TRANSPORT AND SOURCES OF SEDIMENT IN THE MISSOURI RIVER BETWEEN GARRISON DAM AND THE HEADWATERS OF LAKE OAHE, NORTH DAKOTA, MAY 1988 THROUGH APRIL 1991

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 95-4087

Prepared in cooperation with the

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1995

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
millimeter (mm)	0.03937	inch
ton, short (2,000 pounds)	0.9072	megagram

Milligrams per liter (mg/L) is a unit expressing the concentration of a chemical constituent in solute as weight (milligrams) of solute per unit volume (liter) of water.

Transport and Sources of Sediment in the Missouri River Between Garrison Dam and the Headwaters of Lake Oahe, North Dakota, May 1988 through April 1991

By Wayne R. Berkas

Abstract

Sediment data were collected on and along the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991 to characterize sediment transport in the river. Specific study objectives were to (1) identify erosional and depositional reaches during two steady-state low-flow periods and one steady-state high-flow period; (2) determine if the reaches are consistently eroding or depositing, regardless of streamflow; and (3) determine the sources of suspended sediment in the river.

Erosional and depositional reaches differed between the two low-flow periods, indicating that slight changes in the channel configuration between the two periods caused changes in erosional and depositional patterns. Erosional and depositional reaches also differed between the low-flow periods and the high-flow period, indicating that channel changes and increased streamflow velocities affect erosional and depositional reaches.

The significant sources of suspended sediment in the Missouri River are the riverbed and riverbanks. The riverbed contributes to the silt and sand load in the river, and the riverbanks contribute to the clay, silt, and sand load. The contribution from tributaries to the suspended-sediment load in the Missouri River usually is small. Occasionally, during low-flow periods on the Missouri River, the Knife River can contribute significantly to the suspended-sediment load in the Missouri River.

INTRODUCTION

The Missouri River is the largest river in North Dakota. Mean recorded streamflow in the Missouri River at Bismarck, N. Dak., is more than 80 percent of the total mean streamflow in the State. The Missouri River is regulated by dams in Montana (Fort Peck Dam), North Dakota (Garrison Dam), and South Dakota (Oahe Dam, Big Bend Dam, Fort Randall Dam, and Gavins Point Dam; fig. 1). Of the original 390 mi of river in North Dakota, only about 90 mi are not inundated by backwater from dams. These 90 mi are located between Garrison Dam and the headwaters of Lake Oahe, which is about 20 mi downstream from Bismarck.

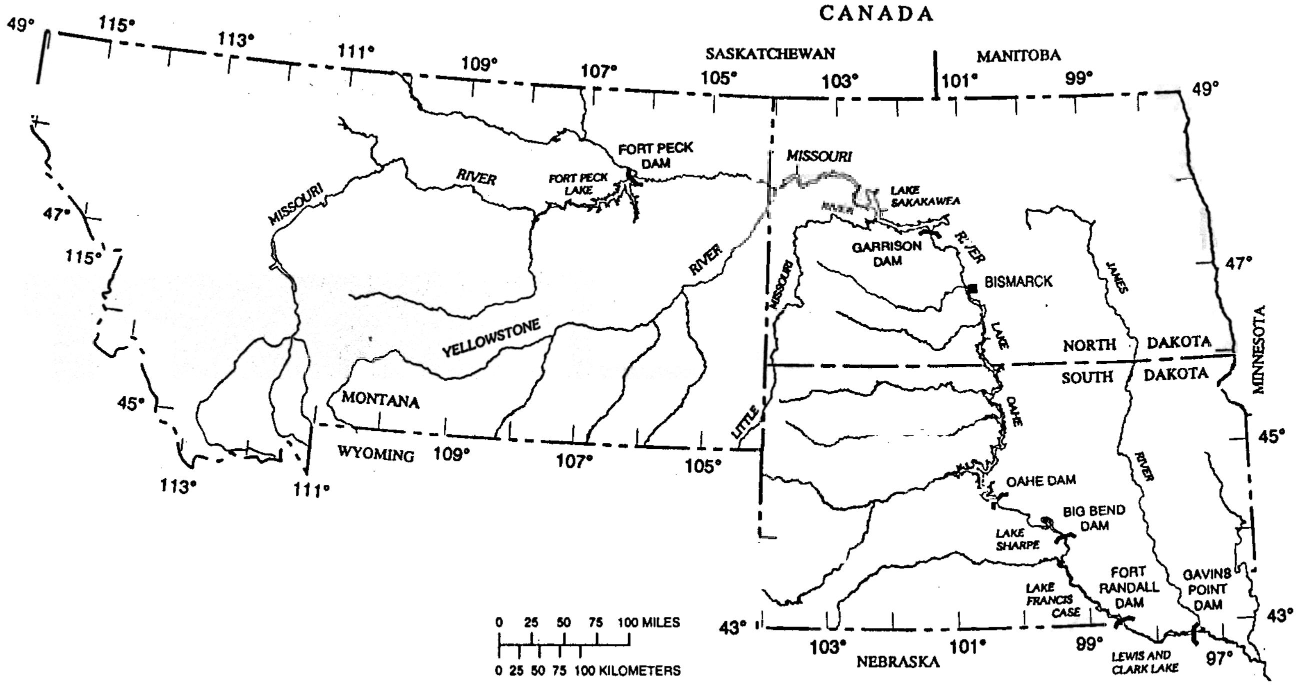


Figure 1. Location of major dams and reservoirs on the Missouri River.

Sediment transported by the Yellowstone, Missouri, and Little Missouri Rivers settles in Lake Sakakawea. The reservoir has a 100 percent trap efficiency for sediment; therefore, water discharged from Lake Sakakawea has a negligible suspended-sediment concentration. Sediment transported by the Missouri River downstream from the reservoir can only come from the (1) riverbed, (2) riverbanks, and (3) tributaries.

Rivers tend to equilibrate with regard to channel shape, channel slope, sediment transport, and streamflow velocity. When one of these characteristics changes, the others also change until the river again is in equilibrium (Williams and Wolman, 1984). After completion of Garrison Dam in 1953, sediment removed from the riverbed downstream from the dam was not replaced by sediment removed from the riverbed and riverbanks upstream from the dam. Thus, the riverbed began to erode. By 1976, mean bed elevations in the Missouri River had decreased as much as 13 ft within 4 mi of Garrison Dam (Williams and Wolman, 1984). The decrease in bed elevation caused a decrease in channel slope, the decrease in channel slope caused a decrease in streamflow velocity, the decrease in streamflow velocity caused a decrease in sediment transport, and the decrease in sediment transport caused a decrease in erosion. Characteristics of the river are adjusting continually toward a re-established equilibrium condition.

Concerns have been raised about the possible effects of changes in the Missouri River channel. Some landowners are concerned about the loss of property to bank erosion. Others are concerned that sediment removed from the riverbed immediately downstream from the dam will be deposited farther downstream, particularly where the Missouri River flows into Lake Oahe. If sediment deposition continues, the bed elevation might increase and land near the river might flood more frequently than in the past.

To anticipate future changes caused by sediment erosion and deposition in the Missouri River channel downstream from Garrison Dam, a better understanding of sediment transport in the river is needed.

Therefore, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, began a study to determine transport characteristics in the Missouri River downstream from Garrison Dam. The objectives of this study are to (1) identify erosional and depositional reaches under high- and low-flow conditions and (2) determine the sources of suspended sediment in the river.

Purpose and Scope

The purpose of the report is to (1) document erosional and depositional reaches during two stable low-flow periods and one stable high-flow period; (2) document consistency or variability of erosion or deposition, by reach, under different flow conditions; (3) describe the sources of suspended sediment in the river.

The study reach is an 86-mi reach of the Missouri River downstream from Garrison Dam (fig. 2). The study reach includes 20 sites on the Missouri River at which measurements were made and samples were collected and 34 sites at which bank-material samples were collected. In addition, measurements were made and samples were collected at a site on the Knife River and a site on the Heart River. Data were collected during May 1988, May 1989, and April 1991.

Approach

Sediment-transport characteristics were measured at main-stem and major tributary sampling sites along the study reach during two steady-state low-flow periods and one steady-state high-flow period. Erosional and depositional reaches were identified by the comparison of suspended-sediment concentrations at the sampling sites. Data collected during the two low-flow periods were compared to data collected during the high-flow period to determine if the erosional and depositional reaches varied between low- and high-flow conditions. Particle-size data from suspended-sediment, bedload, bed-material, and bank-material samples were compared to determine the sources of suspended sediment in the river.

The first low-flow sampling period was from May 3 to May 6, 1988. Beginning May 1, discharge from Garrison Dam was maintained at 18,000 ft^3/s for 4 days. Suspended-sediment samples were collected at 20 sites on the Missouri River and at two tributary sites (fig. 2). Streamflow was measured and intensive sampling was conducted at eight of these sampling sites (S1, S5, S10, S17, S20, S21, T1, and T2). Less intensive sampling was conducted at the remaining sampling sites. Suspended-sediment samples were collected with a US D-77 suspended-sediment sampler, and bed-material samples were collected with a US BMH-60 bed-material sampler.

At each intensive sampling site, suspended-sediment samples were collected from about 20 verticals in the river cross section. The samples were composited at the laboratory and analyzed for suspended-sediment concentration and particle-size distribution. Bed-material samples were collected at about eight locations in the cross section and analyzed individually for particle-size distribution.

At each less intensive sampling site, suspended-sediment samples were collected from about eight verticals in the river cross section. The samples were composited at the laboratory and analyzed for suspended-sediment concentration and percentage of material larger than 0.062 mm (sand break). Bed-material samples were collected at about three locations in the cross section and analyzed individually for particle-size distribution.

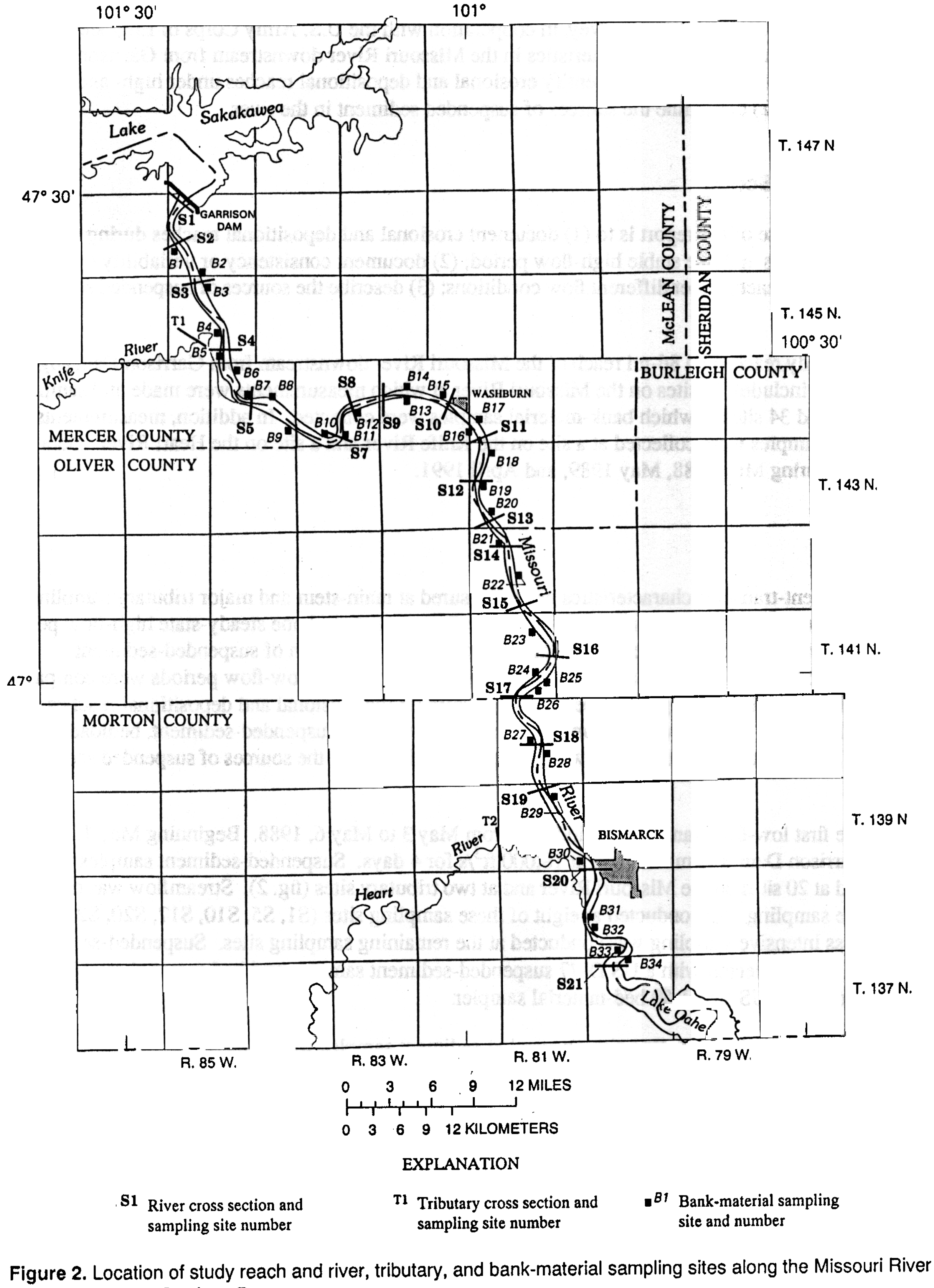


Figure 2. Location of study reach and river, tributary, and bank-material sampling sites along the Missouri River downstream from Garrison Dam.

The second low-flow sampling period was from May 2 to May 5, 1989. Beginning May 1, discharge from Garrison Dam was maintained at 17,500 ft^3/s for 3 days. Streamflow measurements were made and suspended-sediment samples were collected using the same procedures as in 1988 and at the same sites as in 1988. Bedload samples were collected at sampling sites S5, S10, S17, and S21 with a Helley-Smith bedload sampler that had a 3.22-expansion-ratio nozzle and a 0.25-mm mesh bag. Bedload samples were collected at 20 equally spaced locations in the river cross section. The sampler rested on the riverbed for 1 or 2 minutes, depending upon the site. Two sets of samples were collected about 1 hour apart and analyzed for total bedload and particle-size distribution.

The high-flow sampling period was from April 15 to April 18, 1991. Beginning April 13, discharge from Garrison Dam was maintained at 31,800 ft^3/s for 5 days. Streamflow measurements were made and suspended-sediment samples were collected using the same procedures as in 1988 and at the same sites as in 1988. Bedload samples were collected at sampling sites S5, S10, S17, S20, and S21 using the same procedures as in 1989; and bed-material samples were collected at 12 sampling sites using the same procedures as in 1988.

From May 23 to June 7, 1990, bank-material samples were collected at 34 sampling sites (fig. 2) along the study reach where the banks were actively eroding. Material was collected from the top, middle, and toe of the bank. Samples were collected when streamflow was low and the toe of the bank was above the water. A clay layer about 1-ft thick existed at the toe of the bank at some sampling sites. For sampling sites where a clay layer existed, only material from the top and middle of the bank was composited at the laboratory. The samples collected from the clay layer were not composited with the other bank-material samples because the clay layer existed in only a small part of the bank. For sampling sites where no clay layer existed, material from the top, middle, and toe was composited at the laboratory. Particle-size distributions were determined for the composited samples and for some of the samples collected from the clay layer.

SEDIMENT-TRANSPORT CHARACTERISTICS

The total suspended-sediment load in a river consists of sediment that is suspended in the water column and sediment that is bounced along the riverbed. The US D-77 sampler cannot sample the water column within 7 in. of the riverbed. The Helley-Smith bedload sampler samples from the riverbed to 3 in. above the riverbed and allows particles smaller than 0.25 mm to pass through the sampler. Thus, the water column was not sampled adequately in the interval from 3 to 7 in. above the riverbed. The total suspended-sediment load for this study was calculated by multiplying the suspended-sediment concentration by the streamflow and adding the bedload. Sediment transported in the interval from 3 to 7 in. above the riverbed was not incorporated into the total suspended-sediment load calculation because sediment in that interval was not measured.

Many studies have been done to determine the velocity necessary to detach a particle from a riverbed. All studies indicate that the detachment velocity is, at least, dependent upon the mass of the particle and the cohesion of the particle to the riverbed. The relation between detachment velocity and particle size, based on work done by Hjulstrom (1935) using quartz grains, is shown in figure 3 (Vanoni, 1975). The particles most easily detached are quartz particles about 0.25 mm in diameter. As particles become smaller than 0.25 mm, the cohesion between particles increases and the velocity necessary to detach a particle also increases. As particles become larger than 0.25 mm, the mass of the particle increases, and, again, the velocity necessary to detach a particle increases. Generally, if the detachment velocity is greater than 0.6 ft/s, quartz particles about 0.25 mm in diameter can be removed from the riverbed (fig. 3). Because sand generally is composed of quartz particles, the relation between detachment velocity and particle size for sand particles should be similar to the relation for quartz particles.

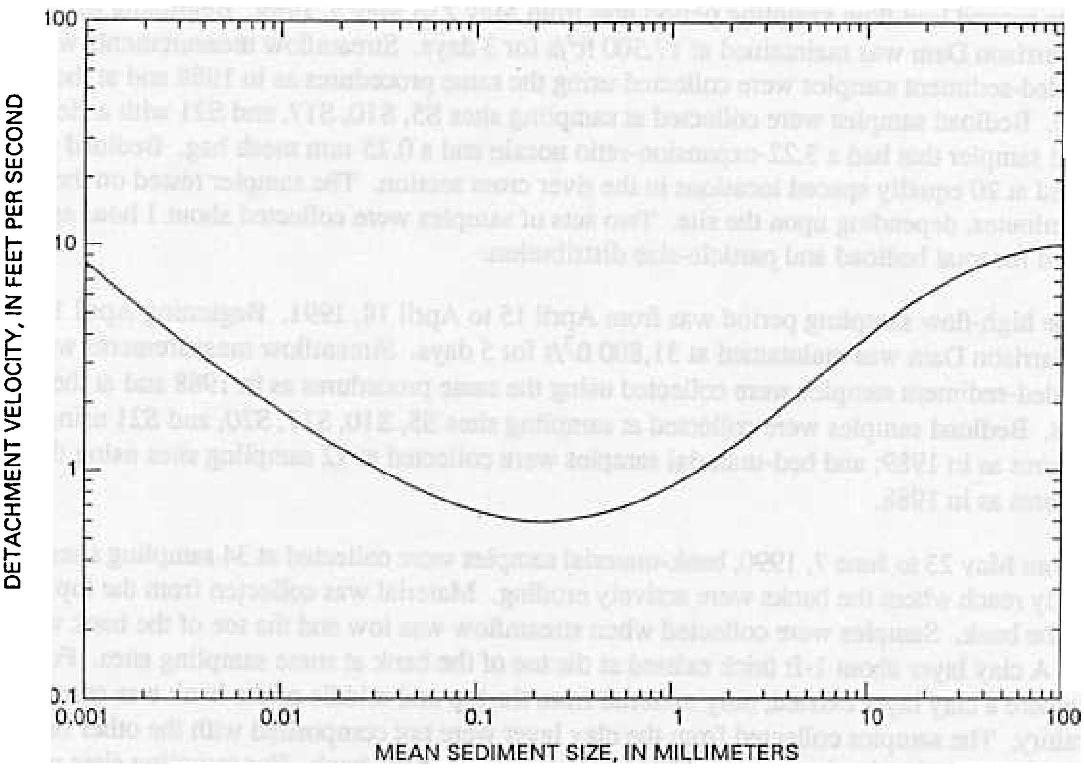


Figure 3. Detachment velocities for quartz particles as a function of mean sediment size. (Reprinted from Vanoni, 1975, p. 102, and published with permission.)

Streamflow Conditions

Sediment in a river is transported by flowing water. The characteristics of the transporting medium should be uniform throughout the study reach when comparing erosion and deposition in different subreaches of the river. Therefore, a steady discharge from Garrison Dam was established and maintained for 3 to 5 days during each of the sampling periods. Sampling began at least one day after the steady discharge was established to ensure that all of the sampling in the study reach was completed during conditions of steady-state flow. Streamflow was measured at sampling sites S1, S5, S10, S17, S20, and S21 (fig. 2). Discharge from Garrison Dam (sampling site S1) during May 1988 was 18,000 ft^3/s; discharge during May 1989 was 17,500 ft^3/s; and discharge during April 1991 was 31,800 ft^3/s (table 1). Generally, streamflow in the study reach was steady during May 1988 and April 1991. During May 1989, streamflow increased 14 percent between sampling sites S1 and S21. This increase might have a slight effect on sediment transport.

Average velocities provide insight on the erosive potential of a river. Generally, the bottom velocity of a river is about one-half the average velocity (Rantz and others, 1982). If the bottom velocity is great enough to overcome the mass of a particle and the cohesion of a particle to the riverbed, the particle can be removed from the riverbed. Average velocities in the river cross sections used in this study were all greater than 2 ft/s (table 1), indicating a large potential for erosion. The average velocity generally increased when streamflow increased, indicating the potential for erosion increases during high-flow periods.

Table 1. Streamflow and channel characteristics in the Missouri River and major tributaries downstream from Garrison Dam during May 1988, May 1989, and April 1991

[ft^3/s, cubic feet per second; ft/s, feet per second; ft, feet; --, data not available]

Sampling site number	Date	Streamflow (ft^3/s)	Average velocity (ft/s)	Maximum measured velocity (ft/s)	Average channel depth (ft)	Maximum channel depth (ft)	Channel width (ft)
S1	5-03-88	18,000	2.52	3.35	17.7	23.6	410
S1	5-02-89	17,500	2.45	3.22	17.8	22.5	400
S1	4-15-91	31,800	3.82	4.96	20.2	26.3	410
T1	5-03-88	82	1.26	1.70	1.1	1.6	59
T1	5-02-89	418	2.13	3.87	2.5	4.5	78
T1	4-15-91	47	1.09	1.46	1.2	2.1	36
S5	5-04-88	18,300	2.53	3.65	8.6	29.6	840
S5	5-03-89	18,300	2.66	4.03	7.8	28.2	882
[1]S5	4-16-91	31,600	2.48	4.65	7.3	29.0	1,744
S10	5-04-88	18,600	2.05	3.13	8.5	16.9	1,080
S10	5-03-89	19,300	2.27	3.37	7.8	16.1	1,080
S10	4-16-91	32,400	2.87	4.16	10.2	19.4	1,100
S17	5-05-88	17,900	2.57	3.35	8.3	19.7	838
S17	5-04-89	18,900	2.61	3.45	8.3	20.7	870
S17	4-17-91	32,900	3.29	4.65	11.5	21.3	865
S20	5-05-88	19,200	2.25	3.98	11.6	27.2	738
S20	5-04-89	19,600	2.39	4.03	8.8	21.6	932
S20	4-18-91	32,800	2.81	4.75	9.3	27.0	1,250
T2	5-06-88	0	--	--	--	--	--
T2	5-05-89	118	.89	1.11	1.4	2.1	93
T2	4-18-91	40	.42	.69	1.3	2.6	57
S21	5-06-88	19,000	2.48	4.37	10.4	18.9	740
S21	5-05-89	19,900	2.74	4.59	10.1	28.4	720
S21	4-18-91	32,700	3.43	5.20	11.5	29.0	825

[1]Streamflow was measured 500 feet downstream from sampling site S5 so average velocity cannot be compared to previous measurements.

The average velocity in a river cross section can be misleading when a river's potential for erosion is evaluated. Parts of the river cross section have less-than-average velocities and parts have greater-than-average velocities. The maximum measured velocity at each streamflow measurement location on the river was greater than 3.0 ft/s and some maximum measured velocities were greater than 4.0 ft/s (table 1), indicating that parts of the river cross section have a large potential for erosion.

The average channel depth, the maximum channel depth, and the channel width of the Missouri River and tributaries at streamflow measurement locations are given in table 1. These channel characteristics were used to compare large changes between sampling periods. The channel characteristics were determined from streamflow measurements. The streamflow measurements were not necessarily made at exactly the same locations during each sampling period, except at sampling sites S10 and S20 where streamflow measurements were made from bridges. Generally, the changes in channel depth and channel width are slight and are attributed to measurements being made at different locations during each sampling period or to changes in streamflow. The distinct change in channel depth and channel width at sampling site S20 between May 1988 and May 1989 cannot be attributed solely to measurement locations because all measurements were made from a bridge.

Suspended-Sediment Concentrations in the Missouri River

Suspended-sediment samples were collected at all sampling sites during May 1988, May 1989, and April 1991. Suspended-sediment concentrations determined from these samples are given in table 2 and shown in figure 4 for each of the sampling periods. The width of the plots in figure 4 is proportional to the suspended-sediment concentration at each sampling site. Erosional reaches between successive sampling sites are indicated by an increase in the width of the plot, and depositional reaches are indicated by a decrease in the width of the plot. Suspended-sediment concentrations between sampling sites should not be estimated from figure 4.

The suspended-sediment concentrations at sampling sites S1, S5, S10, S17, S20, and S21 were determined from samples collected from about 20 verticals in each of the river cross sections. The concentrations at the remaining sampling sites were determined from samples collected from about eight verticals in each of the river cross sections. Hubbell and others (1956) indicated that 10 or more equally spaced, depth-integrated verticals are necessary to adequately estimate (within 5 percent) the true suspended-sediment concentration in sand-bed rivers. Thus, the suspended-sediment concentrations determined from samples collected from about eight verticals have more variability and are less accurate than the concentrations determined from samples collected from about 20 verticals.

The smallest suspended-sediment concentrations occurred during May 1988 when discharge from Garrison Dam was 18,000 ft^3/s. Data indicate erosional reaches occurred from sampling sites S5 to S7, S10 to S11, S12 to S13, S15 to S17, S18 to S19, and S20 to S21. Depositional reaches occurred from sampling sites S8 to S9, S11 to S12, S17 to S18, and S19 to S20. Stable reaches occurred from sampling sites S1 to S5, S7 to S8, S9 to S10, and S13 to S15.

The May 1989 samples were collected when discharge from Garrison Dam was 17,500 ft^3/s. Data indicate erosional reaches occurred from sampling sites S4 to S5, S8 to S10, S12 to S13, S14 to S15, S16 to S18, and S19 to S21. Depositional reaches occurred from sampling sites S10 to S12, S13 to S14, S15 to S16, and S18 to S19. Stable reaches occurred from sampling sites S1 to S4 and S5 to S8.

Table 2. Suspended-sediment concentrations in the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991

[mg/L, milligrams per liter; ft^3/s, cubic feet per second; <, less than]

Sampling site number	River mile determined in 1960	Suspended-sediment concentration (mg/L)		
		May 1988 (18,000 ft^3/s)	May 1989 (17,500 ft^3/s)	April 1991 (31,800 ft^3/s)
[1]S1	1,389.5	1	<1	2
S2	1,384.9	2	2	4
S3	1,382.0	2	2	8
S4	1,377.7	8	6	77
[1]S5	1,372.7	8	19	302
S7	1,364.7	42	32	68
S8	1,362.3	47	36	79
S9	1,359.6	32	66	268
[1]S10	1,355.2	38	102	284
S11	1,351.5	78	66	120
S12	1,347.1	18	50	177
S13	1,344.5	41	81	110
S14	1,341.7	56	40	290
S15	1,337.3	59	60	162
S16	1,333.5	71	52	101
[1]S17	1,328.6	91	96	350
S18	1,325.0	53	149	184
S19	1,320.9	93	75	223
[1]S20	1,314.5	46	118	180
[1]S21	1,303.5	124	182	320

[1]Intensive sampling site.

The April 1991 samples were collected when discharge from Garrison Dam was 31,800 ft^3/s. Data indicate erosional reaches occurred from sampling sites S3 to S5, S8 to S10, S11 to S12, S13 to S14, S16 to S17, S18 to S19, and S20 to S21. Depositional reaches occurred from sampling sites S5 to S7, S10 to S11, S12 to S13, S14 to S16, S17 to S18, and S19 to S20. Stable reaches occurred from sampling sites S1 to S3 and S7 to S8.

Although the 1988 and 1989 samples were collected during similar streamflow conditions, the erosional and depositional reaches differed during the two sampling periods. The reaches from sampling sites S12 to S13, S16 to S17, and S20 to S21 remained erosional during the two sampling periods, and the

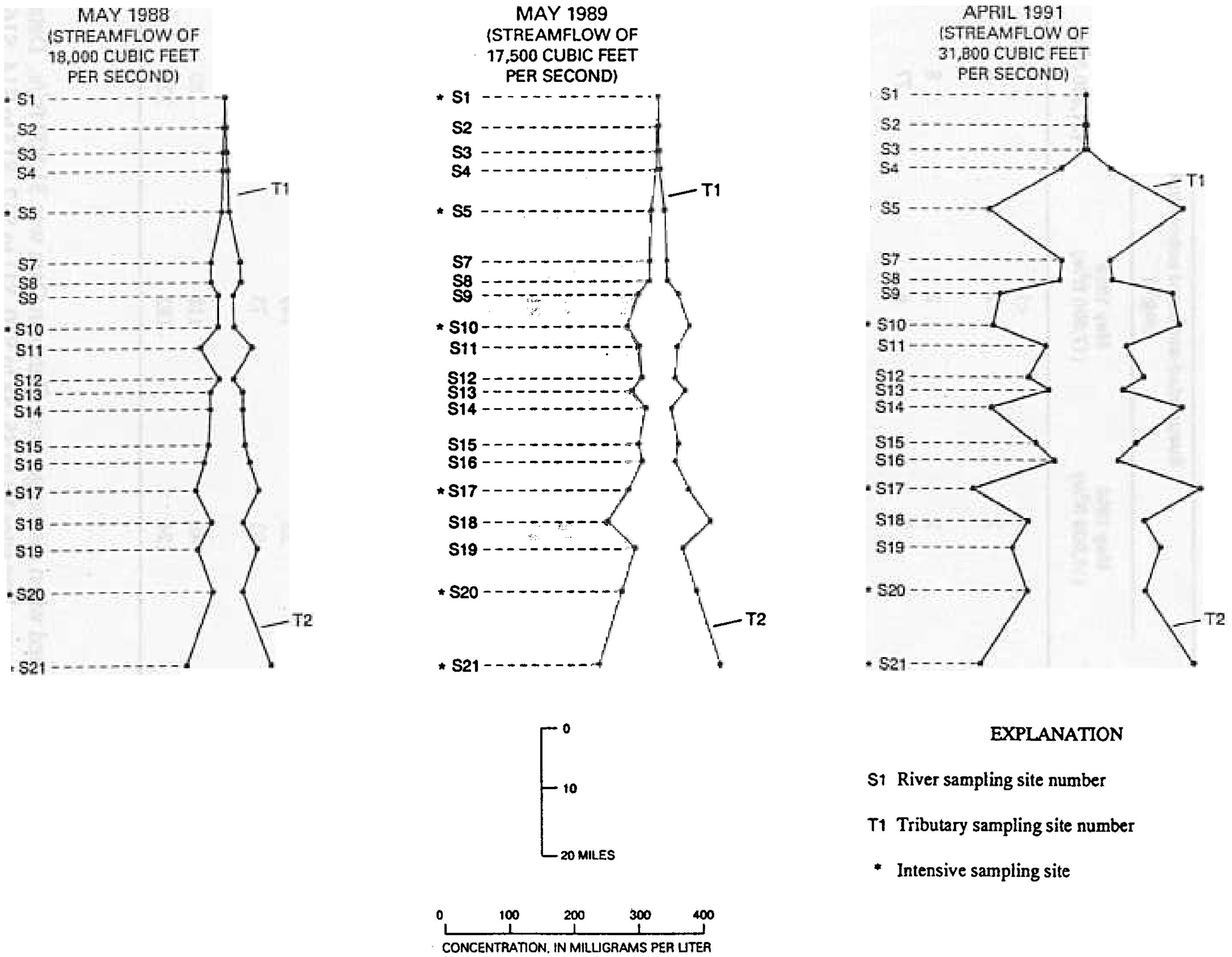


Figure 4. Suspended-sediment concentrations in the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991. Erosional reaches between successive sampling sites are indicated by an increase in the width of the plot and depositional reaches are indicated by a decrease in the width of the plot.

reaches from sampling sites S1 to S4 and S7 to S8 remained stable. All other reaches changed from 1988 to 1989. The lack of consistency between the reaches can be explained partly by movement of the sand-bed channel. Sand-bed channels are particularly unstable because sand is easily eroded; thus, slight changes in the channel configuration between 1988 and 1989 caused changes in erosional and depositional patterns. Another explanation for the lack of consistency could be the sampling variability inherent in the less intensively sampled sites. Although reaches were classified by identifying significant changes in suspended-sediment concentrations, sampling variability, if large enough, could cause false classification of reaches.

Without exception, suspended-sediment concentrations were larger in samples collected from each sampling site during the high-flow period than in samples collected during the low-flow periods. This difference was caused by greater streamflow velocities. Average velocities in the river cross sections during the high-flow period generally were greater than average velocities during the low-flow periods (table 1). Greater streamflow velocities can detach a wider range of particle sizes; thus, suspended-sediment concentrations can be larger.

The reaches from sampling sites S1 to S3 were stable during all sampling periods. This indicates that no further erosion is expected in these reaches of the river, providing discharge from Garrison Dam is less than 30,000 ft^3/s.

The reach from sampling sites S20 to S21 was eroding during all sampling periods. Usually, Lake Oahe is a short distance downstream from sampling site S21. The Missouri River formed a delta upon entering the lake, and the delta deposits could have extended as far upstream as sampling site S21. Drought conditions in the upper Missouri River Basin before and during the study caused a decrease in the size of Lake Oahe; thus, the upper limit of the lake receded to a point many miles downstream from sampling site S21. Lake Oahe could not support the delta deposits near sampling site S21, and these deposits began to erode as the lake receded. The increase in suspended-sediment concentration from sampling sites S20 to S21 is largely a result of eroding delta deposits.

The most upstream suspended-sediment concentrations greater than 50 mg/L occurred at sampling site S11 during May 1988, at sampling site S9 during May 1989, and at sampling site S4 during April 1991. The suspended-sediment concentration was larger during the high-flow period than during the low-flow periods because streamflow velocities in the river were greater during the high-flow period. The greater streamflow velocities (during the high-flow period) were able to detach and suspend larger particles between sampling sites S3 and S5 than the smaller streamflow velocities (during the two low-flow periods) were able to detach.

Suspended-Sediment Particle Size in the Missouri River

The suspended-sediment samples collected during May 1988, May 1989, and April 1991 were analyzed for particle-size distribution. In 1988 and 1989, enough suspended sediment was collected at sampling sites S5, S10, S17, S20, and S21 to do a complete particle-size distribution. An insufficient amount of suspended sediment was collected at the other sampling sites, so a sand break (percentage of suspended sediment larger than 0.062 mm) analysis was done instead of a more detailed particle-size distribution. In 1991, enough suspended sediment was collected at each of the sampling sites to do a complete particle-size distribution. The particle-size distribution of suspended sediment in the Missouri River is given in table 3, and the percentage of suspended sediment larger than the sand break (0.062 mm) is shown in figure 5.

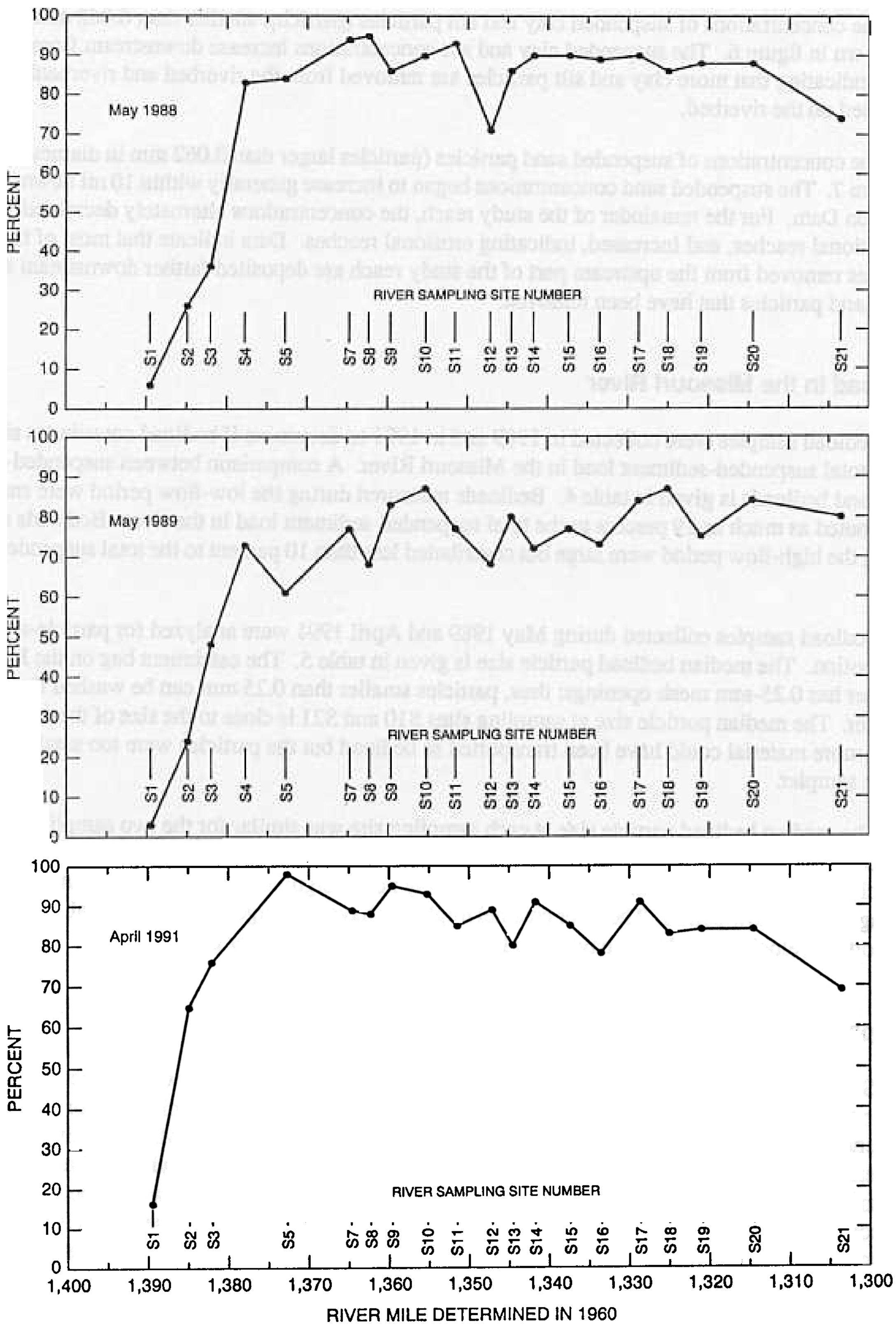


Figure 5. Percent of suspended sediment larger than sand break (0.062 millimeter) in the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991.

The concentrations of suspended clay and silt particles (particles smaller than 0.062 mm in diameter) are shown in figure 6. The suspended clay and silt concentrations increase downstream from Garrison Dam, indicating that more clay and silt particles are removed from the riverbed and riverbanks than are deposited on the riverbed.

The concentrations of suspended sand particles (particles larger than 0.062 mm in diameter) are shown in figure 7. The suspended sand concentrations began to increase generally within 10 mi downstream from Garrison Dam. For the remainder of the study reach, the concentrations alternately decreased, indicating depositional reaches, and increased, indicating erosional reaches. Data indicate that most of the sand particles removed from the upstream part of the study reach are deposited farther downstream and replace other sand particles that have been removed.

Bedload in the Missouri River

Bedload samples were collected in 1989 and in 1991 to determine if bedload contributes significantly to the total suspended-sediment load in the Missouri River. A comparison between suspended-sediment loads and bedloads is given in table 4. Bedloads measured during the low-flow period were small but contributed as much as 19 percent to the total suspended-sediment load in the river. Bedloads measured during the high-flow period were large but contributed less than 10 percent to the total suspended-sediment load.

Bedload samples collected during May 1989 and April 1991 were analyzed for particle-size distribution. The median bedload particle size is given in table 5. The catchment bag on the Helley-Smith sampler has 0.25-mm mesh openings; thus, particles smaller than 0.25 mm can be washed through the sampler. The median particle size at sampling sites S10 and S21 is close to the size of the mesh openings. Thus, more material could have been transported as bedload but the particles were too small to be caught by the sampler.

The median bedload particle size at each sampling site was similar for the two sampling periods. Although the particle-size distribution is biased because of the sampler, the similarity indicates that particles transported during the high-flow period may not be significantly larger than particles transported during the low-flow period. The river channel might not have had larger particles available for transport or the bottom velocities might not have been large enough to detach larger particles.

Suspended-Sediment Load in Tributaries

Streamflow measurements were made and suspended-sediment samples were collected from the Knife River and the Heart River (fig. 2) during the three sampling periods to determine the contribution of suspended-sediment in the tributaries to the suspended-sediment load in the Missouri River. The suspended-sediment concentrations and loads in the tributaries and the suspended-sediment load in the Missouri River are given in table 6. Data indicate that occasionally, during low-flow periods on the Missouri River, the Knife River can contribute significantly to the suspended-sediment load in the Missouri River. During May 1989, the suspended-sediment load in the Knife River was greater than the suspended-sediment load in the Missouri River at sampling site S5. Most of the increase in suspended-sediment concentration from sampling sites S4 to S5 probably was caused by inflow of sediment-laden water from the Knife River. Although the suspended-sediment loads in the Knife River and the Missouri River were calculated from data collected on different days, the loads indicate that sediment was deposited in the Knife River downstream from sampling site T1 and in the Missouri River downstream from sampling site S4.

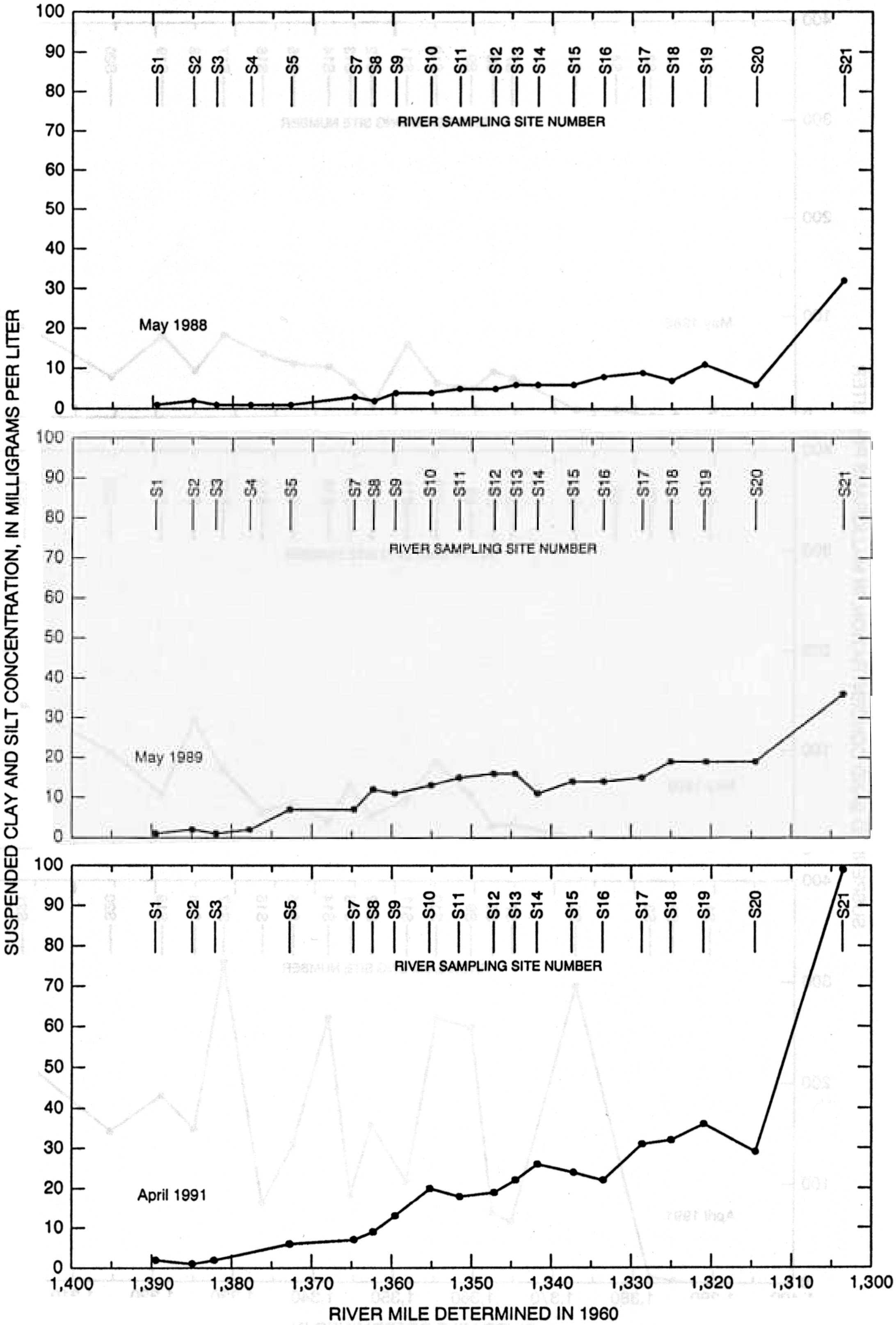


Figure 6. Suspended clay and silt concentrations in the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991.

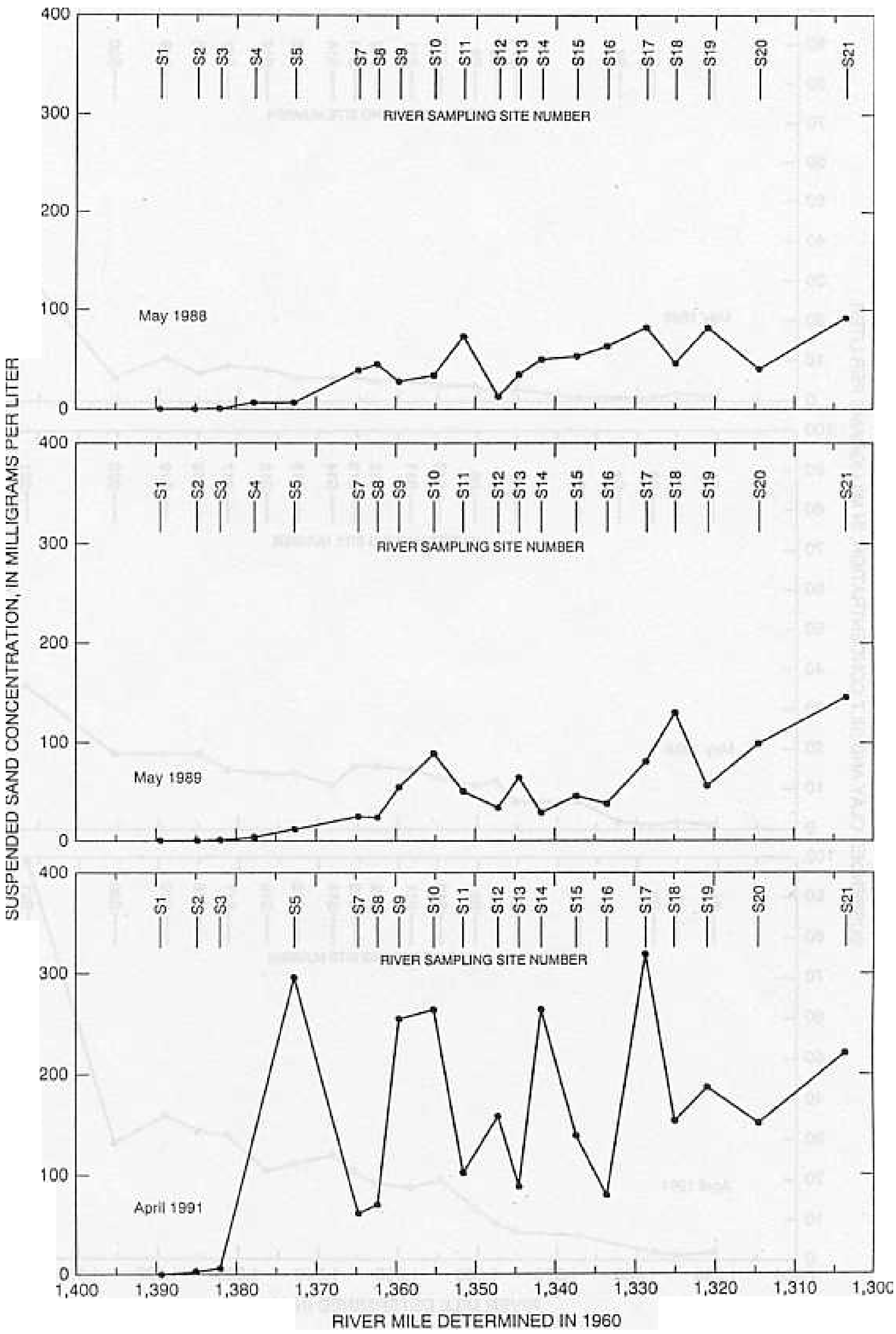


Figure 7. Suspended sand concentrations in the Missouri River downstream from Garrison Dam during May 1988, May 1989, and April 1991.

Table 4. Suspended-sediment loads, bedloads, and total suspended-sediment loads in the Missouri River downstream from Garrison Dam during May 1989 and April 1991

[ft^3/s, cubic feet per second; <, less than]

Sampling site number	Date	Streamflow (ft^3/s)	Suspended-sediment load (tons per day)	Bedload (tons per day)	Total suspended-sediment load (tons per day)	Percent of total suspended-sediment load as bedload
S5	5-03-89	18,300	939	134	1,070	13
S5	4-16-91	31,600	25,800	2,630	28,400	9
S10	5-03-89	19,300	5,320	1,210	6,530	19
S10	4-16-91	32,400	24,800	1,000	25,800	4
S17	5-04-89	18,900	4,900	763	5,660	13
S17	4-17-91	32,900	31,100	1,080	32,200	3
S20	4-18-91	32,800	15,900	164	16,100	1
S21	5-05-89	19,900	9,780	88	9,870	<1
S21	4-18-91	32,700	28,300	227	28,500	<1

Table 5. Median bedload particle size in the Missouri River downstream from Garrison Dam during May 1989 and April 1991

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

Sampling site number	River mile determined in 1960	Median particle size (millimeters)	
		May 1989 ($17,500\ ft^3/s$)	April 1991 ($31,800\ ft^3/s$)
S5	1,372.7	0.33	0.34
S10	1,355.2	.26	.26
S17	1,328.6	.32	.31
S21	1,303.5	.28	.28

SOURCES OF SEDIMENT

Sediment transported by the Missouri River downstream from Garrison Dam comes from the riverbed, the riverbanks, and tributaries.

Riverbed

Sediment transported by a river is stored on the riverbed. When a river channel is at equilibrium with streamflow, material removed from the riverbed constantly is replaced by material removed farther upstream. Bed material in the Missouri River typically is sand size or larger (fig. 8). Clay and silt particles comprise a small percentage of the bed material because little energy is required to keep clay and silt particles suspended. Clay and silt particles do not settle on the riverbed unless velocities in the river become extremely small.

The removal of sediment from the Missouri River channel has decreased the mean bed elevation by as much as 13 ft downstream from Garrison Dam (Williams and Wolman, 1984). Erosion will continue until the channel slope has decreased enough so that velocities become too small to detach particles from the riverbed or until the bed material becomes too large to be detached by existing velocities. Because sand particles about 0.25 mm in diameter are the easiest to detach from the riverbed, these particles are the first to be removed. If the bottom velocities are great enough, particles larger than 0.25 mm in diameter also will be removed. If particles removed from the riverbed are not replaced, as is the case with the Missouri River directly downstream from Garrison Dam, the size of the particles that compose the riverbed should become larger. This will happen only if particles on the riverbed have a wide range of sizes.

Particle-size analyses of bed material collected during May 1988 and April 1991 indicate that the riverbed generally is composed of sand particles between 0.10 and 1.0 mm in diameter (fig. 8). Most of the samples contained less than 25 percent clay and silt or gravel. This indicates that particles on the riverbed have a narrow range of sizes. A significant amount of erosion would have to occur in the river channel before gravel particles become dominant in the river cross section. Gravel particles are found upstream from sampling site S4 where the bed elevations have decreased the most (Williams and Wolman, 1984). In fact, bed-material samples were not collected at sampling site S2 during April 1991 because

Table 6. Suspended-sediment concentrations and loads in the Knife River (sampling site T1) and the Heart River (sampling site T2) and suspended-sediment load in the Missouri River downstream of tributary confluence

[mg/L, milligrams per liter; ft^3/s, cubic feet per second; --, data not collected or calculated]

Sampling site number	Date	Streamflow (ft^3/s)	Suspended-sediment concentration (mg/L)	Suspended-sediment load in tributary (tons per day)	Suspended-sediment load in Missouri River (tons per day)
T1	5-03-88	82	116	26	[1]395
	5-02-89	418	1,740	1,960	[1]939
	4-15-91	47	54	7	[1]25,800
T2	5-06-88	0			[2]6,360
	5-05-89	118	138	44	[2]9,780
	4-18-91	40	45	5	[2]28,500

[1]Calculated from data for sampling site S5.

[2]Calculated from data for sampling site S21.

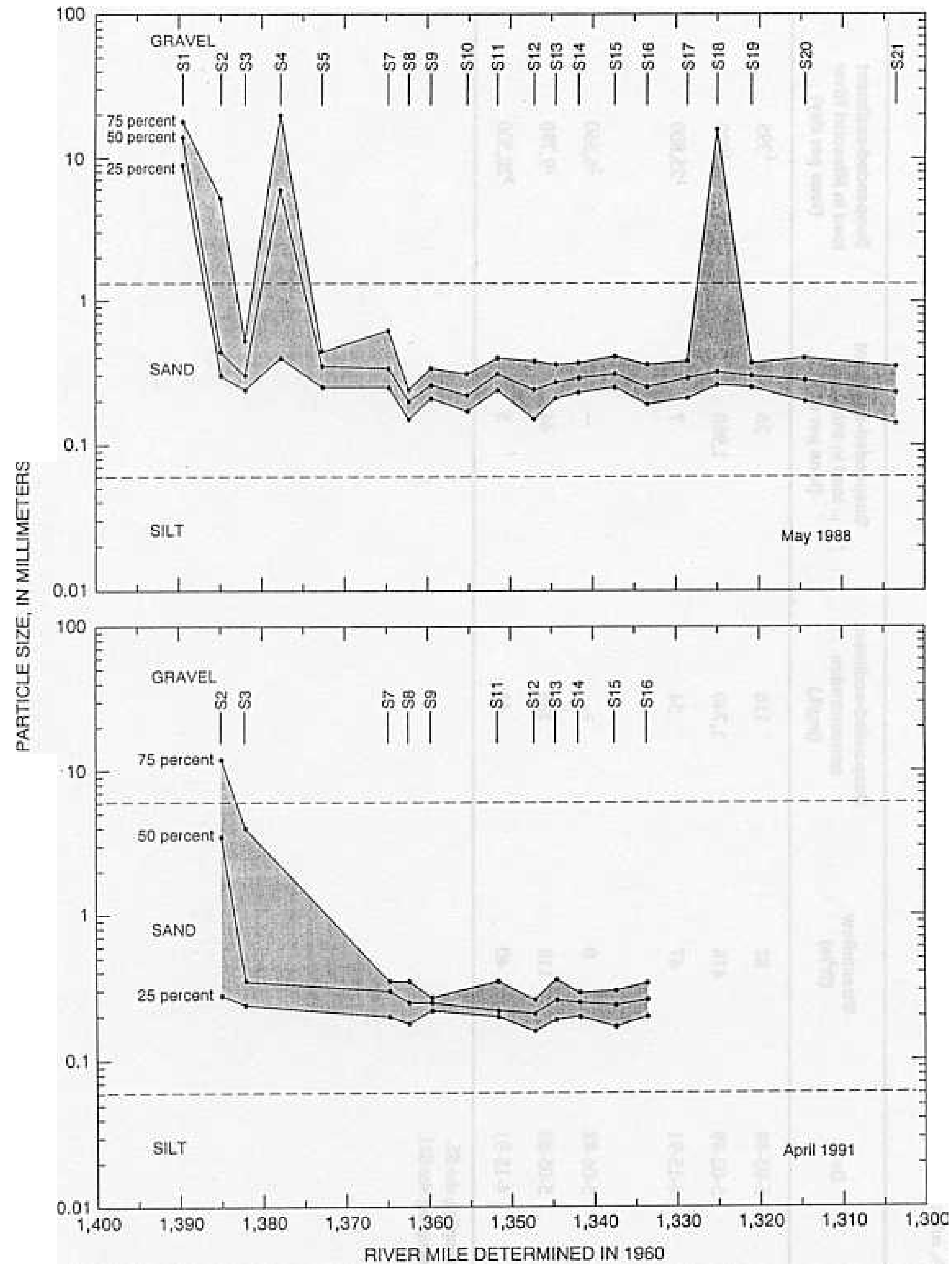


Figure 8. Particle-size distribution of bed material in the Missouri River downstream from Garrison Dam during May 1988 and April 1991. Solid lines represent the particle size where 25 percent, 50 percent, and 75 percent of the bed material is smaller than that size.

bedrock was observed across most of the river cross section. The large particles in the riverbed upstream from sampling site S3 indicate why suspended-sediment concentrations did not increase substantially between sampling sites S1 and S3 during the three sampling periods.

Riverbanks

Bank-material samples were collected at 34 sampling sites (fig. 2) along the study reach where the banks were actively eroding. Data indicate no apparent trend exists in riverbank particle-size distribution with distance downstream from Garrison Dam (fig. 9). Therefore, particle-size data from each sampling site were composited mathematically into a unit histogram (fig. 10) that represents the particle-size distribution in bank material along the river. Data indicate that the bank material is composed of clay, silt, and sand and that more than 50 percent of the material is sand.

Tributaries

For the most part, the suspended-sediment contribution from the tributaries to the suspended-sediment load in the Missouri River is insignificant. At times, however, the tributaries carry more sediment to the Missouri River than is being transported by the Missouri River (table 7). Although the Heart River did not provide a substantial suspended-sediment load to the Missouri River during this study, the Knife River did provide a substantial load during May 1989.

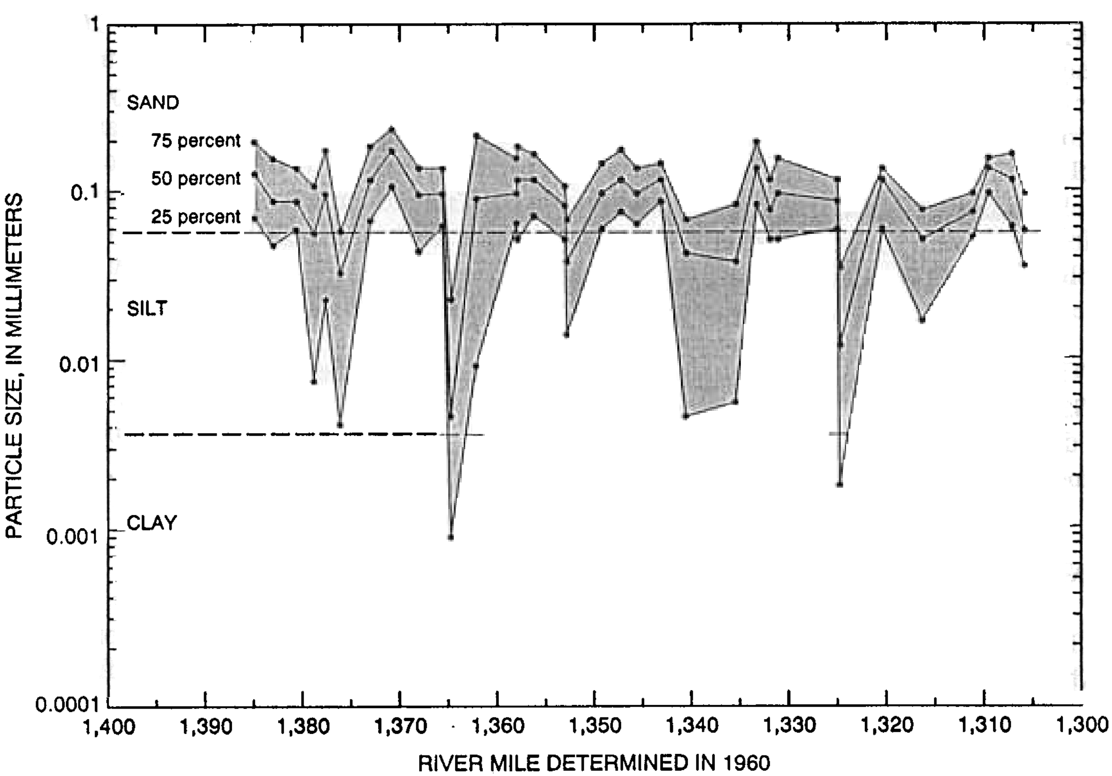


Figure 9. Particle-size distribution of bank material in the Missouri River downstream from Garrison Dam, May 23 to June 7, 1990. Solid lines represent the particle size where 25 percent, 50 percent, and 75 percent of the bank material is smaller than that size.

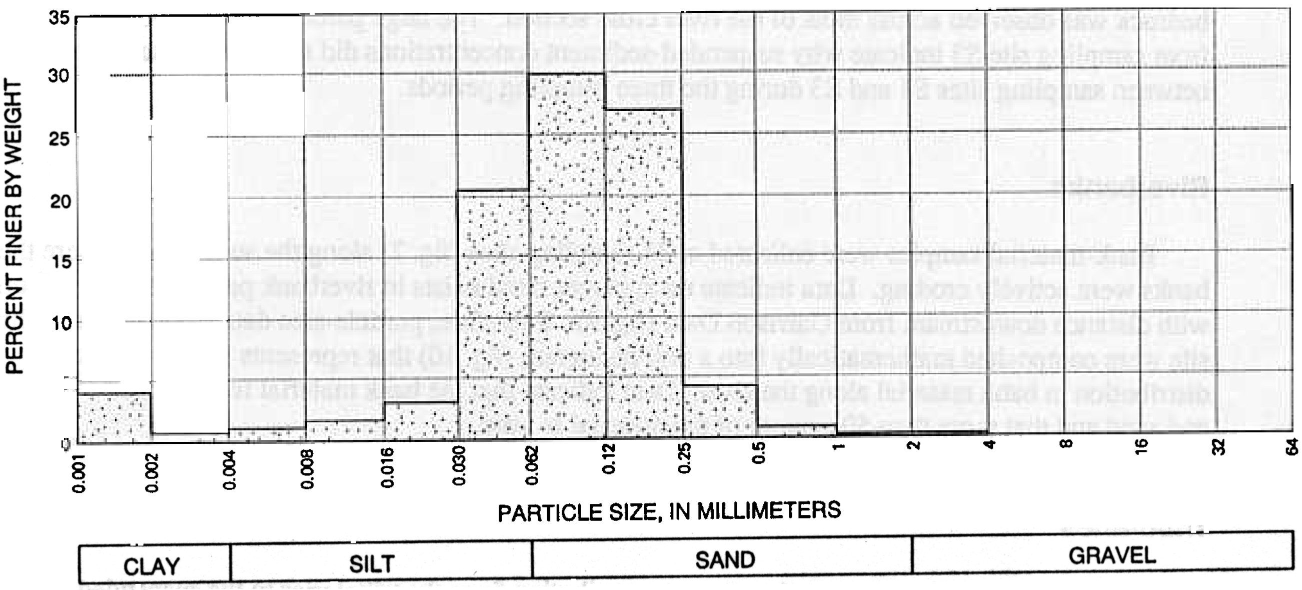


Figure 10. Particle-size distribution in bank-material samples collected from 34 sampling sites along the Missouri River downstream from Garrison Dam, May 23 to June 7, 1990.

On May 2, 1989, the suspended-sediment load in the Knife River (sampling site T1) was greater than the suspended-sediment load in the Missouri River upstream and downstream from the confluence with the Knife River. The Knife River was transporting 1,690 tons of sand per day and 270 tons of clay and silt. The Missouri River upstream from the Knife River (sampling site S4) was transporting 207 tons of sand per day and 77 tons of clay and silt. On May 3, 1989, the Missouri River downstream from the Knife River (sampling site S5) was transporting 573 tons of sand per day and 366 tons of clay and silt. These data indicate that the suspended-sediment load in the Missouri River increased significantly between sampling sites S4 and S5. Most of the increase probably was caused by inflow from the Knife River. The data also indicate that more sand was transported in the Knife River downstream from sampling site T1 and in the Missouri River downstream from sampling site S4 than in the Missouri River downstream from sampling site S5. The sand probably was deposited in the Knife River downstream from sampling site T1, in the Missouri River downstream from sampling site S4, or in both.

The Knife River can be a significant source of suspended sediment to the Missouri River at sampling site S5, but the Missouri River accumulates more suspended sediment from the riverbed and riverbanks with distance downstream. By the time the water reaches sampling site S21, the contribution of suspended sediment from the Knife River probably is insignificant, as indicated in figures 6 and 7.

CONTRIBUTIONS TO SEDIMENT LOAD

The suspended sediment in the Missouri River downstream from Garrison Dam comes from the riverbed, riverbanks, and tributaries. A quantitative determination of the contribution from each of the sources at any sampling site on the Missouri River is beyond the scope of this report, but data presented in this report indicate the relative significance of each source.

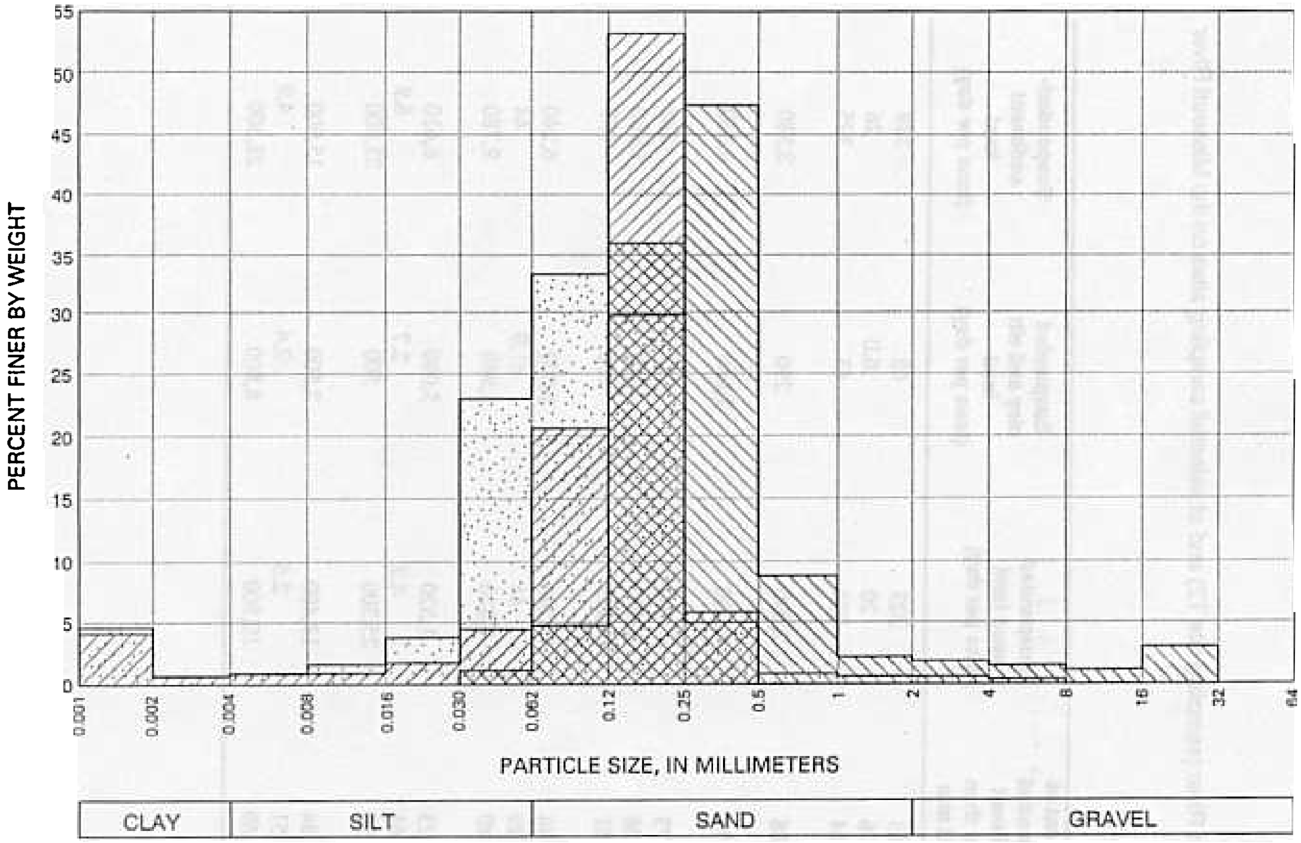
Contributions from the riverbed and riverbanks to the suspended-sediment load were evaluated by comparing suspended-sediment, bed-material, and bank-material particle-size distributions (fig. 11). The suspended-sediment data were collected at sampling sites S5, S10, S17, S20, and S21 during May 1988;

Table 7. Suspended-sediment loads in the Knife River (sampling site T1) and the Heart River (sampling site T2) and at selected sampling sites on the Missouri River during May 1988, May 1989, and April 1991

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; mm, millimeters; --, data not available]

Sampling site number	Date	Streamflow (ft^3/s)	Suspended-sediment concentration (mg/L)	Percent of suspended sediment larger than 0.062 mm	Suspended sand load (tons per day)	Suspended clay and silt load (tons per day)	Suspended-sediment load (tons per day)
S4	5-03-88	[1]18,000	8	83	323	65	388
T1	5-03-88	82	116	76	20	6.0	26
S5	5-04-88	18,300	8	84	332	63	395
S20	5-05-88	19,200	46	88	2,090	290	2,380
T2	5-06-88	0	--	--	--	--	--
S21	5-06-88	19,000	124	74	4,700	1,660	6,360
S4	5-02-89	[1]17,500	6	73	207	77	284
T1	5-02-89	418	1,740	86	1,690	270	1,960
S5	5-03-89	18,300	19	61	573	366	939
S20	5-04-89	19,600	118	84	5,240	1,000	6,240
T2	5-05-89	118	138	99	44	<1.0	44
S21	5-05-89	19,900	182	80	7,820	1,960	9,780
S4	4-15-91	[1]31,800	77	23	1,520	5,090	6,610
T1	4-15-91	47	54	61	4.2	2.7	6.9
S5	4-16-91	31,600	302	98	25,300	500	25,800
S20	4-18-91	32,800	180	84	13,400	2,500	15,900
T2	4-18-91	40	45	51	2.5	2.4	4.9
S21	4-18-91	32,700	320	69	19,500	8,800	28,300

[1]Streamflow at sampling site S4 is assumed to be equal to streamflow at sampling site S1.



EXPLANATION

Composite of suspended sediment in Missouri River downstream from Garrison Dam. Samples collected during May 1988

Composite of bed material in Missouri River downstream from Garrison Dam. Samples collected during May 1988

Composite of bank material in Missouri River downstream from Garrison Dam. Samples collected from May 23 to June 7, 1990

Figure 11. Particle-size distribution of suspended sediment (May 1988), bed material (May 1988), and bank material (May 23 to June 7, 1990) in or along the Missouri River downstream from Garrison Dam.

the bed-material data were collected at sampling sites S5 through S21 during May 1988; and the bank-material data were collected at 34 sampling sites where the banks were actively eroding from May 23 to June 7, 1990. The suspended sediment is composed of clay, silt, and sand; the bed material is composed predominantly of sand with little silt and gravel and no clay; and the bank material is composed mainly of silt and sand with some clay (fig. 11). The Knife River may have contributed most of the clay and silt particles in the Missouri River at sampling site S5, but clay and silt concentrations increased downstream from that site. The additional clay particles must have come from the riverbanks because the riverbed contained no clay particles and few silt particles. The silt and sand particles suspended in the river come from the riverbed and the riverbanks.

The increasing suspended-sediment concentrations in the Missouri River downstream from Garrison Dam indicate that the riverbed and riverbanks continue to erode. Williams and Wolman (1984) stated that the river channel downstream from Garrison Dam began widening after the dam was completed and theorized that the channel widening will continue until an equilibrium width is reached. Using regression, Williams and Wolman (1984) estimated that the cross sections would reach 95 percent of the equilibrium width within 2 to 90 years after the dam was completed. Thus, suspended-sediment contributions from the riverbanks are expected to decrease with time. A river that has sandy banks will meander from side to side, however, eroding old banks and forming new banks while keeping a constant channel width through time. Therefore, the Missouri River will transport sediment downstream from Garrison Dam indefinitely.

The riverbed contributes to the silt and sand load transported by the Missouri River. Also, as shown in figure 11, the suspended sediment has a larger percentage of sand than the bank material, meaning the additional sand particles in suspension must have come from the riverbed.

SUMMARY

Sediment data were collected on and along the Missouri River downstream from Garrison Dam to characterize sediment transport in the river. Suspended-sediment and bed-material data were collected during a low flow of 18,000 cubic feet per second during May 1988; suspended-sediment and bedload data were collected during a low flow of 17,500 cubic feet per second during May 1989; and suspended-sediment, bedload, and bed-material data were collected during a high flow of 31,800 cubic feet per second during April 1991. Bank-material data were collected from May 23 to June 7, 1990.

Suspended-sediment data collected during the two low-flow periods indicate that slight changes in the channel configuration between the two periods caused changes in erosional and depositional reaches during the two sampling periods. Three reaches remained erosional, four reaches remained stable, and all others changed.

Suspended-sediment data collected during the high-flow period indicate that channel changes and increased streamflow velocities affected erosional and depositional reaches between the low-flow periods and the high-flow period. One reach remained erosional during all sampling periods, two reaches remained stable, and all others changed. The erosional reach was from sampling sites S20 to S21. Material eroded from this reach probably came from delta formations deposited in earlier years when Lake Oahe extended as far upstream as sampling site S21. The stable reaches were from sampling sites S1 to S3.

The suspended-sediment concentration was larger during the high-flow period than during the low-flow periods because streamflow velocities were greater during the high-flow period. The greater streamflow velocities were able to detach and suspend larger particles.

Particle-size data indicate that, downstream from sampling site S4, most suspended sediment was larger than the sand break (0.062 millimeter in diameter). The percentage of sand transported by the river did not change significantly between the low-flow periods and the high-flow period. The median particle size for suspended sediment collected at most sampling sites was classified as fine sand (0.12 to 0.25 millimeter in diameter). Little difference exists between the median particle size for each sampling period. The suspended clay and silt concentrations increase downstream from Garrison Dam, indicating that more clay and silt particles are removed from the riverbed and riverbanks than are deposited on the riverbed.

Bedload samples were collected during a low-flow period and a high-flow period. Bedloads measured during the low-flow period contribute as much as 19 percent to the total suspended-sediment load in the river. Bedloads measured during the high-flow period contribute less than 10 percent to the total suspended-sediment load. The contribution of bedload as a percentage of the total suspended-sediment load in the Missouri River decreases as streamflow increases.

The contribution from tributaries to the suspended-sediment load in the Missouri River downstream from Garrison Dam usually is small. Occasionally, during low-flow periods on the Missouri River, the Knife River can contribute significantly to the suspended-sediment load in the river.

Most suspended sediment in the Missouri River downstream from Garrison Dam comes from the riverbed and the riverbanks. The riverbed contributes to the silt and sand load in the river, and the riverbanks contribute to the clay, silt, and sand load.

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