SUSPENDED SEDIMENT IN MINNESOTA STREAMS

By L. H. Tornes

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4312

Prepared in cooperation with the

MINNESOTA DEPARTMENT OF NATURAL RESOURCES, and the

U.S. ARMY CORPS OF ENGINEERS

St. Paul, Minnesota

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
702 Post Office Building
St. Paul, Minnesota 55101
Telephone: (612) 725-7841

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Bldg. 41
Box 25425
Denver, Colorado 80225
Telephone: (303) 236-7476

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

Readers who may prefer to use metric (International System) units rather than the inch-pound units can make conversions using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
cubic foot (ft^3)	28.32	liter (L)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
ounce avoirdupois (oz avdp)	28,350	milligrams (mg)
square mile (mi^2)	2.590	square kilometer (km^2)
ton, short (2,000 lb)	0.9072	megagram (Mg)
tons per square mile (t/m^2)	0.3503	megagrams per square kilometer (Mg/km^2)

SUSPENDED SEDIMENT IN MINNESOTA STREAMS

By L. H. Tornes

ABSTRACT

Suspended-sediment samples have been collected by the U.S. Geological Survey from 115 sites on Minnesota streams since October 1960. Data from 42 sites were sufficient for characterizing sediment concentrations and yields. Average concentrations ranged from 4.4 milligrams per liter on the Baptism River in northeastern Minnesota to 190 milligrams per liter on the Root River in the southeast.

Log-linear equations that describe the sediment-transport curve were developed for 33 daily sediment stations and used to estimate long-term sediment yields. Average annual yields ranged from less than 1.0 ton per square mile on the Pelican River, to more than 200 tons per square mile on the Root and Whitewater Rivers and Deer Creek. Estimates indicated that under extreme circumstances the average annual sediment load for 2 years could be transported in slightly more than one day.

Analysis showed that more than 90 percent of the annual sediment load was carried during 3 to 9 months of the year. On the average, almost 25 percent of the annual sediment load was transported during April. Generally, it was found that less than 4 percent of the average annual load was transported during December, January, and February, which indicates that sampling frequency could be reduced during winter.

INTRODUCTION

Background and Concepts

Fluvial sediment, particles derived from rocks or biological materials which are transported by, suspended in, or deposited by streams, is a problem because it results in siltation of reservoirs and navigation channels. Fluvial sediment can sorb and transport many harmful substances including organic chemicals such as PCB's and pesticides, eutrophication-causing nutrients, and toxic metals (Baker, 1980).

Fluvial sediment originates from several sources. Soil particles exposed by cultivation, construction activities, and clear cutting of forests can be loosened by raindrops and sheet and rill erosion and carried to receiving waters. Erosion of stream banks and streambeds also contributes to the sediment load of a stream.

The amount of sediment carried by a stream primarily depends on (1) the availability of erodible sediments: a stream originating in a region having a predominance of exposed bedrock will normally carry far less sediment than a comparable stream originating in an area mostly covered by unconsolidated soils, (2) the particle size of fluvial sediments: generally, small particles are readily suspended and transported, whereas larger particles tend to move along or deposit on the streambed, (3) stream velocity: increased stream velocity generally results in increased turbulence which can support more and larger sediment particles than less-turbulent waters, and (4) viscosity: increased viscosity reduces the rate at which sediment particles fall to the streambed.

This report discusses only suspended-sediment data. Suspended sediment is that part of the fluvial sediment maintained in suspension by turbulence or existing in suspension as a colloid in the sampled zone (from the water surface to a point about 0.3 foot above the streambed). A substantial part of the total fluvial sediment may be carried in the unsampled zone (less than about 0.3 foot from the streambed), an area that has not been sampled with reproducible accuracy (Guy and Norman, 1970). The unsampled zone carries both suspended sediment and bedload sediment. The relatively large particles of the bedload sediment are moved along the streambed by rolling or skipping and may become deposited on the streambed for extended periods.

Many terms are used in this report to describe suspended sediment. The following definitions are provided for clarification.

<u>Suspended-sediment concentration</u> (mg/L) is the velocity-weighted concentration of suspended sediment expressed as milligrams of dry sediment per liter of water-sediment mixture.

<u>Suspended-sediment discharge</u> (tons/day) is the rate at which dry weight of sediment passes a section of a stream in a given time. It is computed by multiplying streamflow times mg/L times 0.0027.

<u>Suspended-sediment load</u> (tons) is quantity of suspended sediment passing a section in a specified period.

<u>Daily concentration</u> (mg/L) is the time-weighted concentration of suspended sediment passing a stream section during a 24-hour day.

<u>Suspended-sediment yield</u> [(tons/day)/mi^2] is the suspended-sediment discharge or load per unit of drainage area for a stream.

The amount of suspended sediment transported by streams can be discussed in terms of discharges, loads, or yields. Discharge and load are similar terms describing the amount of sediment transported by a stream in a unit of time. They are useful in describing the amount of sediment carried past a site or possibly delivered to a lake or impoundment where reduced turbulence selectively drops the sediment load to the bottom. Discharge and load are limited in their utility, however, because they are largely affected by flow of the stream: a large river with a minimal sediment concentration would probably have a much larger sediment load than a small creek carrying a high sediment concentration. As a result, basin comparisons are complicated by the size of the watersheds and the volume of water draining them.

Suspended-sediment yields, however, take the size of the watershed into consideration making basin comparisons more accurate. In watersheds of several thousand square miles or less, yields generally provide a reasonable estimate of sediment being carried from the land surface to the sampling site. In most rivers, and particularly larger rivers with very large watersheds, however, sediment will be deposited in the channel, flood plains, lakes, and impoundments along the river upstream from the sampling site resulting in measured yields that probably are much lower than actual watershed yields. Suspended-sediment transport will be discussed in this report in terms of basin yield to facilitate basin comparisons.

A more detailed discussion of erosion and sediment transport and deposition is presented in "Fluvial Sediment Concepts" (Guy, 1970).

Purpose and Scope

Samples were collected from 115 sites on Minnesota streams and analyzed for suspended-sediment concentration. The data were collected between October 1960 and September 1981, mostly as part of a cooperative program between the U.S. Geological Survey and various State and Federal agencies. Records obtained range from one sample at one site to daily samples at a site for a 13-year period. The purpose of this report is to summarize and interpret these data.

This report updates a report by Collier (1974) by using data collected at 43 sites on 33 Minnesota streams from October 1967 through September 1981. The report summarizes data on sediment concentrations, and relationships between sediment discharge and streamflow are used to estimate long-term sediment yields.

Areal variations and similarities in sediment yield are discussed and related to generalized soil types and to a lesser extent, to land use. Apparent trends in sediment concentrations and yields are presented. The annual distribution of sediment load is discussed and related to methods of data collection. The effectiveness of the cooperative sediment-data-collection network of the U.S. Geological Survey in Minnesota is evaluated and suggestions for future data collection are presented.

Previous Investigations

Fluvial sediment samples were collected on the Minnesota, Zumbro, and Root Rivers in Minnesota by the U.S. Army Corps of Engineers, St. Paul District, during March-June 1937 and May-June 1938. The results were reported by Lane (1938).

Measurements of the sediment concentration in several Minnesota streams were made by the U.S. Geological Survey during 1960-62 and the results were reported by Maderak (1963). The results of sampling conducted during a major flood in 1965 were reported in the publication "Water Resources Data for Minnesota," (U.S. Geological Survey, 1966).

Sediment yield of watersheds in the Upper Mississippi River basin were estimated in a study by the Upper Mississippi River Comprehensive Basin Study Coordinating Committee (1970). These estimates were based primarily on the similarity of sediment yields throughout a given area. Measured yields for streams in Iowa and Wisconsin were extrapolated into Minnesota by land-resource areas (Collier, 1974).

A paper by Collier (1974) summarizing sediment data collected in Minnesota by the U.S. Geological Survey during October 1967 to September 1971 incorporated data from 21 sites on 18 streams for which 1 to 4 years of record were available. Based on the limited record, preliminary estimates of sediment yield of Minnesota watersheds were presented.

Physical Setting

Minnesota, which is near the center of North America, has a total area of 84,068 square miles. Average annual precipitation in Minnesota ranges from about 20 inches in the northwest to about 32 inches in the southeast (Brown and others, 1969). Figure 1 is a map of Minnesota showing the streams included in this report and the cities or towns closest to the sediment-sampling stations.

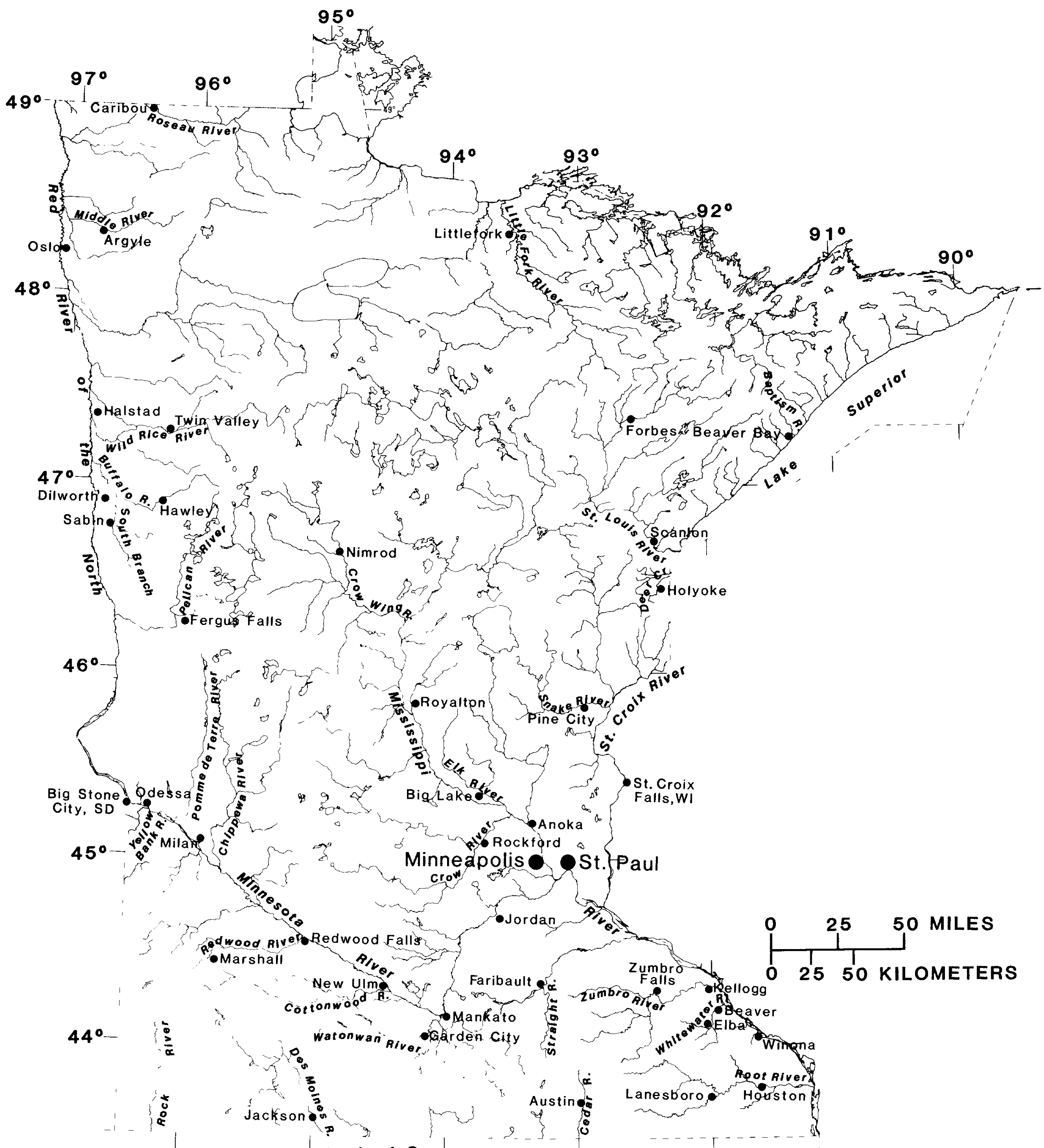
Glacial activity, which has affected most of Minnesota, contributed to development of the major soil types shown in figure 2. Rocks at the surface range from bedrock having low erodibility in the northeast to loess deposits, which are highly susceptible to erosion, in the southeast. Most of the State has clayey or sandy soils, both of which are potentially erodible. Deposits of peat in northern Minnesota, although unstable, are protected from erosion by vegetative cover and are not subject to high erosive forces because of the flat relief in areas of these deposits.

Erosion generally is most severe during urban development, cultivation, clearcut logging, and other activities that disturb or remove the natural protective vegetation and soil cover. Figure 3 is a generalized land-use map of Minnesota. Most of the northeastern part of the State is forested, but has some open pasture and limited cultivation. The far western and southern parts of Minnesota are intensively cultivated. Between these areas lies a transitional zone with a combination of cultivated areas, pasture, and forests. Urban areas are scattered throughout the State, but the largest is the Twin Cities Metropolitan Area.

SAMPLE COLLECTION AND ANALYSIS

Sediment samples are collected using the methods of Guy and Norman (1970) and shipped to the U.S. Geological Survey sediment laboratory in Iowa City, Iowa, for analysis. The analyses determine concentration and particle sizes of the sediment using methods described in Guy (1969).

Records of suspended sediment are prepared using the methods described in Porterfield (1972). The type of sampling program determines which of three types of sediment records is prepared for each station. Samples are collected



Base from U.S. Geological Survey
Minnesota state base map

Figure 1.--Location of streams included in this report

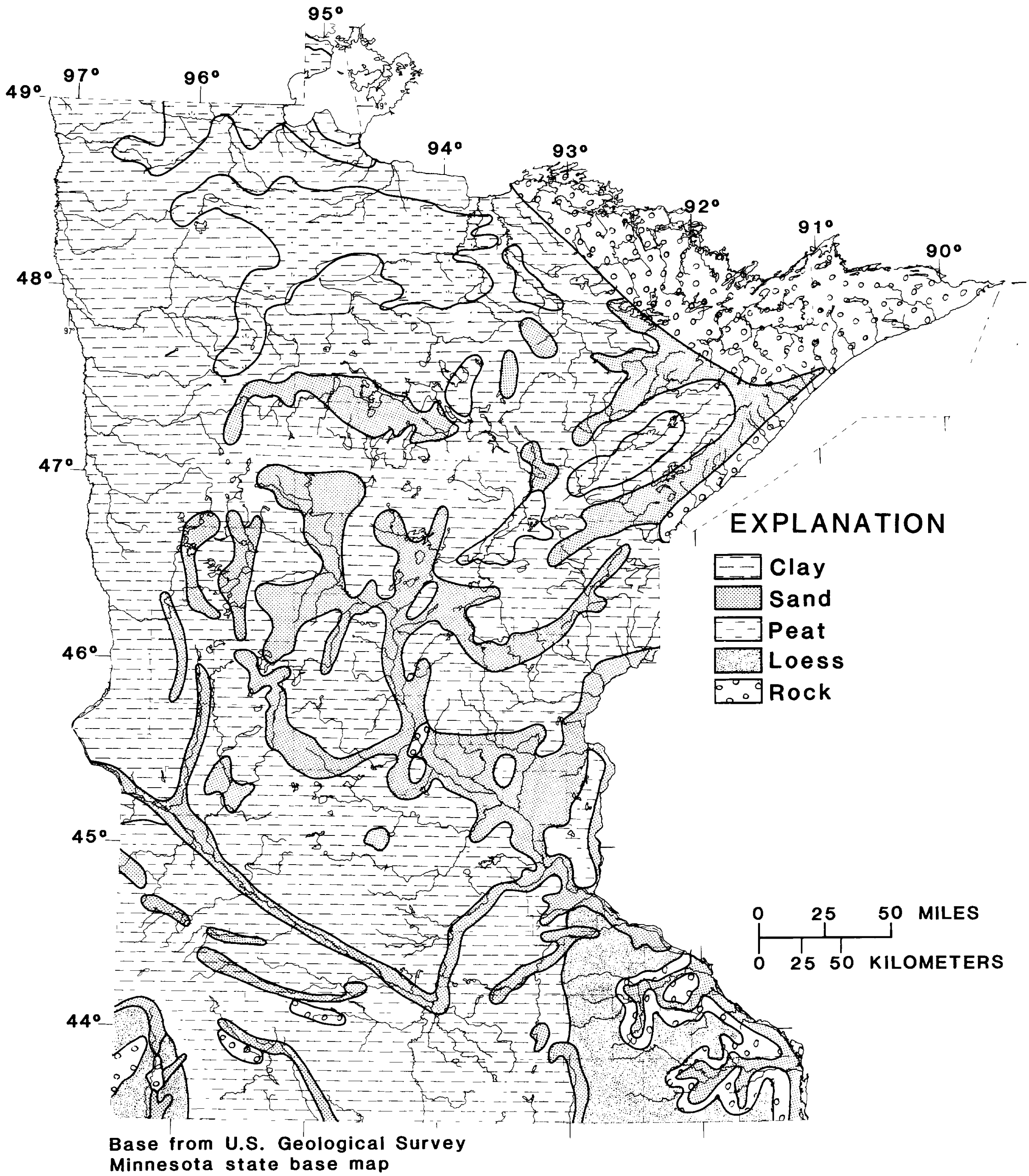


Figure 2.--Generalized soil types in Minnesota (from Borchert and Yaeger, 1968, p. 8)

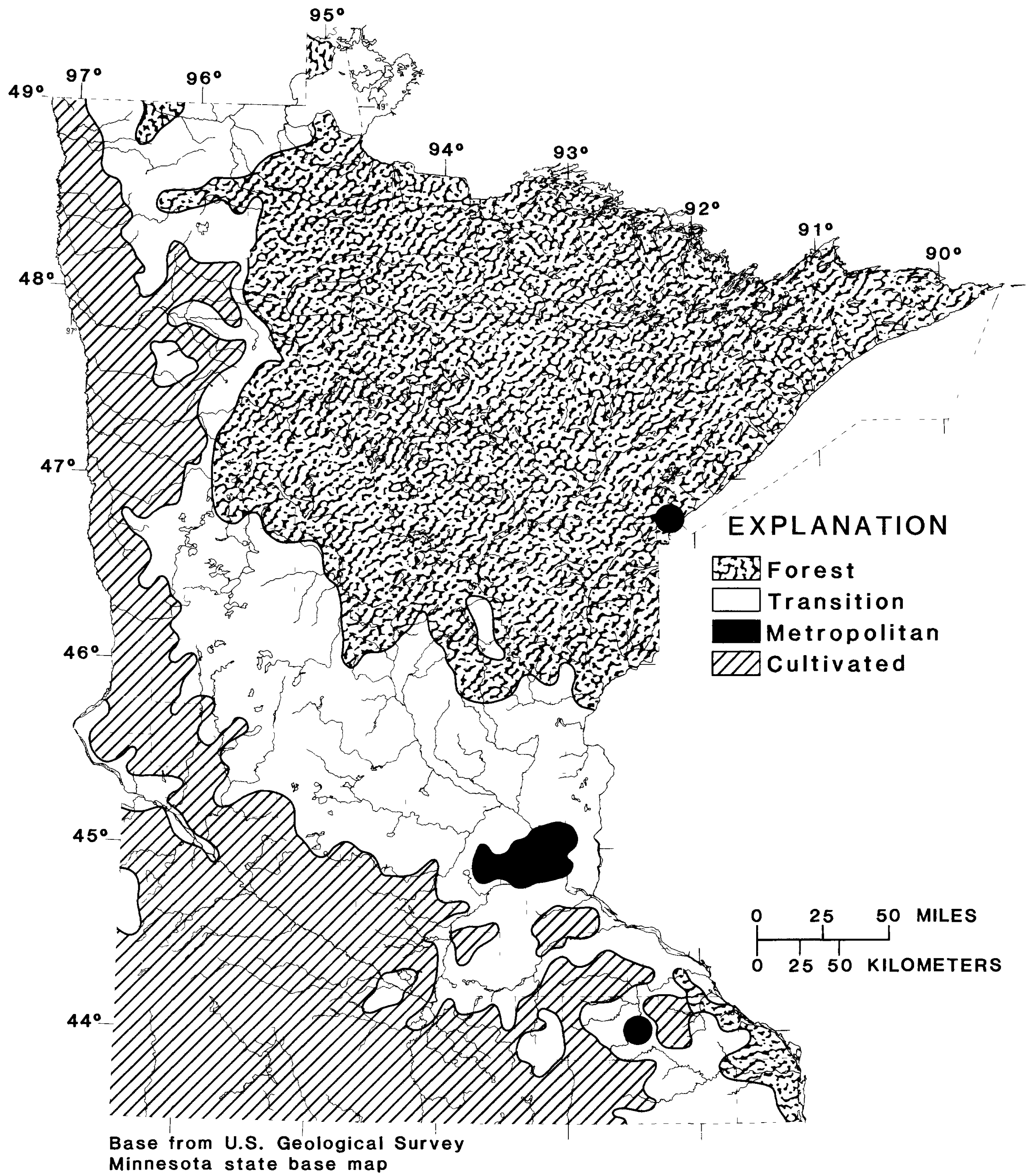


Figure 3.--Generalized land use in Minnesota (from Borchert, 1974, p. 10)

at daily sediment stations usually one or more times a day, and the concentrations are used with the daily record of streamflow to calculate daily suspended-sediment loads for the period of record. Samples are collected at periodic daily sediment stations primarily during periods when the stream stage exceeds a predetermined level; records are prepared in the manner of daily stations for the sampling periods. Concentrations of samples collected at regular intervals from sites and the flows at the time of sampling are used to calculate instantaneous suspended-sediment discharge. Figure 4 shows the location of sediment-sampling stations discussed in this report. All types of sediment records are stored in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). The records are also published in the annual water-data reports of the U.S. Geological Survey (1970-82).

STATISTICAL ANALYSIS

The data in this report were analyzed and summarized using procedures in the Statistical Analysis System (SAS)[1] documented in Ray (1982a and b). Least-squares regression analysis was used to find equations that describe the sediment-transport curve [the relation of the natural-logarithm (log) of the sediment discharge to the log of the streamflow] for selected stations. The accuracy of regressing sediment discharge against streamflow has been questioned by some statisticians, but has been shown to be comparable to regressing concentration against streamflow (Saul Rantz, U.S. Geological Survey, written commun., 1968). Equations resulting from regression analysis of selected stations were adjusted by adding one-half the mean-square-error term resulting from the analysis (Heien, 1968) and are used to extrapolate a long period of sediment-discharge record from a relatively short-term record.

Stations having daily sediment discharge and streamflow data were selected for regression analysis using the following criteria: (1) the daily streamflow record must span at least five of the years between October 1967 and September 1981, and (2) the sediment record must span at least two open-water seasons (about 1 1/2 years), which should make the data more representative of long-term conditions.

Values computed from regression equations were plotted against the streamflow and compared to plots of the data. The relationship between log values of streamflow and sediment discharge was linear for only a few stations. It was determined that the most accurate method of mathematically representing non-linear sediment-transport curves was to develop linear equations that describe two or three segments of the curve (G. Douglas Glysson, U.S. Geological Survey, Quality of Water Branch, written commun., 1984). Linear equations were considered acceptable only if the probability that a true relationship exists was greater than 95 percent (F-values significant at the alpha <0.05 level).

---

[1]The use of the brand name in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

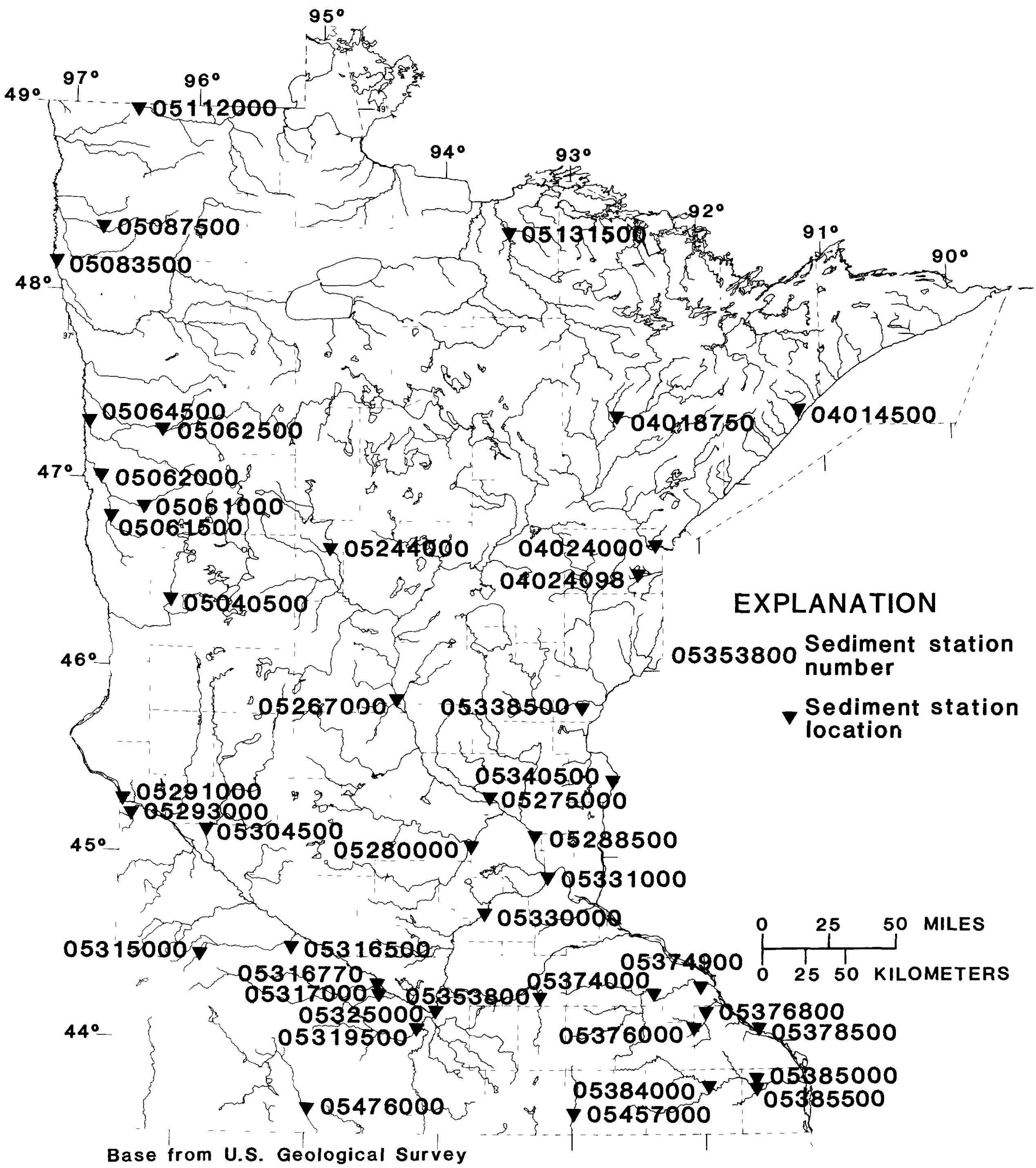


Figure 4.--Location of frequently sampled suspended-sediment stations in Minnesota

The equations that describe the sediment-transport curve for a station were applied to representative streamflow values from the flow-duration curve (the percentage of time that values of streamflow are equaled or exceeded) for that station. Application of the sediment-transport curve to the flow-duration curve can be used to provide a satisfactory estimate of long-term sediment loads (Miller, 1951; Colby, 1956). For this report, representative streamflow values were taken from the respective flow-duration curves obtained using the PCTL procedure in SAS (Reinhardt, 1980). Flow-duration curves for several stations were extended by establishing a short-term flow-duration relationship between the station of interest and a nearby "index" station having a longer period of record and using that relationship to develop a curve from the long-term curve of the index station (Searcy, 1959). Computed sediment loads were divided by the drainage area of the watershed above each sampling site to provide the sediment yield.

Trend analysis was performed using the SAS procedure SEASKEN developed by Hirsch and others (1982). Stations having six or more years of instantaneous or daily sediment record were tested for trend analysis. This procedure compares data only from the same periods of the year to avoid the effects of annual variations. Data from daily sediment stations were divided into 12 periods, whereas data from instantaneous sediment stations were divided into only four periods because of the limited number of samples. Trends were considered to be significant if the probability that the variable is independent of time is less than 10 percent (alpha <0.10).

EQUATIONS FOR SEDIMENT-TRANSPORT CURVES

Figure 5 is a logarithmic plot of the suspended-sediment discharge against streamflow for the Minnesota River at Mankato (05325000). The three-segment regression lines are drawn in to show how the unadjusted equations for this station relate to the data. The three "legs" of the curve indicate the changing character of sediment transport as the streamflow makes the transition from normal flows to high flows. Much scatter of the data about the regression line is apparent in figure 5, showing that an estimated value could be substantially different from an individually measured sediment discharge.

The upper extreme of the regression lines and, hence, the resulting equations tend to underestimate the actual sediment discharge. Extremely high sediment concentrations occur when large quantities of sediment are mobilized and washed into the stream during the rapid rise in streamflow following a runoff event. During streamflow recession, sediment concentrations generally are greatly reduced resulting in lower sediment discharge. On most streams the recession has a much longer duration (several days on large rivers) than the rise, resulting in a larger number of daily values that tend to weight the regression line towards sediment-discharge values obtained during recession.

Table 1 is a list of 33 stations with the equation, and the applicable range of streamflow for each leg of the sediment-transport curve. These equations may be used to approximate the sediment load for the station at given streamflows, but resultant values should be used with caution as actual load values can be substantially different from calculated loads.

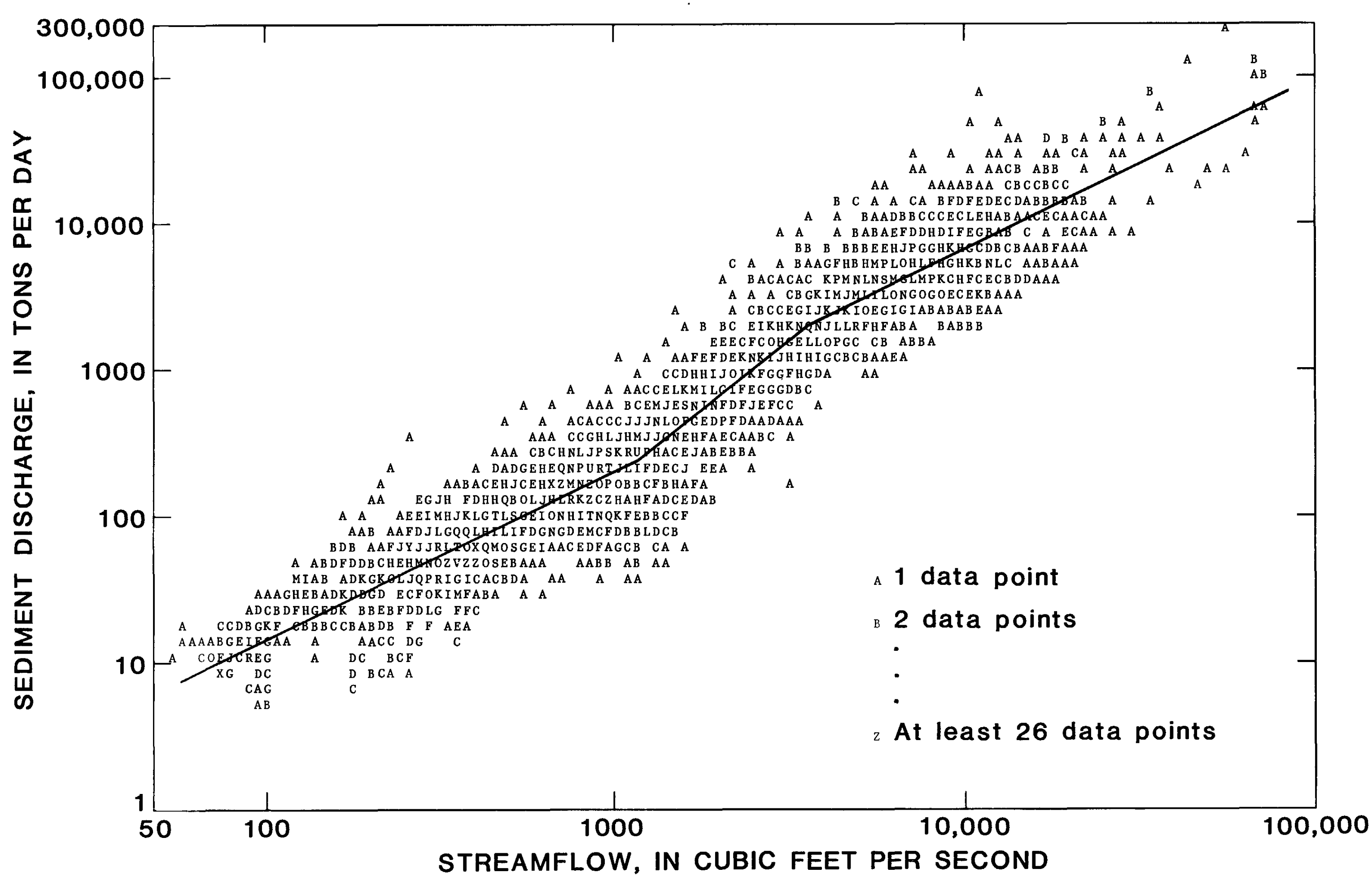


Figure 5.--Sediment-transport curve for the Minnesota River at Mankato

Table 1.--Equations for sediment-transport curves

[Q, streamflow in cubic feet per second (ft^3/s); S, sediment discharge in tons per day]

Station	Equation	Coefficient of variation	Applicable streamflow range (in cubic feet per second)
Baptism River near Beaver Bay, MN	$S=0.0154Q^{0.936}$	220	0-263
	$S=0.0000366Q^{2.06}$	33	264-2,480
St. Louis River at Forbes, MN	$S=0.00160Q^{1.56}$	53	0-860
	$S=0.0000265Q^{2.12}$	13	861-5,170
Deer Creek near Holyoke, MN	$S=0.0447Q^{1.63}$	37	0-2.5
	$S=0.0218Q^{2.15}$	96	2.6-194
Pelican River near Fergus Falls, MN	$S=0.0139Q^{1.26}$	29	0-333
	$S=0.000000203Q^{3.17}$	13	334-688
Buffalo River near Hawley, MN	$S=0.283Q^{0.852}$	41	0-34
	$S=0.124Q^{1.10}$	13	35-1,930
South Branch Buffalo River at Sabin, MN	$S=0.119Q^{0.924}$	130	0-41
	$S=0.0297Q^{1.23}$	22	42-3,350
Buffalo River near Dilworth, MN	$S=0.298Q^{0.968}$	18	0-13,500
Wild Rice River at Twin Valley, MN	$S=0.0879Q^{1.06}$	52	0-178
	$S=0.00185Q^{1.81}$	12	179-5,900
Middle River at Argyle, MN	$S=0.0764Q^{1.05}$	74	0-92
	$S=0.0195Q^{1.34}$	12	93-2,300
Little Fork River at Littlefork, MN	$S=0.0368Q^{1.04}$	22	0-833
	$S=0.0000518Q^{2.02}$	8.8	834-20,100
Crow Wing River at Nimrod, MN	$S=0.0000997Q^{1.90}$	25	0-1,060
	$S=0.0107Q^{1.20}$	7.4	1,061-2,650
Elk River near Big Lake, MN	$S=0.0112Q^{1.33}$	128	0-350
	$S=0.227Q^{0.742}$	23	351-2,700
Crow River at Rockford, MN	$S=0.00749Q^{1.51}$	15	0-935
	$S=5.06Q^{0.548}$	9.0	936-7,730

Table 1.--Equations for sediment-transport curves--Continued

Station	Equation	Coefficient of variation	Applicable streamflow range (in cubic feet per second)
Mississippi River near Anoka, MN	$S=0.0231Q^{1.01}$	26	0-3,960
	$S=0.000000855Q^{2.23}$	13	3,961-49,400
Whetstone River near Big Stone City, SD	$S=0.179Q^{0.962}$	200	0-70
	$S=0.0183Q^{1.51}$	22	71-3,660
Yellow Bank River near Odessa, MN	$S=0.248Q^{0.927}$	210	0-114
	$S=0.00532Q^{1.74}$	14	115-2,590
Chippewa River near Milan, MN	$S=0.269Q^{1.02}$	13	0-3,800
Redwood River near Marshall, MN	$S=0.224Q^{1.17}$	23	0-115
	$S=0.0209Q^{1.68}$	11	116-4,760
Redwood River near Redwood Falls, MN	$S=0.249Q^{1.15}$	13	0-13,200
Minnesota River at New Ulm, MN	$S=0.511Q^{0.888}$	14	0-417
	$S=0.0713Q^{1.23}$	15	418-2,900
	$S=6.23Q^{0.670}$	8.8	2,901-56,900
Cottonwood River near New Ulm, MN	$S=0.265Q^{0.984}$	30	0-97
	$S=0.0185Q^{1.56}$	11	98-2,500
	$S=0.135Q^{1.31}$	7.9	2,501-27,100
Watonwan River near Garden City, MN	$S=0.153Q^{1.09}$	13	0-350
	$S=0.00232Q^{1.81}$	9.8	350-4,000
Minnesota River at Mankato, MN	$S=0.100Q^{1.12}$	12	0-1,190
	$S=0.000518Q^{1.87}$	8.5	1,191-4,600
	$S=0.286Q^{1.12}$	6.5	4,601-76,200
Straight River near Faribault, MN	$S=0.00940Q^{1.66}$	17	0-39
	$S=0.0115Q^{1.59}$	9.5	40-3,810
Zumbro River at Zumbro Falls, MN	$S=0.0000403Q^{2.24}$	14	0-4,870
	$S=0.00947Q^{1.58}$	6.5	4,871-19,500

Table 1.--Equations for sediment-transport curves--Continued

Station	Equation	Coefficient of variation	Applicable streamflow range (in cubic feet per second)
Zumbro River at Kellogg, MN	$S=0.0000221Q^{2.51}$	18	0-2,950
	$S=8.83Q^{0.875}$	5.9	2,951-13,700
Whitewater River near Beaver, MN	$S=0.00207Q^{1.94}$	26	0-137
	$S=0.00000120Q^{3.48}$	18	138-570
	$S=4.55Q^{1.06}$	6.0	571-8,760
Mississippi River at Winona, MN	$S=0.000130Q^{1.62}$	12	0-147,000
Root River near Lanesboro, MN	$S=0.0000195Q^{2.89}$	29	0-545
	$S=0.295Q^{1.35}$	12	546-6,890
Root River near Houston, MN	$S=0.0000156Q^{2.57}$	16	0-3,150
	$S=0.0185Q^{1.68}$	6.6	3,151-18,200
South Fork Root River near Houston, MN	$S=0.000519Q^{2.32}$	17	0-124
	$S=0.00000215Q^{3.47}$	13	125-602
	$S=276Q^{0.558}$	7.5	603-6,480
Cedar River near Austin, MN	$S=0.00924Q^{1.52}$	20	0-1,760
	$S=0.000148Q^{2.06}$	11	1,761-7,120
Des Moines River at Jackson, MN	$S=0.158Q^{1.09}$	15	0-2,200
	$S=0.00297Q^{1.60}$	9.6	2,201-15,500

SUSPENDED-SEDIMENT CONCENTRATIONS

Table 2 is a comprehensive listing of sediment-related data for 33 daily sediment stations in or adjacent to Minnesota. The basic descriptive information listed for each station includes the U.S. Geological Survey station-identification number, the station name, and the drainage area. The median streamflow was obtained from the flow-duration curve developed from the streamflow record between October 1967 and September 1981. The maximum daily streamflow is provided to indicate how much extrapolation was required to compute maximum yields. Most of the stations listed have a full 14 years of streamflow record but the few exceptions should be noted. The Pelican River near Fergus Falls, South Branch Buffalo River at Sabin, and the Zumbro River at Zumbro Falls each have 13 years of streamflow record. The Minnesota River at New Ulm has 9 years of streamflow record. The Zumbro River at Kellogg and the Whitewater River near Beaver have 6 years of streamflow record. Deer Creek near Holyoke and the Watonwan River near Garden City have only 5 years of streamflow record. To facilitate comparisons between stations, the flow-duration curves for the Minnesota River at New Ulm, Zumbro River at Kellogg, Whitewater River at Beaver, and Watonwan River near Garden City were extended to 14, 13, 14, and 14-year periods, respectively, using nearby index-station flow-duration curves. Streamflow-record values for these stations are qualified with an "E." An index station could not be found near Deer Creek, so discussion of data from that site is applicable only to the period from October 1976 through September 1981.

The rest of table 2 summarizes the sediment data for each of the stations listed. The period of record, expressed as the numeric month and year, shows the time during which station operations included suspended-sediment sampling, which does not mean that samples were collected continuously during the period. Days of record shows the number of daily values summarized and used to determine equations of the sediment-transport curves. Average daily concentration values were computed by dividing the median sediment discharge by the median streamflow. Maximum daily concentration values were either computed by dividing the maximum sediment discharge by the maximum streamflow (qualified with an "E"), or the maximum measured concentration, whichever was higher.

Figure 6 is a map showing the location of sites and the average suspended-sediment concentrations listed in table 2 and instantaneous concentrations discussed later in the report. The sites are designated using the third through sixth digits of the station numbers listed in table 2 with additional digits added to resolve ambiguities. Appropriate boundaries showing the sediment concentration for the watershed of a site were determined subjectively by considering factors that might result in substantial changes in sediment concentrations, including tributary inflows, land use, soil types, and relative concentrations between groups of stations.

Average suspended-sediment concentrations at most sites in the northern half of Minnesota were below 50 mg/L (milligrams per liter). Average concentrations at sites on the Baptism (0145), St. Louis (0187), Pelican (0405), Little Fork (1315), and Crow Wing (2440) Rivers were below 20 mg/L. These sites are in areas with rocky or predominantly sandy soils (fig. 2) and forested or transitional land use (fig. 3). Average sediment concentrations at the two

Table 2.--Summary of suspended-sediment concentrations and yields for selected daily sediment stations

[E, estimated value; *, record less than 14 years (see text)]

Station number	Station name	Drainage area (mi^2)	14-year Streamflow record (ft^3/s) Maximum	Median	Sediment record: Sampling period (month-year)	Number of days	Maximum streamflow (ft^3/s)	Extended 14-year sediment record: Concentration (mg/L) Maximum	Average	Yield (t/mi^2) Maximum daily	Average annual
04014500	Baptism River near Beaver Bay, MN	140	6,860	63	12-67 to 8-70	234	2,480	160E	4.4	20.9E	14.2E
04010750	St. Louis River at Forbes, MN	713	6,130	250	1-68 to 9-70	350	5,170	221	13	4.3	11.4E
04024098	Deer Creek near Holyoke, MN*	7.77	194	2.2	10-76 to 9-81	1,505	194	3 600	27	232E	236E
05040500	Pelican River near Fergus Falls, MN*	482	688	65	12-67 to 9-69	182	688	208	15	.79	1.0E
05061000	Buffalo River near Hawley, MN	322	1,970	26	3-77 to 9-78	403	1,930	455	65	2.2	5.0E
05061500	South Branch Buffalo River at Sabin, MN*	522	8,200	6.0	3-77 to 9-78	371	3,350	195	38	3.7E	3.2E
05062000	Buffalo River near Dilworth, MN	1,040	13,500	35	3-71 to 9-81	748	13,500	771	98	3.4	4.5E
05062500	Wild Rice River at Twin Valley, MN	888	5,900	64	3-71 to 9-79	1,627	5,900	1 140	42	13.9E	17.2E
05087500	Middle River at Argyle, MN	265	3,790	1.3	3-68 to 7-70	307	2,300	250	29	4.6E	4.9E
05131500	Little Fork River at Littlefork, MN	1,730	20,600	430	4-71 to 8-79	434	20,100	524	17	15.5E	33.0E
05244000	Crow Wing River at Nimrod, MN	1,010	3,580	389	12-67 to 8-70	418	2,650	66	7.9	.19E	1.2E
05275000	Elk River near Big Lake, MN	615	5,800	179	11-75 to 9-81	178	2,700	78	23	.51	2.2E
05280000	Crow River at Rockford, MN	2,520	15,000	285	8-75 to 9-81	595	7,730	457	50	.58	5.1E
05288500	Mississippi River near Anoka, MN	19,100	72,300	6,010	8-75 to 9-81	2,234	49,400	300E	14	3.1E	8.1E
05291000	Whetstone River near Big Stone City, SD	389	6,090	7.5	10-73 to 9-81	2,910	3,660	2 540	61	24.4E	22.5E
05293000	Yellow Bank River near Odessa, MN	398	6,640	7.0	10-73 to 9-81	2,922	2,590	1 300E	79	59.8E	31.5E

Station number	Station name	Drainage area (mi^2)	14-year Streamflow record (ft^3/s)		Sediment record			Extended 14-year sediment record			
								Concentration (mg/L)		Yield (t/mi^2)	
			Maximum	Median	Sampling period (month-year)	Number of days	Maximum stream-flow (ft^3/s)	Maximum	Average	Maximum daily	Average annual
05304500	Chippewa River near Milan, MN	1,870	10,100	113	3-73 to 8-81	695	3,800	1 020	110	3.7	5.8E
05315000	Redwood River near Marshall, MN	303	4,760	7.9	1-68 to 9-71	264	4,760	2 600	120	104E	57.9E
05316500	Redwood River near Redwood Falls, MN	697	13,200	25	10-68 to 9-70	164	13,200	900	150	21.6	17.6E
05316770	Minnesota River at New Ulm, MN	9,530	57,000E	445E	10-67 to 9-76	3,287	56,900	776	110	3.6	5.5E
05317000	Cottonwood River near New Ulm, MN	1,280	27,100	78	12-67 to 9-76	955	27,100	3 650	92	76.5	55.7E
05319500	Watonwan River near Garden City, MN	812	7,600E	71E	10-77 to 8-80	276	4,000	1 200E	83	30.2E	54.0E
05325000	Minnesota River at Mankato, MN	14,900	76,200	1,200	10-67 to 9-81	5,114	76,200	2 850	92	16.6	66.1
05353800	Straight River near Faribault, MN	442	5,410	88	12-67 to 9-71	359	3,810	1 330	60	22.4E	44.1E
05374000	Zumbro River at Zumbro Falls, MN*	1,130	19,500	378	3-71 to 8-75	314	19,500	1 900	23	50.3E	49.3E
05374900	Zumbro River at Kellogg, MN*	1,400	21,500E	540E	8-75 to 9-81	2,232	13,700	6 670	110	45.5	104E
05376800	Whitewater River near Beaver, MN	271	17,100E	125E	7-75 to 9-81	2,118	8,760	7 690	71	515E	260E
05378500	Mississippi River at Winona, MN	59,200	218,000	22,800	12-74 to 9-81	2,210	147,000	393	24	1.1	5.1E
05384000	Root River near Lanesboro, MN	615	11,800	219	12-67 to 9-71	82	6,890	5 020	190	151E	249E
05385000	Root River near Houston, MN	1,270	18,200	533	12-67 to 9-81	2,959	18,200	16 500	110	209E	221E
05385500	South Fork Root River near Houston, MN	275	6,480	124	7-75 to 9-81	2,263	6,480	11 800	110	306	173E
05457000	Cedar River near Austin, MN	425	7,120	103	3-71 to 9-81	355	7,120	1 520	38	41.4	30.9E
05476000	Des Moines River at Jackson, MN	1,220	15,500	64	1-68 to 9-81	1,336	15,500	956	85	14.2	14.0E

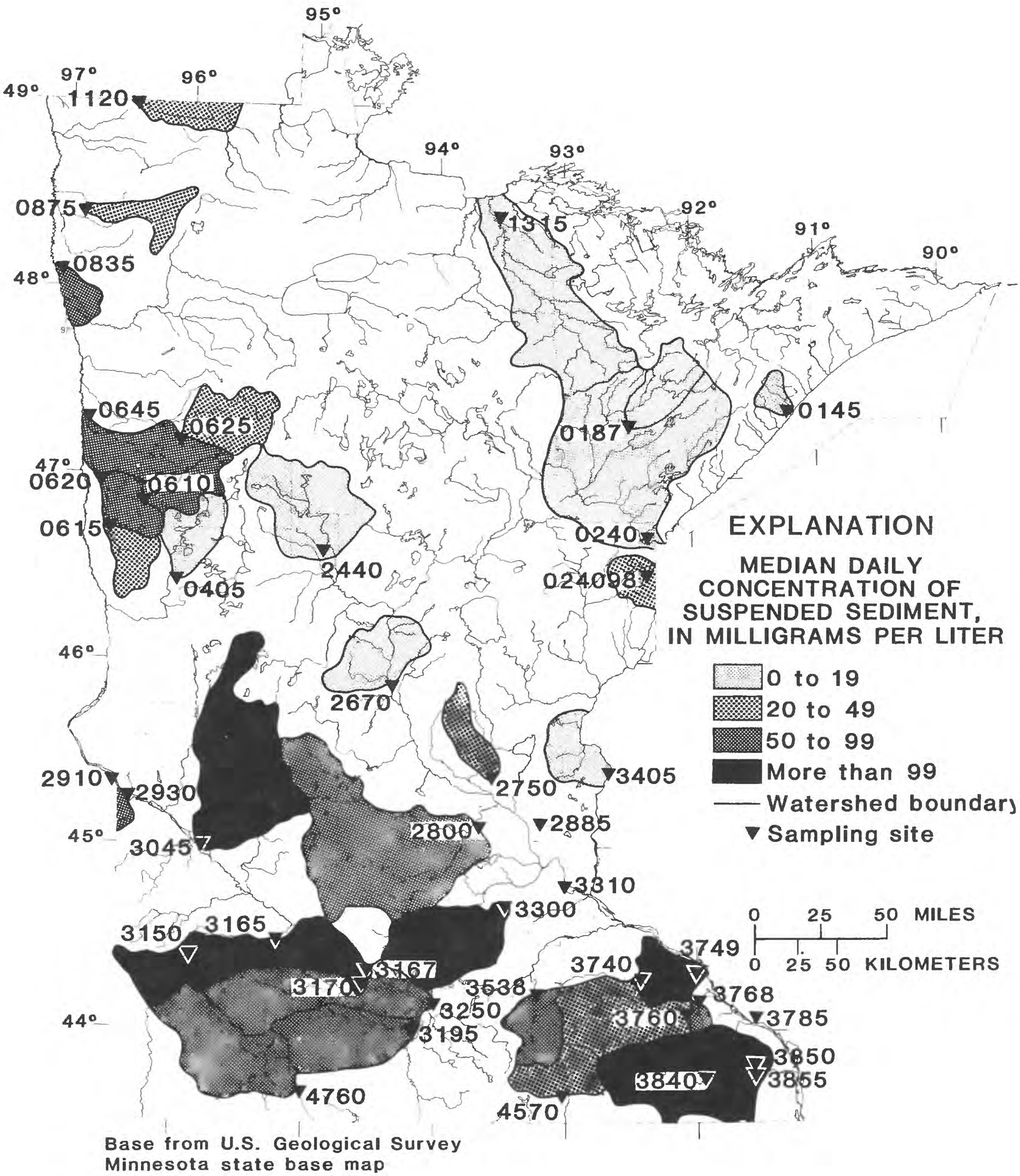


Figure 6.--Average suspended-sediment concentrations for selected watersheds in Minnesota

sites on the main stem of the Buffalo River (0610 and 0620) were in the 50 to 100 mg/L range. Cultivation of clay soils may increase sediment concentrations in the Buffalo River.

Maximum daily sediment concentrations in northern Minnesota varied considerably, but the apparent variation may be an artifact of the sampling schedules, which may have missed sampling the real maximums. The highest daily concentration was measured at Deer Creek, but maximum concentrations above 500 mg/L also were measured on the main stem of the Buffalo River and on the Wild Rice and Little Fork Rivers. Clay deposits observed in these basins may erode during high flows, resulting in the high sediment concentrations.

The southern half of Minnesota is covered predominantly by soils developed on clay and loess, and the area generally is heavily cultivated. This combination of factors resulted in average concentrations of 50 mg/L or more at all but a few sites. Elk River near Big Lake (2750) drains predominantly sandy soils which are not easily carried as suspended sediment. Average sediment concentrations for sites on the Mississippi River at Anoka and Winona (2885 and 3785) are not shown in figure 6 because their large drainage areas, combination of flows from several tributaries, and upstream impoundments that allow sediments to settle to the bottom probably make their concentrations less than what might be expected locally. Maximum sediment concentrations also were not notably high at these sites. Small impoundments above the sampling sites on the Zumbro River at Zumbro Falls and the Cedar River near Austin may keep average concentrations low but do not appear to prevent high maximum concentrations measured at these sites.

Streams near the headwaters of the Minnesota River, such as the Whetstone River in South Dakota (2910) and the Yellow Bank River (2930), carried relatively low average concentrations of suspended sediment (less than 100 mg/L). Average concentrations at sites farther downstream in the Minnesota River basin were near 100 mg/L and ranged from 83 mg/L on the Watonwan River to 150 mg/L on the Redwood River.

Maximum suspended-sediment concentrations at most sites in the Minnesota River basin commonly were high. Concentrations exceeded 2,000 mg/L in the Whetstone, Redwood, and Cottonwood Rivers, as well as at the main-stem site at Mankato. The maximum daily concentration measured in the basin (3,650 mg/L) was at the Cottonwood River near New Ulm. The wide fluctuations indicated by the difference between average and maximum concentrations in this relatively flat basin suggest that most sediment is transported after storms erode fine-grained soils exposed by heavy cultivation.

Average suspended-sediment concentrations of tributaries to the Mississippi River in southeast Minnesota generally were more than 50 mg/L. Average concentrations in the Zumbro River at Kellogg (3749) and the main stem and south fork of the Root Rivers (3840, 3850 and 3855) were more than 100 mg/L. The highest average concentration in table 2, 190 mg/L, occurred at the Root River near Lanesboro (3840). The average concentration in the Cedar River (4570) was about half that found in the Des Moines River (4760) and both were less than 100 mg/L.

Maximum daily concentrations measured in tributaries to the Mississippi River were high, exceeding 5,000 mg/L at several stations. High concentrations were found in the Zumbro and Whitewater Rivers, but the highest maximum concentrations were measured on the south fork and main stem of the Root River. Runoff from watershed slopes that exceed 12 feet per mile combined with tillage of loessial soils (Broussard and others, 1975) probably resulted in the high concentrations.

Instantaneous suspended-sediment samples have been collected systematically from several stations throughout Minnesota as part of interpretive hydrologic projects and the U.S. Geological Survey's National Stream Quality Accounting Network. Most of the stations in these programs have been sampled only a few times, but enough data have been collected at several stations to allow characterization of sediment concentrations and yields. Table 3 is a statistical summary of sediment concentrations and yields for stations in and adjacent to Minnesota that have been sampled for instantaneous sediment concentrations 40 or more times. The range and median of the streamflows when the samples were collected is listed to show the characteristics of streamflow the sediment data represent. Minimum sediment concentrations and yields are not listed as they were relatively insignificant, being less than 10 mg/L and 0.002 t/mi^2 (tons per square mile), respectively. The maximum values in table 3 may not accurately represent extremes because the systematic methods may not have sampled true extremes.

The median suspended-sediment concentrations listed in table 3 are comparable, regionally, to the median concentrations listed in table 2 and are displayed in figure 5 with those values. Two stations, Baptism River near Beaver Bay and Little Fork River at Littlefork, are listed in tables 2 and 3 because they were operated as daily and instantaneous sampling sites at different, although overlapping, times. The additional data provided by table 3 show that sediment concentrations in the Red River of the North generally are higher than concentrations listed in table 2 for tributaries to the Red River. Instantaneous concentrations for the Mississippi River at Royalton are similar to median concentrations listed for the Mississippi River at Anoka and Winona, but concentrations listed in table 3 for the Mississippi River at St. Paul are much higher, probably because of high concentrations from the Minnesota River that empties into the Mississippi River a few miles above the St. Paul station. Concentrations in the St. Croix River were the lowest measured and were comparable to concentrations listed for the Baptism River in tables 2 and 3.

SUSPENDED-SEDIMENT YIELDS

Maximum daily yield and average annual yield to be expected at daily sediment stations are given in the two columns at the right in table 2. The majority of average values and several of the maximum values are marked with an "E" to indicate that the values are estimated based on the sediment-transport/flow-duration calculations described earlier in this report. The maximum daily yields are either the maximum recorded yield or the maximum yield calculated from the sediment-transport equations, whichever is higher. Minimum daily yields and concentrations are not listed in table 2, as they were almost always at or near zero.

Table 3.--Summary statistics for instantaneous suspended-sediment concentrations and yields from selected sites

Station number	Station name	Drainage area (mi^2)	Period of record (month-year)	Number of samples	Streamflow (ft^3/s)			Sediment concentration (mg/L)		Daily sediment yield (t/mi^2)	
					Maximum	Minimum	Median	Maximum	Median	Maximum	Median
04014500	Baptism River near Beaver Bay, MN	140	10-74 to 9-81	50	1,040	1.4	61	38	5.5	0.3	0.0093
04024000	St. Louis River Scanlon, MN	3,430	10-74 to 9-81	57	30,700	284	1,400	220	11	5.3	.011
05064500	Red River of the North at Halstad, MN	21,800	10-76 to 9-81	65	19,200	23	510	730	52	.49	.0029
05083500	Red River of the North at Oslo, MN	31,200	3-73 to 12-77	54	42,400	200	1,600	1,060	76	1.1	.0066
05112000	Roseau River below State Ditch 51 near Caribou, MN	1,570	10-74 to 9-81	56	3,000	.9	41	183	24	.10	.0018
05131500	Little Fork River at Littlefork, MN	1,730	9-75 to 9-81	50	20,000	46	312	279	22	7.1	.0092
05267000	Mississippi River near Royalton, MN	11,600	1-75 to 9-81	63	22,490	580	3,620	91	15	.16	.0091
05330000	Minnesota River near Jordan, MN	16,200	10-74 to 9-81	84	32,100	150	1,330	799	137	1.6	.024
05331000	Mississippi River at St. Paul, MN	36,800	1-74 to 6-77	45	34,100	1,060	5,940	564	64	.62	.018
05340500	St. Croix River at St. Croix Falls, WI	6,240	11-74 to 9-81	77	28,500	909	4,490	54	4.0	.42	.0061
05376000	North Fork White-water River at Elba, MN	101	10-70 to 8-81	124	2,510	20	38	5,190	40.5	187	.044

Average annual sediment yields from selected watersheds listed in table 2 are shown in figure 7. Yields are based on total drainage area above a station, but, to eliminate some confusion and possible misrepresentation of data for stations within the same basins that have overlapping drainage areas, yields in figure 7 are shown for the adjacent parts of the watersheds, as delineated on figure 5. As an example, the drainage area for the Mississippi River at Winona would cover about two-thirds of Minnesota and much of Wisconsin and would overlap the yields displayed for many of its tributaries, however, the yields for this site and the Mississippi River at Anoka are not shown on figure 4 because, for reasons stated earlier, they probably are not representative of local yields.

The amount of sediment carried by Minnesota streams was highly variable, both statewide and regionally. In the northeast section of the State, average annual yields ranged from 11.4 t/mi^2 in the St. Louis River basin (0187) to nearly 240 t/mi^2 (table 2) in the Deer Creek basin (0240). Deer Creek and adjacent watersheds are underlain by fine-grained, red-clay soils that are subject to severe erosion (Olcott and others, 1978). Most of the watersheds in central and northwestern Minnesota, including the Buffalo, Pelican, Crow Wing, Elk, Chippewa, and Crow, had annual sediment yields that were about 5 t/mi^2 or less. The Wild Rice (0625) and Little Fork (1315) River basins had substantially higher yields than adjacent sites that probably result from the transport of clays noted earlier.

Maximum daily sediment yields in northern Minnesota were highest in two of the three sampled tributaries to Lake Superior. The highest daily yield was measured at Deer Creek near Holyoke (0240), and probably resulted from erosion of clay deposits. The next highest daily yield, which was measured on the Baptism River (0145), was extrapolated using the sediment-transport-curve equation. This yield value may be inaccurate, because the streamflow used in the extrapolation was more than 2.5 times the streamflow at the time of the highest measured sediment load. However, the presence of sand deposits in the watershed (fig. 2), relief that exceeds 90 feet per mile near the sampling site (Olcott and others, 1978), and an irregular channel that increases turbulence during higher flows suggest that yields of this magnitude occur in the Baptism River watershed.

The heavily cultivated clay and loessial soils of southern Minnesota generally contributed the greatest quantities of suspended sediment. Annual sediment yields ranged widely in the Minnesota River basin, from less than 6 t/mi^2 at the Chippewa River (3045) and Minnesota River at New Ulm (3167) sites to more than 66 t/mi^2 measured yield at the Minnesota River at Mankato (3250). Many of the tributaries to the Minnesota river carried yields in excess of 50 t/mi^2. Maximum daily yields in the Minnesota River basin ranged from a measured low of 3.6 t/mi^2 at the Minnesota River at New Ulm (3167) to an estimated 104 t/mi^2 at the Redwood River near Marshall (3150).

The highest sediment yields were from watersheds draining into the Mississippi River in southeastern Minnesota. The adjacent watersheds of the Straight River (3538) and upper reaches of the Zumbro River (3740) had similar average annual yields approaching 50 t/mi^2. Both streams drain areas cf heavily tilled soils developed on loess deposits. The highest average annual

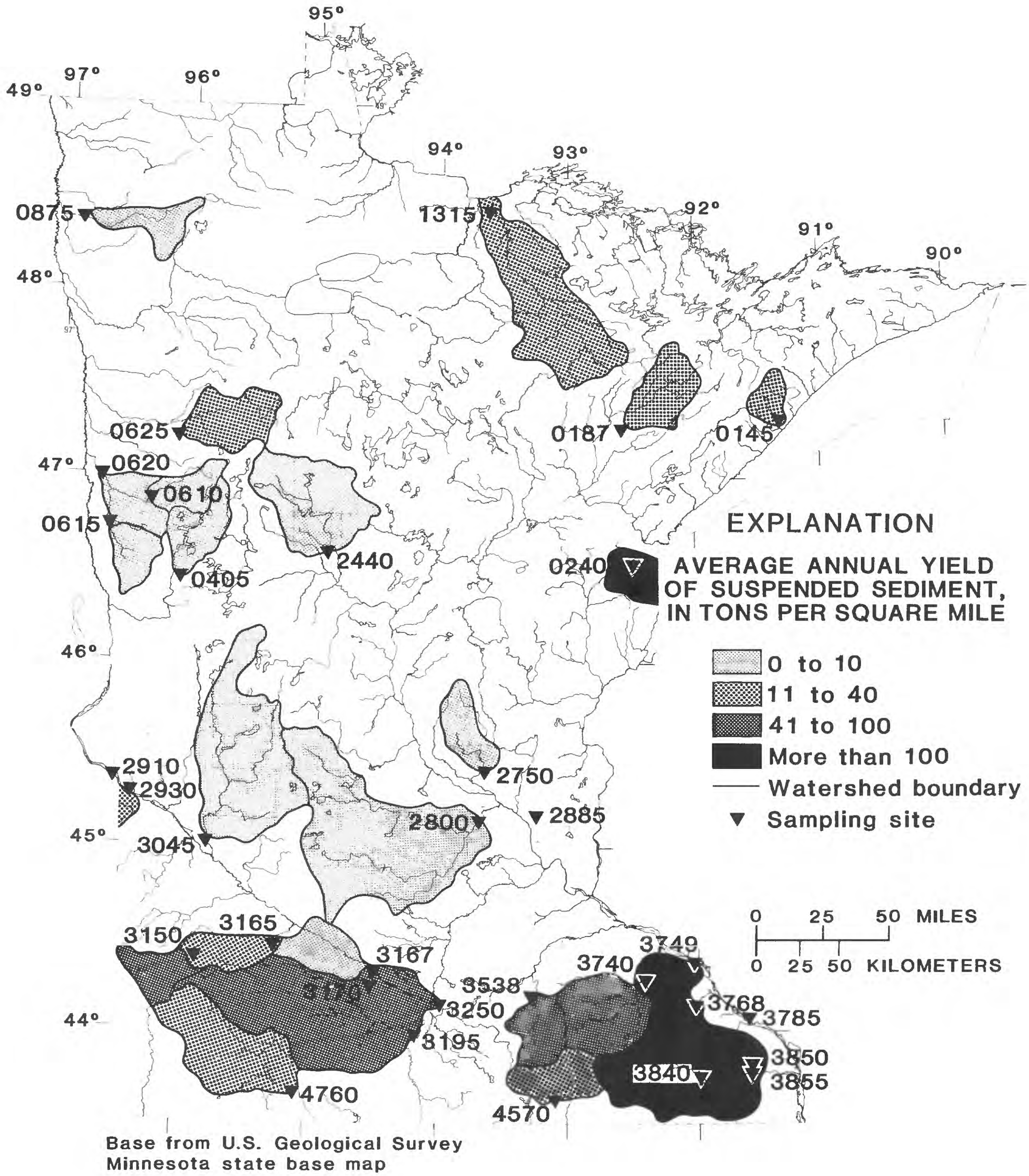


Figure 7.--Average annual suspended-sediment yields from selected watersheds in Minnesota

yields in the State were found for sites sampled on the main stem and south fork of the Root River and, especially, the Whitewater River, which had annual yields of 260 t/mi^2 (table 1). Cultivation (fig. 3) of soils derived from clay, silt, and loess with relief that exceeds 1,000 feet per mile, combined with average annual precipitation of more than 30 inches (Broussard and others, 1975) probably result in the high sediment yields from the Root and Whitewater River watersheds.

It is apparent (see table 2) that maximum daily sediment yields at several stations may exceed the average annual yield and, at stations on the Yellow Bank, Redwood, Whitewater, and South Fork Root Rivers, the maximum daily yield may be nearly double the average annual yields. During extremely high flows at these stations, such large quantities of sediment are mobilized that the normal sediment load for 2 years may be carried past the sampling site in slightly more than 1 day.

Median instantaneous yields from table 3 are substantially lower than average yields listed in table 2. Lower yield values probably result from the lack of data collected during higher streamflows when the rate of suspended-sediment transport is higher. Median values listed in table 3 show that yields generally were lowest in northern Minnesota and in the St. Croix River basin. High yields from the Minnesota River basin probably augmented sediment yields of the Mississippi River at St. Paul. The highest median yield was found in the North Fork Whitewater River basin, which is in a heavily cultivated area disected by steeply sloping stream banks that expose loess deposits.

PARTICLE-SIZE DISTRIBUTION OF SUSPENDED SEDIMENT

Samples from selected sites are analyzed routinely to determine the percentage of suspended sediment finer than 0.062 millimeters (mm), defined as the minimum size of particles classified as sand and termed the sand-fine split. Some determinations have been made of the complete particle-size distribution of sediment, but these determinations have not been made at enough stations to be useful in interpreting sediment characteristics. Table 4 shows the statistical distribution of the percentage of suspended sediment finer than 0.062 mm for those stations having at least 20 determinations of the sand-fine split.

Table 4 indicates that at some time almost every station listed carried all fine material. Minimum percentages show that at some time, probably during higher flows, all the stations listed carried at least 35 percent sand or larger particles. The minimum percentage finer than 0.062, listed as zero for the St. Croix River, probably is not an accurate value; the concentration for this analysis was only 1 mg/L and the analytical methods used are subject to large inaccuracies when sediment concentrations are exceptionally low.

Median values listed in table 4 show that about 90 percent of the sediment carried by the streams was finer than sand. In comparing the medians, the Minnesota River near Jordan appears to carry the highest percentage of sand-sized and larger particles, whereas the Red River of the North at Halstad and the Root River near Houston appear to carry the largest percentage of fines.

Table 4.--Statistical summary of the percentage of suspended sediment finer than 0.062 millimeters

Station number	Station	Number of samples	Percentage finer than 0.062 millimeters		
			Minimum	Maximum	Median
04014500	Baptism River near Beaver Bay, MN	35	61	100	86
04024000	St. Louis River at Scanlon, MN	36	43	100	89
05064500	Red River of the North at Halstad, MN	48	57	100	98
05083500	Red River of the North at Oslo, MN	50	46	99	92
05112000	Roseau River below State Ditch 51 near Caribou, MN	41	32	100	90
05131500	Little Fork River at Littlefork, MN	40	56	100	92
05267000	Mississippi River at Royalton, MN	47	55	100	92
05330000	Minnesota River near Jordan, MN	63	17	97	81
05331000	Mississippi River at St. Paul, MN	28	60	99	89
05338500	Snake River at Pine City, MN	20	65	100	84
05340500	St. Croix River at St. Croix Falls, WI	63	0	100	94
05376000	North Fork Whitewater River at Elba, MN	22	30	99	92
05385000	Root River near Houston, MN	26	59	100	97

It is possible that particle sizes could be related more closely to velocities at the sampling sites than to the land use or soils in the basins, although the particle size of erodible sediments in the watershed could be a factor.

Parametric and nonparametric statistical tests were performed to determine if the percentage of suspended sediment finer than sand correlates with sediment concentration, streamflow, or sediment load. Parametric tests generally did not result in significant correlations, but the nonparametric tests showed positive correlations significant at alpha<0.05 between the percentage finer than sand and sediment concentrations for the Baptism, St. Louis, Red, Little Fork, St. Croix, North Fork Whitewater, and Root Rivers. Correlations with streamflow significant at alpha<0.05 were found only for the Red, North Fork Whitewater, and Root Rivers, but probably were spurious as the correlation coefficients ranged from positive to negative and were found for relatively few stations.

TRENDS IN SUSPENDED SEDIMENT

Of 22 long-term sediment stations tested, 12 were found to have statistically significant temporal trends in sediment concentration and(or) discharge. The trends in streamflow, sediment concentration, and sediment load for these twelve stations are shown in table 5. It should be noted that these trends are based on relatively short periods of record, as listed, and often may result primarily from annual variations in the elements that make up the local climate. It is, however, useful to take note of these trends to determine in the future if the trends have continued.

Sediment concentrations have declined at the first four stations listed. These stations, located on the Baptism, Roseau, Little Fork, and Mississippi Rivers, respectively, generally did not have an accompanying significant decrease in streamflow, which indicates that the amount of sediment carried by the stream has been reduced. A significant decrease in sediment discharge also occurred at most of these stations, especially the Mississippi River near Royalton.

Sediment concentrations and discharges decreased at the Minnesota and Cottonwood River stations, both near New Ulm in the Minnesota River basin, but as these were accompanied by a significant decrease in streamflow, the decreased sediment concentration and discharge probably resulted only from a reduction in the sediment-carrying capacity of these streams. The Minnesota River near Jordan had a significant increase in sediment discharge, which probably was caused by the increase in streamflow. This could be caused by increased runoff and erosion above this station. Different trends are listed for the New Ulm and Jordan stations on the Minnesota River, but, as each of these occurred during different time periods, they are not comparable.

A significant upward trend in streamflow is apparent on the Zumbro, Whitewater, and South Fork Root Rivers. Sediment discharges and, generally, concentrations also increased significantly during the 1975-through-1981 sampling period. On the North Fork Whitewater and Root Rivers, no trend in streamflow was detected, but sediment concentrations and discharges decreased.

Table 5.--Statistically significant annual trends in streamflow, sediment concentration, and sediment discharge for stations having statistically significant trends in sediment concentration or discharge

[+, increasing; -, decreasing; .., trend not significant]

Station number	Station	Period of record (month-year)	Trend		
			Stream-flow	Sediment concen-tration	Sediment discharge
04014500	Baptism River near Beaver Bay, MN	10-74 to 9-81	..	-	..
05112000	Roseau River below State Ditch 51 near Caribou, MN	10-74 to 9-81	-	-	-
05131500	Little Fork River at Littlefork, MN	9-75 to 9-81	..	-	-
05267000	Mississippi River near Royalton, MN	1-75 to 9-81	..	-	-
05316770	Minnesota River at New Ulm, MN	10-67 to 9-76	-	-	-
05317000	Cottonwood River near New Ulm, MN	12-67 to 9-76	-	-	-
05330000	Minnesota River near Jordan, MN	10-74 to 9-81	+	..	+
05374900	Zumbro River at Kellogg, MN	8-75 to 9-81	+	+	+
05376000	North Fork Whitewater River near Elba, MN	10-70 to 9-81	..	-	-
05376800	Whitewater River near Beaver, MN	7-75 to 9-81	+	..	+
05385000	Root River near Houston, MN	12-67 to 9-81	..	-	-
05385500	South Fork Root River near Houston, MN	7-75 to 9-81	+	+	+

MONTHLY DISTRIBUTION OF SEDIMENT LOAD

Streamflow varies seasonally throughout Minnesota because of freezing during winter, thawing during spring, and seasonal variations in precipitation and runoff. Intuitively, it is apparent that suspended-sediment concentrations and loads would vary seasonally depending on streamflow and the erodibility of the soil. Knowledge of the seasonal distribution of sediment loads would be helpful in planning a cost-effective sampling program that would concentrate effort when most sediment is transported and diminish effort during the remainder of the year.

Suspended-sediment loads from 19 mean-daily sediment stations were chosen to determine the percentage of the average annual load carried during each month. Data were analyzed from stations having at least 2 years of sediment record and at least two samples for each month (one sample from each of the two, or more, years). Data from stations sampled primarily during periods of high flow were not analyzed, as the months in which the high flows occurred would be disproportionately weighted by the high sediment loads.

Table 6 shows the mean monthly percentage of the annual sediment load and the cumulative percentage for the 19 stations analyzed. Almost one-fourth of the annual sediment load was carried by these rivers during April. More than 90 percent of the load was carried during the 7 months March-September. Less than 4 percent of the annual load was carried during the winter months December, January, and February.

It required 3 to 9 months for 90 percent of the annual sediment load to be carried past the stations analyzed. The largest percentage of the annual load was usually carried during April when soil exposure generally is at its maximum following snowmelt and before protective vegetation has emerged. The highest percentage of the annual load for seven stations occurred during June or July, months with the highest monthly precipitation and frequent large storms that could produce the maximum daily yields shown in table 2. At all but two stations, less than 10 percent of the annual sediment load was carried during the months of December, January, and February when the ground is frozen and precipitation generally occurs as snow.

Application of this information to the sediment-data-collection network would suggest that intensive sampling should be performed primarily during March through September when more than 90 percent of the annual sediment load generally is carried. This approach could provide the optimum cost/benefit ratio and make funds available to sample other sites of interest.

EVALUATION OF SEDIMENT NETWORK

The sediment-data-collection network operated by the U.S. Geological Survey depends on funding from local, State, and other Federal agencies. Funding has been available to monitor or characterize ongoing problems, resulting in many projects of relatively short duration that do not represent long-term conditions.

Table 6.--Mean monthly percentage and cumulative percentage of annual sediment load

Month	Percentage	Cumulative percentage
April	24.9	24.9
July	17.3	42.2
March	14.9	57.1
June	13.4	70.5
May	10.2	80.7
August	6.0	86.7
September	4.8	91.5
October	2.7	94.2
November	2.2	96.4
February	1.3	97.7
December	1.2	98.9
January	1.0	100

Figures 5 and 6 show that many areas of the State have not been sampled adequately for definition of sediment-transport characteristics. Only a few or no samples have been collected from most streams in north-central Minnesota, including the upper reaches of the Mississippi River and its tributaries and parts of the Red Lake River basin. Some rivers in west-central Minnesota, parts of the Red River of the North and the Pomme de Terre River, drain areas underlain by clayey soils and may carry significant quantities of sediment, but have not been sampled adequately to define their sediment-transport characteristics. Samples have not been collected in the southwest corner of Minnesota where the Rock River and other streams drain areas underlain by loess deposits, which may have sediment yields similar to those in the southeast part of the State. Only one site on the north shore of Lake Superior, Baptism River near Beaver Bay, has been sampled for suspended sediment, but considering the similar soil type and land use throughout the north-shore area, this site is probably representative of the area.

Areas where sediment concentrations and loads are substantial might warrant further investigation. For example, the Little Fork River at Littlefork has a higher sediment yield than other sites in the area, but it is not known if this is a local or basin-wide characteristic. The data in this report show the effects of erosion in some basins; what is not known is the cause. High sediment yields in the Minnesota, Whitewater, and Root River basins may be related to agricultural practices. Small, detailed studies in these areas should provide a cause-and-effect relationship that could justify more conservative soils management locally.

At the time this report was being written (1984), 16 sites throughout Minnesota were being sampled for suspended-sediment concentration. Three of these were to be sampled daily throughout the year, two were to be sampled daily during March-August, and the rest were to be sampled four to six times during the year. All 11 of the nondaily sediment stations are funded primarily by the U.S. Geological Survey as part of the National Stream Quality Accounting Network and Hydrologic Benchmark program, and probably will be sampled for several more years. The five daily and periodic-daily stations, Mississippi River at Anoka, Whetstone River near Bigstone City, S. Dak., Yellow Bank River near Odessa, Minnesota River at Mankato, and Mississippi River at Winona, have been sampled for periods from 6 to 14 years, and the relationship between sediment discharge and streamflow, and average discharges and concentrations are reasonably well defined. Sampling frequency could be reduced at these stations so that funds could be made available to sample at other sites. However, at these daily sediment stations, except the Minnesota River at Mankato, sampling still is needed to provide data during high flows when most fluvial sediment is transported.

NEED FOR FURTHER STUDY

Operation of the sediment-data-collection network needs to continue throughout Minnesota to provide baseline data from which trends and changes can be detected. Previously sampled sites could be resampled to determine if sediment-transport characteristics have changed. Several of the sites listed in table 2 could be sampled at peak flows to verify the estimated peak-daily sediment yields. A report such as this one might be prepared every few years to redefine suspended-sediment characteristics of Minnesota streams.

More intensive studies could be conducted from the existing data base. The relationship between sediment particle size and sediment transport might result in more accurate descriptive equations than those in this report. Models capable of predicting sediment concentrations and sediment discharge possibly could be developed by regressing sediment against numerical representations of such parameters as land use, runoff, and soil types.

SUMMARY AND CONCLUSIONS

This report summarizes daily and instantaneous suspended-sediment data collected from 43 sites in and adjacent to Minnesota by the U.S. Geological Survey during 1967-81. Average sediment concentrations generally were less than 50 mg/L throughout northern Minnesota and the St. Croix River basin. Concentrations approached and frequently exceeded 100 mg/L in the Minnesota River basin. Sediment concentrations in the Root River averaged as much as 190 mg/L and maximum daily concentrations exceeded 10,000 mg/L.

Log-linear equations were developed to describe the sediment-transport curve for 33 daily sediment stations. These equations were applied to values from the flow-duration curves to provide long-term average annual sediment yields. Average annual yields ranged from less than 1.0 t/mi^2 in the Pelican River basin to 260 t/mi^2 in the Whitewater River basin. Average annual yields in northern Minnesota were less than 35 t/mi^2, except in the Deer Creek watershed where yields were 236 t/mi^2. The Minnesota River basin had yields that ranged from 5.5 to 66 t/mi^2.

Analysis of data from 12 long-term sediment stations showed significant trends in sediment concentrations and(or) loads. Downward trends were detected at three stations in northern Minnesota and at the Mississippi River near Royalton. There was a mixture of minor upward and downward trends at sites in the rest of the State, but an increase in sediment discharge was detected at the Minnesota River near Jordan. Some of the trends, however, undoubtedly reflect short-term variations in climate rather than long-term changes in sediment characteristics.

Analysis showed that more than 90 percent of the annual sediment load was measured during 3 to 9 months of the year. Most of the sediment load was carried during April when an average of 24.9 percent of the annual load was measured. The lowest average percentage of the annual load was carried during December, January, and February. It is possible that reduced sampling frequency during winter still could adequately quantify annual loads while reducing the cost of operating daily-sediment stations.

Some streams in northern, west-central, and southwestern Minnesota have not been adequately sampled for suspended-sediment concentrations and loads. The few sites that are sampled for daily sediment concentrations are fairly well characterized at lower flows, but need to be intensively sampled during high flows. More intensive studies could be made using the existing data base to develop models that incorporate data on land use, runoff, and soil type so as to improve predictions of sediment concentrations and yields.

REFERENCES

Baker, R. A., 1980, Contaminants and sediments, Volume 1, Fate and transport, case studies, modeling, toxicity: Ann Arbor, Mich., Ann Arbor Science, 558 p.

Borchert, J. R., 1974, Perspective on Minnesota land use: Minnesota State Planning Agency, St. Paul, Minn., 56 p.

Borchert, J. R., and Yaeger, D. P., 1968 [1969], Atlas of Minnesota resources and settlement: Minnesota State Planning Agency, St. Paul, Minn., 262 p.

Broussard, W. L., Farrell, D. F., Anderson, H. W., and Felsheim, P. E., 1975, Water resources of the Root River watershed, southeastern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-548, scale 1:250,000, 3 sheets.

Brown, H. B., Tideman, P. L., and Calkins, C. F., 1969, Atlas of Minnesota occupancy, (3d ed.): Dubuque, Iowa, Wm. C. Brown Book Company, 181 p.

Colby, B. R., 1956, Relationship of sediment discharge to streamflow: U.S. Geological Survey Open-File Report, 170 p.

Collier, C. R., 1974, An approximation of sediment yields from watersheds in Minnesota: American Society of Agricultural Engineers Paper 74-2506, 12 p.

Guy, H. P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, Bock 5, Chap. C1, 58 p.

____ 1970, Fluvial sediment concepts: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chap. C1, 55 p.

Guy, H. P., and Norman, V. W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chap. C2, 59 p.

Heien, D. M., 1968, A note on log-linear regression, Journal of the American Statistical Association, v. 3, p. 1034-1038.

Hirsch, R. M., Slack, J. R., and Smith, R. A., 1982, Techniques of trend analysis for monthly water-quality data: Water Resources Research, 1982, v. 18, no. 1, p. 107-121.

Lane, E. W., 1938, Report on investigation of sediment carried by rivers of St. Paul, U.S. Engineer District 1937 and 1938: Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Icwa, 42 p.

Maderak, M. L., 1963, Quality of waters, Minnesota, a compilation, 1955-62: Minnesota Department of Conservation, Division of Waters, Bull. 21, p. 88-94.

Miller, C. R., 1951, Analysis of flow-duration, sediment-rating curve method of computing sediment yield: U.S. Bureau of Reclamation, Hydrology Branch, 55 p.

Olcott, P. G., Ericson, D. E., Felsheim, P. E., and Broussard, W. L., 1978, Water Resources of the Lake Superior watershed, northeastern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-582, scale 1:500,000, 2 sheets.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chap. C3, 66 p.

Ray, A. A., 1982a, SAS user's guide: basics, 1982 edition: SAS Institute, Incorporated, Cary, North Carolina, 923 p.

____ 1982b, SAS user's guide: statistics, 1982 edition: SAS Institute, Incorporated, Cary, North Carolina, 584 p.

Reinhardt, P. S., 1980, SAS supplemental library user's guide, 1980 edition: SAS Institute, Incorporated, Cary, North Carolina, 202 p.

Searcy, J. K., 1959, Flow-duration curves, manual of hydrology, part 2: low-flow techniques: U.S. Geological Survey Water-Supply Paper 1542-A, 33 p.

Upper Mississippi River Comprehensive Basin Study Coordinating Committee, 1970, Upper Mississippi River Comprehensive Basin Study, Vol. III, Appendix G Fluvial Sediment, 77 p.

U.S. Geological Survey, 1966, Water resources data for Minnesota, 1965--part 2, water-quality records: U.S. Geological Survey Water-Data Report, 218 p.

____ 1970-75, Water resources data for Minnesota, 1968-74--part 2. Water-quality records: U.S. Geological Survey Water-Data reports (published annually).

____ 1976-77, Water resources data for Minnesota, 1975-76: U.S. Geological Survey Water-Data Reports MN-75-1 and MN-76-1 (published annually).

____ 1978-82, Water resources data for Minnesota, water years 1977-81, volumes 1 and 2: U.S. Geological Survey Water-Data Reports MN-77-1 and 2 to MN-81-1 and 2 (published annually).

☆U.S GOVERNMENT PRINTING OFFICE.1987-755-593/40118