Sedimentation and Chemical Quality of Surface Water in The Heart River Drainage Basin, North Dakota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1823

Prepared as part of a program of the Department of the Interior for development of the Missouri River basin

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SEDIMENTATION AND CHEMICAL QUALITY OF SURFACE WATER IN THE HEART RIVER DRAINAGE BASIN, NORTH DAKOTA

By M. L Maderak

ABSTRACT

The Heart River drainage basin of southwestern North Dakota comprises an area of 3,365 square miles and lies within the Missouri Plateau of the Great Plains province Streamflow of the Heart River and its tributaries during 1949–58 was directly proportional to the drainage area After the construction of Heart Butte Dam in 1949 and Dickinson Dam in 1950, the mean annual streamflow near Mandan was decreased an estimated 10 percent by irrigation, evaporation from the two reservoirs, and municipal use

Processes that contribute sediment to the Heart River are mass wasting, advancement of valley heads, and sheet, lateral stream, and gully erosion In general, glacial deposits, terraces, and bars of Quaternary age are sources of sand and larger sediment, and the rocks of Tertiary age are sources of clay, silt, and sand The average annual suspended-sediment discharges near Mandan were estimated to be 1,300,000 tons for 1945–49 and 710,000 tons for 1950–58

The percentage composition of ions in water of the Heart River, based on average concentrations in equivalents per million for selected ranges of streamflow, changes with flow and from station to station During extremely low flows the water contains a large percentage of sodium and about equal percentages of bicarbonate and sulfate, and during extremely high flows the water contains a large percentage of calcium plus magnesium and bicarbonate The concentrations, in parts per million, of most of the ions vary inversely with flow

The water in the reservoirs—Edward Arthur Patterson Lake and Lake Tschida—during normal or above-normal runoff is of suitable quality for public use Generally, because of medium or high salinity hazards, the successful long-term use of Heart River water for irrigation will depend on a moderate amount of leaching, adequate drainage, and the growing of crops that have moderate or good salt tolerance

INTRODUCTION

The investigation of sedimentation and chemical quality of the surface water in the Heart River basin was needed for planning the development, management, and use of the water resources of the area. The sedimentation was studied to determine the quantity and characteristics of sediment being transported by the Heart River, and the chemical quality of water was studied to determine the kind and amount of dissolved material in the streams and the suitability of the water for different uses.

This report presents the results of this investigation that began in 1945. Basic data obtained from October 1945 to September 1952 have been published in the annual reports of the U.S Geological Survey entitled "Quality of Surface Waters of the United States." Additional data were obtained during a reconnaissance of the basin in October 1960. Supplementing these data were suspended-sediment records for 1949–54 published by the U.S. Army Corps of Engineers (1957) and unpublished chemical-quality records for 1955 and 1957 furnished by the U S Bureau of Reclamation

The investigation, a part of the program of the Department of Interior for the development of the Missouri River basin, was made by personnel of the Water Resources Division of the U.S Geological Survey under the general supervision of P C. Benedict, regional engineer, who was succeeded by D M Culbertson, district engineer

DESCRIPTION OF THE BASIN

The Heart River drainage basin covers an area of 3,365 square miles in southwestern North Dakota It is an elongated basin about 120 miles long and 30 miles wide (fig. 1). The altitude ranges from 1,650 feet near Mandan in Morton County to about 2,850 feet near Fryburg in Billings County. The Heart River basin, which has dendritic drainage, is between the Knife River drainage basin on the north and the Cannonball River drainage basin on the south Farming and ranching are the principal occupations Crops have been irrigated by surface water since the construction of the Heart Butte Dam in 1949 and the Dickinson Dam in 1950. Mandan and Dickinson, the two largest cities, have populations of 10,525 and 9,971, respectively, U.S. Bureau of Census (1960).

The semiarid climate in the Heart River basin is characterized by long cold winters and short warm summers. U.S Weather Bureau records show that the annual precipitation during 1931–55 averaged 16.34 inches at Mandan, 17.16 inches at Richardton, and 15.68 inches at Dickinson In general, about 75 percent of the annual precipitation falls during April through September, and about 50 percent falls during May, June, and July. The average annual snowfall is about 35 inches; the accumulation of snow generally melts by the end of March. Variations in the annual precipitation at Dickinson and Mandan for 1921–59 are fairly large (See fig 2) The 10-year moving average was greater than the long-term average during 1942–50 for Dickinson and during 1944–59 for Mandan

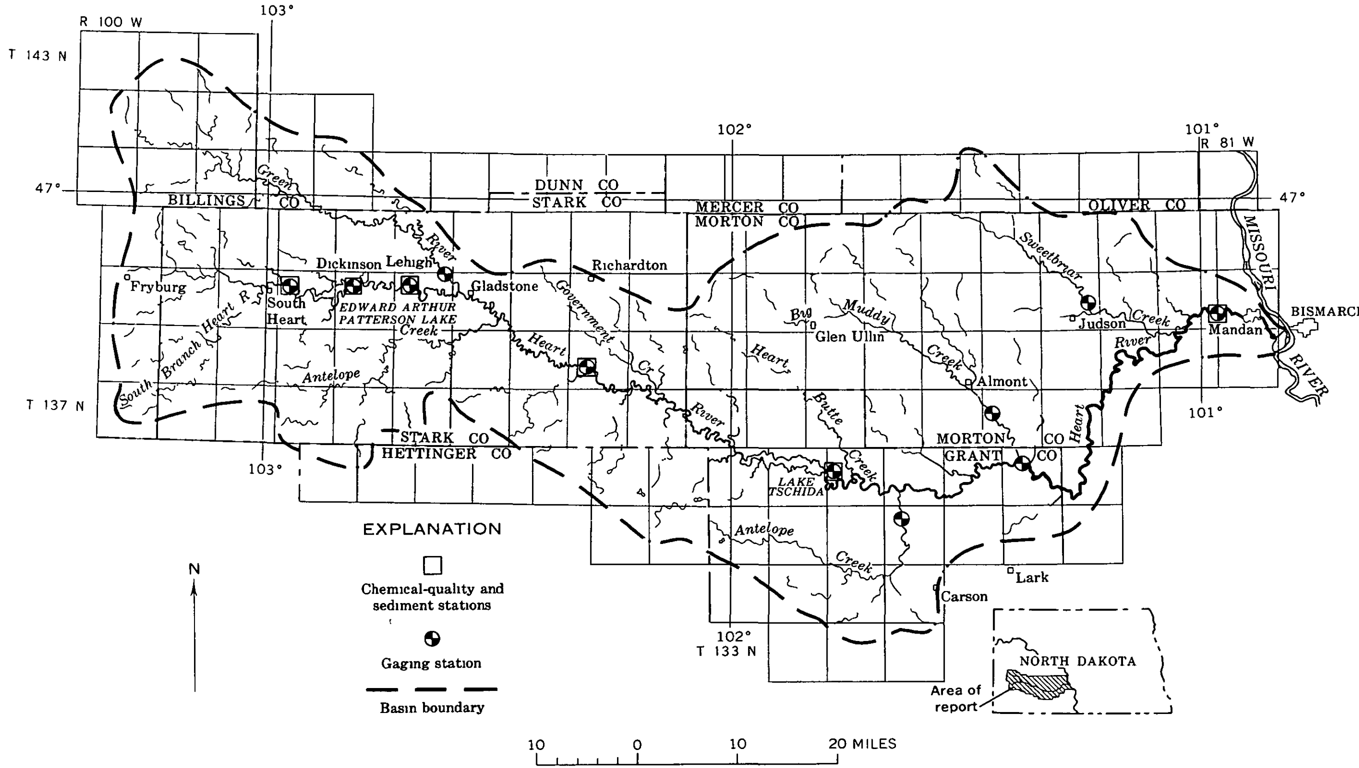

FIGURE 1.—Heart River basin

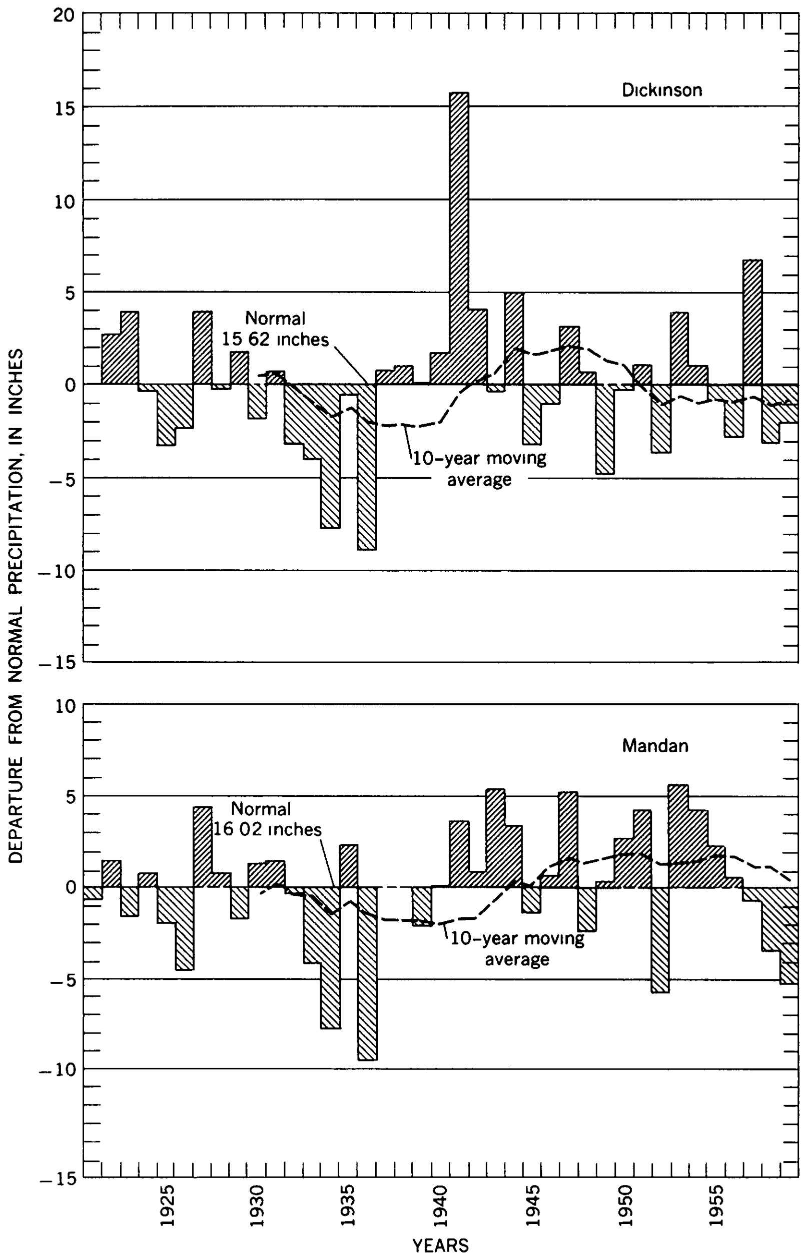

FIGURE 2—Departure from normal precipitation at Dickinson and Mandan, 1921–59

The Heart River basin is in the Missouri Plateau, which is part of the Great Plains province (Fenneman, 1931). A generalized division of the basin by Fenneman characterizes the eastern half as glaciated plateau and the western half as unglaciated plateau. The eastern half of the basin has many hills that contain remnants of ground moraines and scattered erratics, and the western half of the basin, except for a badlands area near South Heart (fig. 3), has a rolling topography broken by buttes; some of the buttes have a sandstone caprock. Terraces, benches, and rather steep escarpments border most of the Heart River and its tributaries. The fairly well integrated drainage system, well-formed valleys, low stream gradients (figs. 4–5), and meandering streams indicate that the Heart River drainage basin is in the late mature stage of the fluvial cycle.

FIGURE 3.—Badland topography, 8 miles south of South Heart.

GEOLOGY

The Heart River basin occupies the southeastern part of the Williston structural basin, which was formed by orogenic movements that have progressed intermittently since Ordovician time. Before glaciation, repeatedly transgressing and regressing seas deposited sediments within a slowly subsiding basin. The consolidated rocks are sandstones, shales, carbonates, and evaporites; they dip gently toward the center of the Williston basin, which is about 25 miles north of the Heart River basin. During Pleistocene time, glaciers covered the eastern half

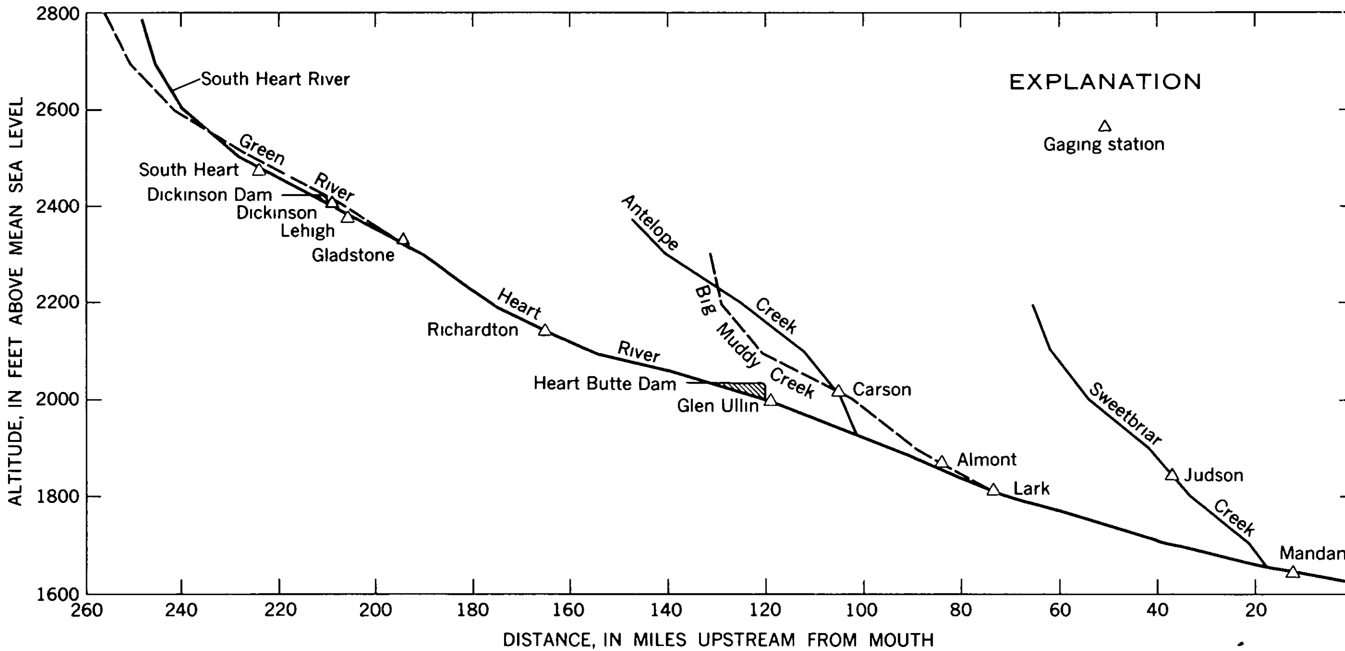

FIGURE 4.—Profile of the Heart River and some of its tributaries

FIGURE 5.—Meander in the Heart River, about 18 miles downstream from Heart Butte Dam.

of the basin, and their recession resulted in the deposition of glacial sediments. Rocks of pre-Pleistocene age and the areal extent of the glaciers in the basin are shown on plate 1, and a generalized section of surface rocks is shown in table 1.

TABLE 1.—*Generalized section of surface rocks*

System	Series	Formation	Member	Approximate maximum thickness (feet)
Quaternary	Recent and Pleistocene	Flood plain, terrace, and glacial deposits		75
Tertiary	Oligocene	White River		150
	Eocene	Golden Valley		200
	Paleocene	Fort Union	Sentinel Butte	100
			Tongue River	500
			Cannonball	150
			Ludlow	20
Cretaceous	Upper Cretaceous	Hell Creek		[1]20

[1] Exposed.

CRETACEOUS SYSTEM

The Hell Creek Formation of Late Cretaceous age crops out in the southeastern part of the basin. It is about 265 feet thick, but only about 20 feet is exposed along the Heart River. The formation is composed of interbedded sandstones and shales of a nonmarine origin.

TERTIARY SYSTEM

The Paleocene Ludlow Member of the Fort Union Formation is composed of shales, poorly consolidated calcareous sandstones, and interbedded lignite. The thickness of the Ludlow increases toward the west.

The Paleocene Cannonball Member of the Fort Union Formation overlies and forms a gradational contact with the Ludlow Member. The fossiliferous Cannonball and the Ludlow represent a transition between marine and continental environments. The Cannonball, which thins toward the west, is composed predominantly of sandy shales, shaly sandstones, and interbedded thin lenticular limestones. In general, the sandstones are poorly indurated and grade to shale toward the west.

The Paleocene Tongue River Member of the Fort Union Formation conformably overlies the Cannonball Member. It is a continental deposit composed mostly of yellow to light-tan beds of sandstone and of alternating beds of lignite and shale. (See fig. 6.) The Paleocene Sentinel Butte Member of the Fort Union Formation conformably overlies the Tongue River Member. It is composed of mostly dark shales, of interbedded lignite, and of thin lenticular sandstones of local extent. The Sentinel Butte was probably deposited in an environment similar to that of the Tongue River. The two members are shown as one unit in figure 6 because reliable differentiation is not possible; generally, however, the Tongue River Member crops out extensively in the basin, and the Sentinel Butte Member crops out only in the western part.

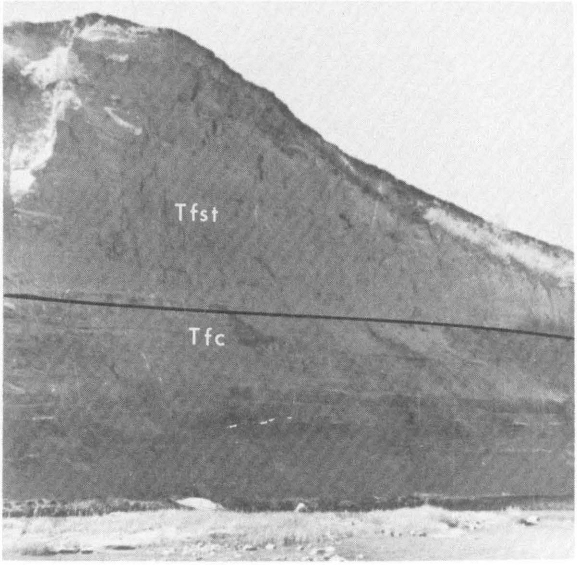

FIGURE 6.—Outcrop of Sentinel Butte and Tongue River Members (undifferentiated) TfFt, (approximately the upper 70 ft) and Cannonball Member of the Fort Union formation, Tfc, about 7 miles downstream from Heart Butte Dam.

The Golden Valley Formation of Eocene age conformably overlies the Fort Union Formation. It crops out in the southwestern part of the basin and as outliers along the northern part of the basin. The Golden Valley consists of claystones and interbedded siltstones and sandstones in the lower part and of gray to yellow micaceous siltstones and sandstones separated locally by lignite beds in the upper part This formation was probably deposited in an environment similar to that of the Tongue River and Sentinel Butte Shale Members. The Golden Valley thins toward the east.

The White River Formation of Oligocene age is the youngest consolidated unit in the basin. The formation conformably overlies the Golden Valley Formation; however, where the Golden Valley is not present, the White River lies unconformably on the Fort Union Formation. The White River is largely a fresh-water lacustrine deposit composed of soft white calcareous shales, sandstones, and thin limestones

QUATERNARY SYSTEM

The sediments of Quaternary age are composed of unconsolidated flood plain, terrace, and glacial deposits. The flood plain and the terrace deposits consist of gravel, sand, silt, and clay that were derived from sedimentary rocks The glacial deposits are in the eastern half of the basin and consist of remnants of old ground moraines and scattered erratics. Glaciation in the Heart River basin was probably restricted to Kansan time (Hainer, 1956).

STREAMFLOW

Streamflow data are available for 11 stations on the Heart River and tributaries. (See fig. 1.) Of the many natural physical factors that influence streamflow, climate is probably the most effective. The cumulative average percentages, by months, of streamflow and precipitation for 1944–49 are shown in figure 7. From October to February the percentage of streamflow is less than the percentage of precipitation, but during February, as the snow and ice began to melt, the percentage of streamflow increases significantly. On the average about 88 percent of the streamflow for the water year occurs by the end of May, whereas only about 57 percent of the annual precipitation has fallen.

The average streamflow in acre-feet per year per square mile, decreases only slightly from the headwaters to the mouth of the Heart River, however, during 1945–58, the minimum and maximum annual averages tended to increase in the downstream direction The extreme values were 10 5 and 116 acre-feet per square mile near South Heart and 16 and 126 acre-feet per square mile near Mandan (See fig 8) Gen-

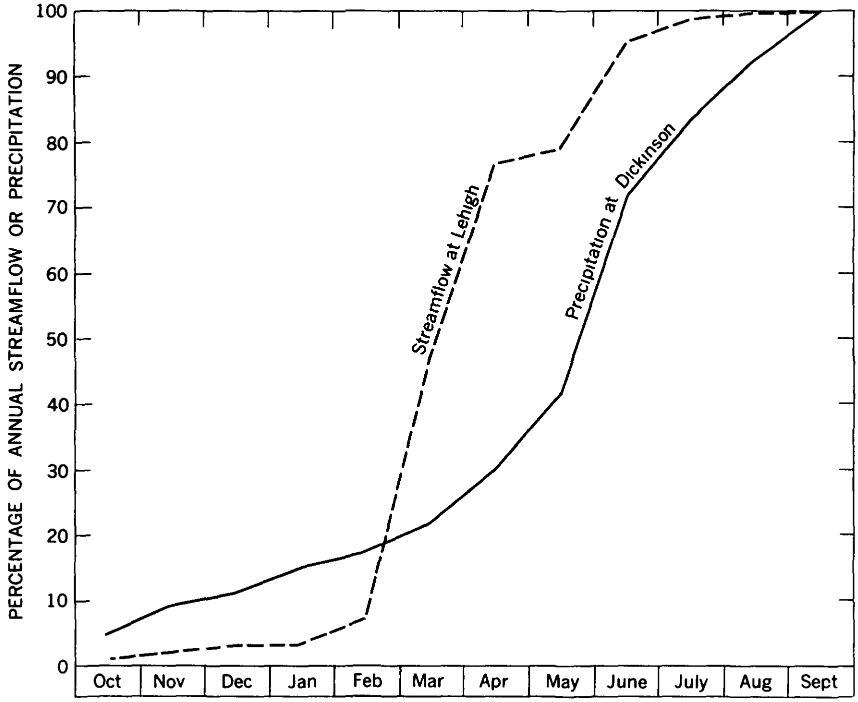

FIGURE 7.—Cumulative average percentages of precipitation and streamflow, 1944–49

erally, the volume of streamflow varies more in the tributaries than in the main stem. The above-average streamflow during 1947–52 resulted from above-average precipitation (fig. 2), and the below-average streamflow during 1953–58 resulted from a deficiency of precipitation

Flow-duration curves for the Heart River are shown in figures 9–11 The relatively flat slopes at the lower end of the curves for South Heart, Dickinson, and Lehigh indicate that significant amounts of surface and ground water from perennial flow are stored in the drainage basin; the steep slopes at the lower end of the curves for Richardton, Glen Ullin, and Mandan indicate negligible storage Because most of the high flows in the Heart River result from snowmelt, the flow-duration curves for most of the stations tend to have a flat slope at the upper end. The curves for Glen Ullin and Mandan indicate that the distribution of flow has not changed greatly since the construction of Heart Butte Dam (See fig 11) Probably the most significant change after dam construction was an increase in the median flow, which increased from 22 to 30 cfs (cubic feet per second) at Glen Ullin and from 35 to 60 cfs at Mandan In general, the flow

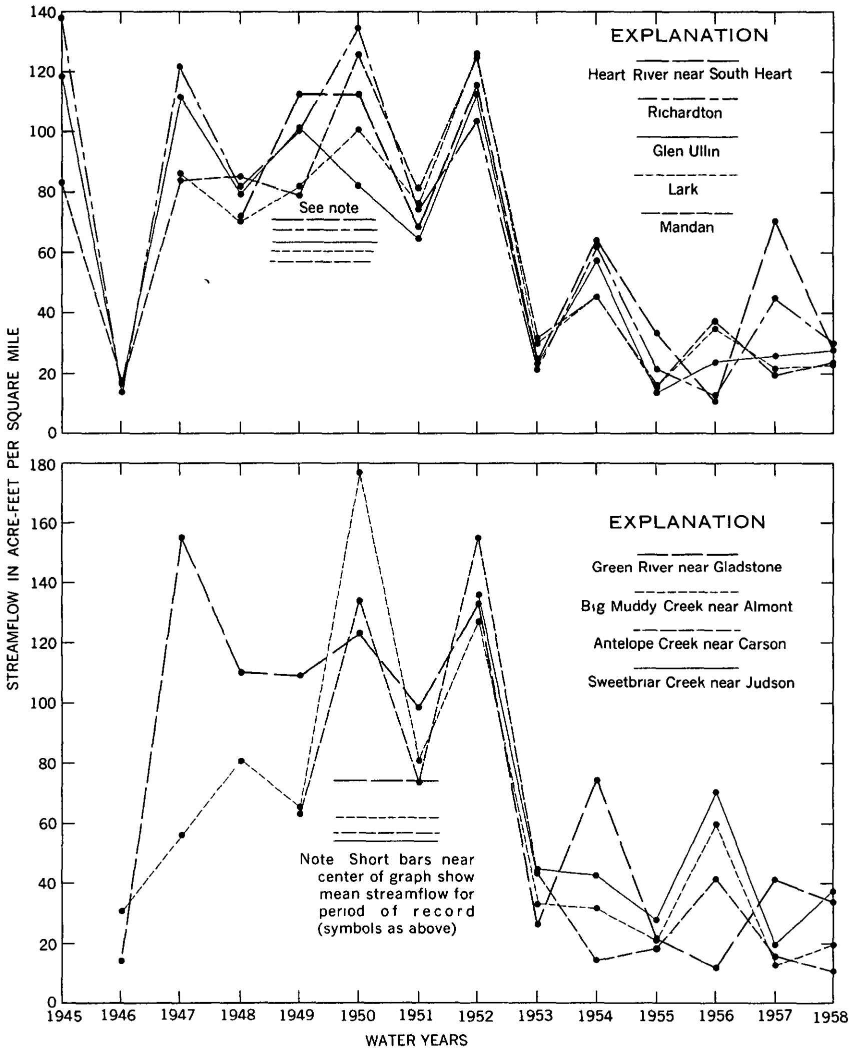

FIGURE 8—Annual streamflow of the Heart River and some of its tributaries, 1945–58

characteristics of the tributaries are similar to the flow characteristics of the Heart River near Lehigh, Dickinson, and South Heart (See figs. 9 and 12.) Median and mean streamflows at the gaging stations are shown in table 2. The mean is based on available records through 1958, and the median is derived from the flow-duration curves.

The annual streamflow for the main-stem stations was not corrected for irrigation, evaporation, nor municipal use, however, the percentage of water used for irrigation and the percentage of water evaporated

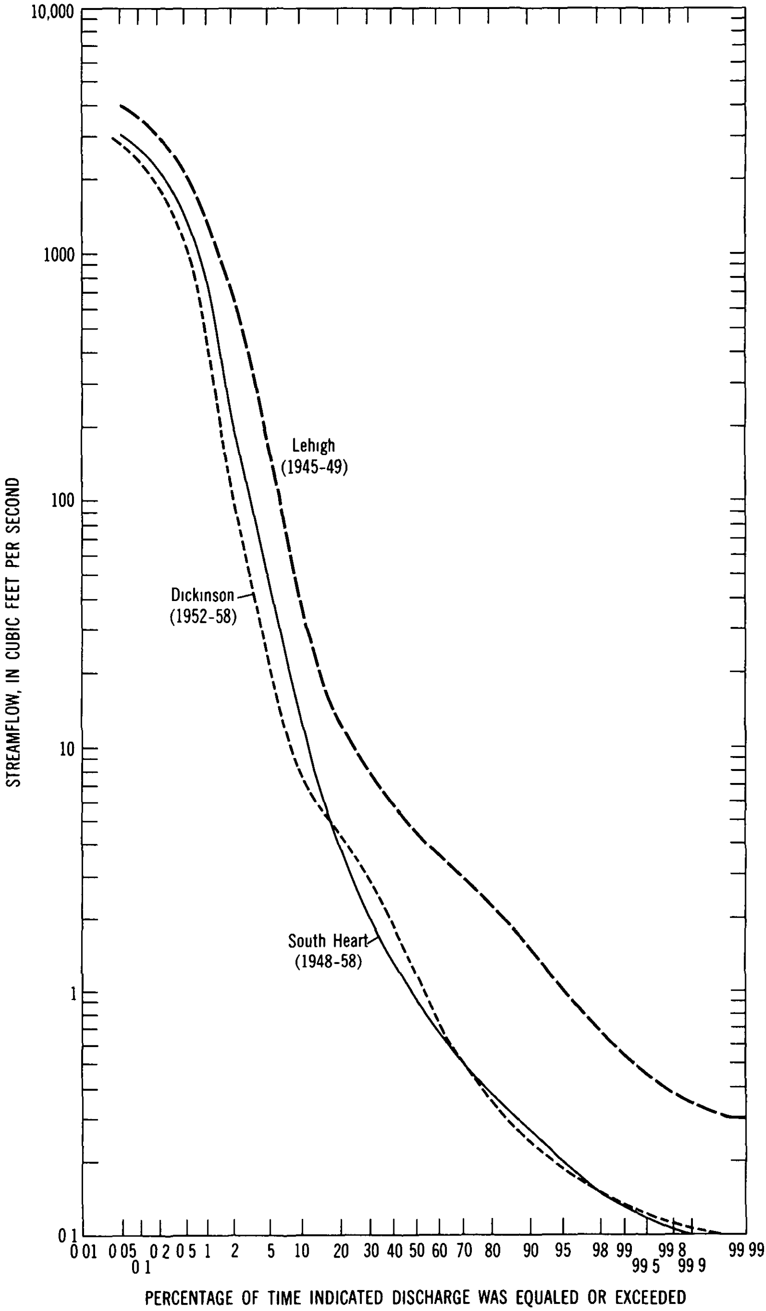

FIGURE 9 —Duration curves of daily flows for Heart River near South Heart, near Dickinson, and at Lehigh

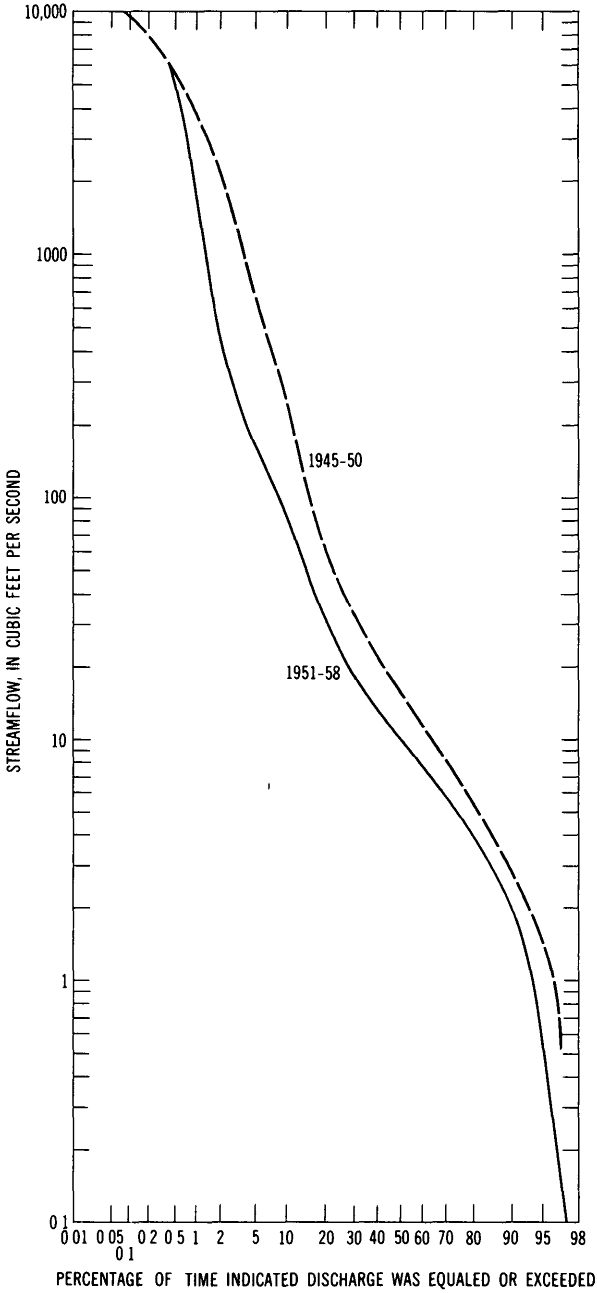

FIGURE 10—Duration curves of daily flows for Heart River near Richardton, before and after construction of Dickinson Dam

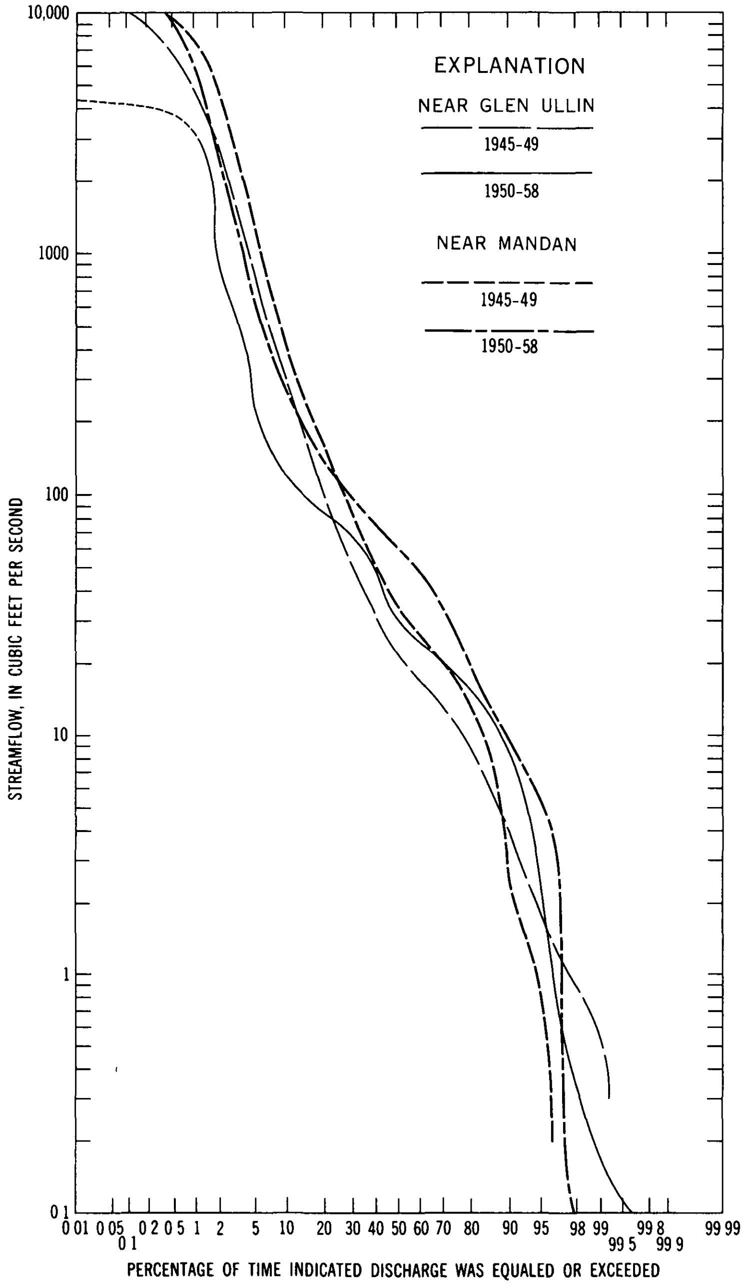

FIGURE 11 —Duration curves of daily flows for Heart River near Glen Ullin and near Mandan, before and after construction of Dickinson and Heart Butte Dams

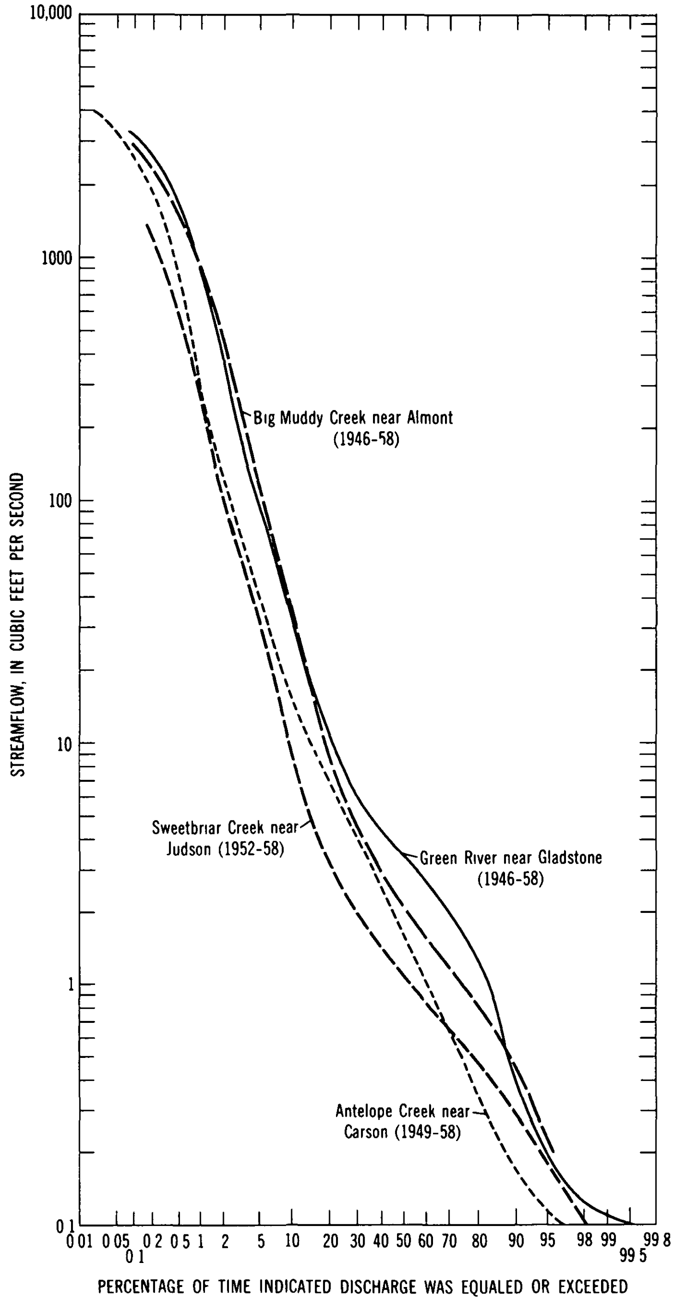

FIGURE 12—Duration curves of daily flows for Green River near Gladstone, Antelope Creek near Carson, Big Muddy Creek near Almont, and Sweetbriar Creek near Judson

TABLE 2 —*Median and mean streamflow in the Heart River basin*

Gaging station	Period of record	Area (sq mi)	Median streamflow (cfs)	Mean streamflow	
				Acre-feet	Cubic feet per second
Heart River near South Heart	1946–58	315	0 96	22,660	31 3
Heart River below Dickinson Dam, near Dickinson	1951–58	404	1 22	16,290	22 5
Heart River at Lehigh	1943–51	443	4 6	37,570	51 9
Green River near Gladstone	1945–58	356	3 4	26,060	36 0
Heart River near Richardton	1920–21, 1943–58	1,240	[1] 16 0	83,260	115
Heart River below Heart Butte Dam, near Glen Ullin	1943–58	1,710	[2] 22 0	108,600	150
Antelope Creek near Carson	1948–58	221	1 60	12,450	17 2
Big Muddy Creek near Almont	1945–58	456	2 08	27,950	38 6
Heart River near Lark	1946–58	2,750	----------	166,500	230
Sweetbriar Creek near Judson	1951–58	157	1 08	8,620	11 9
Heart River near Mandan	1928–32, 1937–58	3,310	[3] 35 0	189,700	262

[1] 10 1 cfs after construction of Dickinson Dam
[2] 30 0 cfs after construction of Heart Butte Dam
[3] 60 0 cfs after construction of Heart Butte Dam

were estimated for the basin. Storage for flood control, irrigation, and municipal use began in Edward Arthur Patterson Lake, formerly Dickinson Reservoir, on May 23, 1950, and in Lake Tschida, formerly Heart Butte Reservoir, on September 23, 1949. The total capacity of

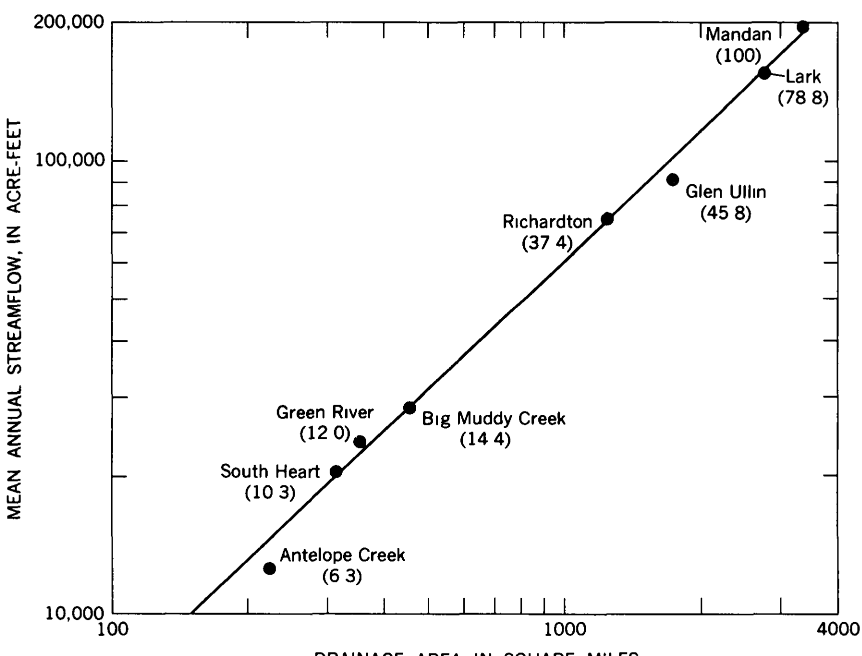

FIGURE 13 —Relation of mean annual flow to drainage area, Heart River and some of its tributaries, 1949–58 Streamflow expressed as percentage of the flow near Mandan is shown in parentheses

the Edward Arthur Patterson Lake is 25,700 acre-feet, dead storage is 1,100 acre-feet, and the conservation storage is 5,900 acre-feet The total capacity of Lake Tschida is 428,000 acre-feet, dead storage is 6,750 acre-feet, and the active conservation storage is 69,040 acre-feet Irrigation in the basin has increased since the completion of the two dams. In Stark and Morton Counties, 3,700 acres were irrigated in 1950 and 8,500 acres were irrigated in 1959 (U S. Bur Census, 1952, 1960). The volume of water used annually for irrigation is estimated to be 12,500 acre-feet, which is only 6 6 percent of the mean annual flow near Mandan. The average annual lake evaporation for southwestern North Dakota is about 35 inches per year (Kohler and others, 1959). The 6,000 acre-feet of water estimated to evaporate annually from the two lakes is only 3.2 percent of the mean annual flow near Mandan for the period of record through 1958 Because of irrigation, evaporation from two lakes, and municipal use, the mean annual streamflow near Mandan was decreased by an estimated 10 percent, or about 19,000 acre-feet

The linear curve in figure 13 indicates that the streamflow during 1949–58 was proportional to drainage area. Streamflow expressed as the flow near Mandan is shown in parenthesis.

FLUVIAL SEDIMENT

J. C. Mundorff (unpub. data) defined fluvial sediment as the "material that originates mostly from the disintegration of rocks and is transported by, suspended in, or deposited from water; it includes the chemical and biochemical precipitates and the organic material, such as humus, which has reached such an advanced stage of disintegration and decomposition that the original structure and characteristics of the living organic unit are not recognizable." Suspended sediment in fluvial sediment that is maintained in suspension by the upward components of turbulent currents or as a colloid

The study of fluvial sediment in the Heart River basin was begun by the Geological Survey in 1946. Suspended-sediment samples were collected and analyzed using standard equipment and methods of the Geological Survey; figure 14 shows the period of record and the frequency of sampling at the different stations. Additional suspended-sediment samples and some bed-material samples were collected in October 1960

SEDIMENT DISCHARGE

The quantity and characteristics of suspended sediment depend on many interrelated physical conditions—streamflow, velocity, water temperature, and amount and size of material available for transportation. Suspended-sediment discharge, as the term is used in this

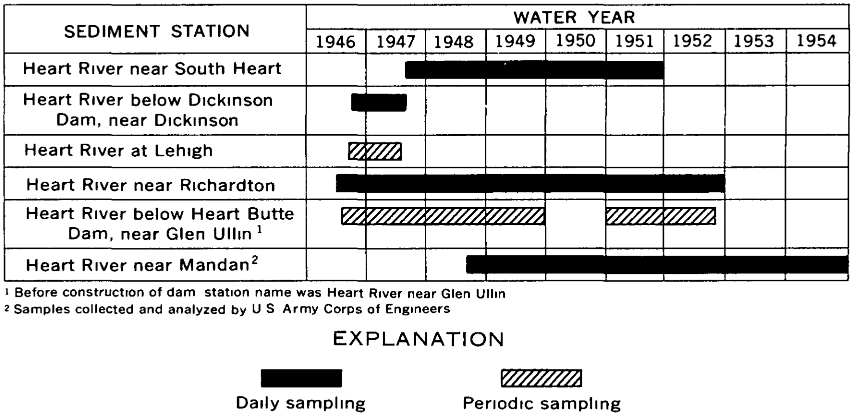

FIGURE 14—Duration of records and sampling frequency for sediment stations

report, is the sediment discharge that can be computed directly from the streamflow and the concentration of depth-integrated sediment samples. The part of the stream traversed by a depth-integrating sampler is called the sampled zone and includes the flow from the stream surface to a point about 0.3 or 0.4 foot from the streambed

In general, the concentrations of suspended sediments near South Heart, Richardton, and Glen Ullin increase with streamflow at a

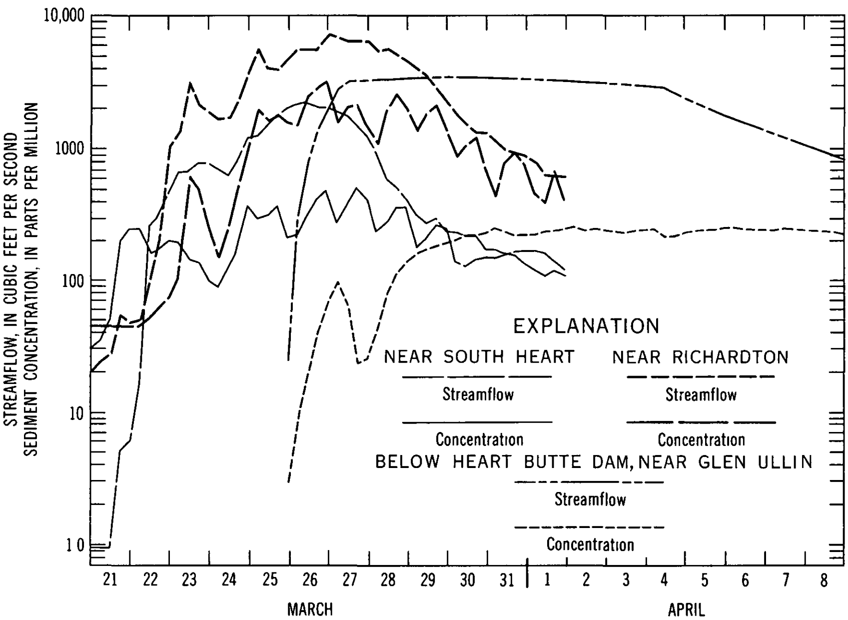

FIGURE 15—Streamflow and sediment concentrations for Heart River, March 21 to April 8, 1951

fairly uniform rate (fig. 15); however, the peak concentration may occur before, at, or after the peak streamflow. Normally, the peak concentration near Glen Ullin lags behind the peak streamflow about 3 days; therefore, the increase in concentration in suspended sediment on March 26, 1951, probably resulted from erosion of the channel and banks between the dam and the sampling station.

The relation of suspended-sediment discharge to streamflow commonly indicates a seasonal trend for streams in the northern Great Plains Seasonal curves for low flows during late fall and winter, for snowmelt during spring, and for runoff during summer thunderstorms can be plotted if data are available for a period of several years In the Heart River basin, the relation of sediment discharge to streamflow probably changes from season to season, but because of the relatively short period of sediment record and the construction of main-stem dams during this period, reliable seasonal curves cannot be established. For Heart River near South Heart, a curve showing the relation of sediment discharge to streamflow for the 1951 water year (fig 16) indicates seasonal variation For streamflows that

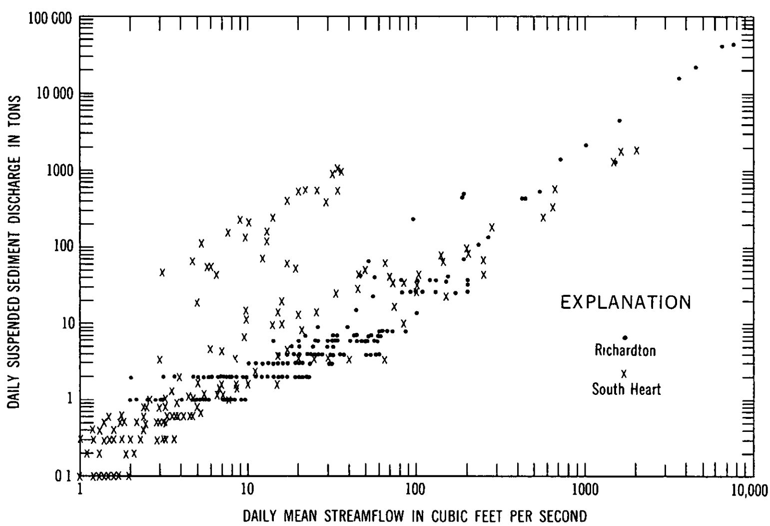

FIGURE 16—Relation of suspended-sediment discharge to streamflow for Heart River near South Heart and near Richardton, 1951 water year

ranged from about 5 to 35 cfs, the points representing sediment discharges of about 50 to 1,100 tons per day are for periods of runoff during summer thunderstorms The points representing sediment discharges of about 0 2–25 tons per day are for periods of base flows and snowmelt. Further, the effect of Edward Arthur Patterson Lake on sediment discharge near Richardton is evident if sediment discharge is compared to streamflow near South Heart and Richardton. During 1951, when sediment discharges of about 1,000 tons per day occurred at streamflows of 30–35 cfs near South Heart, the sediment discharge was about 10 tons per day near Richardton; apparently, nearly all the sediment from the drainage basin upstream from Dickinson Dam was deposited in the lake and was not transported by the Heart River.

The suspended-sediment discharge near Dickinson and Glen Ullin has been reduced because of the Dickinson and Heart Butte Dams. The relation of sediment discharge to streamflow near Glen Ullin (fig 17) indicates a large reduction in the sediment discharge after the construction of the dams, particularly at high streamflows Average annual sediment discharges, estimated from the curves in figures 11 and 17, were 540,000 tons for 1945–49 (before dam construction) and 11,000 tons for 1950–58 (after dam construction). The sediment discharge for the 1951 water year was 22,000 tons The average annual sediment discharges near Dickinson were estimated to be 36,200 tons before dam construction and 700 tons after dam construction

The effect of the dams on the average annual suspended-sediment discharge near Mandan is small (See fig. 18.) The average annual sediment discharge, estimated from the 1948–49 curve in figure 18 and from the 1945–49 curve in figure 11, was 1.3 million tons. The decrease in discharge, estimated from the 1952–53 curve in figure 18 and from the 1945–49 curve in figure 11, was 320,000 tons; the same curve in figure 11 was used to estimate the average annual sediment discharges before and after construction of the dams The average annual sediment discharge for 1950–54 was 1.02 million tons (U S Army Corps of Engineers, 1957) The average annual sediment discharge for 1950–58, estimated from the 1952–53 curve in figure 18 and from the 1950–58 curve in figure 11, was 710,000 tons The average sediment discharge for 1950–58 was less than the average for 1950–54 because the percentage of streamflow between 120 and 10,000 cfs was smaller for 1950–58 than for 1950–54; most of the sediment is discharged at high streamflows. The decrease in the average sediment discharge of the Heart River because of deposition in upstream reservoirs has improved the quality of the water by reducing the sediment concentration; however, the deposition of sediment in the reservoirs is also reducing their capacity for storage

Data for the period 1949–51 indicate that the annual suspended-sediment discharge in tons per square mile increased downstream in the Heart River (fig 19) The downstream increase was more pronounced in 1949 before the construction of either dam than in 1950 or 1951 when the lakes trapped some of the sediment from the western

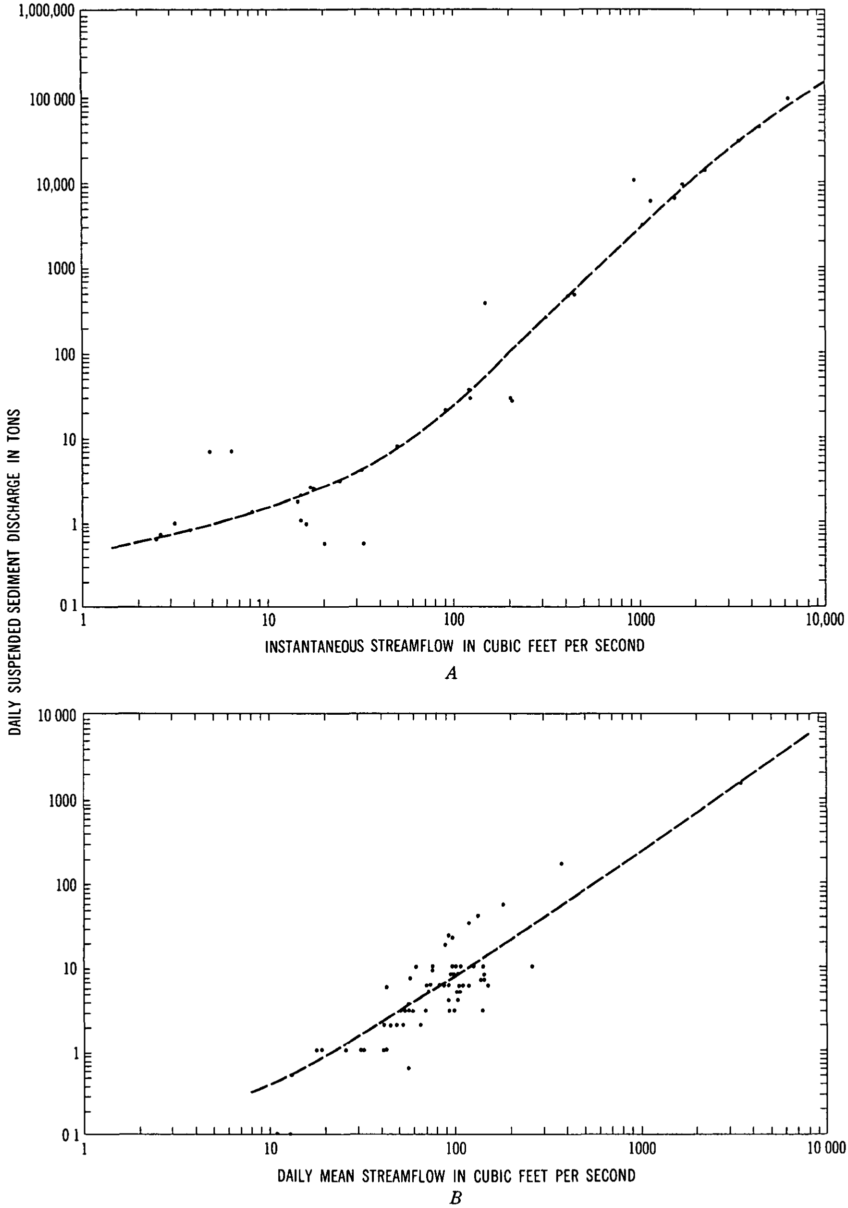

FIGURE 17—Relation of suspended-sediment discharge to streamflow for Heart River near Glen Ullin, before (*A*) and after (*B*) construction of Dickinson and Heart Butte Dams

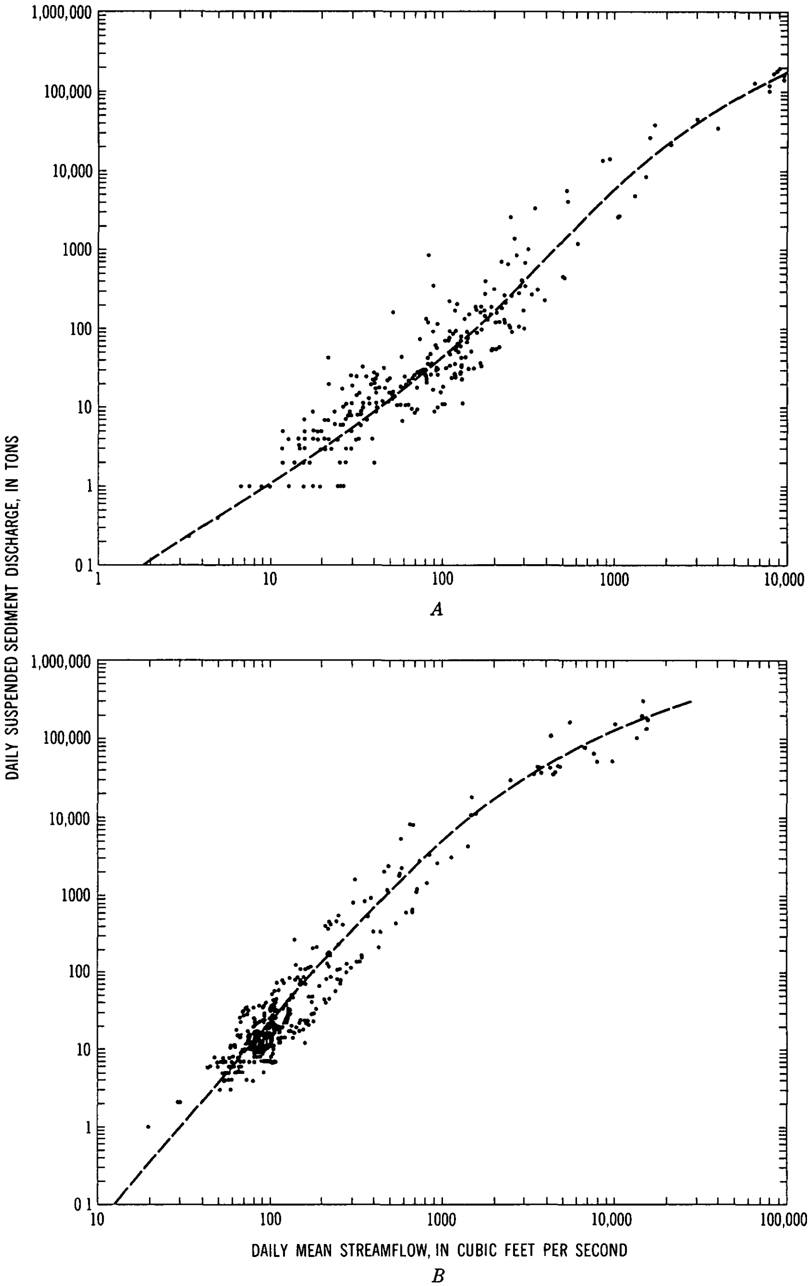

FIGURE 18—Relation of suspended-sediment discharge to streamflow for Heart River near Mandan, before (*A*) and after (*B*) construction of Dickinson and Heart Butte Dams

half of the drainage basin. Amount and intensity of surface runoff may have been partly responsible for the variations in suspended-sediment discharge at a station between 1949 and 1950 or 1951

The retention of sediment in the lakes affects both the concentration and the particle-size distribution of suspended sediment downstream from the dams The concentration decreases, whereas the percentage of sediment finer than 0 062 mm (millimeter) increases; after dam construction the percentage of fine material increased near Richardton from 82 to 87 and near Glen Ullin from 73 to 100 (See table 3)

The unmeasured sediment discharge, as explained by Colby (1957), is the difference between the total sediment discharge and the sediment

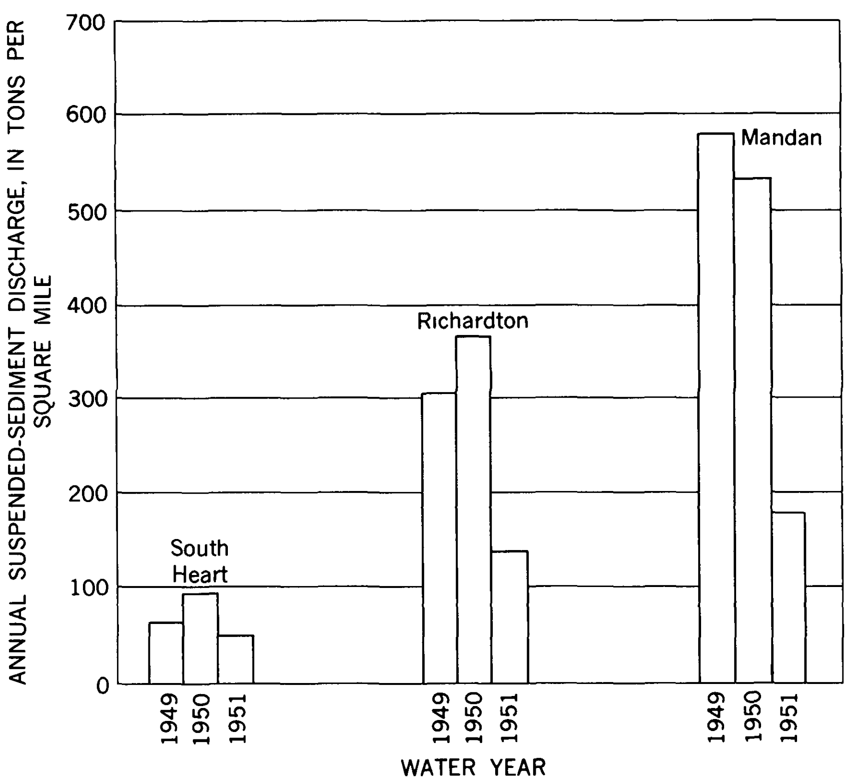

Figure 19—Annual suspended-sediment discharge for Heart River near South Heart, near Richardton, and near Mandan

discharge that can be computed directly from the streamflow and the concentration of depth-integrated samples. It includes the sediment that is discharged as bedload and part of the sediment that is discharged in suspension below the sampled zone The unmeasured sediment discharge for Heart River near Richardton, approximated by the Colby method (1957), increases in proportion to streamflow at about the 1.5 power (See fig. 20.) The computations of unmeasured sediment discharge were based on daily samples collected at a bridge section that has steep grassy banks. The scatter of points in figure 20 may be due to changes in velocity, temperature, and depths and to differences in the size distribution of suspended sediment.

The unmeasured sediment discharge near Richardton and perhaps near Mandan averages 10 or 11 percent of the total sediment discharge (fig. 21) As a percentage of total sediment discharge, the unmeasured sediment discharge will be above the 10-percent average when suspended-sediment concentrations are small (during low flow or spring runoff) and below average when suspended-sediment concentrations are large (during high flows derived from thunderstorms)

TABLE 3 —*Effect of construction of dams on the average percentage of suspended sediment in Heart River*

Sediment station	Number of samples		Suspended sediment (percent finer than 0 062 mm)	
	Before dams	After dams	Before dams	After dams
Near South Heart	36		98	
Below Dickinson Dam, near Dickinson	1		98	
At Lehigh	2		88	
Near Richardton	30	15	82	87
Below Heart Butte Dam, near Glen Ullin	21	[1] 3	73	100
Near Mandan [2]		60		71

[1] Samples collected at outflow tube of Heart Butte Dam
[2] Data from U S Army Corps of Engineers (written commun)

SOURCE OF SEDIMENT

Streams and mass-wasting processes are important agents of erosion Slump, which is a slow form of mass wasting, is generally more ef-

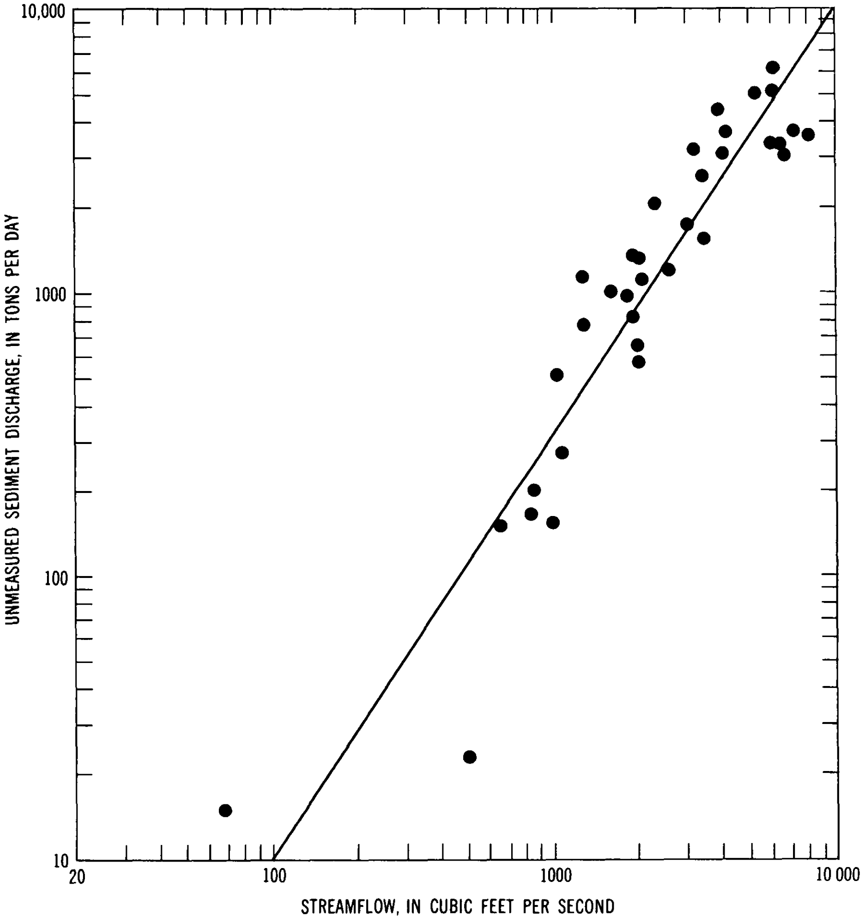

FIGURE 20—Relation of unmeasured sediment discharge to streamflow for Heart River near Richardton, 1947–52

fective in areas composed of moist, poorly consolidated rocks or unconsolidated sediments Debris fall, which is a more rapid form of mass wasting, is common in the Heart River basin where bank slopes are steep and where sediment may fall directly into the stream (fig 22). Sheet erosion, gully erosion, and the advancement of valley heads are processes that also contribute sediment to the Heart River (fig 23)

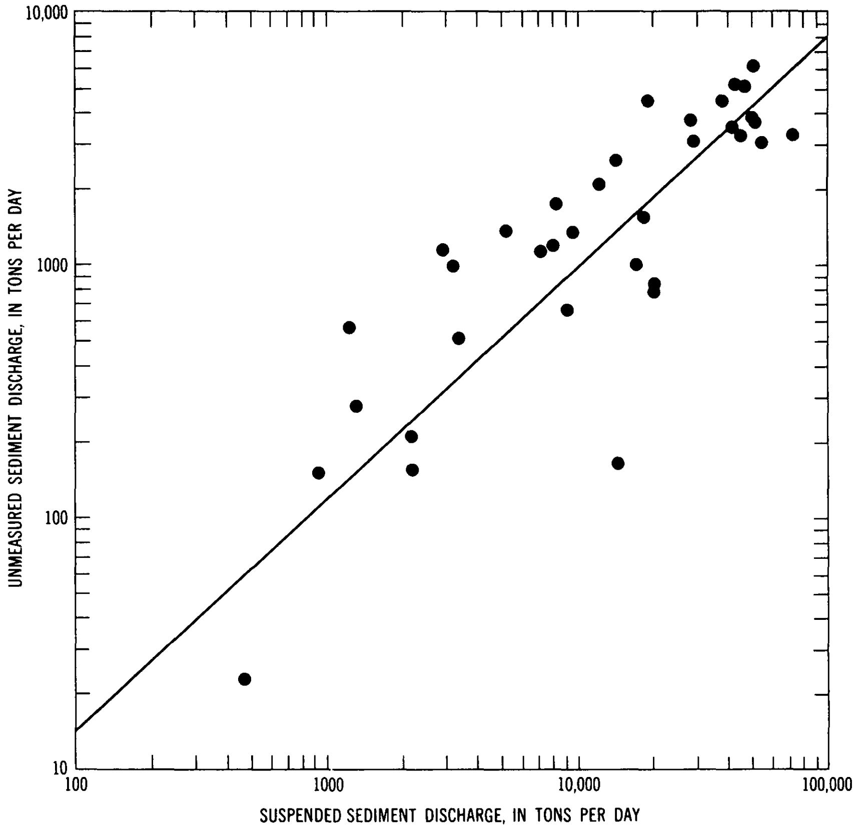

FIGURE 21.—Relation of unmeasured suspended-sediment discharge to measured suspended-sediment discharge for Heart River near Richardton

About 15 percent of the area of exposed rocks in the Heart River basin are of Quaternary age, and about 85 percent are of Tertiary age. Data are not available for determining the geologic unit that contributes the major amount of sediment; however, some general conclusions can be drawn from visual observations and from analyses of samples of streambeds, bars, and terrace deposits in the basin. The average of the analyses indicates that 73 percent of the material is coarser than silt and 34 percent is coarser than sand. In general, glacial deposits, terraces, and bars of Quaternary age are sources of sand and sediments larger than sand; the rocks of Tertiary age are sources of clay, silt, and sand.

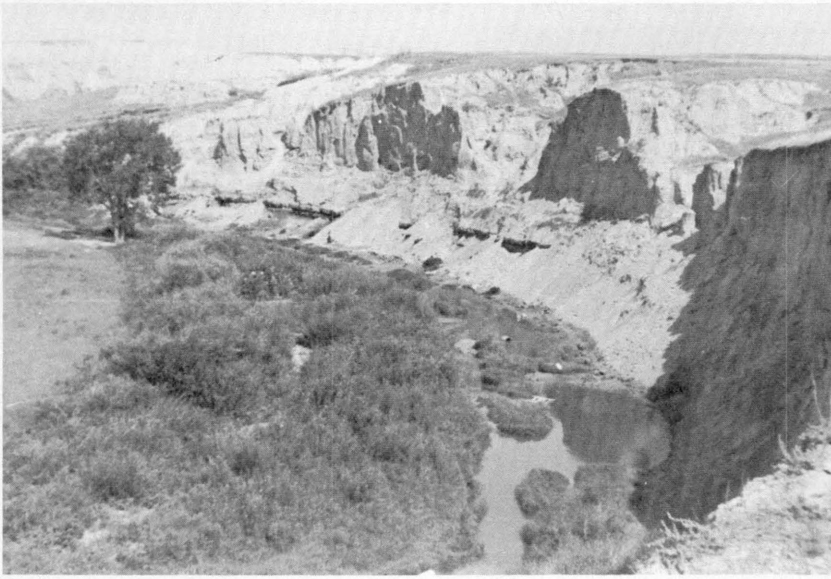

FIGURE 22.—Accumulation of sediment from debris fall along the Heart River, about 2 miles west of Dickinson and about 1 mile upstream from Dickinson Dam. Sediment eroded from an outcrop of the Tongue River Member of the Fort Union Formation.

FIGURE 23.—Headcut and gully along Government Creek near Richardton.

CHEMICAL QUALITY OF SURFACE WATER

The study of the chemical quality of surface water in the Heart River basin was begun by the U S Geological Survey in 1945. The period of record and the frequency of sampling at the different stations are shown in figure 24. In addition, data for water samples obtained in 1955 and 1957 and analyzed at the U.S Salinity Laboratory in Riverside, Calif., were furnished by the U.S. Bureau of Reclamation. The chemical quality of the ground water in the Heart River basin has been discussed by Swenson (Tychsen, 1950).

The results of the individual water analyses for each station were plotted on a graph to determine average concentrations for selected ranges of streamflow Instantaneous streamflow in cubic feet per second was used as the independent variable, and the individual cations (calcium, magnesium, sodium, and potassium) and the anions (bicarbonate, carbonate, sulfate, chloride, fluoride, and nitrate) in equivalents per million were used as the dependent variables The sum of the cations taken from the individual curves drawn through the plotted points balanced with the sum of the anions within 5 percent The percentage of the cations and anions computed from the curves

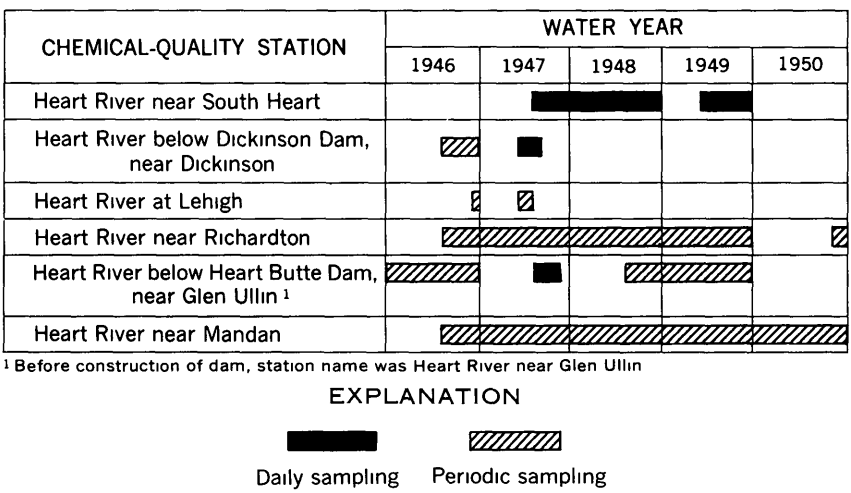

FIGURE 24 —Duration of records and sampling frequency for chemical-quality stations

for the selected ranges of flow were plotted on multiple-trilinear diagrams (Piper, 1944), average concentrations in equivalents per million taken from the curves were converted to parts per million and are used in conjunction with the trilinear diagrams to explain the changes in the quality of the water. Trilinear diagrams and data on chemical constituents in parts per million are used to show the average change in water quality at selected ranges of flow; the diagrams and the data can be used to show changes in the quality of the water in a downstream direction.

From the multiple-trilinear diagram, differentiation of water type is possible by using a binomial value written in the form of a "decimal fraction," whose two terms are "(1) the percentage of hardness-causing constituents (calcium and magnesium) among the cations, and (2) the percentage of bicarbonate (and carbonate, if present) among the anions" (Piper, 1944) For example, 29.53 would indicate a water in which the calcium and magnesium amount to 29 percent of all the cations in equivalents per million and in which the bicarbonate and carbonate amount to 53 percent of all the anions.

HEART RIVER NEAR SOUTH HEART

The percentage composition of the ions in the Heart River near South Heart changes with streamflow (See fig. 25 and table 4.) Although the percentage of calcium and magnesium increases as streamflow increases, the concentration of these ions in parts per million decreases. The average concentrations of all ions vary inversely with streamflow

Most of the high flows in the Heart River result from snowmelt, which is very low in dissolved constituents. Most of the low flows are supplied by ground water, which is probably high in sodium and sulfate; deposits of sodium sulfate commonly form along the stream channel. Some sulfate is probably derived from pyrite, marcasite, and other sulfur-bearing minerals associated with coal in the Sentinel Butte and Tongue River Members of the Fort Union Formation, which crop out along the Heart River near South Heart. Bicarbonate may be eroded from the cementing material of some sandstones and the shales. Calcium and magnesium are in the soils and clays of the two members. When the streamflow is low, the quality of the water is not suitable for most uses. When the streamflow is high, the water is of good quality; but high flows are of short duration.

HEART RIVER NEAR DICKINSON

The investigation of the water in the Heart River near Dickinson was made prior to the construction of the dam, which was built to control floods and to impound water for irrigation and municipal use. Because most of the data were collected during the spring runoff when the greatest amount of the water is impounded, the data were probably representative of the water that enters Edward Arthur Patterson Lake.

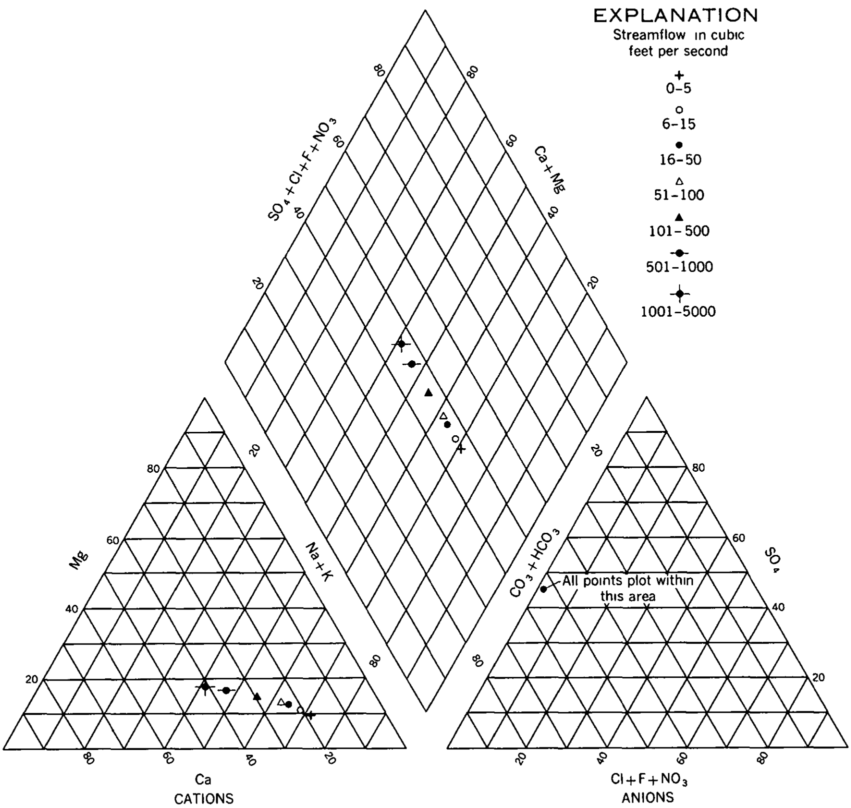

FIGURE 25 —Percentage composition computed from average concentrations, in equivalents per million, for selected ranges of streamflow for Heart River near South Heart, 1947–49

TABLE 4 —*Average concentration of dissolved constituents, in parts per million, and water type for Heart River near South Heart, 1947–49*

Range of streamflow (cfs)	Ca	Mg	Na+K	HCO_3+CO_3	SO_4	$Cl+F+NO_3$	Dissolved solids	Water type
0–5	68	22	299	604	413	7	1,110	29 53
6–15	52	17	198	439	303	5	800	32 53
16–50	38	13	127	305	211	4	550	36 53
51–100	30	10	87	226	156	3	410	38 53
101–500	21	7	46	133	91	2	260	45 53
501–1,000	15	4	23	67	46	2	150	53 53
1,001–5,000	12	3	14	43	29	1	90	59 53

The percentage composition of the ions changes with streamflow, the "decimal fraction" changed from 32 54 at the lowest range of flow to 53.69 at the highest range (See fig 26 and table 5) The sharp increase in percentages of bicarbonate and magnesium at flows of more than 100 cfs is probably the result of inflow from upstream tributaries that drain areas in which the White River and Golden

Valley Formations crop out. Inflow from these upstream tributaries is negligible except during spring runoff and during intense thunderstorms.

The average concentrations in parts per million for most of the ions decrease as streamflow increases (table 5). Most of the samples on which these averages are based were collected when the quality of the water was affected significantly by snowmelt; therefore, the averages are probably lower than they would have been if the samples had been representative of year-round conditions

The quality of the water that enters the Edward Arthur Patterson Lake during the spring runoff is probably similar to the quality of water at the 101- to 500-cfs range During long periods of drought the quality of water in the lake gradually changes and eventually approximates the average concentrations shown in table 5 for the 0- to 15-cfs ranges

Chemical-quality standards that have been established by the U S Public Health Service (1962) for water to be used on interstate carriers for drinking and culinary purposes can be used as guides to establish recommended maximum concentrations for public supplies. The maximum concentrations for some of the chemical constituents are shown in the following table

Constituent	*Recommended maximum concentration (ppm)*
Iron (Fe)	0 3
Sulfate (SO_4)	250
Chloride (Cl)	250
Fluoride (F)	[1]1 5
Nitrate (NO_3)	45
Dissolved solids	500

[1] Based on temperature data for Dickinson and Mandan

Except for being moderately hard, the water in the lake during normal or above-normal runoff is generally of suitable quality for public use The concentrations of chloride, fluoride, and nitrate probably never approach their maximum limits. During long periods of drought, however, the concentrations of sulfate and dissolved solids may be higher than the recommended maximums. Also, at times the iron concentration may exceed 0 3 parts per million The use of water having sulfate concentrations greater than 250 ppm and dissolved solids greater than 500 ppm does not seem to cause any physiological effects other than a laxative action on new users. Iron concentrations above the maximum of 0.3 ppm are not physiologically harmful in fact, trace amounts of iron are an essential nutrient, but concentrations higher than 0.5–1.0 ppm can be tested. Iron concen-

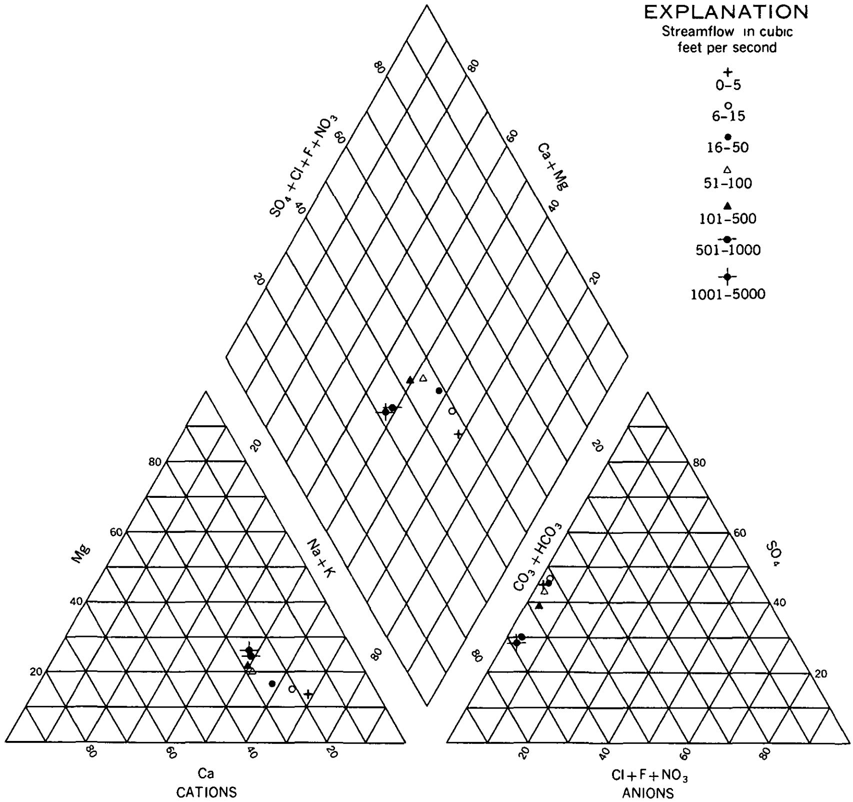

FIGURE 26 —Percentage composition computed from average concentrations, in equivalents per million, for selected ranges of streamflow for Heart River near Dickinson, 1946–47

TABLE 5 —*Average concentration of dissolved constituents, in parts per million, and water type for Heart River near Dickinson, 1946–47*

Range of streamflow (cfs)	Ca	Mg	Na+K	HCO_3+CO_3	SO_4	Cl	F	NO_3	Dissolved solids	Water type
0–5	52	24	223	470	310	2 6	0 5	1 5	860	32 54
6–15	38	17	131	282	203	1 8	4	1 7	540	37 51
16–50	27	12	74	171	124	1 3	3	1 8	330	42 52
51–100	21	9	44	121	76	1 0	3	1 9	220	49 55
101–500	14	6	27	85	46	9	2	2 1	140	51 58
501–1,000	10	6	21	80	29	8	2	2 2	110	52 67
1,001–5,000	9	6	18	73	24	8	2	2 4	100	53 69

trations above the 0 3 ppm also tend to stain laundry and porcelain fixtures.

The U.S. Salinity Laboratory Staff (1954) introduced a diagram for classifying irrigation water; the diagram is based on the sodium-adsorption-ratio (SAR) and the specific conductance of the water

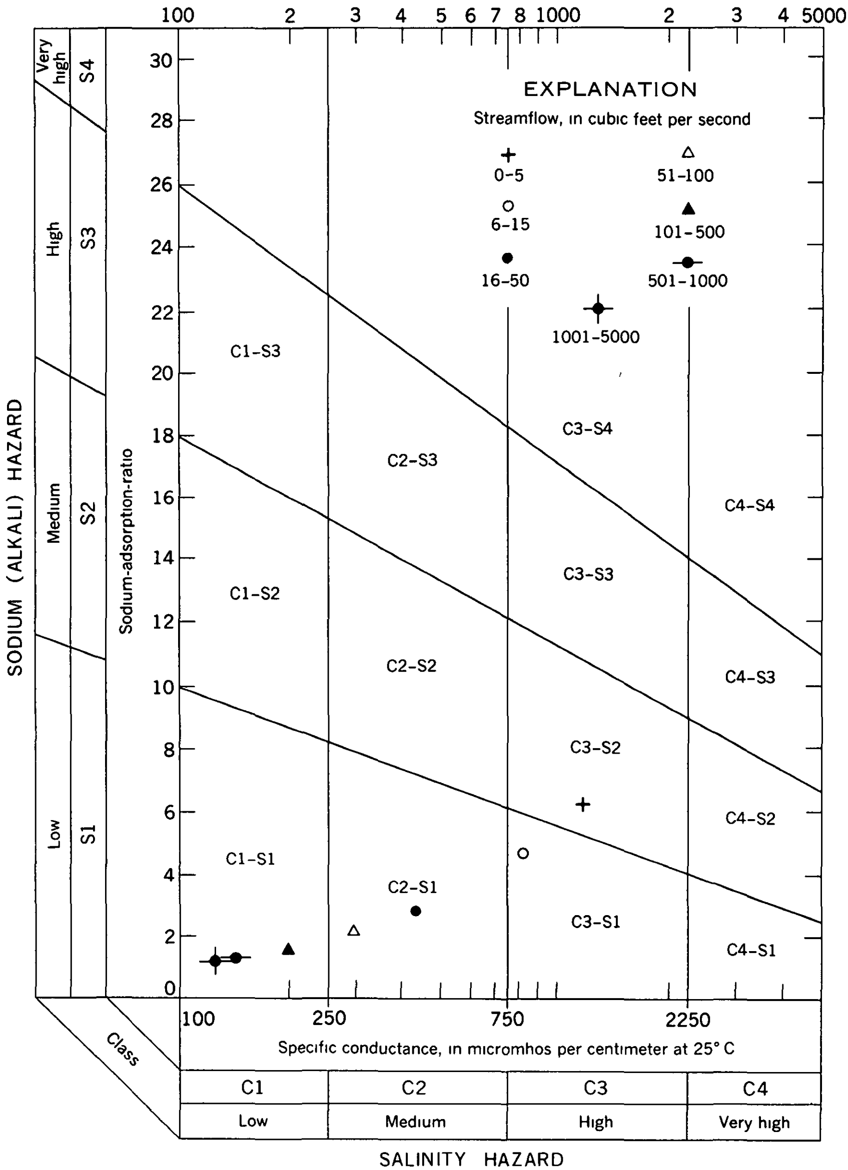

FIGURE 27 —Classification of water for irrigation, Heart River near Dickinson Diagram by U S Salinity Laboratory Staff (1954)

The sodium-adsorption-ratio and specific conductance for the average concentrations shown in table 5 were plotted in figure 27 to determine the salinity and sodium hazards of the water in the Heart River near Dickinson during 1946–47. The plotted points indicate that the water during periods of high flow has low sodium and low salinity hazards. Because most of the high flows are from spring runoff, the water from Edward Arthur Patterson Lake is assumed to have low sodium and low salinity hazards. The mixing of water from successive spring runoffs and low-flow periods with water already in the lake, however, may change the salinity hazard from low to medium. If runoff is below normal for several consecutive years, the water in the lake would probably have a low sodium hazard and a high salinity hazard. Water having a high salinity hazard is not considered suitable for irrigation unless adequate drainage is provided and unless crops having a moderate to good salt tolerance are grown.

HEART RIVER NEAR RICHARDTON

The change in water type with flow in the Heart River near Richardton is indicated by the change in "decimal fraction" from 34.41 at the lowest range of flow to 63.54 at the highest range. (See fig. 28 and table 6.) Part of the change is due to inflow from Green River and Antelope Creek Sulfate, which is the predominant anion during low flow, is probably contributed by inflow from Antelope Creek and by ground-water inflow. At extremely high flows, Antelope Creek, which drains part of the badlands area south of South Heart, probably contributes a water that has high percentages of magnesium and bicarbonate.

The average concentrations in parts per million are higher in the water near Richardton (table 6) than near South Heart or Dickinson. The increase in concentrations from Dickinson to Richardton, however, would have been much less if the averages for Dickinson had been representative of year-round conditions.

At flows of more than 100 cfs, the water near Richardton is of suitable quality for public use. At flows of less than 100 cfs, the water may contain more than the 250 ppm of sulfate recommended by the U S Public Health Service (1962)

HEART RIVER NEAR GLEN ULLIN

During 1945–49, before construction of Heart Butte Dam, the "decimal fractions" for the water in the Heart River near Glen Ullin were 30 46 at the lowest range of flow and 69 61 at the highest range During 1950, the first year that water was impounded in Lake Tschida, the "decimal fraction" for the lake water at an altitude of 2,061 feet

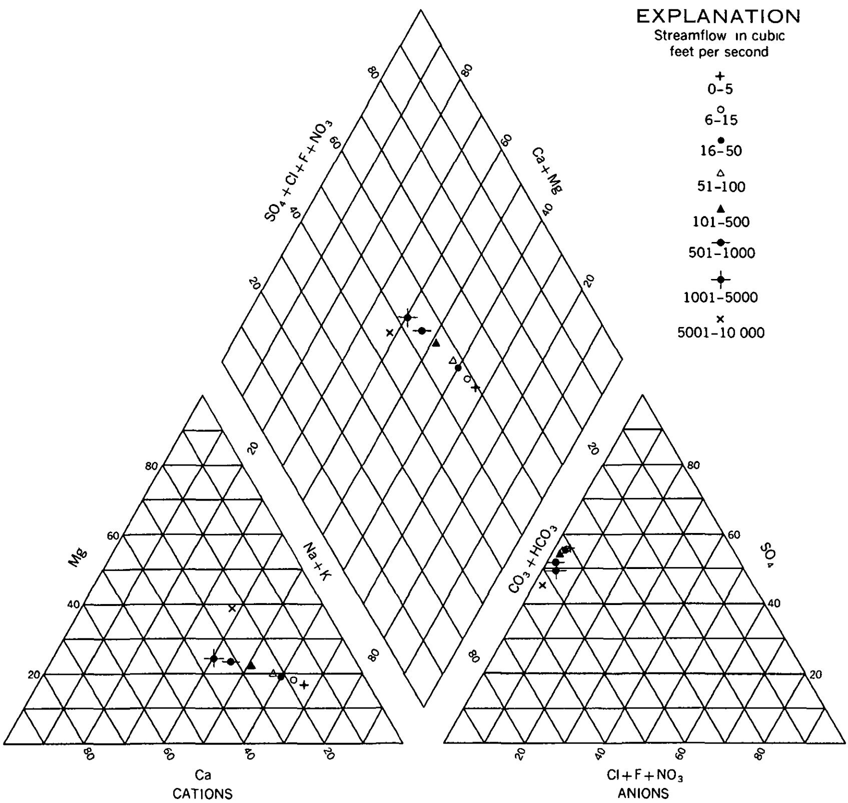

FIGURE 28.—Percentage composition computed from average concentrations, in equivalents per million, for selected ranges of streamflow for Heart River near Richardton, 1946–50

TABLE 6.—*Average concentration of dissolved constituents, in parts per million, and water type for Heart River near Richardton, 1946–50*

Range of streamflow (cfs)	Ca	Mg	Na+K	HCO_3+CO_3	SO_4	Cl+F+NO_3	Dissolved solids	Water type
0–5	63	41	292	488	518	21	1,180	34 41
6–15	58	35	223	404	423	15	960	37 42
16–50	53	29	169	331	341	12	780	40 43
51–100	48	24	133	287	288	9	650	44 43
101–500	42	20	90	223	216	6	490	49 44
501–1,000	36	16	58	171	149	4	350	55 47
1,001–5,000	28	12	36	116	94	4	230	60 48
5,001–10,000	21	8	23	85	53	3	160	63 54

was 53 50, which approximates the type of water at a flow of 101–500 cfs in the Heart River prior to dam construction. (See fig. 29 and table 7.) After 7 years the "decimal fraction" for the lake water was 45 56 at an altitude of 2,059 feet. The change in percentage composition from 1950 to 1957 was partly the result of evaporation and of differences in quality of inflow.

Concentrations in parts per million of water from Lake Tschida during 1950 and 1957 (table 7) indicate that on the average the water is of suitable quality for public supply according to standards of the U.S. Public Health Service (1962). The concentrations were also used to compute the average sodium-adsorption-ratio and specific conductance to determine the sodium and salinity hazards of the water for irrigation. The plotted points in figure 30 indicate that the water entering Lake Tschida would have a medium sodium hazard and a high salinity hazard at the lowest range of flow and a low sodium hazard and a medium salinity hazard at the highest range The water in Lake Tschida, which had a low sodium hazard and a medium salinity hazard during 1950 and 1957, can be used for irrigation if a moderate amount of leaching occurs

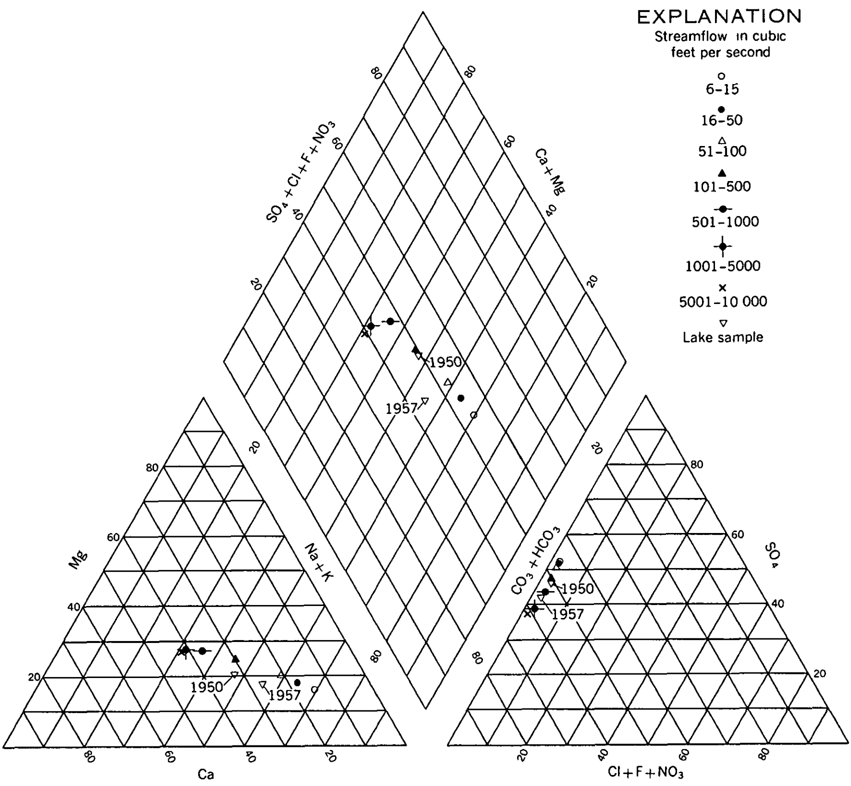

FIGURE 29 —Percentage composition computed from average concentrations, in equivalents per million, for selected ranges of streamflow for Heart River near Glen Ullin, 1945–49

TABLE 7 —*Average concentration of dissolved constituents, in parts per million, and water type for Heart River near Glen Ullin and for Lake Tschida*

Range of streamflow (cfs)	Ca	Mg	Na+K	HCO_3+CO_3	SO_4	$Cl+F+NO_3$	Dissolved solids	Water type
Heart River near Glen Ullin								
1946–49								
5–15	52	34	283	494	442	14	1,080	30 46
16–50	47	29	198	384	341	11	830	36 46
51–100	45	25	138	305	252	8	630	42 48
101–500	41	20	71	201	149	5	390	55 51
501–1,000	38	17	41	159	103	4	290	65 53
1,001–5,000	35	14	30	146	77	4	230	69 58
5,001–10,000	33	12	27	142	67	3	220	69 61
Lake Tschida								
1950								
2,061 [1]	37	14	62	176	129	6	360	53 50
1957								
2,059 [1]	42	17	99	261	155	6	480	45 56

[1] Lake altitude, in feet

HEART RIVER NEAR MANDAN

During 1946–49 the "decimal fraction" for the Heart River near Mandan changed from 29.45 for the lowest range of flow to 73.61 for the highest range (fig. 31 and table 8); however, the "decimal fractions" for the ranges of flow changed very little from Glen Ullin to Mandan. The percentages of the constituents remained fairly constant, probably because the tributaries that drain areas composed of glacial deposits and rocks of the Cannonball Member of the Fort Union Formation contribute a similar type water.

After dam construction the "decimal fraction" for the lowest range of flow near Mandan was 38.51. The water released from Lake Tschida, for which the "decimal fraction" during 1957 was 45.56 (table 7), changes in percentage composition and in dissolved solids as it moves downstream. The chemical constituents of the water in the river are affected by evaporation, tributary inflow, and return flow from irrigation

Water in the Heart River near Mandan has a low sodium hazard and a high salinity hazard (fig. 32) and, therefore, may be unsuitable for irrigation unless adequate drainage is provided and unless crops having a moderate to good salt tolerance are grown Except for concentrations of sulfate and dissolved solids, which during low flow exceed the maximum limits recommended by the U.S. Public Health Service (1962), the water is of suitable quality for public use.

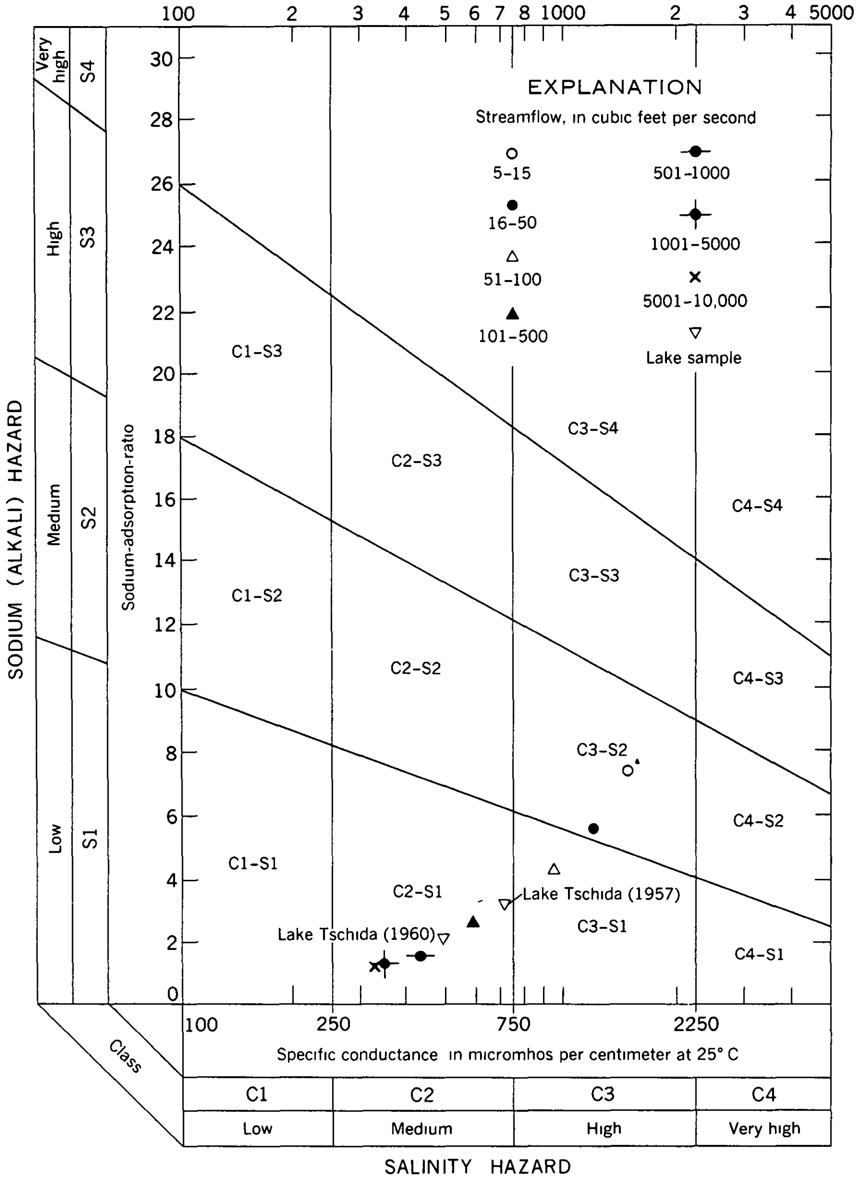

FIGURE 30—Classification of water for irrigation, Heart River near Glen Ullin Diagram by U S Salinity Laboratory Staff (1954)

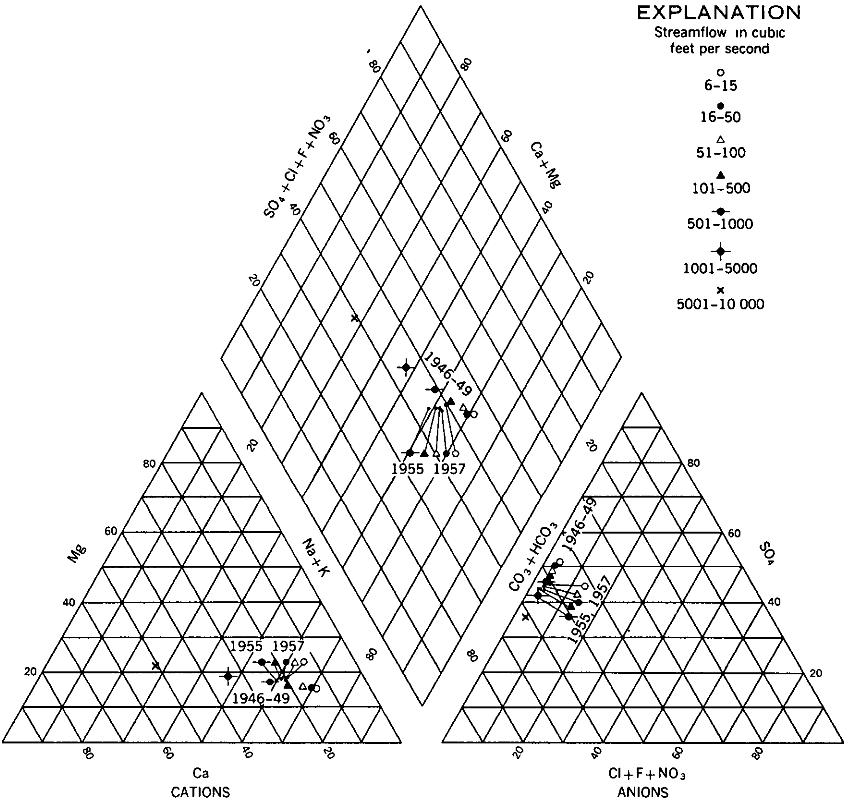

FIGURE 31 —Percentage composition computed from average concentrations, in equivalents per million, for selected ranges of streamflow for Heart River near Mandan, 1946–49, 1955 and 1957

TABLE 8 —*Average concentration of dissolved constituents, in parts per million, and water type for Heart River near Mandan*

Range of streamflow (cfs)	Ca	Mg	Na+K	HCO_3+CO_3	SO_4	$Cl+F+NO_3$	Dissolved solids	Water type
1946–49								
5–15	46	30	276	440	394	24	1,000	29 45
16–50	44	26	223	378	319	18	830	31 47
51–100	42	23	191	336	279	14	740	33 48
101–500	40	20	143	281	216	10	600	37 49
501–1,000	39	16	102	232	164	8	470	42 52
1,001–5,000	38	13	60	108	112	6	340	53 55
5,001–10,000	37	10	23	146	67	5	220	73 61
1955 and 1957								
5–15	53	31	198	414	292	22	830	38 51
16–50	45	26	162	350	239	17	680	38 52
51–100	40	23	145	317	212	15	600	39 52
101–500	33	18	113	257	165	10	480	39 53
501–1,000	26	13	85	201	122	7	370	41 55

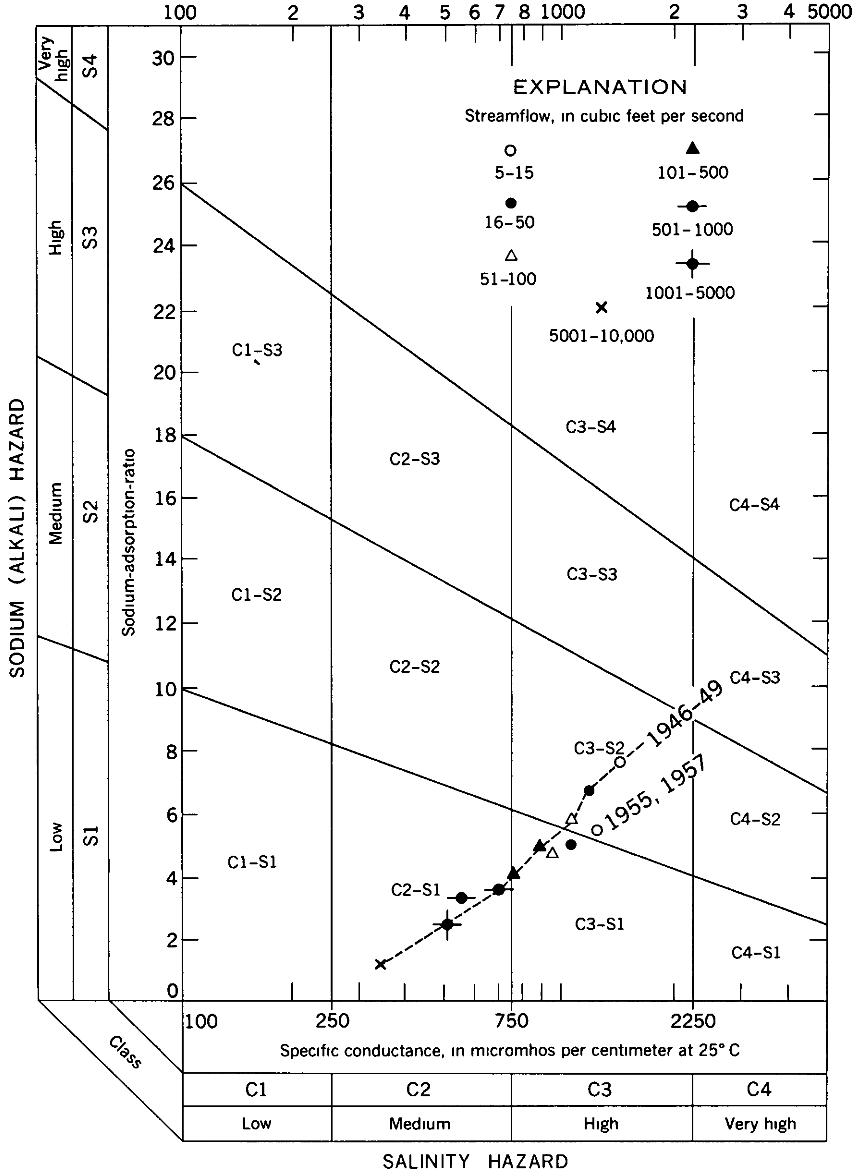

FIGURE 32 —Classification of water for irrigation, Heart River near Mandan Diagram by U S Salinity Laboratory Staff (1954)

CONCLUSIONS

Streamflow during 1949–58 was proportional to drainage area in the Heart River basin.

Heart Butte Dam and Dickinson Dam, completed in 1949 and 1950, respectively, have reduced the suspended-sediment concentration and discharge downstream The average annual suspended-sediment discharge near Mandan was estimated to be 1,300,000 tons before construction of the two dams, and it decreased about 320,000 tons after construction of the dams.

Sheet, gully, and lateral stream erosion, advancement of valley heads, and mass wasting are processes that contribute sediment to the Heart River The poorly indurated Tertiary rocks are the sources of clay, silt, and sand; the Quaternary rocks are the sources of material larger than sand

In general, the water in the Heart River contains a large percentage of sodium and about equal percentages of bicarbonate and sulfate during extremely low flows, the water contains a large percentage of calcium plus magnesium and a large percentage of bicarbonate during extremely high flows.

The water in Edward Arthur Patterson Lake and Lake Tschida during normal or above-normal runoff is of suitable quality for public use.

In general, because of medium or high salinity hazards, the use of water in the Heart River for irrigation will require a moderate amount of leaching, adequate drainage, and the growing of crops having a moderate or good salt tolerance

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