SUSPENDED SEDIMENT IN TRAIL CREEK AT MICHIGAN CITY, INDIANA

By Charles G. Crawford and David V. Jacques

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4019

Prepared under contract with the

U.S. ARMY CORPS OF ENGINEERS

Indianapolis, Indiana

1992

DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. Geological Survey

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
5957 Lakeside Boulevard
Indianapolis, Indiana 46278

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton, short (ton)	0.9072	megagram
ton per day (ton/d)	0.9072	megagram per day
ton per square mile (ton/mi^2)	0.3503	megagram per square kilometer
ton per year (ton/yr)	0.9072	megagram per annum

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9\ (°F - 32)$$

The following term and abbreviation is also used in this report:

milligram per liter (mg/L)

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ABSTRACT

Trail Creek is a small (54.1-square-mile drainage area) tributary of Lake Michigan located in northwestern Indiana. A harbor at the mouth of the stream has experienced excessive sediment deposition. A study was done to investigate the suspended-sediment characteristics of Trail Creek. The study included analysis of suspended-sediment concentration and particle-size data, and estimates of annual suspended-sediment load. Suspended-sediment concentrations ranged from only a few milligrams per liter at low flows to about 300 milligrams per liter at high flows. At low flows, the suspended sediment was mostly silt- and clay-sized material (less than 0.062 millimeter). The percentage of silt- and clay-sized material gradually decreased to about 50 percent of the suspended sediment at high flows. Estimates of the annual suspended-sediment load for the 1981-90 water years were calculated by the flow-duration, rating-curve method. Annual loads ranged from 3,690 to 8,250 tons. The average annual load for the 10-year period was 6,180 tons. Annual suspended-sediment yield (load per unit drainage area) averaged 114 tons per square mile; this value is within the range of values from 14 other previously investigated streams in northern Indiana. Average annual yields of these 14 streams ranged from 11 to 152 tons per square mile; the median annual yield was 56 tons per square mile.

INTRODUCTION

Background

Trail Creek is one of the few tributaries to Lake Michigan in Indiana. Recreational boaters and commercial fishing are important aspects of the local economy. Most of the activity centers on salmon and trout fishing in Lake Michigan. Because of a salmonid stocking program managed by the Indiana Department of Natural Resources, Trail Creek is Indiana's most noted salmonid stream.

A harbor has been established at the mouth of Trail Creek to support the salmonid industry. The U.S. Army Corps of Engineers is authorized to maintain an 18-foot-deep navigation channel in the lower reaches of Trail Creek; however, rapid accumulation of sediment in the navigation channel has become a problem. The channel was dredged in 1980, 1986, and 1987, and, as of this writing (1992), it is again in need of dredging. Possible sources of the sediment are erosion and transport of sediment from the upstream areas of the basin or storm and combined sewers that discharge into the lower channel and harbor.

Sediment is inorganic and organic material that is transported by, suspended in, or deposited by streams. The quantity of sediment transported by a stream in a specified time is designated the sediment load. It is typically expressed as an annual value in tons, an average value in ton/yr, or as a yield (load per unit area) in ton/mi^2. The sediment load is not equivalent to the denudation or erosion rate of the drainage basin, primarily because of storage and changes in storage within the basin. The sediment load can be divided into two components on the basis of the mode of transportation (Colby, 1963, p. A12). Suspended sediment is material held in suspension by turbulent currents or by colloidal suspension. Bedload is material that remains very close to the streambed and is transported by sliding, skipping, or rolling along the bed. The rate of movement of sediment past a point in a stream is designated the sediment discharge.

The U.S. Geological Survey, under contract with the U.S. Army Corps of Engineers, began a study in 1990 to characterize suspended-sediment in Trail Creek at Michigan City, Indiana. The information will be used to assess whether the upland areas of the basin are contributing enough sediment to cause the sediment deposition problem in the harbor.

Purpose and Scope

This report presents (1) suspended-sediment concentration and discharge data; (2) particle-size distribution of suspended sediment; and (3) estimates of mean annual suspended-sediment load for the 1981-90 water years (the water year used for this report is the 12-month period that begins October 1 and ends September 30). The report also describes the methodology used to estimate the mean annual suspended-sediment load and to estimate the uncertainty in the estimated load. The information contained in this report is based on suspended-sediment data collected by the U.S. Geological Survey from 1977-81 and 1990-91 and includes data from 64 instantaneous observations of suspended-sediment concentration and discharge collected at Trail Creek.

PHYSICAL SETTING OF THE STUDY AREA

Trail Creek is a small perennial stream draining 54.1 mi^2 of northwestern Indiana (fig. 1). The stream discharges directly into Lake Michigan. Its headwaters are drained by four tributaries located approximately 8 mi inland (East Branch, West Branch, Waterford Creek, and Wolf Run). Land use in the basin is very diverse. Approximately 70 percent of the basin is agricultural, whereas the remaining 30 percent is heavily developed and includes part of Michigan City, Indiana.

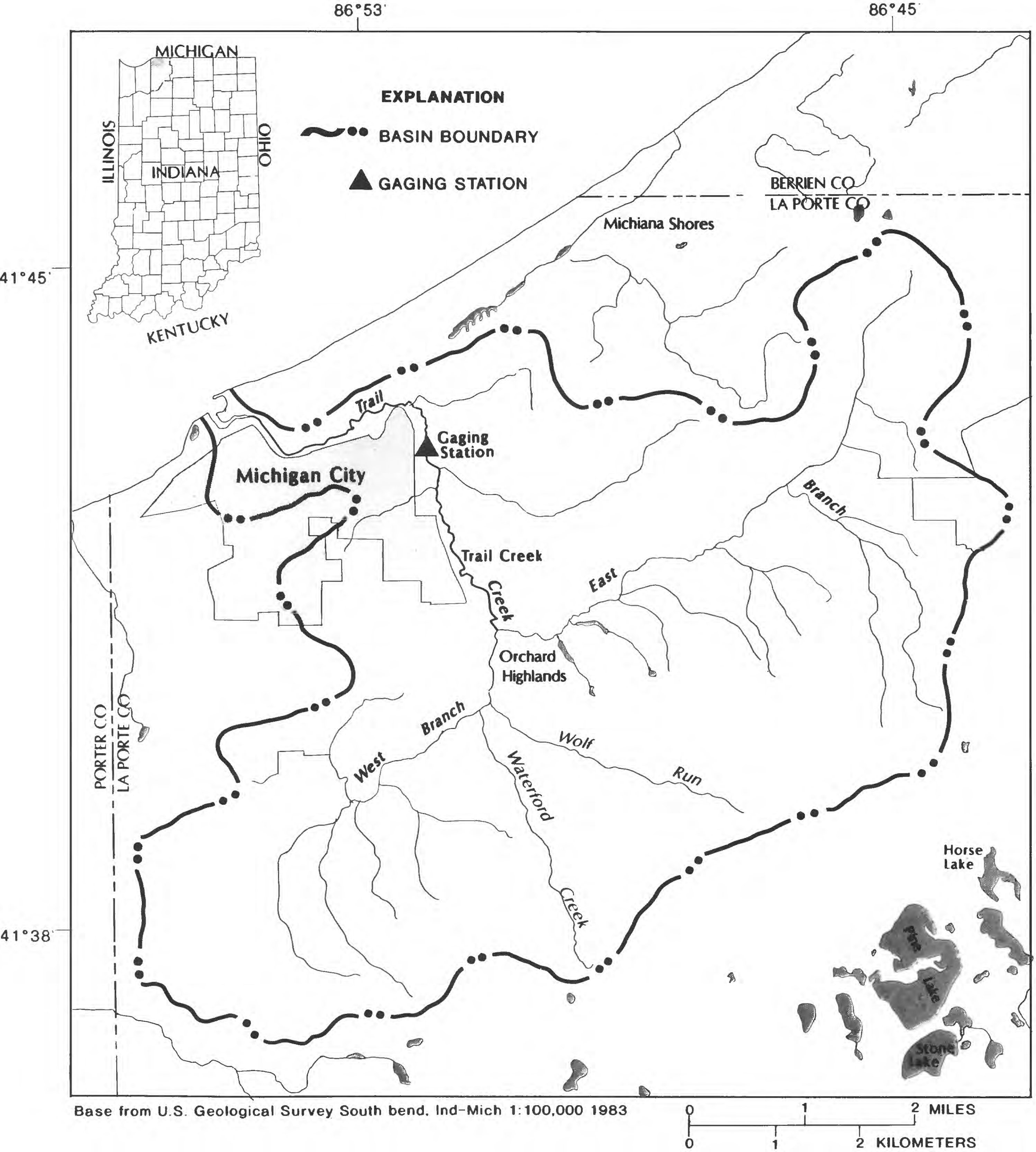

Figure 1.--Trail Creek basin and location of gaging station on Trail Creek.

The basin is underlain by bedrock consisting of black shales and dolomitic limestones of Devonian age. The bedrock is covered by approximately 150 ft of surficial material (Gray, 1983). The bottom 120 ft of this material is till deposited by the several episodes of glaciation that affected northern Indiana. The top 30 ft of the surficial deposits consists of lacustrine and eolian derived sediments associated with Lake Michigan. In late Pleistocene time, the southern part of the Lake Michigan Basin was occupied by glacial Lake Chicago, which was approximately 40 to 50 ft higher than the present day level of Lake Michigan (Schneider, 1966). As Lake Chicago retreated, it left behind a complex lacustrine area in which successive stages of retreat are represented by deposits in step-like intervals. This area was termed the Calumet Lacustrine Plain by Schneider (1966). The plain has low relief, generally less than 50 ft, and is marked by abundant low sand ridges. The headwaters of the stream, located in the southernmost part of the basin, are contained within a different physiographic province. This area is composed of a complex end moraine of Wisconsin Age that lies approximately 150 ft above the lacustrine plain. Schneider (1966) termed this area of relatively high relief the Valparaiso Morainal Area. These features are part of a very extensive physiographic province that can be traced through parts of Wisconsin, Illinois, Indiana, and Michigan. In Indiana, this region is referred to as the Northern Moraine and Lake region.

Soils within the basin are of recent origin, and vary widely in characteristics. Unlike most parts of northern Indiana, which are dominated by clay-rich soils of glacial origin, soils within the Trail Creek Basin are composed mostly of sand. Soils range from loose sandy soils of beach deposit and eolian origin to black sandy and loamy soils of lacustrine origin. The black soils are remnants of former marshlands and contain a large percentage of organic compounds, making these soils extremely productive farmland. The loose sands are agriculturally unproductive and very susceptible to drought. All soils within the basin are highly transmissive because of their high sand content. Consequently, drainage within the basin is good despite the low topographic relief.

Climate within the basin is greatly affected by Lake Michigan. The lake acts as a heat source in early winter, raising temperatures above those of surrounding areas, but also is responsible for lowering temperatures below surrounding areas the rest of the year. The region has average temperatures ranging from 24 ^{o}F in January to 73 ^{o}F in July. The average annual temperature is 50 ^{o}F. The area receives an average of 38 in. of precipitation annually. Sixty percent of the precipitation falls during April-September. Snowfall is unpredictable and frequently is very heavy because of the effect of Lake Michigan. Average annual snowfall within the basin is 72 in.; single prolonged snow storms deposit as much as 24 in. of snow.

The U.S. Geological Survey has monitored the streamflow of Trail Creek since June 1969. The streamflow-gaging station is located at Springland Avenue in Michigan City, 4.2 mi from its confluence with Lake Michigan (fig. 1). The drainage area at the station is 54.1 mi^2. Channel slope upstream of the gage averages 6.4 ft/mi. Long-term average flow (1971-90) for the stream is 72.6 ft^3/s, which is equivalent to 18.2 in. of runoff. The minimum daily flow observed in the stream was 20 ft^3/s in August 1977. The maximum instantaneous flow recorded was 2,430 ft^3/s in July 1986.

SUSPENDED-SEDIMENT SAMPLING METHODS

All suspended-sediment samples were collected at the U.S. Geological Survey gaging station on Trail Creek. Suspended-sediment samples were collected in depth-integrating samplers, using procedures described by Guy and Norman (1970). Suspended-sediment concentration and particle size were determined by laboratory procedures described by Guy (1969).

Suspended-sediment discharge for a sample was calculated using the following equation:

$$Qs = k\ Qw\ Cs, \tag{1}$$

where Qs is the instantaneous suspended-sediment discharge, in ton/d;

k is a units conversion factor (k = 0.0027 when Qw is in ft^3/s, Cs is in mg/L, and Qs, is in ton/d);

Qw is the instantaneous streamflow, in ft^3/s; and

Cs is the instantaneous suspended-sediment concentration, in mg/L.

SUSPENDED-SEDIMENT CONCENTRATION AND PARTICLE SIZE

Suspended-sediment concentration and particle-size data collected from Trail Creek are listed in table 1. Suspended-sediment concentrations are low (less than 50 mg/L) at low streamflows (less than 150 ft^3/s) but rise to a maximum concentration of about 300 mg/L as streamflow increases. The variation of suspended-sediment concentration and streamflow is shown in figure 2.

Silt- and clay-size materials (less than 0.062 millimeters in diameter) comprised 39 to 94 percent of the suspended sediment. The percentage of sand in samples from Trail Creek is higher than for other streams in northern Indiana (Crawford and Mansue, 1988), reflecting the presence of sandy soils in the basin. Silt- and clay-size materials decreased from about 90 percent of the total suspended sediment at low streamflows to about 50 percent at high streamflows. The percentage of silt- and clay-size materials is negatively correlated with streamflow, although this correlation is highly variable. The variation of particle size and streamflow is shown in figure 3.

Table 1.--Suspended-sediment data

[--, no data]

Date	Time	Streamflow (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)	Percentage of suspended-sediment finer than 0.062 millimeters
10-26-77	1515	49	5	0.66	--
11-30-77	1215	48	16	2.1	--
01-17-78	1600	79	15	3.2	--
03-21-78	1730	748	182	368	--
03-22-78	1010	401	162	175	--
07-25-78	1410	100	63	17	--
10-04-78	1330	38	14	1.4	--
11-08-78	1150	44	16	1.9	--
12-07-78	1040	63	12	2.0	--
01-10-79	1550	49	29	3.8	--
02-08-79	1530	55	20	3.0	--
04-04-79	1500	119	32	10	--
05-23-79	0840	60	23	3.7	--
06-27-79	0935	37	35	3.5	--
07-31-79	1445	40	38	4.1	76
09-13-79	1350	33	16	1.4	--
10-23-79	1110	51	8	1.1	--
11-28-79	1155	117	47	15	--
01-17-80	0910	108	80	23	--
03-05-80	0845	62	18	3.0	--
04-22-80	1555	63	37	6.3	93
06-11-80	1015	73	75	15	94
08-08-80	0845	28	33	2.5	--
09-17-80	1130	265	180	129	--
11-24-80	1615	49	7	0.93	--
01-27-81	1030	114	33	10	--
05-28-81	0915	68	51	9.4	88
07-27-81	1600	97	89	23	89
09-30-81	1600	76	137	28	88
06-14-90	1455	53	58	8.3	86

Table 1.--Suspended-sediment data--Continued

Date	Time	Streamflow (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)	Percentage of suspended-sediment finer than 0.062 millimeters
07-03-90	0845	46	E118	E15	E87
08-03-90	1030	42	43	4.9	66
08-20-90	2015	769	159	330	51
08-21-90	0755	442	107	128	54
08-21-90	0840	423	109	124	56
08-21-90	1020	389	120	126	54
08-21-90	1225	357	126	121	64
09-13-90	1053	52	20	2.8	80
09-14-90	1150	102	101	28	91
10-09-90	1820	399	143	154	52
10-09-90	2305	463	155	194	49
10-10-90	1005	719	165	320	56
10-10-90	1205	761	150	308	59
10-10-90	1530	802	154	333	47
10-10-90	1700	811	142	311	45
10-10-90	1810	811	134	293	45
10-17-90	2047	81	24	5.2	53
10-17-90	2216	171	190	88	45
10-17-90	2324	152	63	26	75
10-18-90	0119	205	150	83	71
10-18-90	0631	280	204	154	76
10-18-90	0817	286	185	143	76
11-05-90	1640	636	205	352	39
02-19-91	1400	283	129	99	57
02-28-91	1620	75	14	2.8	64
04-17-91	1350	238	77	49	68
06-01-91	0016	621	211	354	77
06-01-91	0214	640	294	508	78
06-01-91	0410	666	278	500	72
06-01-91	0612	691	273	509	74
06-01-91	0809	706	221	421	68
06-01-91	1008	675	228	416	73
06-01-91	1207	605	191	312	69
06-06-91	0814	75	23	4.7	70

E indicates estimate

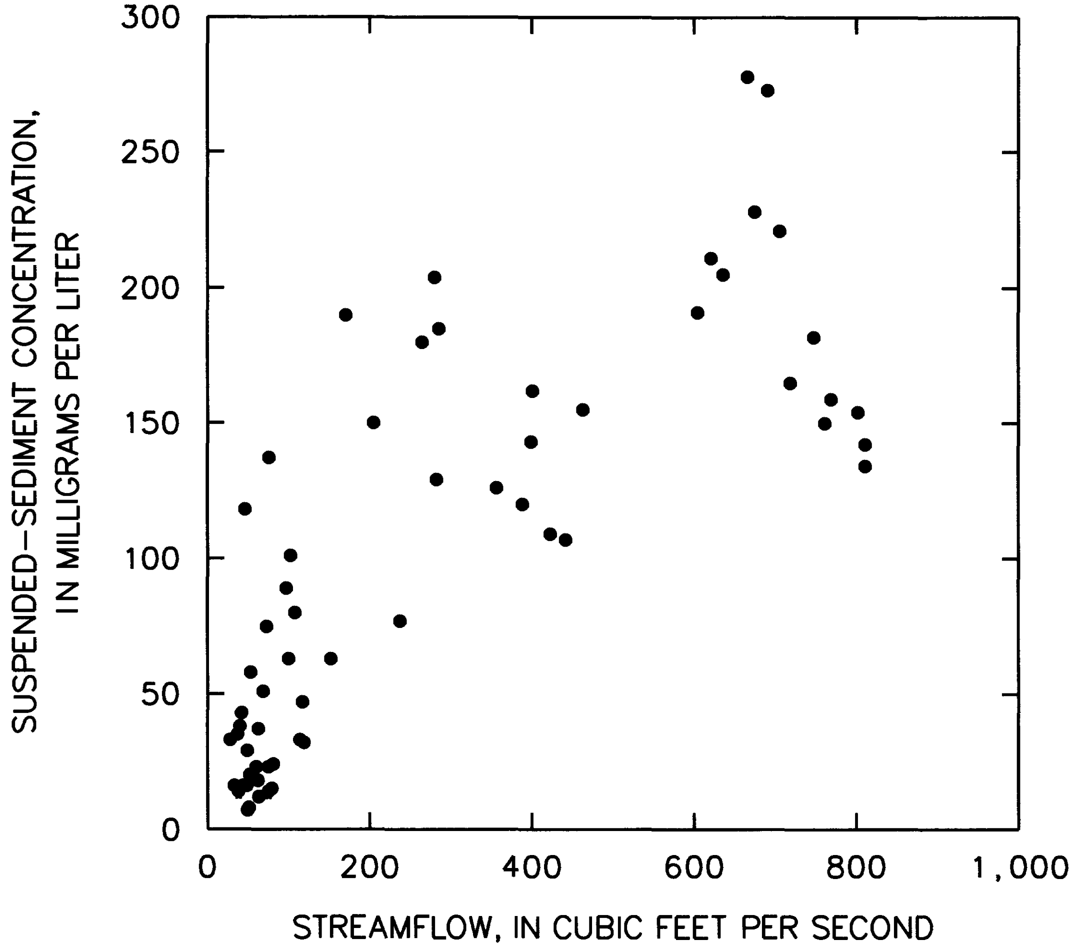

Figure 2.--Variations in suspended-sediment concentration and streamflow in Trail Creek at Michigan City.

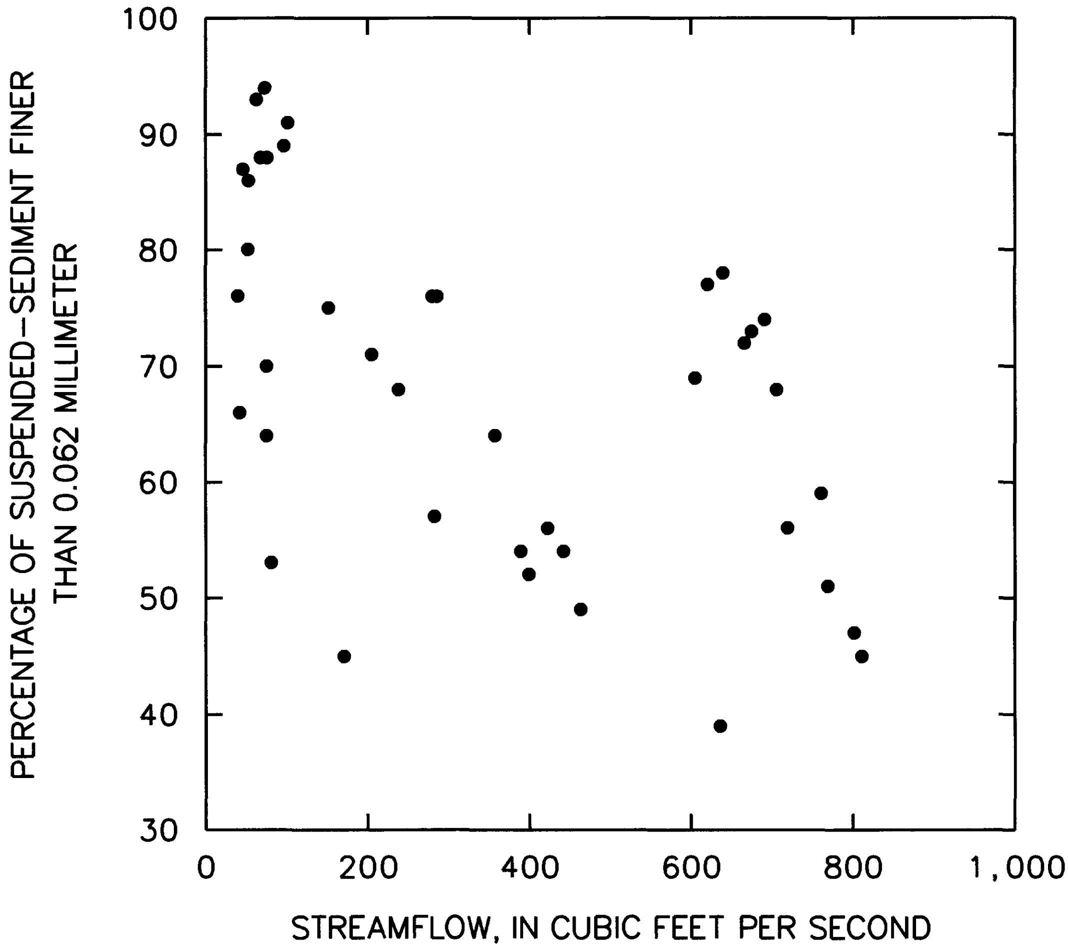

Figure 3.—Variations in percentage of suspended sediment finer than 0.062 millimeter and streamflow in Trail Creek at Michigan City.

Suspended-sediment discharge data collected from Trail Creek are listed in table 1. Mean annual suspended-sediment loads for Trail Creek were estimated by the flow-duration, rating-curve method described by Miller (1951). For this report, only suspended-sediment load is reported and discussed. A suspended-sediment rating curve and a flow-duration curve are used in this method. A suspended-sediment rating curve is an empirical relation between suspended-sediment load and streamflow that is typically prepared by plotting suspended-sediment discharge and streamflow on logarithmic coordinates (Grenney and Heyse, 1985). Colby (1956, p. 10-25) also discusses the use of sediment-rating curves. Linear regression was used to quantify the relation between suspended-sediment discharge and streamflow. Three polynomial functions were evaluated:

First-order polynomial:

$$\ln Qs = b0 + b1 (\ln Qw) + e, \qquad (2)$$

Second-order polynomial:

$$\ln Qs = b0 + b1 (\ln Qw) + b2 (\ln Qw)^2 + e, \qquad (3)$$

Third-order polynomial:

$$\ln Qs = b0 + b1 (\ln Qw) + b2 (\ln Qw)^2 + b3 (\ln Qw)^3 + e, \qquad (4)$$

where ln Qs is the natural logarithm of the suspended-sediment discharge;

ln Qw is the natural logarithm of streamflow;

b0, b1, b2, and b3 are regression coefficients; and

e is the residual error (the amount that any value of ln Qs differs from the regression line).

The second- and third-order polynomials allow the regression line to have a curved shape, which is sometimes observed in the logarithmic relation between suspended-sediment discharge and streamflow. The best fitting regression equation was selected on the basis of the coefficient of determination and residuals analysis. The coefficient of determination is a statistic that measures the proportion of the total variation of the dependent variable explained by the regression. Generally, the higher the coefficient of determination the better the regression equation explains the relation between the variables. The residuals were analyzed to determine if the assumptions of linear regression were not violated (that they were independent and identically distributed). For a more detailed discussion of these criteria, see Chatterjee and Price (1977, p. 9-10, 55-56), Daniel and Wood (1980, p. 17, 27-43), or Draper and Smith (1981, p. 19, 141-182).

Functions of the form shown in equations 2 to 4 must be transformed from logarithmic to arithmetic scale before they can be used to obtain estimates of suspended-sediment discharge. Estimates of suspended-sediment discharge will be biased if a simple inverse transformation of the logarithmic form of the model is used. The reader is referred to Miller (1984) for a discussion of transformation bias in curve fitting. A nonparametric correction for transformation bias, the smearing estimate (Duan, 1983), was used to correct for transformation bias in equations presented in this report. By use of the smearing estimate, an approximately unbiased estimate of the mean suspended-sediment discharge for a given streamflow, was obtained from the following equation:

$$Qs = \exp(f(\ln Qw)) \frac{\Sigma \exp(e)}{n}, \qquad (5)$$

where exp indicates that the quantity in the parentheses is raised to the base of the natural logarithm;

f(ln Qw) is the polynomial function describing the relation between the logarithms of suspended-sediment discharge and streamflow with estimated regression coefficients; and

n is the number of observations used with the linear-regression analysis to obtain the coefficients of the rating curve.

A discussion of transformation methods as related to sediment transport may be found in Cohn and others (1989), Farr and Clarke (1984), Ferguson (1986a and 1986b), and Koch and Smillie (1986).

A second-order polynomial best described the relation between the logarithms of suspended-sediment discharge and streamflow for Trail Creek. The transformed relation is

$$Qs = \exp(-8.742 + 3.002 (\ln Qw) - 0.117 (\ln Qw)^2)\ 1.20, \qquad (6)$$

The value 1.20 is the bias correction factor. The mean-square error of this equation is 0.377. The relation of suspended-sediment discharge and streamflow for Trail Creek is shown in figure 4. The rating curve shown in figure 4 is drawn over the range of flows used to estimate the mean annual suspended-sediment load for Trail Creek. The flow-duration curve of daily mean streamflow for the 1981-90 water years is shown in figure 5.

Equation (5) gives an estimate of the expected suspended-sediment discharge for any specified streamflow. In the flow-duration, rating-curve method, weighted estimates for representative flows are summed to obtain an estimate of the mean daily suspended-sediment discharge as follows:

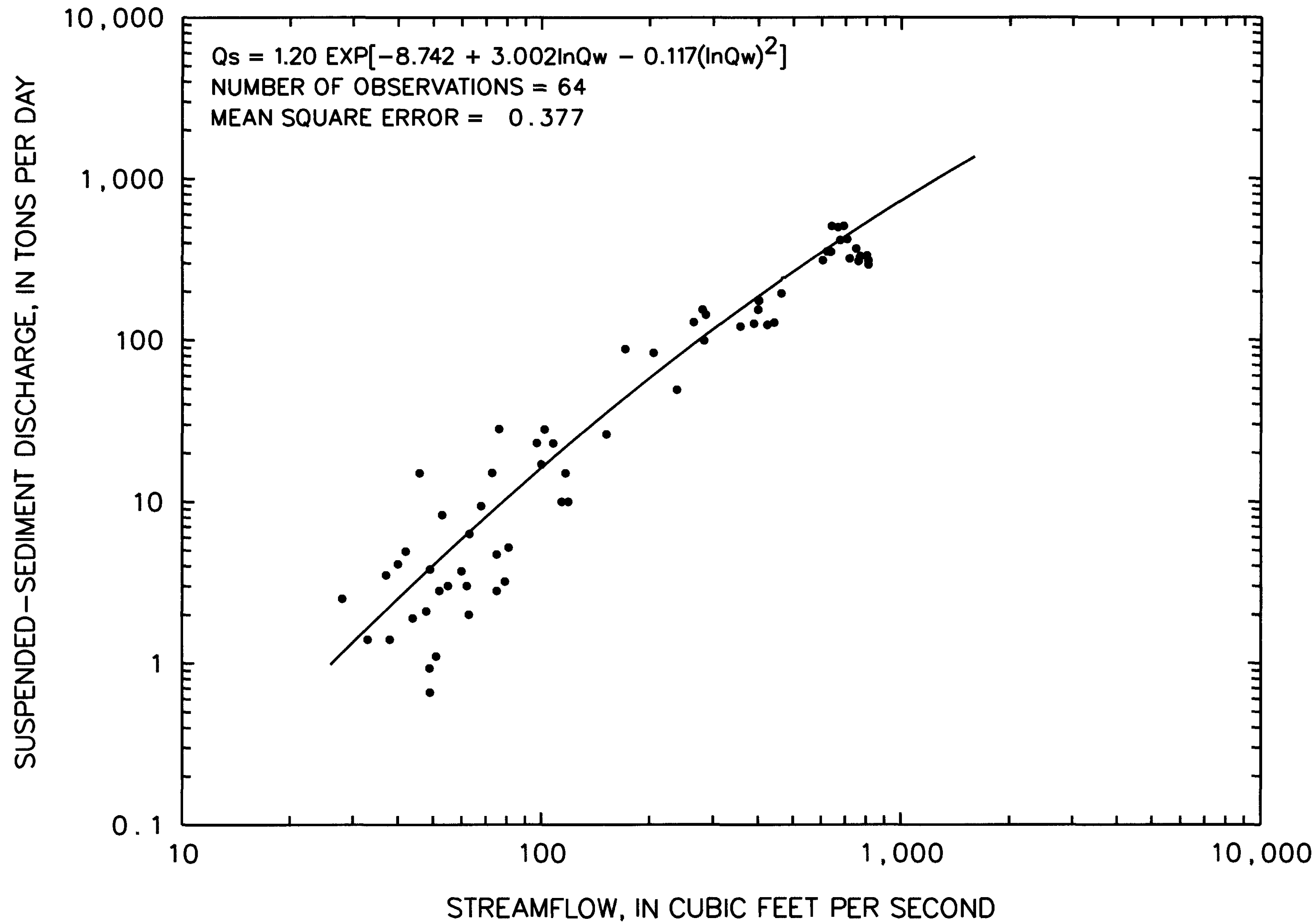

Figure 4.−−Suspended−sediment rating curve, Trail Creek at Michigan City.

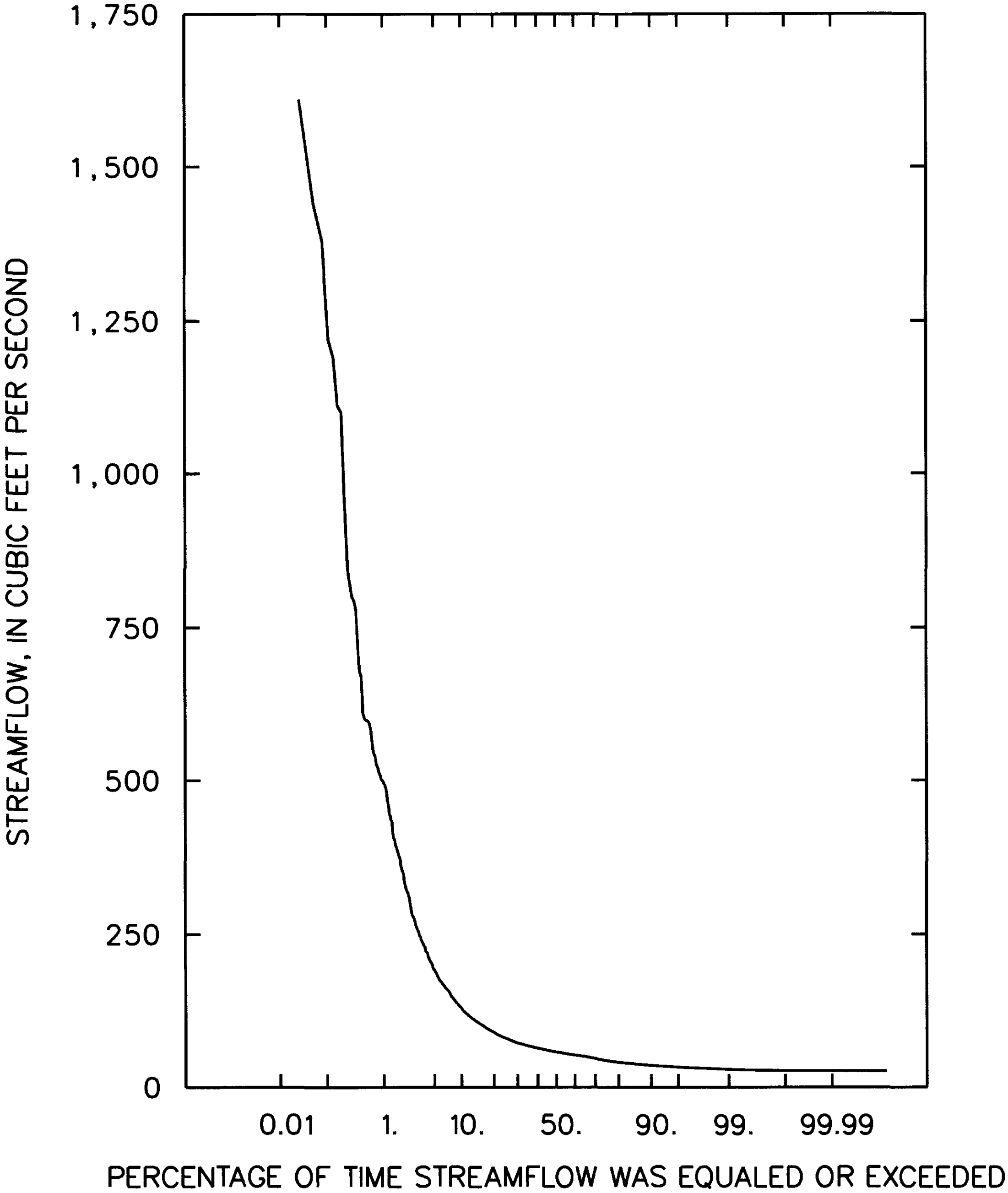

Figure 5.--Flow-duration curve of daily mean streamflow for 1981-90 water years, Trail Creek at Michigan City.

$$Qs_D = \sum_{i=1}^{I} F_i \, Qs_i$$

$$Qs_D = \sum_{i=1}^{I} F_i \, \exp(f(\ln Qw_i)) \, \frac{\Sigma \exp(e)}{n}, \qquad (7)$$

where Qs_D is the estimate of the mean daily suspended-sediment discharge;

I is the total number of streamflow values in the flow duration;

i is a subscript denoting the ith streamflow value;

F_i is the frequency of occurrence associated with the ith representative streamflow value; and,

Qs_i is the estimate of the mean suspended-sediment discharge for the ith streamflow.

An estimate of the mean annual suspended-sediment load, L, is obtained by multiplying the estimated mean daily suspended-sediment discharge, Qs_D, by 365. Example calculations using this method are given in Crawford and Mansue (1988) and Flint (1983).

An estimate of the uncertainty in the mean annual suspended-sediment load was calculated by the jackknife method (Stuart and Ord, 1987, p. 338). The jackknife is a method for examining sampling properties of a statistic, with no requirement for distributional assumptions. The method is a resampling scheme based on computing the statistic for various subsamples of the original data set. A jackknife estimate of the variance of the estimated mean load can be obtained using the equation:

$$Var[L] = \frac{n-1}{n} \sum_{i=1}^{I} [L_{(n-1,i)} - \overline{L_{(n-1)}}]^2, \qquad (8)$$

where $L_{(n-1,i)}$ is the estimated mean load calculated from equation (7) using the n - 1 values that excludes the ith discharge/streamflow observation; and,

$\overline{L_{(n-1)}}$ is the mean of the $L_{(n-1,i)}$.

An estimate of the standard deviation of the estimated mean load is obtained by taking the square root of the variance. Approximate 95-percent confidence limits can be obtained by subtracting or adding twice the standard deviation to the estimated mean load.

Estimated annual suspended-sediment loads for the 1981-90 water years are shown in table 2. The annual loads ranged from 3,690 to 8,250 tons. The average annual load for the 10-year period is 6,180 tons. Annual suspended-sediment yield (load per unit drainage area) ranged from 68 to 153 ton/mi^2 and averaged 114 ton/mi^2. Estimated average annual suspended-sediment yields from 14 other streams in the Northern Moraine and Lake region of Indiana ranged from 11 to 152 ton/mi^2 (Crawford and Mansue, 1988, p. 67). The median annual suspended-sediment yield of the 14 streams was 56 ton/mi^2.

Approximate 95-percent confidence limits are less than ± 20 percent of the estimated mean load. These confidence limits take into account only the variability of the sample data. A fundamental assumption of linear regression is that the data used for the regression are representative of the population from which they were collected. If this is not the situation, regression results will not be valid. The data used in this study were collected during two different time periods. Forty-five percent of the data were collected during 1977-81, the remaining data were collected during 1990-91. Of the data collected during 1990-91, most were collected during four storms. Nearly all of the observations collected at streamflows exceeding 300 ft^3/s were obtained during these four storms. It is possible that conditions in the basin during these four storms are not representative of temporal variability in the basin. If so, the rating curve obtained for this study and, consequently, the estimated suspended-sediment loads, might not be representative of temporal changes in suspended sediment that occur in the basin. This probably is not the case, however. Annual suspended-sediment load estimated for 1981-90 using just the 1977-81 sample data and estimated using just the 1990-91 sample data were within 4 percent of one another and were not statistically different. The least accurate of these estimates was within 10 percent of the annual suspended-sediment load determined using the combined data. If the data collected during 1990-91 were not representative, it is unlikely that the data collected from the two time periods would have provided results so similar.

Table 2.--Estimated annual suspended-sediment loads, 1981-90

Water year(s)	Estimated annual suspended-sediment load (tons)	Standard deviation of estimated annual suspended-sediment load (tons)	Annual runoff (inches)
1981	7,050	520	21.2
1982	8,120	550	23.1
1983	6,850	550	21.8
1984	5,450	430	19.0
1985	6,950	640	19.3
1986	6,530	470	20.9
1987	3,690	310	16.5
1988	3,950	370	17.1
1989	4,970	360	17.4
1990	8,250	560	22.6
Mean annual load 1981-90	6,180	430	19.9

SUMMARY AND CONCLUSIONS

Trail Creek is a 54.1-mi^2 tributary of Lake Michigan located in northwestern Indiana. A harbor has been built at the mouth of the stream in Michigan City, Indiana, to support the recreational and commercial fishing industry that is important to the local economy. Use of the harbor has been limited by excessive sediment deposition. The harbor was dredged in 1980, 1986, and 1987, and as of this writing (1992), it is again in need of dredging. This report describes a study done to investigate the suspended-sediment characteristics of Trail Creek. The study included analysis of suspended-sediment concentration and particle-size data, and estimates of annual suspended-sediment load. Data collected at the U.S. Geological Survey streamflow-gaging station on Trail Creek during 1977-81 and 1990-91 were used in this study.

Suspended-sediment concentration is positively correlated with streamflow. At low flows, the suspended-sediment concentration was typically less than 50 mg/L. Concentrations increased rapidly as streamflow increased, reaching 200 to 300 mg/L at high flows.

The percentage of silt- and clay-size materials (less than 0.062 millimeter) is negatively correlated with streamflow, although this correlation is highly variable. At low flows, silt- and clay-sized materials accounted for about 90 percent of the suspended sediment. This percentage decreased to about 50 percent at high flows. The percentage of course-grained materials in Trail Creek is higher than in other northern Indiana streams. This can be attributed to the surrounding surficial material, which consists of beach and lacustrine deposits with a large proportion of sand.

A suspended-sediment rating curve was developed by use of linear regression to relate the natural logarithms of suspended-sediment discharge and streamflow and an appropriate correction for transformation bias. The best-fit relation between suspended-sediment discharge (Qs) and streamflow (Qw) is given by the relation:

$$Qs = \exp(-8.742 + 3.002 (\ln Qw) - 0.117 (\ln Qw)^2) 1.20.$$

Estimates of the annual suspended-sediment load for the 1981-90 water years were calculated using the flow-duration, rating-curve method. Annual loads ranged from 3,690 to 8,250 tons. The average annual load for the 10-year period was 6,180 tons. The jackknife method was used to obtain an estimate of the uncertainty in the estimated suspended-sediment loads. The uncertainty was estimated to be less than ± 20 percent of the calculated load. Suspended-sediment yield (load per unit drainage area) averaged 114 ton/mi^2. This value is within the range of values from 14 other previously investigated streams within the Northern Moraine and Lake region of Indiana. Annual suspended-sediment yields from these streams averaged 11 to 152 ton/mi^2; the median annual yield was 56 ton/mi^2.

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