GROUND-WATER-FLOW SYSTEMS IN THE POWDER RIVER STRUCTURAL BASIN, WYOMING AND MONTANA

by James G. Rankl and Marlin E. Lowry

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CONVERSION FACTORS

Multiply	by	To obtain
acre	0.4047	hectare
foot (ft)	0.3048	meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day

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

This study of regional ground-water flow in the Powder River structural basin was intended to describe the water resources of an area of coal development and to determine the effects of the development on the water resources. The basin receives only about 12 to 16 inches of precipitation per year. The bedrock units described consist of the Fox Hills Sandstone and the Lance Formation of Late Cretaceous age, the Fort Union Formation of Paleocene age, and Wasatch Formation of Eocene age. These formations are heterogeneous, consisting predominantly of shale and sandstone.

Water wells in the area principally are for livestock and domestic supplies. Water for these supplies generally can be obtained from wells less than 500 feet deep. The water from the shallow wells generally is a calcium sulfate or calcium sodium sulfate type. Some industrial wells are drilled to depths greater than 5,000 feet to obtain larger quantities of water; these wells commonly tap several formations. Water from deep wells generally is a sodium bicarbonate type.

The types of streams in the area are perennial, ephemeral, and interrupted. Some of the perennial streams in the basin originate in nearby mountains.

Northward regional ground-water flow that is stratigraphically controlled can be inferred from potentiometric data, but discharge areas in the northern part of the basin could not be identified on the basis of chemical quality of water from springs and shallow wells. The chemical quality of ground water from shallow depth in the northern part of the basin is affected more by local conditions than by regional flow.

Potentiometric data indicate that most streams in the Powder River structural basin should receive base flow from a regional ground-water system. However, such base flow is not evident in streamflow records. Streamflow data collected at fourteen stations on eight streams show that base flow occurs at six of the stations, but base flow during the nongrowing season occurred only in Otter Creek and the Little Powder River. The three largest streams included in the analysis were the Powder, Belle Fourche, and Cheyenne Rivers. Of the three, only the Belle Fourche had base flow, and it was present only during the period of largest precipitation, but not during the period of minimum evapotranspiration. The locations of the streams that do not have base flow and the period of base flow that occurs in most streams indicate that base flow, where present, is from local systems rather than a regional system.

The absence of base flow in streams derived from ground water moving through the regional system is the result of the nonhomogeneity of the formations. The nonhomogeneity of the formations precludes the use of simple water-level maps as a substitute for sets of stratigraphically based potentiometric maps.

Analysis of streamflow records indicates that alluvial and clinker aquifers have more measurable effect on flow at the stations analyzed than do bedrock aquifers. The alluvium contributes flow to some streams, but most streams probably lose water to the alluvium to replace water discharged by evapotranspiration.

The existence of those areas of natural ground-water discharge from a regional ground-water system consisting of the Wasatch-Fox Hills sequence in the Powder River structural basin that would be inferred from potentiometric data could not be substantiated. Therefore, it is concluded that the regional flow system may have a smaller flow than previously thought, and that measurable effects from surface mining and water development will affect mostly local flow systems. However, more data are necessary to describe local and subregional flow systems and their relation to the regional system.

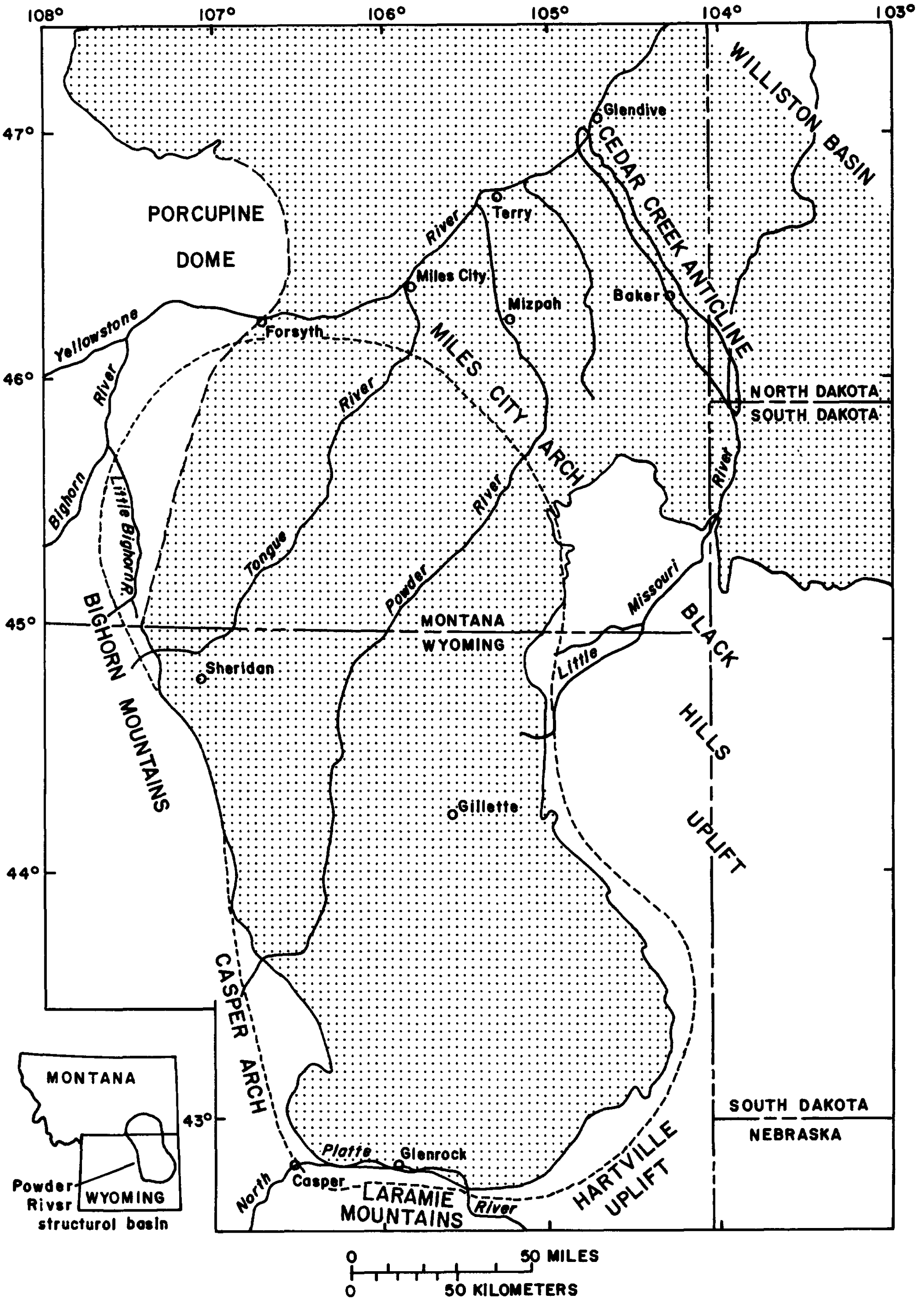
INTRODUCTION

The development of the coal resources that began in the Powder River structural basin (fig. 1) in the mid-1970's required additional water supplies and possibly could have a negative effect on existing supplies. The U.S. Geological Survey, under its coal-hydrology program, began extensive studies in the basin in both Montana and Wyoming in 1975.

Purpose and Scope

This report, which is one of several that resulted from the studies, summarizes the relative amounts of regional and local ground-water flow in the basin.

The initial concept of the ground-water-flow system was that the vertical component of ground-water flow was large enough for a regional flow system to measurably sustain the flow in the principal streams. If true, the characteristics of regional ground-water flow should be indicated by the seasonal characteristics of base flow in the the principal streams. Few streamflow data for studying the ground-water/surface-water relations would have been available, had a consistent period of record been used for the analysis; therefore, any continuous-record station with 5 or more years of record through water year 1977 was included. Some analyses of long-term records were done before the records for water year 1977 were available; analyses and illustrations using these data were not updated to include water year 1977. Analyses of flow data for streams or stream reaches in which the natural flows are substantially affected by releases of water from reservoirs are not included in this report.



EXPLANATION

——— — — CONTACT OF UPPER CRETACEOUS FOX HILLS SANDSTONE--Dashed where inferred. Contacts interpreted from Keefer (1974), Ross and others (1955), and Lewis and Roberts (1978)

- - - - - - - - - OUTLINE OF POWDER RIVER STRUCTURAL BASIN--Approximately located

Figure 1.--Relation of the Powder River structural basin to nearby structural features and approximate areal extent of Fox Hills Sandstone.

Data on ground-water chemistry were analyzed to determine if there was evidence of a regional flow system that was stratigraphically controlled. Examples of local ground-water systems were included in the report to illustrate how local systems may increase or decrease flow in streams.

Precipitation

Precipitation in the basin is sparse and not evenly distributed throughout the year. This, in turn, affects the flow in streams and ground-water recharge. Maps of average annual precipitation for Montana (Cordell, 1960) and Wyoming (Lowers, 1960; and National Weather Service, Cheyenne, Wyo., written commun., 1966) indicate that the range in precipitation in the central part of the basin is from about 12 to 16 in. Greater precipitation occurs near the mountains. Nearly one half the average annual precipitation occurs during the months of April, May, and June. The driest period is during the winter, when only about 15 percent of the precipitation occurs.

Normal monthly precipitation for the 1941-70 period at Miles City, Mont. (elevation 2,628 ft above sea level); Gillette, Wyo. (elevation 4,565); and Glenrock, Wyo. (elevation 4,948) are shown in figure 2. The location of these communities is shown in figure 1.

Geology

The formations for which regional ground-water flow is discussed in this report include those in the Wasatch-Fox Hills sequence. The sequence includes the Fox Hills Sandstone and Lance (Hell Creek) Formations of Late Cretaceous age, the Fort Union Formation of Paleocene age, and the Wasatch Formation of Eocene age. The areas of outcrop of these formations and older and younger formations, except the alluvium, are shown on plate 1. The location of the Powder River structural basin and its relation to nearby structural features is shown in figure 1.

Formations within the sequence are heterogeneous, and any assumption about the hydrologic connection between individual aquifers in the formations should be justified. The Fox Hills Sandstone is composed of fine- to medium-grained sandstone beds deposited during receding marine seas. Deposition was in barrier-island, neritic, and marine environments. The overlying Lance (Hell Creek), Fort Union, and Wasatch Formations consist of continental deposits of sandstone, shale, mudstone, coal, and local lenses of carbonate rocks. In many places, clinker has been formed by the burning of coal that has baked overlying shale, siltstone, and sandstone.

The Wasatch-Fox Hills sequence is about 1,350 ft thick in southeastern Mont. (Taylor, 1968, p. 4-6) and thickens to at least 7,000 ft in Converse County, Wyo. The difference in thickness is due to original differences in deposition and to subsequent erosion.

In describing the spatial dimensions of the Fox Hills Sandstone, Weimer (1961, p. 84) states, "The Fox Hills Sandstone is a lithogenetic unit consisting of a series of individual sand bodies." The geographic extent of a single sand described by Weimer (1961, p. 94) was 6 to 7 mi wide and hundreds

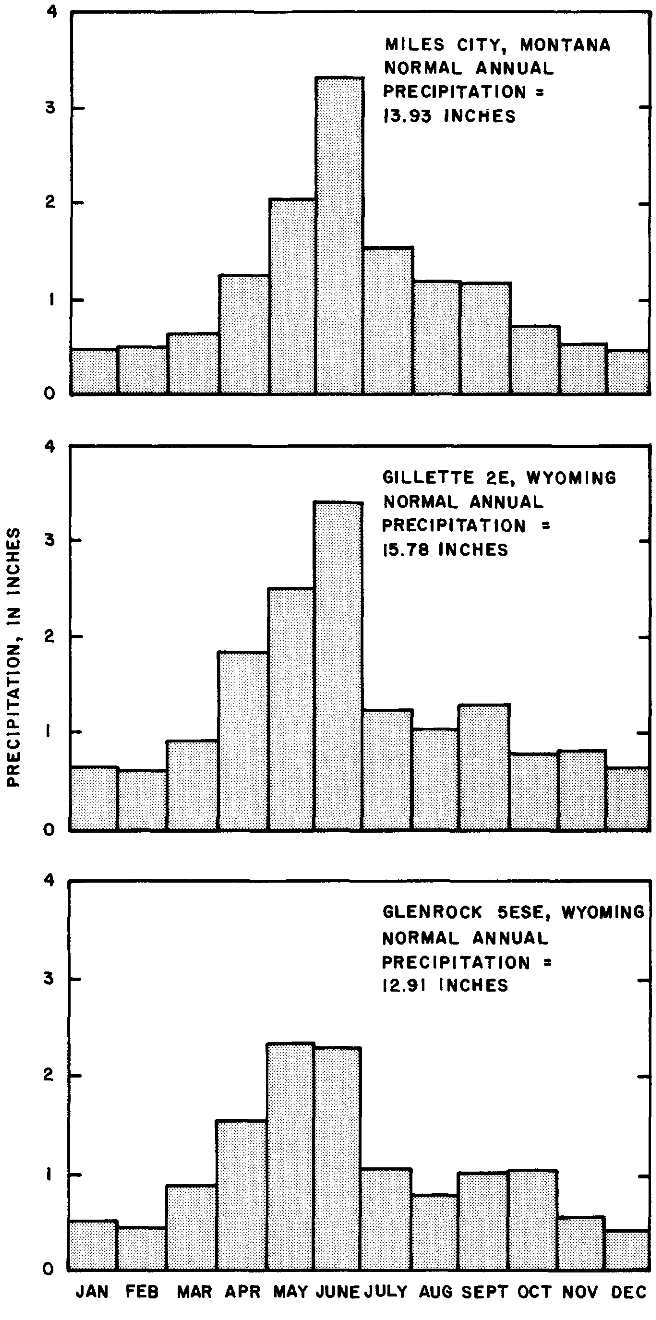


Figure 2.--Normal monthly precipitation for selected stations in the Powder River Basin, 1941-70.

of miles long. Although this sand could be correlated over a long distance, the continuity of sand deposition is probably broken by inlets and deltaic deposits. The Fox Hills has been recognized in the northwestern part of the basin in Wyoming (Gill and Cobban, 1966, pl. 3), but is poorly developed and not mapped along much of the western side of the basin.

Flores (1979) and Flores and Canavello (1979) have mapped the stratigraphic sequence of the Tongue River Member of the Fort Union Formation exposed along the Powder River in northern Wyoming and southern Montana. The maximum distance an individual sand was correlated was about 10 mi. This is similar to the extent of sands in the Wasatch Formation. Sharp and others (1964, p. 553), in a study of the Pumpkin Buttes area, state that most of the sandstone lenses are as much as 6 to 8 by 4 to 5 mi in areal extent, and that the largest single mappable sandstone is traceable for more than 12 mi across the area.

The mountains are the principal source of resistant rock, and the rocks are the source of most of the coarse-grained alluvium in the basin. Locally, the younger Tertiary rocks (Tertiary undivided on plate 1) and clinker are sources of coarse-grained alluvium in the basin. The difference in composition of the alluvium in the Powder River drainage basin, which originates in the Bighorn Mountains, and the Belle Fourche River drainage basin, which originates in the area underlain by the Wasatch-Fox Hills sequence, is shown by descriptions of alluvial deposits by Leopold and Miller (1954). The oldest alluvial formations described in the Powder River drainage contain cobbles, sand, and gravel (Leopold and Miller, 1954, p. 8-11). Prevalence of silt in all the alluvium, however, was noted by Leopold and others (1964, p. 438).

They describe the valley along the Powder River as one that was alluviated with a thick section of very uniform silt in late Pleistocene and post-Pleistocene time. Uniform silt is exposed in places along the walls of the present channel and composes a major proportion of the valley fill.

The maximum known thickness of the alluvium in the Powder River Basin in Wyoming is about 100 ft, but the thickness commonly is 30 ft or less (Wells, 1982). The thickness in Montana is similar.

GROUND WATER

Aquifer Data

Most of the data available to describe aquifers in the Wasatch-Fox Hills sequence are from stock and domestic wells; however, hydraulic-head data from these wells are not adequate to define potentiometric surfaces in the area. Large differences in hydraulic head occur with depth; therefore, a potentiometric map is meaningful only if it is for a specific horizon. Stock and domestic wells generally are completed in small intervals of single formations at depths of less than 500 ft. At these depths, yields of about 20 gal/min can be obtained with a chemical quality suitable for stock and domestic use. Because there is large topographic relief in the area and because these wells are completed in sandstone aquifers at differing depths, a specific horizon within a geologic unit is difficult to correlate from well to well. Therefore, the hydraulic-head data is not sufficient to define a potentiometric surface for a specific horizon.

Industrial and public-supply wells are of little more value for potentiometric maps than are domestic or stock wells. Rarely is a well completed throughout the entire interval of a single formation or member. The authority granting permits to appropriate ground water may specify certain depth intervals from which water can be obtained, or may permit all sands in the interval of the well depth to be used. Therefore, the wells may be open only to a small interval within a formation, or may be open through an interval that includes several formations.

Water from the alluvium has not been developed extensively because better-quality water occurs in the underlying Wasatch-Fox Hills sequence, and because large yields generally are not possible as most of the alluvium is fine-grained. Measured transmissivities of the alluvium in areas where it is underlain by the Wasatch-Fox Hills sequence range from 449 to 1,337 ft^2/d.

Chemical Quality of Water

The chemical quality of the water in the Wasatch-Fox Hills sequence can be used to determine recharge and discharge areas for ground water in the basin. The method has been described by Thorstenson and others (1979). Riffenberg (1925) described the quality of ground water in the northern Great Plains in Montana and North Dakota. His descriptions of the quality of water in the Fort Union and Lance Formations apply to the quality of water in the more inclusive Wasatch-Fox Hills sequence throughout the Powder River structural basin. His description of water in surficial deposits applies to the quality of water in the alluvium in the basin. The following is abstracted from that report:

> Water from surficial deposits that contain less than 600 mg/L (milligrams per liter) dissolved solids may generally be divided into two chemical types, a calcium magnesium carbonate type and a calcium magnesium sulfate type. Dissolved-solids concentrations of more than 600 mg/L generally are due to the addition of sodium and sulfate.

Water from shallow wells completed in the Fort Union and Lance Formations is of similar quality to water from the surficial material. The water from deep wells is soft; that is, sodium plus potassium exceeds calcium plus magnesium. Many water samples contain carbonate as well as bicarbonate, and although some contain large concentrations of sulfate, others contain very little. The dominant reactions that control the chemical quality of water in the Fort Union and Lance Formations are cation-exchange softening and sulfate reduction. Sulfate reduction is not a reversible reaction (Thorstenson and others, 1979, p. 1493). Riffenburg (1925, p. 46) states that there is a definite relation between hardness and well depth; water from 100 to 125 ft deep generally is soft, and all water from below 125 ft is soft.

The change in chemical quality of water with depth in the basin is shown in figure 3. The data are from computer files of the U.S. Geological Survey. Samples without analysis for bicarbonate or where the depth of the well was unknown were deleted, and only the most recent sample was used if there were multiple samples; springs were assumed to be 1 ft deep. The data were sorted by 100-ft depth intervals, from 0 to 1,000 ft, and the average concentrations of the principal cations and anions were determined. There is a decrease in calcium and magnesium and sulfate and an increase in bicarbonate down to a depth of about 500 ft. Deeper than 500 ft the concentration of dissolved constituents is relatively uniform. The decrease in total cations and anions to a depth of about 500 ft (fig. 3) has not been explained.

STREAMFLOW

Three types of streams are present in the Powder River structural basin: (1) perennial, (2) ephemeral, and (3) interrupted. The perennial streams in the Powder River Basin are of two types--those that originate in the mountains and flow through the basin and those that originate in the basin.

The preceding terms, perennial, ephemeral, and interrupted, have been defined by Meinzer (1923, p. 57-58): "A perennial stream, or stretch of a stream, is one which flows continuously. * * * An ephemeral stream, or stretch of a stream, is one that flows only in direct response to precipitation. * * * An interrupted stream is one which contains perennial stretches with intervening intermittent or ephemeral stretches."

Records of streamflow in the Powder River Basin were analyzed using flow-duration curves, graphs of average-daily discharge, and average annual runoff to determine the type of stream and the relation between ground water and surface water. The flow-duration curve has been described by Searcy (1959, p. 1) as a: "* * *cumulative frequency curve that shows the percent of time during which specified discharges were equaled or exceeded in a given period." Considerable information can be abstracted from a flow-duration curve when analyzed in conjunction with information on basin geology, vegetation, climate, and average-daily discharge. In this report, the flow-duration curve is used to describe flow characteristics of streams and is not used for predictive purposes.

Interpretation of the shapes of the flow-duration curves are described by Searcy (1959, p. 22): "A curve with a steep slope throughout denotes a highly variable stream whose flow is largely from direct runoff, whereas a curve with a flat slope reveals the presence of surface- or ground-water storage which tends to equalize the flow." A change in slope of a flow-duration curve can provide as much or more information as the steepness or flatness of the slope. For example, a decrease in the slope in the lower part of the flow-duration curve can indicate small ground-water discharge. An increase in slope indicates the depletion of either surface- or ground-water storage or both.

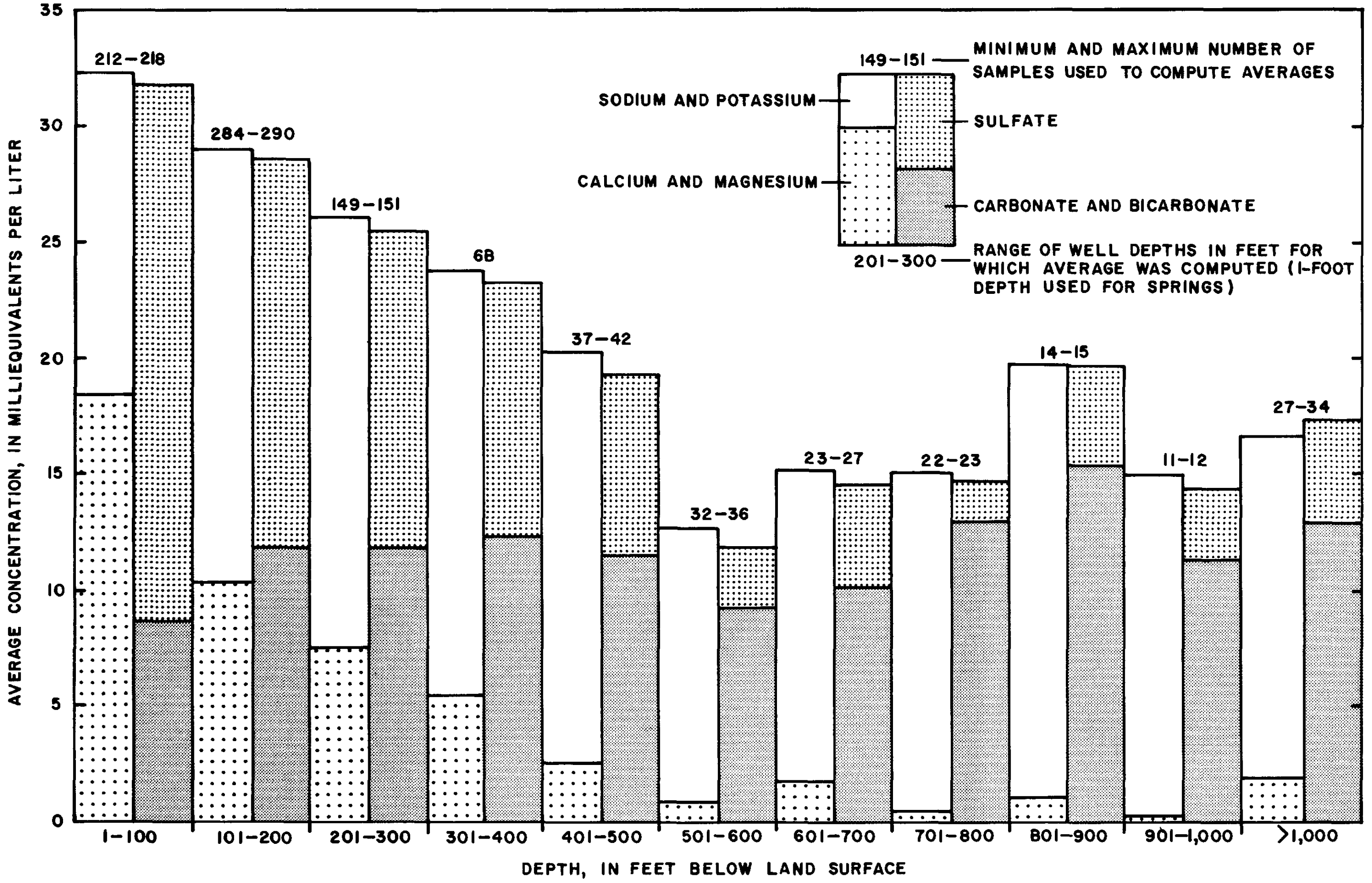


Figure 3.--Differences in the chemical quality of water with depth in the Wasatch-Fox Hills sequence.

Flow-duration curves were drawn for two periods: October-March, which approximates the dormant period of vegetation; and April-September which approximates the growing period of vegetation. There is variation from year to year, but generally October through March is the period of least evapotranspiration and April through September is the period of greatest evapotranspiration.

Graphs of average-daily discharge, computed by averaging the streamflow for each calendar day of the water year, were prepared for all streamflow-gaging stations in the Powder River Basin with 5 or more years of record. The averages of daily values are used because annual and seasonal trends or changes in streamflow often are masked by flow variability. The average-daily discharge can be used to determine long-term averages of base flow, changes in base flow due to evapotranspiration, and changes in flow in a reach between gaging stations. Hydrographs using averages of periods longer than one day obscure trends and changes in small flows because of runoff from precipitation.

Three streamflow records--the Niobrara River at the Wyoming-Nebraska State line (station number 06454000); Black Thunder Creek near Hampshire, Wyo. (06376300); and Dead Horse Creek near Buffalo, Wyo. (06313700)--are used to show the flow in three different types of drainage basins. The surficial formations in the Niobrara basin have a high infiltration rate. Therefore, the river has small peak flows and uniform ground-water discharge. The seasonal flow-duration curves (fig. 4) for the Niobrara River have a very flat slope, indicating a uniform ground-water contribution. The two curves cross, indicating that during the growing season there are periods of larger flows because of direct runoff and also periods of smaller flows because of evapotranspiration. The average-daily-discharge hydrograph (fig. 5) shows a 0.8 ft^3/s difference between winter ground-water discharge and late-summer discharge. The flow increased because evapotranspiration decreased after the first freeze in the fall.

Black Thunder Creek basin is drained by an ephemeral stream that has no ground-water discharge but flows as a result of rainstorms or snowmelt runoff. Seasonal flow-duration curves (fig. 6) for Black Thunder Creek have steep slopes and are approximately parallel; these are typically shaped curves for an ephemeral stream. The steep slopes are the result of streamflow variability, while the parallelism indicates that the cause of runoff is the same for both periods, but that it occurs more frequently during the growing season. The average-daily-discharge hydrograph (fig. 7) is typical for an ephemeral stream.

Average annual runoff from the Black Thunder Creek basin is nearly identical to that of the Niobrara River basin. The Black Thunder Creek basin had 0.127 in. of runoff, all from direct runoff from rainfall or snowmelt, and the Niobrara River basin had 0.128 in., mostly from ground-water discharge. Average annual precipitation in the Niobrara River basin is about 2 in. greater than average annual precipitation in the Black Thunder Creek basin. This additional precipitation is taken up by evapotranspiration.

Dead Horse Creek basin is drained by an interrupted stream. The streamflow-gaging station on Dead Horse Creek was located just downstream from a perennial reach of the stream; therefore, flow at the gage was intermittent.

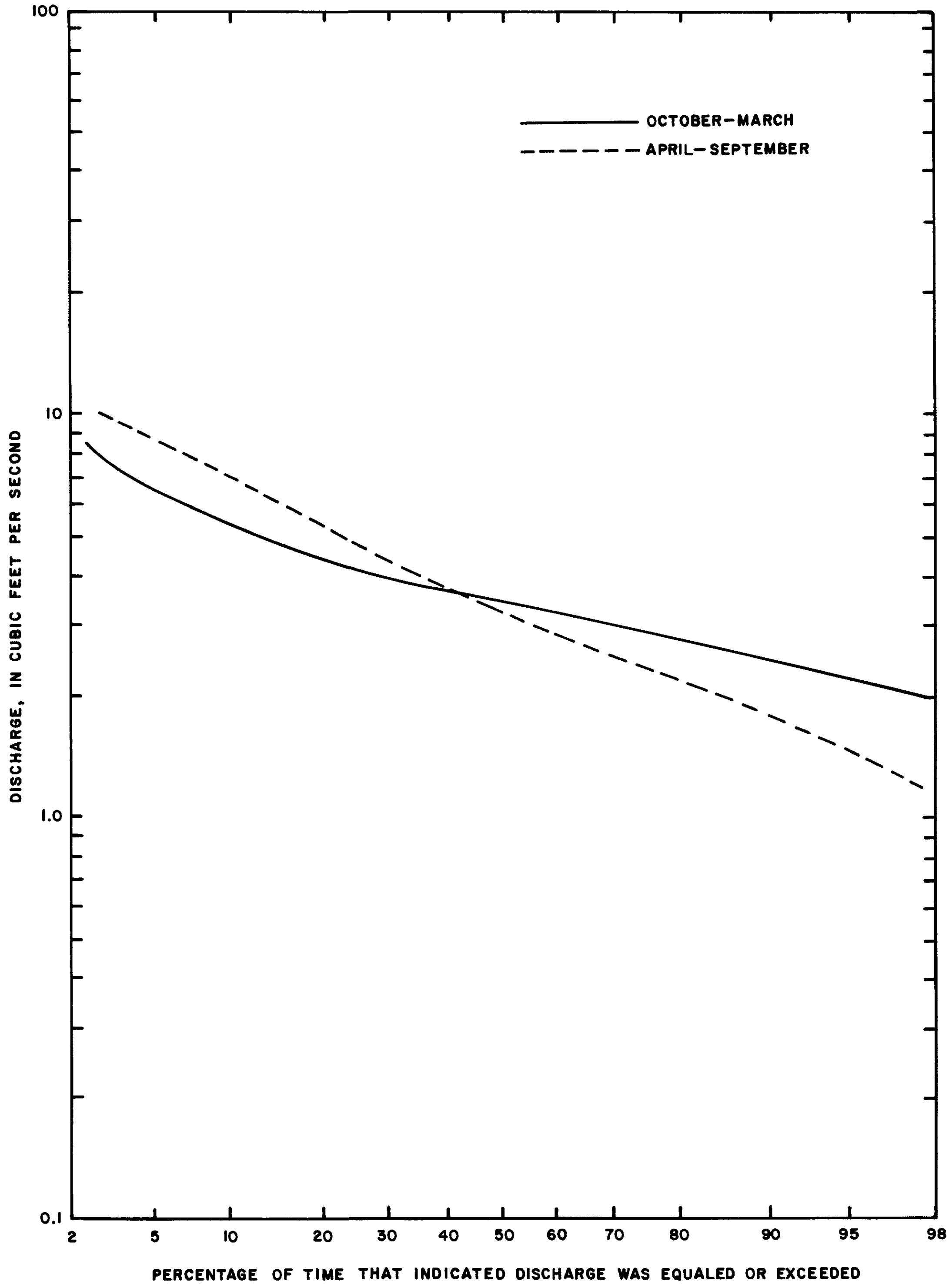


Figure 4.--Flow-duration curves for the Niobrara River at Wyoming-Nebraska State line (06454000), 1956-77 water years.

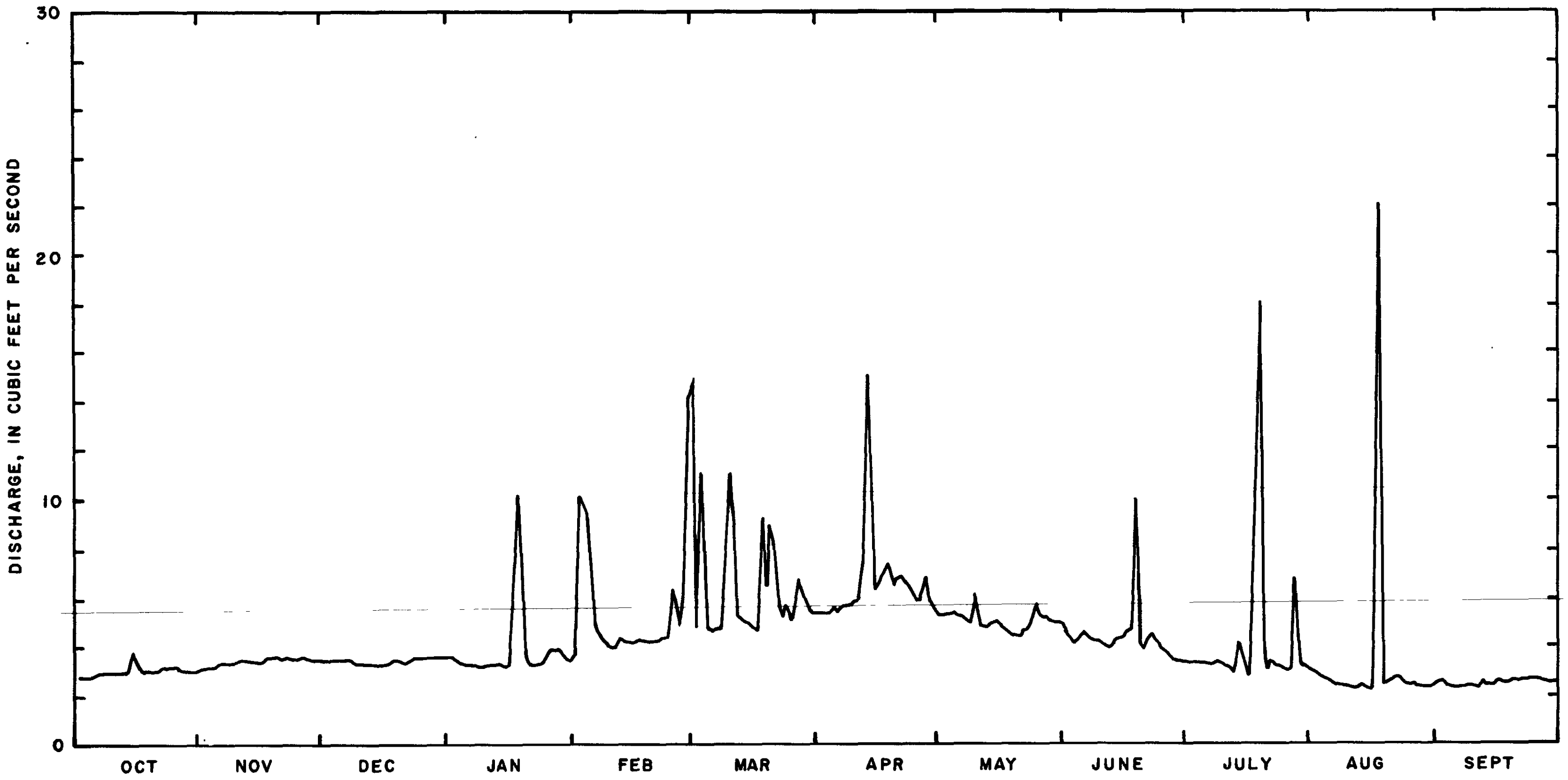


Figure 5.--Average-daily-discharge hydrograph for the Niobrara River at Wyoming-Nebraska State line (06454000), 1956-77 water years.

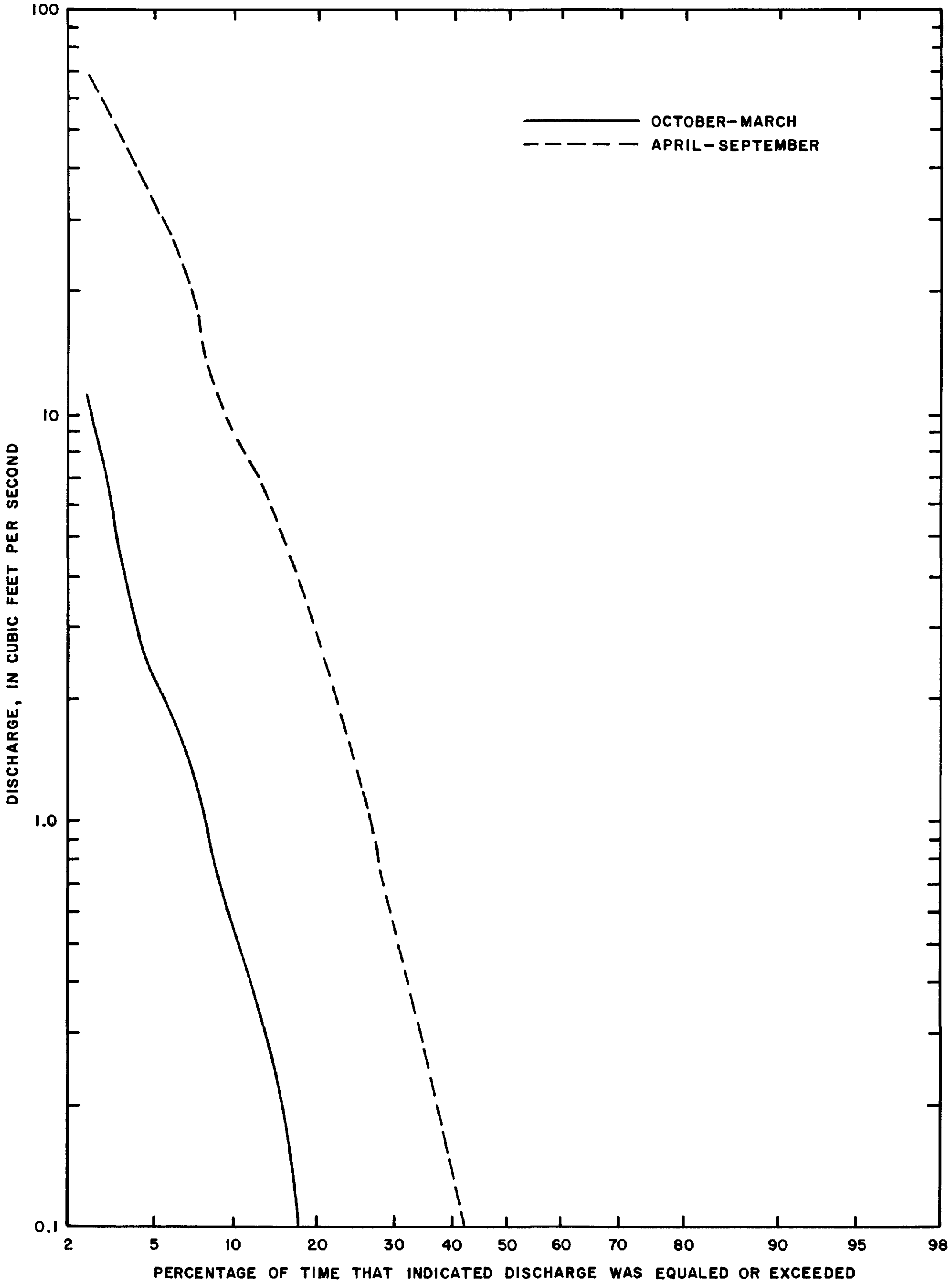


Figure 6.--Flow-duration curves for Black Thunder Creek near Hampshire, Wyo. (06376300), 1972-77 water years.

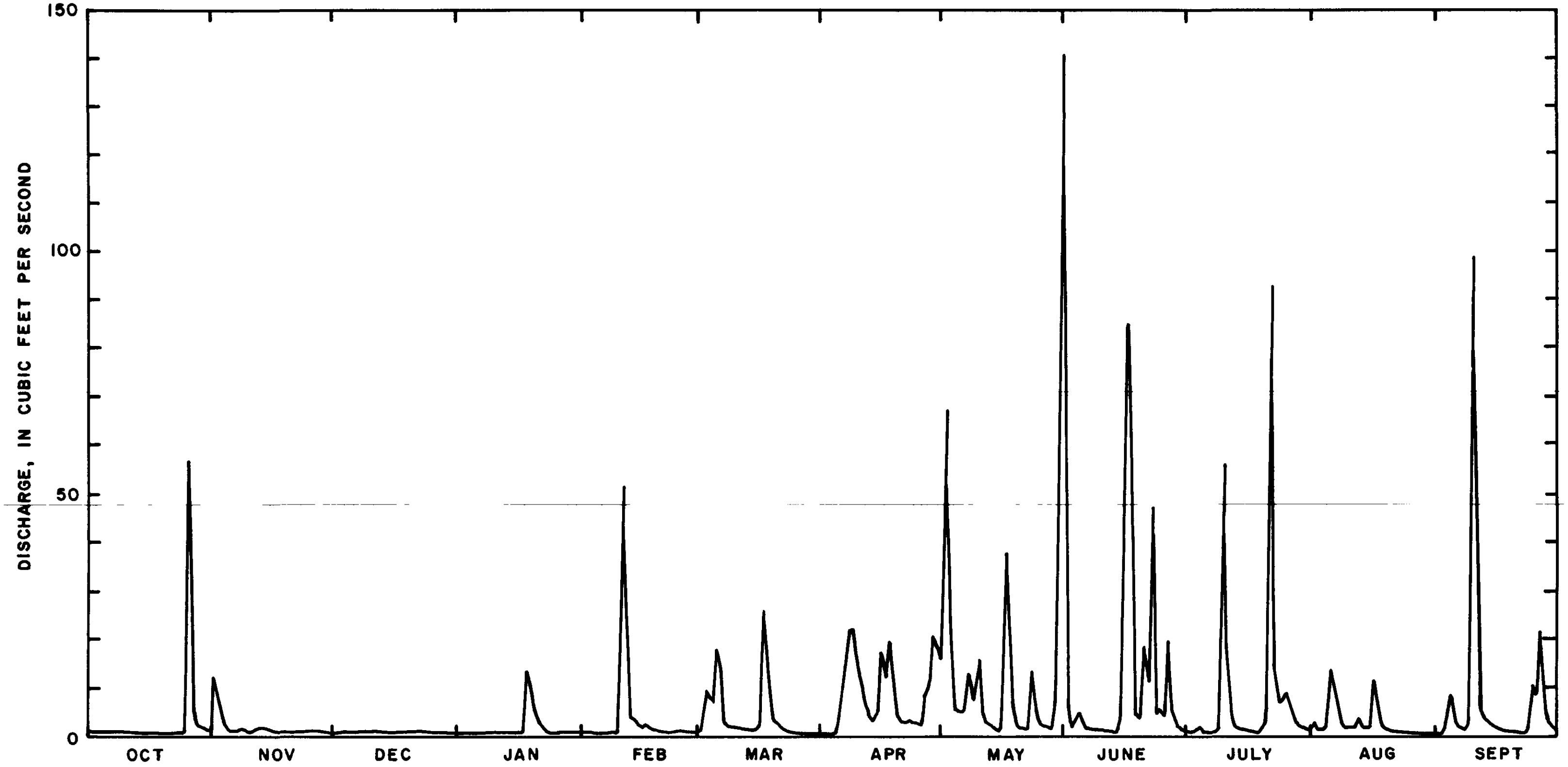


Figure 7.--Average-daily-discharge hydrograph for Black Thunder Creek near Hampshire, Wyo. (06376300), 1972-77 water years.

Intermittent flow is indicated by the change in the slope of the flow-duration curve (fig. 8) between 0.2 and 0.04 ft^3/s. The intermittent flow is too small to show at the scale of the average-daily-discharge hydrograph (fig. 9). Average annual runoff was 0.170 in.

REGIONAL GROUND-WATER-FLOW SYSTEMS

Two systems of regional ground-water flow are possible: (1) Northward flow that is stratigraphically controlled (fig. 10), and (2) flow into the major streams (fig. 11). Some northward flow must occur because the potential for northward flow exists. The lowest static water level known is in a well in the southern part of the basin. The well is completed in the lower part of the Lance Formation and the Fox Hills Sandstone at a depth of 6,330 ft. The altitude of the water level in the well is about 500 ft lower than the altitude of the outcrop along the North Platte River and about 1,800 ft higher than the land surface at the northern extent of the basin along the Yellowstone River. Flow into major streams, such as shown in figure 11, has been proposed, and the potential for the flow exists. The altitude of the bottom of most wells drilled in the interstream areas is higher than nearby streams levels, and flowing wells are common at stream level.

The concept of regional ground-water flow that is stratigraphically controlled was examined on the basis of water quality; the concept of flow into major streams was examined by analysis of streamflow.

Stratigraphic Control

If regional ground-water flow occurs, as shown in figure 10, it should be possible to identify discharge areas by an increase in the number of springs and shallow water wells that yield sodium bicarbonate type water. There is a northerly gradient, the formations thin because of differences in original deposition, and the Wasatch and part of the Fort Union and Lance Formations have been eroded from the northern part of the basin and all the formations have been eroded from the Ceder Creek anticline (fig. 1 and plate 1). Thus some discharge from the regional ground-water-flow system should take place in the northern part of the basin.

The percentage of wells and springs that contain large concentrations of sodium bicarbonate is shown in 0.3-degree intervals of latitude in figure 12. It was decided arbitrarily to use only samples in which: (1) The concentration of sodium plus potassium was at least twice that of the calcium and magnesium, to eliminate calcium bicarbonate water that sometimes occurs in recharge areas; and (2) the bicarbonate was at least twice that of the sulfate, to indicate water that had moved a sufficient distance through the aquifers to be affected by sulfate reduction. This method of distinguishing water in recharge and discharge areas is similar to that used by Thorstenson and others (1979) to describe ground-water flow in the Hell Creek and Fox Hills in North Dakota.

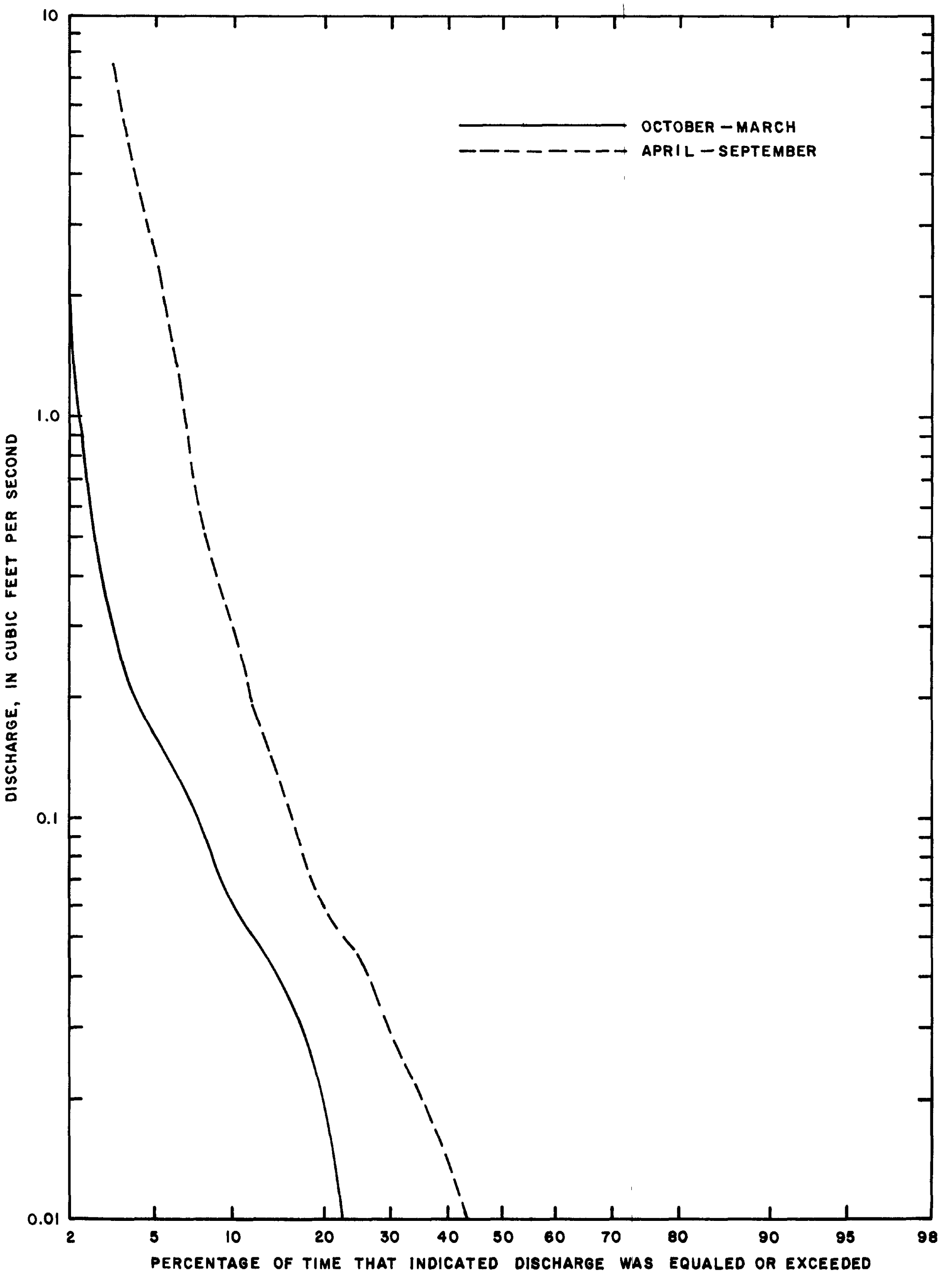


Figure 8.--Flow-duration curves for Dead Horse Creek near Buffalo, Wyo. (06313700), 1971-77 water years.

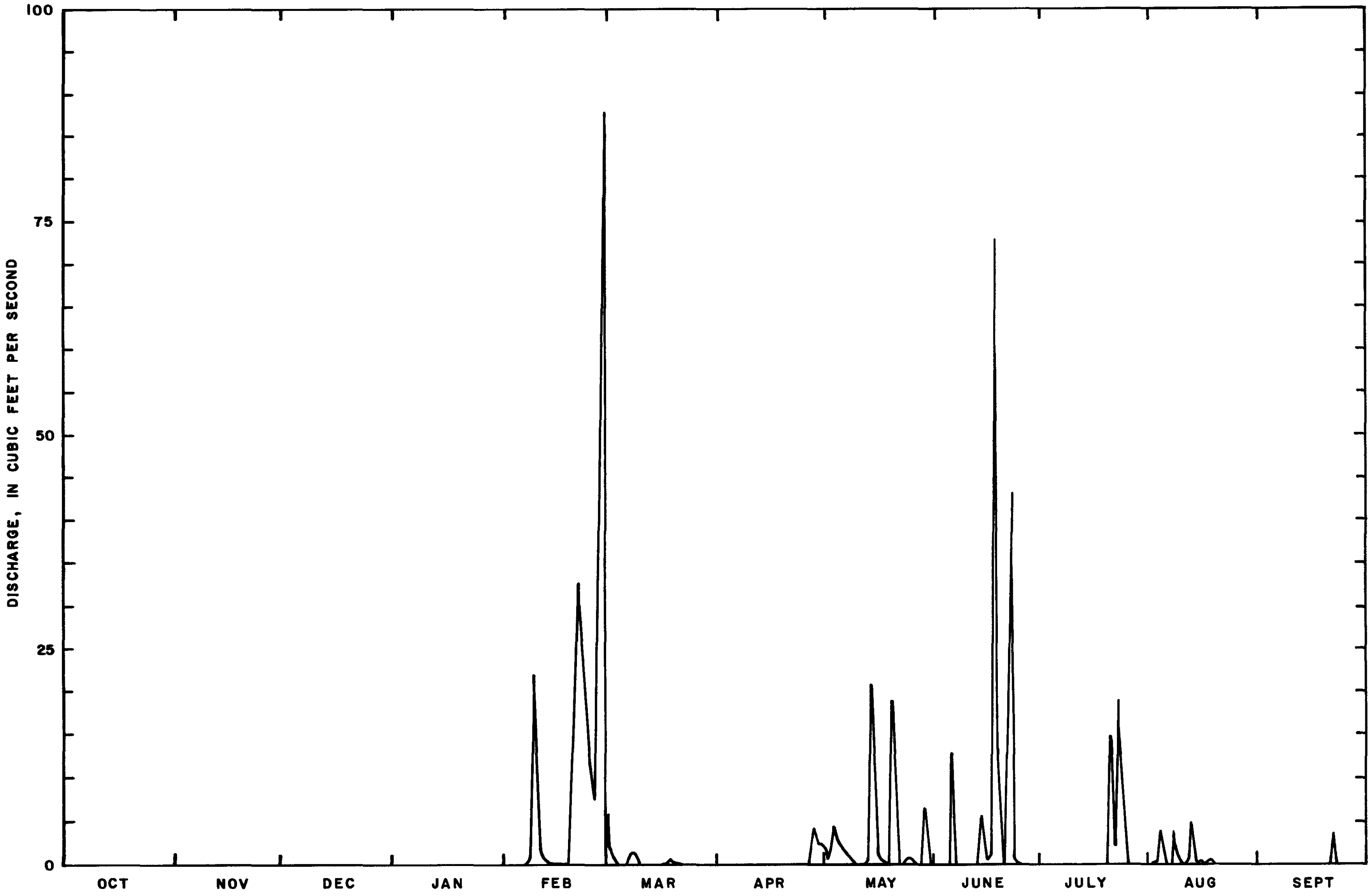


Figure 9.--Average-daily-discharge hydrograph for Dead Horse Creek near Buffalo, Wyo. (06313700), 1971-77 water years.

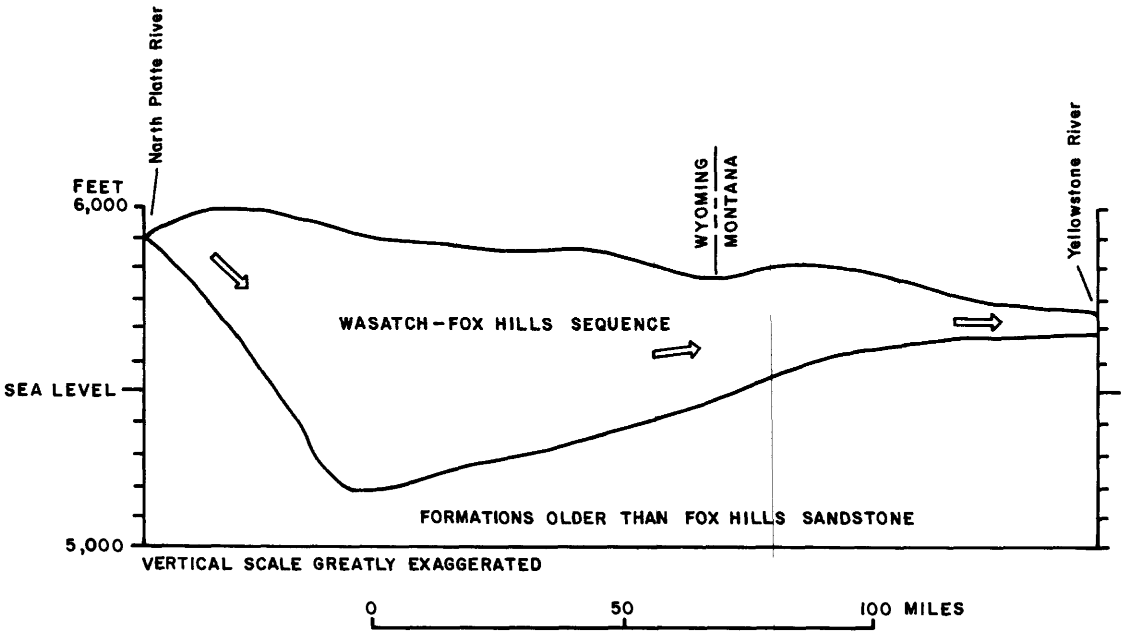


Figure 10.--Regional ground-water flow (arrows) controlled by stratigraphy. Section is along 106° west longitude, from the North Platte River in Wyoming to the Yellowstone River in Montana.

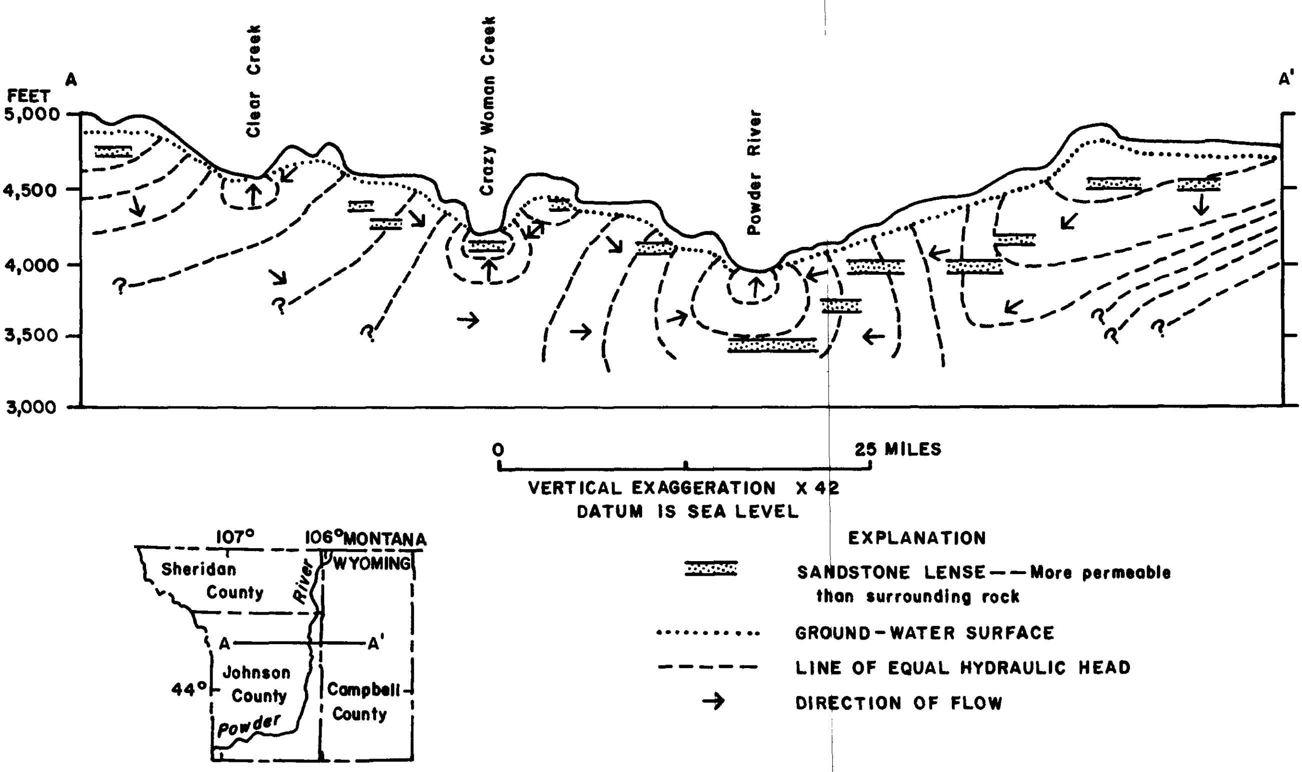


Figure 11.--Regional ground-water flow into major streams. (Modified from Hagmaier, 1971, fig. 15.)

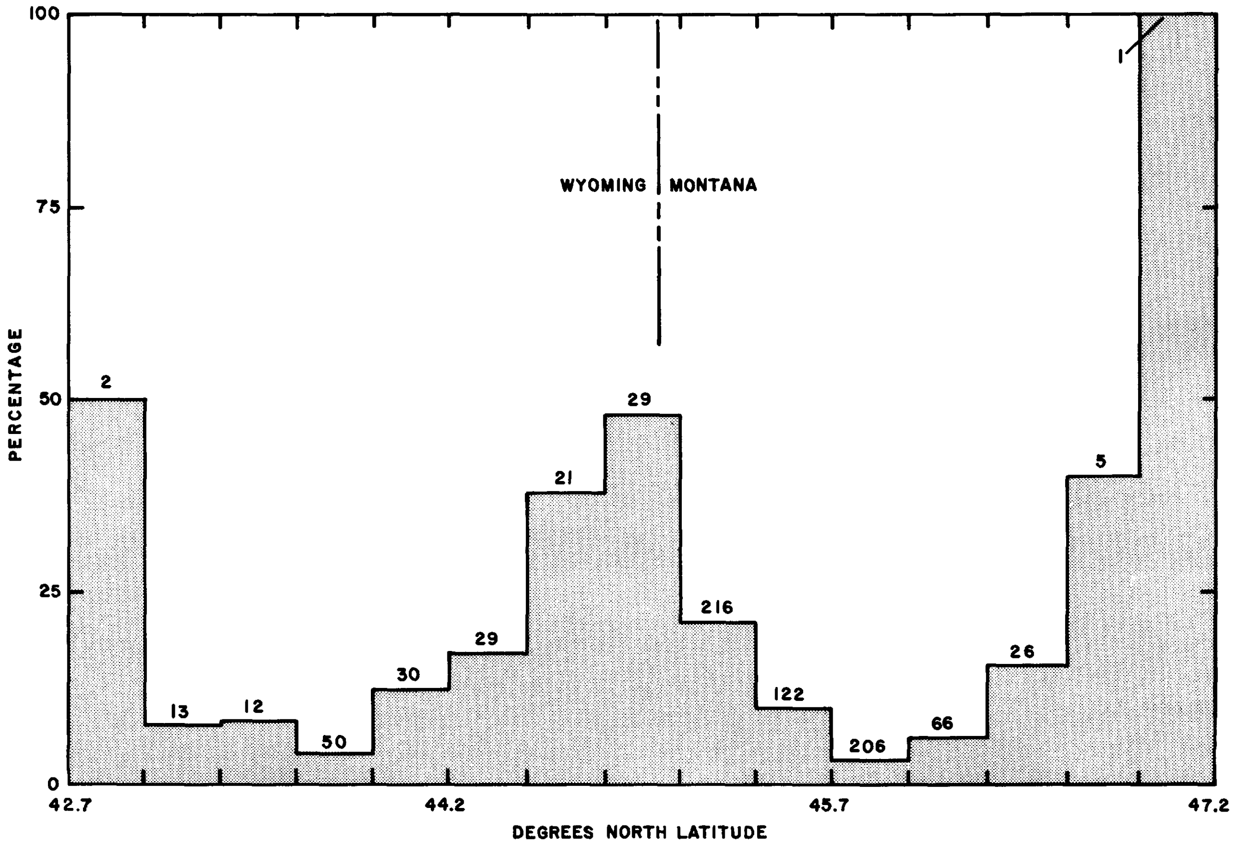


Figure 12.--Percentages of wells less than 250 ft deep and springs that yield sodium bicarbonate type water. Number of samples in 0.3-degree interval shown above bar.

The data (fig. 12) do not indicate that there is an increase in ground-water discharge in the northern part of the area. There is an increase in the percentage of shallow wells that yield bicarbonate type water in the area of the State line, but this is an area of intensive sampling of shallow wells that are completed in coal. Sulfate reduction requires organic carbon and, therefore, occurs more readily in coal than in sandstone aquifers.

Discharge to Streams

The ground-water discharge into streams that originate in the basin in areas underlain by the Wasatch-Fox Hills sequence was determined from the analysis of flow-duration curves and average-daily-discharge hydrographs. Ground-water discharge from the rocks in the Wasatch-Fox Hills sequence into the Powder River was determined from the analysis of the difference in discharge between streamflow-gaging stations located in reaches underlain by the Wasatch-Fox Hills sequence.

BASIN STREAMS

Eight streamflow-gaging stations on seven streams that originate in the area underlain by the Wasatch-Fox Hills sequence have 5 or more years of record and were included in the analysis. The data (table 1) indicate that generally there is measurable ground-water contribution only to Otter Creek and to the Little Powder River during the non-growing season. Base flow where present in other streams, such as Pumpkin Creek, occurs during the period of greatest precipitation, but not after the growing season when evapotranspiration is minimal. This indicates that base flow is from a local system that is dependent on precipitation for each year's discharge.

Powder River

Long-term discharge records indicate a decrease in flow in the Powder River from Sussex, Wyo., to Locate, Mont. (See figs. 13, 14, 15, and table 2.) The change in flow was determined by subtracting the average-daily discharges, at an upstream station, or stations, from the average-daily discharges at a downstream station. Changes in flow for the low flow period listed in table 2 were visually determined from graphs in figures 13, 14, and 15. Water in the reach between Sussex and Locate does not move from the stream into bedrock because the potentiometric surface in the bedrock is higher than the stream. No difference in streamflow is caused by underflow in the alluvium at the gaging stations, as there is exposed bedrock in the stream channel at the three streamflow-gaging stations downstream from Sussex. Water is not diverted for irrigation outside the valley.

The quantity lost during the winter months is too great to be stored as ice; therefore, the only plausible explanation is that water moves to the alluvium along the reach between gaging stations for an extended period to replace that which is evaporated and transpired during the growing season. That the hydraulic gradient is from the stream to the alluvium was confirmed for only one location in the reach, and then only for October 24, 1979. The stage graph for a different stream, Cheyenne River near Dull Center (fig. 16), shows that the hydraulic gradient at this location in the basin remains from the stream to the alluvium, at least until December. The low permeability indicated by the slow response of the water in the alluvium to that in the Cheyenne River is consistent with the silty character of the alluvium along the Powder River.

LOCAL GROUND-WATER-FLOW SYSTEMS

Flow in local ground-water systems appears to dominate over the flow in a regional system. Local systems that have been identified from analysis of streamflow in the basin are: (1) Bedrock, (2) alluvial, and (3) clinker. Areally the discharge of ground water from bedrock aquifers within the Wasatch-Fox Hills sequence is substantial. However, only intermittent and interrupted flow, such as described for Dead Horse Creek (p. 10), was identified in the analysis of streamflow. Much of the ground-water discharge from bedrock aquifers is above stream level because of the nonhomogeniety of the formations. This water is evaporated and transpired during the growing

Table 1.--Summary of ground-water and surface-water relations of streams originating in areas underlain by the Wasatch-Fox Hills sequence, from flow-duration curves and average-daily-discharge hydrographs

Station No.	Station name	Drainage area (square miles)	Ground-water discharge indicated	Base flow in nongrowing season (cubic ft per second)	Period of record (water years)	Figures showing curves and hydrographs
06307740	Otter Creek at Ashland, Mont.	707	yes	4	1972-77	21, 22
06308400	Pumpkin Creek near Miles City, Mont.	697	yes	0	1972-77	21, 23
06313700	Dead Horse Creek near Buffalo, Wyo.	155	yes	0	1971-77	8, 9
06324970	Little Powder River above Dry Creek near Weston, Wyo.	1,230	yes	1	1972-77	--
06325500	Little Powder River near Broadus, Mont.	1,974	yes	5	1957-72	--
06376300	Black Thunder Creek near Hampshire, Wyo.	535	no	0	1972-77	6, 7
06386500	Cheyenne River near Riverview, Wyo.	5,270	no	0	1948-74	--
06426500	Belle Fourche River below Moorcroft, Wyo.	1,670	yes	0	1944-70	--

season and does not contribute to base flow. Some of the discharge is stored as ice during the winter months, and the quantity can not be separated from snowmelt runoff. Local ground-water systems in the alluvium and clinker have a more pronounced effect on streamflow than the regional flow system; examples of these systems are described in the following sections.

Alluvial Systems

Alluvial systems that deplete flow in the streams probably are the predominant type of alluvial system in the basin, but some streams may gain water from alluvial aquifers. Examples of these two conditions are given in the following pages. In some streams the difference between losing water to or gaining water from the alluvium is marginal. A reversal in the relation between water in the Cheyenne River near Dull Center, Wyo. (06365900) and the

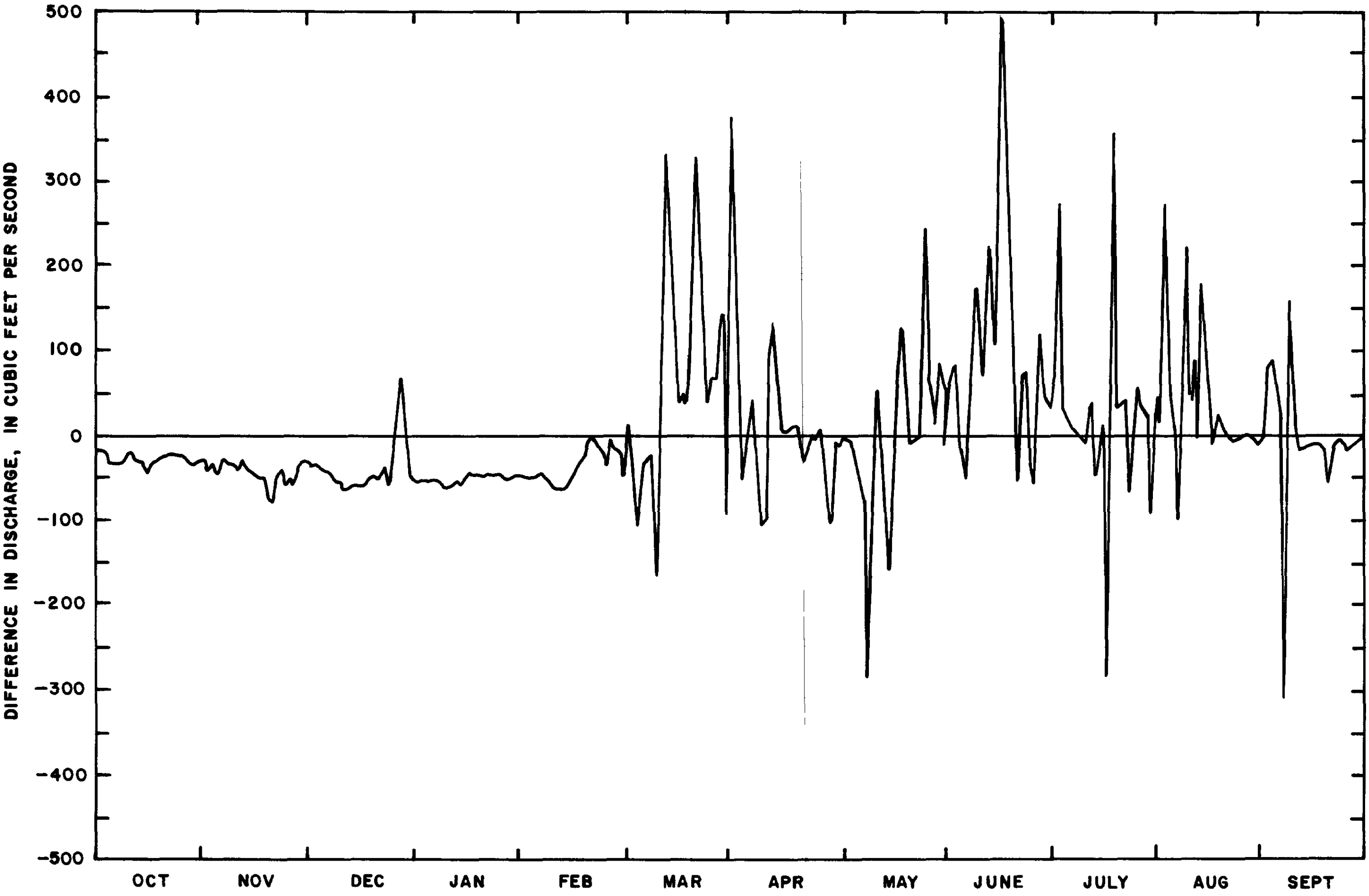


Figure 13.--Differences between the average-daily discharge at Powder River at Arvada, Wyo. (06317000), and the sum of average-daily discharges at Powder River at Sussex, Wyo. (06313500) and Crazy Woman Creek near Arvada, Wyo. (06316500), 1951-57 water years.

alluvium that resulted from scouring of the channel by record high flow in 1978 is shown in figure 16. The first part of the graph shows the stage is higher in the stream than in the alluvium until at least December. Floods later in the water year scoured the channel and recharged the alluvium, and the relation was reversed. The scouring is shown by the difference in stage (about 0.5 ft) between the last of October 1977 and the middle of September 1978. The discharge was about 0.1 ft^3/s during the two periods.

Losing Streams

The Powder River loses water to the alluvium in the reach from Sussex, Wyo. to Locate, Mont. (table 2, p. 25); the loss is attributed to evapotranspiration from the alluvium. This type of system probably is prevalent in the basin.

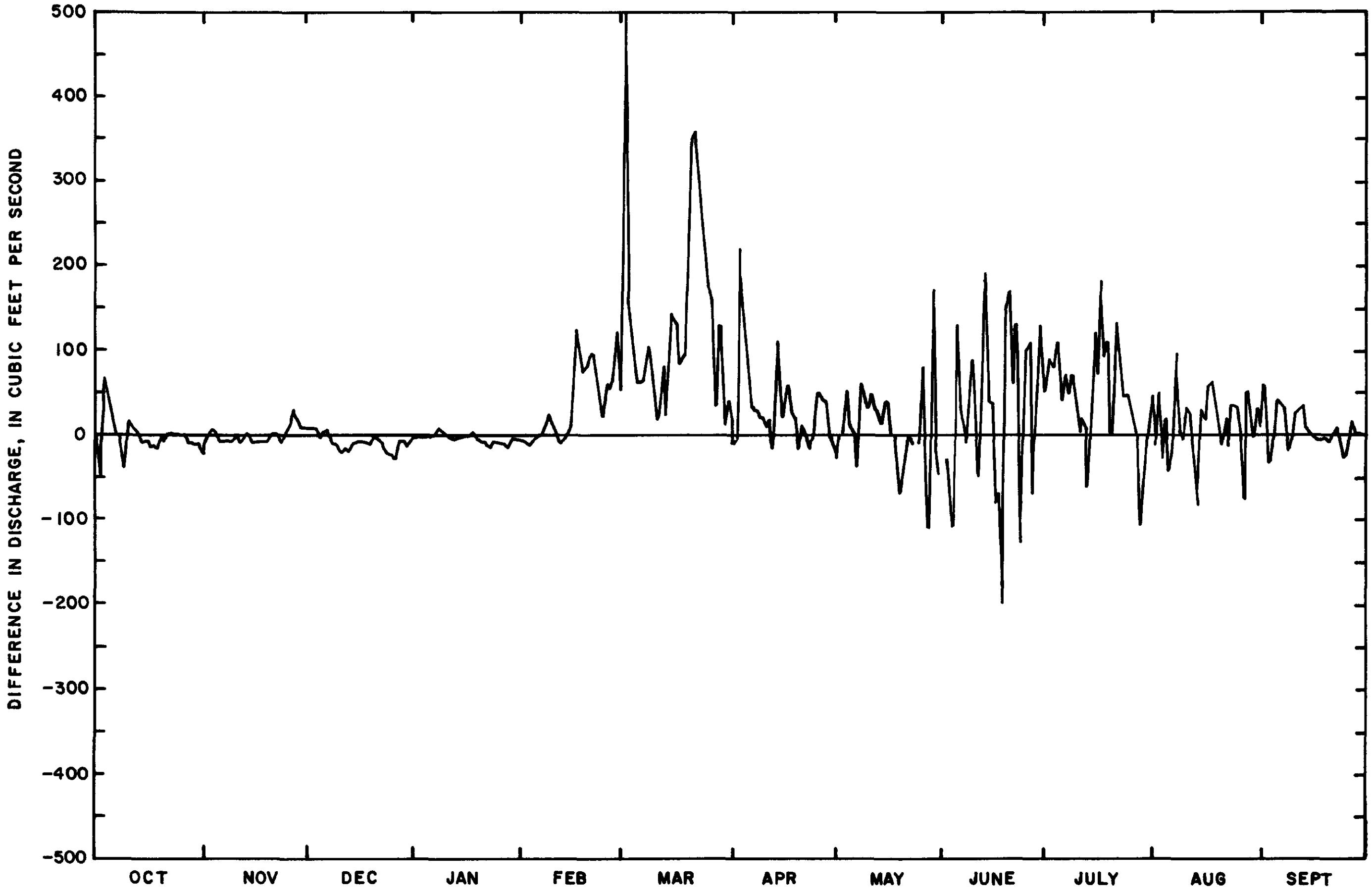


Figure 14.--Differences between the average-daily discharge at Powder River at Moorhead, Mont. (06324500), and the sum of the average daily discharges at Powder River at Arvada, Wyo. (06317000) and Clear Creek near Arvada, Wyo. (06324000), 1940-72 water years.

Remote-sensing methods were used to determine densities and distributions of vegetation in the valley of the Powder River between Sussex, Wyo. and Locate, Mont. These data were used as an indicator of transpiration by vegetation on the Powder River flood plain. No attempt was made to quantify the transpiration; however, the consumptive use of water from the system is directly related to vegetation density. The data were taken from two sequential Landsat scenes recorded September 17, 1974. The area in the two scenes extends from Sussex, Wyo. in the south to the mouth of the Powder River in Montana in the north.

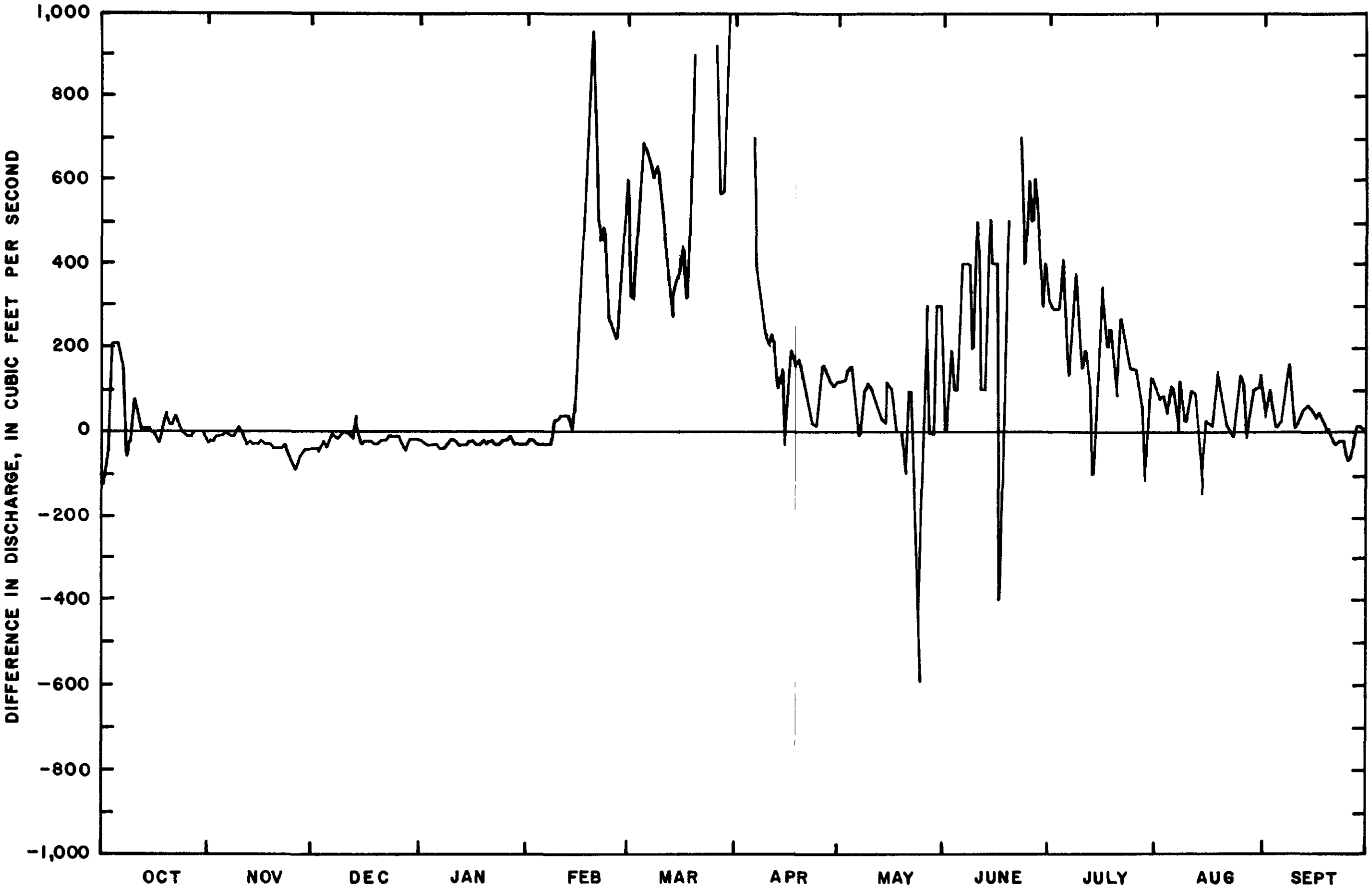


Figure 15.--Differences between the average-daily discharges at Powder River at Locate, Mont. (06326500) and Powder River at Moorhead, Mont. (06324500), 1940-72 water years.

Two spectral signatures for vegetation that were established by G.K. Moore (U.S. Geological Survey, oral commun., 1979) were used to determine the number of acres of land per valley mile of the Powder River that have dense vegetation. The reach studied was from Sussex, Wyo. to Locate, Mont., a reach of 199 valley mi. The reflected energy is measured in arbitrary units from 0 for black and 255 for white. The following table lists the spectral signatures used for this study:

Band	Wavelength (micrometer)	Reflected energy	
		Signature I	Signature II
4	0.5 to 0.6	40 to 56	57 to 70
5	0.6 to 0.7	24 to 58	46 to 66
6	0.7 to 0.8	54 to 128	72 to 94
7	0.8 to 1.1	60 to 152	72 to 100

Table 2.--Summary of change in low flow in the Powder River from average-daily discharge during periods of minimal runoff

Downstream station		Upstream station(s)		Area of segment (square miles)	Change in discharge (cubic feet per second)	Period of record (water years)
Station No.	Station name	Station No.	Station name			
06317000	Powder River at Arvada, Wyo.	06316500	Crazy Woman Creek near Arvada, Wyo.	2,004	-68	1951-57
		06313500	Powder River at Sussex, Wyo.			
06324500	Powder River at Moorhead, Mont.	06324000	Clear Creek near Arvada, Wyo.	928	-10	1940-72
		06317000	Powder River at Arvada, Wyo.			
06326500	Powder River near Locate, Mont.	06324500	Powder River at Moorhead, Mont.	5,016	[1]-30	1940-72

[1] Inflow from perennial tributary streams between Moorhead and Locate, Mont. was not subtracted from the average-daily discharge.

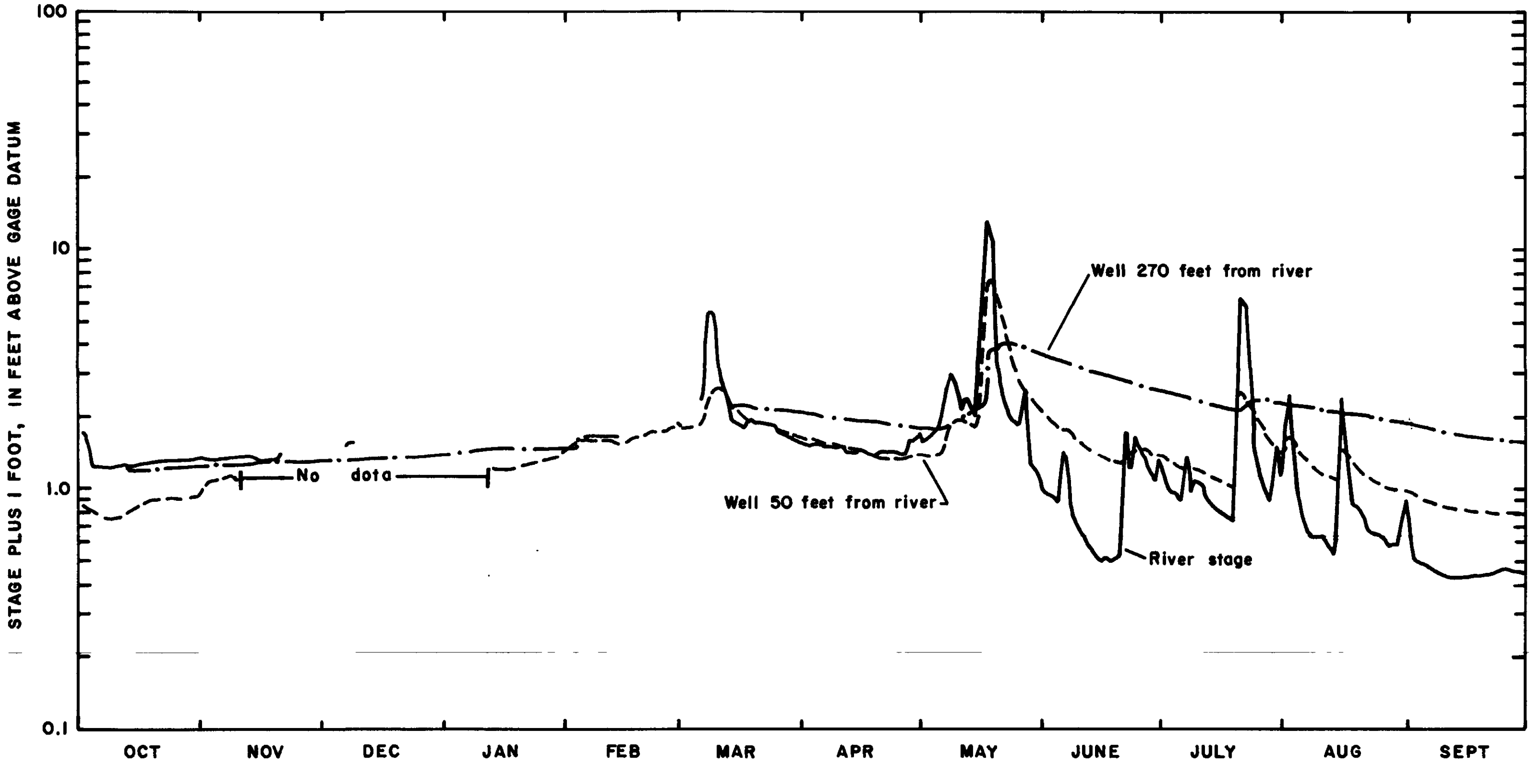


Figure 16.--Relations of water levels in the alluvium to the stage of the Cheyenne River near Dull Center, Wyo. (06365900), 1978 water year.

A field check was made to determine the vegetation type and to verify the changes in density. Vegetation types include alfalfa, native grasses, cottonwoods, and saltcedar. Some reaches of the valley had irrigated grain crops, which would be dormant at the time of year that the Landsat scenes were recorded. The density, in acres, is a function of the amount of irrigated cropland, the valley width, and the amount of irrigation. A graph showing the vegetation density measured at one-mile increments along the Powder River valley (fig. 17) indicates that the downstream reach has much more vegetation, hence greater transpiration.

Table 2 (p. 25) indicates that the loss of flow from the Powder River from Arvada, Wyo. to Moorhead, Mont. and from Moorhead, Mont. to Locate, Mont. is nearly the same when converted to common base. The average loss of flow per valley mile in the Powder River during late fall and early winter was 0.31 ft^3/s between Arvada, Wyo., and Moorehead, Mont., and 0.30 ft^3/s between Moorhead and Locate, Mont. There is perennial tributary inflow in the reach between Moorhead and Locate that could not be subtracted from the average-daily discharge because the tributary streams were not gaged during the period; whereas, all the perennial inflow (Clear Creek) in the reach from Arvada to Moorhead was subtracted. Water from Clear Creek is diverted for irrigation above the confluence of the Powder River. Therefore, some return flow to the Powder River is not accounted for and the source of the water for the irrigation that centers around valley mi 82 on figure 17 is not the Powder River.

Where there is a large area of sandstone in contact with alluvium, alluvium could collect water from the bedrock and convey it to the stream. However, the relation that probably prevails in much of the area is shown by water levels measured in wells in Sheridan County, Wyo., during 1960-61. This was the driest period in Sheridan from 1900 to 1980.

Water-level changes in four wells are shown in figure 18. Wells B1 and B2 are completed in bedrock and are in topographic locations such that the bottom of the wells are above the level of the nearest perennial stream. Wells A1 and A2 are completed in the alluvium near the stream channel and in reaches where the flow is ephemeral. Well A1 is in an area underlain by marine shale. Well A2 is in an area underlain by the Tongue River Member of the Fort Union Formation.

Water-level declines in the wells in bedrock show a relatively uniform decline. The flattening of the slope of the hydrograph of well B1 and rise in the hydrograph of well A2 in the spring of 1961 was probably recharge from snowmelt. Precipitation would be greater at these two wells because they are at higher elevations and snow would accumulate because the areas are more forested. The rise of water levels in well B2 in the fall of 1961 occurred after a period of rainfall that filled a stock pond on an ephemeral stream at the well site (Lowry and Cummings, 1966, p. 14).

In contrast to the trend of the water levels in wells completed in bedrock, the water levels in wells completed in the alluvium show that little or no recharge occurred during the period and that discharge is by evapotranspiration. The reasoning used to attribute the discharge to evapotranspiration is: (1) If discharge was by underflow, the water-level decline should continue in winter, (2) a hypothesis that underflow in the alluvium is the

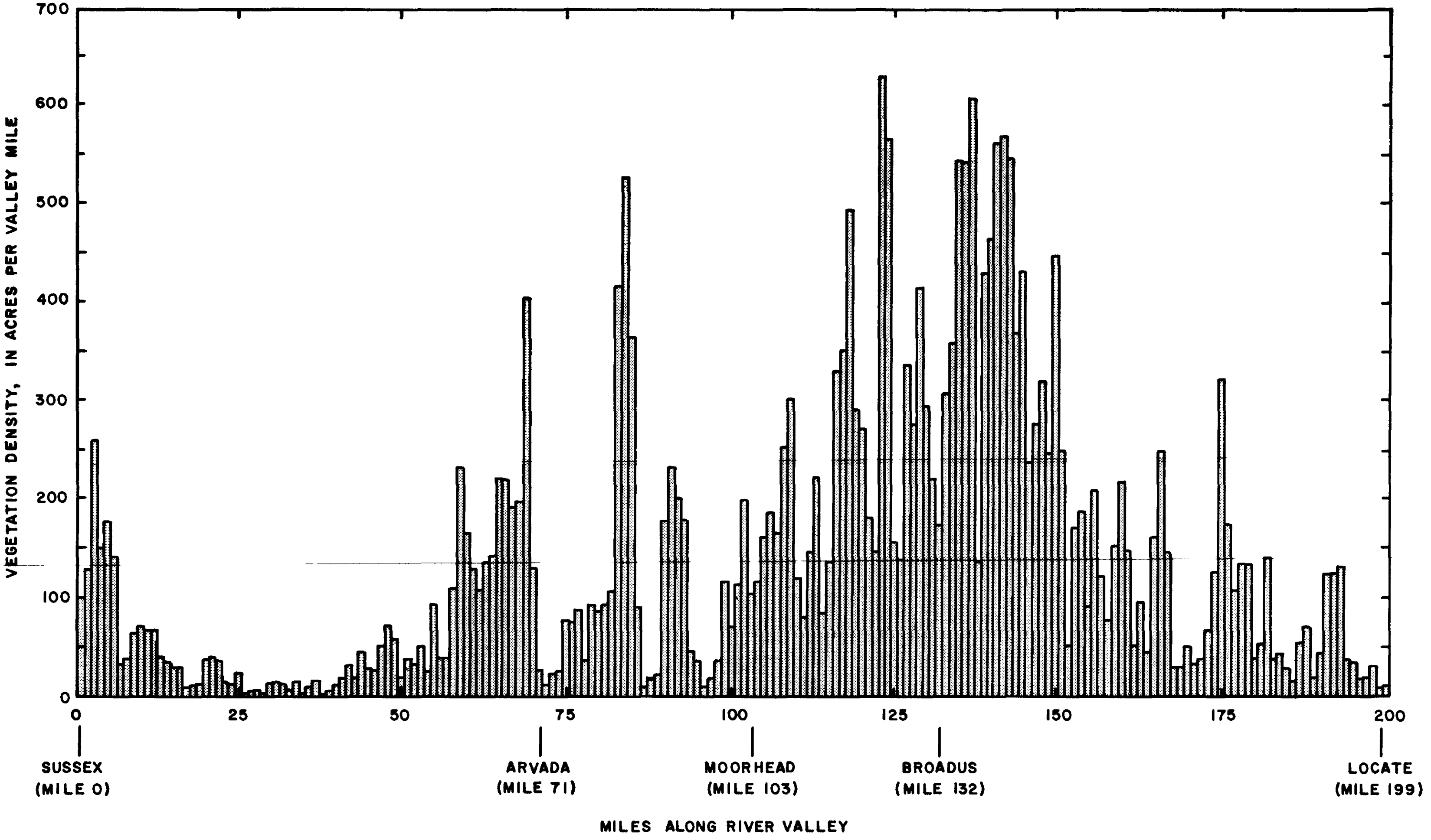


Figure 17.--Vegetation density along the Powder River valley. Locations of gaging stations shown on horizontal axis.

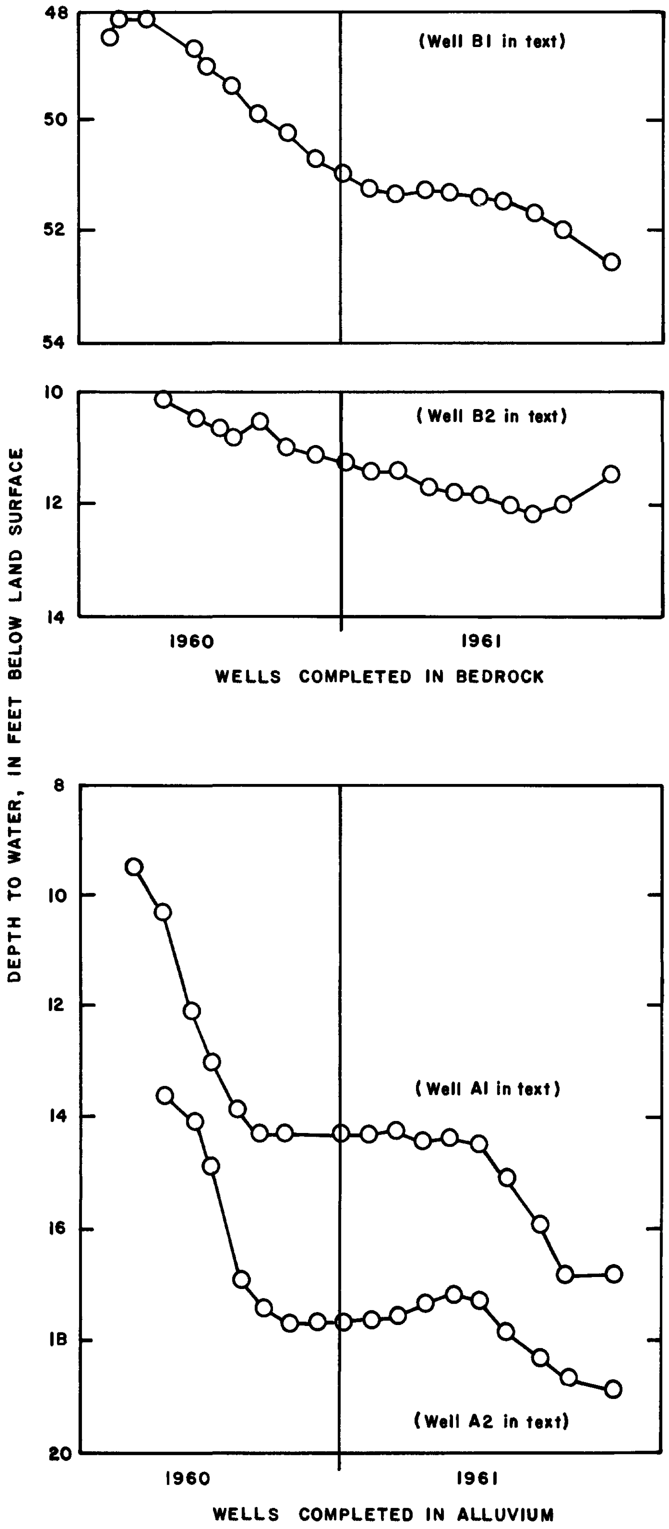


Figure 18.--Water levels in two wells completed in bedrock and two wells completed in the alluvium, Sheridan County, Wyo.

same as recharge from bedrock in both wells is rejected because the bedrock in the area of well A1 is the relatively impermeable marine shale, and the bedrock in the area of well A2 is the Tongue River Member of the Fort Union Formation, and (3) the seasonal change in water-level decline corresponds to the seasonal periods of high and low evapotranspiration.

Gaining Streams

The Little Missouri River is used as an example of a gaining stream within the structural basin, although much of the course of the river is not on rocks of the Wasatch-Fox Hills sequence. Bedrock in most of the course is relatively impermeable shale that precludes measurable base flow from a source other than the alluvium for much of the reach shown on plate 1. The relatively impervious nature of the shale is indicated by the large runoff, relative to that from streams underlain by the Wasatch-Fox Hills sequence.

The flow-duration curve (fig. 19) shows there is flow at Camp Crook more than 95 percent of the time. On October 23, 1979, there was only interrupted flow in the river to approximately the Wyoming-Montana State line, but north of the State line no points of zero flow were observed. Flow at Capitol, Mont., was 1.23 ft^3/s, and flow at the streamflow-gaging station at Camp Crook, S. Dak. (06334500) was 4.1 ft^3/s.

The Hell Creek Formation crops out at the streamflow-gaging station; however, it is a recharge area, rather than a discharge area, for the formation (Thorstenson and others 1979, p. 1481). Therefore, all the baseflow at Camp Crook is attributed to ground-water discharge from the alluvium.

For the Little Missouri River to gain sufficient water from alluvium to maintain perennial flow at the streamflow-gaging station, the alluvium must be coarser or more extensive, or both, than normally found in valleys elsewhere in the basin. The area of alluvium is more extensive relative to nearby drainages (fig. 20). Whitcomb and Morris (1964, p. 42), in describing alluvium of the Little Missouri and Belle Fourche River drainages in Crook County, Wyo., state that the course of the Little Missouri River almost entirely is on soft shale and, consequently, little coarse material was deposited. However, the Belle Fourche River crosses resistant rocks and probably contains considerable quantities of sand and gravel. Before the Belle Fourche River was captured by a stream head-cutting westward, it flowed northward across Stoneville Flats into the present drainage of the Little Missouri River. During that period it would have provided coarse-grained material to the alluvium of the present Little Missouri River in Montana. Another source of coarse-grained material are the formations mapped as Tertiary-undivided on plate 1.

Clinker

The hydrologic properties of clinker are different enough from other rocks in the Wasatch-Fox Hills sequence that clinker sometimes is considered as a separate aquifer (U.S. Department of the Interior, 1977a, p. 143). Runoff from two adjoining basins was compared with areas less than 3 mi^2. One

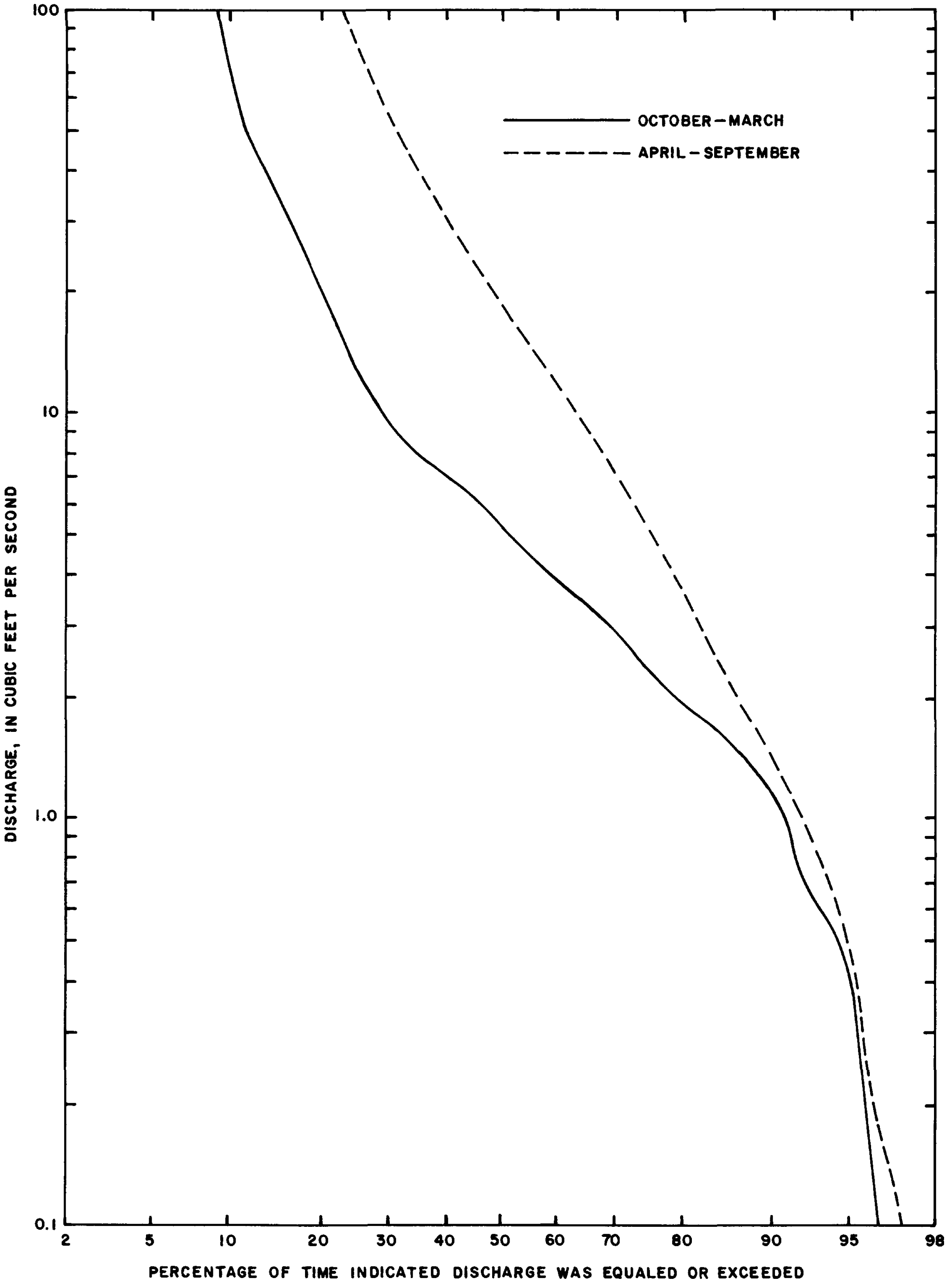


Figure 19.--Flow-duration curves for Little Missouri River at Camp Crook, S. Dak. (06334500), 1957-77 water years.

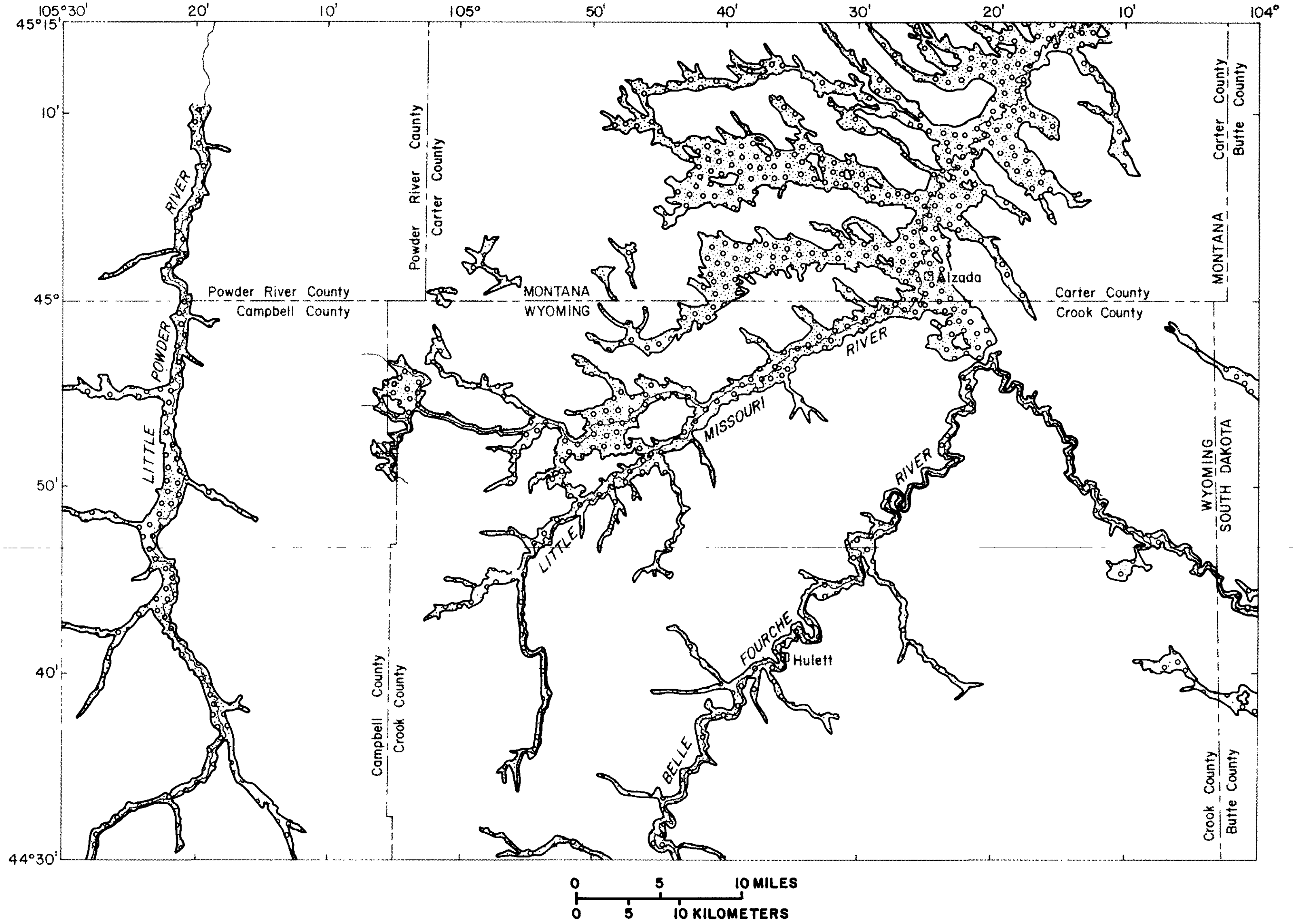


Figure 20.--Extent of the alluvium in the upper part of the Little Missouri River basin and nearby drainages.

was underlain by large areas of clinker, and most of the other was underlain by unaltered rocks of the Fort Union Formation. Runoff from the basin without large areas of clinker was five-to-eight times greater than the one underlain by large areas of clinker (U.S. Department of the Interior, 1977b, p. 81).

The affect that large areas of clinker has on the hydrology of a basin is shown by a comparison of Otter and Pumpkin Creek drainage basins. The Otter Creek drainage basin has a large area of clinker, which results in larger infiltration of precipitation and larger perennial base flow, but less total runoff than the adjoining basin. Although the alluvium in the two drainage basins is similar (S.E. Slagle, U.S. Geological Survey, oral commun., 1982) and the drainage basins are nearly identical in area, the streams have significantly different runoff characteristics, and their juxtaposition precludes that the difference in runoff is due to differences in ground-water inflow from a regional ground-water system or in precipitation.

The drainage area, runoff characteristics, area of clinker, and differences in the area of cropland in the two drainage basins are shown in table 3. The area of clinker was planimetered from maps in reports by Bryson and Bass (1973), Bryson (1952), Bass (1932), Warren (1959), Parker and Andrews (1939), and Pierce (1936). The area of cropland was computed as described previously for the Powder River valley (p. 24). The flow-duration curves for the stations on the two streams are shown in figure 21, and the average-daily-discharge hydrographs are shown in figures 22 and 23.

Table 3.--Runoff and factors affecting runoff, Otter Creek at Ashland, Montana (06307740), and Pumpkin Creek near Miles City, Montana (06308400)

Station No.	Station name	Drainage area (square miles)	Area of exposed clinker (square miles)	Area of vegetation (square miles)	Average annual runoff[1] (inches)	Base flow in nongrowing season (cubic ft per second)
06307740	Otter Creek at Ashland, Mont.	707	90	83	0.156	4
06308400	Pumpkin Creek near Miles City, Mont.	696	47	38	.275	0

[1] Period of record is water years 1972-77.

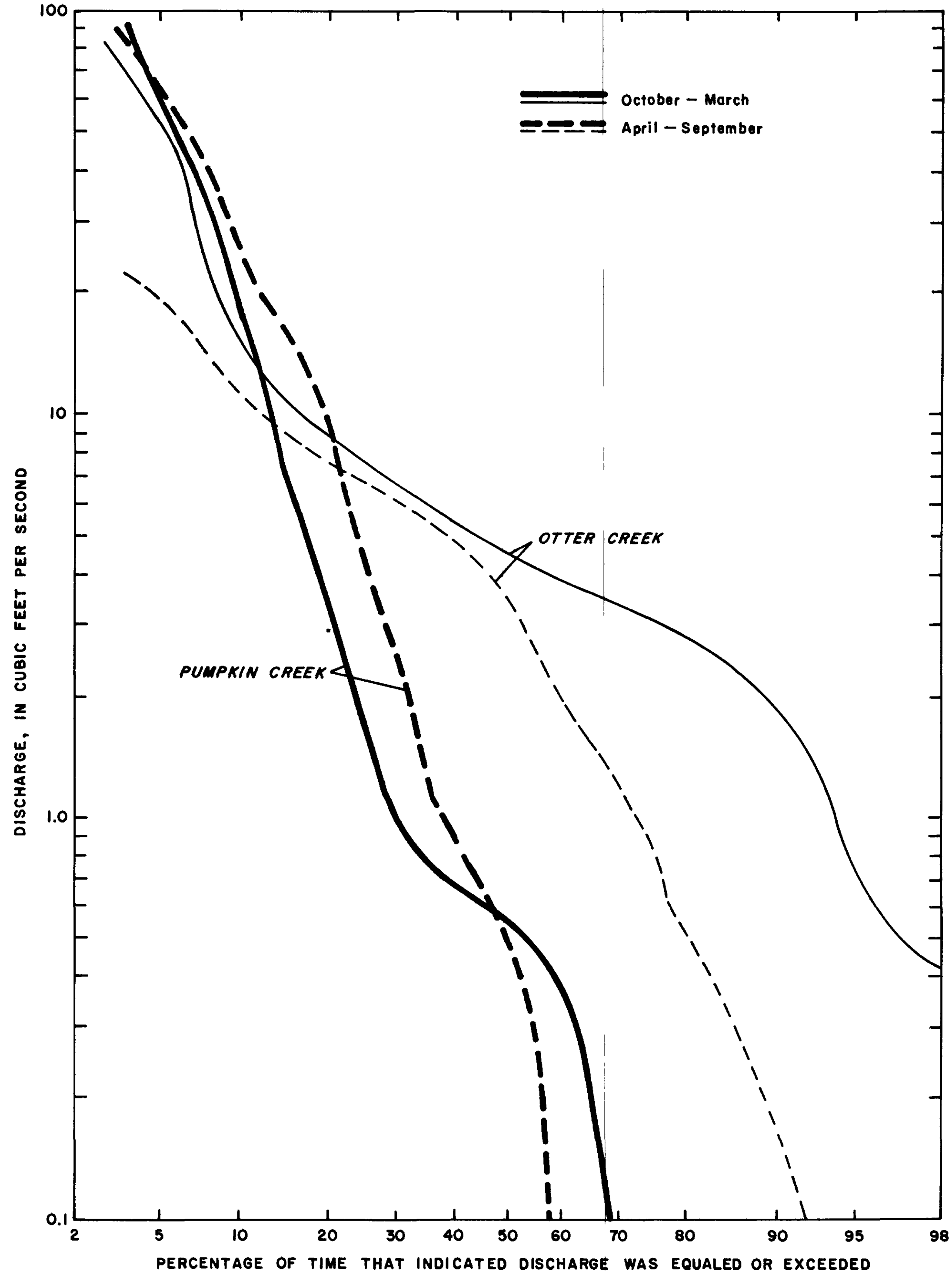


Figure 21.--Flow-duration curves for Otter Creek at Ashland, Mont. (06307740) and Pumpkin Creek near Miles City, Mont. (06308400), 1972-77 water years.

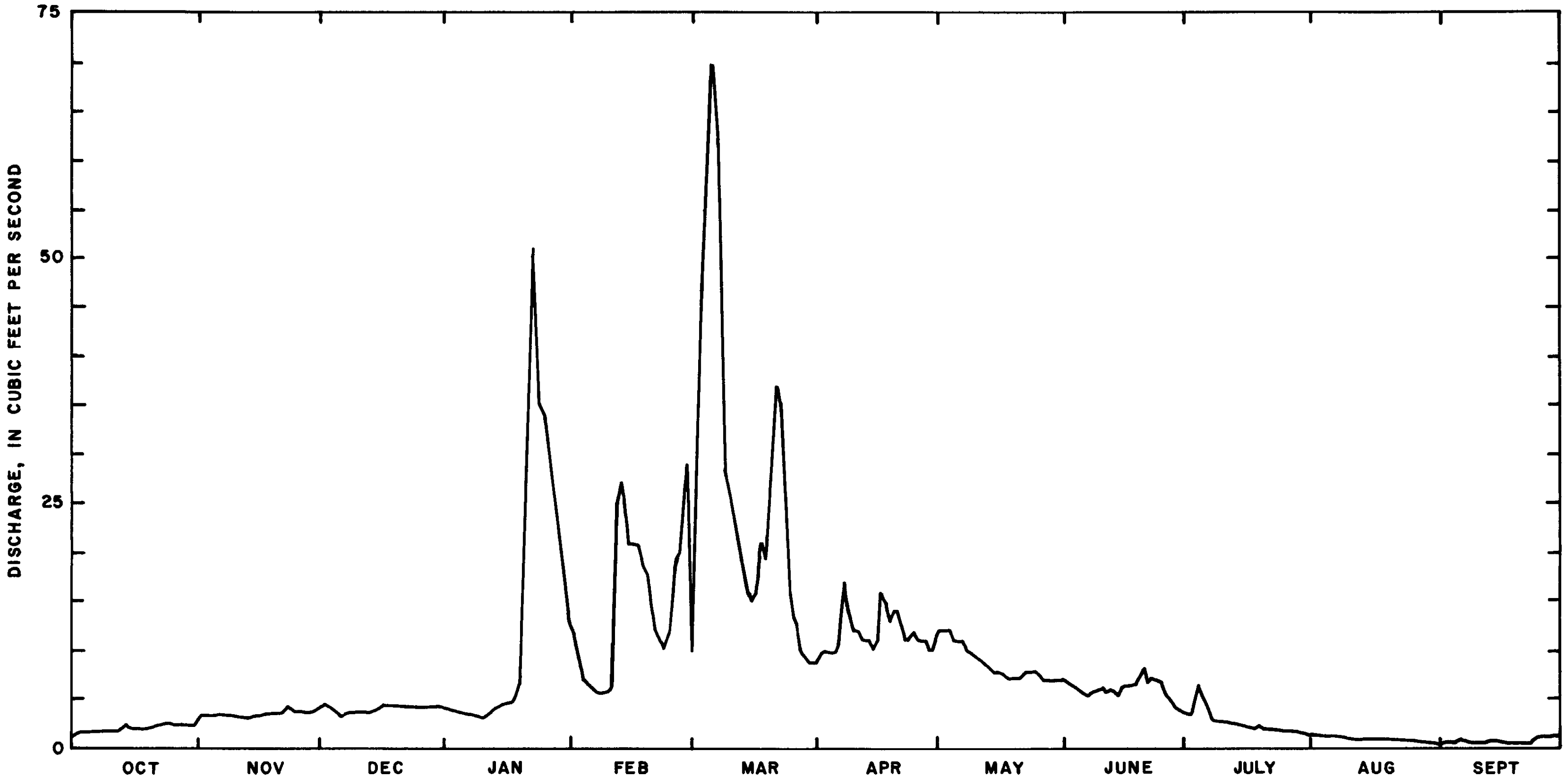


Figure 22.--Average-daily-discharge hydrograph for Otter Creek at Ashland, Mont. (06307740), 1972-77 water years.

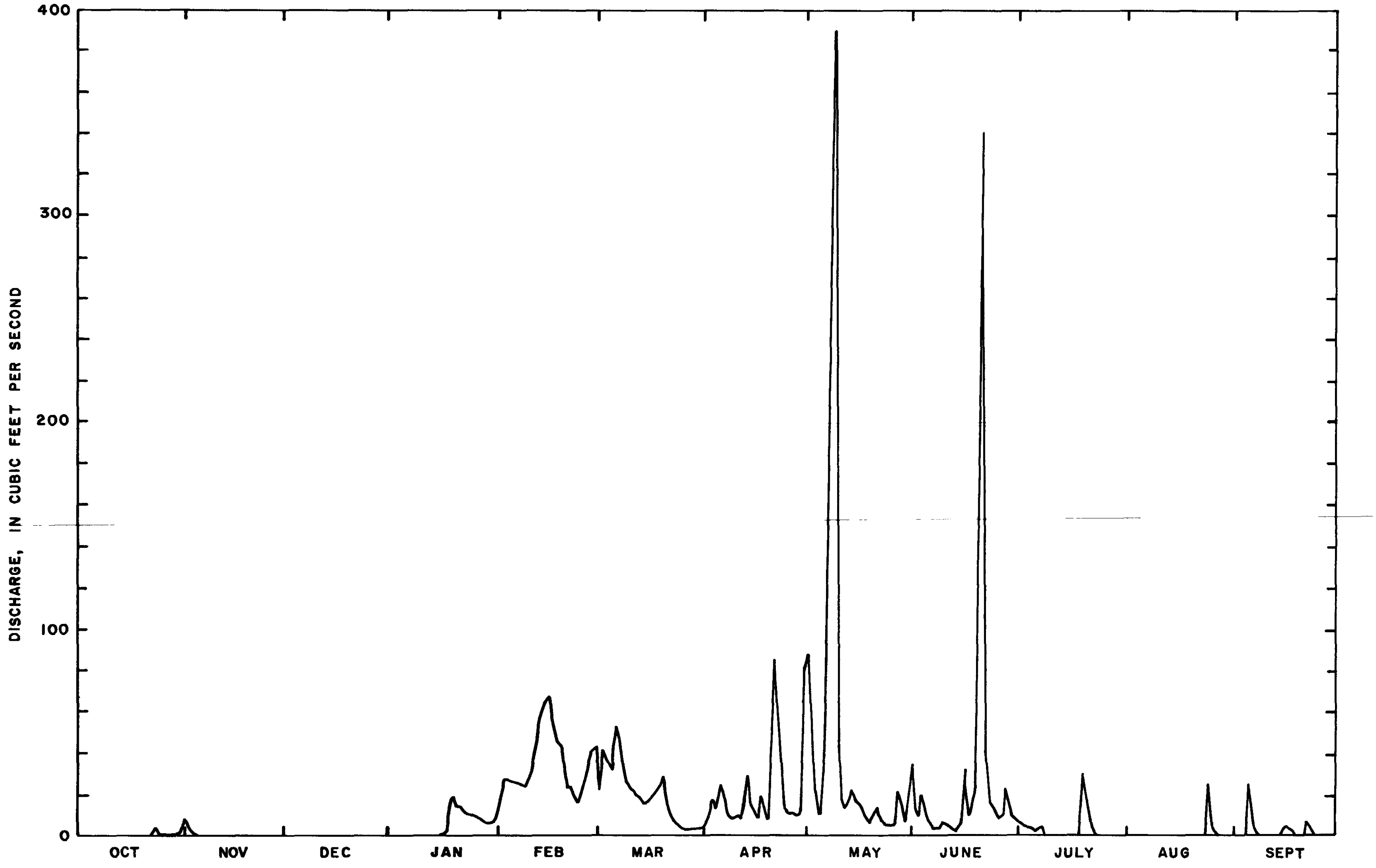


Figure 23.--Average-daily-discharge hydrograph for Pumpkin Creek near Miles City, Mont. (06308400), 1972-77 water years.

CONCLUSIONS

Areas of natural ground-water discharge from a regional ground-water system that consists of the Wasatch-Fox Hills sequence in the Powder River structural basin that would be inferred from potentiometric data could not be substantiated. Therefore, it is concluded that the regional flow system may have a smaller flow than previously thought, and that measurable effects of surface mining and water development will affect mostly local flow systems. However, more data are necessary to describe local systems and their relation to the regional system.

Potentiometric data indicate that most streams in the Powder River structural basin should receive base flow from a regional ground-water system; however, such base flow is not evident in streamflow records. Streamflow data collected at 14 stations on 8 streams show that base flow occurs at 6 of the stations, but that base flow during the nongrowing season occurred only in Otter Creek and the Little Powder River. Of the three largest streams included in the analysis -- the Powder, Belle Fourche, and Cheyenne Rivers -- only the Belle Fourche had base flow, which was present only during the period of largest precipitation, but not during the period of minimum evapotranspiration. The locations of the streams that do not have base flow and the period during which base flow occurs in most streams indicate that base flow, where present, is from local systems rather than a regional system.

The absence of base flow in streams from ground water moving through the regional system is the result of the nonhomogeneity of the formations which produces a small regional effective transmissivity, and the combined effects of evaportranspiration from, and storage in, the stream alluvium. The nonhomogeneity of the formations precludes the use of simple water-level maps as a substitute for sets of stratigraphically based potentiometric maps.

Northward regional flow that is stratigraphically controlled, which would not necessarily contribute to base flow of streams, can be inferred from potentiometric data, but discharge areas in the northern part of the basin could not be identified on the basis of chemical quality of water from springs and shallow wells. The chemical quality of ground water from shallow depth in the northern part of the basin is affected more by local conditions than by regional flow. Taken together, these lines of evidence suggest that the regional flow, and therefore effective regional transmissivity is smaller than previous investigators have suggested.

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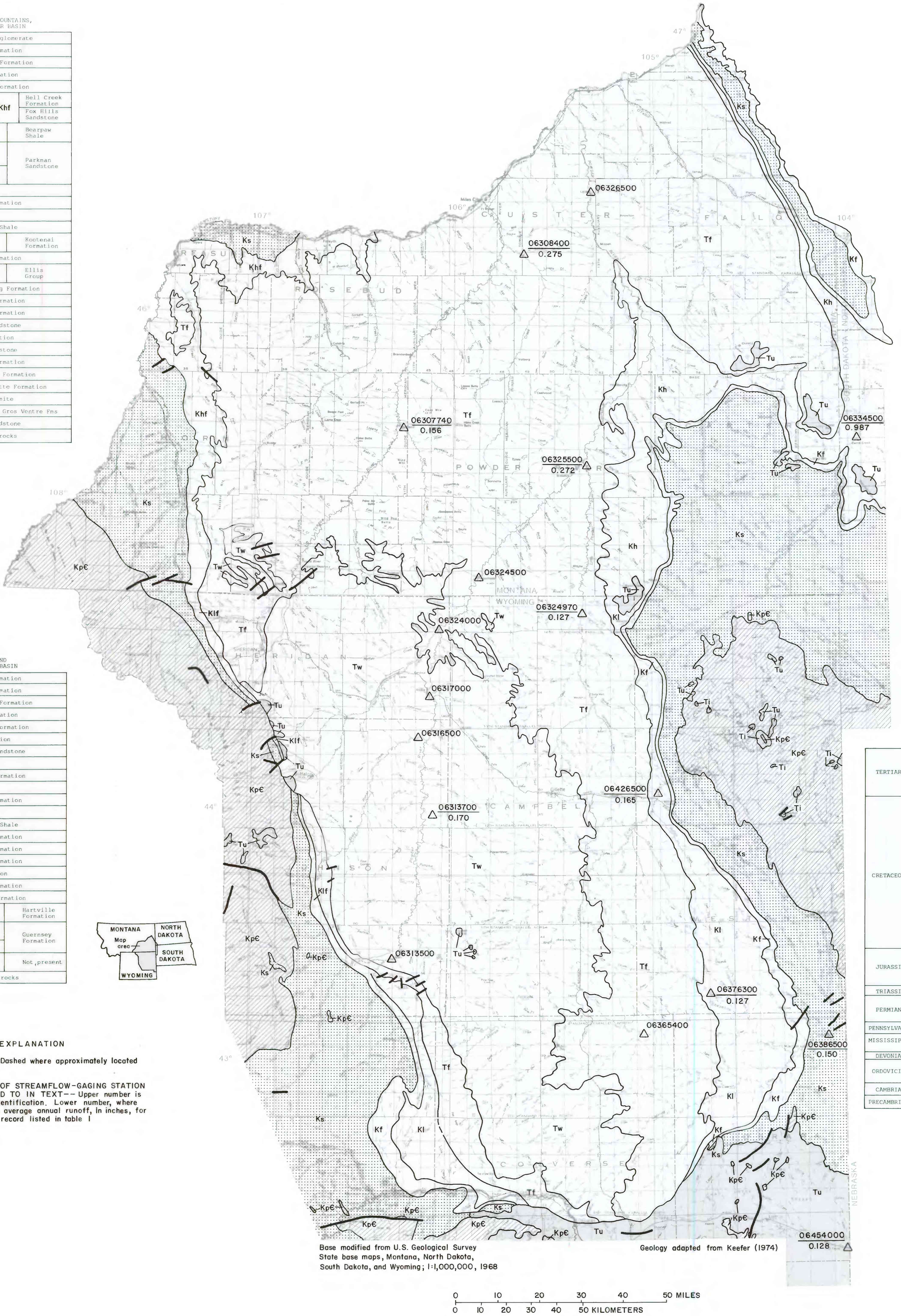
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 85-4229
PLATE 1

BIGHORN MOUNTAINS, PRYOR MOUNTAINS,
AND WESTERN POWDER RIVER BASIN

TERTIARY	Tu	Moncrief Conglomerate		
		Arikaree Formation		
		White River Formation		
	Tw	Wasatch Formation		
	Tf	Fort Union Formation		
CRETACEOUS	Klf	Lance Formation	Khf	Hell Creek Formation
		Fox Hills Sandstone		Fox Hills Sandstone
	Ks	Bearpaw Shale		Bearpaw Shale
		Judith River Formation		Parkman Sandstone
		Claggett Shale		
		Cody Shale		
		Frontier Formation		
		Mowry Shale		
		Thermopolis Shale		
	KpꞒ	Cloverly Formation		Kootenai Formation
JURASSIC		Morrison Formation		
		Sundance Formation		Ellis Group
		Gypsum Spring Formation		
TRIASSIC		Chugwater Formation		
PERMIAN		Goose Egg Formation		
PENNSYLVANIAN		Tensleep Sandstone		
		Amsden Formation		
MISSISSIPPIAN		Madison Limestone		
DEVONIAN		Jefferson Formation		
		Souris River Formation		
		Beartooth Butte Formation		
ORDOVICIAN		Bighorn Dolomite		
CAMBRIAN		Gallatin and Gros Ventre Fms		
		Flathead Sandstone		
PRECAMBRIAN		Crystalline rocks		



Base modified from U.S. Geological Survey
State base maps, Montana, North Dakota,
South Dakota, and Wyoming; 1:1,000,000, 1968

Geology adapted from Keefer (1974)

0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS

LARAMIE MOUNTAINS AND
SOUTHERN POWDER RIVER BASIN

TERTIARY		Tu	Ogallala Formation	
			Arikaree Formation	
			White River Formation	
		Tw	Wasatch Formation	
		Tf	Fort Union Formation	
CRETACEOUS	Klf	Kl	Lance Formation	
		Kf	Fox Hills Sandstone	
			Lewis Shale	
		Ks	Mesaverde Formation	
			Cody Shale	
			Frontier Formation	
			Mowry Shale	
			Thermopolis Shale	
		KpꞒ	Cloverly Formation	
JURASSIC			Morrison Formation	
			Sundance Formation	
TRIASSIC			Jelm Formation	
			Red Peak Formation	
PERMIAN			Goose Egg Formation	
PENNSYLVANIAN			Casper Formation	Hartville Formation
MISSISSIPPIAN			Madison Limestone	Guernsey Formation
DEVONIAN			Not present	
CAMBRIAN			Flathead Sandstone	Not present
PRECAMBRIAN			Crystalline rocks	

EXPLANATION

——— – – CONTACT--Dashed where approximately located

━━━ FAULT

06313700 △ / 0 170 LOCATION OF STREAMFLOW-GAGING STATION REFERRED TO IN TEXT--Upper number is station identification. Lower number, where shown, is average annual runoff, in inches, for period of record listed in table 1

BLACK HILLS AND
EASTERN POWDER RIVER BASIN

TERTIARY	Tu	White River Formation		
	Ti	Intrusive rocks		
	Tw	Wasatch Formation		
	Tf	Fort Union Formation		
CRETACEOUS	Kl	Lance Formation	Kh	Hell Creek Formation
	Kf	Fox Hills Sandstone		
	Ks	Pierre Shale		
		Niobrara Formation		
		Carlile Shale		
		Greenhorn Formation		
		Belle Fourche Shale		
		Mowry Shale		
		Newcastle Sandstone		
		Skull Creek Shale		
	KpꞒ	Fall River Formation		
		Lakota Formation		
JURASSIC		Morrison Formation		
		Sundance Formation		
		Gypsum Spring Formation		
TRIASSIC		Spearfish Formation		
PERMIAN		Minnekahta Limestone		
		Opeche Formation		
PENNSYLVANIAN		Minnelusa Formation		
MISSISSIPPIAN		Pahasapa Limestone		
DEVONIAN		Englewood Limestone		
ORDOVICIAN		Whitewood Dolomite		
		Winnepeg Formation		
CAMBRIAN		Deadwood Formation		
PRECAMBRIAN		Crystalline rocks		

GENERALIZED GEOLOGIC MAP SHOWING LOCATION OF STREAMFLOW-GAGING STATIONS, POWDER RIVER STRUCTURAL BASIN, WYOMING AND MONTANA