SEDIMENT YIELDS OF RIVERS IN THE SOUTHERN PENINSULA OF MICHIGAN

Thesis for the Degree of M. S.
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ABSTRACT

SEDIMENT YIELDS OF RIVERS IN THE
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By

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Sedimentation is a very important environmental and economic factor in the United States. There are many variables that influence the suspended sediment yield of a river or stream. Some of the more important variables are gross erosion of the soil, the slope or energy gradient of the river, the trap efficiency of lakes and ponds along the watercourse, and the particle size and density of the sediment.

It has been shown by various research projects that it is possible to make sediment yield predictions for rivers within the same physiographic area. This research was undertaken to determine a meaningful relationship between the sediment yield of a river, and some other easily derived watershed parameter. The research for this thesis has been confined to the rivers of the southern peninsula of Michigan.

James N. Wade

Suspended sediment yields were computed using data from suspended sediment concentration records, and streamflow statistics. The results show that there is a difference in the rate of sediment yield between the summer and winter months in some Michigan rivers. A close correlation was established between annual sediment yield, and drainage area, for rivers with watersheds that are in multiple land use. This relationship can be used to predict the sediment yield of locations on rivers where sediment stations have not been established.

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James N. Wade

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INTRODUCTION

Each year vast quantities of soil are eroded from the land by the forces of falling rain and running water. Some of this material reaches streams and rivers and is carried away as suspended sediment. Suspended sediment can greatly lower the water quality of a stream, making it less useful for fish and wildlife, recreational use, domestic use, agricultural use, and industrial use. Suspended sediment, when deposited, can clog rivers, lakes, and harbors. The removal of sediment is very costly, and in many cases the continued use of the watercourse or lake cannot justify the cost of the removal of the sediment.

The sediment yield of streams and rivers has been studied extensively in many states. These studies have lead to methods of accurately predicting the sediment yield of rivers in the physiographic area studied. In Michigan there has been extensive stream gauging and water sampling, but a method of reasonably estimating the suspended sediment yield of ungauged rivers has not previously been devised.

This thesis discusses the process of erosion, transportation, and deposition of sediment. Methods of suspended sediment sampling, sample analysis, and determining suspended sediment concentration are outlined. The thesis refers to current sources of suspended sediment yield predictions and analyses that have been made previously for Michigan rivers. Using the available data, analyses will be made to show the similarity and differences between the suspended sediment transport characteristics of rivers in the lower peninsula of Michigan. A method for predicting the sediment yield of rivers in the lower peninsula of Michigan will be proposed and discussed in detail.

Erosion from Rainfall and Runoff

There are two main types of erosion affecting the watersheds of Michigan; sheet erosion and stream scour. Sheet erosion begins when the force of falling raindrops dislodges soil particles. Small soil particles less than 0.074 mm easily become suspended in rainwater. The water eventually begins to flow off of the land in microdrainageways. The constant agitation of falling rain helps keep the small soil particles in suspension. Eventually the water will be concentrated into progressively larger watercourses, and some of the suspended soil will drop out of suspension and be left behind.

Sheet erosion rates depend on many factors; soil type, slope steepness and length, vegetative cover, and rainfall intensity. In general, a fine textured soil will erode more easily than a coarse textured soil. Erosion will occur more rapidly on long steep slopes than on nearly level short slopes. Vegetative cover absorbs the energy of falling rain and helps hold the soil in place. Vegetative cover is easily controlled by man and can be an effective tool in preventing erosion. It has been shown that an acre of bare soil can produce 500 times as much eroded soil as an acre of forest land.[1] Rainfall intensity is the initial driving force behind sheet erosion. The longer and more intense a rainfall, the higher the rate of sheet erosion.

Sheet erosion is the predominant type of sediment producer in Michigan. Sheet erosion rates throughout Michigan are generally low when compared to many other physiographic regions. The soils in Michigan are predominantly medium textured and not highly erosive. The rainfall intensities are quite low.[2] The percentage of the land that is covered by permanent vegetation is high, ranging from about 50 per cent in the southern counties to 90 per cent in the northern counties of the lower peninsula.[3]

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[1] U.S., Department of Agriculture, _Predicting Rainfall and Erosion Losses from Cropland East of the Rocky Mountains_, Agricultural Handbook No. 282, Agricultural Research Service and Purdue Experiment Station (Washington, D.C.: Government Printing Office, 1965).

[2] _Ibid_.

[3] U.S., Department of Agriculture, "Conservation Needs Inventory," (n.p., 1965).

Stream bank and bed erosion is another source of sediment in Michigan streams. Flowing water exerts a force on soil particles, and if the force is great enough it will dislodge the particle. The force of water can be expressed simply as the product of the unit weight of water times the depth of water times the slope or energy gradient of the stream.[4] This relationship is known as the Tractive Force Equation, and is used by engineers to determine the force that will be generated by water flowing in canals and drainage channels before they are constructed. Stream forces become quite complex, however, in natural streams where there are variations in flow, channel orientation, and channel shape.

Stream bank and bed erosion is not a large producer of sediment in Michigan. The stream gradients in Michigan are generally low, therefore the energy gradient is low. It can be seen then in the tractive force relationship that if the energy gradient is low, the force producing erosion will be low.

A large percentage of the soil that is moved by sheet erosion does not travel very far. It is deposited where slopes flatten out, in small depressions, in small channels, and is trapped by vegetation. Much of the

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[4]U.S., Department of Agriculture, Soil Conservation Service, Planning and Design of Open Channels, Technical Release No. 25 (Washington, D.C.: Government Printing Office, 1964).

sediment that finally reaches a watercourse is deposited in reaches of slow moving water, or in lakes and ponds. If a particle of suspended sediment is not constantly agitated by turbulent streamflow, it will settle to the bottom and either remain there or continue to be transported as bedload sediment. The physical ability of a lake or pond to retard the movement of sediment is called its trap efficiency. The trap efficiency of a body of water is related to the ratio of the quantity of water retained by the reservoir to the quantity of water flowing into it.[5] It is also related to the amount of time a unit of sediment-laden water remains within the reservoir.

Streams and rivers in Michigan's lower peninsula have characteristically low gradients and flow through numerous lakes, especially in the upper reaches of their watersheds. Much of the sediment that enters these streams is soon trapped, leaving only the finest sediment in suspension to continue on down the watercourse.[6]

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[5] U.S., Department of Agriculture, Soil Conservation Service, Procedure-Sediment Storage Requirements for Reservoirs, Technical Release No. 25 (Washington, D.C.: Government Printing Office, 1968).

[6] Sterling E. Powell, "Reservoir Sediment Accumulations in Southeast Michigan" (unpublished research paper for the Degree of M.S., Michigan State University, 1970).

Common Methods of Determining the Sediment Yield of Rivers

There are two common methods of determining the suspended sediment yield of rivers and streams. The first method involves daily sampling of water, and daily stream gauging. The second method involves the use of the Universal Soil Loss Equation and Sediment Delivery Rate Curves. Both methods have been useful in determining the sediment storage requirements of reservoirs,[7] and in river basin studies. Both methods are capable of making accurate determinations of sediment yields when they are properly used, and both methods have distinct limitations.

Method of Intensive Sediment Sampling and Stream Gauging to Determine the Suspended Sediment Yield of a River

The United States Geological Survey (USGS) maintains numerous suspended sediment sampling stations throughout the United States; seven stations are maintained in Michigan.

> In general, suspended-sediment samples are collected daily with U.S. depth-integrating samplers from a fixed sampling point at one vertical in the cross section. Depth-integrated samples are collected periodically at three or more verticals in the cross section to determine the ratio of the cross-sectional distribution of the concentration to the concentration at the daily sampling vertical. During periods of high or rapidly changing flow, samples are taken two or more times throughout the day.

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[7]U.S., Department of Agriculture, Procedure-Sediment Storage Requirements for Reservoirs.

> During periods of inadequate sampling, daily loads of suspended sediment are estimated on the basis of water discharge, sediment concentrations observed immediately preceding and following the periods, and suspended-sediment loads for other periods of similar water discharge. The estimates are further guided by weather conditions prior to and during the questionable periods.[8]

Samples of sediment-laden water are filtered and the weight of the sediment suspended in a given quantity of water is determined. Sediment concentration is then expressed as parts per million.

> Parts per million or ppm is a unit for expressing the concentration of chemical constituents by weight, usually as grams of constituents per million grams of a solution. In the laboratory the results are expressed as weights of solutes in a given volume of water. To express the results in parts per million, the data must be converted. For most waters this conversion is made by assuming that a liter of water weighs 1 kilogram; and thus, milligrams per liter is equivalent to parts per million. Parts per million, for suspended sediment, is computed as 1 million times the ratio of the weight of sediment to the weight of the mixture of water and sediment.[9]

The quantity of suspended sediment in tons per day that passed the station in the 24-hour sample period is computed next. This is done by multiplying the average streamflow in cubic feet per second times the sediment concentration in ppm times the factor 0.002697. The sediment yield is then determined for the water year in question.

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[8]U.S., Department of Interior, Geological Survey, Water Resources Data for Michigan. Part 2, Water Quality Records (Washington, D.C.: Government Printing Office, 1966), p. 7.

[9]Ibid.

> Water year in Geological Survey reports dealing with surface water supply is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1966 is called the "1966 water year."[10]

The suspended sediment yield for the water year is the summation of the daily yields for that year.

A high degree of confidence can be placed on the suspended sediment yield data obtained from this type of survey and analysis. These surveys, however, are very expensive because of the high cost of establishing the station and keeping it adequately staffed. Another problem is that sediment yields on most rivers vary quite a bit from year to year. In order to determine an average annual sediment yield for a river there should be ten years on record for that river. In Michigan there are only seven stations of this type and most of these stations have been in operation less than six years.

Procedure Using the Universal Soil Loss Equation and Sediment Delivery Rates to Compute Sediment Yield

The sediment yield of a river can be estimated using the Universal Soil Loss Equation which predicts gross erosion, and sediment delivery curves which predict the percentage of the gross erosion that will be carried to a given location on the river.

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[10] *Ibid.*

The Universal Soil Loss Equation is used to compute the quantity of sheet erosion that is lost annually from cropland. It is an imperical equation developed through twenty years of research by the Agricultural Research Service and the Soil Conservation Service. The main purpose of the equation is to compute sheet erosion losses from cropland.

The Universal Soil Loss Equation is:[11]

$$A = KRLSCP$$

where

A, is the computed soil loss per unit area. Usually in tons per acre per year.

R, the rainfall factor, is the number of erosion-index units in a normal year's rain. The erosion index is a measure of the erosive force of specific rainfall.

K, the soil-erodability factor, is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9 per cent slope 72.6 feet long.

L, the slope length factor, is the ratio of soil loss from the field slope length to that from a 72.6-foot length on the same soil type and gradient.

S, the slope-gradient factor, is the ratio of soil loss from the field gradient to that from a 9 per cent slope.

C, the cropping-management factor, is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated.

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[11]U.S., Department of Agriculture, Predicting Rainfall and Erosion Losses from Cropland East of the Rocky Mountains.

P, the erosion-control practice factor, is the ratio of soil loss with contouring, strip-cropping, or terracing to that with straight row farming, up and down slope.

Conversion tables, maps, and charts are published in reference[12] for the factors R, L, S, C, and P. Values for the K factor are found in reference[13].

Land cover percentages are determined from land use studies so that a weighted average value for the factor C can be computed for the watershed. Values for S and L can be determined from topographic maps. The K or soil erodability factor is derived by studying soil maps of the watershed to determine the percentage of each soil. The P factor is estimated from the known crop management practices in a given area. Once all of the factors have been determined they are simply multiplied together to compute the gross erosion in tons per acre per year for the watershed. The gross erosion in tons per year can then be computed by multiplying the gross erosion in T/A/YR times the total number of acres in the watershed.

Sediment Delivery Rate Curves have been built for several regions of the United States. The delivery rate curve that has been used most widely is one developed by

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[12] Ibid.

[13] Powell, "Reservoir Sediment Accumulations in Southeast Michigan," Table VI.

John Roehl[14] (see Figure 1). A delivery rate curve simply relates watershed size to the percentage of total erosion in the watershed that is carried past a specified point as suspended sediment.

Sediment Delivery Rate Curves are built by knowing two watershed parameters; the average annual gross erosion from the watershed, and the average annual sediment outflow from the watershed. The average annual gross erosion in tons is computed by the Universal Soil Loss Equation. The average annual sediment outflow at a selected point in the watershed can be computed from the data obtained by measuring the quantity of sediment that has accumulated in a reservoir of known age and trap efficiency. The annual sediment outflow (O) at the selected point is computed using the following equation:

$$O = Q \times \frac{\frac{1}{TE}}{T}$$

where

O = Annual sediment outflow in tons.

Q = Quantity of sediment measured in the reservoir in tons.

TE = Decimal equivalent of the reservoir trap efficiency.

T = The age of the reservoir in years.

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[14] John W. Roehl, Sediment Source Areas, Delivery Ratios, and Influencing Morphological Factors, Publication No. 59, Commission on Land Erosion, International Association of Scientific Hydrology, 1962, pp. 202-13.

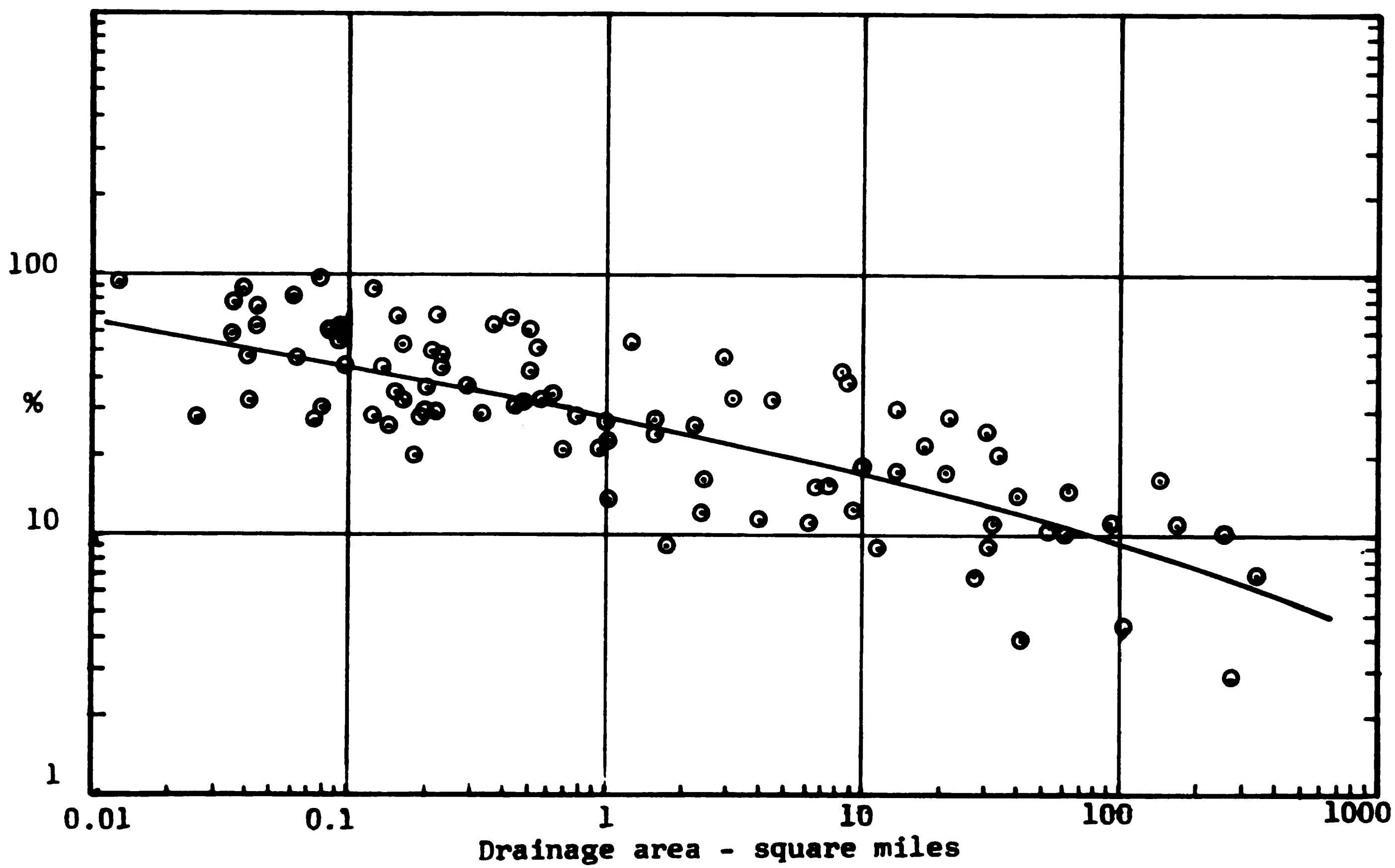

Figure 1.--Sediment delivery rate curve.

The delivery rate of a watershed is then computed by dividing the annual sediment outflow from the watershed by the annual gross erosion.

The curve developed by John Roehl incorporated delivery rates from five different physiographic areas: Red Hills Physiographic Area, Texas and Oklahoma; Missouri Basin Loess Hills, Iowa and Nebraska; Blackland Prairies, Texas; Sand-Clay Hills, Mississippi; Piedmont Physiographic Area, North Carolina, South Carolina, and Georgia. The data from these areas was plotted as the drainage area of the watershed versus the delivery rate percentage. As can be seen from Figure 1, the delivery rate plots traverse nearly one log cycle. This would be expected because of the several physiographic areas represented in the curve.

In order to use the curve one must determine whether to use the high side of the curve, the low side, or the actual curve. Attempts have been made in Michigan to use the delivery rate curve and the Universal Soil Loss Equation to predict the sediment yield of a number of rivers. It seems that the application of this method in Michigan should be done so with care since Michigan represents an entirely different physiographic area than any area represented in the delivery rate curve. The delivery rate curve must also be extrapolated before it can be applied to drainage areas greater than 250 square miles. Some error in delivery rate percentages could result from the extrapolated curve. Many of the rivers in the watersheds that are represented in the delivery rate curve carry much of their sediment load as bedload. Bedload yields as well as suspended sediment yields were thus incorporated in the sediment delivery rate curve. It would seem unwise to apply the delivery rate curve to rivers in the southern peninsula of Michigan that carry most of their total sediment load as suspended sediment. This method, however, has one distinct advantage over the method of daily sampling and stream gauging, it is easy and inexpensive to use.

Predicting Sediment Yield by Graphical Analysis of Daily Suspended Sediment Yields and Related Streamflow Parameters

It seems that there are sizeable gaps in our knowledge of suspended sediment yields from Michigan rivers. Our knowledge heretofore has been based on the results of imperical computations made from data collected in other physiographic areas; or on intensive sampling and stream gauging on a small number of rivers for a short period of time. The problem was to develop a method of using streamflow and sample records that are available to determine annual suspended sediment yields that are realistic.

The first step in the solution was to find out what records and data were available. It was found that periodic suspended sediment samples had been taken by the Water Resources Commission (WRC) of the Michigan Department of Natural Resources on twenty-eight different rivers.[15] Records were available from the Department of Natural Resources for the years 1963 through 1968. The Soil Conservation Service had sampled seventeen rivers over a two-year period and these records were available in published form. Daily streamflow records were available from the United States Geological Survey for locations at or near many of the sediment sampling stations. A statistical summary of streamflow data had been published for the gauging stations that had ten years of record or more.[16] There seemed to be very adequate streamflow records but only sporadic records of sediment concentrations.

The problem was to find a meaningful relationship between sediment concentrations and streamflow. This proposal will be developed fully in the preceding pages.

Procedure for Sampling Suspended Sediment

Suspended sediment samples can be easily taken with any device similar to the one illustrated in Figure 2.

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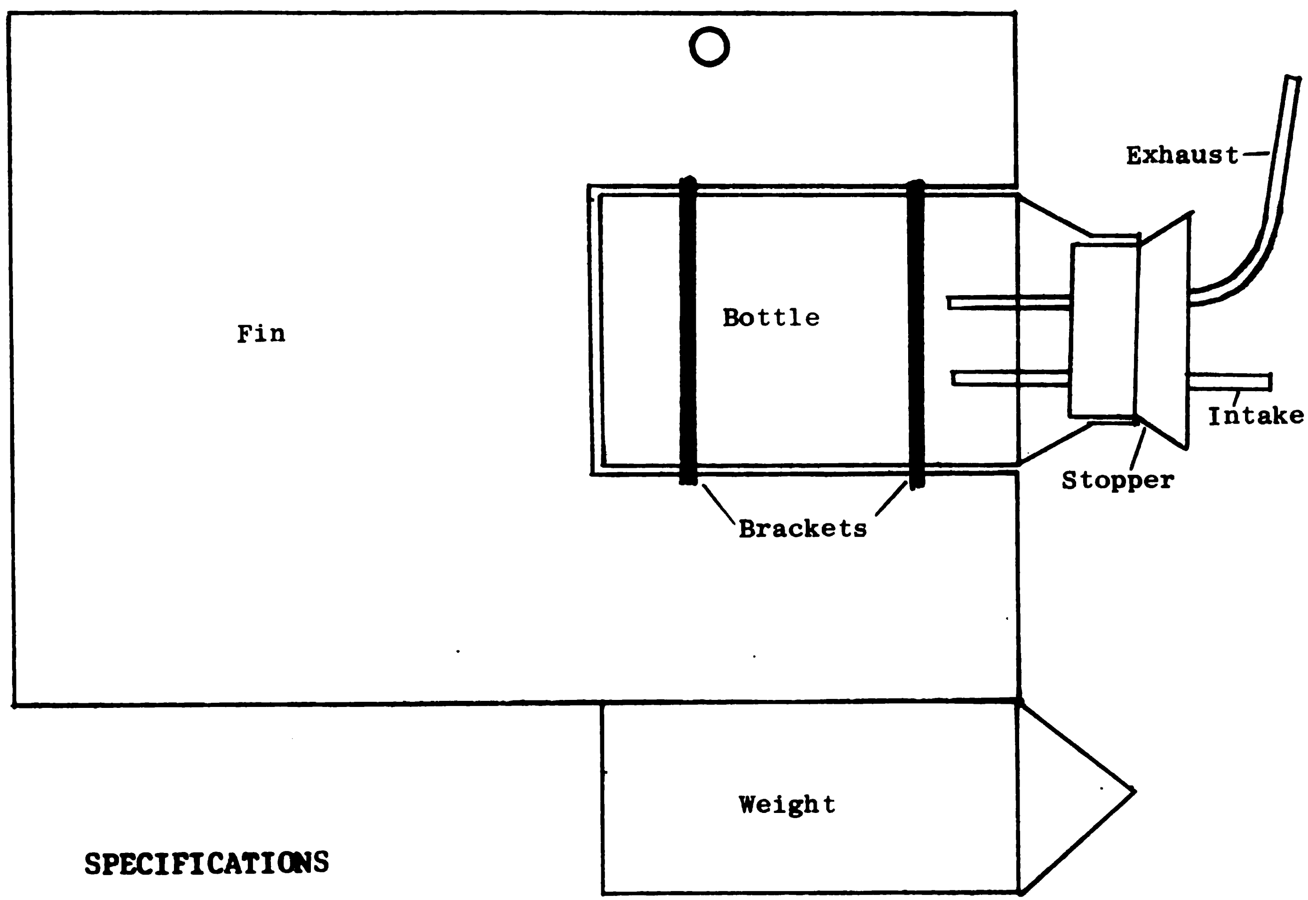
[15] Michigan Department of Natural Resources, Water Quality Records (Lansing, Mich.: Water Resources Commission, 1963-1968).

[16] U.S., Department of the Interior, Geological Survey, Statistical Summaries of Michigan Streamflow Data (Washington, D.C.: Government Printing Office, 1968).



SPECIFICATIONS

BOTTLE CAPACITY-16 oz.
INSIDE DIAMETER OF TUBES-0.3 in.

Figure 2.--Suspended sediment sampler device.

The device is lowered into the water by a nylon rope. The sampler is slowly moved from the water surface to the river bottom and back until it is full. A well designed suspended sediment sampler will take approximately one minute to fill, allowing time to sample all levels. When the sampler bottle is full, the rubber stopper is removed and the bottle is capped and stored in a wooden Coke carton. Samples should be kept cool, and analyzed as soon as possible to avoid algal blooms in the water.

In the laboratory a known volume of the sample, usually 100 ml., is filtered through filter paper. The filter paper is allowed to air dry and is then weighed. By subtracting the weight of the filter paper before filtering from the weight after filtering, the weight of the suspended sediment is determined. The weight of the sediment is then expressed as a concentration in parts per million.

The term "suspended sediment" used in this research means: the suspended particulate matter, whether mineral or organic, that can be filtered out of suspension by normal filter paper. Where data were available on the relative percentages of each type of suspended sediment, it is shown that mineral sediment typically comprises 90 to 100 per cent by weight of the total.

Suspended Sediment Records

As previously mentioned, suspended sediment records were taken from two sources; the Water Resources Commission of the Michigan Department of Natural Resources, and the United States Soil Conservation Service (SCS). Two years of record were available from the Soil Conservation Service and six years of record were available from the Water Resources Commission. Sampling by both organizations had been done on a bi-monthly basis, but in some instances samples were not taken because of bad weather conditions or broken equipment.

Ten of the seventeen Soil Conservation Service stations were eliminated because of inadequate hydrologic records. Nine of the Water Resources Commission stations were eliminated because of incomplete suspended sediment or hydrologic records. A map locating the suspended sediment stations and stream gauging stations used in this study can be found in Figure 3.

Streamflow Records

Every suspended sediment station that was chosen for analysis had a United States Geological Survey stream gauge either at the station, or somewhere nearby within the watershed. Streamflow was pro-rated for sediment stations that were not located at streamflow gauging stations. This was accomplished by means of a drainage area correction factor. Hydrologists have shown that

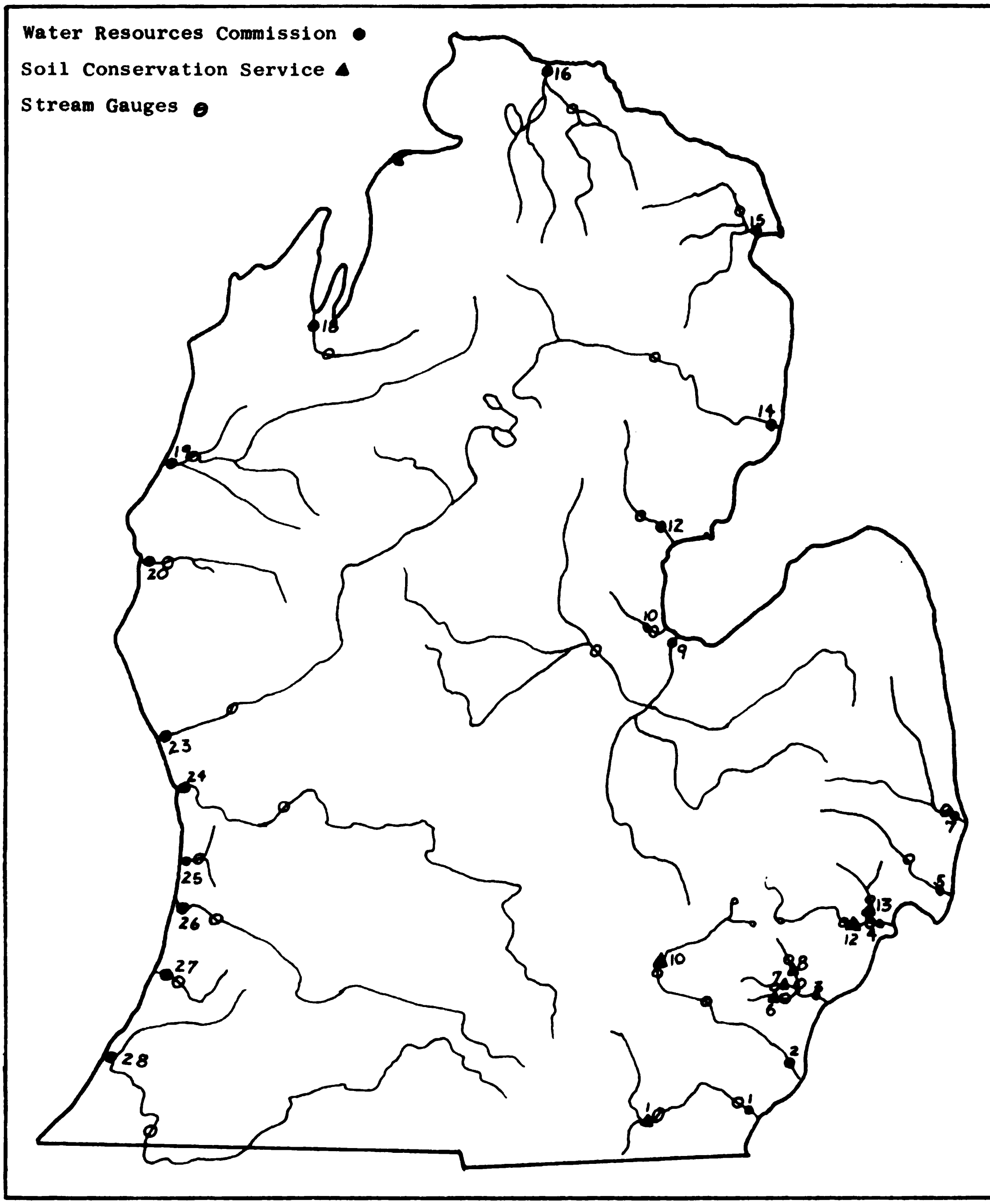


Figure 3.--Water quality monitoring stations.

the streamflow rate at one point along a river can be related to the streamflow at some other point along the same river. This relationship can be approximated by the equation:

$$\frac{Q1}{Q2} = \frac{A1}{A2}^{0.8}$$

where

Q1 and Q2 are the streamflows at drainage areas A1 and A2 respectively.

This relationship was used to determine a streamflow correction factor for some of the sediment stations that were not located near a streamflow gauging station. It must be noted that the exponent "0.8" expressed in this equation is not an absolute value but an average of observed values that range between 1.0 and 0.65.[17]

Graphical Analyses of Suspended Sediment Concentration

Graphs were constructed for the sample stations by plotting streamflow in cfs versus the sediment concentration in parts per million on log-log graph paper. The point spreads for most of the graphs covered nearly one-half a log cycle, but certain relationships could be established. The sediment concentration in each river seemed to increase as the rate of streamflow increased

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[17] U.S. Geological Survey, Peak Discharges for Selected Midwestern Rivers, 1956, pp. 8-13.

(Figure 4). It was noted that the sediment concentration in some rivers seemed to be lower during the period between November 1 and March 31. These rivers were the Saginaw, St. Joseph, Belle, and the Lower Huron. It would seem reasonable that erosion (and thus, sediment concentrations) would be less during the winter months when the ground is frozen and covered by snow.

The sediment concentrations in Michigan rivers do not seem to vary as significantly as the rivers in other physiographic areas. The standard deviation of the sediment concentration data from Michigan varies typically between 5 ppm and 20 ppm as compared to typical standard deviations of 100 ppm to 300 ppm for data from watersheds in Texas, Oklahoma, Nebraska, and Iowa. Most Michigan rivers receive a large part of their normal flow from ground water discharge. The constant inflow of ground water would tend to dilute incoming sediment laden surface runoff and thus held prevent large fluctuations in sediment concentrations.

Sediment concentrations seem to rise significantly in some rivers during periods of excessive streamflow resulting from storm runoff. During a storm the rate of rainfall is often much greater than the capacity of the soil and vegetation to absorb the rain. The runoff from a large storm may therefore be largely surface runoff and thus carry a high concentration of sediment. When soil

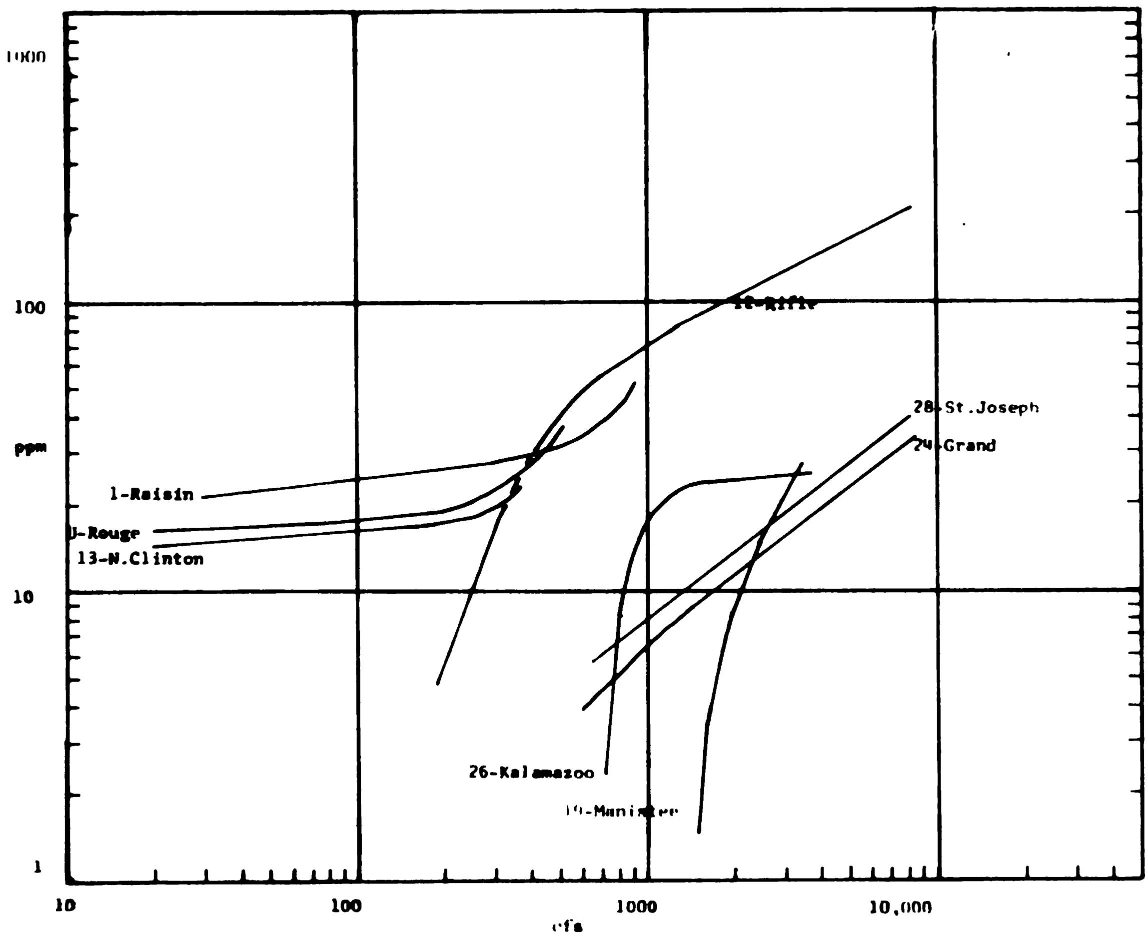

Figure 4.--Streamflow versus sediment concentration curves.

becomes saturated from long periods of rainfall it also loses its capacity to absorb water. If the soil loses its capacity to absorb water during long periods of rainfall, the surface runoff will increase causing a higher sediment concentration in the runoff.

The relationship between sediment concentration and runoff is a qualitative relationship and can not readily be used per se to make suspended sediment yield predictions. Streamflow and sediment concentration data must be expressed in quantitative terms to more easily facilitate sediment yield computations. The relationship between runoff and sediment concentrations will be considered as a variable in the sediment yield predictions.

Graphical Analysis of Sediment Yield Rates

Sediment yield is the quantity of sediment by weight that passes a given point on a river during a given period of time. In order to work with sediment yields, sediment concentration at a given streamflow must be changed to tons/day or some other weight/time relationship. The conversion equation to change streamflow and sediment concentration to tons/day is:

Equation 1. $T/DAY = cfs \times ppm \times 0.002697$

The recordings at each sample station were converted to tons per day. The computations were made on a spread sheet similar to the one in Table 1.

TABLE 1.--Daily yield at gauging stations.

Station	Year	Date of Sampling	Discharge cfs	Suspended Solids ppm	Yield Tons/ Day
28-STJ	1967	4-11	1000	32	86
		8-17	1954	13	68
		9-13	1900	16.5	84.7
		9-28	2823	23.5	173
		10-11	2860	21	163
		10-26	4500	12.5	152
		11-6	5538	19.5	254
	1964	1-8	1916	9	21
		2-11	1822	9	45
		3-17	2935	24	190
		4-14	4498	41	497
		4-29	4853	45	588
		5-13	3527	46	437
		5-27	2615	23	162
		6-12	2259	34	207
		6-26	1976	30	159
		7-16	2047	31	170
		9-18	1278	19	65
		10-16	1633	36	158
28-STJ	1965	1-20	2565	8	55
		1-29	3572	13	124
		2-23	4052	13	142
		4-7	7602	31	635
		4-29	7709	36	748
		6-14	2612	32	224
	1966	1-13	1160	11	34
		1-27	3543	8	76
		2-9	4576	27	333
		2-22	4246	15	171
		3-8	5150	15	208
		3-22	5078	20	273
		4-5	4742	24	306
		4-19	4225	45	512
		5-3	7321	34	671
		5-17	9285	51	1277
		6-14	3751	40	405
		8-5	2077	23	129
		9-9	2116	23	131

Streamflow in cfs was plotted against tons/day sediment yield using the data from each station. The data were plotted on three types of graph paper; full arithmetic paper, semi-logarithmic paper, and full logarithmic paper. It was not possible to obtain a linear relationship on the graph paper used. The relationships were curvilinear and seemed to follow certain trends when compared with one another (see Figures 5, 6, 7, 8, 9, 10). Because of the vast range of magnitude of the data, the curves are presented on 3x4 cycle full logarithmic paper.

As mentioned previously, the sediment concentration for the Saginaw River, Belle River, Lower Huron, and St. Joseph River seemed to be lower during the period of time between November 1 and March 31. For this reason the sediment yield versus cfs for this period of time was plotted with different color pencil than the data from samples taken in the period April 1 to October 31. A distinct relationship was found to exist for each period of time for the four rivers (see Figures 5, 6, 7, 8, 9, 10). The plots for some of the other rivers showed a trend toward this dual relationship, but the total point spread was low enough to assume a single relationship. It can be said with some degree of confidence that the winter conditions of frozen ground and snow cover must reduce sheet erosion and, therefore, the suspended sediment yield of some Michigan rivers.

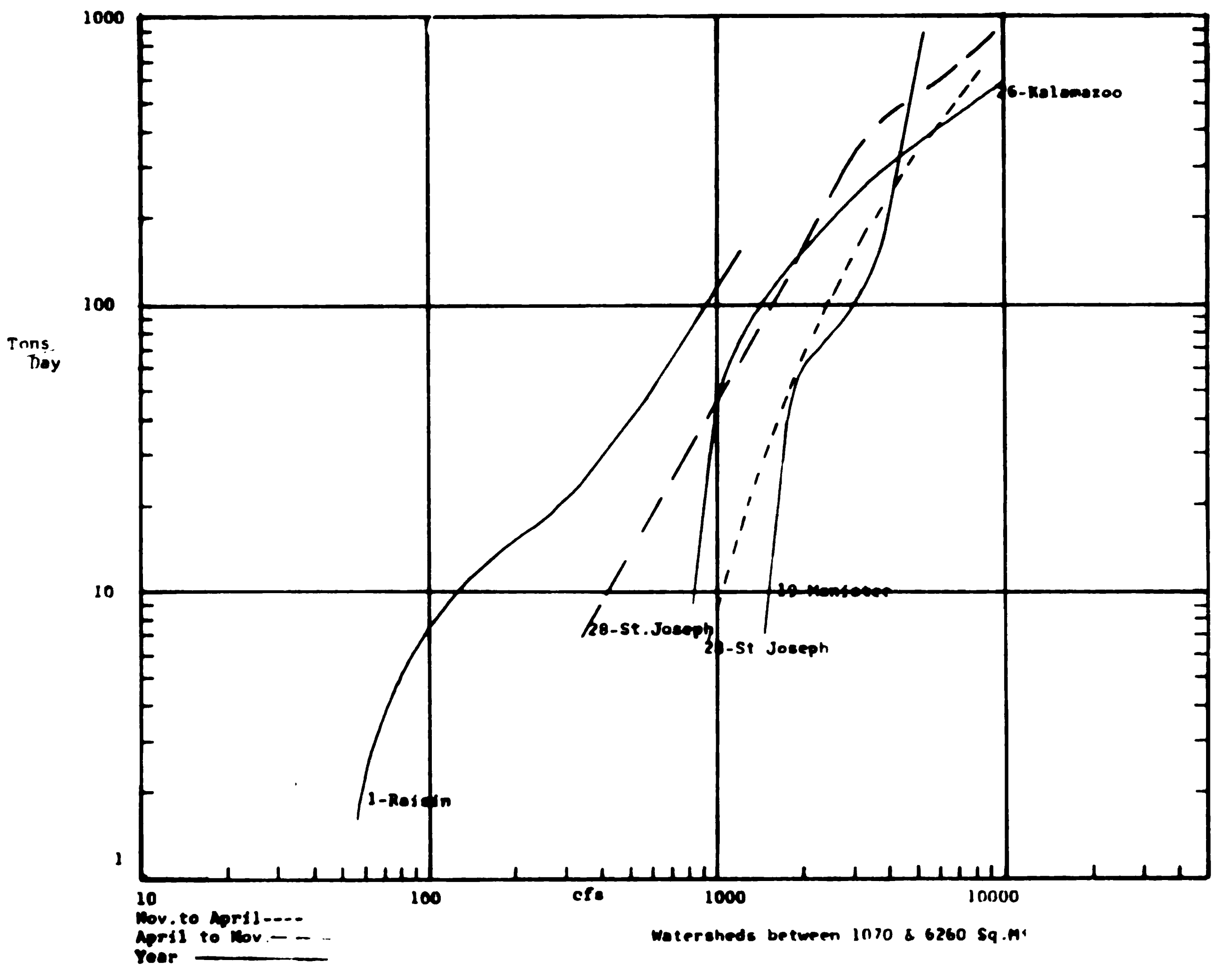

Figure 5.--Streamflow versus sediment yield curves: watersheds between 1070 and 6260 square miles.

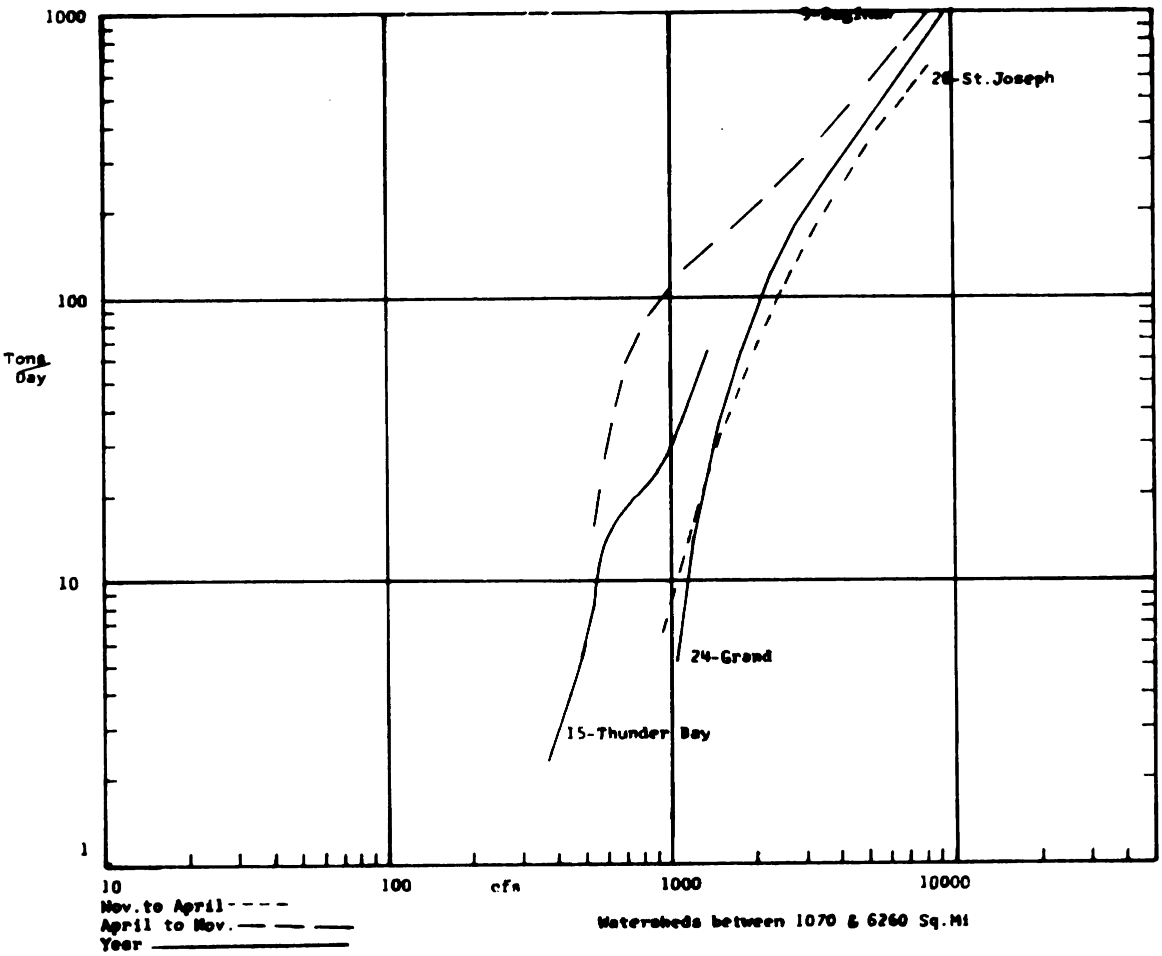

Figure 6.--Streamflow versus sediment yield curves: watersheds between 1070 and 6260 square miles.

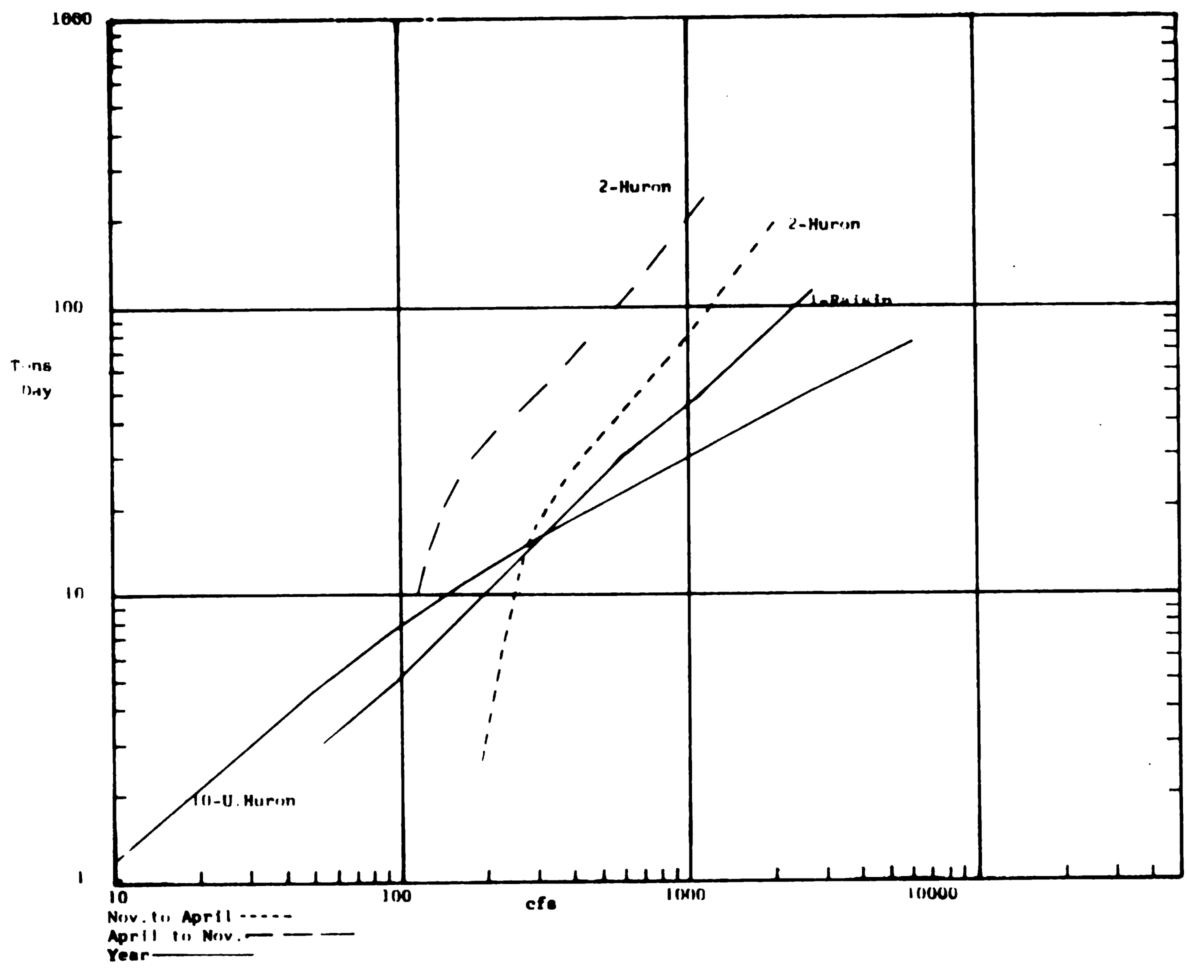

Figure 7.--Streamflow versus sediment yield curves: watersheds between 440 and 892 square miles.

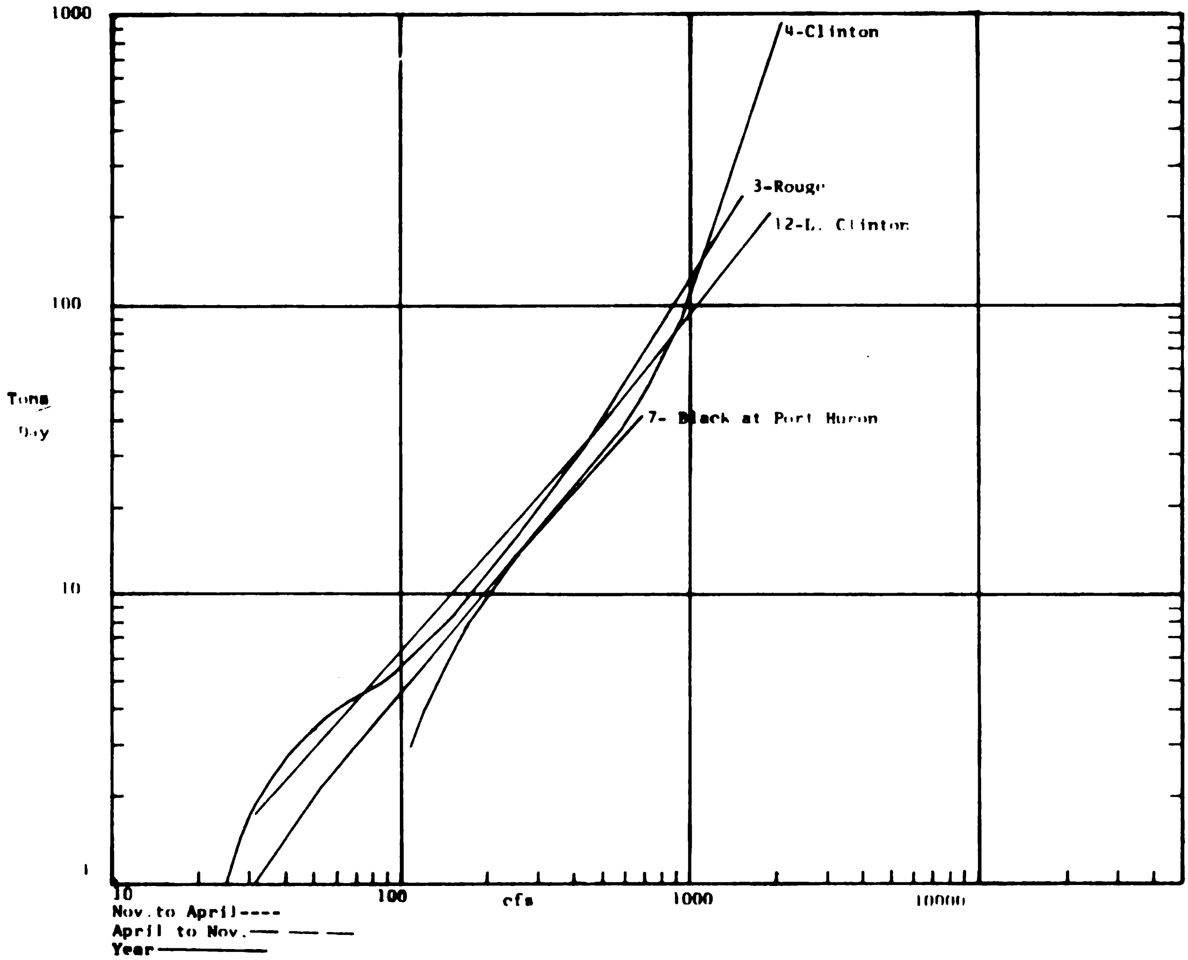

Figure 8.--Streamflow versus sediment yield curves: watersheds between 440 and 892 square miles.

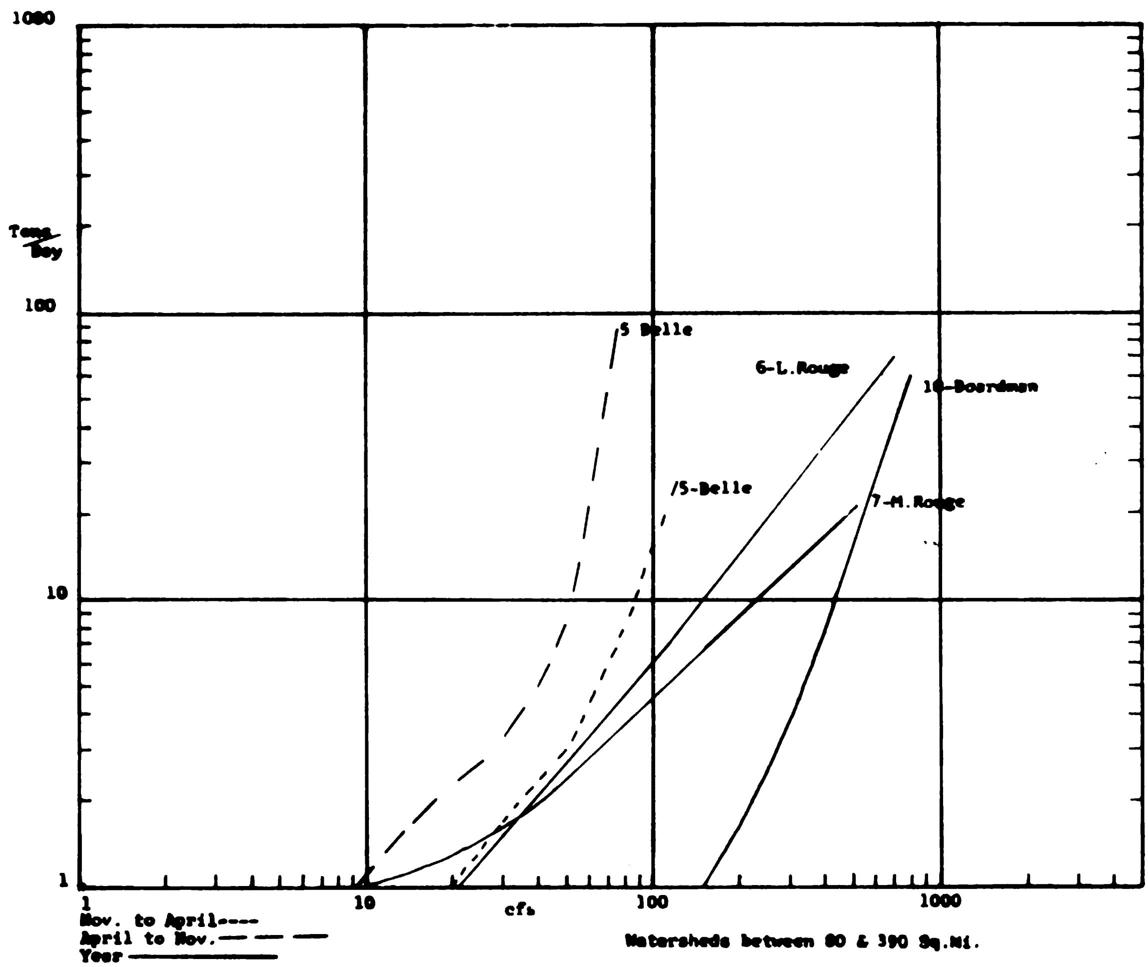

Figure 9.--Streamflow versus sediment yield curves: watersheds between 80 and 390 square miles.

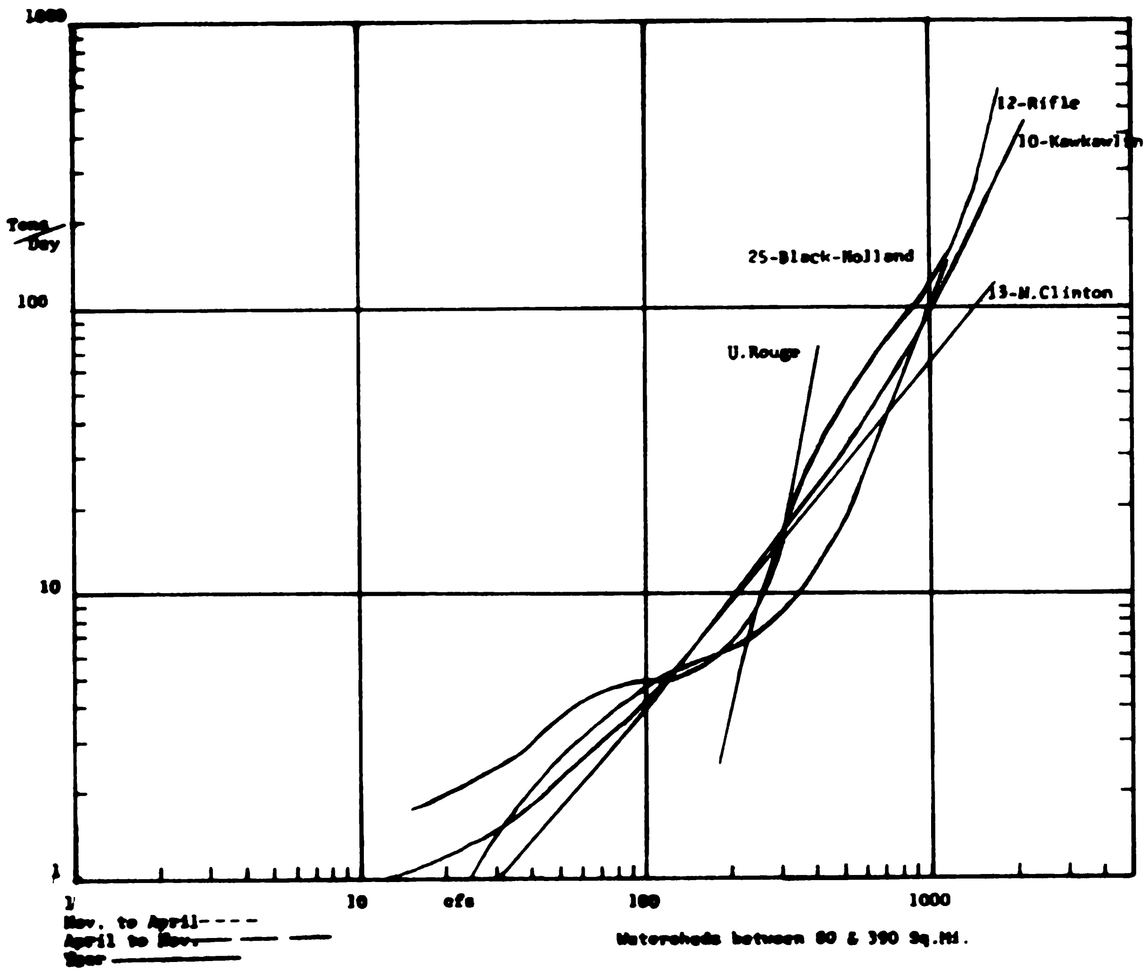

Figure 10.--Streamflow versus sediment yield curves: watersheds between 80 and 390 square miles.

Each graph is more or less the fingerprint of the rivers' rate of sediment transport at a given flow. Meaningful relationships between streamflow and sediment yield could not be determined for the following rivers: Cheboygan, Pere Marquette, Muskegon, and the AuSable. Several reasons for this lack of relationship can be assumed. The AuSable and the Muskegon rivers are regulated by retarding dams. Retention of floodwater runoff and its later release would distort the relationship between streamflow and sediment yield. The two branches of the Cheboygan River, the Pigeon and the Black, each flow through a large lake before they coalesce to become the Cheboygan. The high sediment trapping efficiency of Black Lake and Mullet Lake would tend to distort the streamflow and sediment yield relationship. The soils in the watershed of the Pere Marquette River are composed primarily of sand. The Pere Marquette River transports most of its sediment load as bedload, which is predominantly sand. This can be readily seen at the river's mouth where the Corps of Engineers annually dredges thousands of tons from the Ludington Harbor. Perhaps the relationship between streamflow and suspended sediment are not well defined for rivers that transport primarily bedload sediments.

The relationship between streamflow and sediment yield becomes a qualitative relationship when streamflow rate changes from day to day. A more meaningful expression of sediment yield for a river would be the total mean yield over a given period of time; tons per month, tons per year, etc. In order to derive this expression there should be at least ten year's record of streamflow for the specific location. A statistical analysis of streamflow duration can be used in conjunction with the curve relating streamflow to sediment yield to determine monthly or yearly sediment yields. This method eliminates the tedious process of daily sediment sampling and analysis over a long period of time.

Streamflow duration statistics are found in Statistical Summaries of Michigan Streamflow Data, 1968.[18] A duration table of daily discharge has been determined for each station. "The duration table of daily discharge shows the number of days in each water year during which flow for specified discharges were equaled or exceeded."[19] Annual sediment yields for each station were computed using the following procedure:

1. Fifteen to twenty increments of flow, by percentage of time, were chosen from the flow duration table from 0 to 100 per cent. Example: .5%, 100 cfs; 2%, 90 cfs; 5%, 80 cfs; 10%, 70 cfs.

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[18] U.S., Department of the Interior, Statistical Summaries of Michigan Streamflow Data.

[19] Ibid.

2. A suspended sediment yield for each flow was taken from the curve cfs versus tons/day (Figures 5, 6, 7, 8, 9, 10).
3. Each flow duration percentage was converted to a decimal expression.
4. Each sediment yield value was then subtracted from the next one greater, and that quantity was multiplied by the flow duration decimal equivalent for the streamflow represented by the larger sediment yield quantity. The result of this computation represents the average increase in sediment yield per day of a specific streamflow, over the yield at some lesser streamflow.
5. When the values computed in step 4 are summed, the sum represents the mean daily suspended sediment discharge for the station.
6. If a summer and a winter streamflow versus sediment yield curve have been developed for a station, the computation procedure is undertaken for both curves. The values for each season's daily mean sediment yield are then multiplied by a correction factor. These factors are simply the number of days in the year divided into the number of days in the season. The summer correction is 0.583 and the winter correction is 0.416. The summer and winter values are then summed to derive the

mean daily suspended sediment yield in tons for the station.

7. The mean daily suspended sediment yield in tons can be changed to the mean yearly yield by multiplying the daily yield by 365. An example of a sediment yield computation can be found in Table 2. A tabulation of the suspended sediment stations and the annual suspended sediment yield at these stations is found in Table 3.

Predicting Annual Suspended Sediment Yields in Ungauged Rivers

It is interesting and useful to know the yearly suspended sediment yield at a certain point along a river. The question is raised; is it necessary to set up a gauging station and a sediment sampling station at each point where suspended sediment yield data is desired? As previously mentioned, it is possible in some areas to predict sediment yields using the Universal Soil Loss Equation and a Sediment Delivery Rate Curve. These predictions are most valid when applied to the physiographic area from which the data was gathered to derive the delivery rate curve. It would seem possible then to make suspended sediment predictions using data from rivers in the southern peninsula of Michigan.

The most desirable type of relationship in any method of predicting sediment yields is naturally the

TABLE 2.--Sediment yield computation.

Station	Flow Duration	cfs	D.A. Cor.	Cor. cfs	Season	T/Day	Season Cor.	Cor. T/Day	Inc.	Dur. x Inc.	T/Day Season or Year Average	T/Yr or S Year or Season Total	Year Total Average T/Yr
28-STJ	.013	9300	1.28	11904	Summer	940	.583	575	80	1.16	188.71	68879	91851
	.020	8300		10624		850		495	64	1.28			
	.061	6600		8448		740		431	64	3.90			
	.129	5200		6656		630		367	47	6.06			
	.202	4200		5376		550		320	40	8.08			
	.306	3300		4224		480		280	64	19.58			
	.448	2600		3328		370		216	64	28.67			
	.606	2100		2688		260		152	48	29.08			
	.763	1700		2176		180		105	55	41.97			
	.953	1100		1408		86		50	21	20.01			
	.989	840		1075		50		29	6	5.93			
	.996	750		960		40		13	23	22.9			
	1.0	0		0		0		0	0	0			
28-STJ	.013	9300	1.28	11904	Winter	830	.416	345	41	.533	85.84	31331	
	.020	8300		10624		730		304	46	.920			
	.061	6600		8448		620		258	58	3.53			
	.129	5200		6656		480		200	50	6.45			
	.202	4200		5376		360		150	44	8.88			
	.306	3300		4224		255		106	65	19.89			
	.448	2600		3328		170		71	24	10.75			
	.606	2100		2688		114		47	18	10.90			
	.763	1700		2176		70		29	20	15.26			
	.953	1100		1408		22		9	5	4.76			
	.989	840		1075		10		4	1	.989			
	.996	750		960		7.4		3	3	2.98			
	1.0	0		0		0		0	0	0			

TABLE 3.--Sediment yields.

	Drainage Area	Sediment Yield
	sq. mi.	t/yr
WRC Station		
1 - Raisin	1,070	21,122
2 - Huron	892	20,224
3 - Rogue	464	5,529
4 - Clinton	760	21,659
7 - Black - P.H.	746	6,482
9 - Saginaw	6,260	83,329
10 - Kakawlin	220	2,894
12 - Rifle	390	7,541
15 - Thunder Bay	1,250	1,737
18 - Boardman	285	976
19 - Manistee	2,120	25,404
24 - Grand	5,570	90,732
26 - Kalamazoo	2,060	31,426
28 - St. Joseph	4,681	91,851
SCS Station		
Raisin	455	4,040
L. Rogue	83	954
M. Rogue	104	890
U. Rogue	185	3,161
U. Huron	506	4,792
L. Clinton	445	7,205
N. Clinton	199	1,675

simplest meaningful relationship. The simplest and most easily derived parameter of a watershed is its size or drainage area. Therefore, a plot of suspended sediment in tons/year versus drainage area size in square miles was made for all of the sample stations (Figure 11). A meaningful relationship was derived, and is presented on full logarithmic graph paper. The gradient of the graph decreases above 1,000 square miles, and becomes a curve at this point. The plots for the Boardman River and the Thunder Bay River fell below the curve, and were not incorporated into the curve. Both of these rivers are somewhat different than the rest of the rivers represented on the graph. Their watersheds are predominantly forested and contain a small percentage of agricultural land, and urban land. The other watersheds represented have a variety of land use; forest, agricultural, urban, and suburban. Watersheds that are predominantly forested would be expected to produce less sediment than watersheds in multiple land use. The sediment yield curve can, therefore, be applied to rivers in the southern peninsula of Michigan whose watersheds are in multiple land use.

Comparison of the Sediment Yield Curve to Results of Other Methods

There was a paucity of suspended sediment yield data from actual stream gauging and sampling to compare with the predictions of the sediment yield curve. The

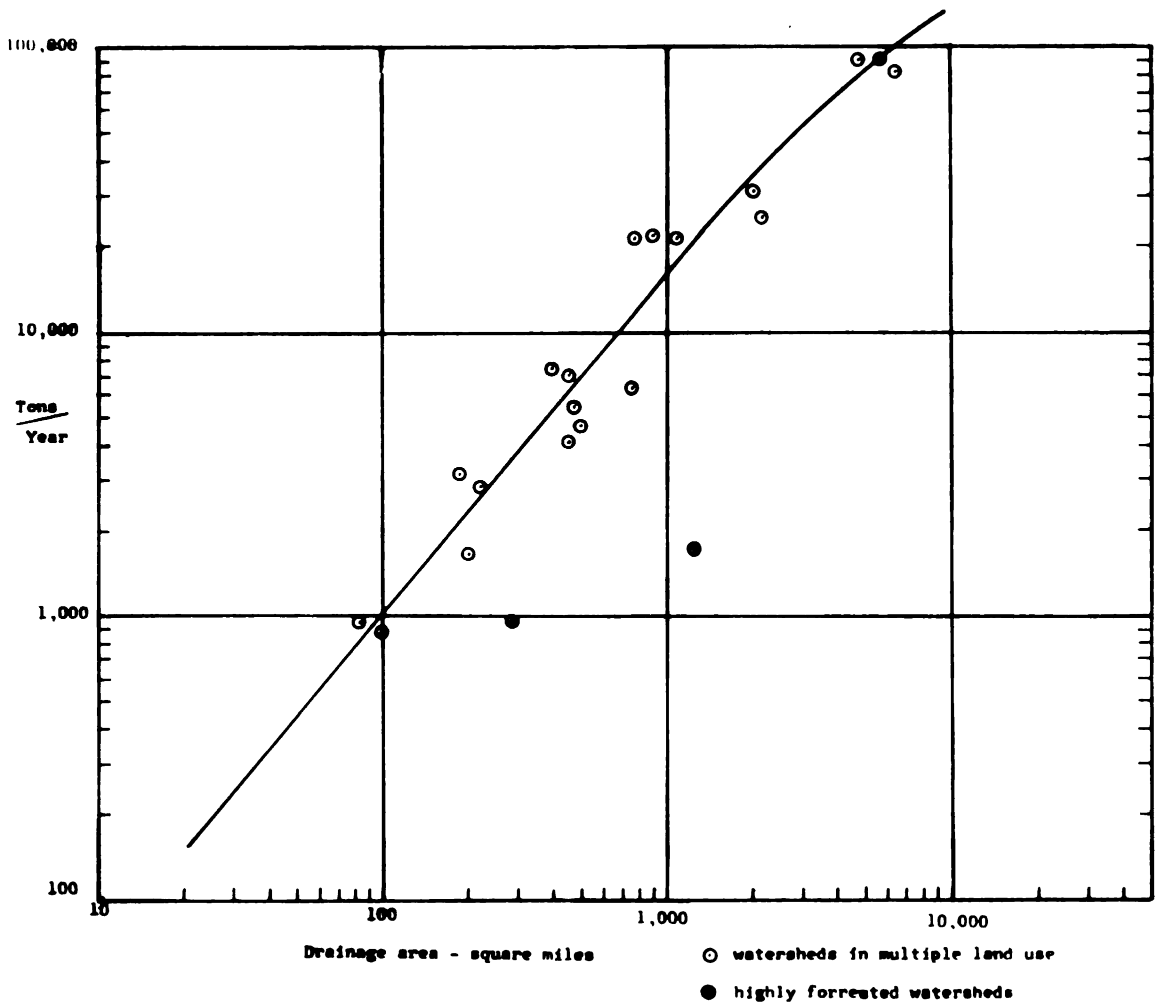

Figure 11.--Drainage area versus annual suspended sediment yield curve.

United States Geological Survey has six sediment recording stations in the southern peninsula of Michigan.[20] The annual suspended sediment yield at these stations is often not given because of incomplete records. The data that is given indicates that annual yields vary from year to year, and that they may be higher or lower than the predicted rates from year to year. The predicted yields are within the range of yields computed by the United States Geological Survey, but there is not enough data from the United States Geological Survey to make a valid comparison.

The United States Soil Conservation Service has computed annual suspended sediment yields for many of the watersheds in Michigan. Their method of computation used the Universal Soil Loss Equation and the Sediment Delivery Rate Curve developed by John Roehl.[21] The Soil Conservation Service data has not been published. The sediment yield curve predicts generally lower annual suspended sediment yields than does the method under comparison (Table 4). This can probably be explained by the fact that the Delivery Rate Curve has such a wide spread of points (Figure 1). Unless it is known whether to use the

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[20] U.S., Department of Interior, Water Resources Data for Michigan.

[21] Roehl, Sediment Source Areas, Delivery Ratios, and Influencing Morphological Factors.

TABLE 4.--Sediment yield predictions.

River	Drainage Area	Sediment Yield Curve	Soil Loss Equation and Delivery Rate Curve
	sq. mi.	t/yr	t/yr
Shiawassee	538	7,700	46,000
Cass	848	13,000	45,900
Raisin	1,034	17,000	117,000
Kalamazoo	2,008	36,000	133,000
Upper Grand	271	3,400	38,800
Manistee	2,006	36,000	34,600
Rifle	489	6,700	15,600
Saginaw	6,242	100,000	147,000
Flint	952	15,000	51,100
Black	750	11,500	42,400
Clinton	782	12,000	47,200
Rouge	582	8,500	47,800
Huron	848	13,000	56,400
Upper Raisin	578	8,400	80,600
Upper St. Joseph	362	4,800	79,400

high, medium, or low side of the Delivery Rate Curve, predictions can be higher or lower than the actual annual sediment yields. To obtain a delivery rate for watersheds exceeding 1,000 square miles, the curve must be extrapolated, which could cause some degree of error.

Use of the Sediment Yield Predictions

Sediment yield predictions are useful in all types of river basin and watershed planning. Sediment, when deposited, clogs channels and lakes, fills harbors, and can damage floodplain cropland. Sediment yield predictions can be used in conjunction with trap efficiency factors, or sediment particle fall velocities to predict the quantity of sediment deposition in a body of water.[22]

The main interest to date has been using sediment yield predictions to determine the sediment storage requirements of reservoirs. The useful life of a reservoir, whether it is for flood prevention, recreation, irrigation, or multiple purpose use, is governed by the rate at which it fills with sediment. Perhaps the use of sedimentation predictions will spread in the future to include many other facets of sediment damage. Flocculation of sediment particles has already been used in sewage treatment plants and water purification stations to eliminate harmful sediment. Perhaps someday sediment yield

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[22]U.S., Department of Agriculture, Procedure-Sediment Storage Requirements for Reservoirs.

predictions will be used to determine the type of facility and amount of flocculant to use to rid entire river systems of sediment.

REVIEW OF THE LITERATURE

The Bureau of Reclamation generally uses the flow duration, sediment rating curve method to derive the average suspended load from the available suspended sediment sampling data.[23]

> The basic sediment-rating curve is a correlation of water discharge and suspended concentration or sediment load in tons per day. It was first developed by Campbell and Bauder. Integration of the sediment rating curve and flow duration curve will give an average suspended sediment load. The basic data for the sediment rating curve and the flow duration curve do not have to be from the same time period. Because discharge records are usually available over a longer time period than suspended sediment records, this method allows the expansion of a relatively small amount of sediment data to the longer period of discharge, provided no event or control has been imposed on the stream to change the basic sediment-water discharge relation.[24]

Sheppard states that:

> Sufficient data to define the average runoff conditions will produce an average curve that can be used with confidence. The water-sediment relation may change

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[23]U.S., Bureau of Reclamation, Analysis of Flow-Duration, Sediment-Rating Curve Method of Computing Sediment Yield, Sedimentation Section, Hydrology Branch, Project Planning Division, 1951.

[24]John R. Sheppard, "Methods and Their Suitability for Determining Total Sediment Quantities," Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963, pp. 272-87.

with the type of runoff, i.e., snowmelt or rainfall, and should be subdivided into more than one curve for different seasons of the same time period. Operational changes on controlled streams may also produce different water-sediment relationships requiring subdivision of the sediment-rating curve and flow duration time periods.[25]

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[25] *Ibid*.

POSSIBLE AREAS FOR ERROR TO OCCUR

Stream gauges were not located at eleven of the suspended sediment sampling stations used in the study. It was fortunate that seven of these stations had at least 80 per cent of the drainage area gauged. The remaining five stations had at least 45 per cent of the drainage area gauged. Daily streamflow records and the statistical analyses of streamflow duration had to be assigned drainage area correction factors. Over short periods of time, the rate of flow in one portion of a watershed is not always proportional to the rate at some point downstream. This is due to the time of concentration of watershed runoff and the rate of travel of the river. Daily readings could therefore be somewhat in error for stations with a smaller percentage of drainage area gauged. It is felt that the long period of gauging represented in the statistical analyses would preclude the possibility of significant error in these streamflow corrections.

Error could occur in the determination of watershed size. The surface area of a watershed is the best indicator of the area of a watershed from which surface runoff is derived. Ground water makes a significant contribution to the streamflow in most Michigan rivers. The drainage area that contributes groundwater to a river is not usually the same area as the surface watershed. Some error in sediment yield predictions could be made by only knowing the area of the watershed that contributes to surface runoff.

SUGGESTIONS FOR FURTHER RESEARCH

Sediment yield curves are valid only for the period of time for which the sediment concentration and hydrologic data remains valid. Changing land use patterns can alter the type and amount of sediment generated within the watershed. Alteration of stream channels by natural or man-made forces can change the regimen of the stream and therefore change its sediment transport characteristics and its hydraulics. As the land use or channel characteristics of a watershed change there arises a need to gather new data to use in the development of a revised sediment yield curve. Sediment yield curves could also be developed for predominantly forested watersheds and for predominantly urban watersheds in the state of Michigan.

There is a paucity of knowledge concerning the bedload transport characteristics of Michigan rivers. There has been a considerable amount of research done on bedload transport resulting in numerous study procedures and equations. Perhaps the procedures that have been developed could be applied to the rivers in Michigan to gain a more complete knowledge of the total sediment transport characteristics of Michigan rivers.

As the velocity of flowing water increases, so does its energy and capacity to carry suspended sediment. There is potential in future research relating stream velocity to sediment discharge. At the present time there are not enough stations available that measure stream velocities in the state of Michigan to make this research feasible. If at some time these stations could be made available, research procedures could be devised to analyze velocity versus sediment discharge relationships for Michigan streams and rivers.

SUMMARY

It has been shown that there is a meaningful relationship between streamflow and suspended sediment concentration in parts per million. There is, as a result, a relationship between streamflow (cfs) and suspended sediment yield (tons). Flow duration statistics can be integrated with the graphical relationship between streamflow and sediment yield to determine mean annual suspended sediment yields at sediment sampling stations. When the mean annual yields for each station are plotted against the drainage area at the station, a suspended sediment yield curve is developed. The curve can be used to predict suspended sediment yields of watersheds in the southern peninsula of Michigan that are in multiple land use.

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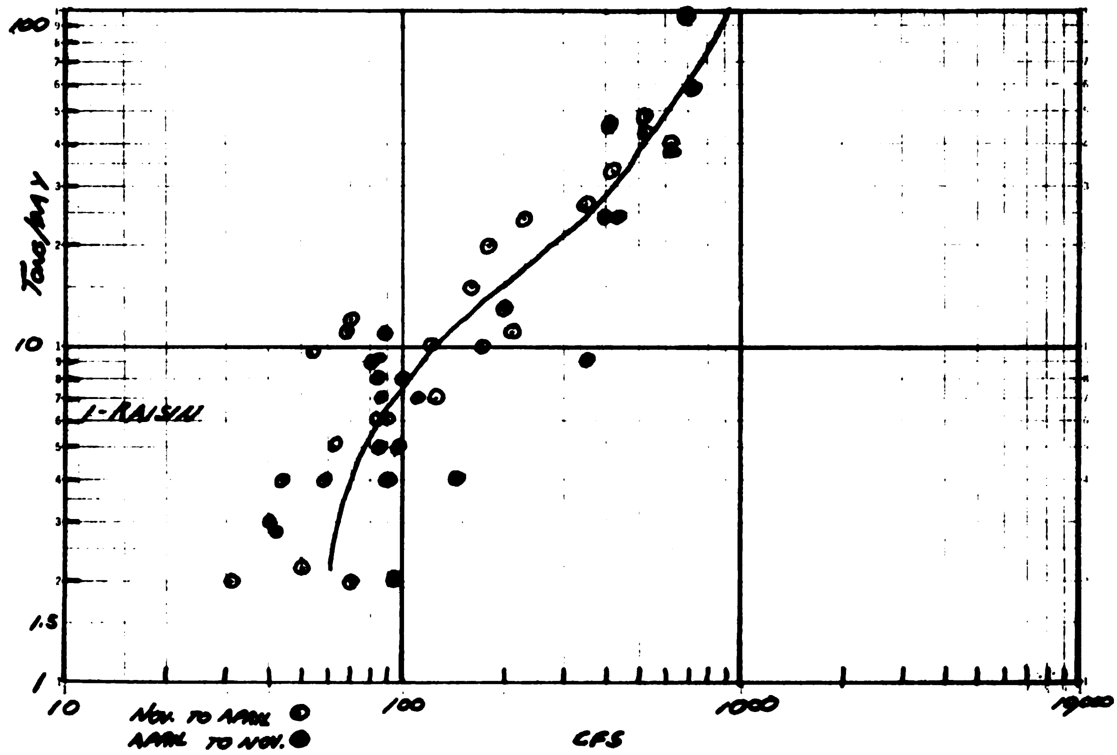

Figure A-1.--STA. 1, Raisin River.

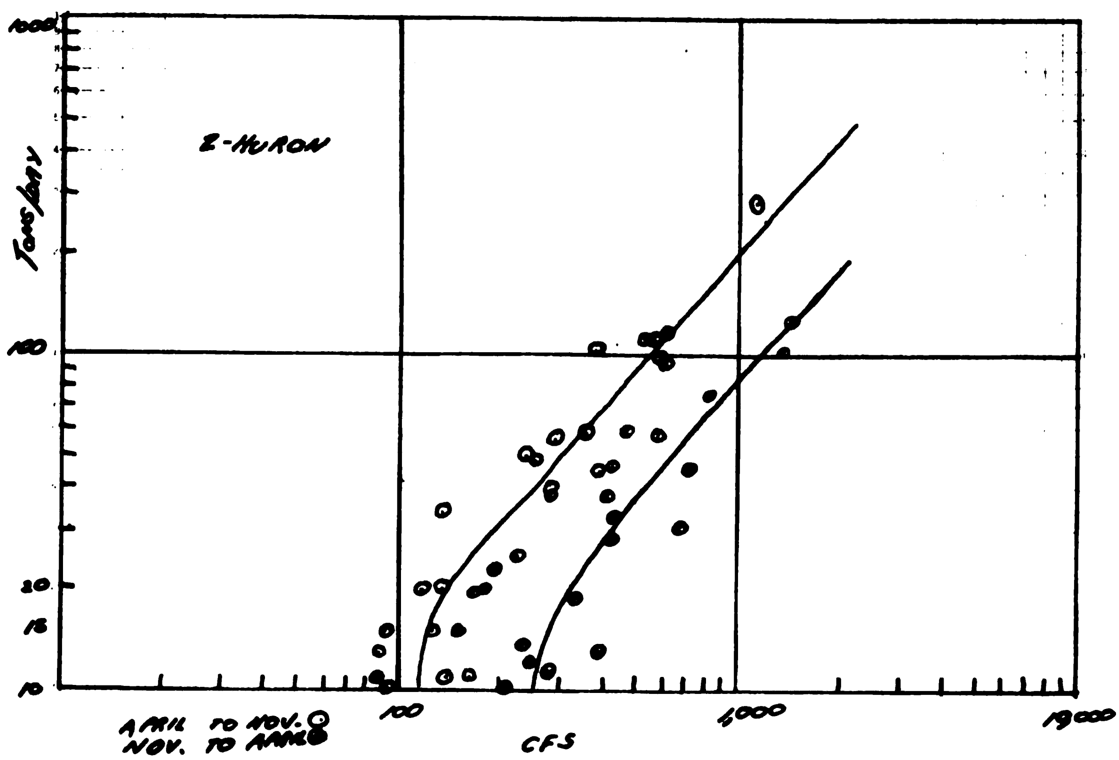

Figure A-2.--STA. 2, Huron River.

APPENDIX

ORIGINAL PLOTS OF STREAMFLOW VERSUS SUSPENDED SEDIMENT YIELD

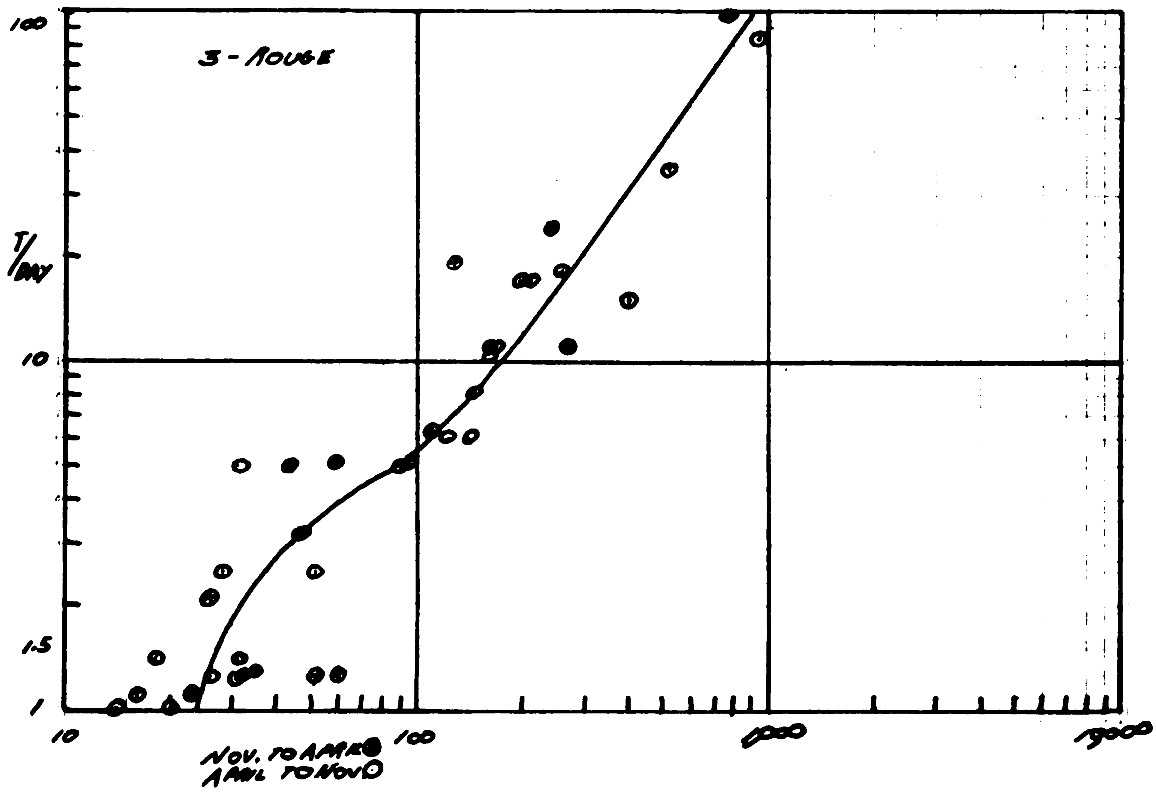

Figure A-3.--STA. 3, Rouge River.

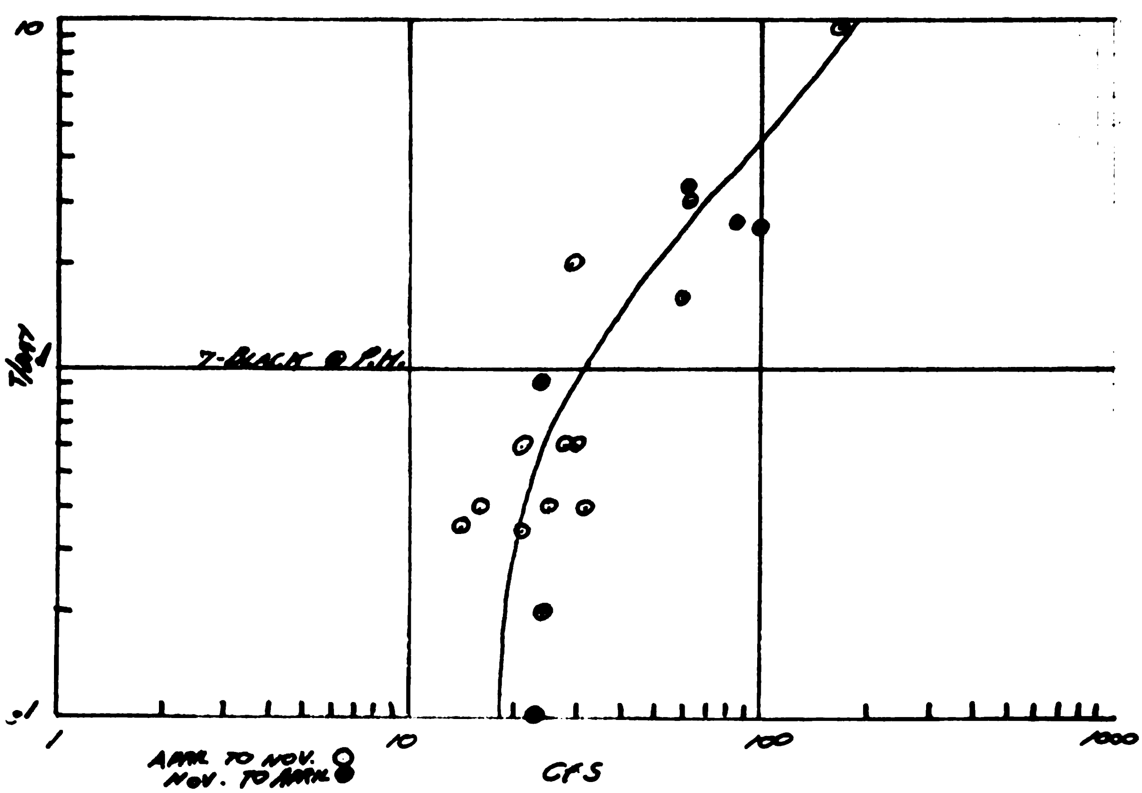

Figure A-4.--STA. 7, Black River at Port Huron.

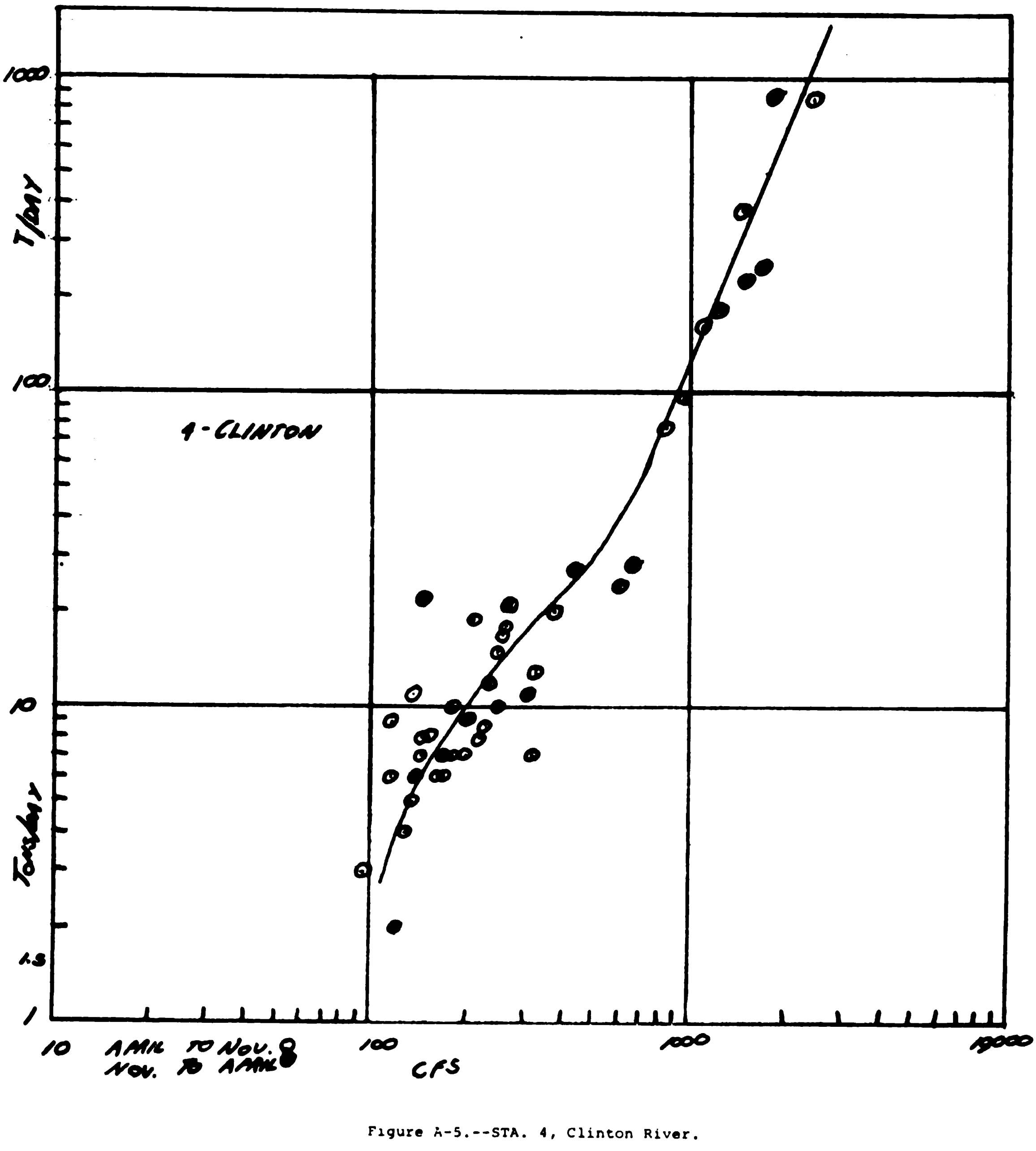

Figure A-5.--STA. 4, Clinton River.

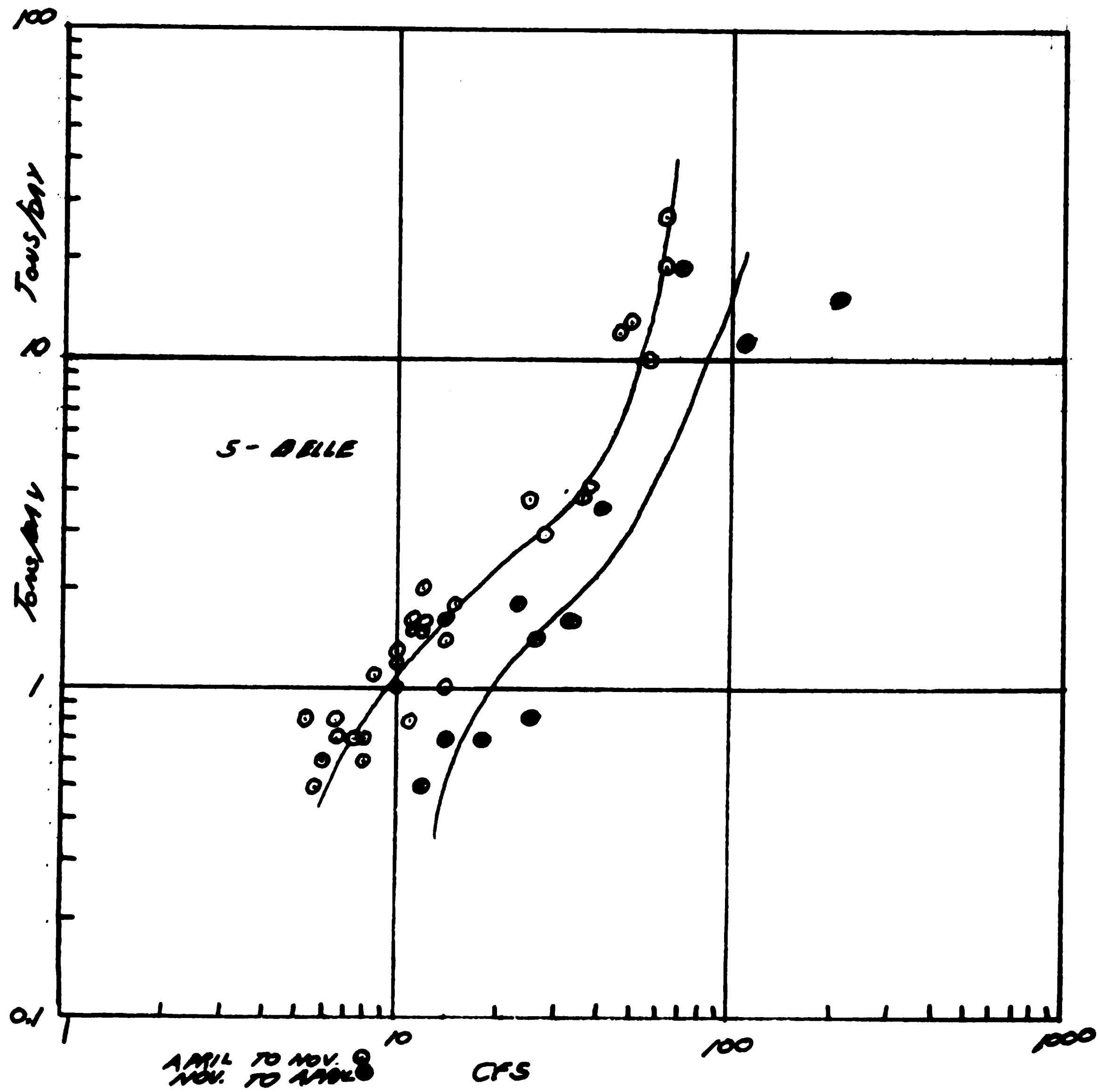

Figure A-6.--STA. 5, Belle River.

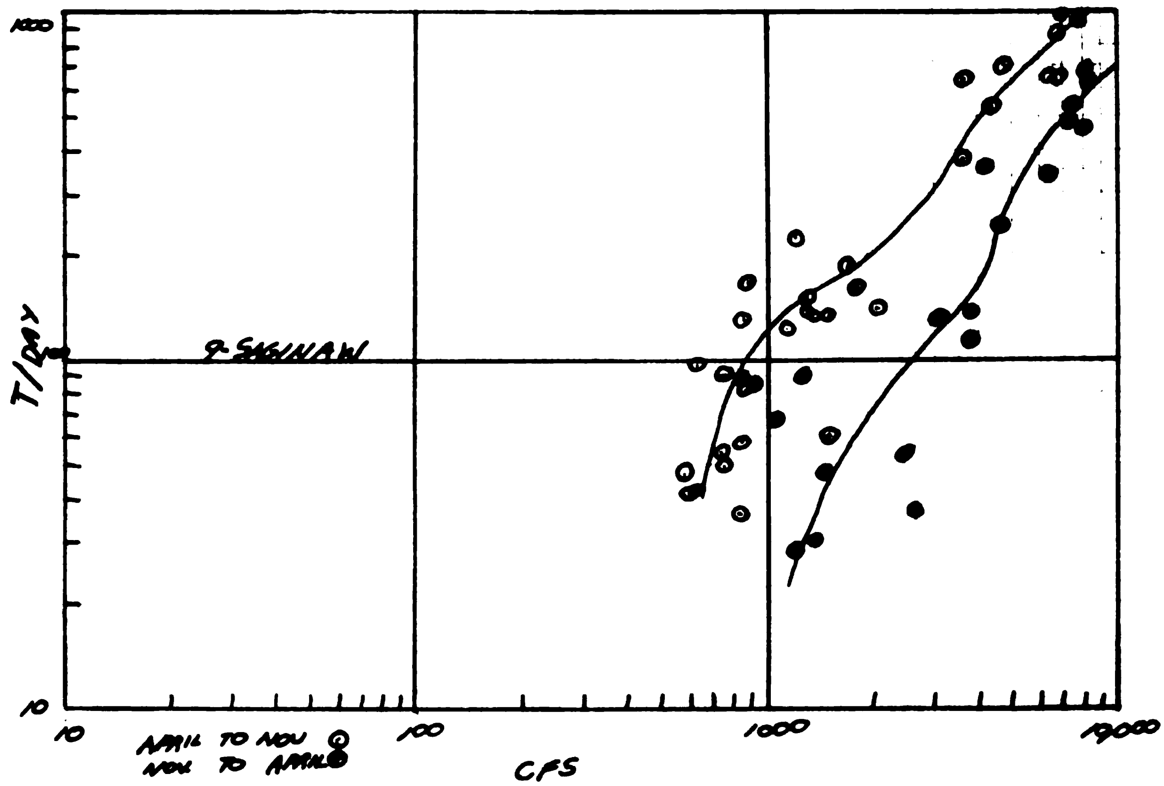

Figure A-7.--STA. 9, Saginaw River.

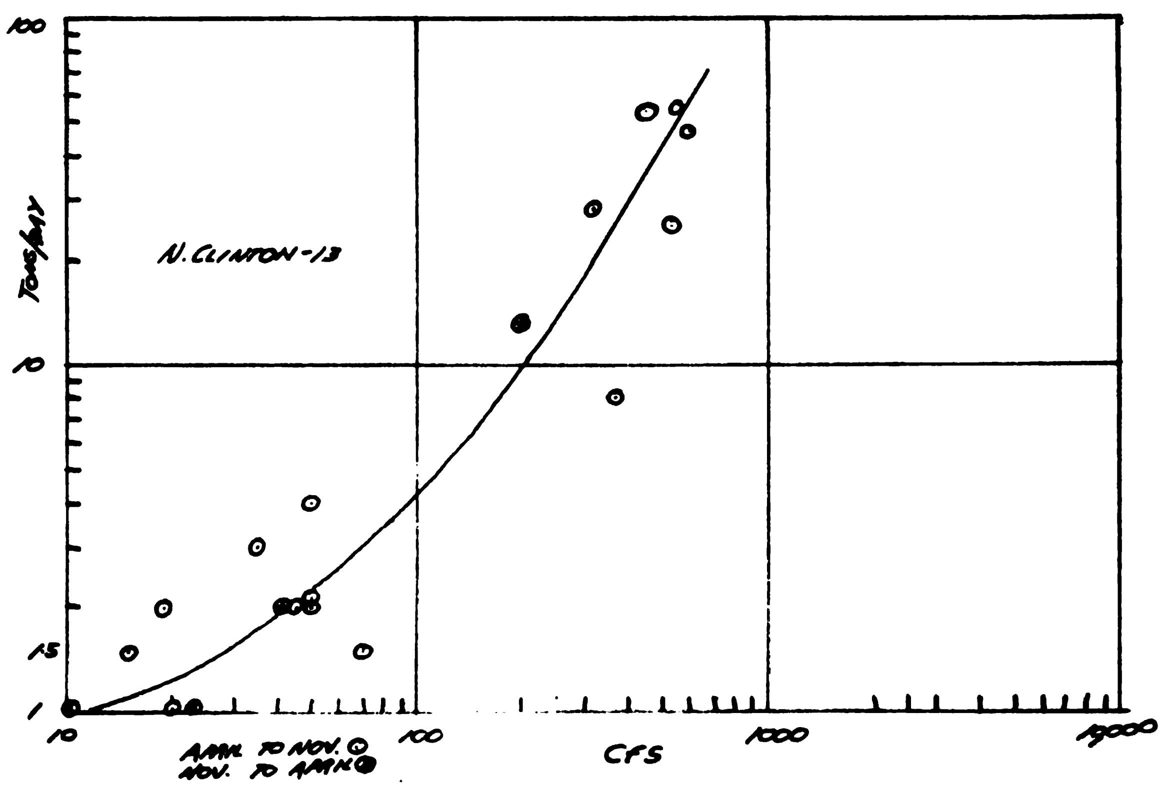

Figure A-8.--STA. 13, N. Clinton River.

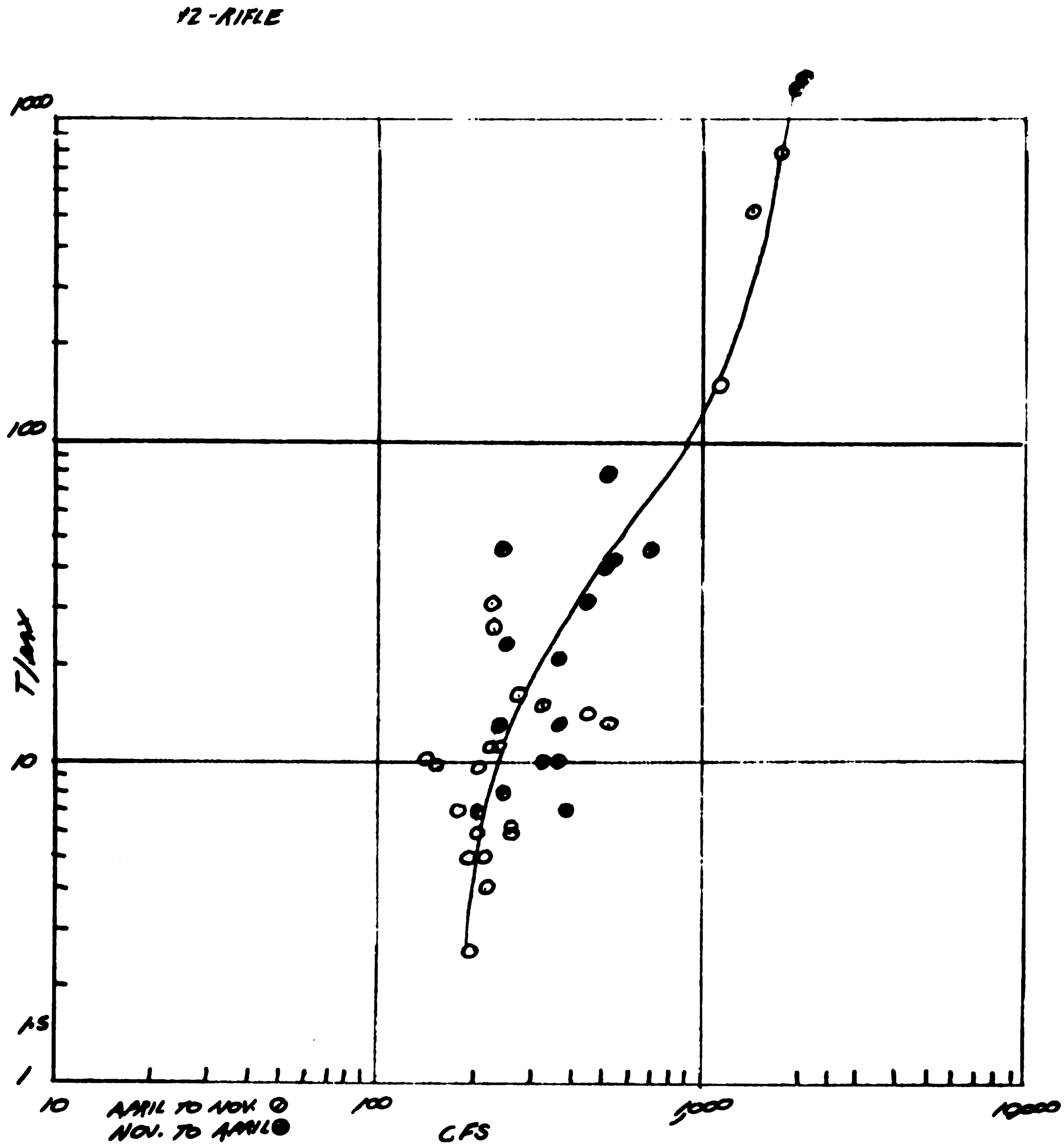

Figure A-9.--STA. 12, Rifle River.

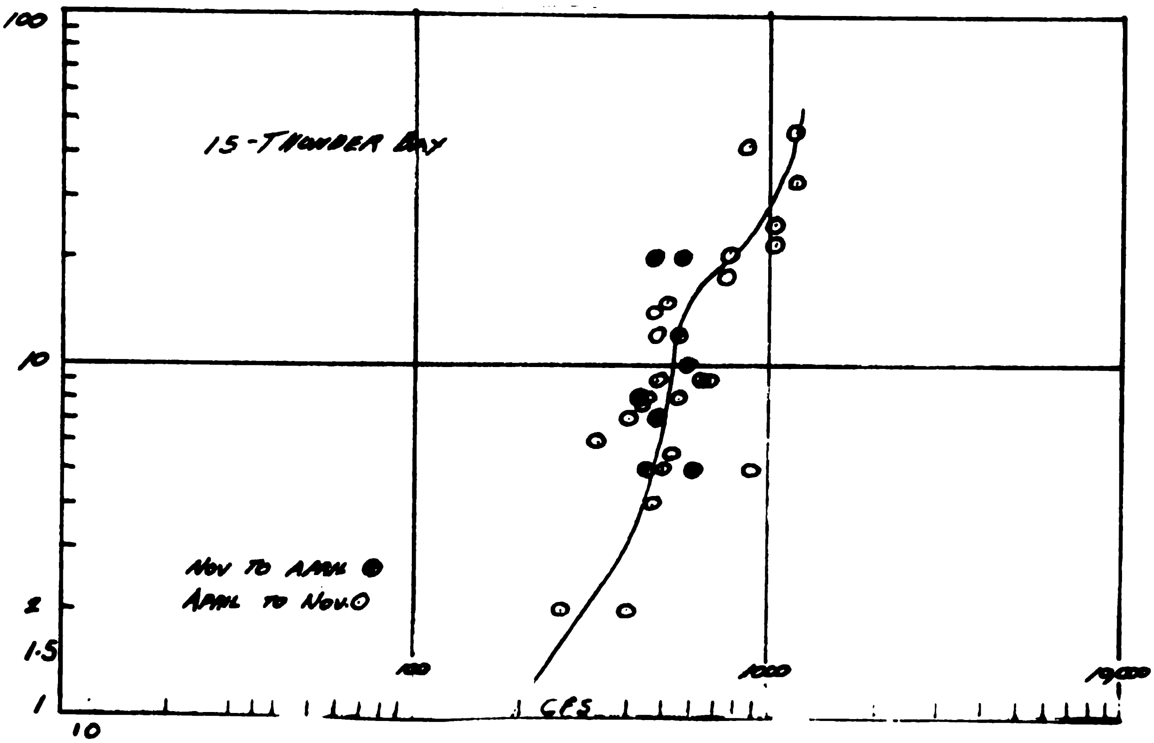

Figure A-10.--STA. 15, Thunder Bay River.

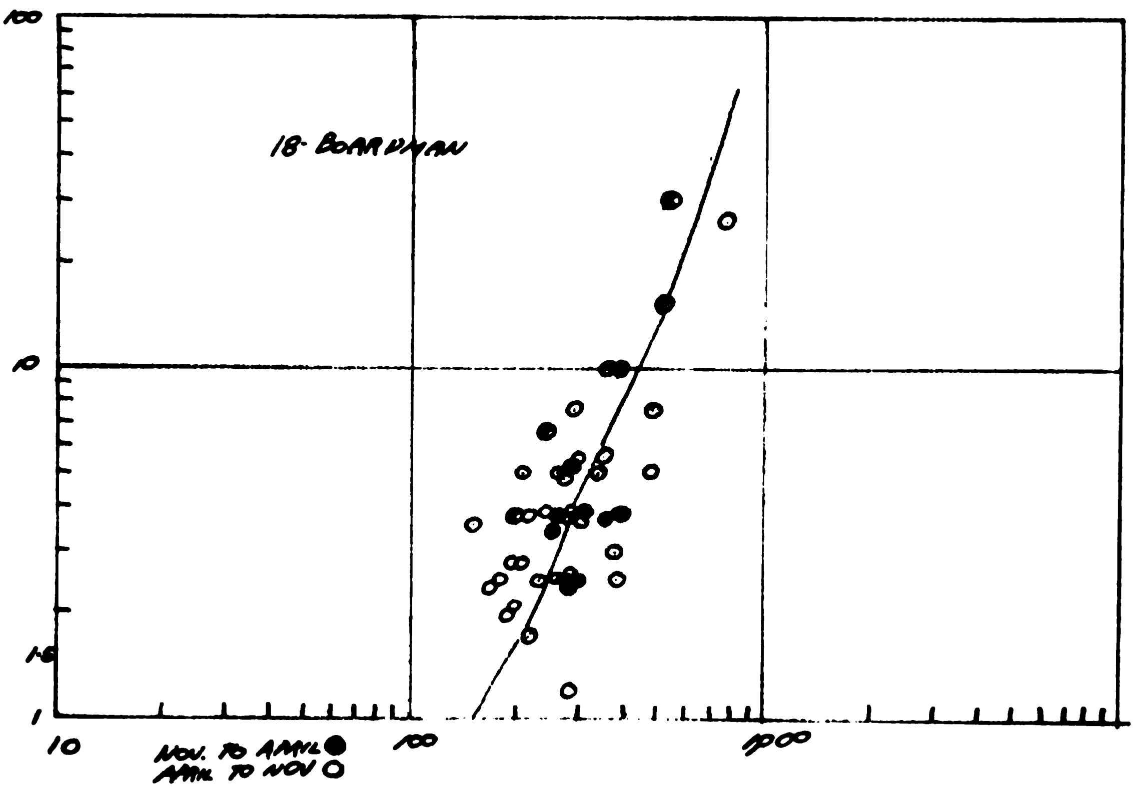

Figure A-11.--STA. 18, Boardman River.

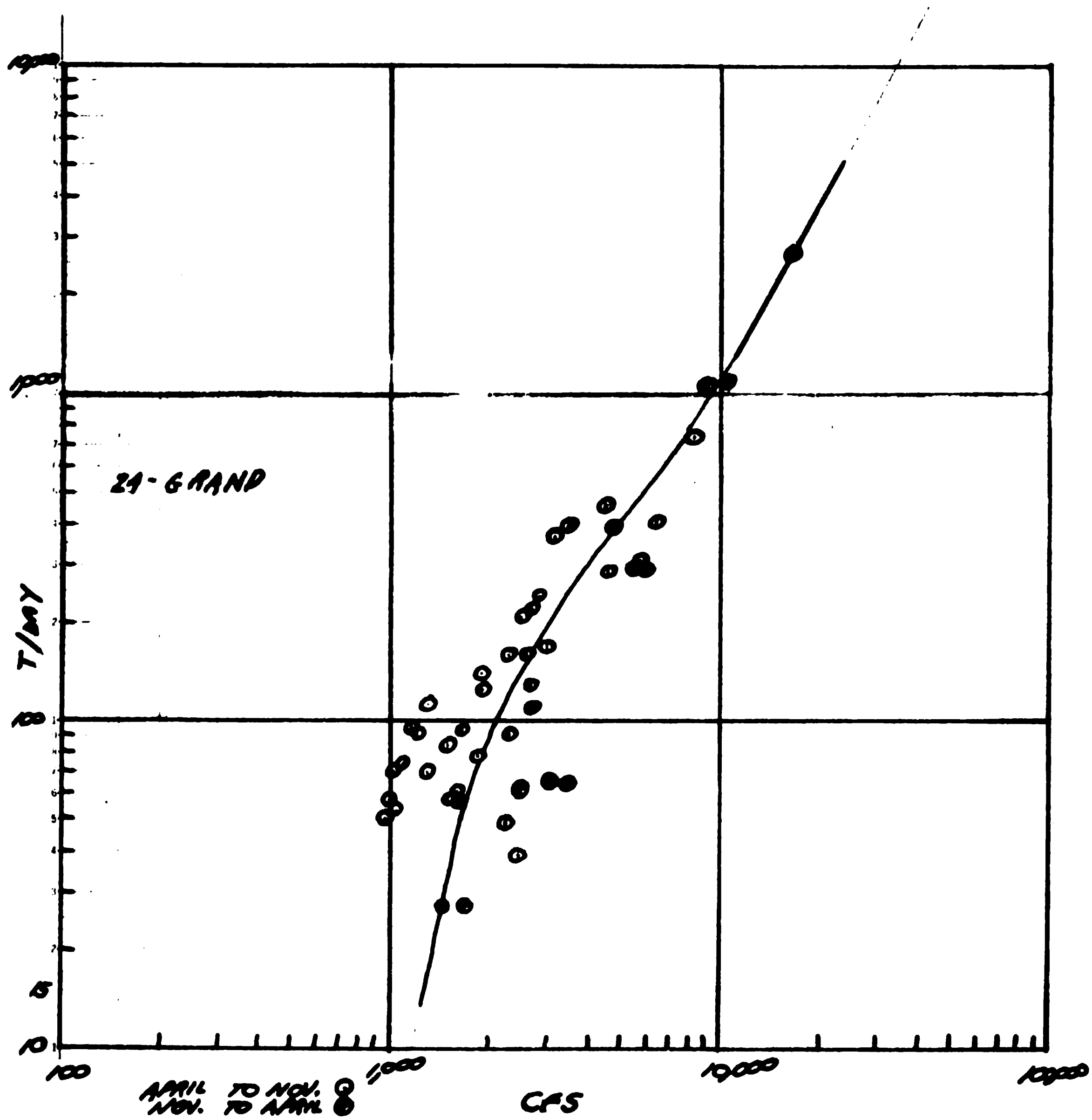

Figure A-12.--STA. 24, Grand River.

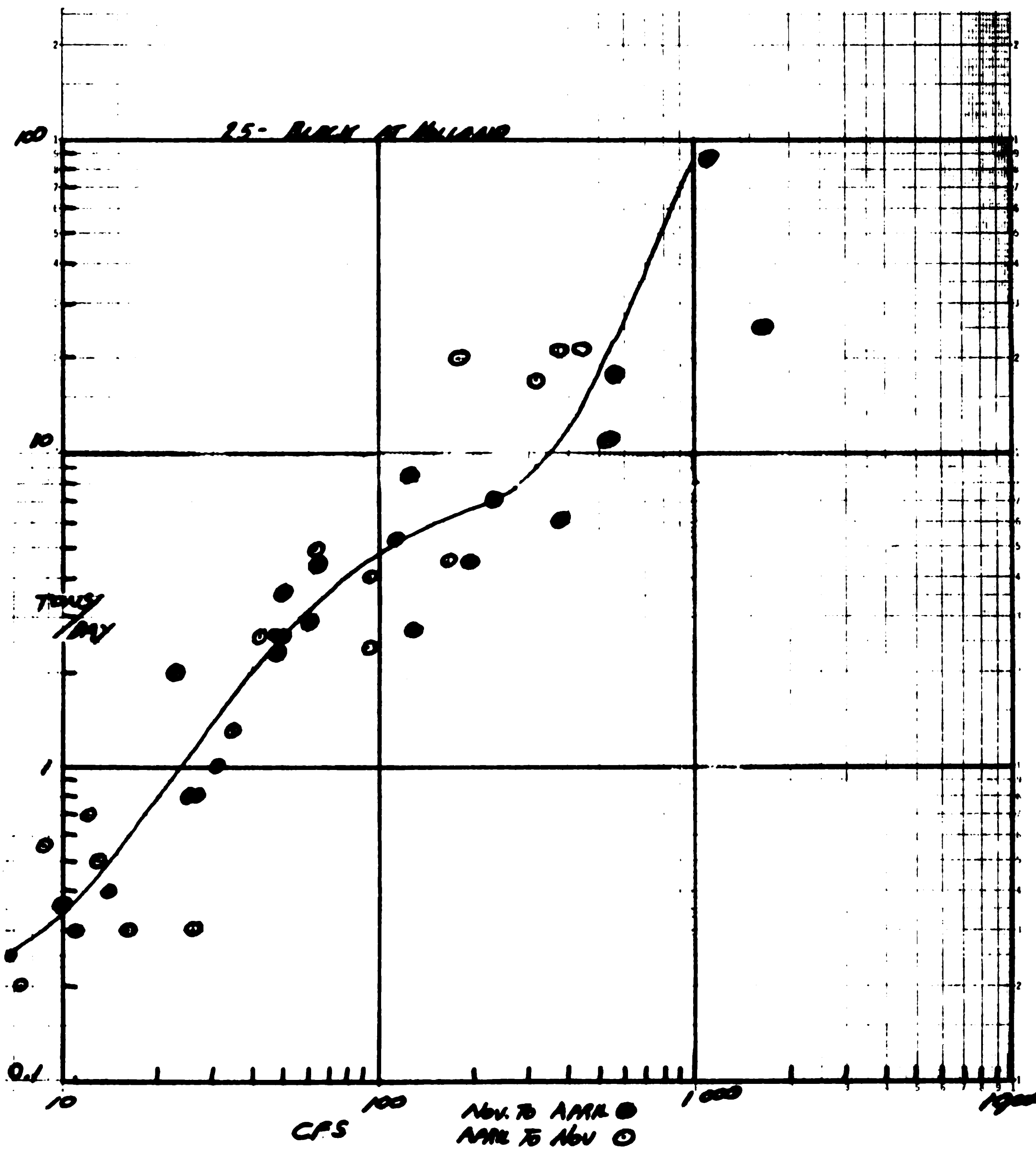

Figure A-13.--STA. 25, Black River at Holland.

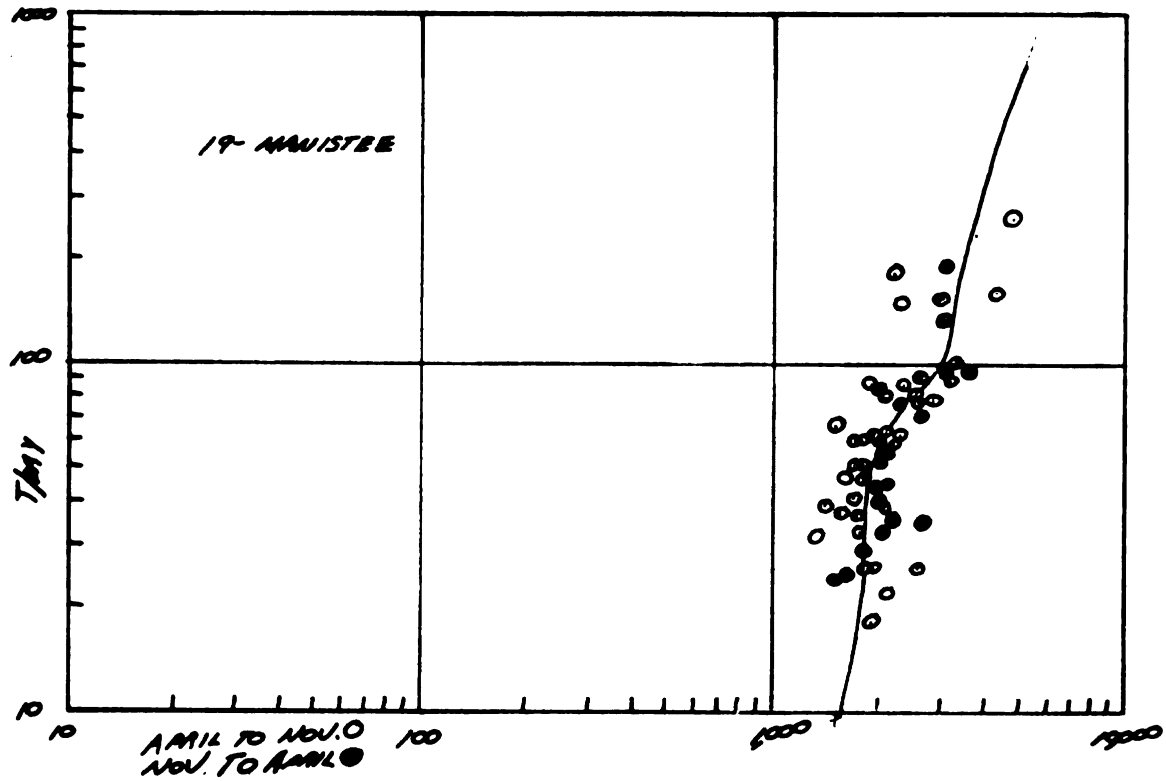

Figure A-14.--STA. 19, Manistee River.

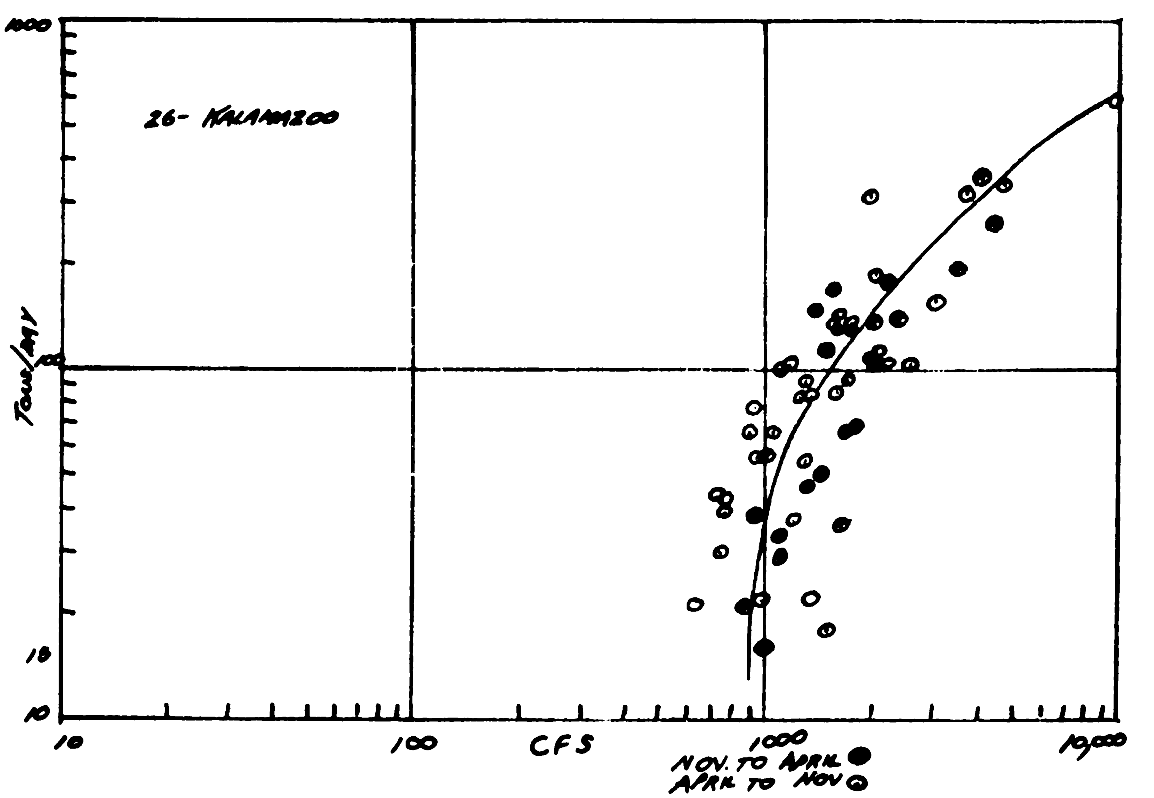

Figure A-15.--STA. 26, Kalamazoo River.

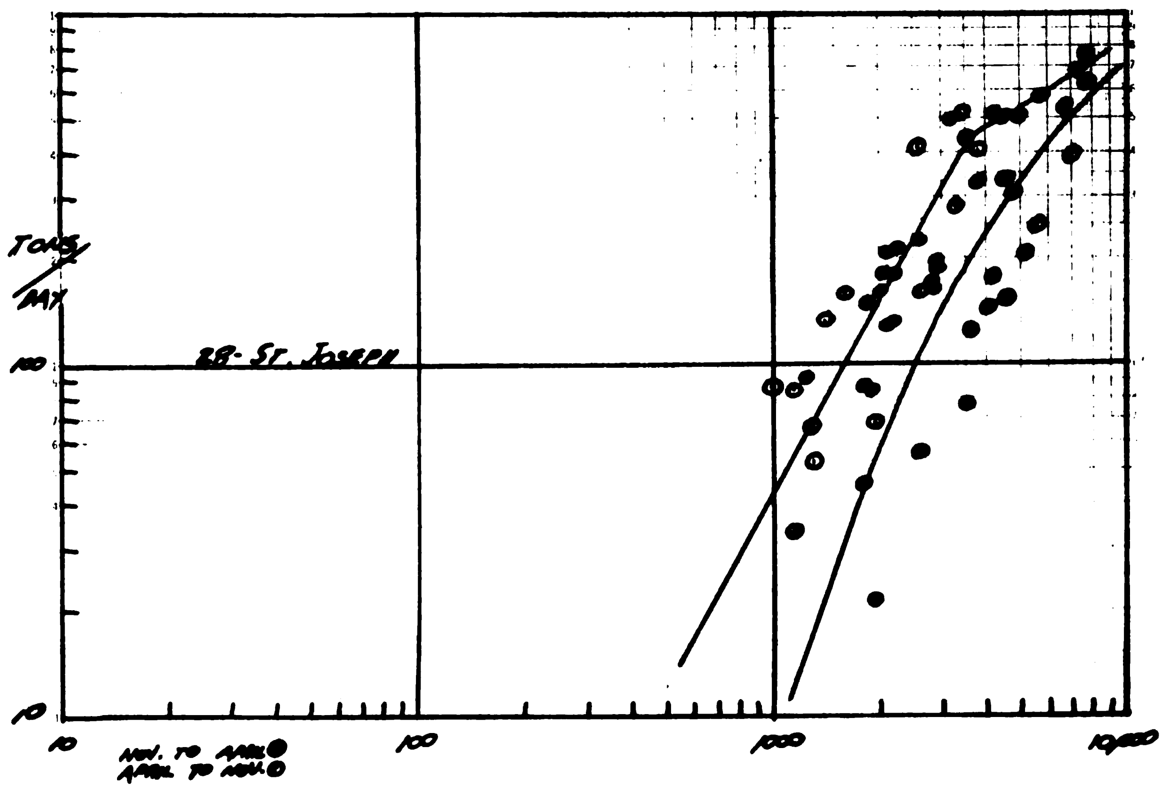

Figure A-16.--STA. 28, St. Joseph River.

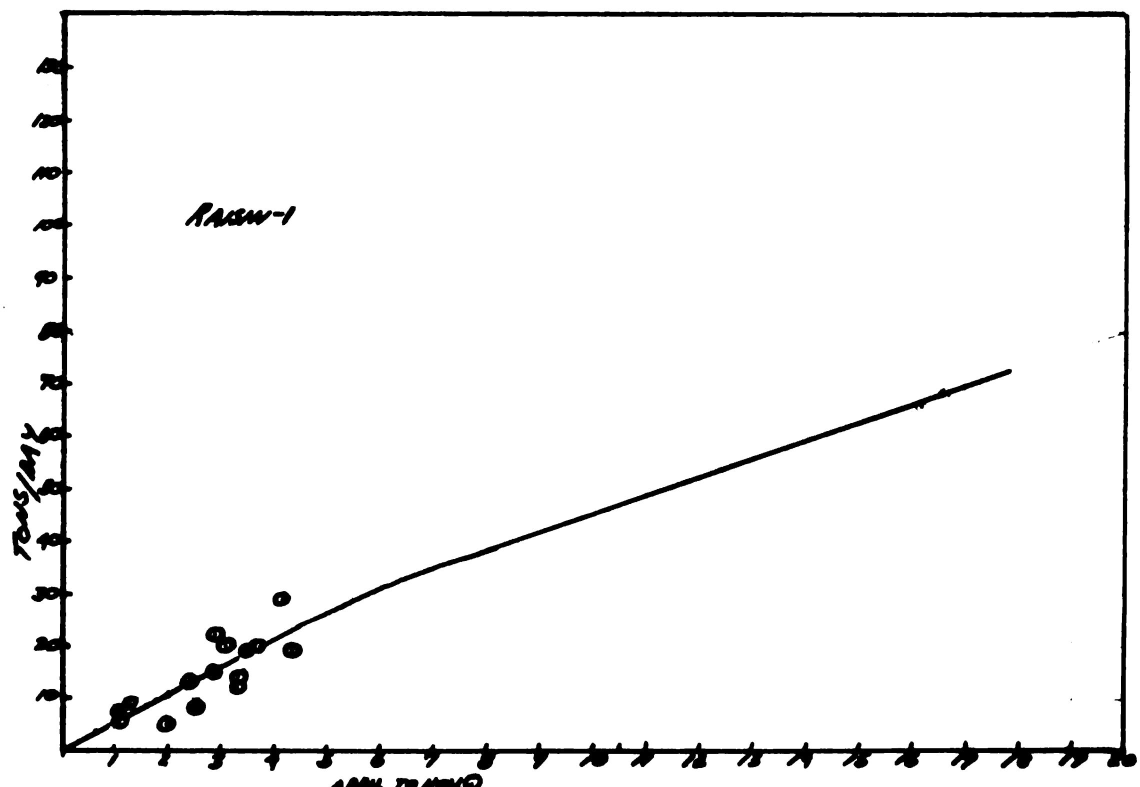

Figure A-17.--Raisin River, STA. 1.

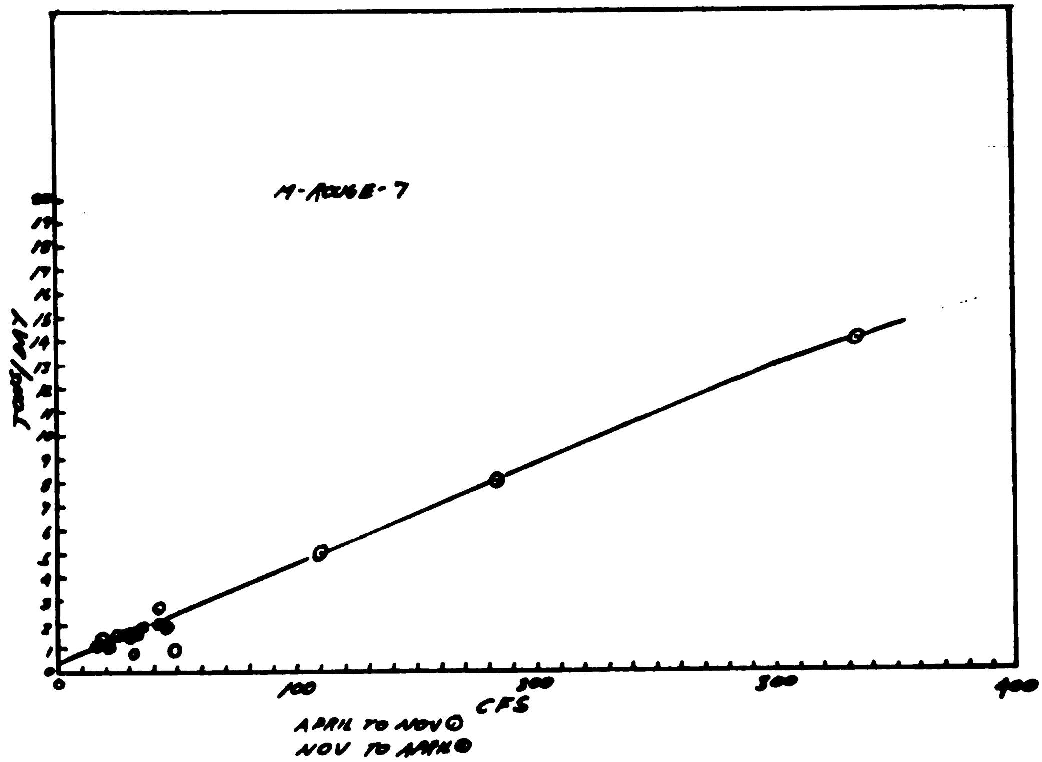

Figure A-18.--Middle River Rouge, STA. 7.

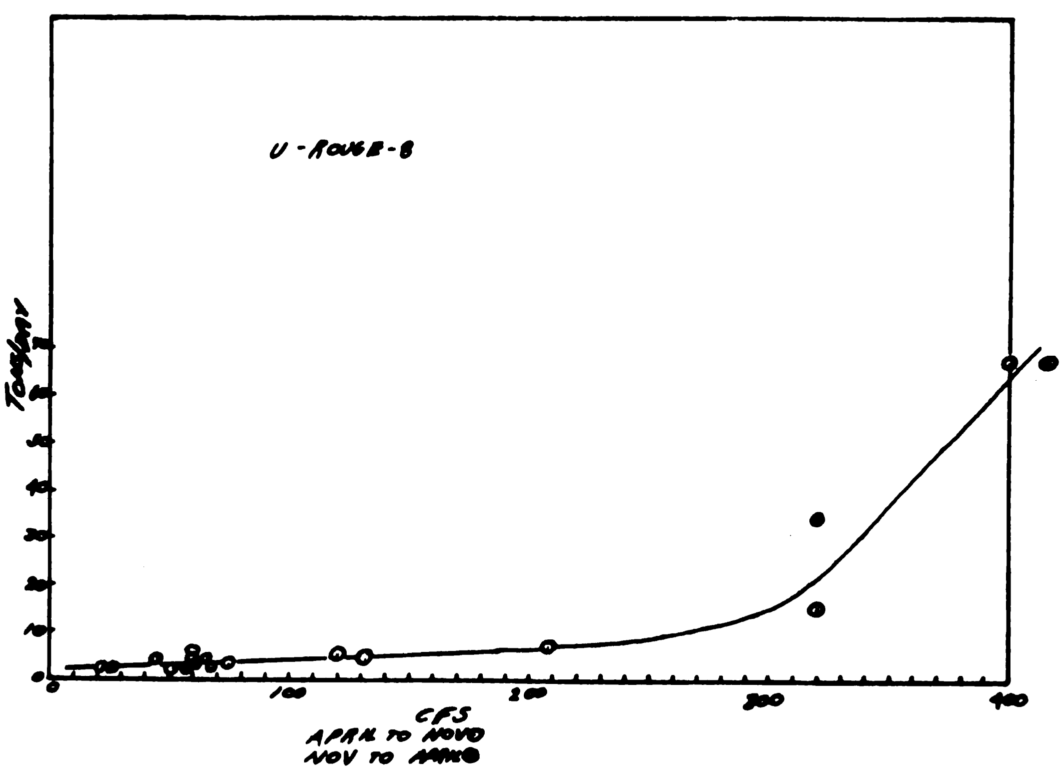

Figure A-19.--Upper Rouge River, STA. 8.

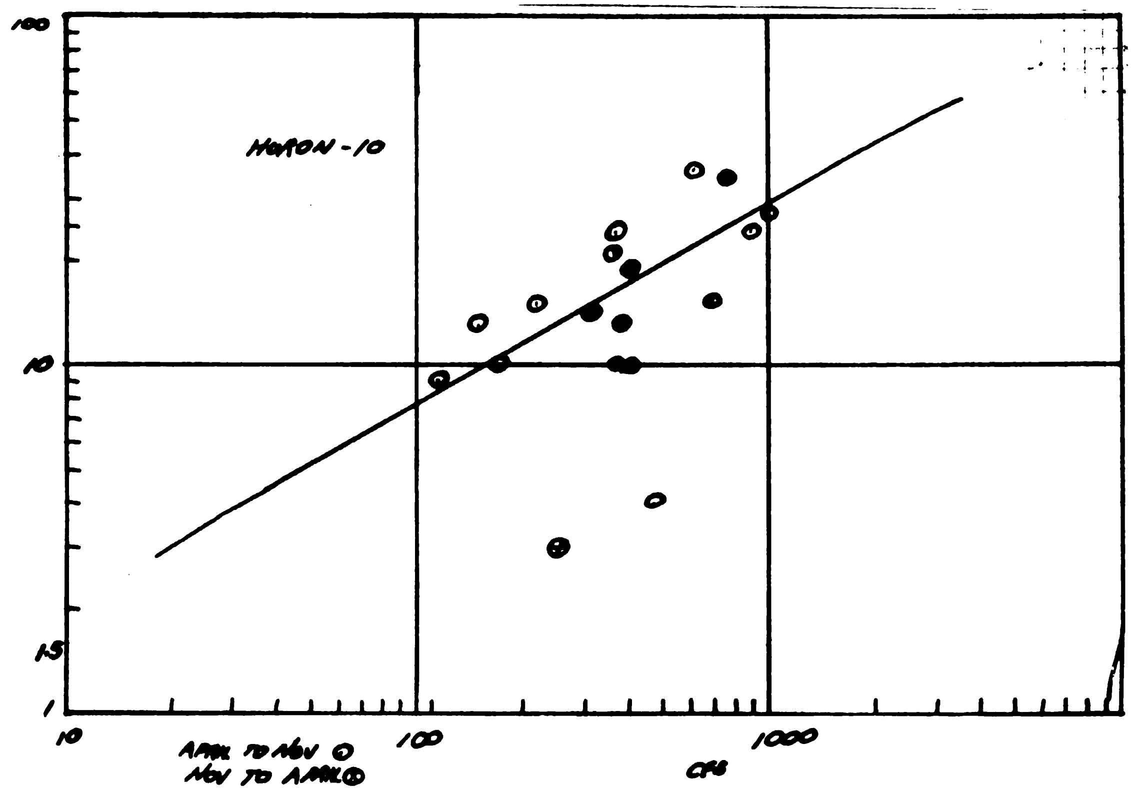

Figure A-20.--Huron River, STA. 10.

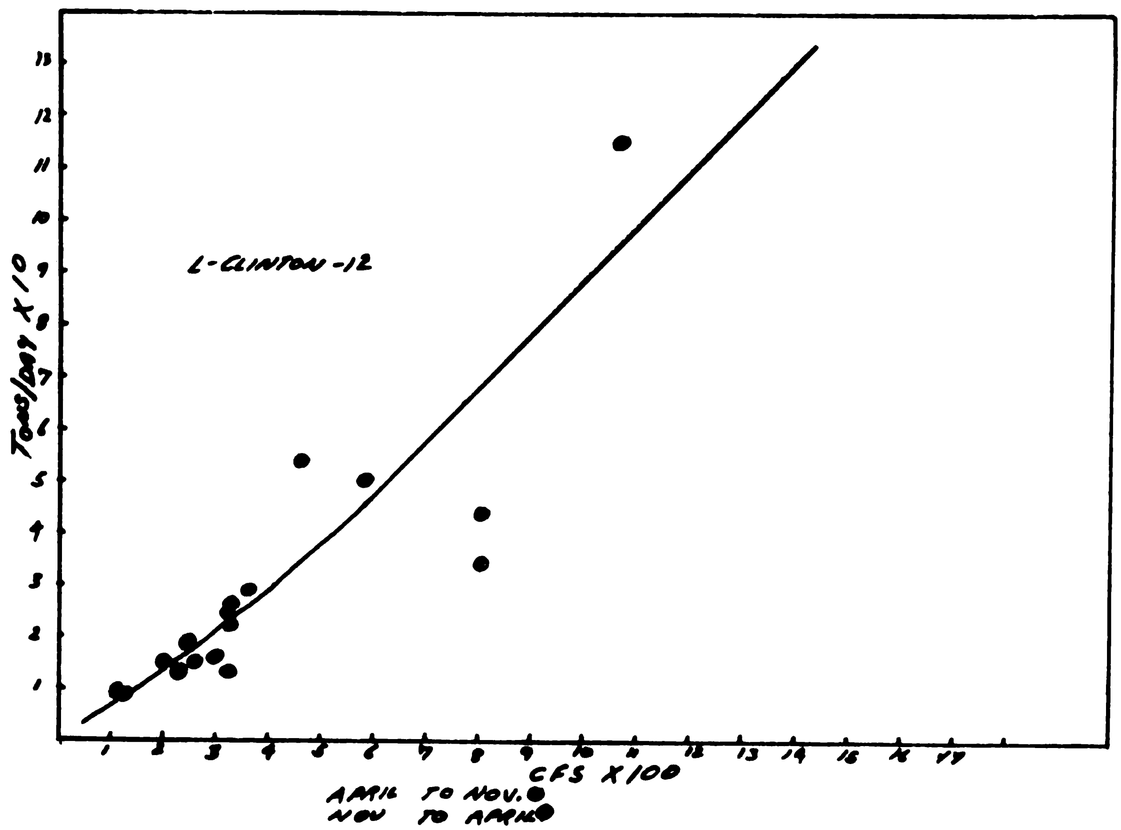

Figure A-21.--L. Clinton River, STA. 12.