperation with the Montana Department of Natural Resources and Conservation, the Wyoming State Engineer, and the Wyoming Water Development Commission, studied the quality of streamflow in the Powder River. The study, which was conducted during 1988-90, included analysis of available data for trends (this report) and application of a water-quality model (separate report) to the Powder River and its major tributaries.

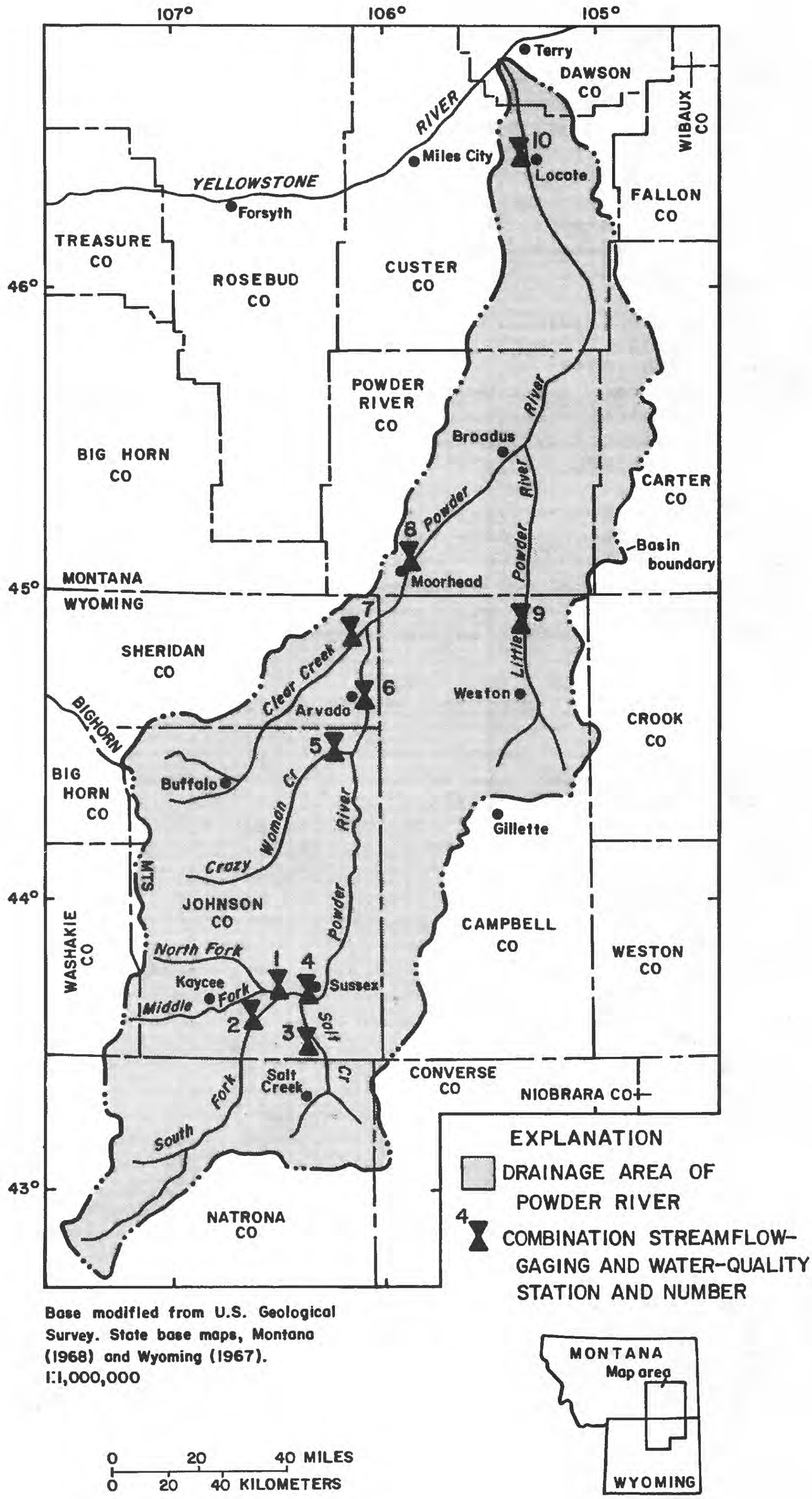

Figure 1.--Location of the Powder River and sampling stations used in the trend analysis.

Purpose and Scope

This report describes the methods of analysis and the trends detected in water quality of the Powder River and its major tributaries. Sites for study were selected from all combination streamflow-gaging and water-quality stations in the basin on the basis of length of record and total number of samples. The relative sodium concentration and the salinity of streamflow of the Powder River were of primary interest, owing to the effects of those characteristics on the suitability of the water for irrigation. Therefore, water-quality characteristics that contributed most to relative sodium concentration and salinity were selected for study.

Water-quality data from samples collected during water years[1] 1968-88 and 1975-88 were analyzed for trends. Sufficient data were available for analysis at seven stations for the period 1968-88 and at nine stations for 1975-88. The shorter period (1975-88) was included because that was the period selected for modeling. Six stations had sufficient data to allow comparison of trend results for the 21-year period with trend results for the more recent 14-year period. Trend analyses were performed using nonparametric statistical methods.

Eight water-quality characteristics were selected for study. The common ions of calcium, magnesium, sodium, sulfate, and chloride were selected because of their relative contribution to salinity. An adjusted sodium-adsorption ratio was selected to represent the relative sodium hazard. Alkalinity was selected because it represents the combined concentrations of bicarbonate and carbonate. Dissolved solids (sum of constituents) was selected because of its representation of overall salinity.

Previous Studies

Previous studies included trend analyses at some Powder River stations. Several previous studies included all or some of the water-quality characteristics that were tested in this study. Wells and Schertz (1983) used linear regression to analyze for trends in dissolved-solids concentrations of samples collected from March 1979 through September 1981 on the Powder River near Locate, Mont. Smith and Alexander (1983, 1985) reported the results of nonparametric trend analyses of the concentrations of common constituents, nutrients, biological variables, and trace elements for water years 1975-81 in the Powder River near Locate. Gallagher and others (1986) reported percentage changes in the monthly and seasonal mean values of selected water-quality characteristics in the Powder River near Locate and at Moorhead, Mont. They compared the mean values of the characteristics between years 1951-60 and 1975-81 near Locate, and between 1951-57 and 1972-84 at Moorhead. Smith and others (1987) analyzed as many as 24 water-quality characteristics for trends in the Powder River near Locate, using the same method as Smith and Alexander (1983, 1985). Cary (1989) used nonparametric trend tests to analyze common constituents, selected properties, and dissolved solids for water years 1952-63 and 1975-85 for the Powder River near Locate and for water years 1967-68 and 1976-85 for the Powder River at Sussex, Wyo.

METHODS OF ANALYSIS

Prior to testing for trends, the data from all stations in the study area were reviewed. After review, values for the water-quality properties of sodium-adsorption ratio and alkalinity were computed from other data. Then, the data selected for trend analysis were statistically analyzed. Next, the data for characteristics significantly related to streamflow were adjusted to remove the effects of stream discharge. Finally, each characteristic was tested for trends.

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[1] A water year is the 12-month period October 1 through September 30. It is designated by the calendar year in which it ends.

Review of Data

The selection of stations and data for analysis depends on several factors. In this study, stations were selected to give the largest number with the longest periods of data collection in the basin. Then, data from the stations were reviewed for sampling schedule, season selection, and effective sample size.

Station Selection

Although water-quality sampling in the Powder River basin began in 1946 (Lowry and others, 1986, p. 114-117), the sampling was only for short periods and at few stations until 1968. At that time, sampling frequency and number of stations sampled were increased because of heightened concern about the quality of streamflow. Activation of the National Stream Quality Accounting Network (NASQAN) in 1972 and the increased concerns about the effects of mineral development in southeastern Montana and northeastern Wyoming resulted in additional sampling beginning in 1975. Thus, data were available at seven stations for 1968-88, and at nine stations for a shorter, overlapping period 1975-88 (table 1, fig. 1). In addition, six stations had data for both periods, so that the results between the longer (21 years) and shorter (14 years) periods could be compared.

Sampling Schedule

The sampling schedule differed among stations (table 1). During water years 1968-88, for example, the length of sample collection ranged from 15 years on Crazy Woman Creek at upper station, near Arvada (station 5) to 21 years on the Powder River near Kaycee (station 1) and at Arvada (station 6). The mean number of samples collected per year during the period ranged from 9.0 on Clear Creek near Arvada (station 7) to 13.0 on the Powder River at Arvada. Sampling-frequency data also indicate changes in schedules through time. The percentage of the period of record in which more than nine samples were collected per year ranged from 48 percent on the South Fork Powder River near Kaycee (station 2) to 86 percent on Salt Creek near Sussex (station 3). Table 1 indicates that one or more samples were collected during each year of the period of record on the Powder River near Kaycee.

Sampling was similar for water years 1975-88. The length of sample collection ranged from 11 years on the South Fork Powder River near Kaycee and the Little Powder River above Dry Creek, near Weston (station 9) to 14 years at four stations on the mainstem Powder River. The mean number of samples collected per year ranged from 8.1 on Clear Creek near Arvada to 10.5 on the Powder River at Moorhead (station 8). The percentage of the period of record in which more than nine samples were collected per year ranged from 43 percent on the South Fork Powder River near Kaycee and on Clear Creek near Arvada to 79 percent on Salt Creek near Sussex. One or more samples were collected during each year of the period of record on the Powder River near Kaycee, at Moorhead, and near Locate (station 10).

The number of samples collected each year at the stations is shown in figure 2. During water years 1968-88, no samples were collected on Crazy Woman Creek at upper station, near Arvada (station 5) for 6 consecutive years. This is the longest period of no samples for the seven stations having 1968-88 data. Of the remaining six stations, samples were collected in all but 3 separate years at one station, in all but 2 years at one station, in all but 1 year at two stations, and each year at two stations. During water years 1975-88, there were 3 years when no samples were collected at two stations. The years were consecutive (1983-85) on the Little Powder River above Dry Creek, near Weston (station 9). Of the remaining seven stations, samples were collected in all but 1 year at three stations, and every year at four stations.

Sampling at most stations was more frequent in water years 1968-81 than in 1982-88. Monthly sampling was common in 1968-81. Beginning in water year 1982, sampling frequency was decreased at all stations. During the drought of 1988, many tributaries and some reaches of the Powder River were dry for all or part of the year. The drought is reflected in the small sampling frequency at some stations.

Table 1.--*Sampling schedule at stations used in the trend analysis*

Station No. (fig. 1)	Sampling station	Length of sampling (years)	Mean number of samples collected per year	Sampling frequency[1] (percent): More than nine samples per year	More than six samples per year	One or more samples per year
	Water years 1968-88					
1	Powder River near Kaycee, Wyo. (06312500)	21	10.0	76	81	100
2	South Fork Powder River near Kaycee, Wyo. (06313000)	18	9.5	48	76	86
3	Salt Creek near Sussex, Wyo. (06313400)	20	10.8	86	90	95
5	Crazy Woman Creek at upper station, near Arvada, Wyo. (06316400)	15	11.0	62	67	67
6	Powder River at Arvada, Wyo. (06317000)	21	13.0	67	81	95
7	Clear Creek near Arvada, Wyo. (06324000)	20	9.0	57	67	90
8	Powder River at Moorhead, Mont. (06324500)	19	10.0	53	84	95
	Water years 1975-88					
1	Powder River near Kaycee, Wyo. (06312500)	14	10.0	71	79	100
2	South Fork Powder River near Kaycee, Wyo. (06313000)	11	9.6	43	71	79
3	Salt Creek near Sussex, Wyo. (06313400)	13	10.4	79	86	93
4	Powder River at Sussex, Wyo. (06313500)	13	9.3	64	71	86
6	Powder River at Arvada, Wyo. (06317000)	14	9.4	57	71	86
7	Clear Creek near Arvada, Wyo. (06324000)	13	8.1	43	50	86
8	Powder River at Moorhead, Mont. (06324500)	14	10.5	50	93	100
9	Little Powder River above Dry Creek, near Weston, Wyo. (06324970)	11	10.0	50	57	64
10	Powder River near Locate, Mont. (06326500)	14	9.0	57	64	100

[1] Sampling frequency is the percentage of years having the specified number of samples.

Season Selection

Water-quality characteristics commonly display seasonality. The test statistic used in this study was calculated from data pairs within seasons to remove the effects of seasonality (Hirsch and others, 1982, p. 109; Smith and others, 1982, p. 6). The number of seasons depends on the sampling frequency; for example, 12 seasons would be specified for samples collected at monthly intervals, whereas 4 seasons would be used for samples collected quarterly (Hirsch and others, 1982, p. 109; Crawford and others, 1983, p. 57; Smith and Alexander, 1983, p. 9).

The results in table 1 indicate that monthly samples were not collected at most stations. The mean number of samples collected per year was at least 9.0 at every station during water years 1968-88 and at every station but one during water years 1975-88. The exception was Clear Creek near Arvada (station 7), where the mean number of samples collected was 8.1. More than six samples per year were collected 70 percent or more of the time at five of seven stations during water years 1968-88 and at six of nine stations during water years 1975-88.

On the basis of these considerations, nine seasons per year, each about 40.5 days long, were selected for trend analysis. Thus, on a water-year basis, the first season would include October (31 days) plus the first 9.5 days of November.

Effective Sample Size

Use of trend tests also requires an adequate sample size. The effective sample size depends on the number of valid data values in each season and on the number of years that data have been collected. The test selected for this study uses one value for each season per year. If more than one sample value is reported during the season in any year, the median of the values is used in the test (J.R. Slack, U.S. Geological Survey, written commun., 1989) and the effective sample size for that season and year is one. Hirsch and Slack (1984, p. 729) indicate that the total number of samples per season needs to be at least 10, and for 5 or fewer samples per season, the covariance approximation might be inaccurate. If the number of seasons selected is more than the number of samples collected each year, the effective sample size will be decreased owing to no data in some seasons. Decreasing the number of seasons can increase the effective sample size in each season, but decreasing the number of seasons too far might mask trends occurring during part of the year.

The effective sample size for each station and season is given in table 2. The criterion of at least 10 samples during each season was met at all stations used for water years 1968-88. However, the criterion was not met at all stations used for 1975-88. Of nine stations used, four had at least 10 samples in every season. Clear Creek near Arvada (station 7) exceeded the minimum effective sample size in only one season (12 samples). Of the seasons considered for water years 1975-88, none had all stations meeting the 10-sample criterion. The percentage of stations equaling or exceeding the minimum ranged from 56 to 89 percent.

Although the criterion of 10 was not met in 27 of 81 instances in water years 1975-88, the effective sample size was either 8 or 9 in 20 of those instances. The conclusion was reached that the effective sample sizes resulting from the selection of nine seasons were generally adequate for trend testing.

Computation of Water-Quality Properties

The water-quality properties of sodium-adsorption ratio and alkalinity were computed from other data. The computation was needed to account for the effect of calcium on sodium-adsorption ratio and to synthesize some laboratory alkalinity data.

Sodium-adsorption ratio (U.S. Salinity Laboratory Staff, 1954, p. 72) commonly is used as a measure of the sodium hazard of irrigation water. However, the effects of the dissolution or precipitation of calcium are not considered (Ayers

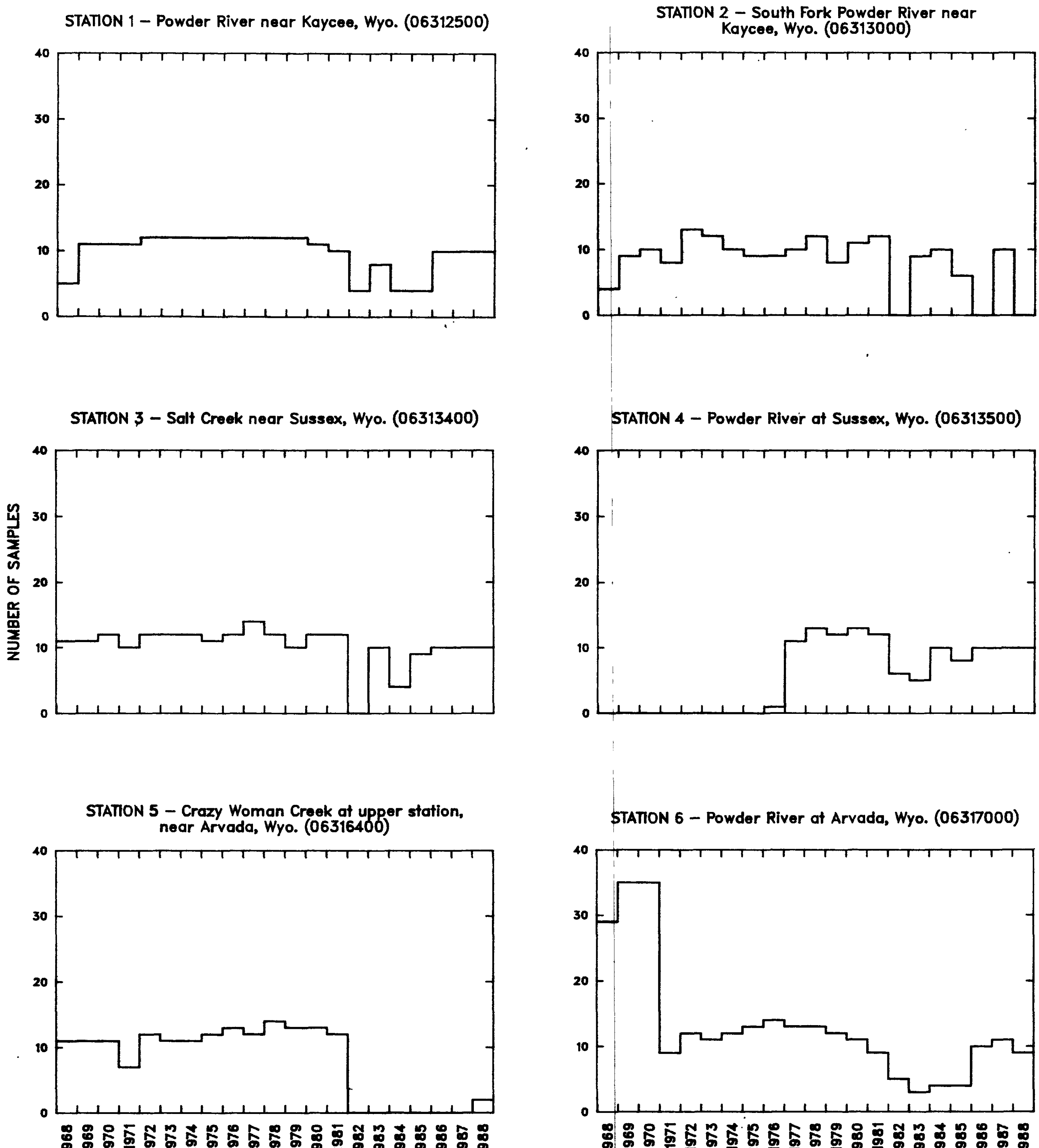

Figure 2.--Sampling frequency at stations used in the trend analysis.

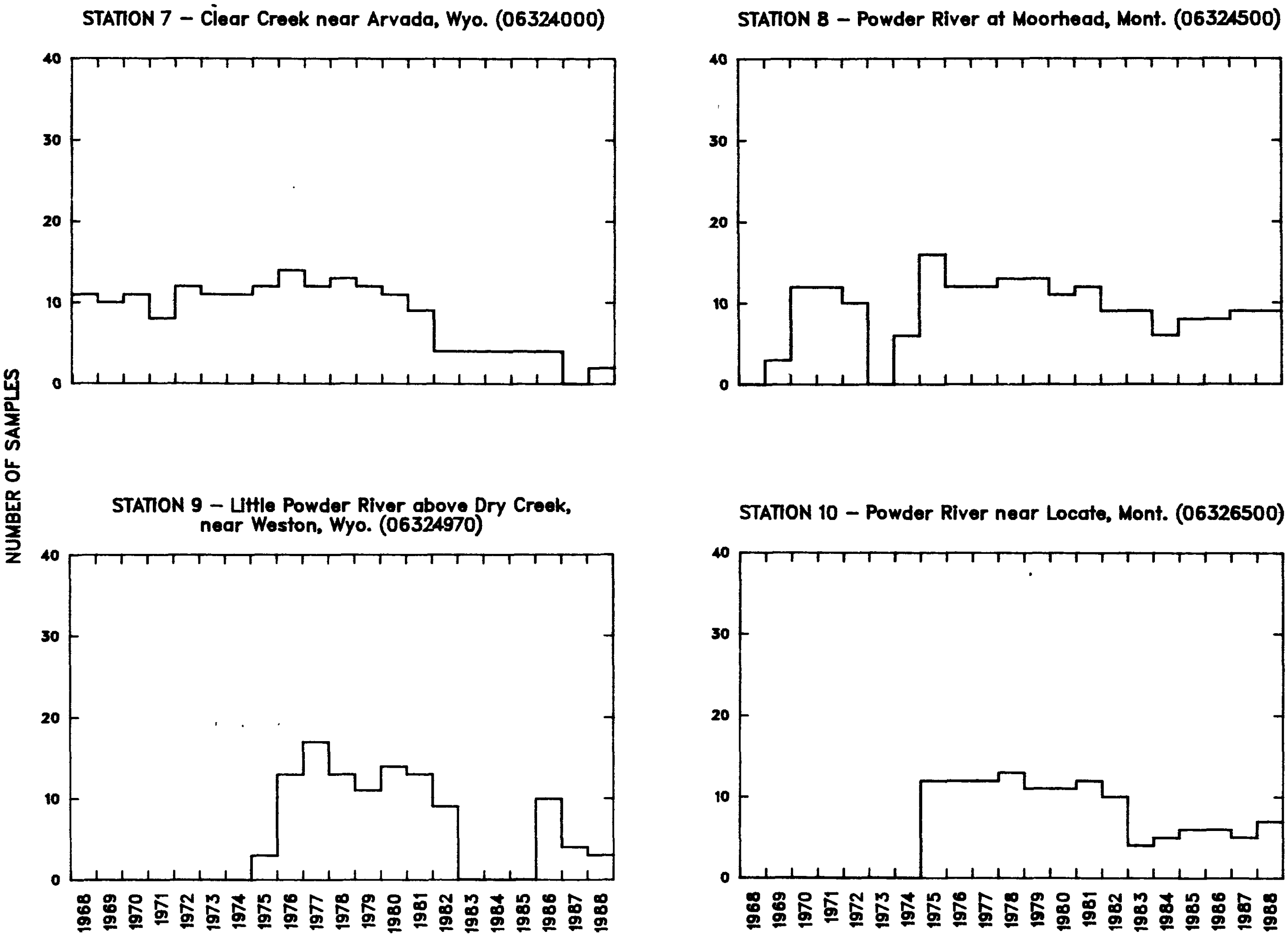

Figure 2.--Sampling frequency at stations used in the trend analysis--Continued

Table 2.--*Effective sample size, by season, at stations used in the trend analysis*

Station No.	Sampling station	Season	Effective sample size									Percent equal to or greater than 10
			1	2	3	4	5	6	7	8	9	
	Water years 1968-88											
1	Powder River near Kaycee, Wyo.		20	17	17	17	20	16	17	17	17	100
2	South Fork Powder River near Kaycee, Wyo.		13	15	13	13	16	14	15	13	11	100
3	Salt Creek near Sussex, Wyo.		18	19	19	18	20	19	18	17	19	100
5	Crazy Woman Creek at upper station, near Arvada, Wyo.		14	14	13	13	13	14	13	15	15	100
6	Powder River at Arvada, Wyo.		16	14	18	15	15	17	17	16	12	100
7	Clear Creek near Arvada, Wyo.		15	16	15	15	15	13	18	16	16	100
8	Powder River at Moorhead, Mont.		14	14	14	13	16	15	14	16	15	100
	Percent equal to or greater than 10		100	100	100	100	100	100	100	100	100	
	Water years 1975-88											
1	Powder River near Kaycee, Wyo.		14	10	13	10	10	13	10	11	10	100
2	South Fork Powder River near Kaycee, Wyo.		7	9	7	8	10	8	9	10	7	22
3	Salt Creek near Sussex, Wyo.		11	11	12	12	13	12	11	11	12	100
4	Powder River at Sussex, Wyo.		10	8	9	10	11	11	11	11	8	67
6	Powder River at Arvada, Wyo.		11	10	12	11	10	11	13	12	10	100
7	Clear Creek near Arvada, Wyo.		8	9	8	9	8	6	12	9	9	11
8	Powder River at Moorhead, Mont.		11	12	12	10	12	11	10	13	12	100
9	Little Powder River above Dry Creek, near Weston, Wyo.		7	8	9	9	7	7	9	10	10	22
10	Powder River near Locate, Mont.		11	12	10	9	12	12	13	12	9	78
	Percent equal to or greater than 10		67	56	56	56	78	67	78	89	56	

and Westcot, 1976, p. 54). An early attempt to account for the changes in calcium concentration resulted in an adjusted sodium-adsorption ratio (Ayers and Westcot, 1976, p. 11, 12) that, according to Suarez (1981, p. 469), overestimated the sodium hazard. Ayers and Westcot (1985) adapted a method proposed by Suarez (1981) to the calculation of an adjusted sodium-adsorption ratio. The method includes the effects of carbon dioxide, bicarbonate, and salinity on calcium. An adjusted calcium concentration is determined from the ratio of the reported concentrations of bicarbonate and calcium, and from the specific conductance of the sample. The adjusted calcium concentration then is substituted into the original sodium-adsorption ratio equation of the U.S. Salinity Laboratory Staff (1954):

$$\text{Sodium-adsorption ratio} = \frac{Na^{+1}}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}} \qquad (1)$$

where Na, Ca, and Mg are expressed in milliequivalents per liter.

In this study, the adjusted sodium-adsorption ratio was computed from the data for each station.

The alkalinity of most natural waters can be attributed primarily to bicarbonate and carbonate (Hem, 1985, p. 106). Although alkalinity usually was not reported for samples collected at the stations before water year 1975, alkalinity was computed from reported concentrations of bicarbonate and carbonate. Concentrations were converted to milliequivalents per liter and summed. The results then were converted to an equivalent quantity of calcium carbonate--the common method of reporting alkalinity.

Because oil-field production water can contain organic acids that affect alkalinity (Hem, 1985, p. 106), and because some tributaries of the Powder River, including Salt Creek, receive oil-field production water, the computed values of alkalinity were compared with reported values. During some years, alkalinity, as well as bicarbonate and carbonate concentrations, were reported. Values of alkalinity for Salt Creek near Sussex (station 3) were computed from data reported during water year 1976, and for the Powder River at Arvada (station 6) were computed from data reported during water year 1981. In most instances, the computed and reported values were equal. In the few instances in which computed values differed from the reported values, the differences were less than 0.5 percent. The results indicate that alkalinity in the Powder River and its tributaries is not affected by anions present in oil-field production water.

Statistical Analysis

The data for water years 1968-88 selected for trend analysis were statistically analyzed; the results are given in table 3. In the Powder River near Kaycee (station 1) and at Moorhead (station 8), and all tributaries but one, mean concentrations of calcium and sodium were larger than mean concentrations of magnesium, whereas mean concentrations of alkalinity and sulfate were larger than mean concentrations of chloride. The exception was the tributary Salt Creek near Sussex (station 3), where the mean concentration of alkalinity was exceeded by that of chloride; inflow of Salt Creek to the mainstem Powder River also affected the relative concentrations of alkalinity and chloride at Arvada (station 6). The mean concentration of alkalinity was larger than that of chloride in the Powder River at Moorhead, owing, in part, to dilution by inflow from Clear Creek near Arvada (station 7). The mean adjusted sodium-adsorption ratio increased in the Powder River between Kaycee and Arvada, primarily as a result of the large concentrations of sodium and alkalinity in Salt Creek near Sussex (the adjusted calcium concentration decreased with increasing bicarbonate concentration). The ratio then decreased in the Powder River between Arvada and Moorhead, in part because of dilution by Clear Creek. Dissolved-solids concentration displayed a similar

Table 3.--*Statistical summary of water-quality data at each station, water years 1968-88*

[Units of measurement are milligrams per liter, except adjusted sodium-adsorption ratio (units). $CaCO_3$, calcium carbonate]

Water-quality characteristic	Number of samples	Minimum	Maximum	Mean	Median	Standard deviation
Station 1--Powder River near Kaycee, Wyo.						
Calcium, dissolved	200	32	128	109	110	90
Magnesium, dissolved	200	12	70	42	44	12
Sodium, dissolved	200	14	250	92	89	39
Adjusted sodium-adsorption ratio	199	.5	5.1	2.2	2.2	.8
Alkalinity, as $CaCO_3$	199	73	246	180	189	33
Sulfate, dissolved	200	78	820	382	390	139
Chloride, dissolved	200	5.6	150	48	48	23
Solids, sum of constituents, dissolved	200	232	1,600	793	801	245
Station 2--South Fork Powder River near Kaycee, Wyo.						
Calcium, dissolved	167	32	550	294	300	90
Magnesium, dissolved	167	14	170	84	85	27
Sodium, dissolved	167	190	930	454	420	158
Adjusted sodium-adsorption ratio	167	3.1	14	7.6	7.2	2.2
Alkalinity, as $CaCO_3$	167	70	309	159	156	42
Sulfate, dissolved	167	500	3,200	1,720	1,700	488
Chloride, dissolved	167	16	580	113	100	74
Solids, sum of constituents, dissolved	167	1,060	4,900	2,780	2,730	769
Station 3--Salt Creek near Sussex, Wyo.						
Calcium, dissolved	212	22	260	79	71	36
Magnesium, dissolved	212	7.8	170	53	48	24
Sodium, dissolved	213	290	2,000	1,390	1,400	323
Adjusted sodium-adsorption ratio	213	7.3	63	38	40	11
Alkalinity, as $CaCO_3$	213	148	1,160	640	643	186
Sulfate, dissolved	214	500	2,100	1,100	1,100	317
Chloride, dissolved	214	63	2,000	1,171	1,300	380
Solids, sum of constituents, dissolved	213	1,180	5,700	4,210	4,240	827
Station 5--Crazy Woman Creek at upper station, near Arvada, Wyo.						
Calcium, dissolved	163	42	580	162	150	74
Magnesium, dissolved	163	7	260	82	77	39
Sodium, dissolved	163	12	380	127	110	67
Adjusted sodium-adsorption ratio	157	.4	7.4	2.4	2.3	1.0
Alkalinity, as $CaCO_3$	158	61	369	196	205	55
Sulfate, dissolved	163	77	2,700	785	690	398
Chloride, dissolved	163	1.7	120	11	9.4	10
Solids, sum of constituents, dissolved	163	282	3,960	1,300	1,170	587
Station 6--Powder River at Arvada, Wyo.						
Calcium, dissolved	188	66	280	148	150	37
Magnesium, dissolved	188	22	120	62	60	19
Sodium, dissolved	188	91	1,500	420	390	181
Adjusted sodium-adsorption ratio	188	2.4	31	9.0	8.5	3.4
Alkalinity, as $CaCO_3$	188	115	548	247	230	77
Sulfate, dissolved	188	270	1,700	867	820	278
Chloride, dissolved	188	3.7	1,300	285	270	163
Solids, sum of constituents, dissolved	188	606	4,730	1,950	1,840	609
Station 7--Clear Creek near Arvada, Wyo.						
Calcium, dissolved	179	23	230	109	110	39
Magnesium, dissolved	179	7.6	120	55	53	23
Sodium, dissolved	179	9.6	200	76	70	37
Adjusted sodium-adsorption ratio	178	.4	3.8	1.7	1.6	.4
Alkalinity, as $CaCO_3$	178	50	393	196	199	56
Sulfate, dissolved	179	60	1,000	453	420	205
Chloride, dissolved	179	.7	48	5.1	4.3	4.5
Solids, sum of constituents, dissolved	179	143	1,640	831	788	330
Station 8--Powder River at Moorhead, Mont.						
Calcium, dissolved	162	23	230	127	130	34
Magnesium, dissolved	163	12	130	58	57	19
Sodium, dissolved	155	3.3	490	247	250	93
Adjusted sodium-adsorption ratio	89	1.5	8.8	5.4	5.7	1.6
Alkalinity, as $CaCO_3$	105	84	470	231	205	69
Sulfate, dissolved	170	140	1,300	665	650	218
Chloride, dissolved	163	.1	420	145	150	76
Solids, sum of constituents, dissolved	207	365	3,379	1,410	1,400	427

pattern. The increase in the Powder River at Arvada was primarily due to larger concentrations in Salt Creek and, to a lesser extent, in the South Fork Powder River and Crazy Woman Creek. The decrease in the Powder River at Moorhead was due, in part, to dilution by inflow from Clear Creek.

The data for water years 1975-88 selected for trend analysis were also statistically analyzed; the results are given in table 4. The data for 1975-88 had many of the same relations as for 1968-88. In the Powder River near Kaycee, at Moorhead, near Locate (station 10), and in all tributaries but one, mean concentrations of calcium and sodium were larger than mean concentrations of magnesium, whereas mean concentrations of alkalinity and sulfate were larger than mean concentrations of chloride. The exception was the tributary Salt Creek near Sussex, where the mean concentration of alkalinity was exceeded by that of chloride; inflow of Salt Creek to the mainstem Powder River also affected the relative alkalinity and chloride concentrations at Sussex (station 4) and at Arvada. During 1975-88, as during 1968-88, the mean concentration of alkalinity was larger than that of chloride in the Powder River at Moorhead, owing, in part, to dilution by inflow from Clear Creek near Arvada. The mean adjusted sodium-adsorption ratio increased in the Powder River between Kaycee and Sussex primarily as a result of the large concentrations of sodium and alkalinity in Salt Creek. The ratio then decreased in the Powder River between Sussex and Arvada, probably because of inflow from ungaged tributaries. Dilution by Clear Creek, in part, caused the ratio to decrease further in the Powder River at Moorhead. The ratio increased again in the Powder River near Locate. Part of the increase might be due to increased sodium and alkalinity concentrations in the Little Powder River. The mean dissolved-solids concentration in the Powder River was larger at Sussex than near Kaycee because of the large mean concentrations in the South Fork Powder River and Salt Creek. The mean dissolved-solids concentration at Arvada was nearly the same as at Sussex, but decreased at Moorhead, after entry of the tributary Clear Creek. The mean concentration increased again near Locate, in part because of the contribution of the Little Powder River.

A comparison of mean values of adjusted sodium-adsorption ratio and mean dissolved-solids concentration at the stations having sufficient data for analysis during both periods indicates some differences. Although the mean values of adjusted sodium-adsorption ratio were the same during both periods in the Powder River near Kaycee and in Salt Creek, the mean ratios were slightly larger during water years 1975-88 than during 1968-88 downstream (stations 6-8). In the Powder River near Kaycee, the South Fork Powder River, and Salt Creek, the mean dissolved-solids concentrations were slightly larger during the longer period; however, in the Powder River at Arvada, Clear Creek, and the Powder River at Moorhead, the concentrations were slightly smaller during the longer period.

Adjustment for Stream Discharge

Variation in stream discharge might cause trends in some water-quality characteristics or mask trends due to other causes in other characteristics. A flow-adjusting procedure was used for characteristics displaying a significant correlation with discharge (Hirsch and others, 1982, p. 119-120; Smith and others, 1982, p. 6-7; Smith and Alexander, 1983, p. 9, 10). The adjustment is intended to remove the effects of variation in discharge. Equations describing the relation between discharge and the water-quality data were obtained by regression analysis. For the few instances where instantaneous discharge was not reported, mean daily discharge was used. The equation that accounted for the largest percentage of the variance in the water-quality data, and whose residuals were most nearly normally distributed, was selected and used to estimate values of the water-quality characteristics. These estimated values were subtracted from the reported values to produce the residuals, or "adjusted" data. The adjusted data were tested for trends.

Flow adjustment of some characteristics might not be appropriate. If the correlation between discharge and a characteristic is not significant according to the regression analysis, the adjustment is not appropriate (Smith and others, 1982, p. 8; Crawford and others, 1983, p. 12).

Table 4.--*Statistical summary of water-quality data at each station, water years 1975-88*

[Units of measurement are milligrams per liter, except adjusted sodium-adsorption ratio (units). $CaCO_3$, calcium carbonate]

Water-quality characteristic	Number of samples	Statistics				
		Minimum	Maximum	Mean	Median	Standard deviation
Station 1--Powder River near Kaycee, Wyo.						
Calcium, dissolved	127	41	190	109	110	29
Magnesium, dissolved	127	12	64	41	42	12
Sodium, dissolved	147	14	200	91	87	37
Adjusted sodium-adsorption ratio	126	.5	4.3	2.2	2.2	.8
Alkalinity, as $CaCO_3$	126	73	246	180	189	33
Sulfate, dissolved	127	92	710	373	370	132
Chloride, dissolved	127	5.6	110	48	46	22
Solids, sum of constituents, dissolved	127	232	1,320	782	793	233
Station 2--South Fork Powder River near Kaycee, Wyo.						
Calcium, dissolved	104	32	470	287	295	99
Magnesium, dissolved	104	16	170	85	88	28
Sodium, dissolved	107	190	930	403	485	137
Adjusted sodium-adsorption ratio	104	4.8	14.2	8.5	8.3	2.0
Alkalinity, as $CaCO_3$	104	70	309	161	160	43
Sulfate, dissolved	104	500	3,200	1,810	1,850	536
Chloride, dissolved	104	16	420	114	100	73
Solids, sum of constituents, dissolved	107	1,230	4,560	2,600	3,040	637
Station 3--Salt Creek near Sussex, Wyo.						
Calcium, dissolved	134	22	150	69	65	29
Magnesium, dissolved	134	7.8	130	46	41	19
Sodium, dissolved	134	290	1,800	1,290	1,400	305
Adjusted sodium-adsorption ratio	134	7.3	59	38	41	12
Alkalinity, as $CaCO_3$	134	148	1,070	647	680	195
Sulfate, dissolved	135	500	2,100	982	910	311
Chloride, dissolved	135	63	1,600	1,070	1,200	355
Solids, sum of constituents, dissolved	134	1,180	5,440	3,890	4,050	734
Station 4--Powder River at Sussex, Wyo.						
Calcium, dissolved	110	31	210	109	110	32
Magnesium, dissolved	110	14	160	49	49	16
Sodium, dissolved	111	85	1,400	520	410	314
Adjusted sodium-adsorption ratio	99	2.7	46	13	10	9.3
Alkalinity, as $CaCO_3$	102	96	850	338	319	139
Sulfate, dissolved	112	140	2,300	696	655	286
Chloride, dissolved	112	5	1,600	401	310	314
Solids, sum of constituents, dissolved	110	452	4,030	1,980	1,760	819
Station 6--Powder River at Arvada, Wyo.						
Calcium, dissolved	132	66	220	141	140	35
Magnesium, dissolved	132	22	120	62	58	19
Sodium, dissolved	132	91	1,500	445	420	195
Adjusted sodium-adsorption ratio	132	2.4	31	9.6	9.3	3.6
Alkalinity, as $CaCO_3$	132	115	548	257	240	78
Sulfate, dissolved	132	270	1,700	865	810	288
Chloride, dissolved	132	4	1,300	302	280	177
Solids, sum of constituents, dissolved	132	606	4,730	1,990	1,870	651
Station 7--Clear Creek near Arvada, Wyo.						
Calcium, dissolved	105	23	230	115	110	41
Magnesium, dissolved	105	7.6	110	56	53	22
Sodium, dissolved	105	10	200	80	78	37
Adjusted sodium-adsorption ratio	104	.4	3.8	1.8	1.8	.6
Alkalinity, as $CaCO_3$	104	50	393	201	200	60
Sulfate, dissolved	104	60	990	466	440	201
Chloride, dissolved	105	1.4	48	5.6	4.3	5.2
Solids, sum of constituents, dissolved	105	143	1,640	856	810	329
Station 8--Powder River at Moorhead, Mont.						
Calcium, dissolved	132	23	220	127	130	34
Magnesium, dissolved	133	15	110	58	57	17
Sodium, dissolved	133	62	490	257	260	88
Adjusted sodium-adsorption ratio	82	2.0	8.8	5.6	5.7	1.5
Alkalinity, as $CaCO_3$	86	110	470	233	238	68
Sulfate, dissolved	134	140	1,300	679	660	210
Chloride, dissolved	135	.1	420	154	160	74
Solids, sum of constituents, dissolved	131	365	2,510	1,420	1,430	386

Table 4.--*Statistical summary of water-quality data at each station, water years 1975-88*--Continued

Water-quality characteristic	Number of samples	Minimum	Maximum	Mean	Median	Standard deviation
Station 9--Little Powder River above Dry Creek, near Weston, Wyo.						
Calcium, dissolved	145	28	320	155	150	62
Magnesium, dissolved	146	10	200	98	97	45
Sodium, dissolved	145	75	930	394	400	167
Adjusted sodium-adsorption ratio	138	2.4	16.5	7.3	7.0	2.5
Alkalinity, as $CaCO_3$	146	77	730	319	328	118
Sulfate, dissolved	146	190	2,500	1,278	1,300	551
Chloride, dissolved	146	4	580	20	12.5	49
Solids, sum of constituents, dissolved	146	379	4,370	2,160	2,350	854
Station 10--Powder River near Locate, Mont.						
Calcium, dissolved	124	20	220	128	130	38
Magnesium, dissolved	124	6	100	59	59	20
Sodium, dissolved	124	61	760	292	290	104
Adjusted sodium-adsorption ratio	97	1.9	13.9	6.3	6.3	1.8
Alkalinity, as $CaCO_3$	99	71	422	226	221	65
Sulfate, dissolved	126	220	2,000	762	740	271
Chloride, dissolved	126	13	340	137	130	66
Solids, sum of constituents, dissolved	124	408	3,440	1,540	1,350	494

Selection of Trend Test

The seasonal Kendall test--a nonparametric statistical method--was used to test for gradual trends. The test, which was developed for water-quality time series displaying seasonality, is described fully by Hirsch and others (1982).

Many water-quality characteristics, including major dissolved constituents and properties, commonly display dependence between consecutive seasonal values; that is, they are serially correlated. However, in an early version of the seasonal Kendall test (Hirsch and others, 1982, p. 110), data from different months were assumed to be independent; thus, the correlation (and covariance) between consecutive values was assumed to be zero. Hirsch and Slack (1984) included an estimate of the covariance in the seasonal Kendall test for instances in which the assumption of independence cannot be made. This modified test is not as powerful as the early version if the data are truly independent. However, it is more accurate than the early version when the data are dependent, provided the number of observations in each season is 10 or more (Hirsch and Slack, 1984, p. 729). The modified test was used in this study.

A significance level of 0.10 was selected. At this level, there is a 10-percent probability that the seasonal Kendall test will indicate a trend when no trend exists.

An estimate of the magnitude of change per year caused by a trend can be obtained by using the slope estimate. Hirsch and others (1982, p. 117) and Smith and others (1982, p. 6) defined the slope estimate to be the median of the slopes of all the data pairs compared in the seasonal Kendall test. Slope estimates were determined in this study for all trends.

The slope estimate can be expressed as a percentage change per year to make comparisons between individual characteristics easier. Smith and others (1982, p. 13, 20) converted the slope estimate of the characteristic to a percentage by dividing the estimate by the mean of the characteristic, then multiplying by 100. When the natural logarithm of the characteristic is analyzed for trend, the slope estimate (b) is converted to a percentage as follows: $100 \cdot (\exp(b)-1)$ (Crawford and others, 1983, p. 12, 13). In this study, all slope estimates were converted to percentages using these procedures.

The trend test is an exploratory statistical technique, and the slopes are estimates of the change in value per year during the period analyzed. No inferences can be made regarding the continuation of a trend into the future. Also, a trend in a characteristic might be statistically significant but have little physical, biological, or chemical significance.

TRENDS IN WATER-QUALITY CHARACTERISTICS

The seasonal Kendall test with correction for serial correlation was applied first to data from water years 1968-88, then to data from water years 1975-88. The resulting trends are described for stations with data for the first period, stations with data for the second period, and stations with data for both periods.

Water Years 1968-88

The results of the trend tests for water years 1968-88 are summarized in table 5. A trend is considered to exist when the computed probability is smaller than the chosen significance level (0.10). The results are for adjusted data with the exception of magnesium and sulfate in Salt Creek near Sussex (station 3). Because the relation between discharge and these two water-quality characteristics was not statistically significant, the characteristics were not adjusted for stream discharge.

The water-quality characteristics whose data displayed significant trends at the 0.10 level are given in table 6. Trends were detected in at least one water-quality characteristic at each station. Significant trends in calcium concentration were detected at three stations, with concentration decreasing at two and increasing at one. The largest decrease was 3.8 percent per year in Salt Creek near Sussex, where the mean concentration was 79 mg/L. The concentration (mean, 109 mg/L) increased 0.9 percent per year in Clear Creek near Arvada (station 7). Magnesium (mean, 53 mg/L) had a trend at a single station, Salt Creek near Sussex, where the concentration decreased 2.5 percent per year. Trends in sodium, all with

Table 5.--*Computed probability values for assessing trends in water-quality characteristics at each station, water years 1968-88*
[<, less than; $CaCO_3$, calcium carbonate]

Station No.	Sampling station	Probability: Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate, dissolved	Chloride, dissolved	Solids, sum of constituents, dissolved
1	Powder River near Kaycee, Wyo.	0.687	0.175	0.980	0.963	0.829	0.009	0.345	0.107
2	South Fork Powder River near Kaycee, Wyo.	.256	.581	.002	<.001	.596	.021	.441	.014
3	Salt Creek near Sussex, Wyo.	<.001	<.001	.209	<.001	.001	<.001	.368	<.001
5	Crazy Woman Creek at upper station, near Arvada, Wyo.	.473	.180	.138	.071	.070	.847	.178	.827
6	Powder River at Arvada, Wyo.	<.001	.163	<.001	<.001	.003	.393	.021	.065
7	Clear Creek near Arvada, Wyo.	.005	.877	.474	.965	.591	.429	.390	.385
8	Powder River at Moorhead, Mont.	.148	.868	.036	.135	.562	.369	.081	.167

Table 6.--*Trends and slope estimates for water-quality characteristics at each station, water years 1968-88*

[Units of measurement in milligrams per liter except as follows: adjusted sodium-adsorption ratio (units). All characteristics flow-adjusted prior to trend testing, except as noted. Trend results: --, trend was not detected at the 0.10 significance level and slope estimate not computed; + , trend was significant and values increased; -, trend was significant and values decreased; slope estimate, in percent per year. $CaCO_3$, calcium carbonate]

		Trend results							
Station No.	Sampling station	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate, dissolved	Chloride, dissolved	Solids, sum of constituents, dissolved
1	Powder River near Kaycee, Wyo.	--	--	--	--	--	-0.4	--	--
2	South Fork Powder River near Kaycee, Wyo.	--	--	+2.9	+2.8	--	+1.3	--	+1.2
3	Salt Creek near Sussex, Wyo.	-3.8	[1]-2.5	--	+1.9	+2.0	[1]-2.6	--	-.9
5	Crazy Woman Creek at upper station, near Arvada, Wyo.	--	--	--	+1.3	+.7	--	--	--
6	Powder River at Arvada, Wyo.	-1.3	--	+1.7	+2.2	+1.3	--	+1.5	+.6
7	Clear Creek near Arvada, Wyo.	+.9	--	--	--	--	--	--	--
8	Powder River at Moorhead, Mont.	--	--	+1.2	--	--	--	+.9	--

[1]Relation between discharge and water-quality characteristic was not statistically significant; therefore, characteristic was not adjusted for stream discharge.

increasing concentration, were detected at one tributary and two mainstem stations. The largest change was in the South Fork Powder River near Kaycee (station 2), where the concentration (mean, 454 mg/L) increased 2.9 percent per year. The adjusted sodium-adsorption ratio increased at four stations, which was more than any other characteristic. Of the four stations, three were on tributaries and one was on the mainstem. The largest change was in the South Fork Powder River near Kaycee, where the ratio (mean, 7.6) increased 2.8 percent per year. Alkalinity concentration increased at one mainstem and two tributary stations. The largest increase was 2.0 percent per year in Salt Creek near Sussex, where the mean concentration was 640 mg/L. Sulfate concentration decreased at one tributary and one mainstem station. The largest decrease in concentration (mean, 1,100 mg/L) was 2.6 percent per year in Salt Creek near Sussex. Sulfate concentration (mean 1,720 mg/L) increased 1.3 percent per year in the South Fork Powder River near Kaycee. Chloride concentration increased at two mainstem stations. The largest change was in the Powder River at Arvada (station 6), where the concentration (mean, 285 mg/L) increased 1.5 percent per year. The decreases and increases in dissolved constituents had varying effects on dissolved solids. Dissolved-solids concentration increased 1.2 percent per year in the South Fork Powder River near Kaycee (mean, 2,780 mg/L), decreased 0.9 percent per year in Salt Creek near Sussex (mean, 4,210 mg/L), and increased 0.6 percent per year in the Powder River at Arvada (mean, 1,950 mg/L).

The areal distribution of trends in the water-quality characteristics for water years 1968-88 is shown in figures 3-10. The decreasing calcium concentration in Salt Creek near Sussex (fig. 3, station 3) might have resulted in the decrease noted in the Powder River at Arvada (station 6). Downstream, in the Powder River

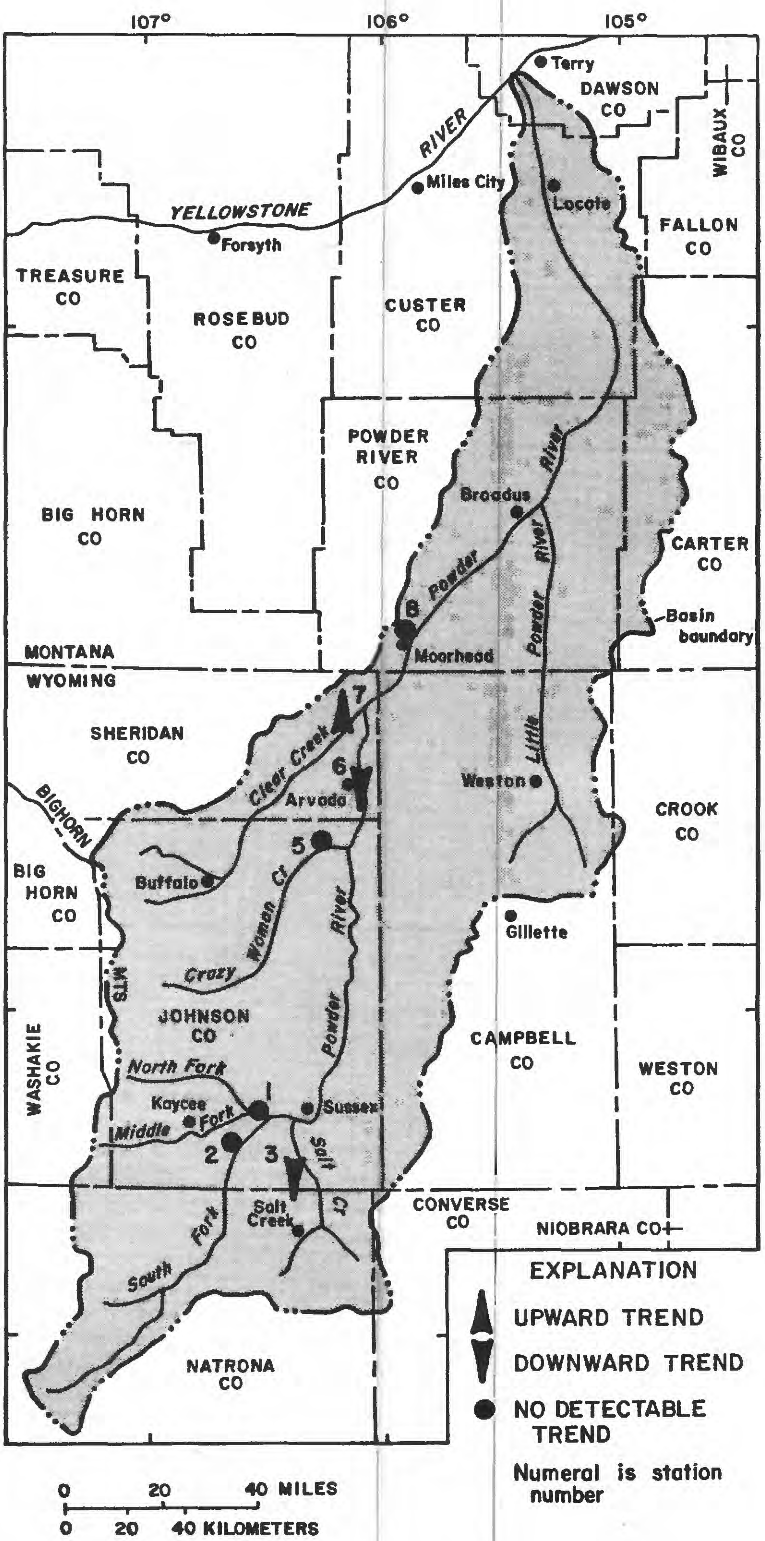

Figure 3.--Trends in calcium concentration, water years 1968-88.

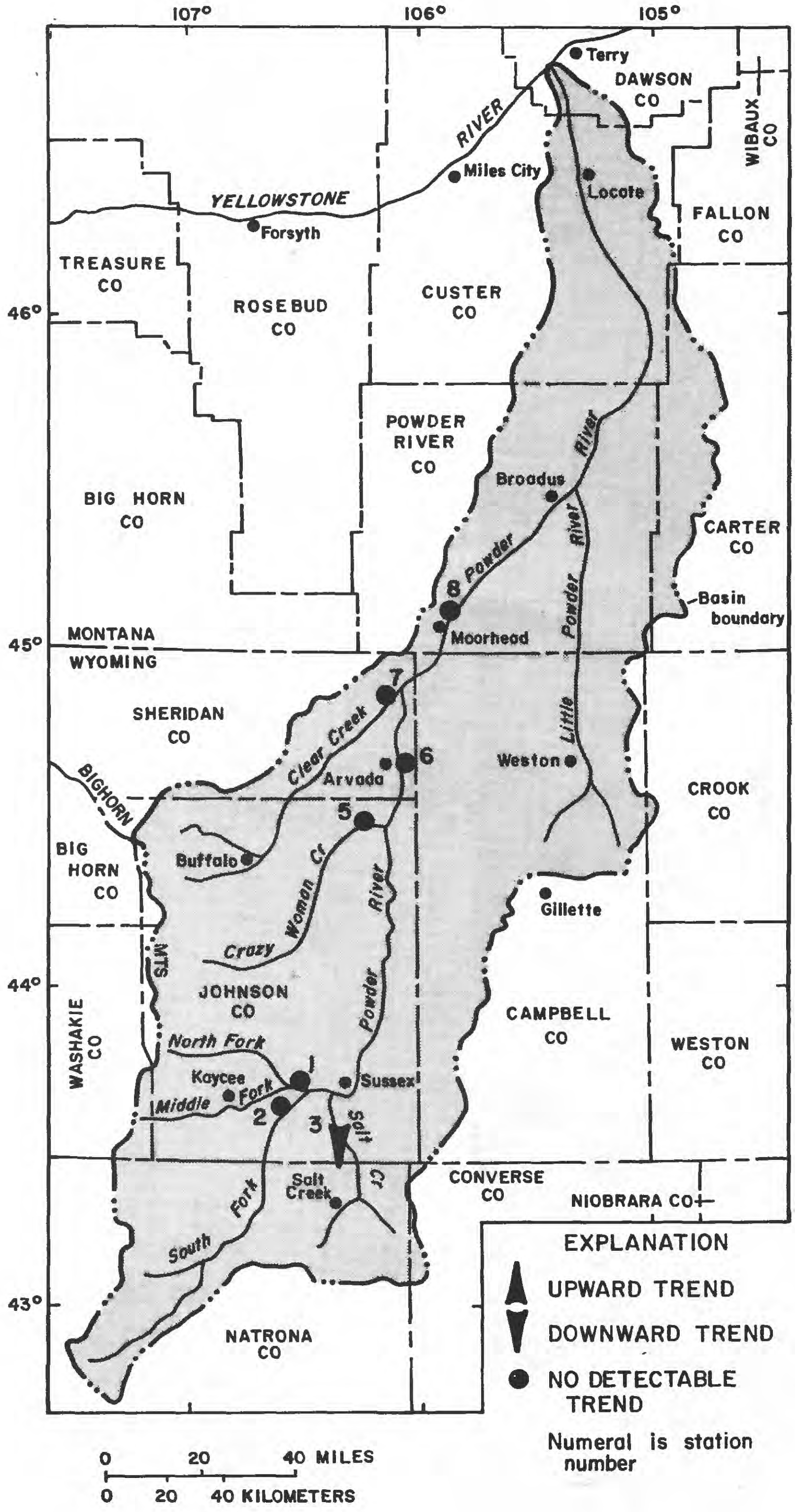

Figure 4.--Trends in magnesium concentration, water years 1968-88.

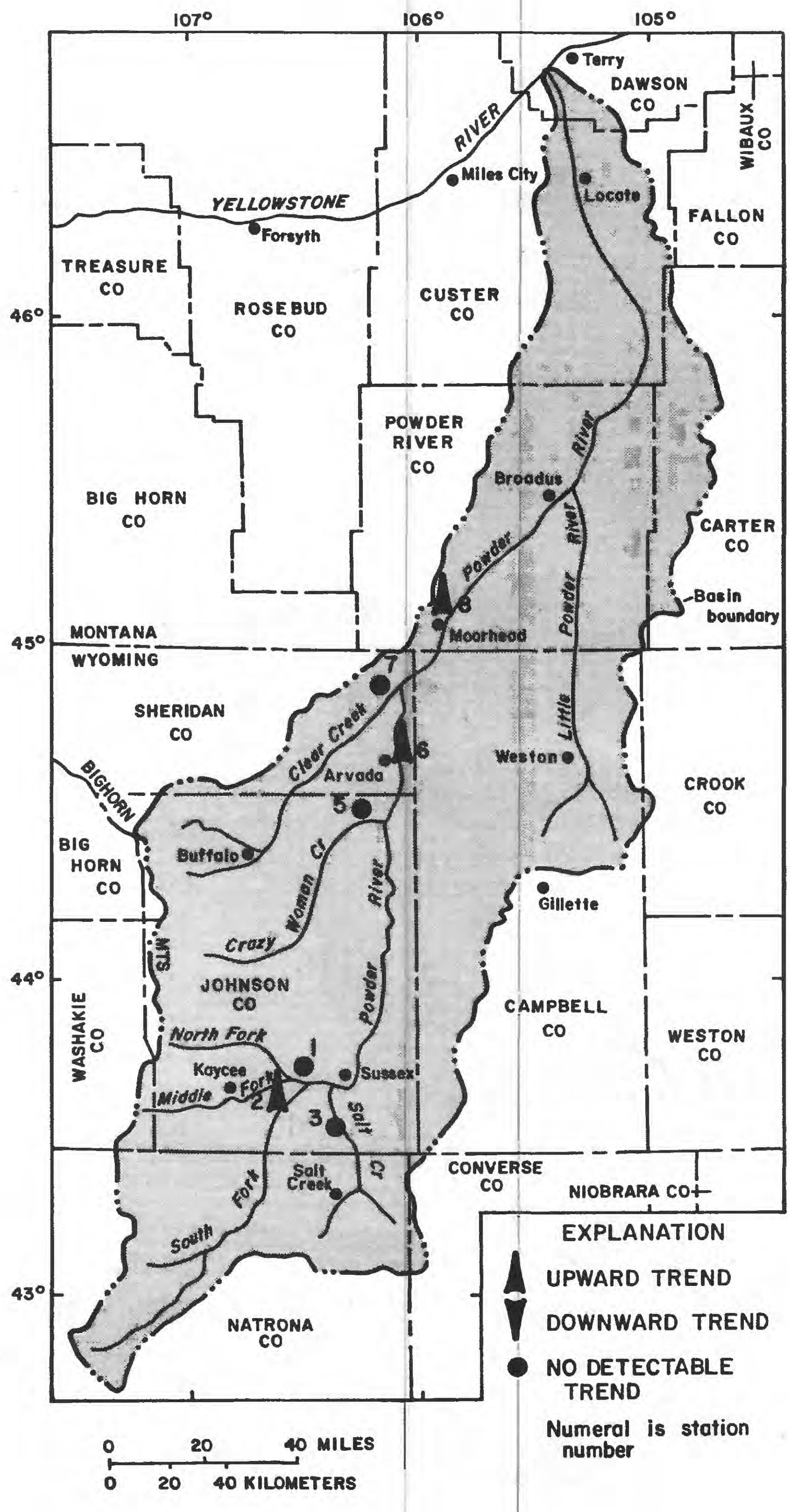

Figure 5.--Trends in sodium concentration, water years 1968-88.

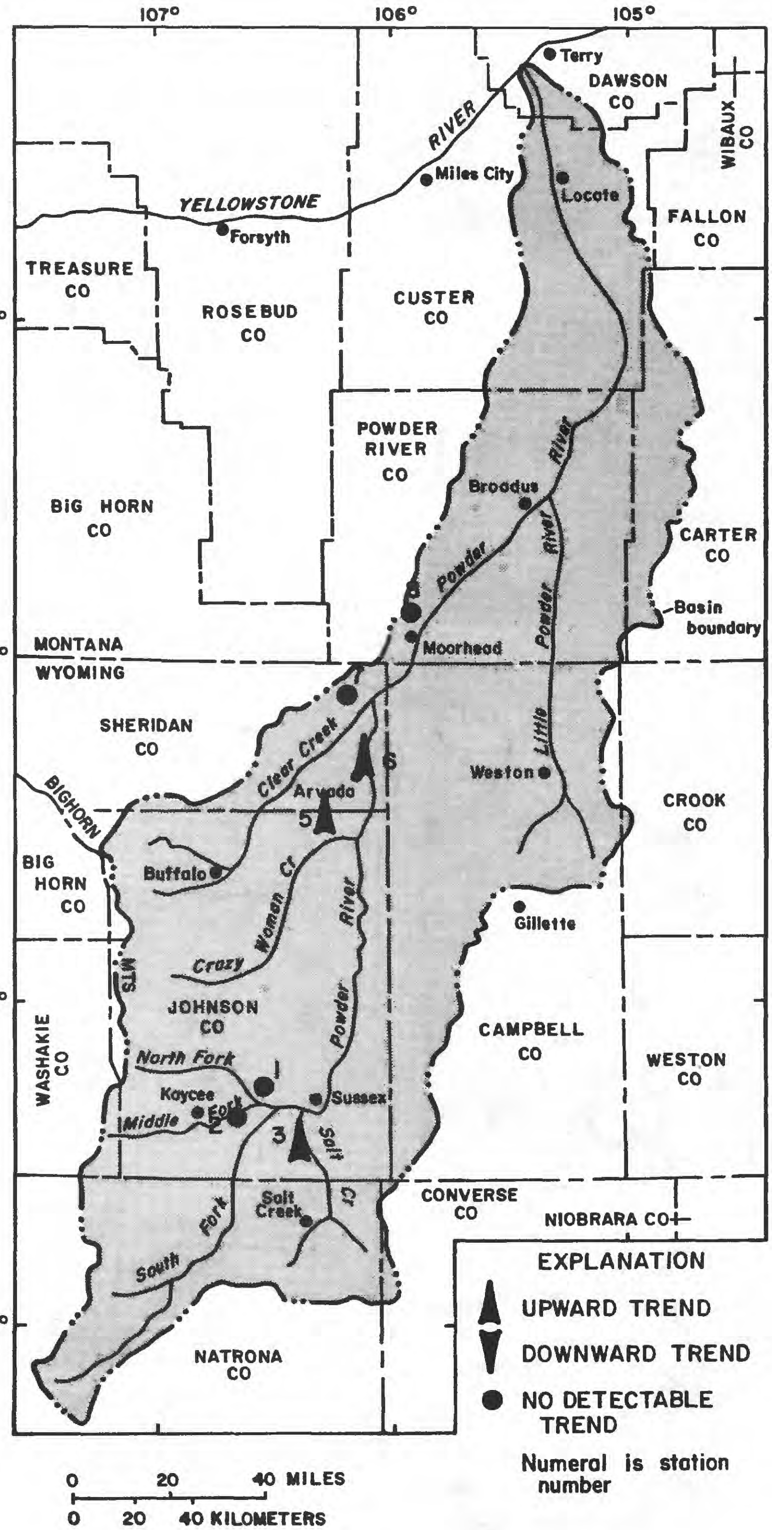

Figure 6.--Trends in alkalinity concentration, water years 1968-88.

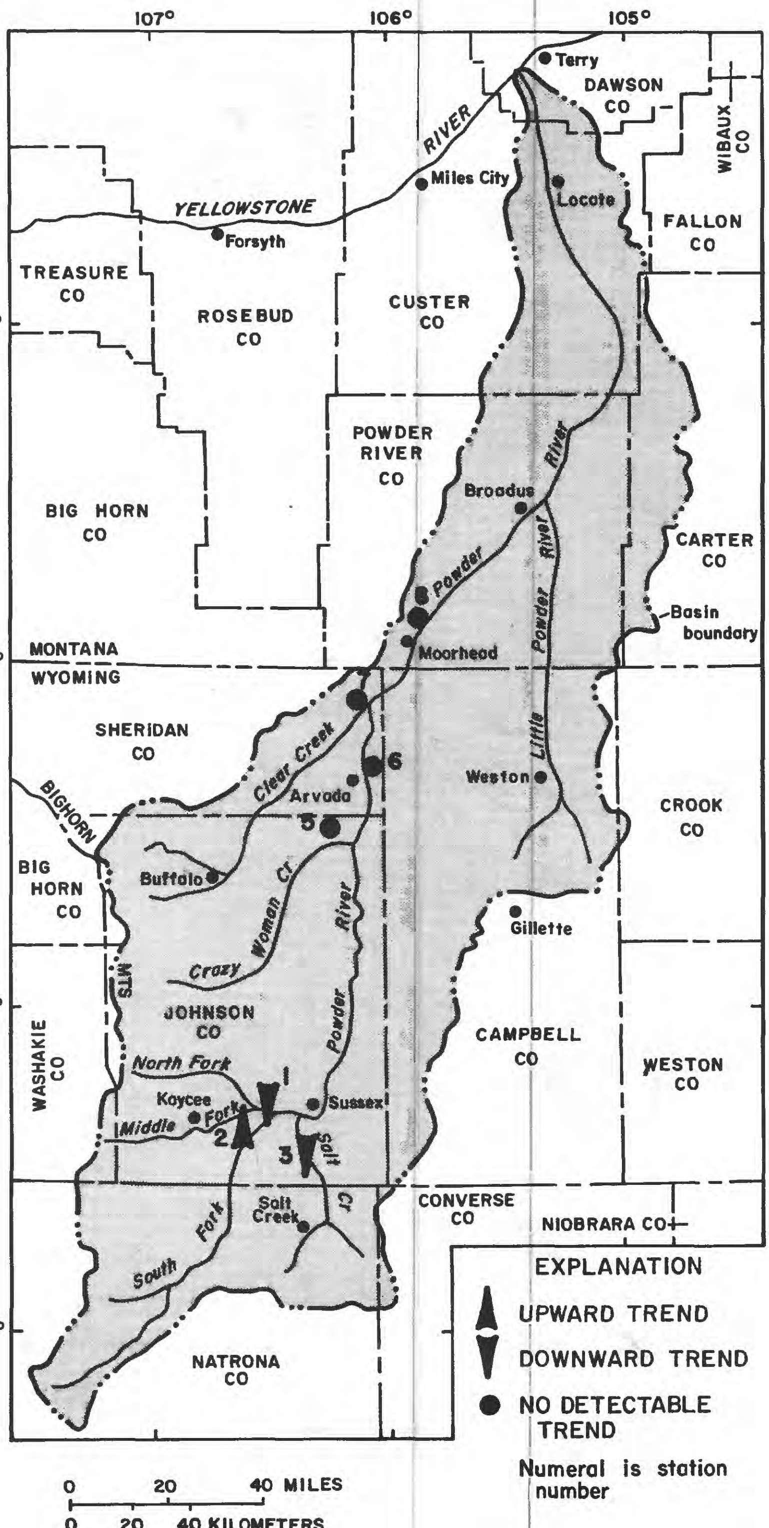

Figure 7.--Trends in sulfate concentration, water years 1968-88.

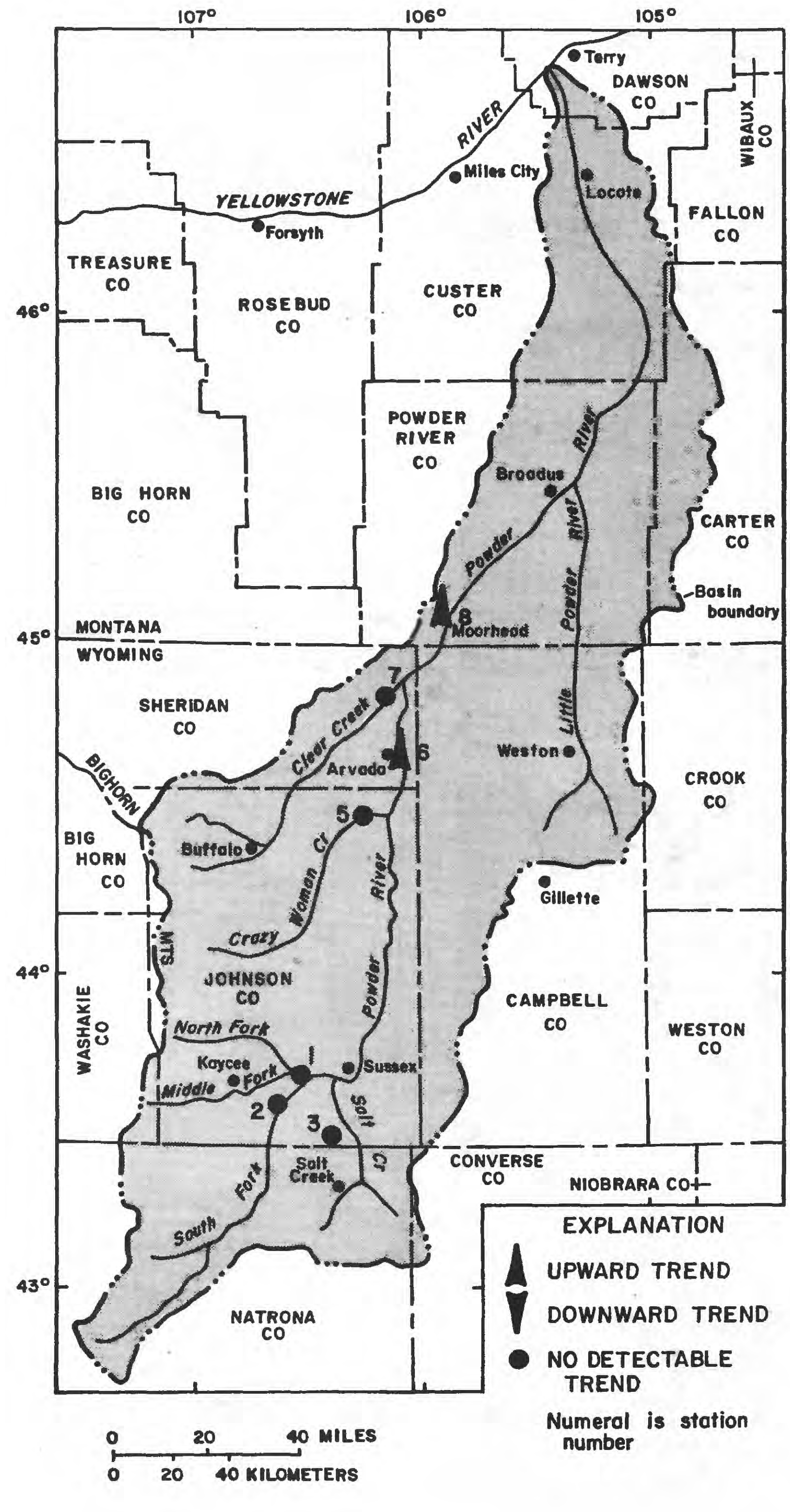

Figure 8.--Trends in chloride concentration, water years 1968-88.

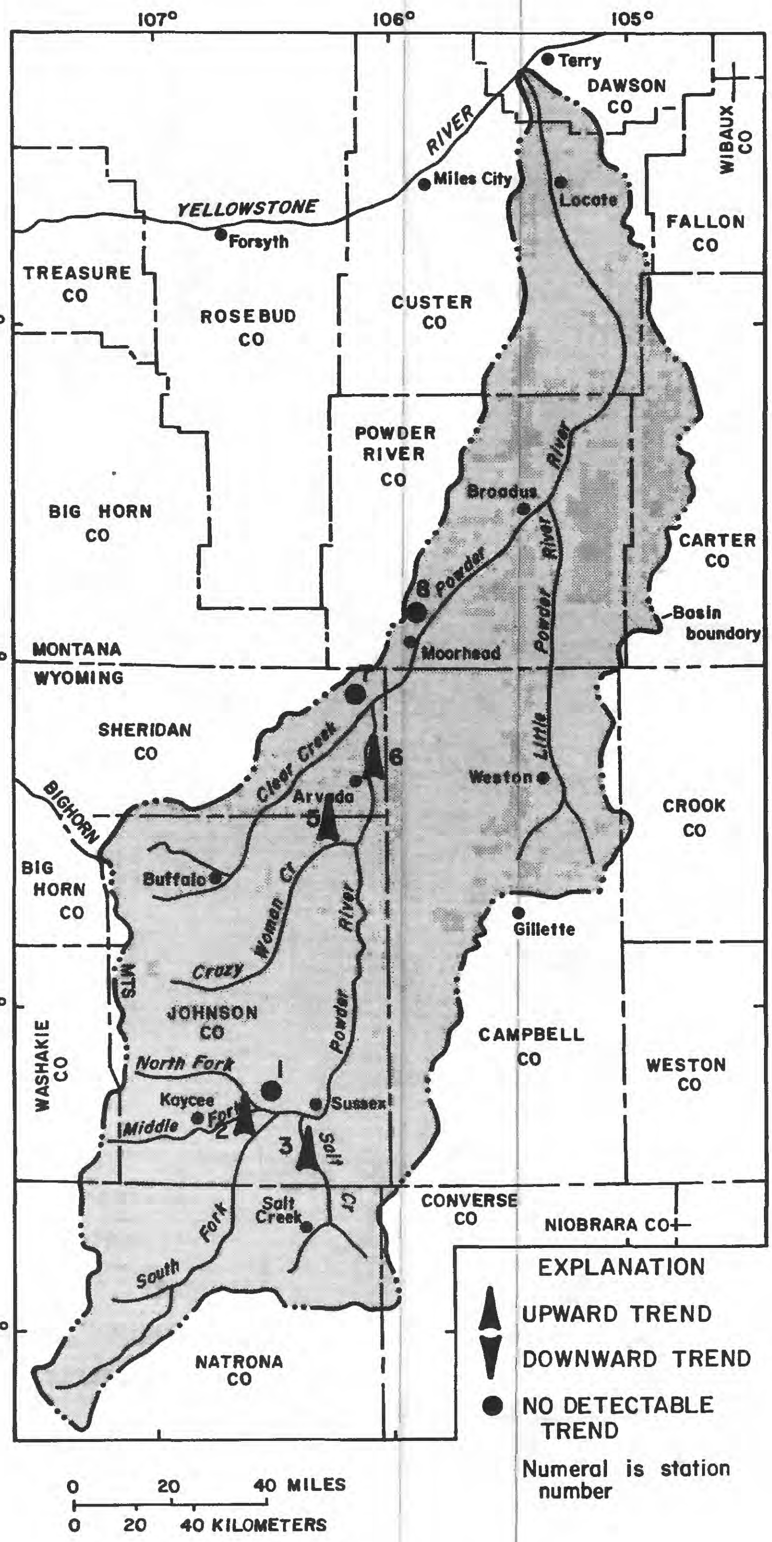

Figure 9.--Trends in adjusted sodium-adsorption ratio, water years 1968-88.

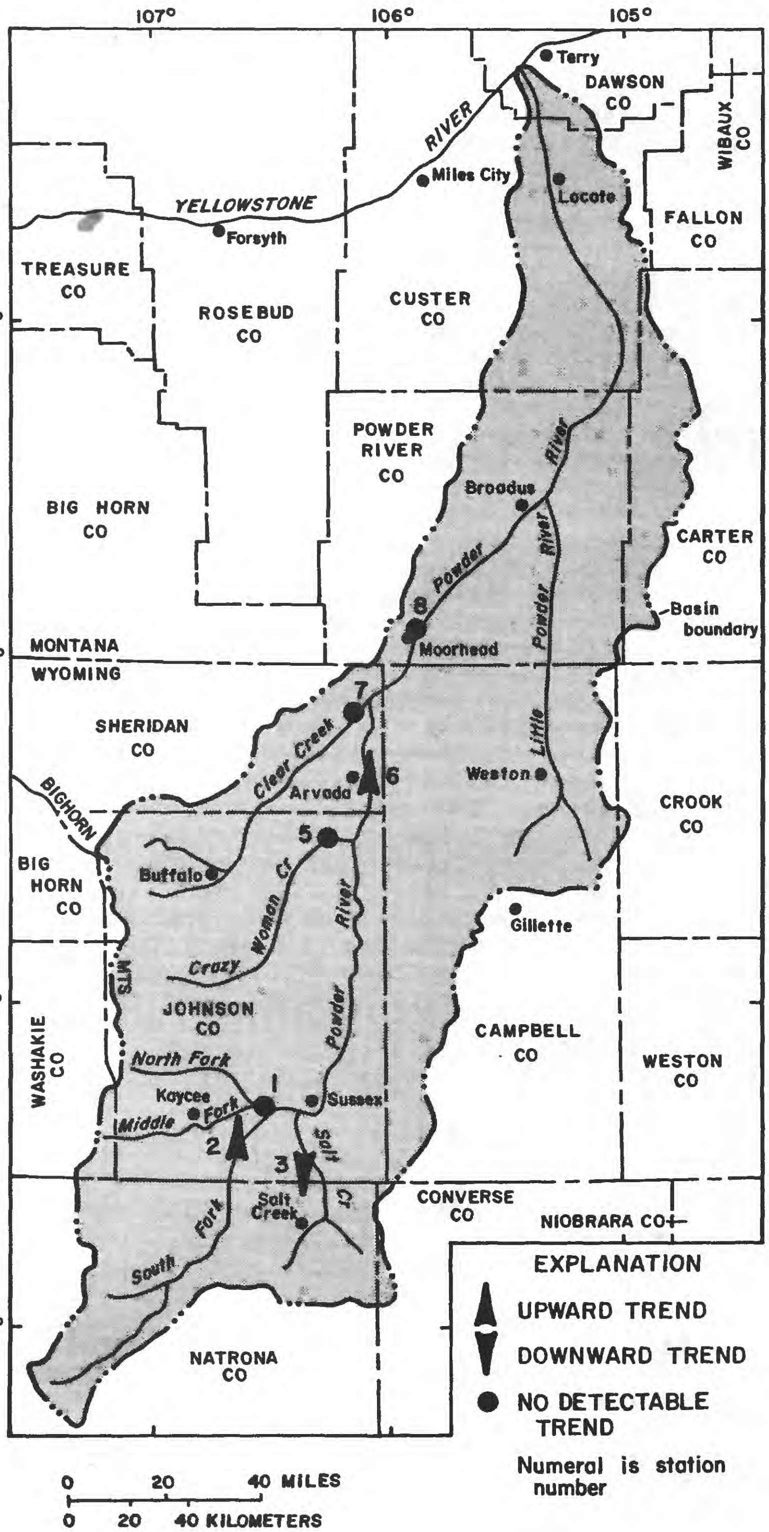

Figure 10.--Trends in dissolved-solids concentration, water years 1968-88.

at Moorhead (station 8), no trend was detected, perhaps because of dilution by Clear Creek near Arvada (station 7). The decreasing magnesium concentration (-2.5 percent per year) in Salt Creek near Sussex (fig. 4, station 3) apparently had little effect on magnesium concentrations in the mainstem Powder River. The increasing sodium concentration in the South Fork Powder River near Kaycee (station 2) may have accounted for the increases noted in the mainstem Powder River downstream (fig. 5). The increase in alkalinity concentration in the Powder River at Arvada (fig. 6, station 6) was accompanied by increases in two upstream tributaries. Downstream, in the Powder River at Moorhead (station 8), no trend was detected, perhaps due, in part, to dilution by Clear Creek. Sulfate concentration had no trend in the mainstem Powder River downstream from the mouth of Salt Creek (fig. 7). The increase in sulfate concentration in the South Fork Powder River near Kaycee (station 2) might have been compensated for by concurrent decreases in sulfate in the Powder River near Kaycee (station 1) and in Salt Creek near Sussex (station 3). Chloride concentration increased in the downstream reaches of the mainstem Powder River (fig. 8) but not in the upstream reaches or in the tributaries. The increase in sodium concentration in the South Fork Powder River near Kaycee (fig. 5, station 2) might indicate an increase in chloride concentration, but no trend was detected.

The adjusted sodium-adsorption ratio and dissolved-solids concentration are determined from concentrations of individual constituents. The adjusted sodium-adsorption ratio is affected by concentrations of sodium, calcium, magnesium, bicarbonate, and salinity. Increases in the adjusted sodium-adsorption ratio at each of the four stations (fig. 9) can be attributed to a combination of changes in concentration of these constituents. The increase in the Powder River at Arvada (station 6) is due, in part, to increases in sodium and bicarbonate (alkalinity) concentrations and decreases in calcium and magnesium concentrations in one upstream tributary. In the South Fork Powder River near Kaycee (station 2) and Salt Creek near Sussex (station 3), the ratio also is affected by changes in dissolved-solids concentration. The absence of a trend in the ratio in the Powder River at Moorhead (station 8), in spite of an increase in sodium, is probably due, in part, to dilution from Clear Creek, and an insufficient increase in sodium to cause a significant increase in the ratio. Dissolved-solids concentration is the sum of concentrations of individual constituents. The small increase in the Powder River at Arvada (fig. 10, station 6) is due, in part, to an increase in the South Fork Powder River near Kaycee (station 2), partly offset by a decrease in Salt Creek. Dilution by inflow from Clear Creek might have resulted in the absence of a trend in the Powder River at Moorhead (station 8). The increase in adjusted sodium-adsorption ratio and the slight increase in salinity in the Powder River at Arvada no longer were evident in the Powder River at Moorhead.

Water Years 1975-88

The results of the trend tests for water years 1975-88 are summarized in table 7. The relations between discharge and all water-quality characteristics were statistically significant. Therefore, the results are for flow-adjusted data.

The water-quality characteristics whose data displayed significant trends at the 0.10 level are given in table 8. Trends were detected in at least one water-quality characteristic at each station. Significant trends in calcium concentration were detected at four stations, with concentration decreasing at three stations and increasing at one. The largest decrease was 3.8 percent per year in Salt Creek near Sussex (station 3), where the mean concentration was 69 mg/L. The calcium concentration (mean, 115 mg/L) increased 1.2 percent per year in Clear Creek near Arvada (station 7). Magnesium concentration decreased at two stations. The largest decrease was 1.6 percent per year in Salt Creek near Sussex, where the mean concentration was 46 mg/L. Sodium concentration increased at three mainstem stations. The largest change was in the Powder River at Sussex (station 4), where the concentration (mean, 520 mg/L) increased 1.8 percent per year. The adjusted sodium-adsorption ratio increased at five stations--two on tributaries and three on the mainstem Powder River. The largest change was in the South Fork Powder River near Kaycee (station 2), where the ratio (mean, 8.5) increased 4.3 percent per year. Alkalinity concentration (mean, 647 mg/L) increased 1.4 percent per year in

Table 7.--*Computed probability values for assessing trends in water-quality characteristics at each station, water years 1975-88*

[$CaCO_3$, calcium carbonate]

		Probability							
Station No.	Sampling station	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate, dissolved	Chloride, dissolved	Solids, sum of constituents, dissolved
1	Powder River near Kaycee, Wyo.	0.496	0.338	0.389	0.238	0.777	0.386	0.017	0.818
2	South Fork Powder River near Kaycee, Wyo.	.598	.306	.203	.076	.276	.136	.506	.291
3	Salt Creek near Sussex, Wyo.	.023	.035	.615	.057	.075	.007	.158	.172
4	Powder River at Sussex, Wyo.	.055	.078	.018	.003	.555	.670	.036	.054
6	Powder River at Arvada, Wyo.	.252	.755	.011	.009	.281	.873	.081	.092
7	Clear Creek near Arvada, Wyo.	.092	.643	.764	.466	.526	.130	.349	.267
8	Powder River at Moorhead, Mont.	.072	.374	.861	.612	.185	.932	.683	.856
9	Little Powder River above Dry Creek, near Weston, Wyo.	.272	.404	.850	.472	.906	.912	.059	.911
10	Powder River near Locate, Mont.	.407	.506	.036	.034	.733	.139	.038	.087

Table 8.--*Trends and slope estimates for water-quality characteristics at each station, water years 1975-88*

[Units of measurement in milligrams per liter except as follows: adjusted sodium-adsorption ratio (units). All characteristics flow-adjusted prior to trend testing. Trend results: --, trend was not detected at the 0.10 significance level and slope estimate not computed; +, trend was significant and values increased; -, trend was significant and values decreased; slope estimate, in percent per year. $CaCO_3$, calcium carbonate]

		Trend results							
Station No.	Sampling station	Calcium, dissolved	Magnesium, dissolved	Sodium, dissolved	Adjusted sodium-adsorption ratio	Alkalinity, as $CaCO_3$	Sulfate, dissolved	Chloride, dissolved	Solids, sum of constituents, dissolved
1	Powder River near Kaycee, Wyo.	--	--	--	--	--	--	+1.3	--
2	South Fork Powder River near Kaycee, Wyo.	--	--	--	+4.3	--	--	--	--
3	Salt Creek near Sussex, Wyo.	-3.8	-1.6	--	+1.6	+1.4	-2.3	--	--
4	Powder River at Sussex, Wyo.	-2.8	-1.3	+1.8	+2.8	--	--	+1.5	+1.3
6	Powder River at Arvada, Wyo.	--	--	+1.6	+2.1	--	--	+1.6	+.9
7	Clear Creek near Arvada, Wyo.	+1.2	--	--	--	--	--	--	--
8	Powder River at Moorhead, Mont.	-1.3	--	--	--	--	--	--	--
9	Little Powder River above Dry Creek, near Weston, Wyo.	--	--	--	--	--	--	+6.4	--
10	Powder River near Locate, Mont.	--	--	+1.4	+1.2	--	--	+2.5	+.9

Salt Creek near Sussex. Sulfate concentration (mean, 982 mg/L) decreased 2.3 percent per year at the same station. Chloride concentration increased at five stations. The largest change was in the Little Powder River above Dry Creek, near Weston (station 9), where the chloride concentration (mean, 20 mg/L) increased 6.4 percent per year. Dissolved-solids concentration increased at three stations on the Powder River. The largest change was in the Powder River at Sussex, where the concentration (mean, 1,980 mg/L) increased 1.3 percent per year. Dissolved-solids concentration increased 0.9 percent per year at the other two stations; the mean concentration was 1,990 mg/L at Arvada and 1,540 mg/L near Locate (station 10).

The areal distribution of trends in the water-quality characteristics for water years 1975-88 is shown in figures 11-18. Calcium concentration decreased in the mainstem Powder River at Sussex (fig. 11, station 4), owing to decreased calcium in Salt Creek. Downstream, calcium concentration had no detectable trend at Arvada (station 6), a slightly downward trend at Moorhead (station 8) in spite of an increase at Clear Creek (station 7), and no detectable trend near Locate (station 10). The decrease in magnesium concentration in the Powder River at Sussex (fig. 12, station 4) appears to be only a local phenomenon in response to a decrease in Salt Creek near Sussex (station 3). Trends in magnesium were not detected farther downstream. Sodium concentration increased at three mainstem Powder River stations, but not at Kaycee or Moorhead (fig. 13, stations 1 and 8). The increases do not appear to be associated with increases upstream or from any tributary that had sufficient data for analysis, however. Failure to detect a trend at Moorhead might be due to inflow of relatively unmineralized water from Clear Creek. Alkalinity concentration increased in Salt Creek near Sussex (fig. 14, station 3), but the increase apparently was insufficient to cause increases downstream. Similarly, a decrease in sulfate concentration at Salt Creek near Sussex (fig. 15) had no apparent effect downstream. Chloride concentration increased all along the mainstem except at Moorhead (fig. 16, station 8). Part of the increase might be due to increases in the Powder River near Kaycee (station 1) and the Little Powder River above Dry Creek, near Weston (station 9).

The effects of changes in concentration of the individual characteristics on adjusted sodium-adsorption ratio and dissolved-solids concentration were variable. The adjusted sodium-adsorption ratio increased at all mainstem stations except Kaycee and Moorhead (fig. 17, stations 1 and 8). The increases appear to be due, in part, to increases in the South Fork Powder River and Salt Creek, and to increases in sodium concentration along the mainstem. The increases in sodium concentration do not appear to be due to increases in the tributaries that were tested for trends. As with other characteristics, the lack of a trend at Moorhead might be due to the contribution of Clear Creek. The increase in the adjusted sodium-adsorption ratio in the South Fork apparently was not accompanied by statistically significant changes in the concentrations of characteristics from which it is computed. Increases in the adjusted sodium-adsorption ratio at Sussex, Arvada, and Locate were consistent with changes in concentrations of the characteristics that are included in the computation of the ratio. Dissolved-solids concentration also increased at Sussex, Arvada, and Locate (fig. 18, stations 4, 6, and 10). The increases were probably due to increases in concentrations of sodium and chloride.

Comparison Between Periods

Six stations had sufficient data for analysis for water years 1968-88 and 1975-88. The resultant data for the six stations, taken from tables 6 and 8, are consolidated in table 9. In the Powder River near Kaycee (station 1), sulfate concentration decreased during 1968-88, but had no trend during 1975-88. Chloride concentration had no trend during 1968-88, but increased during 1975-88. In the South Fork Powder River near Kaycee (station 2), sodium concentration, adjusted sodium-adsorption ratio, sulfate concentration, and dissolved-solids concentration increased during 1968-88. Only adjusted sodium-adsorption ratio had a trend (upward) during 1975-88. In Salt Creek near Sussex (station 3), calcium, magnesium, adjusted sodium-adsorption ratio, alkalinity, and sulfate had the same trends (some upward, some downward) during 1975-88 as during 1968-88. Dissolved-solids concentration had a trend (downward) during 1968-88 but not during 1975-88. In the

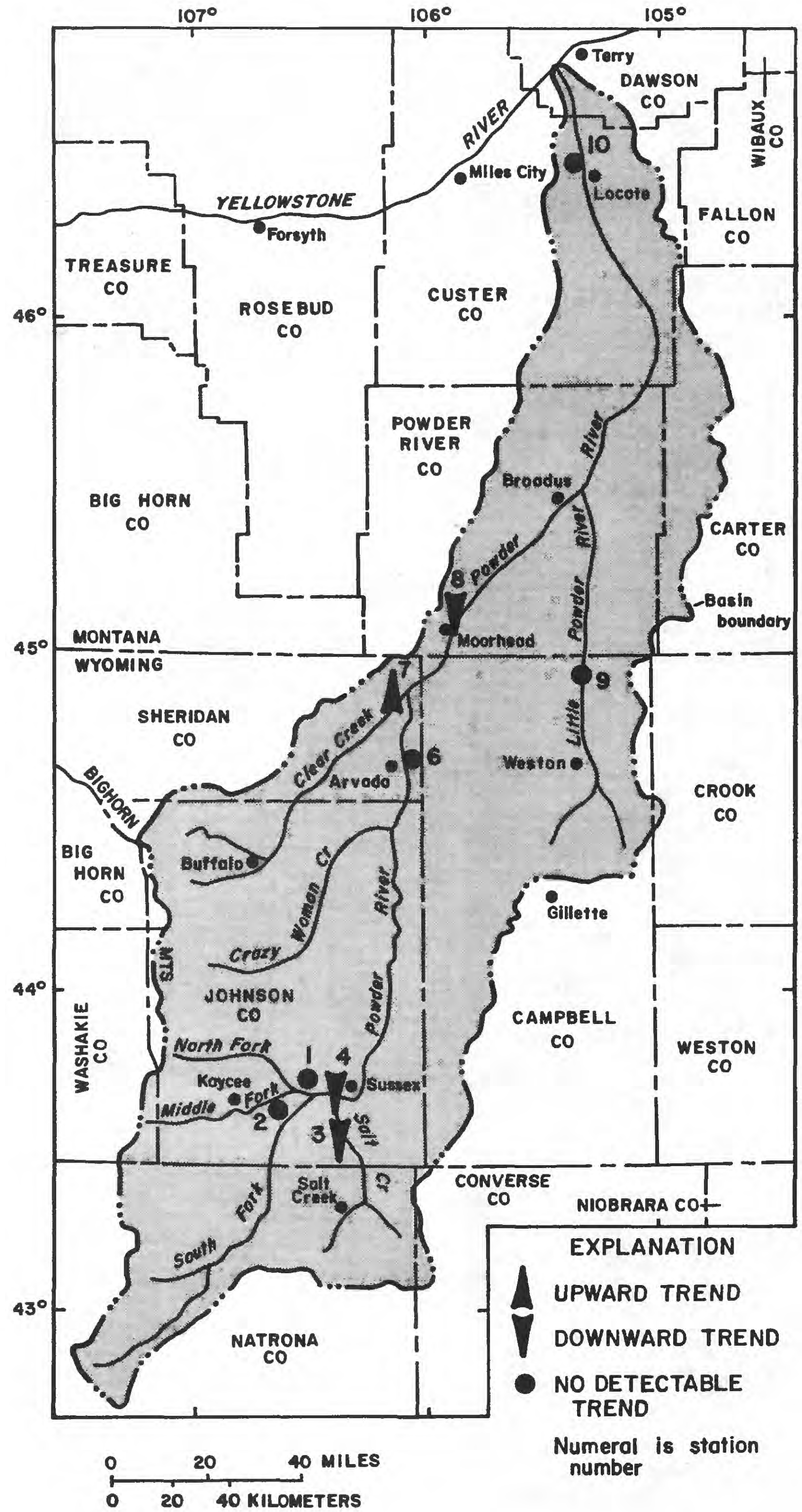

Figure 11.--Trends in calcium concentration, water years 1975-88.

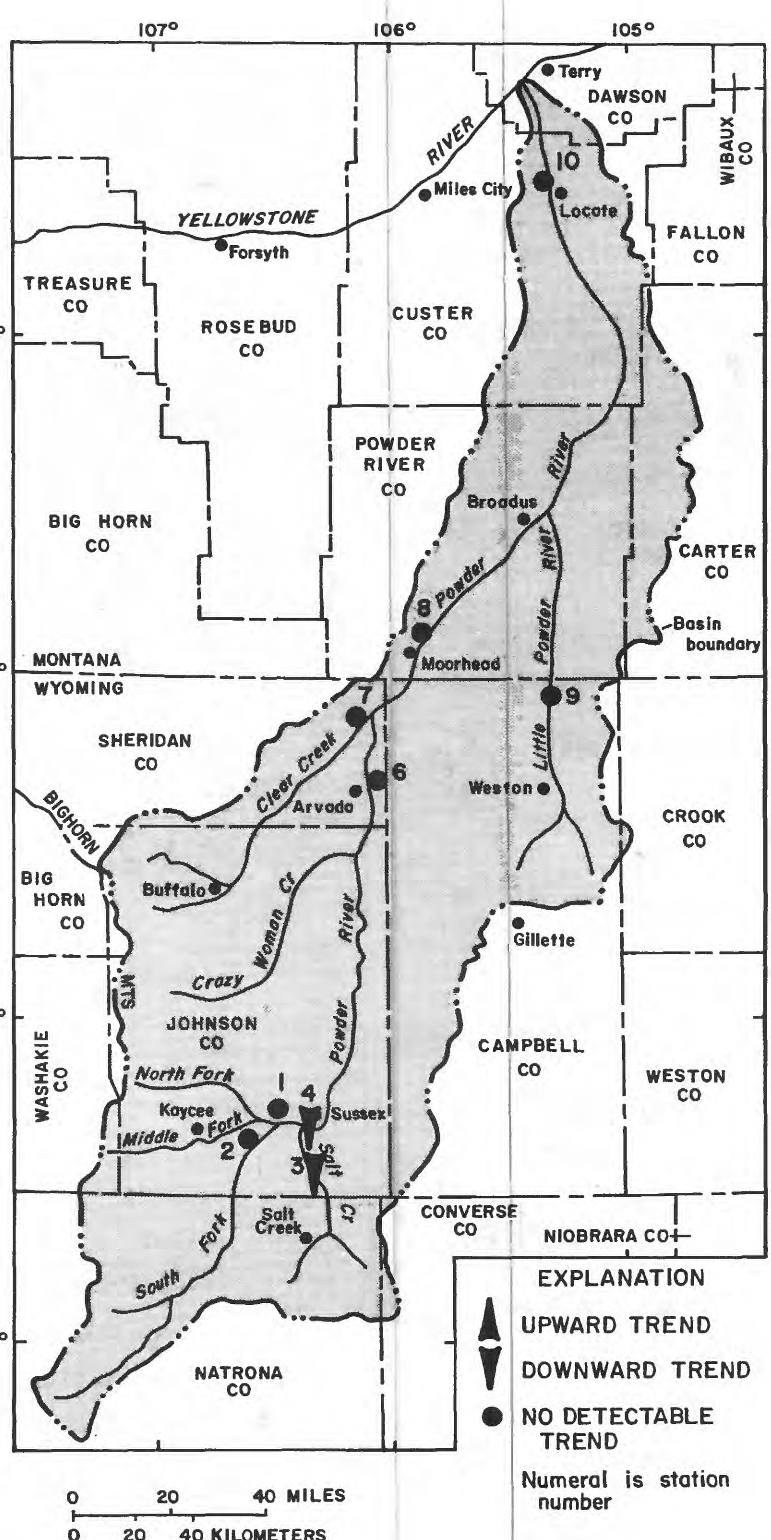

Figure 12.--Trends in magnesium concentration, water years 1975-88.

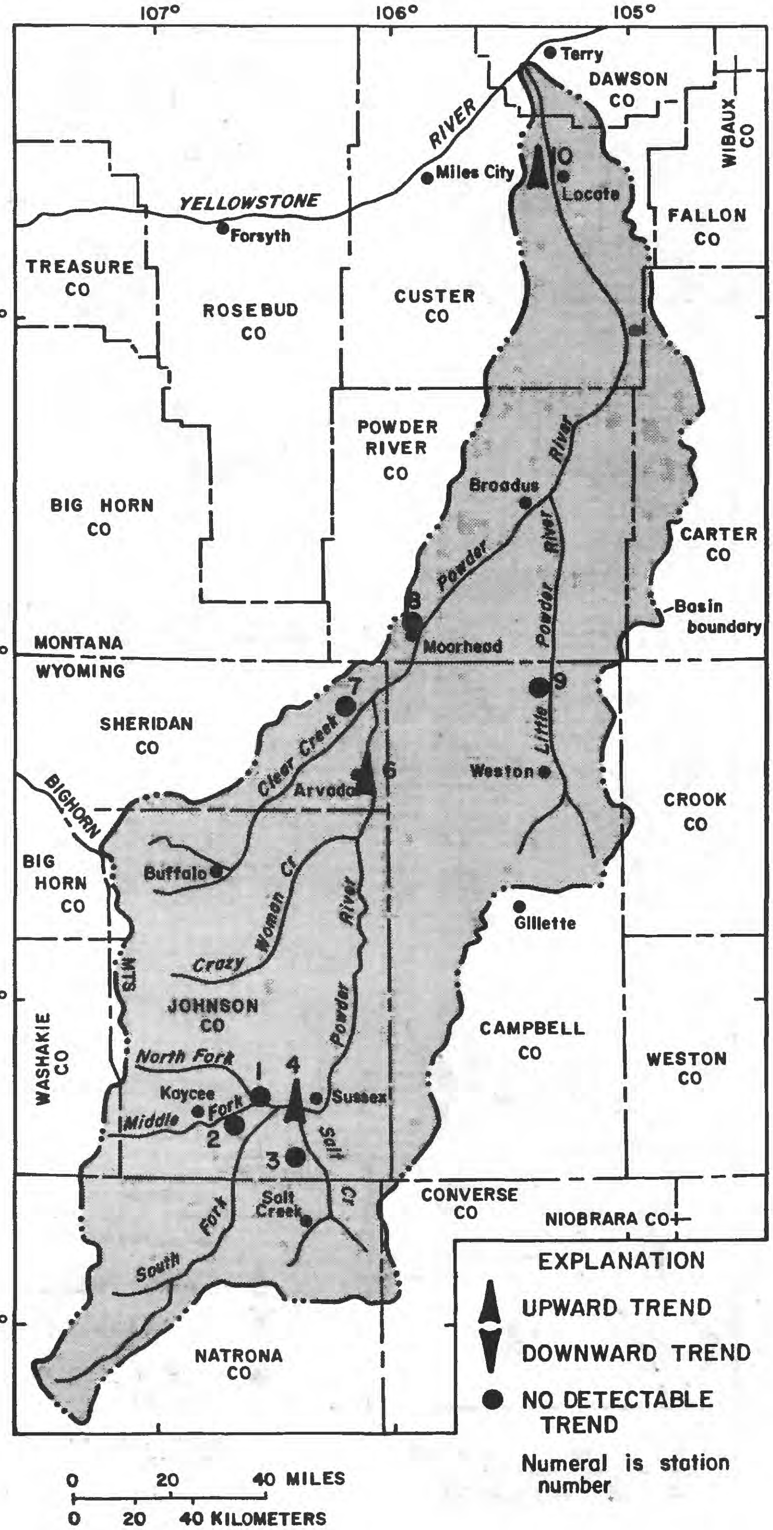

Figure 13.--Trends in sodium concentration, water years 1975-88.

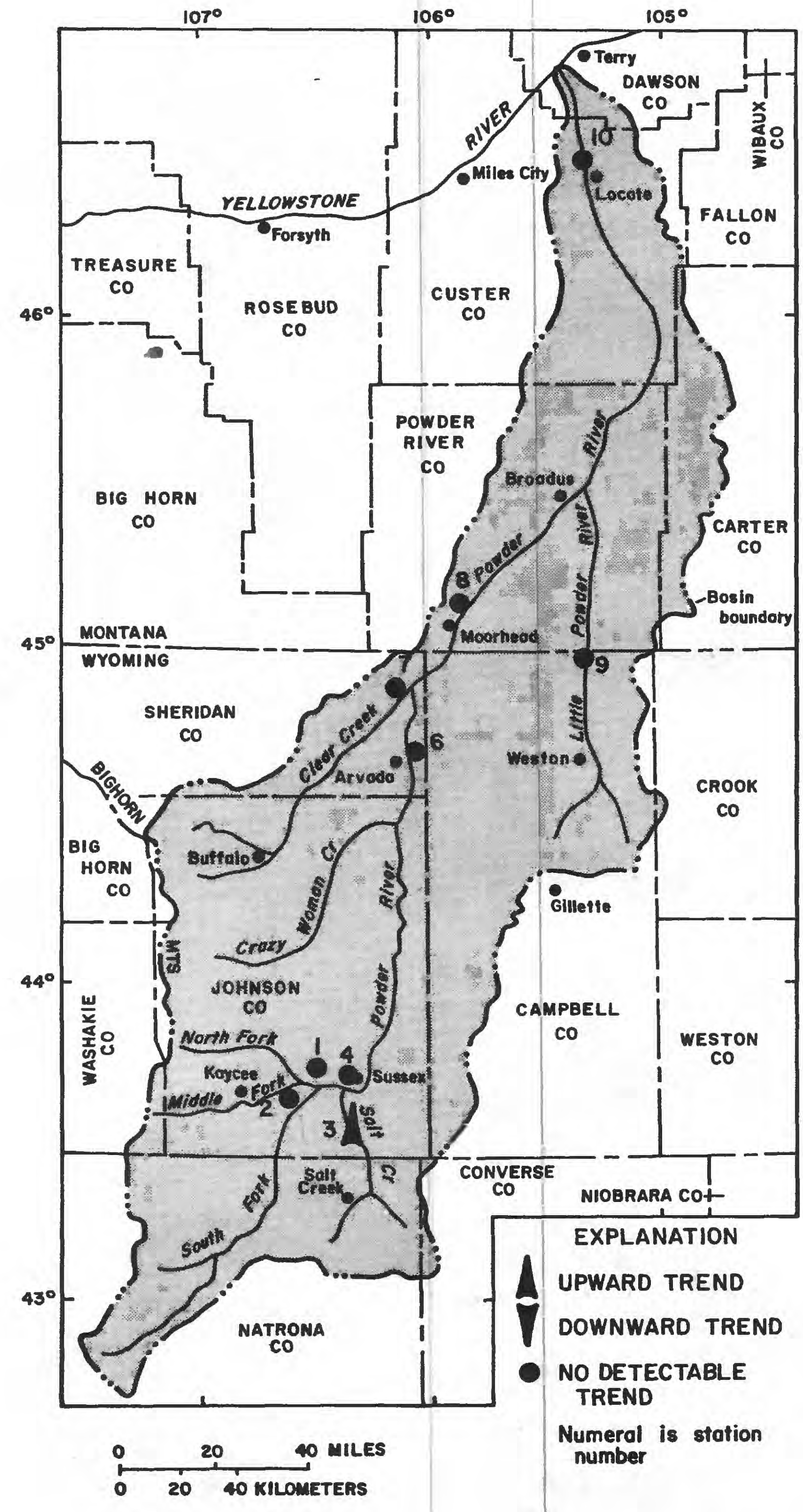

Figure 14.--Trends in alkalinity concentration, water years 1975-88.

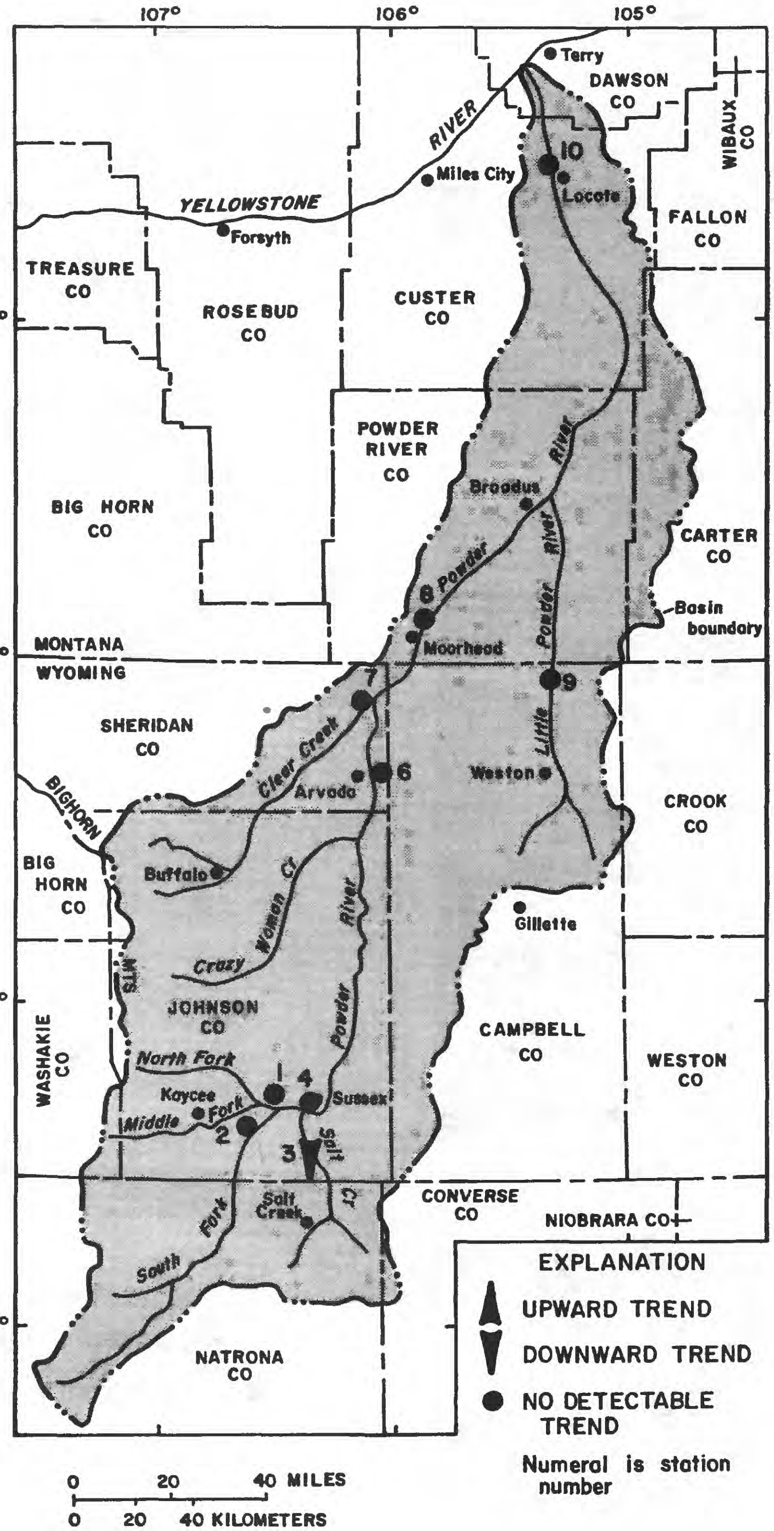

Figure 15.--Trends in sulfate concentration, water years 1975-88.

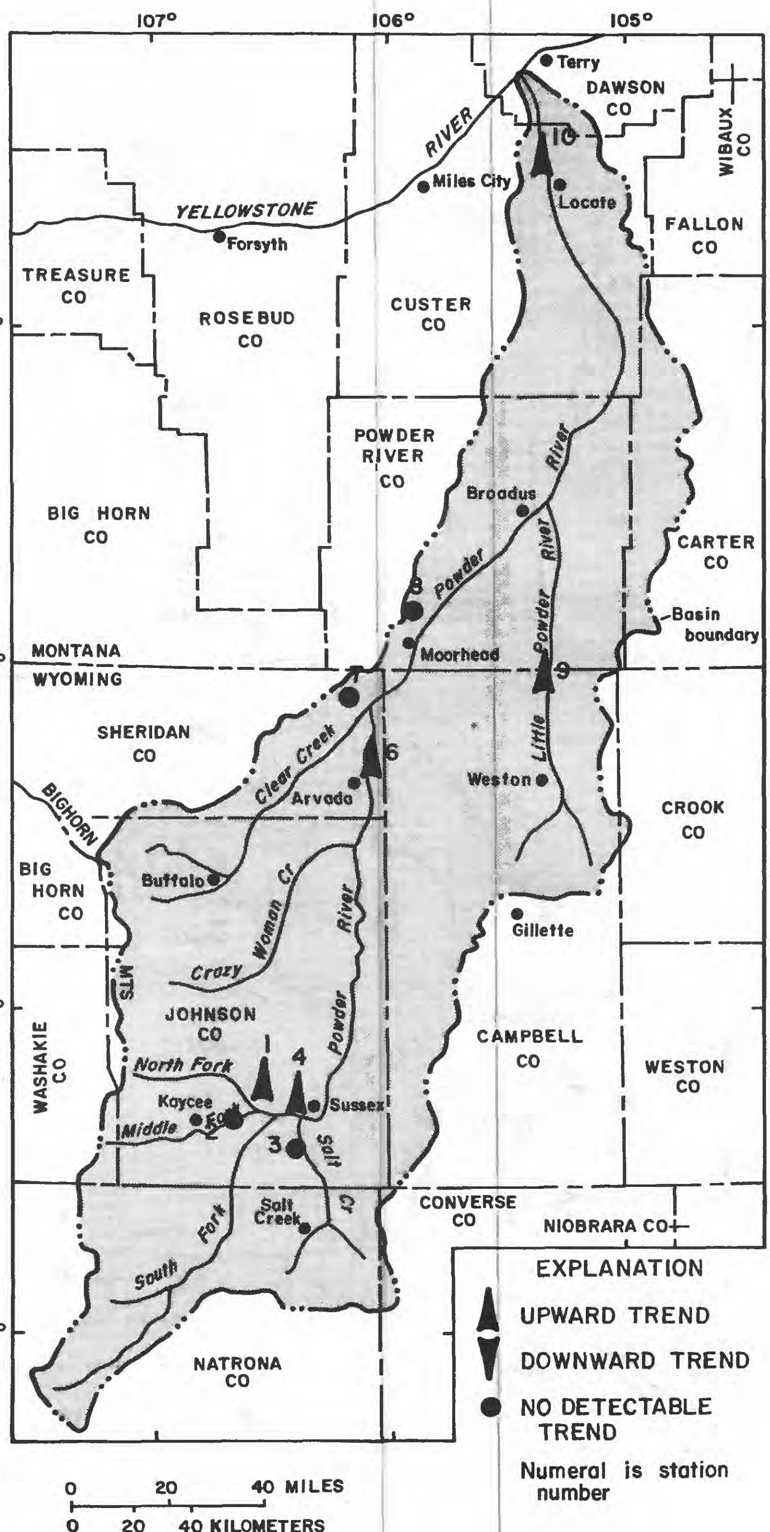

Figure 16.--Trends in chloride concentration, water years 1975-88.

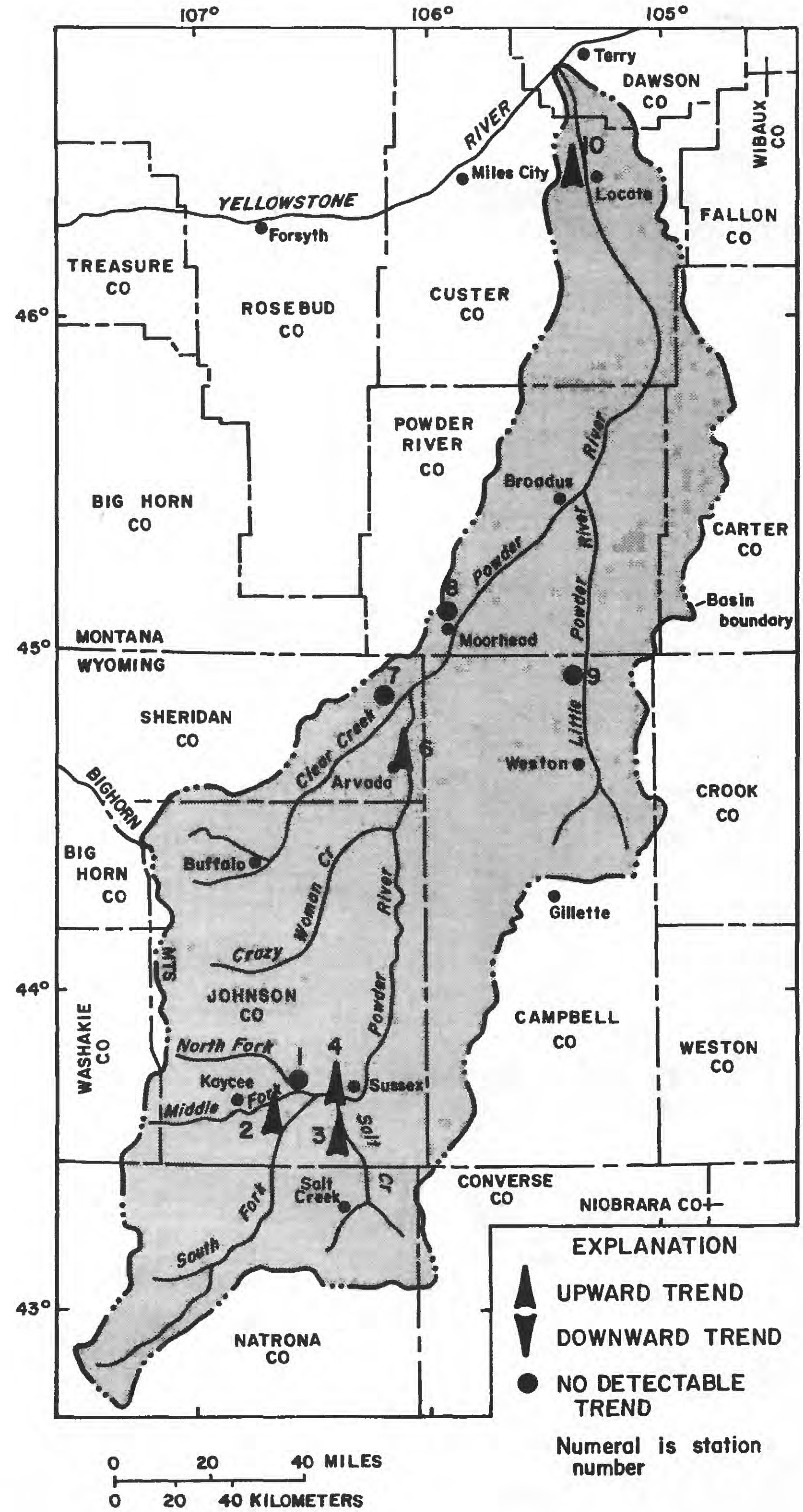

Figure 17.--Trends in adjusted sodium-adsorption ratio, water years 1975-88.

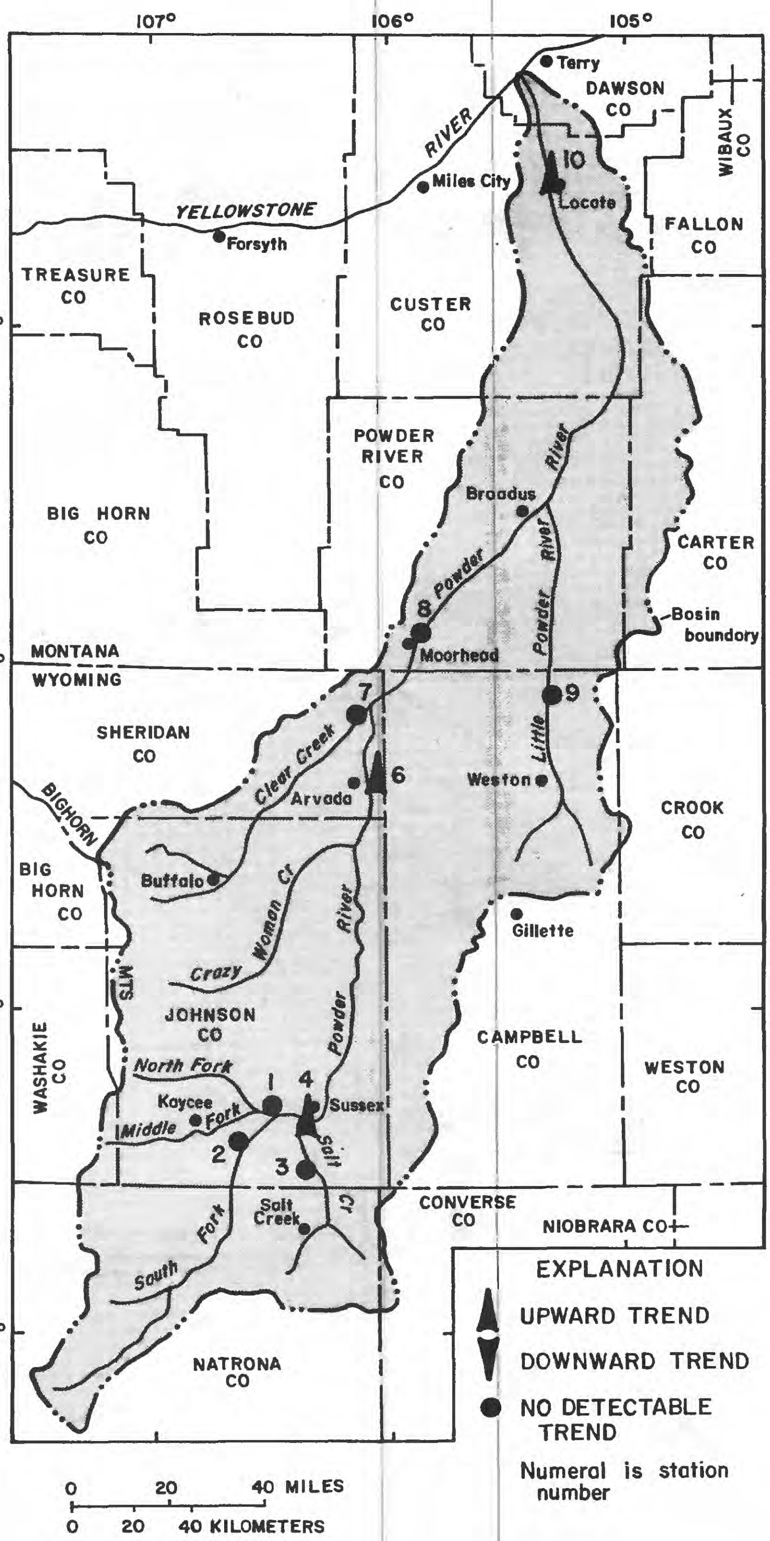

Figure 18.--Trends in dissolved-solids concentration, water years 1975-88.

Table 9.--*Trends in water-quality characteristics at six stations, water years 1968-88 and 1975-88*

[Units of measurement in milligrams per liter except as follows: adjusted sodium-adsorption ratio (units). All characteristics flow-adjusted prior to trend testing, except as noted. Trend results: 0, trend was not detected at the 0.10 significance level; +, trend was significant and values increased; -, trend was significant and values decreased. $CaCO_3$, calcium carbonate]

Station No.	Sampling station	Calcium, dissolved 1968-88	Calcium, dissolved 1975-88	Magnesium, dissolved 1968-88	Magnesium, dissolved 1975-88	Sodium, dissolved 1968-88	Sodium, dissolved 1975-88	Adjusted sodium-adsorption ratio 1968-88	Adjusted sodium-adsorption ratio 1975-88
1	Powder River near Kaycee, Wyo.	0	0	0	0	0	0	0	0
2	South Fork Powder River near Kaycee, Wyo.	0	0	0	0	+	0	+	+
3	Salt Creek near Sussex, Wyo.	-	-	[1]-	-	0	0	+	+
6	Powder River at Arvada, Wyo.	-	0	0	0	+	+	+	+
7	Clear Creek near Arvada, Wyo.	+	+	0	0	0	0	0	0
8	Powder River at Moorhead, Mont.	0	-	0	0	+	0	0	0

Station No.	Sampling station	Alkalinity, as $CaCO_3$ 1968-88	Alkalinity, as $CaCO_3$ 1975-88	Sulfate, dissolved 1968-88	Sulfate, dissolved 1975-88	Chloride, dissolved 1968-88	Chloride, dissolved 1975-88	Solids, sum of constituents, dissolved 1968-88	Solids, sum of constituents, dissolved 1975-88
1	Powder River near Kaycee, Wyo.	0	0	-	0	0	+	0	0
2	South Fork Powder River near Kaycee, Wyo.	0	0	+	0	0	0	+	0
3	Salt Creek near Sussex, Wyo.	+	+	[1]-	-	0	0	-	0
6	Powder River at Arvada, Wyo.	+	0	0	0	+	+	+	+
7	Clear Creek near Arvada, Wyo.	0	0	0	0	0	0	0	0
8	Powder River at Moorhead, Mont.	0	0	0	0	+	0	0	0

[1] Relation between discharge and water-quality characteristic was not statistically significant; therefore, characteristic was not adjusted for stream discharge.

Powder River at Arvada (station 6), sodium, adjusted sodium-adsorption ratio, chloride, and dissolved solids had the same trends (upward) in 1975-88 as during 1968-88. During 1968-88, calcium concentration decreased and alkalinity concentration increased. Neither characteristic had a trend during 1975-88. In Clear Creek near Arvada (station 7), calcium concentration increased during both periods. In the Powder River at Moorhead (station 8), sodium and chloride had upward trends during 1968-88 but no detectable trends during 1975-88. Calcium concentration decreased during 1975-88, but had no trend during 1968-88.

The relative sodium concentration and salinity of streamflow were of primary interest. The adjusted sodium-adsorption ratio increased during both periods at three stations: South Fork Powder River near Kaycee, Salt Creek near Sussex, and Powder River at Arvada. Dissolved-solids concentration increased during both periods at one station: Powder River at Arvada.

Comparison of results between the longer and shorter periods indicates that some trends occurred during one period but not the other. Trends in water-quality characteristics during water years 1968-88, but not during water years 1975-88, might indicate that the trends occurred only during the earlier part of the period 1968-88. Similarly, trends were detected in some water-quality characteristics during water years 1975-88 that were not detected during water years 1968-88. The changes (increase or decrease) in the values might have begun only after water year 1974.

The increases in the adjusted sodium-adsorption ratio and in dissolved-solids concentration that were detected represent degradation in the usefulness of the water for irrigation in some reaches of the Powder River. However, no inferences can be made regarding the continuation of trends into the future. The slope estimates that are provided are the medians of all slope estimates. They are useful for comparing trend results, but do not imply that the trend was a linear change through time (Hirsch and others, 1982, p. 117).

Factors Affecting Results

Some differences in the results of the trend tests were noted between time periods, stations, and water-quality characteristics. Several factors may have contributed to these differences.

Analysis of data from different time periods can affect the results. Trends may exist during one period, then cease or reverse direction during another. Trends also may commence after a period of no trend.

The distribution of the years of missing data also might affect the results. Several years of no data at the beginning or end of a record would result in a shorter effective period, which was true for Crazy Woman Creek at upper station, near Arvada (station 5). Samples were not collected during water years 1982-87, resulting in an effective period of record of water years 1968-81 for Crazy Woman Creek, whereas the effective period of record was nearly 1968-88 at the other stations.

The choice of significance level can affect the reported results of trend tests. For this study, there is a 10-percent probability that the seasonal Kendall test will indicate a trend when no trend exists. The probability of concluding a trend does not exist when, in fact, it does increases with decreasing significance levels, although the quantity of increase is generally not known.

When the data consisted of more than one value per season, the computer program used to perform the analysis selected the median of the values, and used it as the value for that season. If the sampling frequency changed with time, the use of median values during part of the period and individual instantaneous values during the rest of the period might affect the accuracy of the test statistics (J.R. Slack, written commun., 1990). The data for water-quality characteristics at Salt Creek near Sussex (station 3) for water years 1968-88 and the Powder River near Locate (station 10) for 1975-88 were reanalyzed using only the observation closest to the middle of each season. All other values occurring in a season were discarded. The trend test results did not change for any water-quality characteristic, which indicates that, in this study, the trend tests were not appreciably affected by the use of median values.

Seasonality in the variance of the data has been identified by Taylor and Loftis (1989, p. 715) as a factor affecting trend detection. After evaluating eight different trend tests, they concluded that, when the variance of the data is heterogeneous, the seasonal Kendall test with correction for serial correlation was the preferred test (Taylor and Loftis, 1989, p. 726). However, the computed significance level also might be large, which could result in the conclusion of no trend when a trend existed. In this study, the plots of the adjusted data were inspected. Most characteristics appeared not to be appreciably affected by seasonality in the variance. One exception was chloride, which at several stations displayed heterogeneous variance. The flow-adjusting equation selected was the one that most decreased the heterogeneity, as indicated by plots of adjusted data. Weighted regression also was used to decrease heterogeneity.

The sample size might affect the results. Berryman and others (1988, p. 548-549) indicated that at least 10 samples per season are needed when using the seasonal Kendall test with correction for serial correlation. Hirsch and Slack

(1984, p. 729) indicated that the covariance approximation is most accurate when 10 or more samples are available. The approximation might be inaccurate, however, when the number of observations approaches five. The criterion of 10 or more observations was met for all seasons at all stations during water years 1968-88 and at four of nine stations during 1975-88 (table 2). Where the number of observations during some seasons was less than 10, the observations ranged from 6 to 9. Clear Creek near Arvada (station 7) met the criterion in only one season.

Several other factors might explain differences noted between stations. Streamflow from tributaries originating in the mountains generally is less mineralized than streamflow from tributaries originating in the plains and foothills. The Powder River near Kaycee (station 1) and Clear Creek near Arvada are stations on streams originating in the mountains. Dilution by these streams helps to explain some of the results.

Numerous tributaries draining plains and foothills watersheds join the Powder River between the mainstem stations. Some of the differences in data between the mainstem stations might be caused by the intervening tributary inflows.

Irrigation is practiced along several tributaries and in several areas along the mainstem Powder River. Irrigation return flows might increase concentrations of some constituents during the irrigation season and for some time thereafter.

Some tributaries receive oil-field production water that increases concentrations of some constituents and changes water-quality properties. The two tributaries that are most affected by oil-field production water are Salt Creek and, to a lesser extent, the South Fork Powder River.

Values of the adjusted sodium-adsorption ratio are affected by more factors than the unadjusted sodium-adsorption ratio. Changes in the concentration of calcium, magnesium, and sodium will cause changes in the values of both ratios. Unlike the unadjusted sodium-adsorption ratio, changes in the ratio of bicarbonate to calcium can cause changes in the adjusted concentration of calcium. The adjusted concentration also is affected by the specific conductance of the water.

SUMMARY AND CONCLUSIONS

Data for selected water-quality characteristics were evaluated for trends at combination streamflow-gaging and water-quality stations along the Powder River and major tributaries in Montana and Wyoming. The water-quality characteristics that contributed most to relative sodium concentration and salinity were of primary interest, owing to the effects of those characteristics on the suitability of the water for irrigation.

Prior to testing for trends, data from all stations were reviewed. Stations were selected to give the largest number of stations with the longest periods of data collection. Although earlier data were available for a few stations, sampling at most stations did not begin until 1968. A second, more recent period of increased sampling began in 1975. Thus, data were available at seven stations for water years 1968-88 and at nine stations for water years 1975-88. Six stations had sufficient data to allow comparison of trend results between the periods. The sampling schedule differed among stations; period of sample collection ranged from 15 to 21 years for water years 1968-88 and from 11 to 14 years for 1975-88. On the basis of frequency of data collection, nine seasons per year were selected for trend analysis. The effective sample sizes resulting from the selection of nine seasons generally were adequate for trend testing.

Values for some characteristics were computed from other data. An adjusted sodium-adsorption ratio was computed from the data for each station. An adjusted calcium concentration was determined from the ratio of bicarbonate to calcium, and the specific conductance of the water sample. Although alkalinity usually was not reported for samples collected prior to water year 1975, alkalinity was computed from reported concentrations of bicarbonate and carbonate.

The data for water years 1968-88 and 1975-88 were statistically analyzed. At most stations during both periods, mean concentrations of calcium and sodium were larger than mean concentrations of magnesium, whereas mean concentrations of alkalinity and sulfate were larger than mean concentrations of chloride. The mean adjusted sodium-adsorption ratio and dissolved-solids concentration increased as a result of inflow from Salt Creek, but decreased in the Powder River at Moorhead as a result of dilution by inflow from Clear Creek. During water years 1975-88, the mean adjusted sodium-adsorption ratio and dissolved-solids concentration increased again near Locate, owing, in part, to the contribution of the Little Powder River.

The data for all characteristics were adjusted for the effects of discharge if the relation between discharge and the unadjusted data was significant. The unadjusted data were evaluated for trends if the relation was not significant.

The seasonal Kendall test with correction for serial correlation was applied to the data from seven stations for water years 1968-88. The results are for flow-adjusted data, with the exception of magnesium and sulfate in Salt Creek near Sussex, which are for unadjusted data. Trends were detected in at least one water-quality characteristic at each station, and included both increasing and decreasing values. Both the adjusted sodium-adsorption ratio, which measures the relative sodium concentration, and dissolved solids, which measures salinity, are affected by the changes in concentration of the individual water-quality characteristics. The adjusted sodium-adsorption ratio increased at four stations--three tributary and one mainstem. The largest increase (2.8 percent per year) was in the South Fork Powder River near Kaycee, where the mean ratio was 7.6. The ratio increased 1.9 percent per year in Salt Creek near Sussex (mean, 38), 1.3 percent per year in Crazy Woman Creek at upper station, near Arvada (mean, 2.4), and 2.2 percent per year in the Powder River at Arvada (mean, 9.0). Dissolved-solids concentration increased 1.2 percent per year in the South Fork (mean, 2,780 mg/L), decreased 0.9 percent per year in Salt Creek (mean, 4,210 mg/L), and increased 0.6 percent per year in the Powder River at Arvada (mean, 1,950 mg/L). The trends in adjusted sodium-adsorption ratio and dissolved-solids concentration detected in the Powder River at Arvada and the absence of trends in the Powder River at Moorhead are due, in part, to changes in the concentrations of individual water-quality characteristics upstream. The increases at Arvada are due, in part, to changes in concentrations noted in the South Fork, Salt Creek, and Crazy Woman Creek. The absence of trends at Moorhead are due, in part, to dilution by inflow from Clear Creek.

The seasonal Kendall test with correction for serial correlation was applied to adjusted data from nine stations for water years 1975-88. Trends were detected in at least one water-quality characteristic at each station. The adjusted sodium-adsorption ratio increased at five stations--two tributary and three mainstem. The largest increase (4.3 percent per year) was in the South Fork Powder River near Kaycee, where the mean ratio was 8.5. The ratio increased 1.6 percent per year in Salt Creek near Sussex (mean, 38), 2.8 percent per year in the Powder River at Sussex (mean, 13), 2.1 percent per year in the Powder River at Arvada (mean, 9.6), and 1.2 percent per year in the Powder River near Locate (mean, 6.3). Dissolved-solids concentration increased at three Powder River stations: at Sussex, at Arvada, and near Locate. The largest increase was at Sussex (mean, 1,980 mg/L), where the concentration increased 1.3 percent per year. Dissolved-solids concentration increased 0.9 percent per year at the other two stations. The mean concentration was 1,990 mg/L at Arvada and 1,540 mg/L near Locate. Trends in the adjusted sodium-adsorption ratio and dissolved-solids concentration detected in the Powder River at Sussex and at Arvada are due, in part, to changes in concentrations of individual water-quality characteristics in upstream tributaries and to change along the mainstem. The absence of trends at Moorhead are due, in part, to dilution by inflow from Clear Creek. The trends in the adjusted sodium-adsorption ratio and dissolved-solids concentration at Locate are probably due to changes in concentration of individual water-quality characteristics downstream from Moorhead.

Concurrent data for six stations for water years 1968-88 and 1975-88 were compared. The results differed between periods for some characteristics, but not others. The relative sodium concentration and salinity of streamflow were of primary interest. Adjusted sodium-adsorption ratio increased during both periods at three stations: South Fork Powder River near Kaycee, Salt Creek near Sussex, and Powder River at Arvada. Dissolved-solids concentration increased during both periods at one station: Powder River at Arvada.

The increases in adjusted sodium-adsorption ratio and dissolved-solids concentration that were detected represent degradation in the usefulness of the water for irrigation. However, the slope estimates do not imply that the trend was a linear increase during the period. Also, no inferences can be made regarding the continuation of trends into the future.

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