HYDROLOGY OF THE POWDER RIVER ALLUVIUM BETWEEN SUSSEX, WYOMING, AND MOORHEAD, MONTANA

By Bruce H. Ringen and Pamela B. Daddow

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CONVERSION FACTORS

The following factors can be used to convert the inch-pound units in this report to the International System of Units:

Multiply	*By*	*To obtain*
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
foot per day	0.3048	meter per day
foot squared per day	0.0929	meter squared per day
gallon per minute	3.785	liter per minute
cubic foot per second	0.02832	cubic meter per second
acre-foot	1,233.	cubic meter
acre-foot per day	1,233.	cubic meter per day

Temperature can be converted to degrees Fahrenheit (°F) or degrees Celsius (°C) by the following equations:

$$°F = 9/5\ °C + 32$$

$$°C = 5/9\ (°F - 32)$$

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 both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

The generally fine-grained alluvium along the Powder River between Sussex, Wyoming, and Moorhead, Montana, ranges from 4 to 45 feet thick but is usually 10 to 30 feet thick and about one-half mile wide along the reach studied. The length of the study reach is 155 river miles. The water in the alluvium primarily comes from seepage from the river, stored during periods of high streamflow and discharged back to the river in some reaches during low flow. Flow-duration curves indicate ground-water discharge and (or) irrigation return flow to the river near the streamflow-gaging station near Sussex, Wyoming, but not near stations near Arvada, Wyoming, or Moorhead, Montana. The lack of ground-water discharge was supported by analysis of streamflow gains and losses; net annual gains in the reach from Sussex to Arvada in 1978 and 1979 were due to runoff not accounted for between the two sites.

Water in the alluvium has good hydraulic connection with the river. Generally, the bedrock is believed to be isolated from the alluvium and the river. Although the Powder River alluvium does not fully meet the assumptions of the method used, an approximate value of diffusivity of 10,200 feet squared per day was computed for the alluvium at a site near Interstate Highway 90. Approximate values for transmissivity and hydraulic conductivity were calculated from this diffusivity value.

The river rarely was dry at Sussex, but it was dry for at least 1 day in 2 of every 3 years at Arvada, and not so frequently at Moorhead. For 1 year in 2 for the period of record, it was dry at Arvada for 13 consecutive days, and for 1 year in 5 for the period of record, it was dry for 30 consecutive days. At the site near Interstate Highway 90, about 15 percent of the pumpage from a hypothetical well located 200 feet from the river and pumping 50 gallons per minute for 2 days would be drawn from the river. An increasing percentage of the water pumped would come from the river as the distance from the river to the well is decreased or as the well is pumped for longer periods.

The quality of water in the alluvium improves downstream, but even at Moorhead the water does not meet standards recommended by the U.S. Environmental Protection Agency for drinking water. It is acceptable for most livestock uses, but concentrations of certain constituents may limit its use for irrigation or industrial use. Chemically, the water in the alluvium is similar to water in the river. The river water is dominated by sodium and sulfate ions, whereas water in the alluvium is dominated by sodium, calcium, and sulfate ions. The water in the bedrock, however, is dominated by sodium and bicarbonate ions.

The potential for developing water supplies from the alluvium along the Powder River is limited. The areal extent and saturated thickness of the alluvium are not large. Water in the alluvium is supplied primarily by the river, which goes dry periodically. Pumpage from wells completed in the alluvium is highly dependent on water supplied directly from the river, particularly from wells close to the river. As noted above, the quality of water in the alluvium also limits its use as a water supply.

INTRODUCTION

Reliable sources of water are needed to support industrial and municipal growth in northeastern Wyoming, a water-scarce area. The alluvium along the Powder River in northeastern Wyoming is identified as a principal aquifer in some reports (Taylor, 1978, plate 1; and U.S. Water Resources Council, 1980, p. 9). However, preliminary data indicated that the alluvium has good hydraulic connection with the river, generally would yield less than 100 gallons per minute to wells, and contains water that is generally of poor quality. The U.S. Bureau of Land Management and the U.S. Geological Survey cooperated in a hydrologic study of the Powder River alluvium during 1983-85 to determine whether the alluvium should be classified as a principal aquifer.

Purpose and Scope

The purpose of this report is to describe the hydrology of the alluvium along the Powder River between Sussex, Wyoming, and Moorhead, Montana, and the potential for developing water supplies from the alluvium. Study objectives were: (1) To determine the availability and quality of water in the alluvium, and (2) to determine the hydrologic function of the alluvium by observing the relations between water in the alluvium, the river, and the bedrock aquifer.

The study was limited by its short duration and limited funding. Extensive use of existing hydrologic data was made. Only limited new data were collected; the field work was done during 1983 and the data were compiled and analyzed during part of 1984. Results of the study were expected to be nonquantitative or approximate, but sufficient to satisfy objective 1. Detailed data for determining the hydrologic function of the alluvium (objective 2) were collected at only one site.

Previous Investigations

Information about the potential of the Powder River alluvium as an aquifer is available for specific areas. Alluvial aquifer characteristics in Sheridan County, Wyo., were discussed by Lowry and Cummings (1966) and in parts of Johnson County, Wyo., by Whitcomb and others (1966). U.S. Bureau of Reclamation drilling activity within the study area is discussed in a report by Olive (1957). The hydrology of the study area is discussed in a report by Lowry and others (1986); they describe many aspects of the water resources as related to the development of coal. The report includes a bibliography of more than 350 references.

Description of the Study Area

The study area (fig. 1) is the Powder River valley from Sussex, to Moorhead, a distance of about 155 river miles. The drainage areas upstream of streamflow-gaging stations on the Powder River are: 3,090 square miles at Sussex; 6,050 square miles at Arvada; and 8,088 square miles at Moorhead. The river channel is wide, shallow, and sinuous throughout the study reach; for long distances both banks are vertical. The river meanders from one side of the alluvial valley floor to the other; thus the alluvial deposits are vulnerable to fluvial erosion and deposition.

The valley generally is grass-covered, has some trees and underbrush, and is dissected in places by the channels of tributary streams. The most common tree in the area is cottonwood, but there are occasional clumps of willow and Russian olive trees. Saltcedar, greasewood, and saltsage comprise most of the small plants.

The bedrock underlying the alluvium from Sussex to just south of Arvada is the Wasatch Formation of Eocene age. The area north of Arvada is underlain by the Fort Union Formation of Paleocene age. Bedrock is exposed at Arvada, and Moorhead. Both the Wasatch and the Fort Union Formations are composed of sandstone and interbedded shale and coal.

Water development in the valley is limited. Several deep wells for watering livestock have been drilled into the underlying bedrock, but there is currently (1984) no stock, irrigation, industrial, or municipal water use from wells completed in the alluvium. Six small areas irrigated with surface water are farmed: one at Sussex, two downstream from Sussex, one near the mouth of Clear Creek, and two a few miles downstream from the mouth of Clear Creek.

Precipitation in the study area is highly variable from year to year. From 1936 through 1975, annual precipitation ranged from a minimum of 7.0 inches during 1966 to a maximum of 17.1 inches during 1944 at the weather station near Arvada (Lowry and others, 1986, p. 12). Most of the precipitation from November through April is snow. Summertime precipitation occurs as light showers and occasional intense thunderstorms (Lowry and others, 1986, p. 12).

The Powder River is formed by the confluence of four streams. The combined North and Middle Forks of the Powder River contribute mountain snowmelt and runoff for about 50 percent of the total flow at Sussex, the upstream end of the study area (table 1). The South Fork Powder River contributes plains runoff and Salt Creek contributes plains runoff and an unmeasured discharge of brine effluent from the Salt Creek oilfield. Average annual discharge of the Powder River at Sussex was 479 cubic feet per second in 1978, 227 cubic feet per second in 1979, and 154 cubic feet per second in 1980. The long-term average is 188 cubic feet per second.

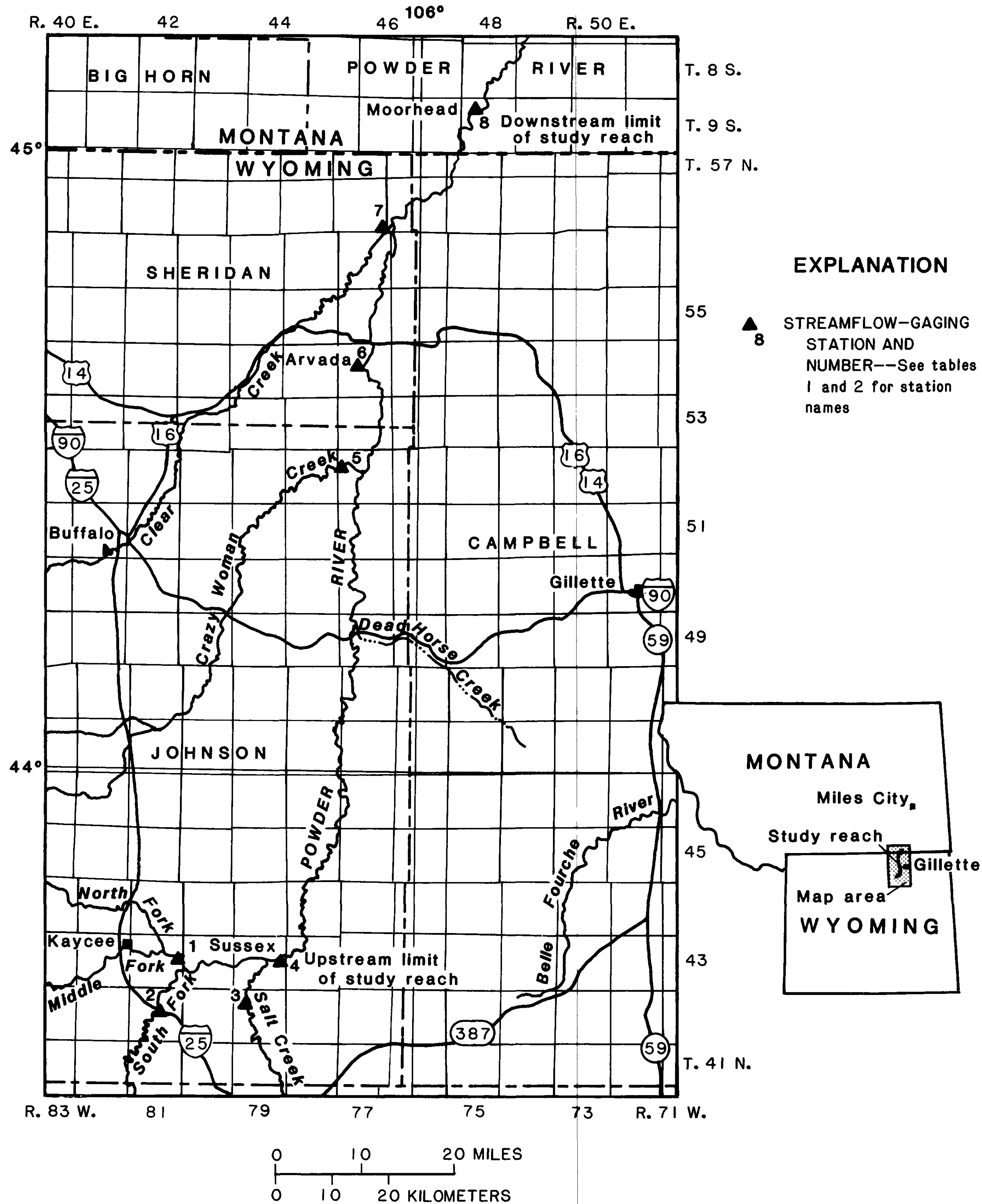


Figure 1.--Location of study reach and streamflow-gaging stations.

Table 1.--*Average annual discharge and percentage of total flow for streams contributing to flow in Powder River at Sussex, Wyo., water years 1979 and 1980*

Streamflow-gaging station	Station number	Water year	Average annual discharge (cubic feet per second)	Percentage of total flow of Powder River at Sussex, Wyoming
Powder River near Kaycee, Wyo. (combined North and Middle Forks)	1	1979	114	50.2
		1980	79.8	51.8
South Fork Powder River near Kaycee, Wyo.	2	1979	35.1	15.5
		1980	27.1	17.6
Salt Creek near Sussex, Wyo.	3	1979	41.2	18.1
		1980	39.5	25.7
Powder River at Sussex, Wyo.	4	1979	227	100
		1980	154	100
Discharge at station 4 minus sum of discharges at stations 1-3		1979	36.7	16.2
		1980	7.6	4.9

Data Collection

Hydrologic data from streamflow-gaging stations and water wells in the study area were used. Discharge and water-surface elevation of the Powder River were obtained from records at three streamflow-gaging stations. An inventory of selected wells in the study area was conducted. Drillers' logs were examined to determine the composition and thickness of the alluvium. The extent of the alluvium was measured from U.S. Geological Survey 1:24,000-scale topographic maps.

Only limited new hydrologic data were collected. Two observation wells were drilled at a site near the Powder River where Interstate Highway 90 crosses the river. Recorders were installed in three other wells at that site to record changes in water levels in the alluvial and bedrock aquifers. A recorder was installed in a stilling well to record the river stage. Other field data collected during the study included periodic water-level measurements in selected wells, and a total of six water samples from the Powder River and selected wells for chemical-quality analysis.

Well-Numbering System

Most wells mentioned in this report are identified by a number based on the U.S. Bureau of Land Management system of land subdivision. An example is illustrated in figure 2. From left to right, the parts of the well number indicate township, range, section, and subdivision of section. Subdivisions

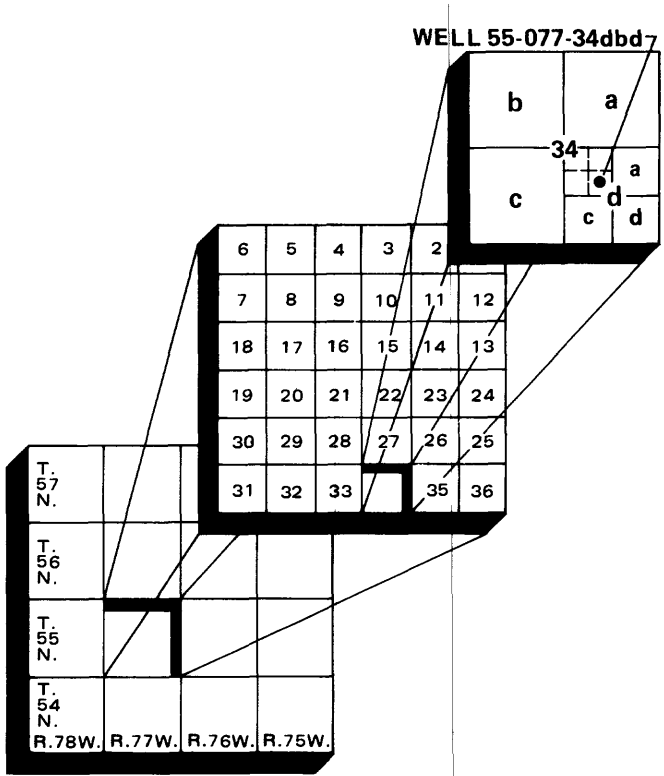


Figure 2.--Well-numbering system.

are designated counterclockwise by letters a, b, c, and d, beginning with the northeast quarter. Successive letters indicate successive subdivisions. If there is more than one well in the smallest subdivision, consecutive numbers beginning with 01 are appended to the well number.

A simpler method was used to identify wells at the Interstate Highway 90 study site. The wells were numbered consecutively beginning with 1; a letter prefix designates the material in which a well was completed (A for alluvium; B for bedrock).

DESCRIPTION OF THE ALLUVIUM

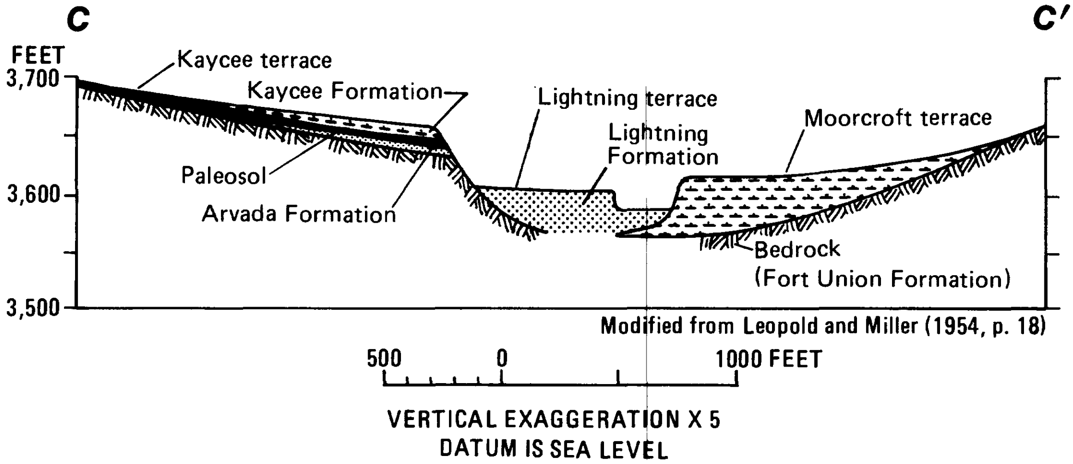
As described by Leopold and Miller (1954, p. 7-11, 17-23), the Powder River (and most other major streams in eastern Wyoming) is bordered by alluvium forming three prominent terraces. Geologic sections near Arvada and Sussex (fig. 3) show these alluvial terraces. The oldest and highest terrace, the Kaycee, stands 55 feet above the river near Arvada, and 53 feet above the river near Sussex. The Kaycee terrace is composed of several alluvial formations, consisting of sandy silt and gravel and coarse sand with cobbles. The Moorcroft terrace is the middle terrace, standing 17 feet above the river near Arvada and 23 feet above the river near Sussex. The Moorcroft is composed of silty, fine-grained alluvium. The lowest terrace, the Lightning, stands 7 feet above the river near Arvada and 5 feet above the river near Sussex. It is somewhat broader than the Moorcroft and is separated from it by an abrupt escarpment. The Lightning terrace is in contact with the stream in many reaches, and consists of silty, fine or medium sand with lenses of coarse sand or fine gravel. It may be the floodplain in some reaches, but generally the floodplain is a slightly lower, narrow, relatively inconspicuous flat bordering the river.

The thickness of the alluvium along the Powder River ranges from about 4 to 45 feet, but commonly is 10 to 30 feet; the alluvium generally is about one-half mile wide. The locations of geologic sections and wells with drillers' logs used to calculate thickness of the alluvium are shown in figure 4. The geologic sections are shown in figure 5, and the drillers' logs are listed at the end of this report (table 7).

HYDROLOGIC FUNCTION OF THE ALLUVIUM

To assess the potential for developing water supplies from the Powder River alluvium, the hydrologic function of the alluvium first must be described. The hydrologic function of the alluvium is defined in this study as how the alluvium stores and transmits water to and from the river and from the bedrock. Recharge to the alluvium along the Powder River is greatest during high flow (high stage) in the river. During low flow (low stage) in the river, the alluvium discharges water back into the river in some reaches. The following information was used to analyze the hydrologic function of the alluvium: flow-duration curves, streamflow gains and losses, responses in wells to changing river stage, and aquifer characteristics of the alluvium.

Near Arvada, Wyo.



Near Sussex, Wyo.

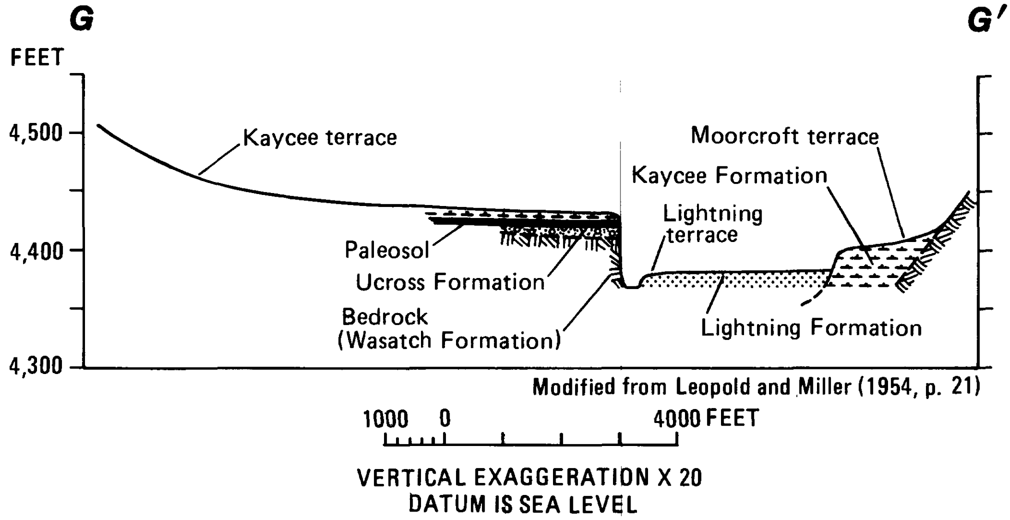


Figure 3.--Geologic sections of the Powder River valley showing three alluvial terraces. (Location of sections shown in fig. 4.)

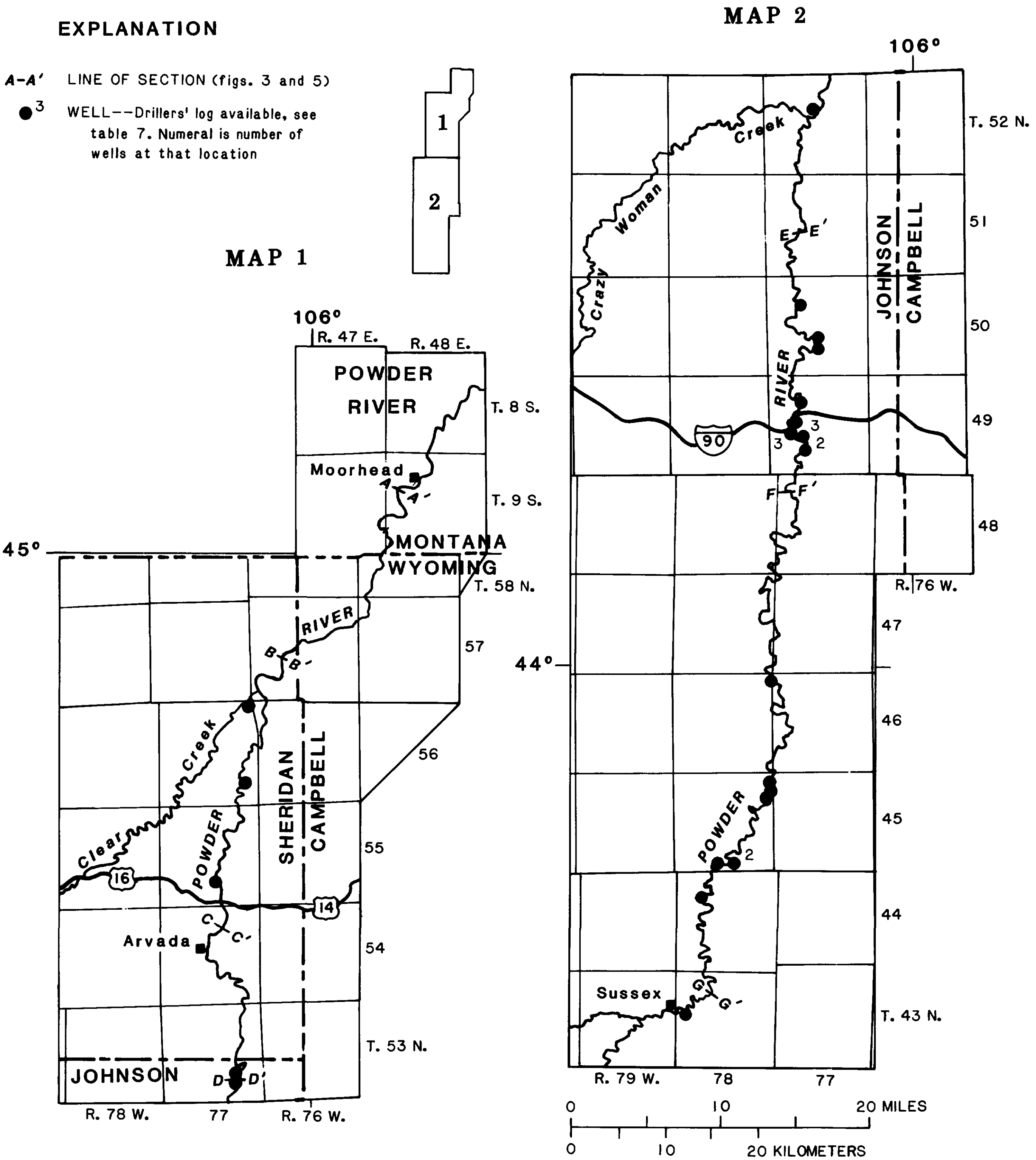


Figure 4.--Location of geologic sections and wells with drillers' logs.

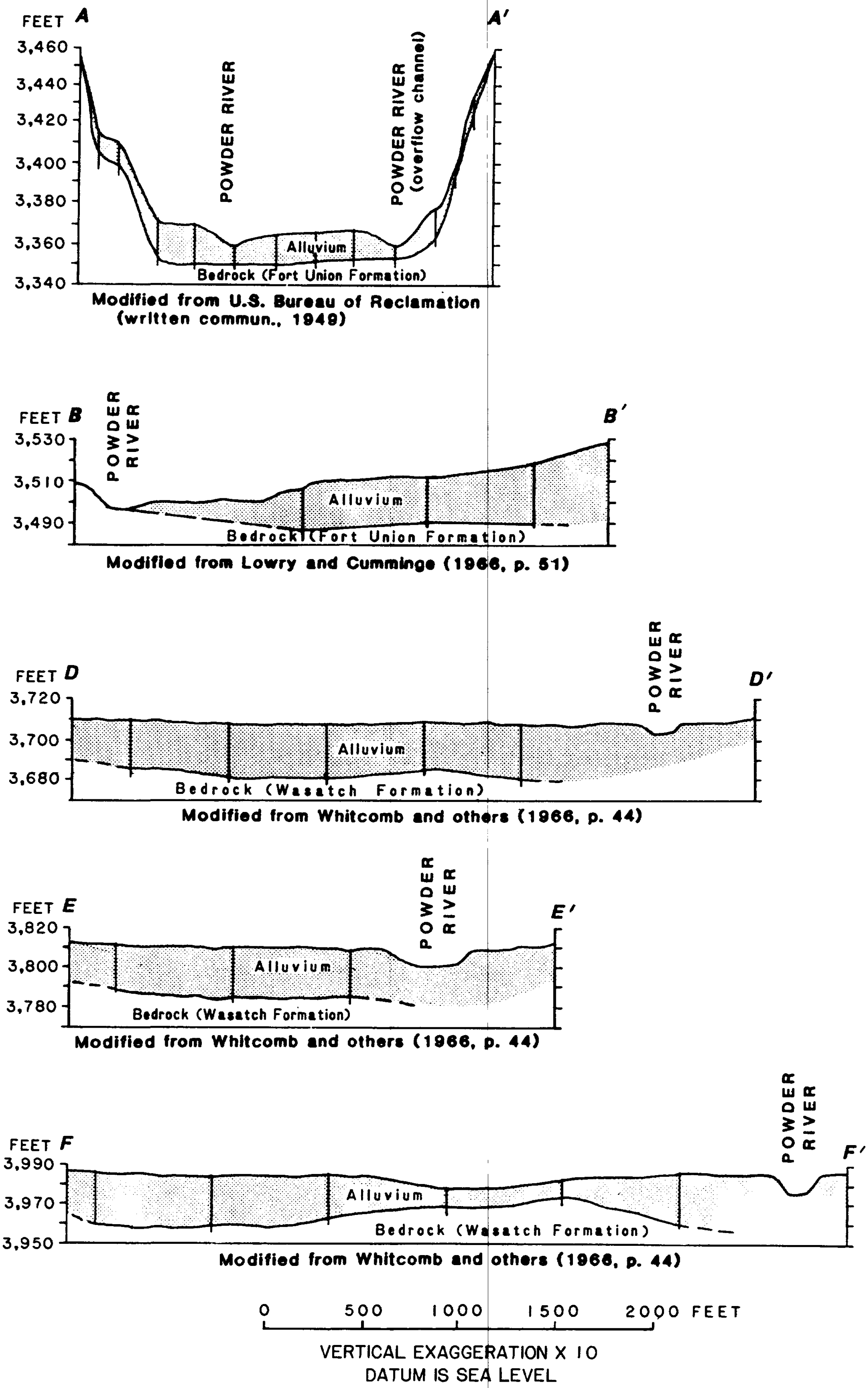


Figure 5.--Geologic sections showing thickness of the alluvium along the Powder River. Vertical lines represent test holes; see original sources for test-hole data. (Location of sections shown in fig. 4.)

Flow-Duration Curves

Flow-duration curves, computed from streamflow records, commonly indicate the presence or absence of ground-water discharge to the river and the variability of streamflow. The curves show the percentage of time during a given period of record that streamflow equalled or exceeded specified flows. According to Searcy (1959, p. 22), the shape of the curve is an indication of the hydrology of the drainage area. A steep slope throughout the length of the curve indicates the flow in the stream is highly variable, with the flow originating mostly from direct runoff; whereas a flat slope usually indicates the effect of surface-water or ground-water storage. A flat slope at the lower end of the curve usually indicates the effect of ground-water storage, while a steep slope indicates its absence (Searcy, 1959, p. 22).

Flow-duration curves for the three streamflow-gaging stations in the study reach are shown in figure 6. All three curves have a steep slope, indicating highly variable flow mostly from direct runoff. The slopes of the curves for Powder River at Arvada and Moorhead are steep throughout, indicating that discharge from ground water is small in the downstream part of the study reach. The curve for Powder River at Sussex, the upstream end of the study reach, is the only curve that flattens out at the lower end. This indicates that, during the period of record, low flows were sustained by a discharge of about 2.8 cubic feet per second or greater, possibly from ground water. Return flow from local irrigation also may help to sustain low flows.

During most years, the ground-water contribution to streamflow at Sussex may be much larger than the minimum indicated by the flow-duration curve. Based on average annual discharge at stations on the three tributaries contributing to the flow at Sussex, ground-water discharge at Sussex was estimated to be 36.7 cubic feet per second in 1979, or 16.2 percent of the total flow, and 7.6 cubic feet per second in 1980, or 4.9 percent of the total flow (see table 1).

Streamflow Gains and Losses

Streamflow gain or loss along a reach of the river is determined by subtracting the streamflow recorded at an upstream streamflow-gaging station and any intervening tributary inflow from the streamflow recorded at a downstream station. An increase (gain) in streamflow at the downstream end of the reach indicates runoff between the two stations or ground-water discharge into the stream channel. A decrease (loss) in streamflow indicates streamflow has been lost to evaporation or transpiration, or that seepage has recharged ground water in the alluvium. The recharge to the ground water from the stream during high flow and the ground-water discharge to the stream during low flow vary, depending on the amount, intensity, and location of precipitation, as well as seasonal variations in runoff and evapotranspiration.

Streamflow gains and losses in the Powder River were computed for the upstream reach between Sussex and Arvada, and for the downstream reach between Arvada and Moorhead. Tributaries accounted for were Crazy Woman Creek between

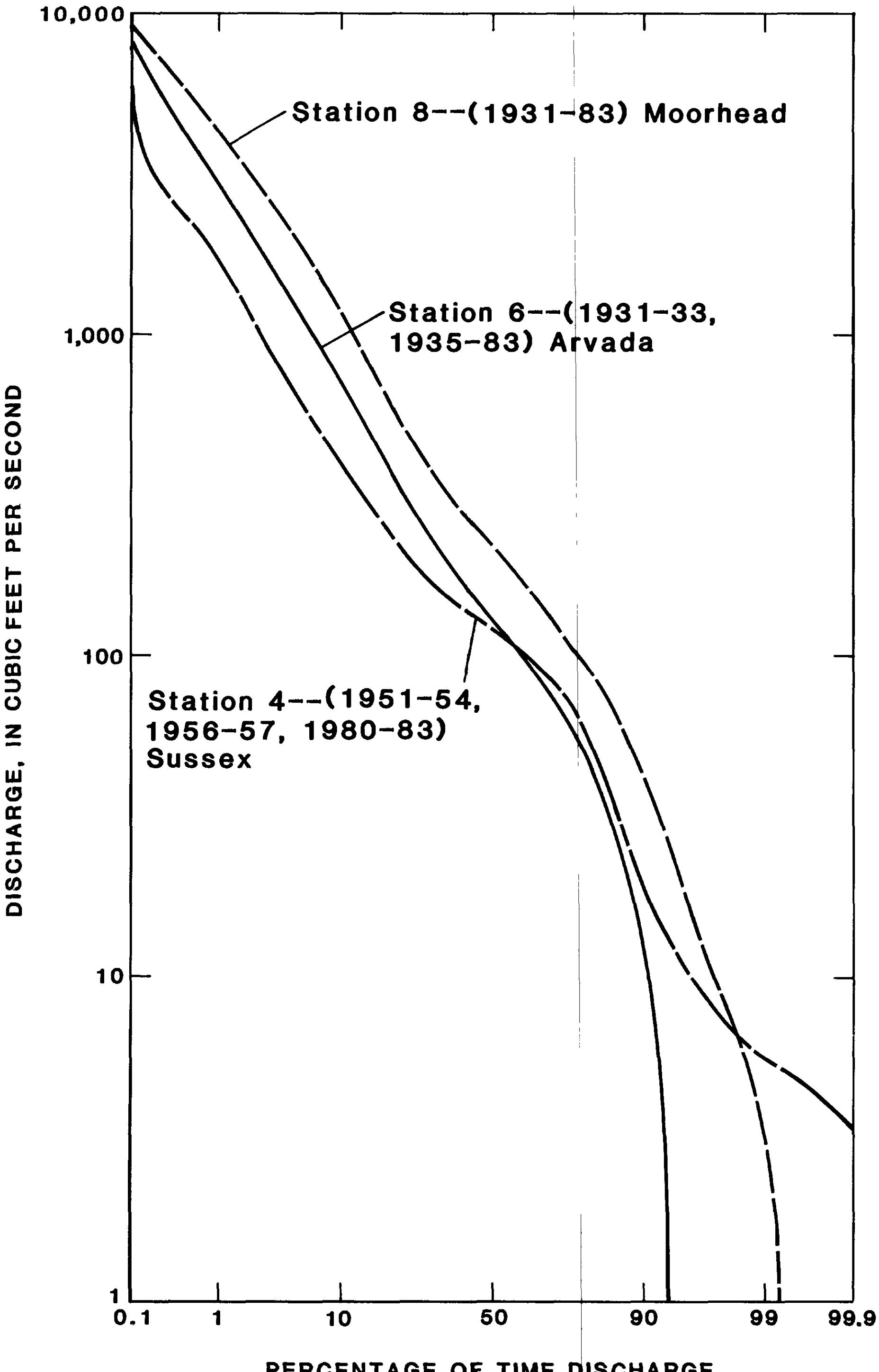


Figure 6.--Flow-duration curves for Powder River streamflow-gaging stations. (Location of stations shown in fig.1)

Sussex and Arvada, and Clear Creek between Arvada and Moorhead. The monthly sums of the differences in daily mean discharges are shown in figure 7 for the reach between Sussex and Arvada, and in figure 8 for the reach between Arvada and Moorhead.

Annual discharge as a percentage of the long-term mean discharge at streamflow-gaging stations along the Powder River is computed for 1978-80 (table 2). In 1978 when discharge at the three stations (4, 5, and 6) along the upstream reach was about 250 percent of the long-term mean discharge, a net gain of 50,500 cubic feet per second was computed for the year between Sussex and Arvada (see fig. 7). Gains in streamflow occurred every month except in January, February, and December. The gains in streamflow in the reach between Sussex and Arvada could have been due to precipitation, snowmelt, or ground-water discharge, although most of the gains probably represent flood runoff not accounted for by Crazy Woman Creek. The losses in streamflow during the low-flow months of January, February, and December indicate seepage to ground water during that period.

In 1979, streamflow was about average, and a very small net gain was recorded for the year (fig. 7). For 7 months (January, February, March, August, September, November, and December) net losses in streamflow between Sussex and Arvada indicate seepage to ground water along the reach. In August and September, evapotranspiration would have accounted for part of the loss. During the low-flow months, ground-water discharge to the stream is not indicated.

In 1980 when stream discharge was about 75 percent of the long-term mean discharge, 6 months of net losses (January, February, May, June, August, and December) between Sussex and Arvada resulted in a net loss for the year (fig. 7). The losses in January, February, and December primarily were caused by seepage into the alluvium, while part of the losses in May, June, and August would have been due to evapotranspiration.

For the downstream reach between Arvada and Moorhead, the annual discharge in 1978 was about 230 percent of the long-term mean discharge, and about 70 percent of the long-term mean in 1979 and 1980 (table 2). Net losses in streamflow were recorded for all 3 years (fig. 8). For 1978, a monthly net gain in streamflow due to precipitation, snowmelt, runoff, or ground-water discharge in the reach was recorded at Moorhead only in January, March, and May. For 1979, the driest of the 3 years, monthly net gains in streamflow were recorded only in January, September, and November. For 1980, monthly net gains were recorded in February, May, June, and August. Net losses of streamflow to ground-water storage in the alluvium or to evaporation and transpiration occurred in the other 8 to 9 months of each year.

The gain-loss analyses agree with the analyses of flow-duration curves for the stations at Arvada and Moorhead. The flow-duration curves for the streamflow-gaging stations show a probable ground-water discharge component that sustains flow during low-flow conditions in the reach near Sussex, but not in the reaches near Arvada or Moorhead. Along the reach from Sussex to Arvada, 2 of the 3 years of record indicate annual net gains in streamflow due to runoff or ground-water discharge to the river. However, losses along the

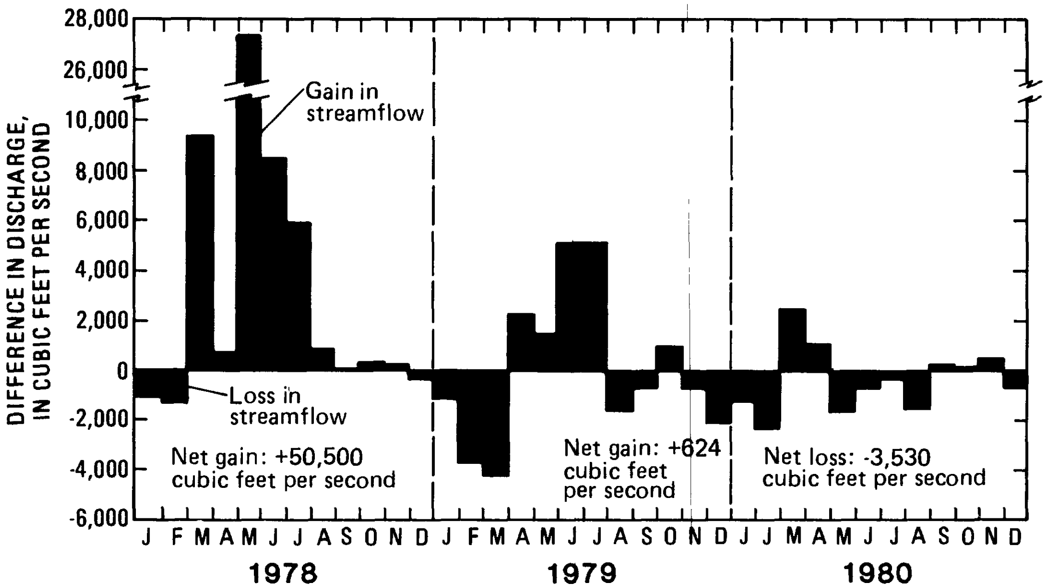


Figure 7.--Gains and losses in streamflow in the Powder River between Sussex, Wyo., and Arvada, Wyo. Computed as the monthly sum of the daily mean discharges in the Powder River at Arvada (station 6) minus the combined monthly sums of daily mean discharges in the Powder River at Sussex (station 4) and Crazy Woman Creek near Arvada (station 5).

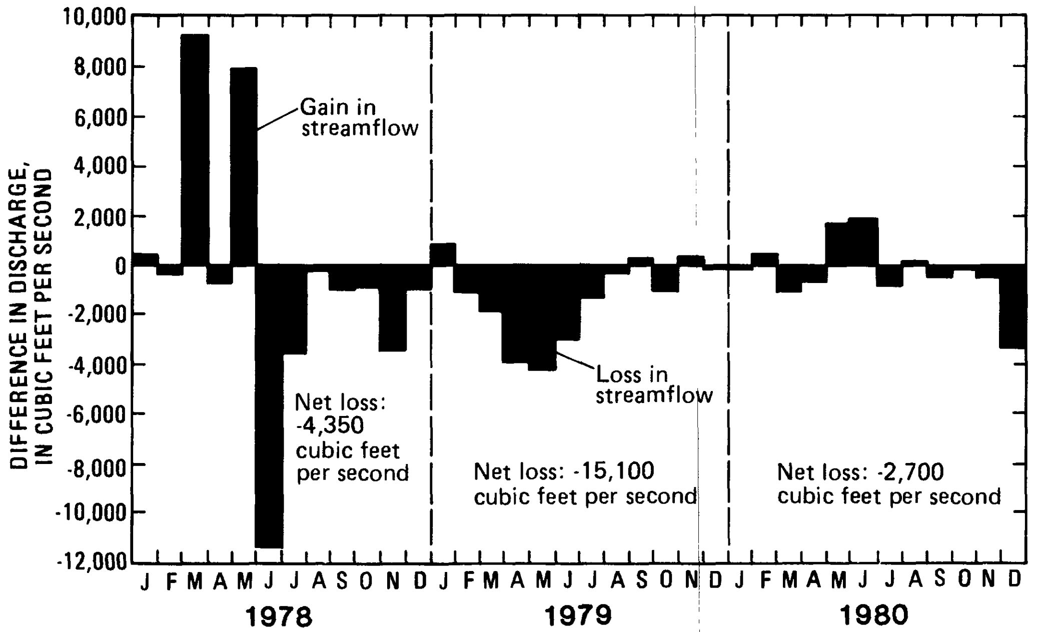


Figure 8.--Gains and losses in streamflow in the Powder River between Arvada, Wyo., and Moorhead, Mont. Computed as the monthly sum of the daily mean discharges in the Powder River at Moorhead (station 8) minus the combined monthly sums of daily mean discharges in the Powder River at Arvada (station 6) and Clear Creek near Arvada (station 7).

Table 2.--*Annual discharge and percentage of the long-term mean discharge at streamflow-gaging stations, 1978-80 water years*

[ft^3/s, cubic feet per second]

Streamflow-gaging station	Station number	Water year 1978 Discharge (ft^3/s)	1978 Percent	1979 Discharge (ft^3/s)	1979 Percent	1980 Discharge (ft^3/s)	1980 Percent
Powder River at Sussex, Wyo.	4	479	255	227	121	154	83
Crazy Woman Creek near Arvada, Wyo.	5	125	232	51.7	98	40.1	80
Powder River at Arvada, Wyo.	6	744	262	284	101	184	66
Clear Creek near Arvada, Wyo.	7	362	198	71.3	39	154	85
Powder River at Moorhead, Mont.	8	1,093	234	312	67	329	71

same reach during the low-flow months indicate a lack of ground-water discharge, thereby corroborating the flow-duration curve analysis for Arvada. Along the reach from Arvada to Moorhead, streamflow losses were recorded during all 3 years, indicating seepage to ground-water storage along that reach, also corroborating the flow-duration curve analysis for Moorhead.

According to J.G. Rankl (U.S. Geological Survey, oral commun., 1985), about 100 miles east of the study area, in the Cheyenne River, evaporation and transpiration consume water from ground-water storage in the alluvium more rapidly than river seepage, precipitation, or other sources recharge ground-water storage. Ground-water storage is so depleted during the growing season that even in October, November, and December, the river is still replenishing the water in the alluvial aquifer. This may be true also for the Powder River in the reach between Arvada and Moorhead. Figure 8 shows a net loss in streamflow for nearly every month from June through December.

Ground-Water Responses to Changing River Stage

Response in ground-water levels to changes in the river stage was analyzed at a site near the Interstate Highway 90 bridge over the Powder River (figs. 9 and 10). Two wells were installed about 425 feet from the river--one completed in the alluvium (well A5) and one completed in the bedrock (well B6) (Wasatch Formation). Water-level recorders were installed in these wells and in an existing well completed in the alluvium about 40 feet from the river (well A1). The river stage was recorded in a stage-measurement gage at the river. All recorders were set to the same arbitrary datum (gage datum) by surveying. Water levels were recorded continuously for 1 year, 1983.

Hydrographs of water-level fluctuations in wells and changes in stage of the Powder River during 1983 are shown in figures 11-13. Only records for runoff in the Powder River are shown. Records for intervening periods indicate that the water levels remained constant on June 12; gradual water-level declines occurred during June 18-June 26, July 2-July 22, July 28-August 4, August 10, and August 25-September 9; and slight fluctuations in the water levels were recorded August 16-August 19 and September 15-September 21.

Most of the runoff events are interpreted as being caused by upstream rains or snowmelt, because there was no flow in nearby Dead Horse Creek (fig. 1) during those periods. However, the June 8 and August 21 hydrographs represent intense local rainstorms that generated large flows in Dead Horse Creek. During June 28 and 29, a small local rain resulted in a small flow in Dead Horse Creek. The gradual rise in all the water levels in the September 22-26 hydrograph probably represents the end of the evapotranspiration season.

Water in Alluvium

During the 1-year period of record, the water level in alluvial well A1, which is 40 feet from the river, was nearly always lower than the river stage, and the water level in alluvial well A5, which is 425 feet from the river, generally was even lower. At this site the water table in the alluvium slopes away from the river. Water-level measurements in four wells A2, A3, A4, and

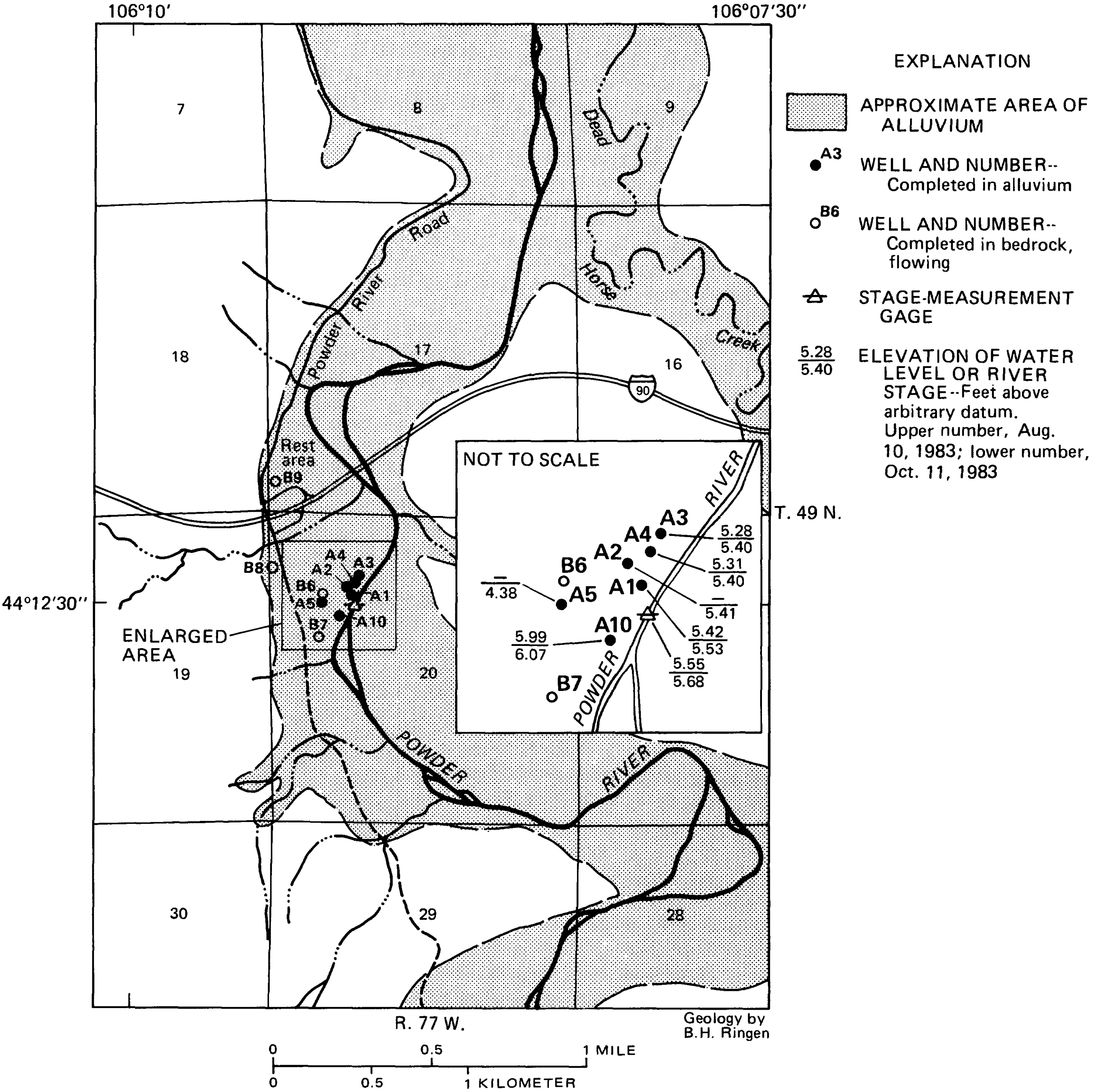


Figure 9.--Location of wells and stage-measurement gage, elevation of water levels in wells, and river stage near the Interstate Highway 90 bridge across the Powder River.

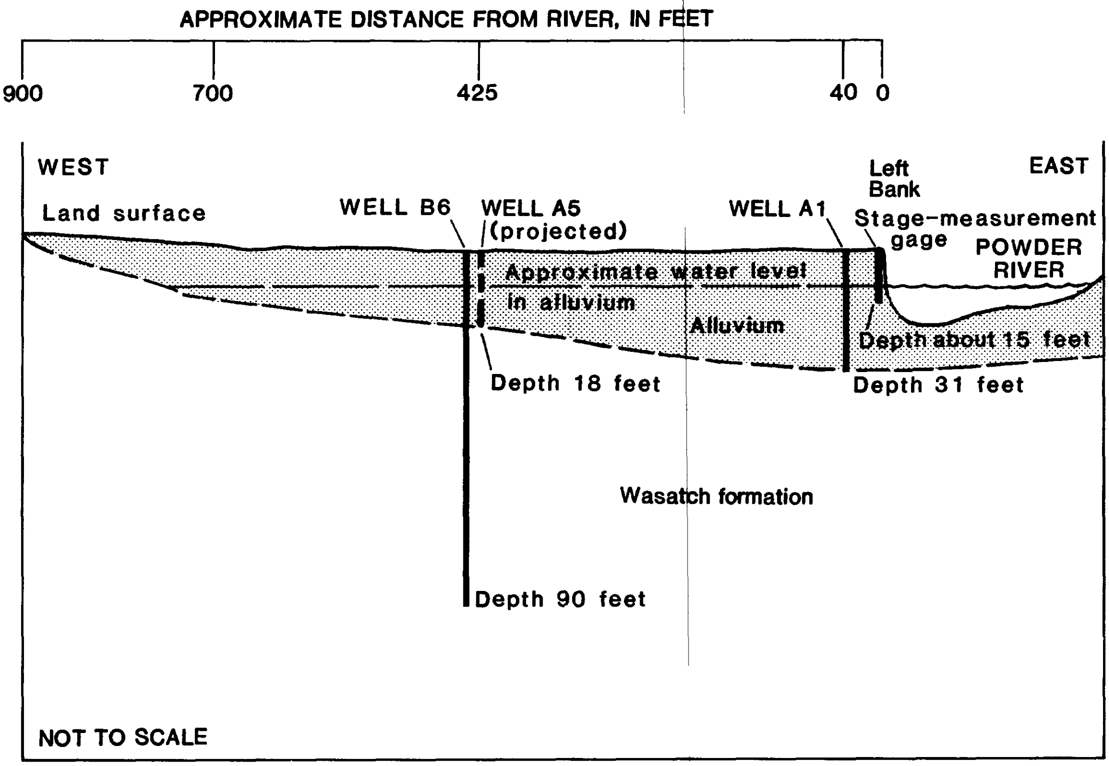


Figure 10.--Generalized hydrogeologic section near Interstate Highway 90 bridge across the Powder River.

A10, completed in the alluvium along a line parallel to the Powder River, indicate a gradient in the alluvium similar to the downstream gradient in the river (see fig. 9).

The hydrographs for wells A1 and A5 show responses to changes in river stage; as expected, well A1 responds sooner and to a greater degree than well A5. The hydrograph for alluvial well A1 shows rises immediately after river stage rises for the major changes in runoff shown in figures 11-13, indicating a direct hydraulic connection between well A1 and the river. The magnitude of the water-level rise in well A1 was about one-half that in the river, or less. The hydrograph for alluvial well A5 reflected the rises and declines of the river stage but to a lesser extent. For example, a small peak corresponding to runoff in the river occurred June 8, but the water-level response otherwise is characterized by gradual, subdued rises and declines that slightly lag in response to the rises and declines of the river stage.

The hydrographs in figures 11-13 also show the periods of streamflow gain and loss at the Interstate Highway 90 site by the relation between water levels in the alluvial well A1 and the river stage. Runoff on June 8 recharged the alluvial aquifer (streamflow loss) as shown by the peak in the alluvial water level; as the river stage decreased below the ground-water level, the ground water was discharged to the river (streamflow gain) from late on June 8 to midday on June 9. For most of the growing season, the river stage was higher than the ground-water level, so the river lost water to the

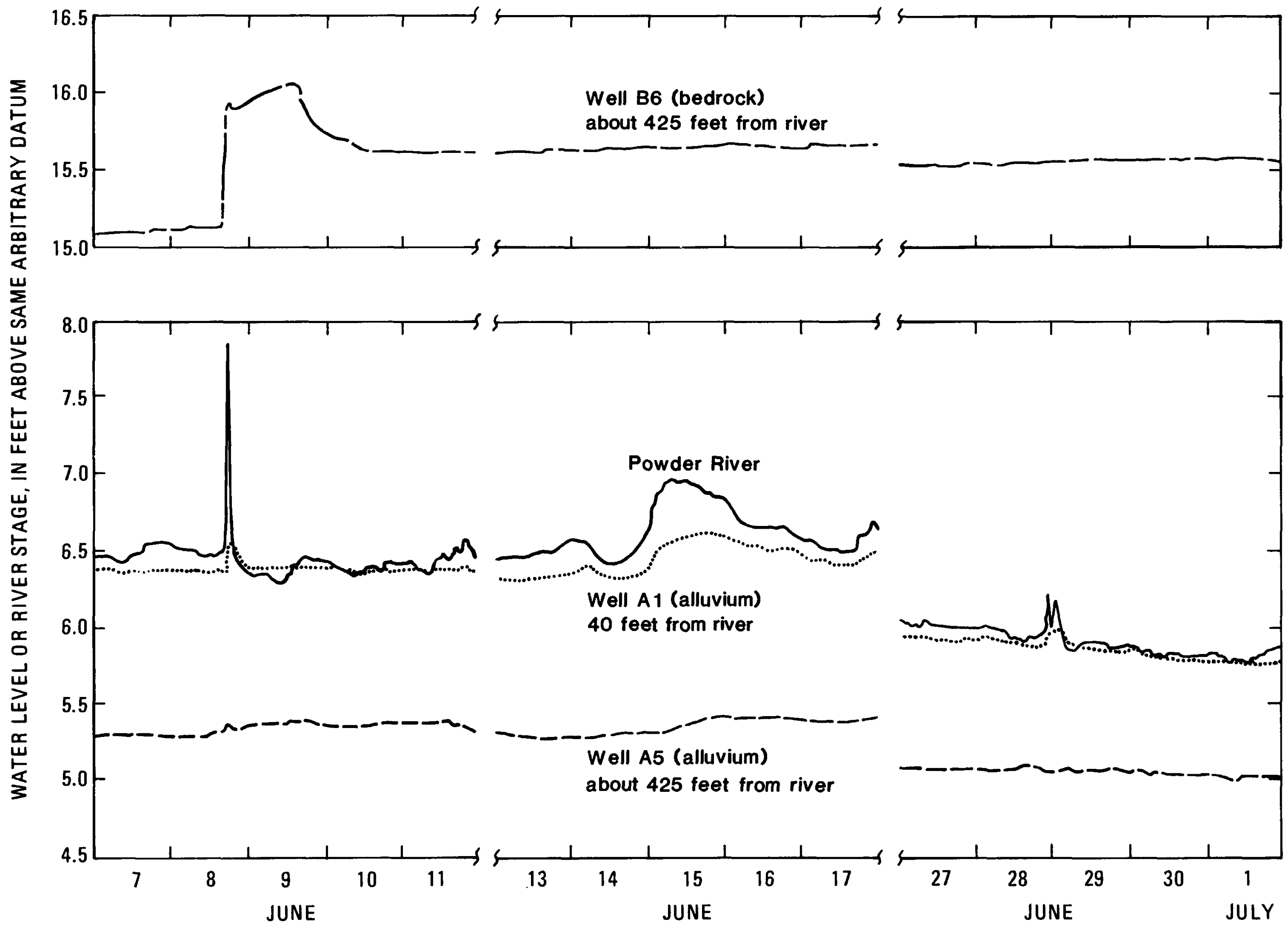


Figure 11.--Water-level fluctuations in wells completed in the alluvium and bedrock, and changes in stage of the Powder River near the Interstate Highway 90 bridge during selected periods, June 7-July 1, 1983.

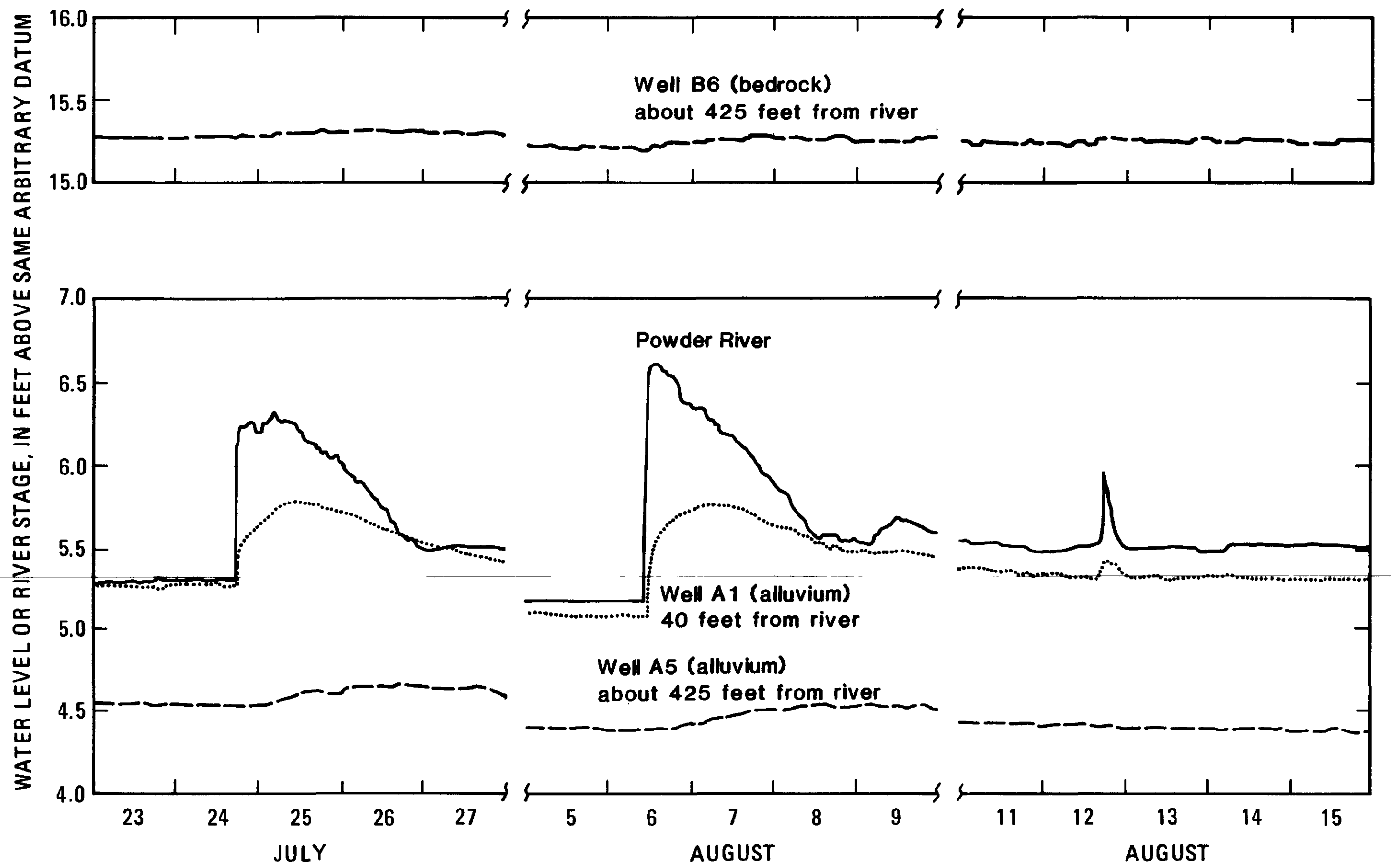


Figure 12.--Water-level fluctuations in wells completed in the alluvium and bedrock, and changes in stage in the Powder River near the Interstate Highway 90 bridge during selected periods, July 23-August 15, 1983.

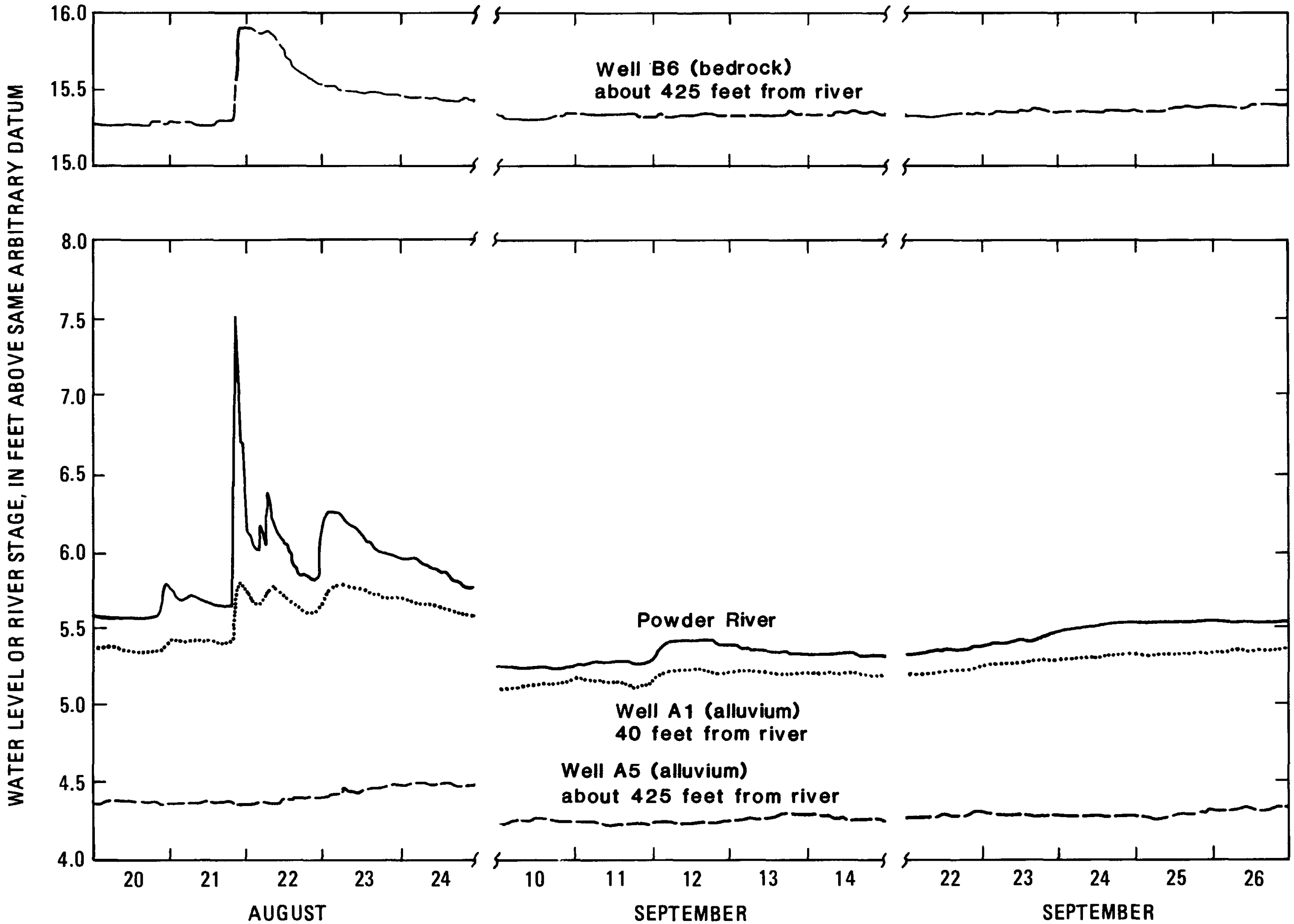


Figure 13.--Water-level fluctuations in wells completed in the alluvium and bedrock, and changes in stage in the Powder River near the Interstate Highway 90 bridge during selected periods, August 20-September 26, 1983.

alluvial aquifer. This seepage of water from the river to the alluvium probably was driven by transpiration from phreatophytes (trees and shrubs) growing on the alluvial-valley floor. The water level in the alluvium as measured in well A5 declined during the summer from about 5.4 feet above datum in June to about 4.3 feet above datum in September.

Water in Bedrock

Water-level changes in well B6, completed in the bedrock, are represented by hydrographs in figures 11-13. Well B6 is 425 feet from the river, is 90 feet deep, and is perforated between 70 and 90 feet below land surface. The artesian water level in well B6 is about a foot above land surface.

Hydraulic head in the bedrock is substantially higher than water levels in the alluvium (water table) or water in the river (figs. 11-13). This is true not only at the Interstate Highway 90 site, but also in other artesian wells completed in the bedrock throughout the study area. Drillers' logs (see table 7 at the back of this report) for almost every well along the Powder River in the study area south of Arvada list a thick blue clay or shale that is at the top of the bedrock. The clay or shale would be expected to effectively isolate the bedrock from the alluvium hydraulically and therefore, from the river in parts of the study area.

The water level in well B6 completed in the bedrock fluctuated a little, but for seven of nine runoff events did not respond measureably when there were changes in the river stage or water levels in the alluvium. However, the water level responded substantially during runoff events on June 8 (fig. 11) and August 21 (fig. 13). In both cases, runoff was caused by intense local rains; concurrently there were large increases in the bedrock water level. The increases were larger than those in either of the wells completed in the alluvium, although maximum recorded river stages were 1 to 2 feet higher than for any of the other seven run-off events. One possible explanation why water levels in the bedrock would respond to a greater degree than water levels in the alluvium after the intense local rains is loading of the confined bedrock aquifer by the weight of water spread over the area of intense rainfall.

Aquifer Characteristics

Hydraulic diffusivity (the ratio of transmissivity to storage coefficient) was calculated for the alluvial aquifer along the Powder River at the Interstate Highway 90 site. This was done to obtain part of the information needed for determining how water in the alluvium responds to pumping and river-stage changes. The flood-wave response method (Pinder and others, 1969) was used. Estimates of transmissivity and storage coefficients are derived less expensively by this method than by aquifer tests. The method generates the predicted or theoretical aquifer response in a one-dimensional ground-water flow system to the passage of a flood wave in the river. A series of type curves is generated, and aquifer diffusivity is obtained by selecting the curve that approximates most closely the observed ground-water hydrograph.

Grubb and Zehner (1973) used this method to calculate diffusivity based on a single flood wave at several sites along the Ohio River, but the method was used in this study to calculate diffusivity for several flood waves at the same site.

The equation in the computer program requires the following data: distance from the river to an impermeable boundary, distance from the observation well to an impermeable boundary, the river-stage hydrograph, the groundwater hydrograph in the observation well, a time step, and estimates of expected aquifer diffusivity values. The program generates the type curves of theoretical aquifer response to the flood wave and calculates root-mean-square differences for the fit of the theoretical aquifer response to the actual aquifer-response hydrograph.

The flood-wave response method is based on the assumptions that the aquifer is isotropic, homogeneous, and of finite width; the stream fully penetrates the aquifer; initial hydraulic head is uniform in the aquifer; and impermeable materials exist below the aquifer and at one side of the aquifer parallel to the stream. Conditions in the Powder River alluvial aquifer at the Interstate Highway 90 site do not meet all the assumptions. The alluvium may not be isotropic and is not homogeneous; the Powder River penetrates about 20 feet of the 30 feet of alluvium; initial head is not uniform; and the valley wall is not parallel to the river.

Kernodle (1978, p. 5-6) explains that for the ideal stream-aquifer relation, which was assumed for the equation in the program:

> The observed response through a complete flood cycle (rising limb, peak, receding limb) can be entirely duplicated by the program if T/S [diffusivity] is known. In instances where the aquifer is not uniform, boundaries are irregular, or recharge from precipitation occurs, the match between calculated and observed water-level response degenerates. Commonly, only the rising limb and the peak of the flood cycle are of use in determining aquifer diffusivity by the flood-wave response technique because the receding limb is the most likely to be affected by non-ideal conditions.

Kernodle (1978, p. 6-7) also states that the equation is derived for a constant value of transmissivity, but in a water-table aquifer, saturated thickness and thus transmissivity, constantly change during the passage of the flood wave:

> . . . the slope of the rising and receding limbs of the response curve will reflect the change in diffusivity with changing saturated thickness. Peak amplitude will also be affected, but peak arrival time is generally the least affected. Once the best possible match between observed and modeled peak arrival time has been obtained, the hydraulic diffusivity of the water-table aquifer may be expressed as $K_a b_m / S_y$ where K_a is the hydraulic conductivity of the aquifer, b_m is the maximum observed saturated thickness of the aquifer during the passage of the flood wave, and S_y is the specific yield of the aquifer.

Although the nonideal conditions at the Powder River site may have "degenerated the match" between the calculated and the observed ground-water response, the best fit of the calculated response curve to the observed response will provide the best estimate of diffusivity.

The program was run using the river stage as the driving force, and well A1 (40 feet from the river) was used as the response well. The predicted hydrographs were matched with the observed hydrographs for well A1. The distance from the response well A1 to the impermeable boundary (see fig. 10) was assumed to be 860 feet, and the distance from the river to the impermeable boundary was assumed to be 900 feet, resulting in a ratio of these distances of 860/900, or 0.95. Kernodle (1978, p. 6) states that the response well should be as far as possible from the valley wall, minimizing the effects of boundary irregularities, and that a ratio of 0.85 to 0.95 will yield the best results using this program. However, he also states there should be an observable time lag between the flood wave in the river and the response in the aquifer. The response in well A1 does not have much time lag (see fig. 11-13), but a 30-minute time step was used in the program to improve this.

Grubb and Zehner (1973) used water levels in a well on the river bank which fully penetrates the aquifer to simulate the water stage in the river, which did not fully penetrate the aquifer. This approach was attempted using water levels in well A1, which fully penetrates the aquifer 40 feet from the river, as a substitute for stream stage, and well A5 (425 feet from the river) as the response well. However, the predicted hydrograph for well A5 did not indicate any water-level response. The ratio of distances between the impermeable boundary and wells A5 and A1 is 475 feet/860 feet or 0.55. The water-level response to flood waves is evident on the water-level hydrographs of well A5 for only a few of the storms (see figs. 11-13).

Water-level data from each of the nine runoff events previously described (figs. 11-13) were used to compute theoretical responses in well A1. Some of the nine events resulted from upstream runoff and passed the study site as flood waves; others were local flash floods or resulted from small local storms. One event represents recovery of the system after the end of evapotranspiration. For each runoff event, nine different theoretical response curves were calculated, based on nine estimates of diffusivity. The smallest root-mean-square difference calculated for each of the nine curves indicated the best fit, and that diffusivity value was recorded as the best estimate for that runoff event.

The results of the computer-simulation runs varied considerably. Diffusivity ranged from 778 to 25,100 feet squared per day, with an average of the nine events of 10,200 feet squared per day (table 3).

There does not seem to be a logical explanation for the variance of diffusivity values on the basis of different types and distribution of precipitation. One small local rain (June 28-29) resulted in a diffusivity value of 20,700 feet squared per day, while another in August yielded a value of 5,180 feet squared per day. A small upstream rain (September 11-12) yielded the largest diffusivity value, and a longer (2-day) upstream rain

Table 3.--*Computed diffusivity values for the Powder River alluvium at the Interstate Highway 90 site*

Date of runoff (1983)	Magnitude and distribution of precipitation	Computed diffusivity (feet squared per second)	Computed diffusivity (feet squared per day)	Trans-missivity (feet squared per day)
June 8	Intense local rain	0.147	12,700	2,540
June 14-16	Upstream rain/mountain snowmelt	.110	9,500	1,900
June 28-29	Small local rain	.240	20,700	4,140
July 24-26	Large upstream rain	.009	778	156
August 6-8	Upstream rain	.050	4,320	864
August 11-12	Small local rain	.060	5,180	1,040
August 21-25	Intense local rain	.080	6,910	1,380
September 11-12	Small upstream rain	.290	25,100	5,020
September 22-24	No precipitation--end of evapotranspiration	.080	6,910	1,380
Average of all nine values		-----	10,200	[a]2,040

[a]Calculated from average diffusivity

(July 24-26) yielded the smallest diffusivity value. The hydrograph for July 24-26 (diffusivity 778 feet squared per day) seems similar to that for August 6-8 (4,320 feet squared per day), but the diffusivity values are not similar. The recovery of the system after evapotranspiration stopped was calculated with a midrange diffusivity value of 6,910 feet squared per day.

Kernodle's (1978, p. 7) guidelines for use of this program state:

> All flood events are not equally suitable for analysis. A flood of short duration and moderate-to-large magnitude following an extended period of water-level recession is preferred. Such an event offers good peak resolution at the observation point and minimizes the effect on water levels by delayed recharge from precipitation (usually associated with the flood event).

Unless the June 8 event (flash flood) was too short to adequately stress the aquifer, it should meet Kernodle's (1978) guidelines. It is of short duration and moderate-to-large magnitude, and it may be the single most representative diffusivity value (12,700 feet squared per day) of the nine. The August 21-25 event is similar, except that multiple peak flows indicated on the river hydrograph may have caused multiple flood-generated waves that may have interfered with the water-level response. Data for the September 22-24 end-of-evapotranspiration period do not meet Kernodle's (1978) guidelines.

Although the Powder River alluvium at the Interstate Highway 90 site does not fully meet the assumptions of the methods, and the flood peaks may not have been ideal, it is assumed that the average of the nine diffusivity values, 10,200 feet squared per day, is an acceptable approximation for the Powder River alluvium. The average diffusivity was used to calculate transmissivity and hydraulic conductivity of the alluvium at the Interstate Highway 90 study site.

Diffusivity is equal to transmissivity divided by storage coefficient, so transmissivity can be calculated if the storage coefficient is known. The storage coefficient of unconfined aquifers is virtually equal to the specific yield, which for most unconfined aquifers ranges from 0.1 to 0.3, averaging about 0.2 (Lohman, 1979, p. 8). The specific yield for the Powder River alluvium is assumed to be 0.2. Therefore, with the average diffusivity calculated for the Powder River alluvium at the Interstate Highway 90 site, transmissivity is estimated to be 2,040 feet squared per day.

Hydraulic conductivity is equal to transmissivity divided by the saturated thickness, which averages 21.5 feet for this site. Hydraulic conductivity is estimated to be 94.9 feet per day. This is consistent with values given by Lohman (1979, p. 53) for medium to medium-to-coarse sand. Generally the alluvium at the site is fine or medium sand with lenses of coarse sand or fine gravel.

AVAILABILITY OF WATER IN THE ALLUVIUM

Saturated Thickness

The saturated thickness of the alluvium varies with river stage, as shown in figures 11-13 for wells A1 and A5 at the Interstate Highway 90 site. Saturated thickness also varies across the cross section as the thickness of the alluvium varies. The range in river stage for the periods of record shown in figures 11-13 was about 2.7 feet. Saturated thickness for the same periods at well A1, where the alluvium is about 31 feet thick, ranged from 20.7 to 22.2 feet; saturated thickness in well A5, where the alluvium is about 18 feet thick, ranged from 7.6 to 8.8 feet. Ranges in stage for the period of record at the three streamflow-gaging stations are 11.5 feet at Sussex, 22.0 feet at Arvada, and 15.0 feet at Moorhead. Because the river is on bedrock at the towns of Arvada and Moorhead, there is no alluvium and hence no saturated thickness for alluvium at those locations.

Periods of No Flow

Periods of no flow in the river limit the availability of water in the alluvium. On days of no flow in the river, pumpage from a well completed in the alluvium would be derived entirely from ground-water storage. Production from the well would decrease more quickly than if there were flow in the river. Statistical indicators of this potential limitation include the number of years having 3 and 7 consecutive days of no flow during the period of record. These are listed in table 4 for the three streamflow-gaging stations on the Powder River.

As the data in table 4 indicate, periods of no flow are much more frequent at Arvada than at Sussex or Moorhead. The frequency of extended periods of no flow at Arvada is shown in figure 14. The Powder River at Arvada was dry for at least 1 day during 70 percent of the years for the period of record, so during about 2 of every 3 years, the river was dry for at least 1 day. For 1 of every 2 years for the period of record the river was dry for 13 consecutive days, and for 1 of every 5 years it was dry for 30 consecutive days.

A different statistical indicator of availability of water in the Powder River during periods of low flow is given in table 5. The table lists the smallest average discharge for 1, 3, 7, 14, 30, and 60 consecutive days for selected years of coincident record at the three streamflow-gaging stations on the Powder River.

Effects of Pumping

Pumping from a well completed in alluvium near a river will induce recharge to the alluvium from the stream or reduce discharge from the alluvium to the stream. This process is called stream depletion. Jenkins (1968) presents a method to calculate the proportion of water coming from each source (stream and alluvium). The method is based on the following assumptions: (1) Transmissivity does not change with time, so the drawdown in a water-table

Table 4.--*Number of years having 3 and 7 consecutive days of no flow for the period of record through 1983 at the Powder River streamflow-gaging stations*

Station name	Station number	Period of record	August		September		October	
			3 days	7 days	3 days	7 days	3 days	7 days
Powder River at Sussex, Wyo.	4	1938-40, 1950-57, 1977-83	0	0	0	0	0	0
Powder River at Arvada, Wyo.	6	1919-83	19	15	21	20	0	0
Powder River at Moorhead, Mont.	8	1929-72, 1974-83	2	1	2	2	0	0

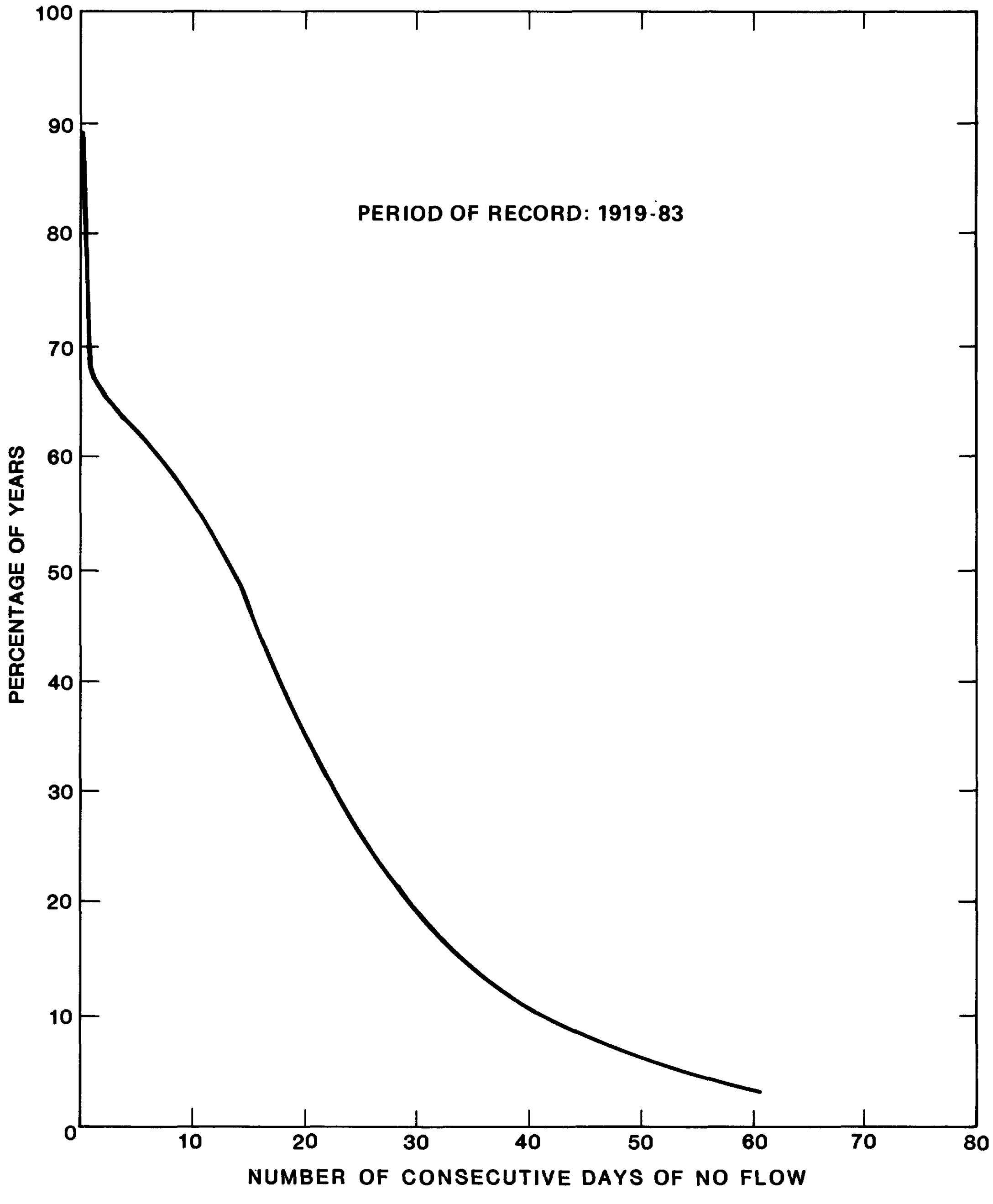


Figure 14.--Percentage of years for the period of record at Powder River at Arvada, Wyo., that no flow occurred for the number of consecutive days indicated.

Table 5.--*Smallest average discharge for 1, 3, 7, 14, 30, and 60 consecutive days during selected years ending March 31 at the Powder River streamflow-gaging stations*

[Period of record listed below station name]

Year	Smallest average discharge for consecutive days indicated below, in cubic feet per second					
	1	3	7	14	30	60
	Powder River at Sussex, Wyo. (station 4) 1938-40, 1950-57, 1977-83					
1951	5.0	5.3	5.6	5.6	8.1	16.0
1953	9.2	9.4	9.4	9.8	10.0	22.0
1954	4.6	5.5	8.1	9.7	9.8	10.0
1956	9.8	9.9	12.0	19.0	25.0	31.0
1957	5.0	5.3	5.4	5.8	6.2	9.2
1979	30.0	32.0	36.0	45.0	69.0	93.0
1980	24.0	26.0	30.0	32.0	48.0	67.0
1981	11.0	13.0	15.0	16.0	23.0	41.0
1982	13.0	14.0	26.0	26.0	27.0	35.0
1983	30.0	30.0	31.0	33.0	91.0	150
	Powder River at Arvada, Wyo. (station 6) 1919-83					
1951	0.0	0.0	0.0	0.0	0.0	5.3
1953	.0	.0	.0	.0	.7	9.7
1954	.0	.0	.0	.0	.0	.2
1956	.0	.0	.0	.0	4.5	16.0
1957	.0	.0	.0	.0	.0	.6
1979	62.0	79.0	80.0	83.0	90.0	104
1980	6.2	8.7	12.0	20.0	37.0	69.0
1981	.0	1.0	5.5	11.0	26.0	67.0
1982	3.6	5.7	7.8	8.5	11.0	21.0
1983	74.0	75.0	78.0	94.0	137	162
	Powder River at Moorhead, Mont. (station 8) 1929-72, 1974-83					
1951	8.0	8.7	9.7	13.0	25.0	50.0
1953	40.0	41.0	49.0	60.0	64.0	77.0
1954	8.0	8.0	8.7	9.8	11.0	18.0
1956	2.8	2.9	3.2	4.8	8.4	20.0
1957	4.4	4.7	5.2	5.7	6.9	10.0
1979	60.0	65.0	71.0	79.0	102	123
1980	54.0	60.0	74.0	104	109	115
1981	78.0	122	148	184	206	263
1982	34.0	35.0	38.0	41.0	45.0	60.0
1983	80.0	81.0	86.0	97.0	129	155

aquifer is negligible compared to the saturated thickness, (2) the water temperatures in the stream and in the aquifer are constant and equal, (3) the aquifer is isotropic, homogeneous, and semi-infinite in areal extent, (4) the stream that forms a boundary is straight and fully penetrates the aquifer, (5) water is released instantaneously from storage, (6) the well is open to the full saturated thickness of the aquifer, and (7) the pumping rate is steady during any period of pumping (Jenkins, 1968, p. 2).

The Powder River site at Interstate Highway 90 does not fully meet these assumptions, but the calculations using hypothetical wells are believed to be helpful as approximations. Assumption 1 may be violated because drawdown may be a substantial proportion of the aquifer saturated thickness. This would cause transmissivity to decrease significantly in the vicinity of the well, resulting in a decrease in the amount of stream depletion relative to the amount of water pumped (Jenkins, 1968, p. 3). Assumption 4 is violated because the Powder River does not fully penetrate the aquifer. Stream depletion again will be decreased, relative to the amount of water pumped. An approximate diffusivity value calculated by the method of Grubb and Zehner (1973) (discussed previously) at the Interstate Highway 90 site is used for this calculation.

Jenkins (1968) presents graphs showing rate and volume of streamflow reduction as a function of pumping time and a streamflow-depletion factor. The streamflow-depletion factor is related to the aquifer transmissivity and specific yield, distance between the stream and the pumping well, location of the aquifer boundary, and the hydraulic connection between the stream and the aquifer.

The percentage of water yielded from the Powder River near Interstate Highway 90 to a hypothetical well was computed using Jenkins' method. Computations were made for distances of 200, 100, 50, and 25 feet from the river, and a constant pumping rate of 50 gallons per minute for 60 days. Diffusivity was assumed to be 10,200 feet squared per day, the average of the diffusivity values calculated previously for the site. The results are shown in figure 15.

The curves in figure 15 illustrate that the longer the well is pumped, the greater is the percentage of yield contributed by the river. For example, after 2 days of pumping a well 200 feet from the river at 50 gallons per minute, about 15 percent of the yield would come from the river; after 7 days, about 40 percent; after 20 days, almost 60 percent; after 60 days river yield is about 75 percent. The closer the well to the river, the faster the percentage of yield from the river increases with time. In a well 25 feet from the river, more than 40 percent of the yield after 1 day of pumping would come from the river. Because accurate values of aquifer characteristics are not available, these results are only approximations; however, they are believed to be representative of the study site.

The contribution of water from the river to a pumping well at other locations along the Powder River in the study area can be approximated by using figure 15, provided that the aquifer characteristics are similar to those for the Interstate Highway 90 site, the pumping rate of the well is 50 gallons per minute, and the dimensions of the pumped well are the same as,

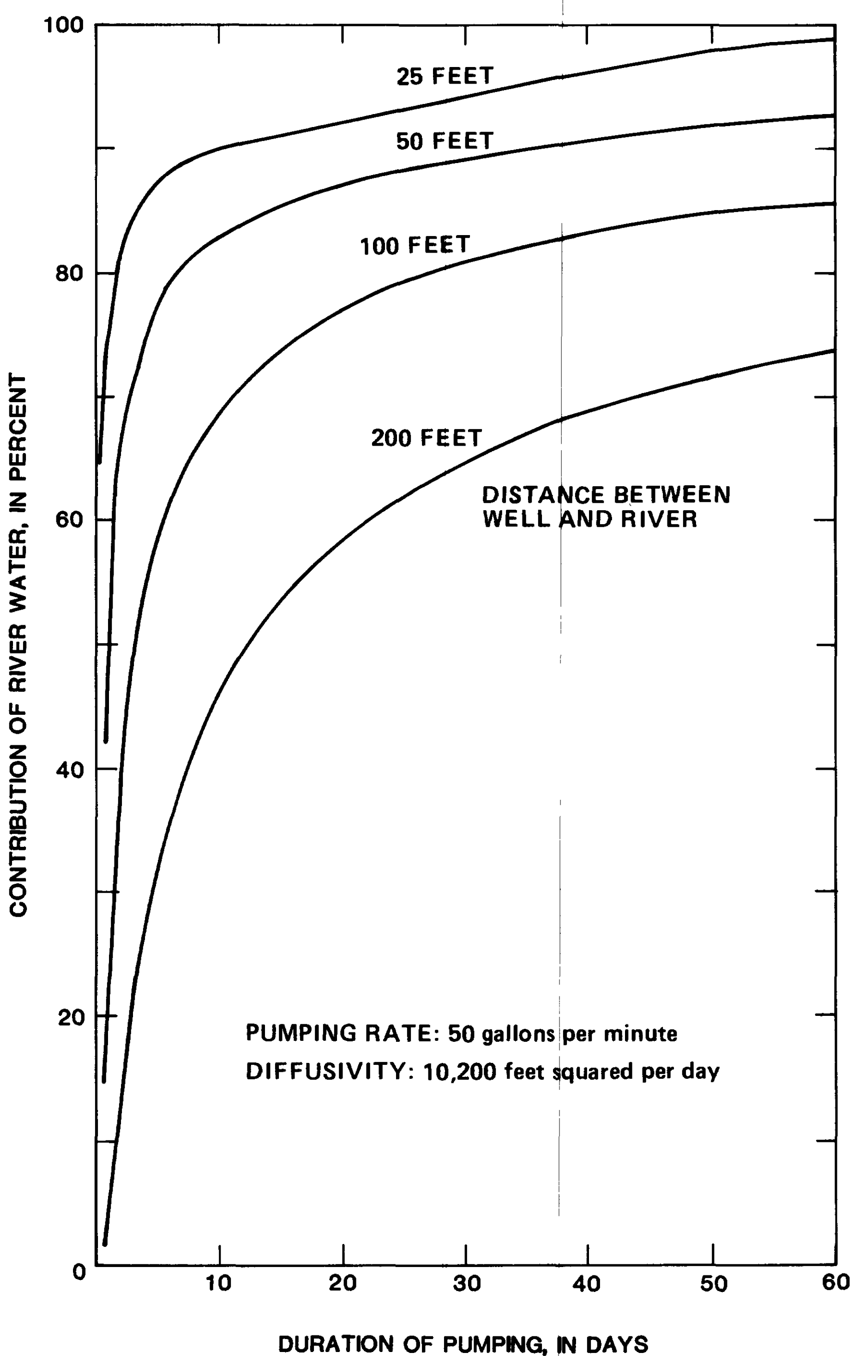


Figure 15.--Contribution of water from the Powder River to a hypothetical pumped well completed in the alluvial aquifer.

or larger than, those of the hypothetical well used in the calculations. If an approximation is needed of the total contribution of water from the river to the aquifer, then the contribution of the river after pumping has stopped, the residual effects of pumping, also must be estimated.

Residual effects of pumping on streamflow depletion continue for some time after pumping has stopped. The stream continues to lose water to the aquifer to fill in the cone of depression created when the well was pumped. This effect can be a significant factor in calculating the effects on the river of pumping a nearby well. Slowing of the rate of streamflow depletion, therefore, indicates that the cone of depression is becoming filled and the water table is recovering to prepumping conditions. Jenkins (1968) shows calculations for estimating cumulative hypothetical streamflow depletion. Calculations of streamflow depletion were made for the site near the Interstate Highway 90 bridge, where diffusivity was assumed to be 3,859 feet squared per day at the time this calculation was made (the average value from table 3 at this site was 10,200 feet squared per day) for a well 50 feet from the Powder River, pumped at 50 gallons per minute for 3 days and then shut off. These calculations show that stream depletion will continue for another 2 days after pumping has stopped.

QUALITY OF WATER

Water quality was investigated in this study to determine the general suitability of water in the alluvium for common uses, and to compare the water in the Powder River, the alluvium, and the bedrock. Water quality in the river varies with the season, flow rate, and location of sampling along the river relative to various tributary inflows. Analysis of water quality for the purposes stated above is based on samples representing only one point in time and one flow rate. The water in the alluvium and in the river are in hydraulic connection, so the water quality is expected to be similar.

Water from the plains drainages (South Fork Powder River and Salt Creek, which includes brine discharge from the Salt Creek oilfield) is of poor quality. Even after mixing with waters of better quality from the mountain drainages (North Fork and Middle Fork Powder River), the quality of the mixed water is such that its use is very limited. In 1979 and 1980 the plains streams contributed about 35 percent of the flow in the Powder River at Sussex, and the mountain drainage, about 50 percent. Because of the exchange of water between the river and the alluvium, the water in the alluvium also is degraded, and the aquifer itself is contaminated, in that chemicals carried by the water sorb to the soil particles.

Samples were collected from the Powder River at the streamflow-gaging stations near Sussex, Arvada, and Moorhead, and from a nearby shallow well completed in the alluvium at each site. Locations are shown in figure 16. The samples at each site were collected at approximately the same time and were analyzed for major ions. In order to compare the chemical composition of water in the river and the alluvium with that in the bedrock aquifer, published analyses of water from wells completed in the Wasatch Formation or Fort Union Formation (Hodson, 1971) were used (locations shown in fig. 16). The water-quality data are listed in table 6.

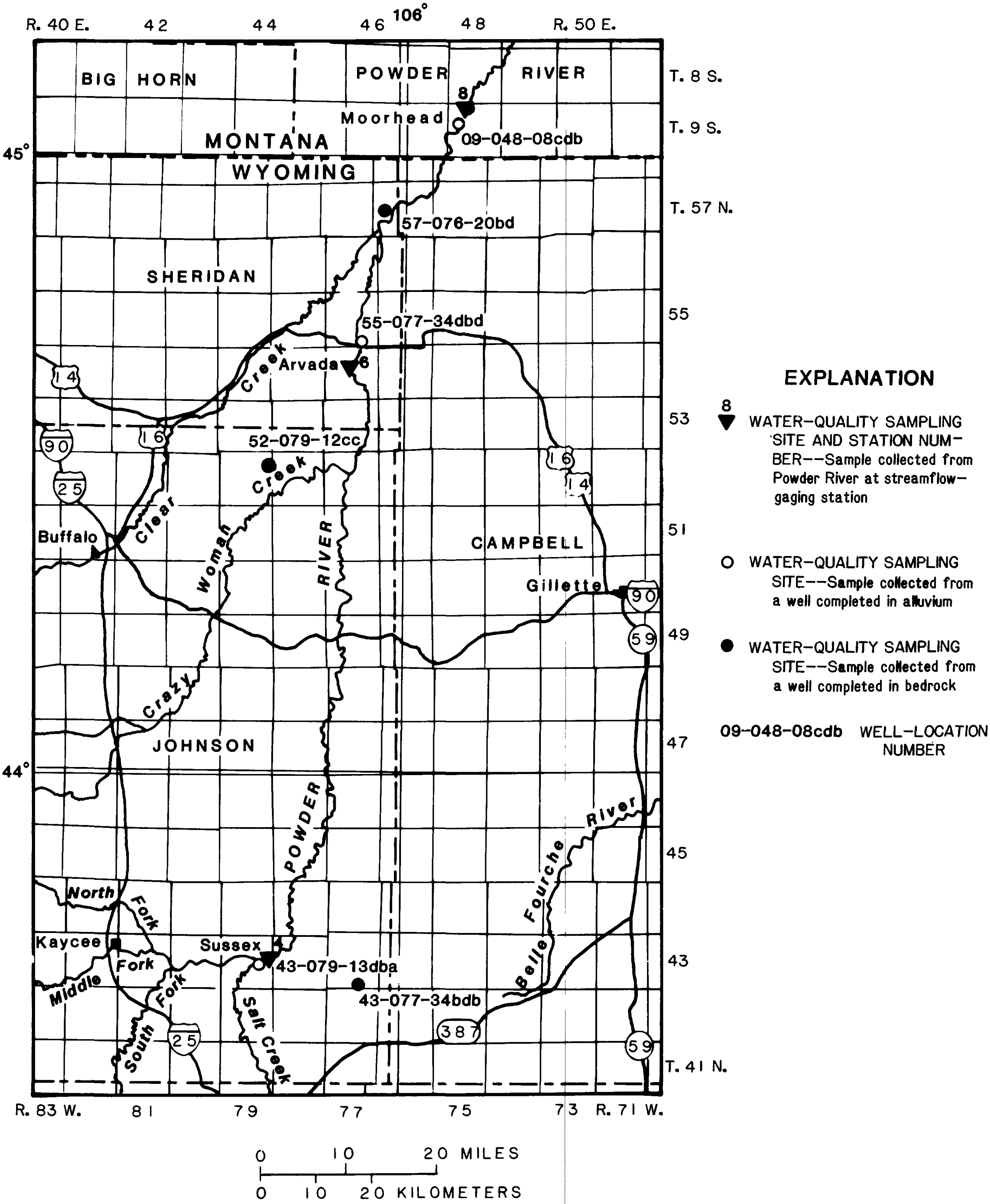


Figure 16.--Location of water-quality sampling sites.

Table 6.--*Physical properties and chemical analyses of dissolved constituents in water from the Powder River, alluvium, and bedrock*

[ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; Qal, alluvium; Tw, Wasatch Formation; Tfu, Fort Union Formation]

Sample location	Station number (see fig. 16)	Well location number (see fig. 16)	Sample date (month-day-year)	Discharge of Powder River at time of sampling (ft^3/s)	Geologic unit	Well depth (feet)	Onsite specific conductance (µS/cm)	Lab specific conductance (µS/cm)	Onsite pH	Lab pH	Temperature (degrees Celsius)
POWDER RIVER											
Sussex	4	-----------	11-10-83	170	---	---	-----	2,250	---	7.8	2.5
Arvada	6	-----------	11-17-83	178	---	---	-----	2,490	---	8.1	4.0
Moorhead	8	-----------	11-16-83	352	---	---	-----	2,040	---	8.2	---
ALLUVIUM											
Sussex	--	43-079-13dba	10-12-83	---	Qal	12	6,000	6,580	7.0	7.1	14.0
Arvada	--	55-077-34dbd	10-14-83	---	Qal	25	2,750	3,310	7.2	7.1	9.5
Moorhead	--	09-048-08cdb	11-01-83	---	Qal	25	2,000	2,030	7.2	7.5	11.0
BEDROCK (from Hodson, 1971, p. 15 and 17)											
Sussex	--	43-077-34bdb	09-04-69	---	Tw	655	533	-----	8.2	---	14.0
Arvada	--	52-079-12cc	10-26-60	---	Tw	160	960	-----	7.6	---	9.0
Moorhead	--	57-076-20bd	10-26-60	---	Tfu	265	2,080	-----	8.2	---	11.0

Table 6.--*Physical properties and chemical analyses of dissolved constituents in water from the Powder River, alluvium, and bedrock*--Continued

Concentration of constituent, in milligrams											
Dis-solved calcium	Dis-solved magne-sium	Dis-solved sodium	Dis-solved potas-sium	Dis-solved bicar-bonate	Dis-solved sulfate	Dis-solved chlo-ride	Dis-solved fluo-ride	Dis-solved silica	Dissolve solids (as sum of constit-uents)	Dissolved nitrogen (NO_2+NO_3 as N)	Total phosphorus
POWDER RIVER											
110	43	370	5.3	351	560	270	0.7	10	1,540	0.6	---
110	52	360	3.7	317	660	270	.5	9.9	1,620	.4	0.1
110	66	270	4.7	305	620	170	.3	6.7	1,400	.2	.1
ALLUVIUM											
670	240	980	9.6	584	3,500	530	.4	16	6,230	.1	.2
230	85	460	7.4	448	1,100	270	.4	12	2,390	.5	.1
150	94	170	12	479	760	11	.3	22	1,470	4.8	.2
BEDROCK (from Hodson, 1971, p. 15 and 17)											
4.6	1.8	121	1.7	211	96	.8	.6	9.5	340	---	---
5.1	2.3	235	1.6	638	1.3	12	1.3	7.9	581	---	---
12	2.2	555	4.4	1,480	2.0	21	1.4	9.1	1,340	---	---

Dissolved-solids concentrations in water samples from the alluvium (table 6) were 6,230 mg/L (milligrams per liter) for the well near Sussex, 2,390 mg/L for the well near Arvada, and 1,470 mg/L for the well near Moorhead. These dissolved-solids concentrations exceed the secondary drinking-water standard of 500 mg/L (U.S. Environmental Protection Agency, 1986). The concentrations are within the range of 106-6,610 mg/L (median 1,700 mg/L) reported by L.R. Larson (Lowry and others, 1986, p. 95) for 38 samples from wells completed in the alluvium of various drainages in northeastern Wyoming. The poor quality of water near Sussex reflects the quality of the water draining from the plains and the oilfields.

For livestock watering (a major water use in the area), the dissolved-solids concentration in the sample from the well near Sussex (6,230 mg/L) is in the range described as reasonably safe for most animals except those that are pregnant or lactating (National Academy of Science and National Academy of Engineering, 1973). The dissolved-solids concentrations in samples from the well near Arvada (2,390 mg/L) and the well near Moorhead (1,470 mg/L) are in the range described as very satisfactory.

The water in the alluvium also might be acceptable for short-term irrigation or for selected industrial uses. Large concentrations of sodium, calcium, and chloride, however, may produce detrimental effects if the water is used for long-term irrigation or for most industrial uses.

Stiff diagrams (Stiff, 1951) are used in figure 17 to compare the ionic composition of water in the Powder River, the alluvium, and the bedrock. The relative magnitude of concentration of individual constituents is shown. Similarity of size and shape indicates similarity of composition.

The diagrams indicate that the water in the Powder River is dominated by sodium and sulfate ions; water in the alluvium is dominated by sodium, calcium, and sulfate ions; and water in the bedrock is dominated by sodium and bicarbonate ions. Based on similar Stiff-diagram shapes, the water in the Powder River and the alluvium is of similar composition, as expected, due to the intermixing of the water. The water becomes less concentrated downstream, particularly in the alluvium. The diagrams for the water from the bedrock are of substantially different shape, indicating a different composition. This also agrees with the previous conclusion that little or no movement of water occurs between the bedrock and the river or the alluvium. Although water quality can vary with depth and location in the bedrock aquifer, water samples from many wells completed in the Fort Union Formation near the Powder River in the northern half of the study area are all dominated by sodium and bicarbonate ions (Hodson and others, 1973, sheet 2).

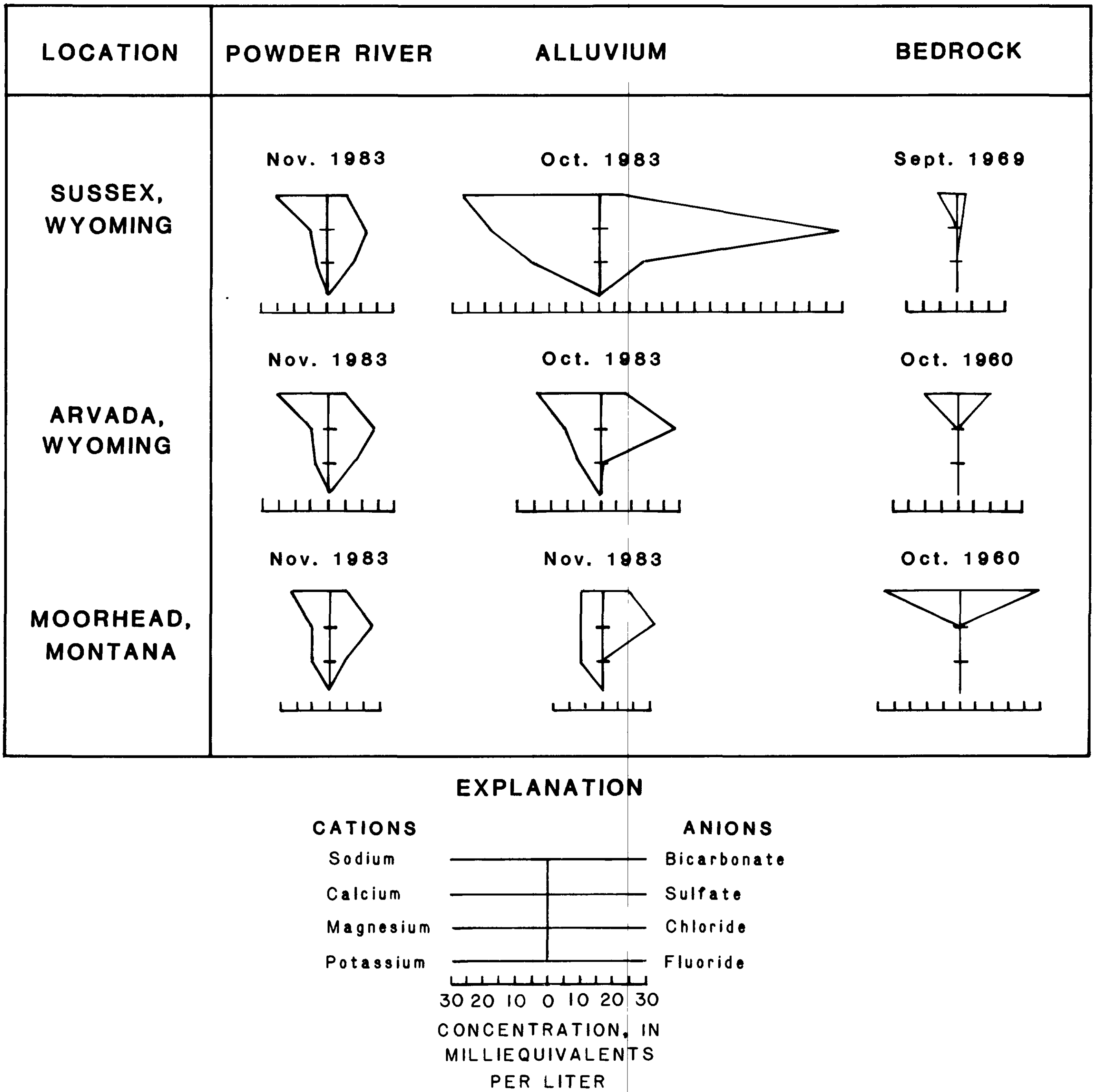


Figure 17.--Concentrations of major ions in water samples from the Powder River, alluvium, and bedrock at three locations (based on table 6).

SUMMARY AND CONCLUSIONS

The potential for developing water supplies from the alluvium along the Powder River from Sussex, Wyoming to Moorhead, Montana was assessed by determining the availability and quality of water in the alluvium and by determining the relations between water in the alluvium, water in the river, and water in the bedrock. Along the 155 river miles of the Powder River in the study area, the generally fine-grained alluvium ranges from 4 to 45 feet thick but commonly is 10 to 30 feet thick and about one-half mile wide.

The main source of water in the alluvium is seepage from the Powder River, stored during periods of high streamflow and discharged back to the river in some reaches during low flow. Flow-duration curves indicate that ground-water discharge and (or) irrigation return flow contribute to streamflow during low-flow conditions at Sussex, but not at Arvada or Moorhead.

During 2 of 3 years studied there were annual net gains in streamflow in the reach between Sussex and Arvada, mainly due to runoff between the two sites. However, streamflow losses during low-flow months indicate a lack of ground-water discharge to the river between Sussex and Arvada. Annual net losses in streamflow were computed for the reach from Arvada to Moorhead for all 3 years studied, indicating a lack of ground-water discharge in 8 to 9 months of each year. There were some gains and some losses during the low-flow months.

Ground-water storage in the alluvium declined during the growing season because discharge by transpiration was in excess of recharge. Water-level fluctuations in a well 425 feet from the river show the effects of recharge and discharge.

The alluvium has direct hydraulic connection with the river, as indicated by the response in two wells, 40 feet and 425 feet from the river, to changes in river stage. The artesian water level in a well completed in the bedrock did not respond substantially to changes in river stage or water levels in the alluvium for seven of the nine runoff events recorded. Possibly due to flood-plain loading, water levels in the well completed in bedrock responded substantially to the two local runoff events that produced the two highest river stages.

The hydraulic head in the underlying confined aquifer was much higher than the water level in the alluvium. A thick blue clay or shale at the top of the bedrock is reported on many drillers' logs, and isolates the bedrock from the alluvium hydraulically and, therefore, from the river in parts of the study area.

Aquifer characteristics were estimated for the alluvium at a site near Interstate Highway 90. Approximate values of diffusivity were computed using the flood-wave response technique. Calculated diffusivity for nine runoff events ranged from 778 to 25,100 feet squared per day, with an average of 10,200 feet squared per day. Assuming a specific yield of 0.2, the average transmissivity was estimated to be 2,040 feet squared per day. On the basis of an average saturated thickness of about 21.5 feet at this site, the hydraulic conductivity was estimated to be 94.9 feet per day.

The saturated thickness of the alluvium varies with river stage and across the cross section as the total thickness of the alluvium varies. Records indicate that the river rarely was dry at Sussex, but it was dry for at least 1 day during about 2 of every 3 years at Arvada, and less frequently at Moorhead. During 1 of every 5 years at Arvada the river was dry for 30 consecutive days.

Near Interstate Highway 90, a hypothetical well 200 feet from the river pumping at 50 gallons per minute for 2 days would derive about 15 percent of the yield from the river; after 7 days, about 40 percent; after 60 days, about 75 percent. A well 25 feet from the river would derive more than 40 percent of the yield from the river after 1 day of pumping. The longer a well is pumped, the greater the percentage of yield contributed by the river. Streamflow depletion continues for some time after pumping is stopped.

Although the quality of water in the alluvium improves downstream, it does not meet standards recommended by the U.S. Environmental Protection Agency for drinking water. Dissolved-solids concentrations in samples from wells completed in the alluvium were 6,230 milligrams per liter near Sussex (reflecting the oilfield brine discharge and plains runoff from Salt Creek), 2,390 milligrams per liter near Arvada, and 1,470 milligrams per liter near Moorhead. For livestock use, the water ranges from reasonably safe for most animals, except those pregnant or lactating, to very satisfactory. Large concentrations of sodium, calcium, and chloride may prevent use for long-term irrigation or for many industrial uses.

The chemical compositions of water in the river and in the alluvium are similar. The river water is dominated by sodium and sulfate ions, whereas water in the alluvium is dominated by sodium, calcium, and sulfate ions. The water in the bedrock, however, is dominated by sodium and bicarbonate ions.

The results of this brief study clearly indicate that the potential for developing water supplies from the alluvium along the Powder River is limited. The areal extent of the alluvium and the saturated thickness generally are not large. Water in the alluvium is supplied primarily by the river, which was dry periodically. Pumpage from wells completed in the alluvium is highly dependent on water derived directly from the river, particularly from wells close to the river. The quality of water in the alluvium also limits its use as a water supply, being unacceptable for drinking water, acceptable for most livestock, and marginal for irrigation or industrial use.

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SUPPLEMENTAL DATA

Table 7.--*Drillers' logs of water wells in the study area*

[Source: Data on file, U.S. Geological Survey, Cheyenne, Wyoming]

Material	Thickness (feet)	Depth (feet)
Well 43-078-18db		
Topsoil	4	4
Yellow clay	16	20
Sandstone	70	90
Blue shale	10	100
Coal	5	105
Blue shale	95	200
Sand	19	219
Blue shale	6	225
Well 44-078-08db		
Sandy soil	18	18
Blue shale	117	135
Sandstone	7	142
Blue shale	178	320
Rock	4	324
Soft sandstone	31	355
Blue shale	29	384
Rock	3	387
Sand	41	428
Blue shale	2	430
Well 45-078-01db		
Soil	5	5
Yellow clay	3	8
Sand and gravel	10	18
Blue shale	57	75
Hard rock	6	81
Blue shale	59	140
Coal	5	145
Blue shale	155	300
Sand	27	327
Blue shale	8	335
Well 45-078-12bd		
Sand	15	15
Gravel	15	30
Blue shale	50	80
Sandstone	1	81
Blue shale	224	305
Sandstone	8	313
Shale	2	315
Well 45-078-12ccd		
Topsoil	4	4
Light clay	4	8
Sand	10	18
Blue shale	65	83
Sand and sandstone	6	89
Gray clay	26	115
Brown shale and coal	7	122
Blue shale	43	165
Sand	5	171
Gray and blue shale	94	265
Red and blue shale	25	290
Gray sand	5	295
Red and blue shale	35	330
Red clay	25	355
Blue shale	13	368
Brown shale	32	400
Fine gray shale	35	435
Blue shale	5	440
Well 45-078-33dc		
Topsoil	4	4
Gravel	12	16
Yellow clay	7	23
Blue shale	162	185
Sand	6	191
Blue shale	87	278
Sand	18	296
Well 45-078-34ad		
Sand	18	18
Gravel	6	24
Blue shale	186	210
Red shale	10	220
Blue shale	50	270
Sand	30	300
Well 45-078-34bc		
Soil, sand, gravel	30	30
Blue shale	110	140
Sand	10	150
Blue shale	50	200

Table 7.--*Drillers' logs of water wells in the study area*--Continued

Material	Thickness (feet)	Depth (feet)
Well 45-078-34bc (Continued)		
Red shale	25	225
Blue shale	41	266
Red and blue shale	122	388
Sand	44	432
Well 46-078-01dd		
Gravel	12	12
Gray shale	23	35
Rock	5	40
Blue shale	70	110
Coal	14	124
Blue shale	96	220
Sandstone	40	260
Blue shale	58	318
Rock	6	324
Blue shale	58	382
Sand	46	428
Well 49-077-08ba		
Sand and gravel	25	25
Shale	5	30
Coal	10	40
Blue shale	140	180
Sandstone	20	200
Blue shale	320	520
Rock	6	526
Coal	6	532
Blue shale	69	601
Sand	55	656
Well 49-077-17ba		
Sandy soil	10	10
Gravel	20	30
Gray shale	28	58
Coal	16	74
Blue shale	146	220
Coal	10	230
Rock	5	235
Blue shale	283	518
Rock	5	523
Blue shale	67	590
Sand	56	646
Well 49-077-20ba		
Sand	8	8
Gravel	18	26
Blue clay	5	31
Well 49-077-20bc01		
Clay	5	5
Sand	15	20
Gravel	10	30
Blue shale	70	100
Sand	25	125
Blue shale and coal	375	500
Rock	1	501
Shale	99	600
Rock	4	604
Sand	11	615
Well 49-077-20bc02		
Sand and mud	9	9
Sand and gravel	18	27
Blue shale	4	31
Well 49-077-20cb		
Sand	10	10
Gravel	18	28
Blue shale	3	31
Well 49-077-20cd01		
Sand and mud	20	20
Well 49-077-20cd02		
Sand and mud	8	8
Gravel	22	30
Shale	1	31
Well 49-077-28ab		
Topsoil	30	30
Blue shale	15	45
Sand	2	47
Blue shale	18	65

Table 7.--*Drillers' logs of water wells in the study area*--Continued

Material	Thickness (feet)	Depth (feet)
Well 49-077-28ab (Continued)		
Brown shale	20	85
Green shale	15	100
Brown shale	15	115
Green shale	45	160
Brown shale	10	170
Green shale	20	190
Blue shale	20	210
Gray shale	10	220
Green shale	22	242
Silt and sand	40	282
Sandstone	15	297
Brown sandy shale	5	302
Blue shale	136	438
Rock	8	446
Blue shale	29	475
Sand	8	483
Blue shale	12	495
Well 49-077-28bc		
Sand and gravel	23	23
Coal	2	25
Blue shale	45	70
Coal	5	75
Blue shale	185	260
Rock	6	266
Blue shale	106	372
Sand	40	412
Well 50-077-09bc		
Topsoil	25	25
Gravel	2	27
Coal	24	51
Shale	20	71
Coal	3	74
Shale	1	75
Rock	1	76
Shale	11	87
Rock	1	88
Shale	54	142
Coal	3	145
Shale	29	174
Sand	5	179
Well 50-077-09bc (Continued)		
Shale	12	191
Sand	10	201
Shale	63	264
Coal	2	266
Shale	46	312
Rock	1	313
Shale	11	324
Rock	1	325
Shale	23	348
Rock	1	349
Shale	2	351
Coal	6	357
Rock	1	358
Shale	3	361
Rock	3	364
Sand	8	372
Coal	4	376
Rock	2	378
Coal	7	385
Shale	102	487
Sand	58	545
Shale	15	560
Well 50-077-28aa		
Topsoil	36	36
Gravel	9	45
Blue shale	31	76
Coal	14	90
Rock	1	91
Shale	64	155
Sand	27	182
Rock	1	183
Sand	20	203
Shale	83	286
Coal	15	301
Shale	17	318
Sand	40	358
Shale	54	412
Rock	2	414
Shale	61	475
Sandstone	5	480
Coal	22	502
Shale	23	525

Table 7.--*Drillers' logs of water wells in the study area*--Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Well 50-077-28aa (Continued)			Well 50-077-28cc (Continued)		
Coal	15	540	Rock	5	489
Shale	50	590	Sand	4	493
Coal	38	628	Shale	52	545
Shale	11	639	Coal	5	550
Sand	19	658	Shale	7	557
Coal	17	675	Rock	3	560
Shale	25	700	Sand	33	593
			Coal	22	615
Well 50-077-28cc			Shale	15	630
Topsoil	20	20	Well 52-077-16bd		
Shale	3	23			
Gravel	20	43	Sand and gravel	30	30
Shale	15	58	Shale	50	80
Rock	4	62	Sand	10	90
Sand	41	103	Shale	100	190
Coal	4	107	Sand	10	200
Shale	62	169	Shale	60	260
Rock	1	170	Sand	20	280
Shale	13	183	Shale	50	330
Rock	2	185	Coal	20	350
Sand	2	187	Shale	170	520
Shale	33	220	Coal	10	530
Sand	3	223	Shale	30	560
Shale	47	270	Sand	45	605
Sand	15	285			
Shale	10	295	Well 53-077-26ba		
Rock	2	297			
Shale	36	333	Sand and gravel	40	40
Rock	2	335	Shale	62	102
Shale	10	345	Sand	6	108
Rock	1	346	Shale	32	140
Shale	29	375	Coal	10	150
Rock	2	377	Shale	10	160
Sand	27	404	Sand	15	175
Shale	9	413	Shale	13	188
Coal	2	415	Sand	77	265
Rock	2	417			
Shale	14	431	Well 53-077-26cc		
Rock	2	433			
Shale	42	475	Sand and gravel	35	35
Rock	1	476	Shale	146	181
Sand	2	478	Sand	9	190
Shale	6	484	Shale	60	250

Table 7.--*Drillers' logs of water wells in the study area*--Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Well 53-077-26cc (Continued)			Well 56-077-01aa (Continued)		
Rock	3	253	Blue shale	48	154
Shale	7	260	Rock	4	158
Sand	25	285	Blue shale	32	190
Shale	61	346	Rock	5	195
Coal	15	361	Blue shale	18	213
Sand	67	428	Sand	7	220
			Blue shale	28	248
Well 55-077-27cd			Sand	7	255
			Black shale	13	268
Soil	10	10	Coal	16	284
Gravel	21	31	Blue shale	8	292
Shale	18	49	Sand	5	297
Coal	16	65	Blue shale	46	343
Shale	20	85	Sand	18	361
Sand	10	95	Blue shale	4	365
Shale	35	130			
Sand	15	145	Well 56-077-25cc		
Shale	18	163			
Coal	13	176	River sand	18	18
Shale	40	216	Gravel	6	24
Sand	11	227	Shale	6	30
Shale	11	238	Coal	5	35
Coal	3	241	Shale	15	50
Shale	41	282	Rock	1	51
Coal	2	284	Shale	6	57
Shale	11	295	Coal	24	81
Sand	5	300	Shale	24	105
Shale	14	314	Sand	7	112
Rock	2	316	Shale	23	135
Shale	14	330	Rock	1	136
Rock	6	336	Shale	9	145
Sand	54	390	Coal	18	163
Coal	34	424	Shale	42	205
Sand	41	465	Rock	3	208
Shale	5	470	Sand	6	214
			Coal	6	220
Well 56-077-01aa			Shale	80	300
			Rock	4	304
Sandy clay	15	15	Shale	17	321
Gravel	5	20	Coal	8	329
Blue shale	7	27	Shale	33	362
Sand	21	48	Sand	44	406
Blue shale	56	104	Shale	34	440
Rock	2	106			

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