SYNTHESIS OF THE SEDIMENT TRANSPORTING CHARACTERISTICS OF ALLUVIAL CHANNELS

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LIST OF SYMBOLS

$\bar{c}$	mean concentration, percent by weight	Page
d	diameter of sediment particle (mean diameter of fraction p of bed material), ft.	
dm	mean diameter of bed material, ft.	
n	Manning roughness coefficient	
p	fraction of bed material of diameter d	
S	energy gradient, ft./ft.	
V	mean velocity, q/y_o, fps	
w	fall velocity of sediment particle, fps	
y_o	depth of flow, ft.	
τ_c	critical tractive force for beginning of sediment movement	
τ_o	boundary shear, or tractive force, at stream bed, $\gamma y_o S$	
$\tau_{o'}$	boundary shear associated with sediment particles	

ABSTRACT

SYNTHESIS OF THE SEDIMENT TRANSPORTING CHARACTERISTICS OF ALLUVIAL CHANNELS

by Gerald Allen Zernial

Using field data obtained by the U. S. Geological Survey in some of their special studies the variability of the relationship between sediment load and stream discharge has been investigated.

A relationship proposed earlier by Dr. E. M. Laursen, which was programmed for a digital computer, was used for computing the sediment load curves. The sediment load as computed for a given discharge was affected by the velocity and depth of flow, by the water temperature, and by the size distribution of the bed material.

It was found that for a given discharge the spread normally obtained in the sediment load can more than adequately be explained by the measured variations that occur in (1) water temperature, (2) flow characteristics of unstable sections, and (3) size distribution of the bed material.

I. INTRODUCTION

Sediment loads transported by alluvial streams are determined by many factors. In a sense the stream is formed by the hydrologic and physical characteristics of the basin--present and past. On the other hand, the physiography of the basin has been formed in large measure by the activity of the stream. Thus, rainfall in its variation from day to day and year to year, soil and rock characteristics, culture, basin size, shape and slope, and stream characteristics are all interrelated in their effect on the sediment load carried by the stream. The complexity of the problem is reduced, however, if it is realized that at a stable cross section, for every discharge there exists a velocity, slope, depth, and, providing the bed material is unchanged, a sediment-transporting capacity. This permits the separation of the runoff characteristics of the stream from the sediment-transporting characteristics. At a stable section, in which the bed material and temperature are the same at all discharges, the sediment load should be a single-valued function of the discharge. For most streams this is not true--measured sediment loads when plotted against discharge form a band, not a single curve. Possible explanations of this variability of sediment load lie in temperature which affects particularly the fall velocity of the particles, and in the surface runoff from the various storms. Not only does the surface runoff deliver water to the stream, but also a sediment load of fine material picked up from the soil mantle. This added fine material entering from surface runoff is mixed with the natural bed material, thus changing the bed material characteristics. It is not unreasonable that for a given flow condition, a change in bed material could change the sediment-transporting capacity of the stream markedly.

If the probable yearly sediment load carried by an alluvial stream is to be predicted with a dependable and a reasonable degree of accuracy, three relatively independent factors must be taken into consideration:

1. The sediment-transporting characteristics of the stream for its natural bed material as determined by velocity, depth, width, slope and temperature at various discharges.
2. The changes occurring in bed material due to sediment delivered to the stream by surface runoff.
3. The hydrologic characteristics of the basin, which determine the probable yearly discharge variations.

The portion of the problem considered in this study is to determine whether the multiple-valued function of sediment load and discharge found in field data can be explained by the effects of the variations that can be expected in the flow, fluid, and sediment characteristics. Field data used in this study were obtained from USGS Water Supply Papers and personal correspondence.

II. DESCRIPTION OF SECTIONS

Middle Loup River

The major portion of the Middle Loup River, upstream from Dunning, Nebraska, which was investigated by the USGS from 1948 to 1952 (1), traverses the sandhill region of north-central Nebraska. The drainage area of the reach considered is approximately 1760 square miles, only 80 square miles of which contribute directly to surface runoff. Because of the sandy mantle flow is derived from groundwater accretion, varying from about 200 to 600 cubic feet per second. For approximately 1500 feet upstream from the turbulence flume, located at Dunning, Nebraska, the channel is straight with a uniform or nearly constant cross section. Although meanders were not well developed, bank erosion was prevalent and the source of most of the sediment load. The topography of the basin was formed by sand dunes and stabilized by sparse trees, brush and grass cover, with the valley floor composed of sand deposited by the stream and topped in some places with a thin layer of soil. The banks of the Middle Loup River through Dunning, Nebraska have been artificially stabilized with trees, brush, and grass.

Investigation of the Middle Loup River by the USGS included six selected river sections and the turbulence flume. However, due to the extreme non-uniformity of some sections, only sections C and C_2 were considered and included herein.

At section C, the upstream side of the turbulence flume which was located at section D, suspended sediment and flow measurements were made in order to define the sediment load and discharge entering the flume. It was anticipated that the difference in suspended and total load at section C and D would be representative of the unmeasured sediment of an average reach. This, however, proved invalid since section C was not representative of normal sections. A permanent water stage recorder and a continuous water- and air-temperature recorder were housed about 15 feet upstream. Three staff gages, one outside the recorder and one at section C and one at section D, were used to establish the slope through the flume. Measurements at section C were made from a walkway which spanned the stream.

Section C_2, about 600 feet upstream from the entrance of the turbulence flume, produced a greater depth and sediment concentration in the left one-half of the channel, with stream velocity remaining fairly uniform across the section. The slope was determined by staff gages located 300 feet up and downstream from the section.

Fivemile Creek

Fivemile Creek (2, 3), a tributary in the Wind River drainage basin in west-central Wyoming, rises in the vicinity of Circle Ridge anticline northwest of Pavillion, Wyoming and joins the Wind River near Riverton, Wyoming. Numerous tributaries join the Wind River, which discharges through Thermopolis, Wyoming, where the name is changed to the Bighorn River. Quantitative analysis of the sediment transported by the Bighorn River at Thermopolis, prior to the construction of Boyson Reservoir, showed that Fivemile Creek contributed approximately 7 percent of the total average water discharge and approximately 57 percent of the total average sediment discharge.

The drainage basin of Fivemile Creek is long and narrow with the floor of the basin characterized by sparse semi-arid vegetation and soils composed of water-deposited silts, clay, and gravel. The headwaters of Fivemile Creek do not reach the Owl Creek mountains, and thus flow resulting from snow-melt is usually small. During the summer, storms occasionally produce stream flow at the gaging station near Pavillion, where much of the year there is no flow. Tributary inflow downstream from the gaging station at Pavillion would be very low were it not for the waste water resulting from irrigation. Not only does the returning waste water contribute to the stream flow, but it also carries sediment. However, even without irrigation, the sediment discharge near the mouth of Fivemile Creek probably would be greater than at the station near Pavillion since stream characteristics are such that a larger load can be carried--thus picking up material from the bed and banks of the channel.

Fivemile Creek flows with an average slope of 32 feet per mile with severe bank erosion prevalent in the lower 25 miles of its course where the gradient is 23 feet per mile. During the years 1949 to 1950, it was estimated by the USGS that 87 percent of the total sediment discharge came from the bed and banks of the stream.

Three sediment and streamflow stations were maintained on Fivemile Creek for 3 or 4 years before October 1, 1952. During the 1949 water year, the station near Pavillion was downstream from the Bureau of Reclamation's

Wyoming Canal. However, in the latter part of 1949, it was moved a short distance upstream from the canal. Another sediment station is near Riverton and is about 3 miles downstream from the mouth of Ocean drain. Much of the sediment at this section was forced into suspension by the flow in a natural contracted section. The third sediment station is near Shoshoni and is about two and one-half miles upstream from the mouth of Fivemile Creek. The sediment at the Shoshoni station was forced into suspension by an artificial contraction. Sediment measurements made at Riverton and Shoshoni sections were considered by the USGS to be nearly total loads. On four days during 1951, sediment concentration measurements were made at the same time at a normal section about three-eighths of a mile upstream from the gaging station and at the daily sampling section, which is also the contracted section. Ratios of total load as indicated at the contracted section to measured suspended-sediment discharge at the upstream normal section ranged from 1.07 to 1.44, or an average of 1.31 for the four days. Similar measurements for the contracted section near Shoshoni for 2 days of August of 1953 yielded ratios of 1.43 to 1.56 when compared with a normal section 400 to 500 feet upstream.

Due to insufficient data for some of the sections, only the Riverton and Shoshoni sections were considered in this study.

Rio Grande

The Rio Grande watershed is located in the southwest United States and northeast Mexico (4, 5). The total area within the outer limits is 335,000 square miles. A large part of this is in closed basins with only

171,900 square miles contributing runoff to the Rio Grande. Meanders of the wide, shallow, silt-laden river are well-defined on the flat valley floor. While flow of the stream is often nil, the river, with its main source in barren, rocky mountain slopes, has the potential to flood the valley in a matter of hours. Frequently referred to as "The Dirtiest River in the World," the river is raising its own bed at a rate of approximately four inches per year.

The mantle of the region consists of sand, rock, and wind-blown deposits. These arid conditions result in sparse vegetation on the basin floor and upper valley slopes. Small tributaries flowing in an east-west direction frequent the basin floor, many having no natural course.

Stream measurements used in this investigation were taken at Bernalillo, New Mexico (6). The station is located two miles northwest of Sandia Pueblo, three miles southwest of Bernalillo, three and a half miles from State Highway 44, and eight and a half miles downstream from the Jemez River. Bed material characteristics were obtained from a study, which included the Bernalillo station, conducted by Vanoni and Brooks (7).

The drainage area contributing to Bernalillo station is approximately 17,300 square miles. This includes 2,940 miles of closed basin in the San Luis Valley in Colorado.

III. METHOD OF ANALYSIS

Field sites from which data were obtained included the Middle Loup River in Nebraska, the Wind River basin in Wyoming, and the Rio Grande in New Mexico. Data for the Middle Loup and a portion of the data for Fivemile Creek were obtained from the pertinent USGS Water Supply Papers. Supplementary material for Fivemile Creek as well as all data for the Rio Grande were obtained from offices of the USGS (2, 3). Even though the USGS and the Bureau of Reclamation have been making special studies in the Rio Grande basin, published data are not presently available. Additional data for the Rio Grande were obtained from a study carried on at the California Institute of Technology (7).

For computing the sediment load, a relationship proposed by Laursen (8) was used:

$$\bar{c} = \Sigma p (d/y_o)^{7/6} \, (\tau_o'/\tau_c - 1) \, f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$$

where $\bar{c}$ is the mean sediment concentration by weight, y_o the depth of flow, p the fraction of bed material of size d, and the function $f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$ is presented in Fig. 1. Due to the difficulty in expressing the function as a polynomial, the relationship was programmed for the MISTIC, a digital computer, using straight line segments for the functional value. Since values of $\frac{\sqrt{\tau_o/\rho}}{w}$, the shear-velocity/fall-velocity ratio, encountered in this study were less than 100, error resulting from the major deviation of the last line segment for the original functional value was not encountered. The program for the relationship was designed for suspended load only by subtracting the bed-load from the total-load function.

Temperature effects on the fall velocity of a particle in suspension are known and can be predicted within reasonable limits. However, the effects of temperature--if there are any--on the critical tractive force τ_c and the particle shear $\tau_{o'}$ are unknown and were not considered. The critical tractive force can be written as τ_c = Cd where C is a coefficient, assumed to be 4.0 in this study, depending on flow conditions near the boundary and the sediment characteristics. The expression $\tau_{o'}$, for the fraction of the total shear, which contributes to the actual movement, was obtained by the use of the Manning equation and Strickler's evaluation of n as a function of the sediment diameter.

$$\tau_{o'} = \frac{v^2 dm^{1/3}}{30\ y_o^{1/3}}$$

These evaluations of τ_c and $\tau_{o'}$ are in accord with the development of the original relationship.

To determine the relative effect of the variations in water temperature, depth of flow (since the sections were unstable), and bed material on the sediment-transportation rate, computations were performed using these as principle variables for each section. Approximate maximum, minimum, and mean values for the depth of flow, for the water temperature, and for the size distribution of bed material were determined from measured values. To determine the effect of variation of one of these factors, mean values of the remaining two factors were used. A mean measured value of slope was used throughout because so few measurements of slope were available.

IV. RESULTS OF ANALYSIS

The characteristics of the Middle Loup basin are such that almost no fine material is added. However, the data from this stream have been used to test the relationship and to assess the effects of instability as shown in Figs. 2 and 3, where the mean velocity is plotted against discharge. The numbers are actual measured depths with the decimal point the plotted point, and the lines are theoretical depths based on a mean width of 82 feet. As shown in Fig. 2, for a discharge of 380 cubic feet per second at section C, the velocity varies from 2.4 to 2.8 feet per second with corresponding depth of flow values of 1.84 and 1.72 feet. Similarly in Fig. 3, section C_2, for a discharge of 410 cubic feet per second the velocity varies from 2.4 to 3.2 feet per second with corresponding depth values of 1.96 and 1.55 feet. The instability resulting from depth and velocity variations at the sections is readily apparent, since for a measured discharge various depth and velocity combinations existed.

Fig. 4 shows a comparison between stream discharge and suspended sediment discharge for section C, with plotted points as actual measured values and theoretical lines for maximum, minimum and mean values of water temperature in the upper graph and of depth of flow in the lower graph. For a discharge of 400 cubic feet per second, the sediment load is increased fivefold by decreasing the depth of flow from 2.0 to 1.5 feet and tenfold by decreasing the depth of flow from 2.0 to 1.0 feet. Theoretical lines obtained from the various depths of flow encountered are approximately parallel and equally spaced with the majority of the measured values lying between the curves for assumed constant depths of 1.5 and 2.0 feet. It is interesting to note that in Fig. 2, where the velocity at section C is plotted against discharge, the majority of the measured values fall between the 1.5 and 2.0 depth lines, and that the actual measured depths of flow also lie between 1.5 and 2.0 feet.

The effect of variations in water temperature on the sediment load was not as large as it was for the variations in depth, and did not produce a set of curves sufficient to enclose the measured values. For the maximum range of water temperatures considered--70 to 32 degrees--the sediment load was increased about 3.5 times for a decrease in temperature from 70 to 32 degrees. The theoretical lines for temperature variations are approximately parallel, but are not equally spaced. The effects resulting from a decrease in the temperature from 70 to 50 degrees are approximately one-third as large as those for a temperature decrease from 70 to 32 degrees.

In Fig. 5 the same analysis was made as in Fig. 4, only this time the factors were taken into consideration at section C_2 rather than section C. At section C_2 the variations in depth of flow were sufficient to band the measured values, and for a discharge of 600 cubic feet per second, the decrease in depth of flow from 2.0 to 1.0 feet produced a sixfold increase in the sediment load. All of the measured values fall between a discharge of 350 and 600 cubic feet per second with the majority of the plotted points lying between the 1.5 and 2.0 depth lines. Again the theoretical lines for various depths of flow were approximately parallel and equally spaced. Temperature effects at section C_2 were such that for a discharge of 600 cubic feet per second, a decrease in the water temperature from 70 to 32 degrees resulted in a 3.5 fold increase in the sediment load, with a 1.5 fold increase being attributed to the decrease in water temperature from 70 to 50 degrees. The bands resulting from water temperature variations are adequate to enclose approximately 90 percent of the measured values with the remaining 10 percent being located in the immediate vicinity of the lines.

Similarly, in Fig. 6 a comparison is shown between stream discharge and suspended sediment discharge for section C and C_2 to determine the effect the characteristics of the bed material have on the transporting rate of the stream. At section C the computed sediment load was increased two-fold by decreasing the maximum size distribution of bed material (mean particle diameter of 0.45 mm) to the minimum size distribution of the bed material (mean particle diameter of 0.28 mm). Thus, with approximately 50 percent of the measured values falling between the bands, the spread of the band was insufficient. At section C_2 the increased sediment load, resulting from decreasing the size distribution of the bed material from its maximum size (mean particle diameter of 0.73 mm), to its minimum size (mean particle diameter of 0.33 mm) resulted in a band sufficient to enclose the measured values. For a discharge of 400 cubic feet per second, the computed sediment load was increased by a multiple of 10 by decreasing the size distribution of the bed material from its maximum value to its minimum value. Variations in the increased sediment load resulting from size distribution of the bed material of section C and C_2 are not unreasonable, since for section C, the variation in maximum and minimum size distribution of bed material, especially the finer material, is not as well pronounced as is the case in section C_2 (see Fig. 7). The greater deviations experienced in the larger particle range for section C contribute little to increasing the spread of the theoretical lines.

At the stations on Fivemile Creek, the same three factors--section instability and temperature, and bed material variability--contribute to the spread of the sediment load-discharge relation. However, the data were handled in a slightly different manner than for the Middle Loup River. Due to the instability of the section, as shown in Fig. 8, where stream discharge is plotted against depth of flow, an arbitrary mean line was drawn for the depth and two other lines were drawn to band the measured values. The measured values were such that for a discharge of 100 cubic feet per second the gaging station near Shoshoni showed depth values from 0. 65 to 1. 0 feet while at the Riverton station values of 0. 8 to 1. 0 feet were obtained.

In the same figure, where stream discharge is plotted against width for the stations near Riverton and Shoshoni, an arbitrary mean width line was drawn through the approximate center of the measured values. For a discharge range from 20 to 400 cubic feet per second, the width varied from approximately 35 to 60 feet for Shoshoni and from 38 to 55 feet for

Riverton. The Riverton section appears to be more stable than the Shoshoni section since the measured values of depth and width at Riverton have less scatter than the Shoshoni section. The maximum and minimum velocities used in the computations were obtained by dividing the discharge by the area, which was taken equal to the mean width times the maximum or minimum depth of flow.

Shown in Fig. 9 is a comparison between stream discharge and suspended sediment load for the station near Shoshoni, with points of actual measured values. The theoretical lines for maximum and minimum bed material were obtained by combining the respective bed material, Fig. 11, with the mean water temperature, 58 degrees, and the mean velocity of flow, and are shown by the dark, solid continuous lines. For each grain size distribution--that is, the maximum and minimum--the range of water temperature, 32 to 78 degrees, was combined with a mean velocity, resulting in two pairs of curves, and the velocity range was combined with the mean temperature, also producing two pairs of curves. The effects of the water temperature and velocity range for each size bed material are shown by the cross-hatched bands between the dashed lines. Effects of the variations in the grain size distribution of the bed material alone were nearly adequate to band the measured values. By decreasing the size distribution of the bed material from the maximum size (mean particle diameter of 0.50 mm) to the minimum size (mean particle diameter of 0.28 mm) the computed sediment load was increased approximately tenfold--that is, from 300 to 3000 tons per day for a discharge of 100 cubic feet per second. For the minimum size bed material, the effects of variation in the water temperature changed the sediment load by a factor of 2.5, where a change in the sediment load by a factor of 3.5 was obtained by varying the velocity of flow. Similarly, for the maximum size bed material, the variation in water temperature changed the sediment load by a factor of 3, with variations in the velocity resulting in a factor of 4.

In Fig. 10 is shown the same comparison as is shown in Fig. 9, but with consideration being given to the gaging station near Riverton. For a discharge of 100 cubic feet per second, a decrease in the size distribution of the bed material--from its maximum size (mean particle diameter of 0.38 mm) to its minimum size (mean particle diameter of 0.22 mm)--resulted in a 7.5 fold increase in the sediment load. Variations in the water temperature and velocity of flow encountered at this section were such that the respective sediment load was changed by factors of 4 and 2 for the maximum size bed material, and of 3 and 2 for the minimum size material. Maximum, mean and minimum temperature values of 77, 61, and 32 degrees were used to assess the effects of temperature at this section.

From the results obtained in Figs. 9 and 10, it is apparent that if conditions resulting in maximum and minimum sediment-transport were assumed, by combining the appropriate depth, temperature, and grain size distribution of bed material, there would be no question as to the computed bands enclosing the measured values. In actual stream flow, any combination of velocity, temperature of water, and size distribution of bed material is possible; however, the probability of occurrence of these maximum or minimum transporting conditions is unknown.

In Fig. 11 is shown the grain size frequency distribution curves for Fivemile Creek near Shoshoni and Riverton, Wyoming. Distributions of the particle size as well as deviations for both sections are very nearly the same, since the mean particle diameters for maximum and minimum bed material were 0. 5 mm and 0. 28 mm near Shoshoni, and 0. 38 mm and 0. 22 mm for the station near Riverton.

Data from the Rio Grande were included in this study to determine the value of the relationship for computing sediment loads for a stream carrying an exceptionally large sediment load. Characteristics of the basin are such that a large quantity of sediment is brought into the stream from the mantle by waste water from irrigation projects and by surface runoff.

Fig. 12 shows a comparison between stream discharge and depth of flow, with plotted points the actual measured values. The parallel lines which band the measured values were computed using maximum and minimum n values of 0. 033 and 0. 015 in the Manning formula. The center or lazy S curve was arbitrarily drawn through the measured values.

It is interesting to note that the majority of the measured values fell between the parallel lines. The lines are so spaced that for a discharge of 500 cubic feet per second, a maximum and a minimum depth of flow of 4. 7 and 3. 0 are possible. Since the width for the section was nearly constant, the velocity of flow could easily be obtained by considering the variation in depth with stream discharges, which is represented by the lazy S curve.

Shown also in Fig. 12 is the size frequency distribution of the bed material for the section. The only values obtainable (7) were for d_{35} and d_{65}; therefore a straight line relation on log probability paper was assumed. Mean particle diameters resulting from the straight line approximation for the maximum and minimum bed material were 0. 40 mm and 0. 23 mm respectively.

Fig. 13 shows a comparison between stream discharge and suspended sediment load, with plotted points the actual measured values. The dark, solid continuous lines were computed from the straight line approximation of maximum and minimum size bed material with water temperature and depth of flow bands similar to those used in the Riverton and Shoshoni sections of Fivemile Creek. Maximum, mean and minimum temperature values of 75, 65, and 57 degrees were used at this section. For a discharge of 10, 000 cubic feet per second, the sediment load was increased sixfold by considering the decrease in the size distribution of the bed material. The effects of water temperature and velocity on the sediment load for minimum and maximum bed material were not as large as they were at the Riverton and Shoshoni sections of Fivemile Creek. Variations in the water temperature and velocity changed the sediment load by a factor of 1. 8 for both the minimum and maximum size bed material. The spread obtained in the sediment load curves computed from maximum and minimum size bed material would enclose the measured values if shifted. The apparent shift that exists for the set of curves can be partially explained by the straight line approximation that was made for the size distribution of the bed material. If finer material than was accounted for in the straight line approximation was present, the resulting computed sediment load curves would be shifted.

Figs. 14 and 15 show a comparison between the composition of the predicted suspended sediment and measured suspended sediment for sections C and C_2 of the Middle Loup River, and the Riverton and Shoshoni sections of Fivemile Creek. The predicted suspended sediment is a mean value which was obtained by averaging the suspended sediment values calculated from concentrations for a specific size bed material.

The predicted suspended sediment for section C_2 resulted in a set of curves that formed a band about the measured values. The measured suspended composition curve is approximately equally spaced between the set of predicted composition curves. Mean particle diameters of 0.24 mm and 0.08 mm for the maximum and minimum size bed material were obtained for the predicted composition, and 0.15 mm for the measured composition.

The predicted suspended sediment and the measured suspended sediment for section C are nearly the same with a mean particle diameter of approximately 0.18 mm for the measured.

Measured suspended sediment values for the Shoshoni section agreed quite well with the predicted suspended sediment. For the predicted suspended sediment a mean particle diameter of approximately 0.06 mm was obtained for both the maximum and minimum size bed material as compared with 0. 07 mm for the measured suspended sediment. It was noted that the measured sediment tended to deviate from the predicted in the smaller particle range. However, for the range that could be predicted the agreement is good.

For the larger particle sizes at the Riverton section the predicted composition curves are nearly the same for the two assumed bed composition, but tend to deviate for the smaller particle sizes. It is interesting to note that the measured composition curve is representative of a well-graded material, which is not normally the case for river sediment loads. The Shoshoni measured suspended load appears to be less uniformly distributed and the Middle Loup sections are even more as would be expected.

V. DISCUSSION OF RESULTS

For a given discharge the spread that normally exists for the sediment load can be explained by the variation in depth of flow which exists at an unstable section, changes that occur in the temperature of the water, and variations in the size distribution of the bed material. From the results of this study, the combined effects resulting from variations in these factors would be more than adequate to explain the spread. In table A is shown the approximate effects that a change in the depth of flow, temperature of the water and size distribution of the bed material have on the parameters contained within the relationship along with the total change in the sediment load obtained from the curves. The approximate change for the individual parameters was obtained from key values.

In part 1 of table A is shown the effect that a variation in the depth of flow has on the parameters, and thus the total change in the sediment load. The percent change in depth of flow shown for each section is an approximate value that was obtained from the velocity, depth of flow, and discharge curves. For section C of the Middle Loup River a 10% increase in the depth of flow resulted in a 35% decrease in the sediment load,whereas for section C_2 of the Middle Loup River and for the Shoshoni and Riverton stations on Fivemile Creek, and the Bernalillo station on the Rio Grande 24%, 55%, 27%, and 20% increases in the depth of flow resulted in decreases of 50%, 66%, 50%, and 30% in the sediment load. Thus, the ratios of the change in sediment to the change in depth of flow of 3. 5 and 1. 2 were obtained. Such variations at first seem strange, but can be explained by considering the effects that a change in the depth of flow has on the various parameters of the relationship. For example, at section C of the Middle Loup River, if a 10% increase in the depth of flow is introduced in the parameter $(d/y_o)^{7/6}$, the numerical value of the parameter is decreased by 12%. Thus, the change in the parameter resulting from a change in the depth of flow would simply be the inverse of the change raised to a power of 7/6. For sections C and C_2 of the Middle Loup River, the Shoshoni and Riverton stations of Fivemile Creek and the Bernalillo station on the Rio Grande, numerical values of 12%, 22%, 40%, 24%, and 19% were obtained from the $(d/y_o)^{7/6}$ parameter.

The effect of a change in the depth of flow on the parameter cannot be as easily obtained. Rewriting the parameter $(\frac{\tau_o'}{\tau_c} - 1)$, one obtains $\frac{q^2 dm^{1/3}}{120\, y_o^{7/3} d} - 1$ where the depth of flow enters to the 7/3 power. To fully assess the effects of the entire parameter, numerical values have to be introduced for the ratio $\frac{\tau_o'}{\tau_c}$, with consideration being given to the change in depth of flow. It is apparent that the closer the ratio $\frac{\tau_o'}{\tau_c}$ approaches unity, the greater will be the influence of a change in the depth of flow. The ratio $\frac{\tau_o'}{\tau_c}$ will have its maximum value for the smallest 5% of the material from which the minimum change of the parameter can be expected. For the larger particles, the ratio of $\frac{\tau_o'}{\tau_c}$ is smaller, giving the maximum change in the parameter--although this may not be fully reflected in the sediment load.

In computing the approximate change in the parameter $(\frac{\tau_o'}{\tau_c} - 1)$ an average mean particle diameter was used. Approximate numerical values of 25%, 55%, 70%, 25%, and 34% were obtained for changes in the parameter for sections C and C_2 of the Middle Loup River, the Shoshoni and Riverton station on Fivemile Creek, and the Bernalillo station on the Rio Grande.

The functional value is determined from the shear-velocity/fall-velocity ratio, $\frac{\sqrt{\tau_o/\rho}}{w}$, which may be rewritten as $\frac{\sqrt{g y_o s}}{w}$. The change in the shear-velocity/fall-velocity ratio, resulting from a change in the depth of flow, can be defined by a simple relation. However, the change in functional value resulting from a change in the depth of flow is dependent upon the segment of the curve from which functional values are obtained. The maximum and minimum slopes of the function curve are 2. 22 and 0.25, so the change in the functional value resulting from a change in the depth of flow is related approximately to the 1. 11 and 0. 125 power of the depth. For the sections considered in this study, approximate numerical values of 12%, 22%, 55%, 29%, and 21% were obtained for changes in the functional parameter.

It is thus clearly evident that the change in sediment load resulting from a change in the depth of flow cannot be defined by a simple ratio. Indeed, the variations obtained in the ratio of the sediment load to the depth of flow are to be expected.

It is noteworthy that, for the sections considered, the changes in the numerical values resulting from a change in the depth of flow introduced in the parameters $(\frac{d}{y_o})^{7/6}$ and $f(\frac{\sqrt{\tau_o/\rho}}{w})$ tended to cancel each other, and, thus, the resulting change in the sediment load could be attributed largely to the effect that a change in the depth of flow has on the parameter $(\frac{\tau_{o'}}{\tau_c} - 1)$.

Shown in the second part of table is the effect that a variation in water temperature has on the sediment load transported by the streams at the various sections considered in this study. The only part of the relationship where water temperature enters, is in the parameter for the shear-velocity/fall-velocity ratio from which the functional value is obtained. For a specific size particle, a decrease in the temperature would result in a decrease in the fall velocity. At the Shoshoni, Riverton and Bernalillo sections, maximum and minimum water temperature were combined with the maximum and minimum grain size distribution of the bed material. Therefore, at these sections for a decrease in water temperature, there corresponds a decrease in the fall velocity for the maximum and minimum size bed material. Since the sediment load transported by a stream is composed mostly of the finer material, with the larger particle sizes contributing little to the stream's load, the change in fall velocities resulting from the decrease in water temperature can be approximated from the smallest 5% of the bed material. The change in functional value resulting from a change in the fall velocity is similar to that discussed previously--that is, the change in the functional value is dependent on the segment of the curve from which the change is being considered. Therefore, the change in sediment load resulting from a change in the temperature of the water cannot be expressed as a simple ratio. For the change in water temperature that was considered at each section, numerical values of 236%, 190%, 230%, 110%, 294%, 135%, 52%, and 88% were obtained for the changes in the parameter.

The data from a study conducted on the Colorado River (9), where the approximate seasonal variation in the water temperature is from 50 to 87 degrees, indicated that a much larger sediment load is carried by the river during the winter than during the summer with approximately the same flow. It was noted that for a given discharge the load may be as much as 2. 5 times as great in the winter as in the summer. The effect of water temperature noted in this study is of this order of magnitude.

In the third part of table A is shown the effect that a decrease in the size distribution of the bed material can have on the various parameters of the relationship as well as the resulting increased sediment load. The change in the size of the smallest 5% of the bed material was used in computing the approximate numerical values for the individual parameters. For a decrease in the particle size with constant temperature the fall velocity of the particle is decreased. Therefore, by decreasing the particle size two factors must be considered as contributions to the change in the sediment load. Analyses similar to those previously discussed may be used to determine the numerical values for the individual parameters when a change occurs in one of the variables contained in the parameter. For the sections considered in this study a change in the bed material from its maximum to its minimum size resulted in the sediment loads being increased by 100%, 900%, 1100%, 510%, and 600%, with the larger portion of the change being attributed to the change in the function of the shear-velocity/fall-velocity ratio. It is thus apparent that the change in sediment load resulting from a change in the size distribution of the bed material cannot be defined by a simple ratio.

Measurements taken at the contracted sections on Fivemile Creek near Shoshoni and Riverton were assumed by the USGS to be total loads. However, due to the programming of the relationship, computations were performed assuming the measured values to be the suspended load only. Anslysis of the computations for these sections show the functional values to be in the range of 500 to 10, 000 for approximately 80% of the finer portion of bed material. Therefore, subtraction of the bed load functional values, which lie in the range from 20 to 30, would have little effect on the computed concentrations. Thus, the error induced in this range for functional values would be no larger and perhaps less than the error that exists in considering the width of the line representing the curve. However, for smaller discharges and lower shear-velocity/fall-velocity ratios, the error introduced in ignoring the bed load is considerably larger.

CONCLUSION

From the results of this study, it is apparent that the relationship used for computing the sediment load transported by a stream is adequate, and that for a given discharge the spread normally obtained in the sediment load can more than adequately be explained by the effects of instability of sections, changes that occur in the water temperature, and changes in size distribution of the bed material.

Analyses similar to those included in this study may be used to predict the sediment load transported by a stream provided sufficient information can be obtained concerning the flow and bed characteristics along with the water temperature. Any stable stream that has been gaged for a reasonable period of time should have sufficient information concerning the hydraulic factors needed for the prediction of the sediment load. For an unstable stream, depth-discharge measurement would have to be made for a reasonable period of time to determine the ranges in depths that can be expected for various discharges. Information obtained from the depth-discharge measurements can then be used to plot stability curves similar to those presented in this study and thus obtain the hydraulic factors needed for the prediction of the sediment load. Variations in water temperature that can be expected for a stream can be reasonably approximated if consideration is given to the geographical location of the stream along with the season of the year and the source of the stream flow. The size distribution of the bed material, and if the bed material is changing, the variations in the size distribution can only be obtained by periodical measurements. If the factors discussed above are at hand, can be obtained, or can be reasonably approximated, the range in sediment load that can be expected for a given discharge can easily be predicted with fair confidence. Since the use of such a relationship is usually in predicting the behavior of the stream over a period of time, the inability to specify the conditions--and, therefore, the load--of a particular flood tends to be averaged out.

TABLE A

Effects of Channel Instability

Stream - section	Measured increase in y_o	Approximate effects on $(d/y_o)^{7/6}$	$\frac{\tau_o'}{\tau_c} - 1$	$f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$	Total effects	Change obtained from curves
Middle Loup River Section C	10%	-12%	-25%	+12%	-25%	-35%
Middle Loup River Section C_2	24%	-22%	-55%	+22%	-55%	-50%
Fivemile Creek Shoshoni	55%	-40%	-70%	+55%	-65%	-66%
Fivemile Creek Riverton	27%	-24%	-55%	+29%	-50%	-50%
Rio Grande Barnalillo	20%	-19%	-34%	+21%	-31%	-30%

Effects of Temperature Variations

Stream - section	Measured increase in temperature	Resulting decrease in fall velocity (w)	$f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right)$	Change obtained from curves
Middle Loup River Section C	54%	42%	236%	233%
Middle Loup River Section C_2	54%	38% max size 43%	190% 230%	191% 225%
Fivemile Creek Shoshoni	59%	min size 50% max size 46%	110% 294%	153% 287%
Fivemile Creek Riverton	58%	min size 55% max size 17%	135% 51%	185% 55%
Rio Grande Bernalillo	24%	min size 25%	88%	80%

Effects of Bed Material Variations

Stream - section	Decrease in d (5%)	Resulting decrease in w	$(d/y_o)^{7/6}$	$(\frac{\tau_o'}{\tau_c} - 1)$	$f(\frac{\sqrt{\tau_o/\rho}}{w})$	Total effects	Change obtained from curves
Middle Loup River Section C	13%	24%	+13%	-13%	+84%	+84%	100%
Middle Loup River Section C_2	49%	68%	+59%	-30%	+1160%	+1189%	900%
Fivemile Creek Shoshoni	49%	71%	+59%	-29%	+1400%	+1430%	1100%
Fivemile Creek Riverton	33%	52%	+59%	-23%	+415%	+431%	510%
Rio Grande Bernalillo	49%	65%	+59%	-24%	+490%	+525%	600%

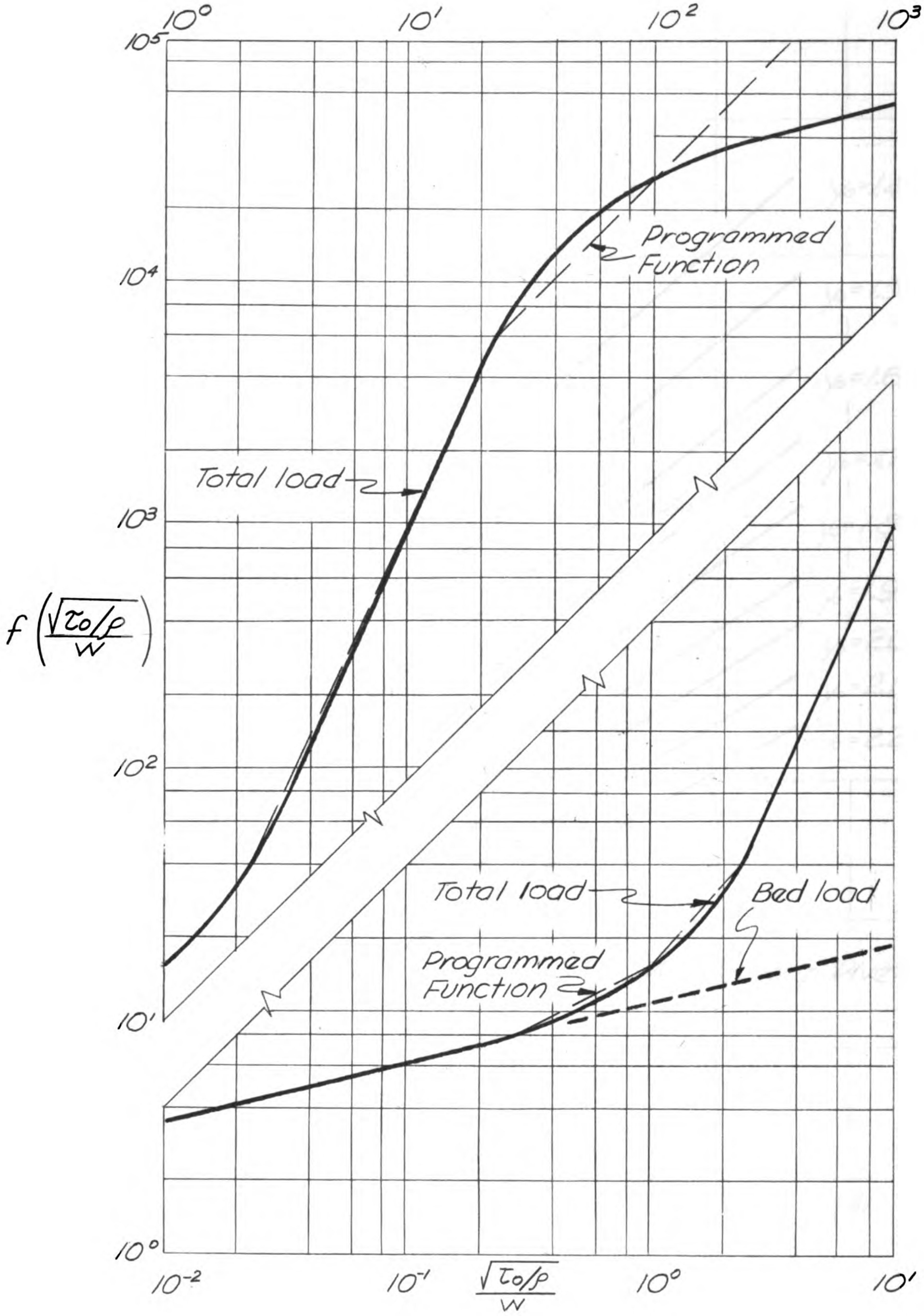


Fig. 1 Relationships for Sediment Load [8]

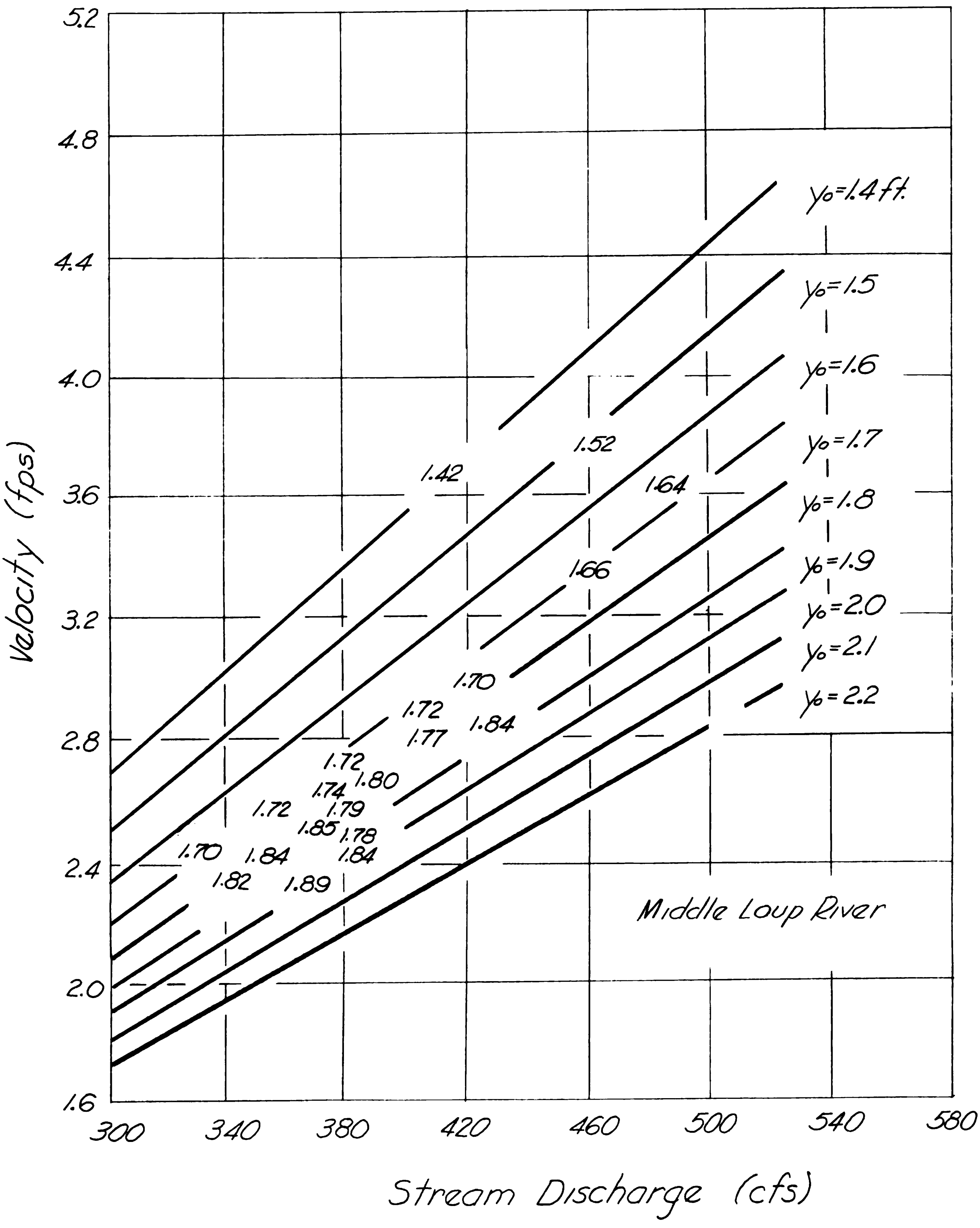


Fig. 2 Discharge vs Velocity at Section C

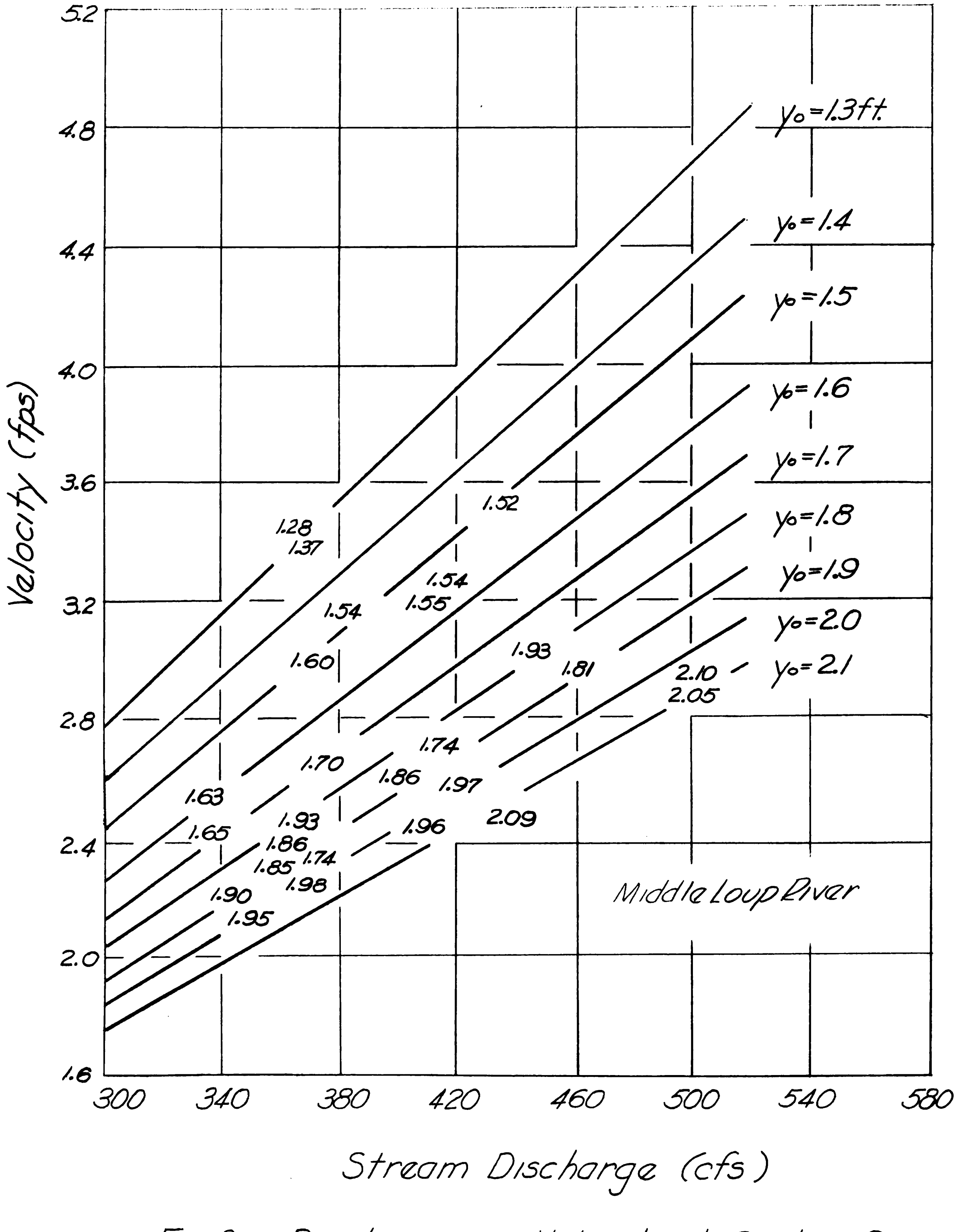


Fig. 3 Discharge vs Velocity at Section C_2

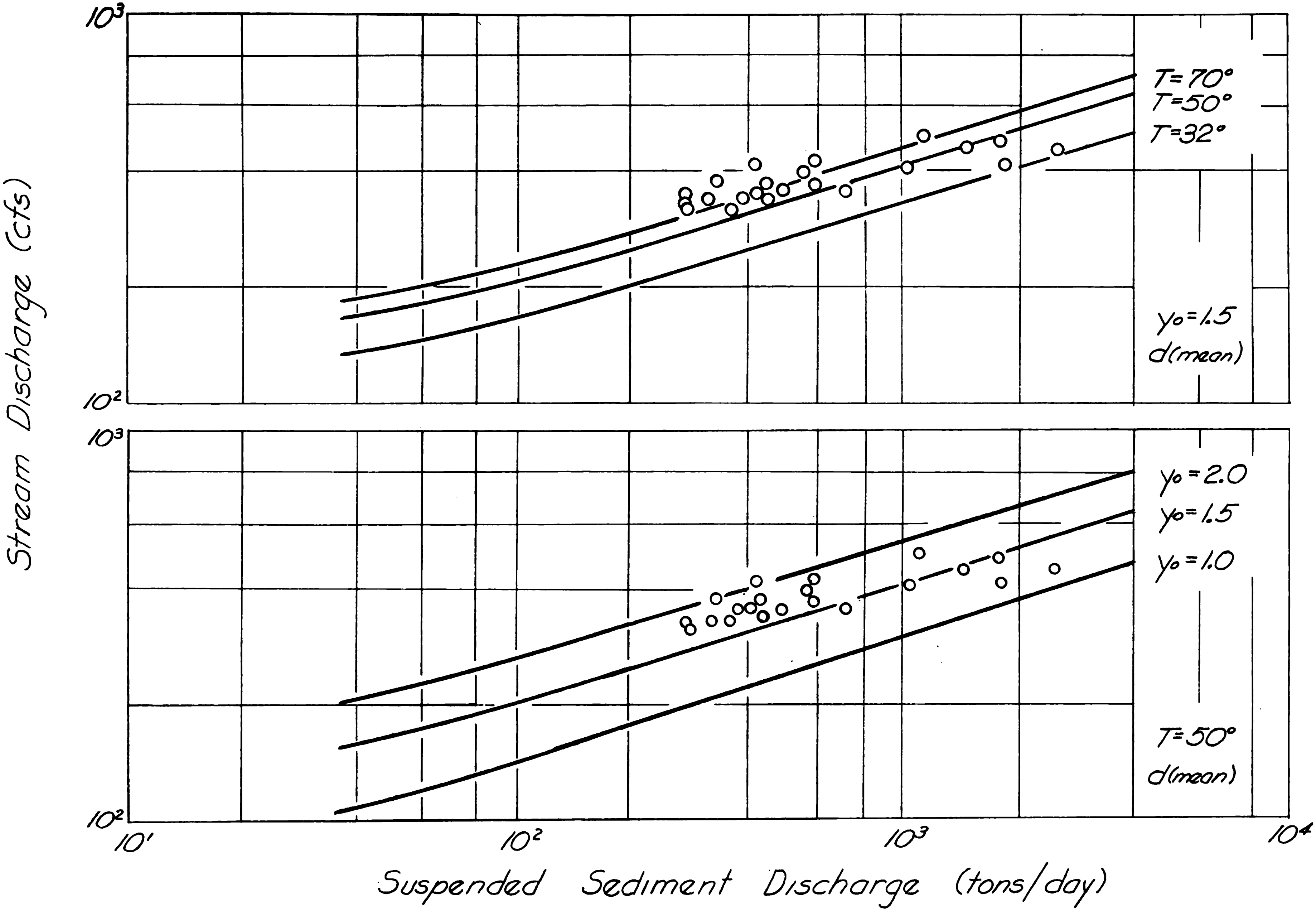


Fig. 4 Sediment Load for Middle Loup River Section C

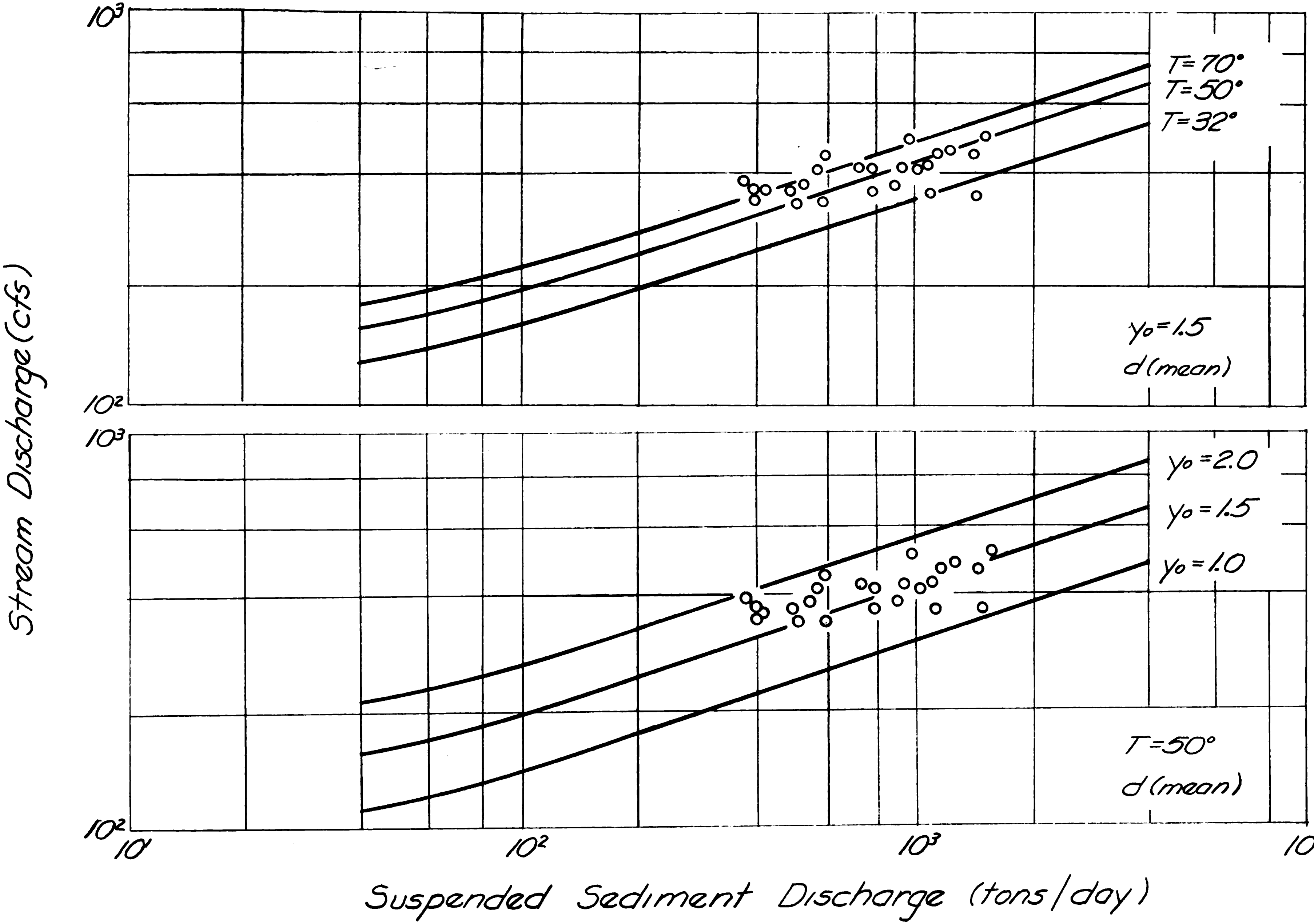


Fig.5 Sediment Load for Middle Loup River Section C_2

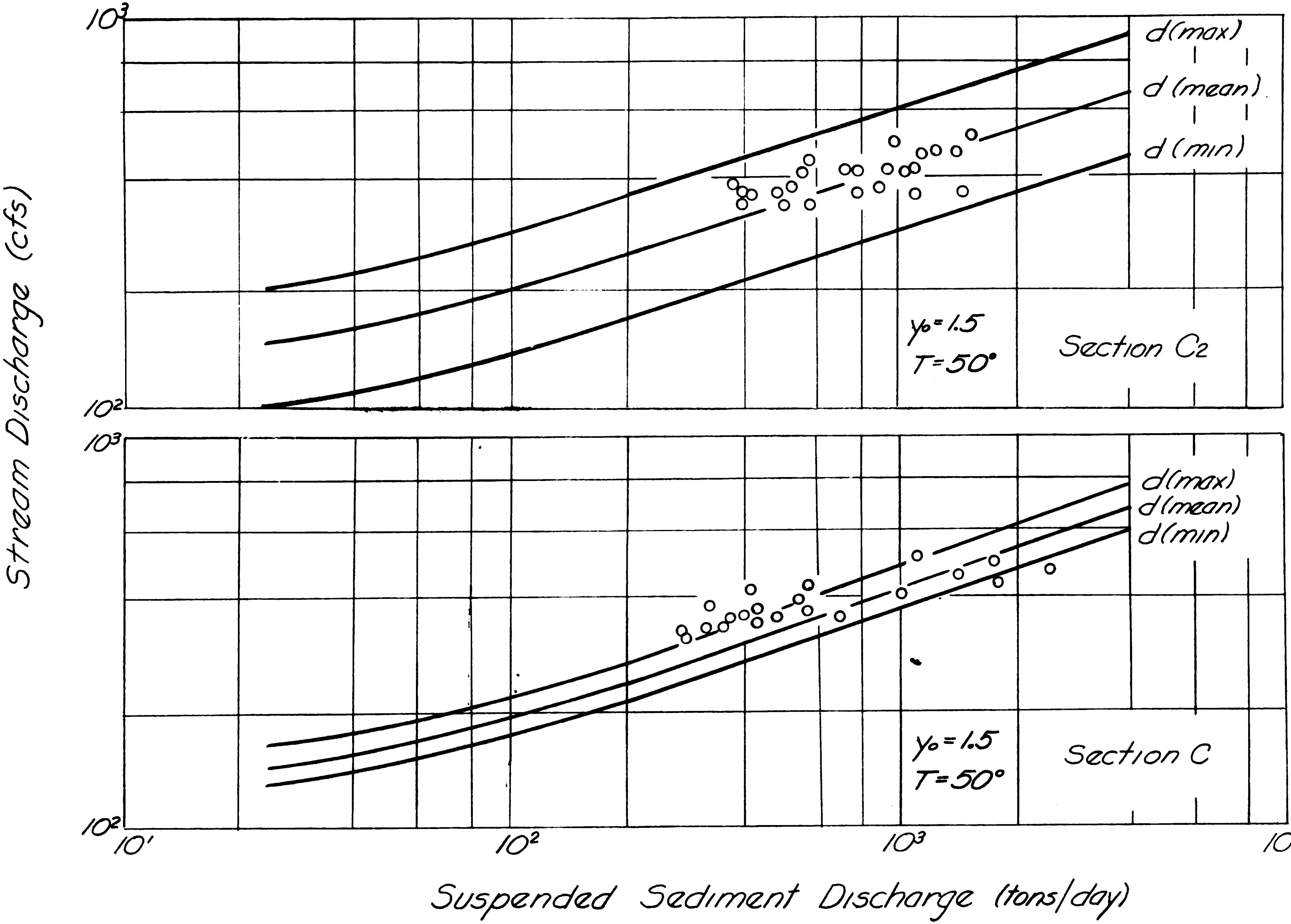
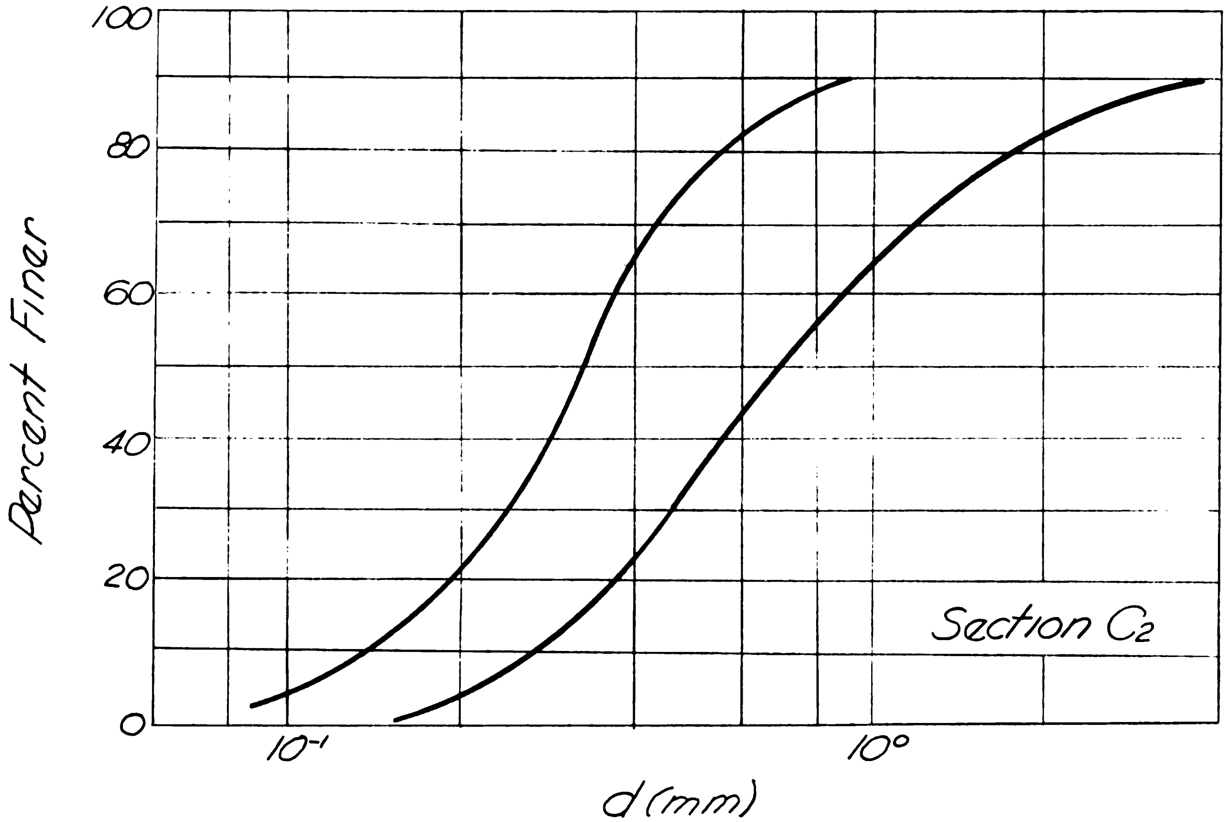


Fig. 6 Sediment Load for Middle Loup River



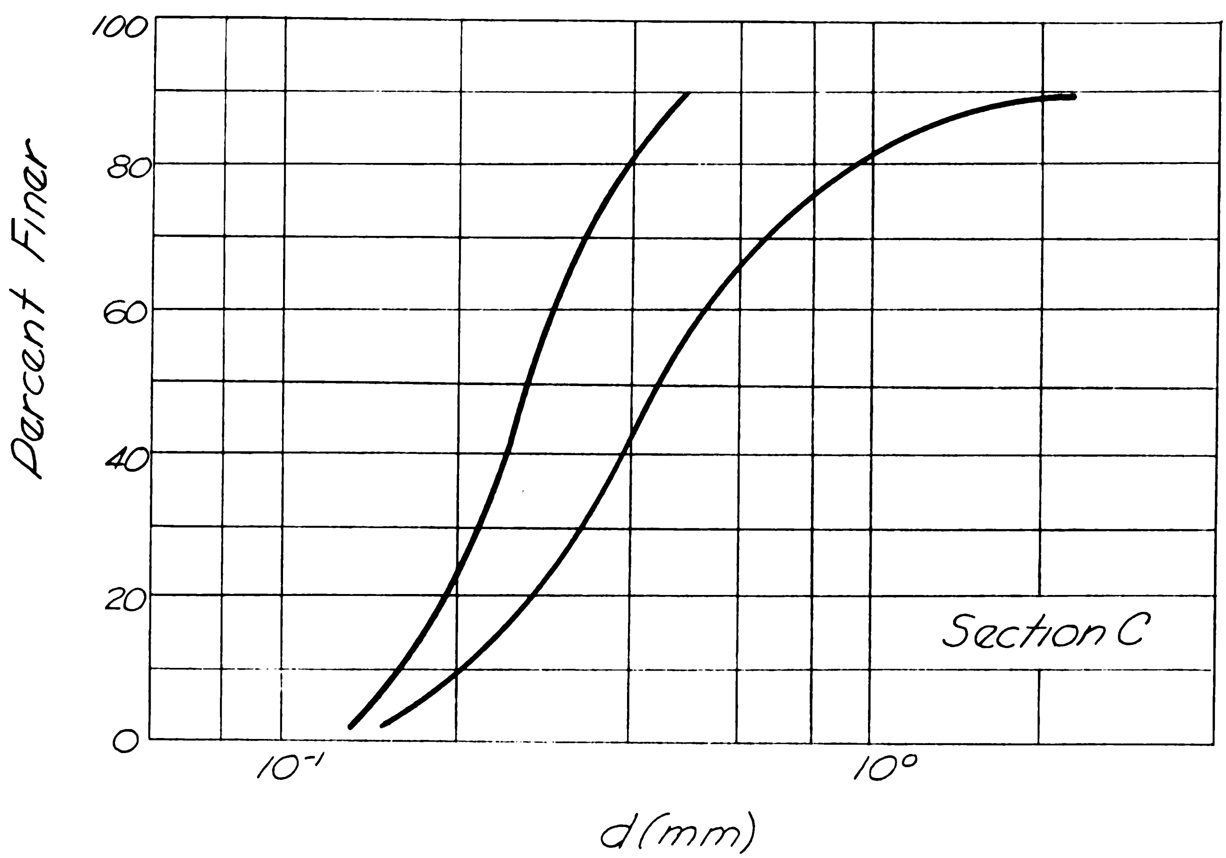


Fig.7 Sediment Characteristics Middle Loup

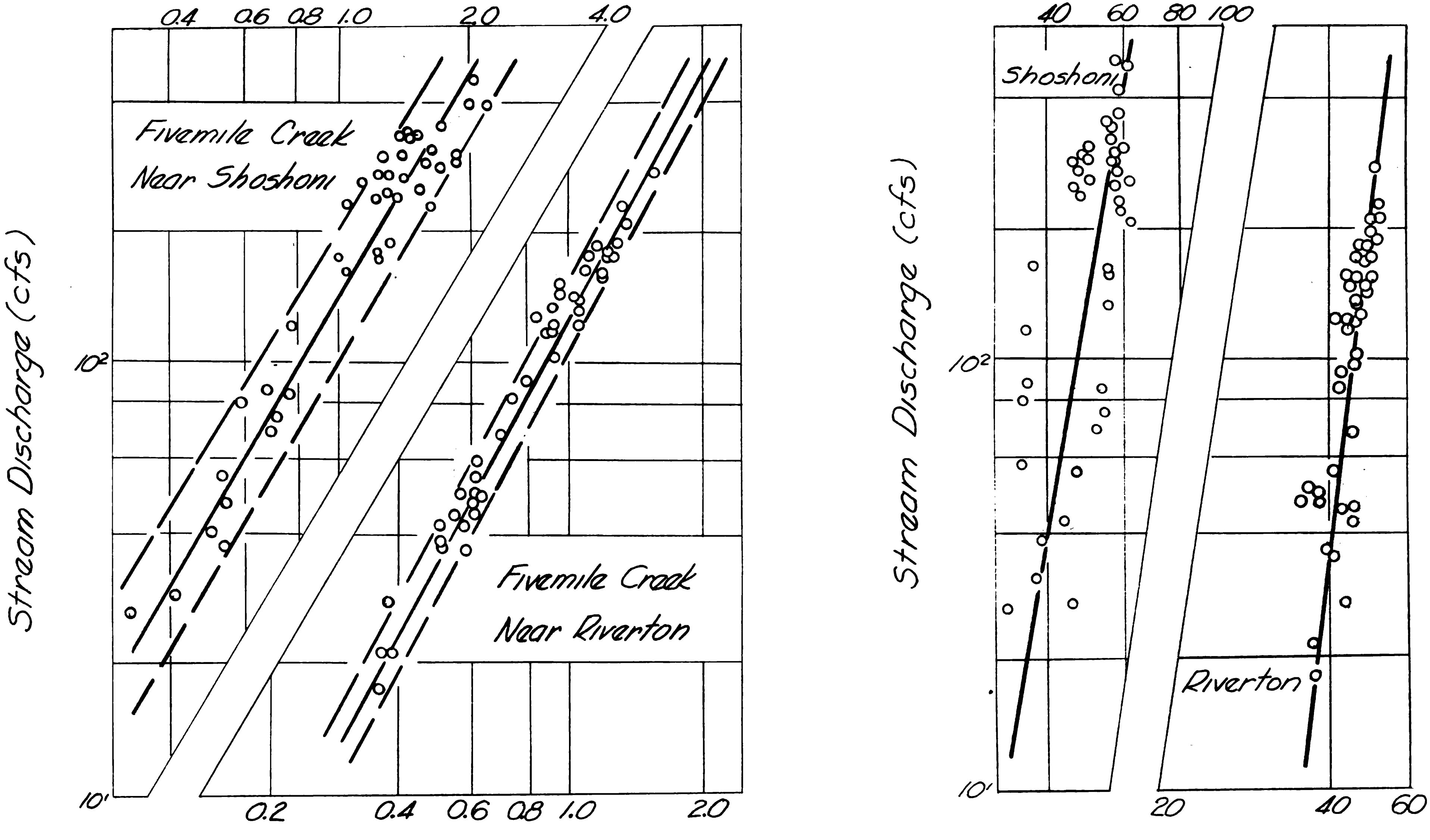


Fig.8 Section Characteristics Fivemile Creek

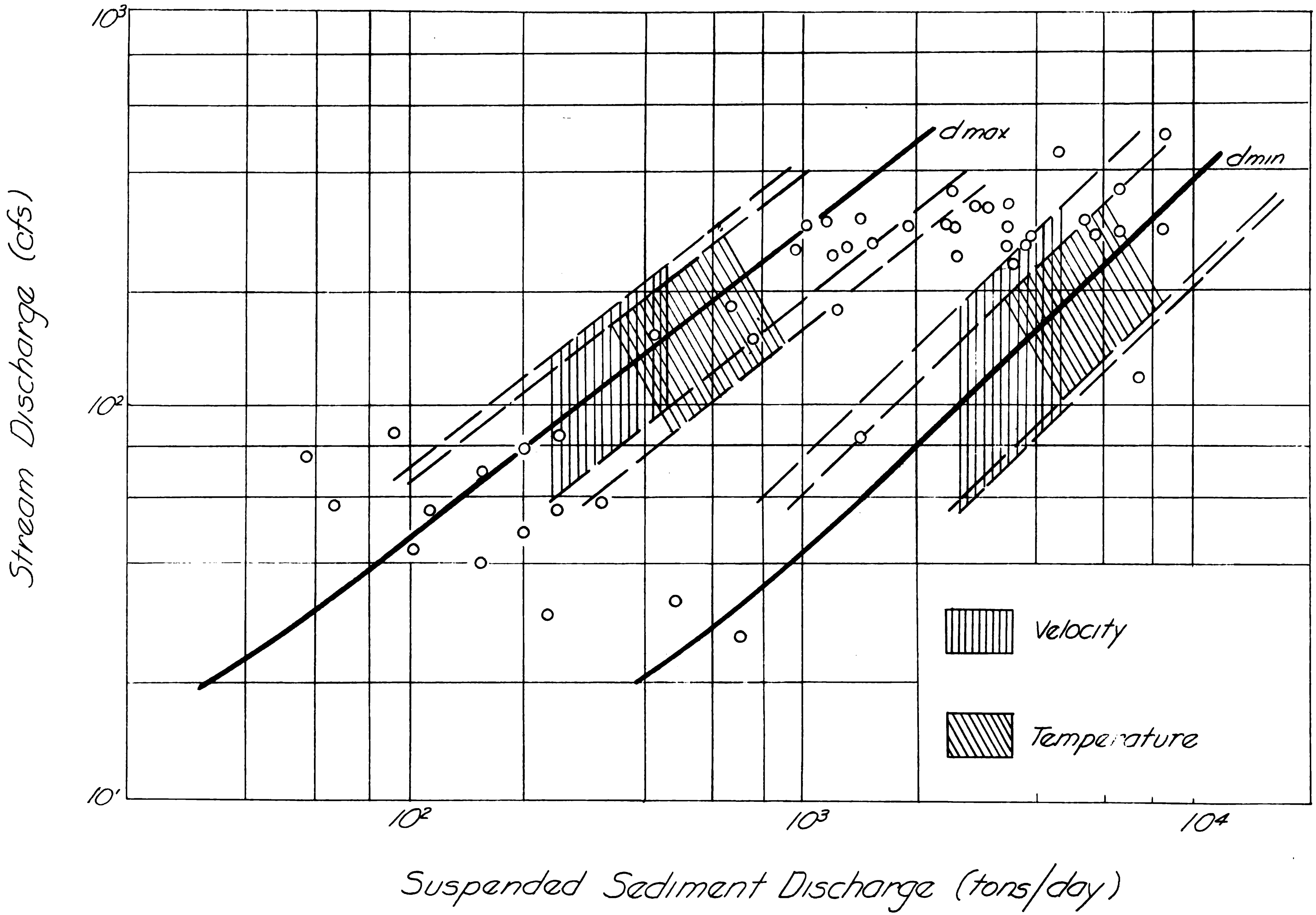


Fig. 9 Sediment Load Fivemile Creek Near Shoshoni

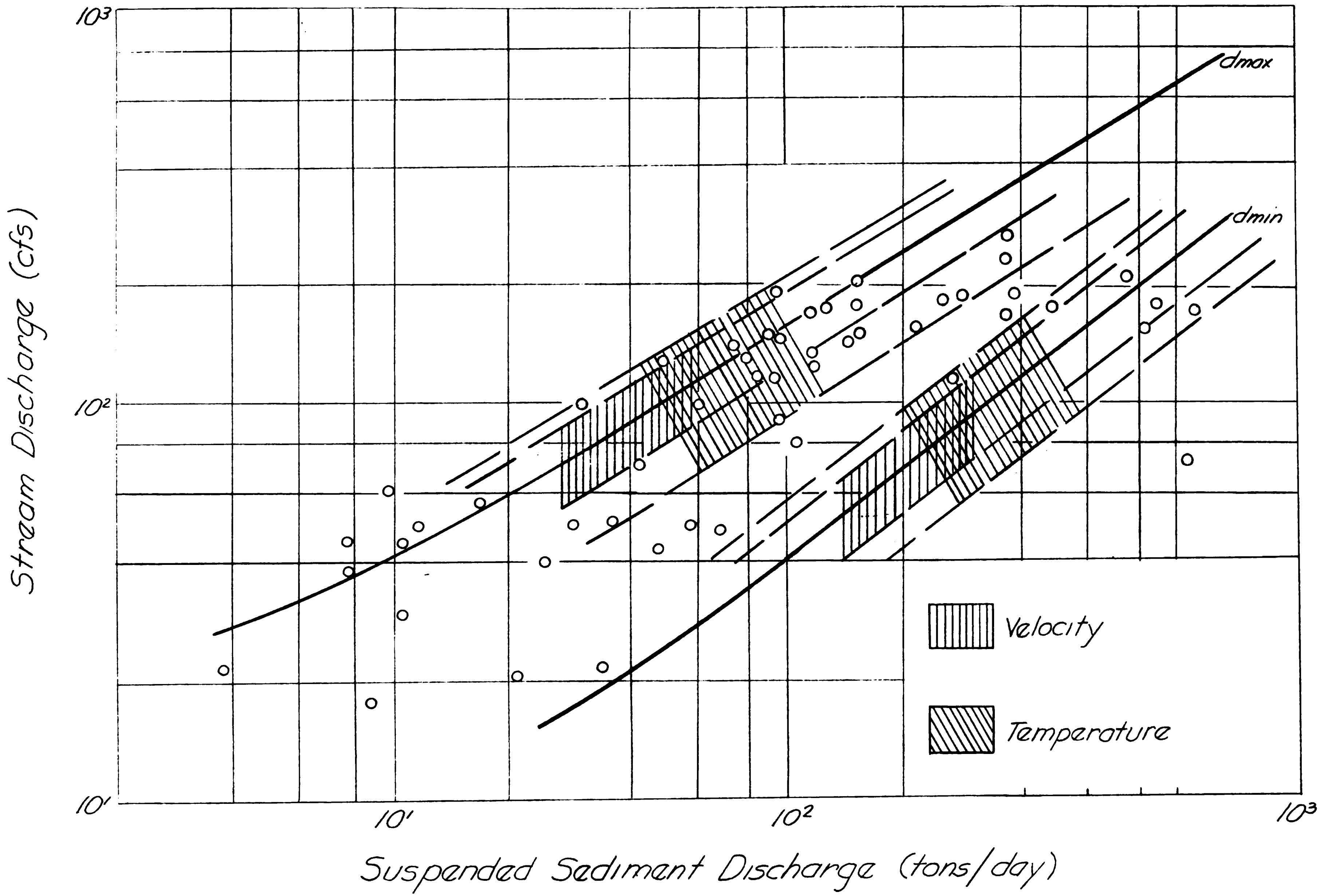
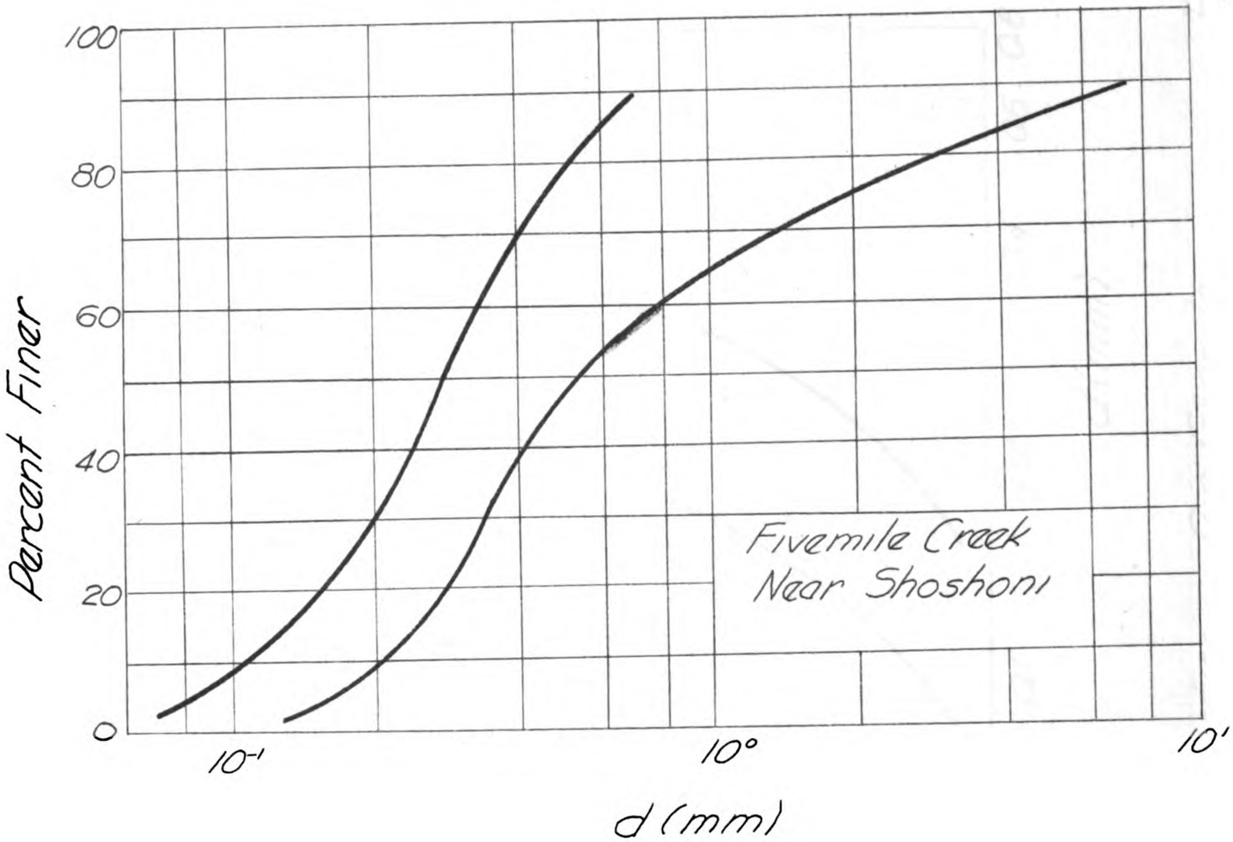


Fig. 10 Sediment Load Fivemile Creek Near Riverton



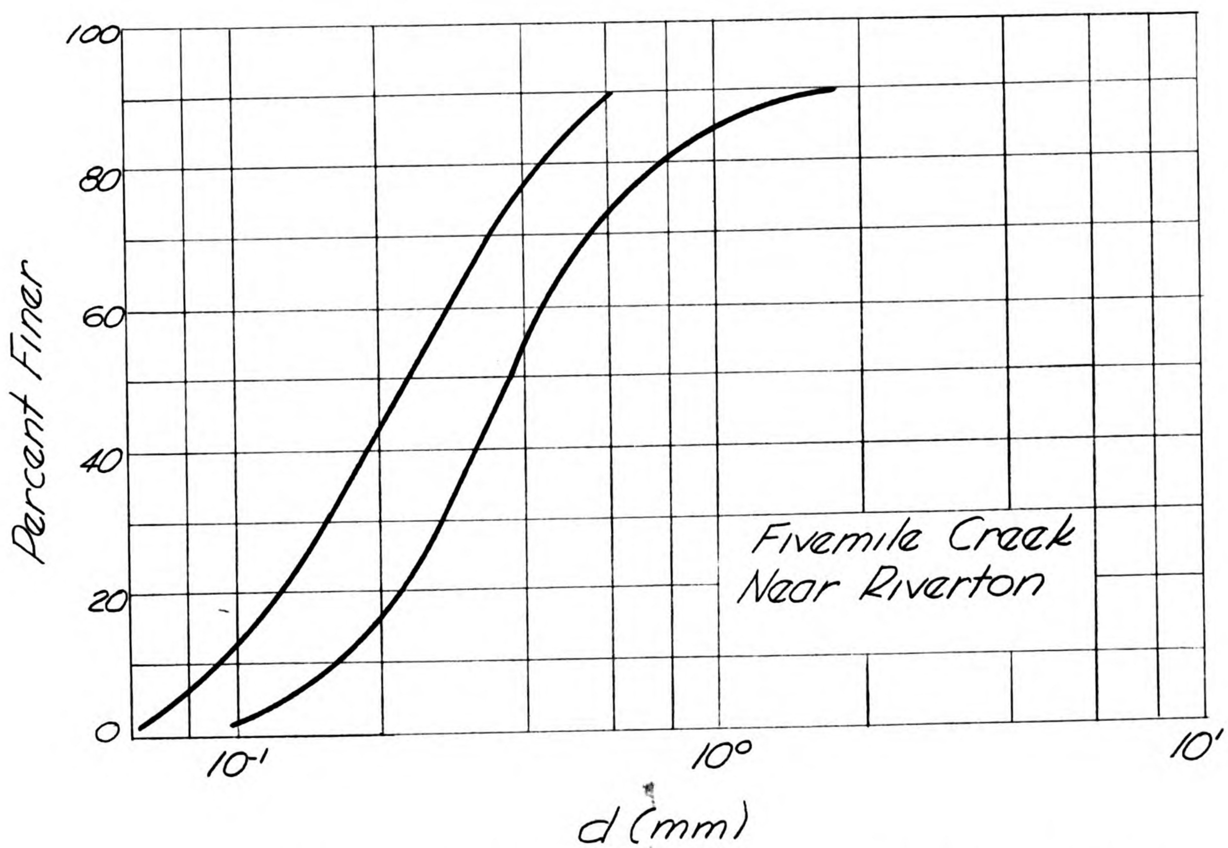


Fig.11 Sediment Characteristics Fivemile Creek

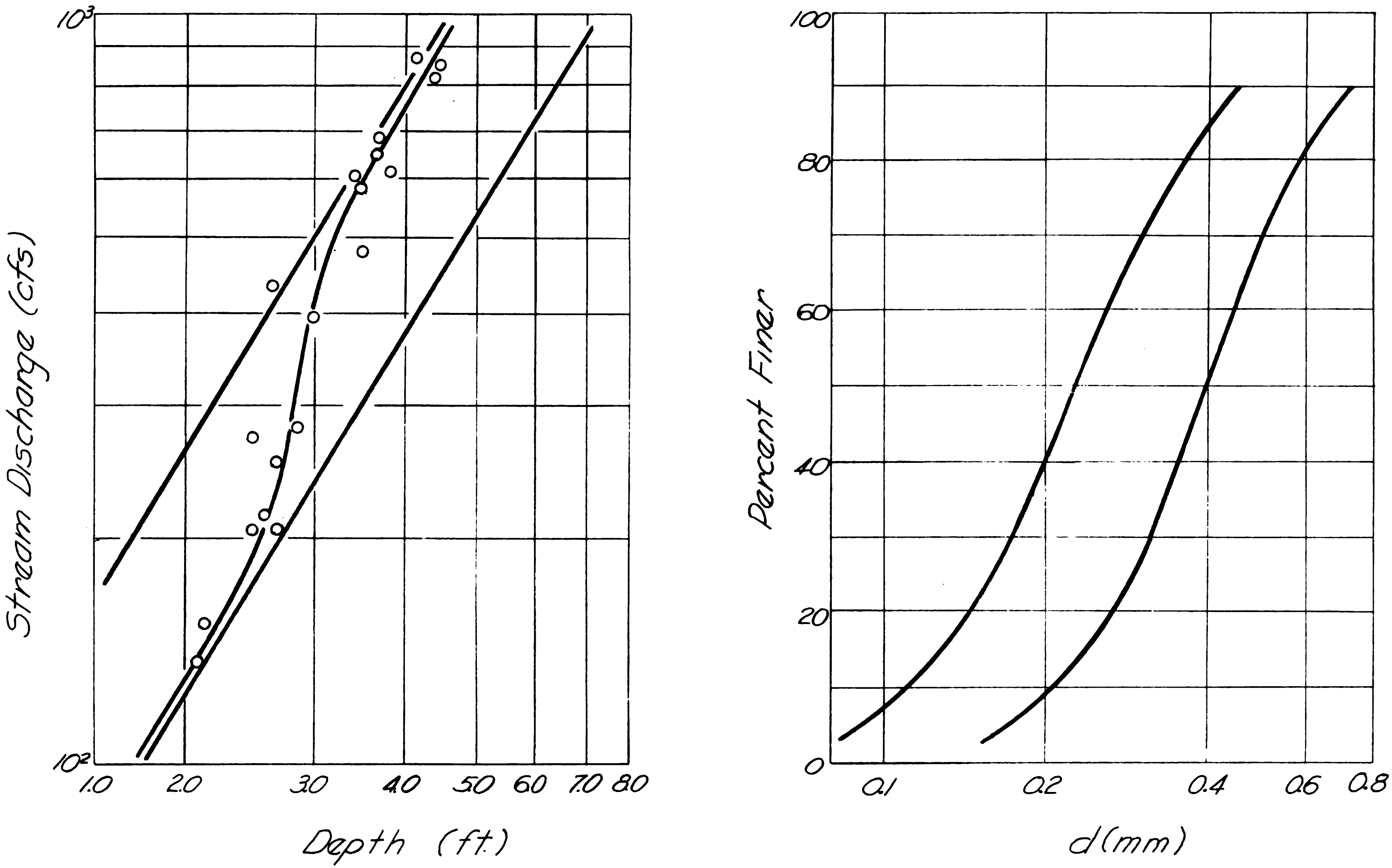


Fig. 12 Section and Sediment Characteristics Rio Grande

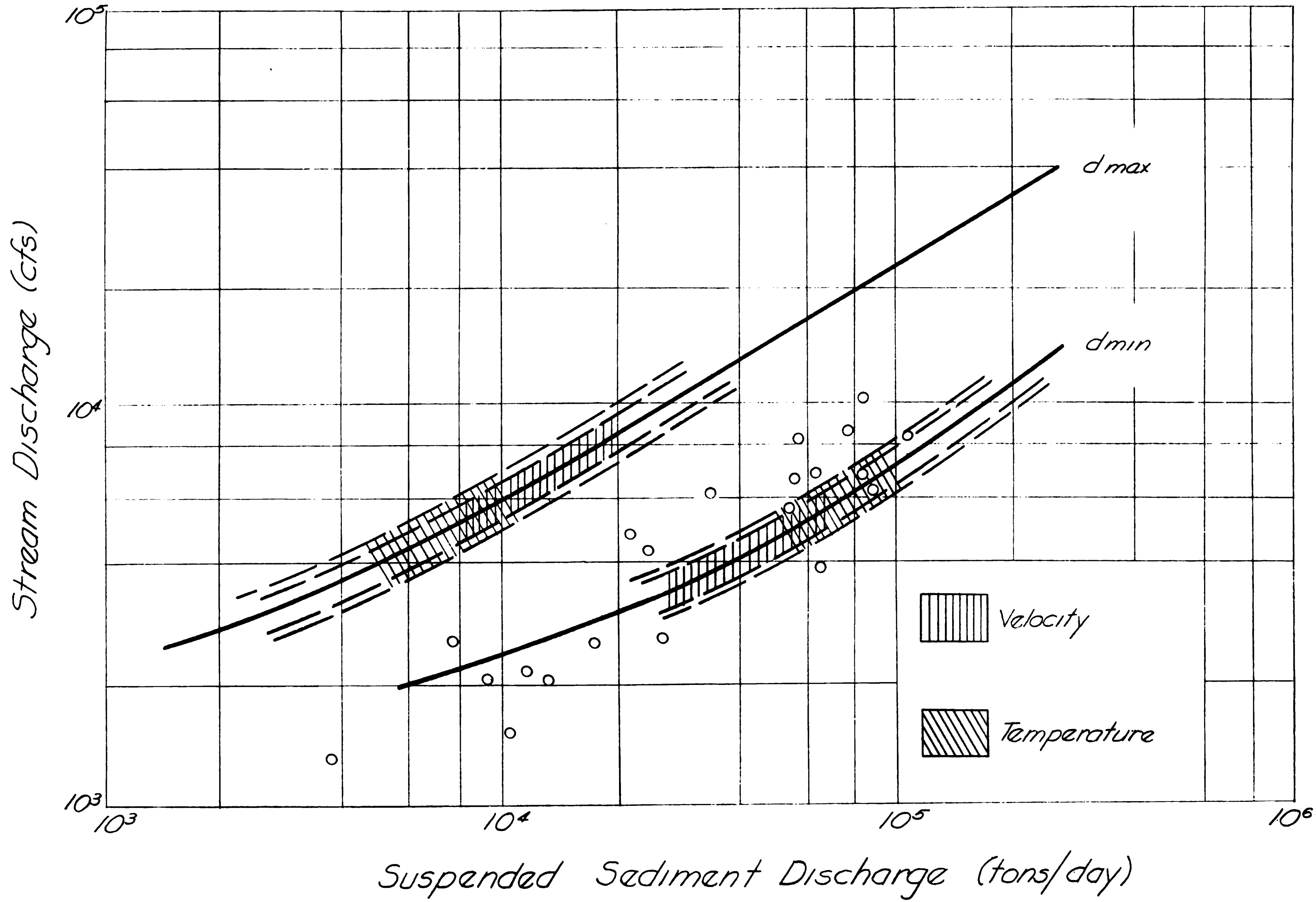


Fig. 13 Sediment Load Rio Grande Near Bernalillo

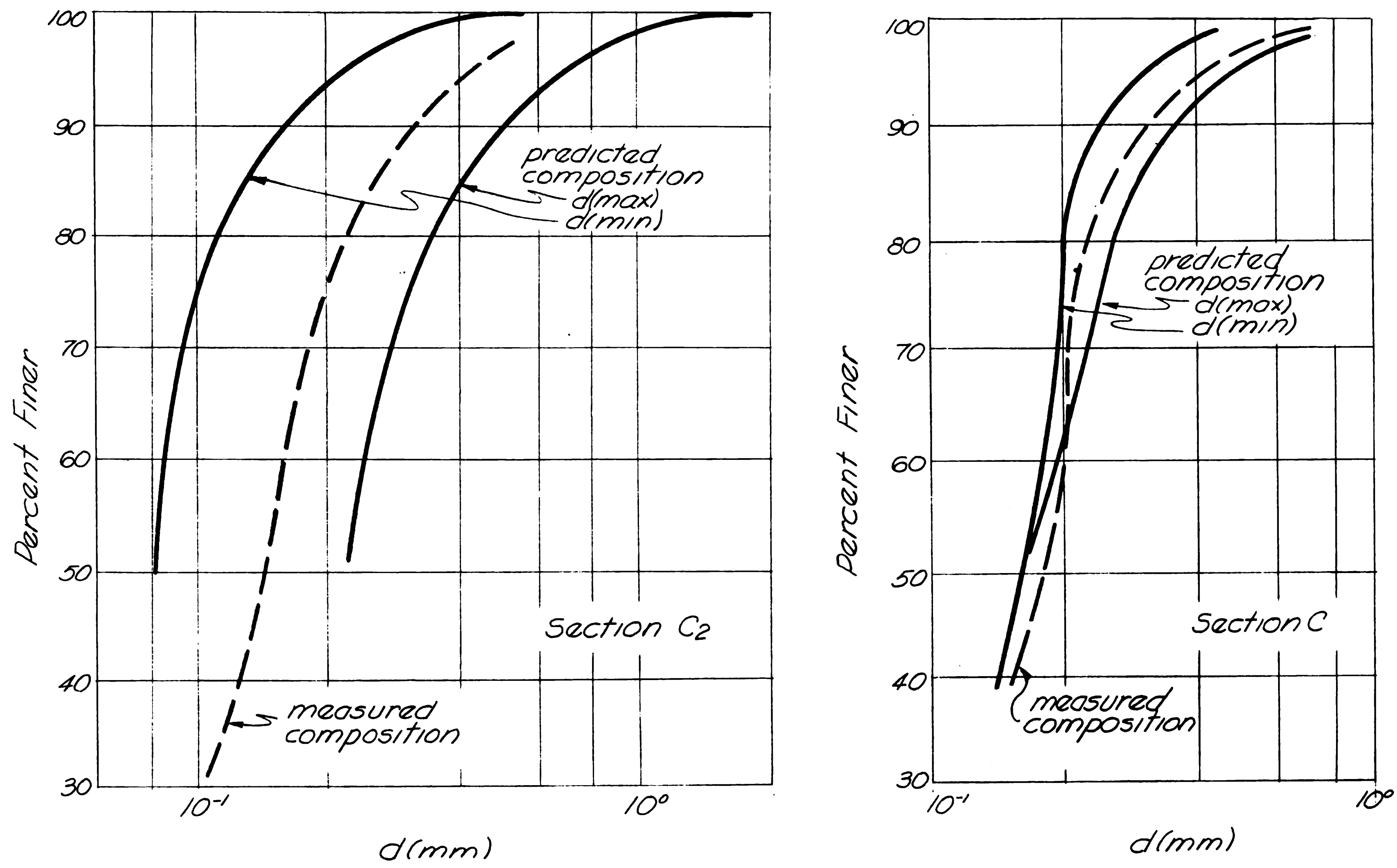


Fig. 14 Predicted Composition of Suspended Load

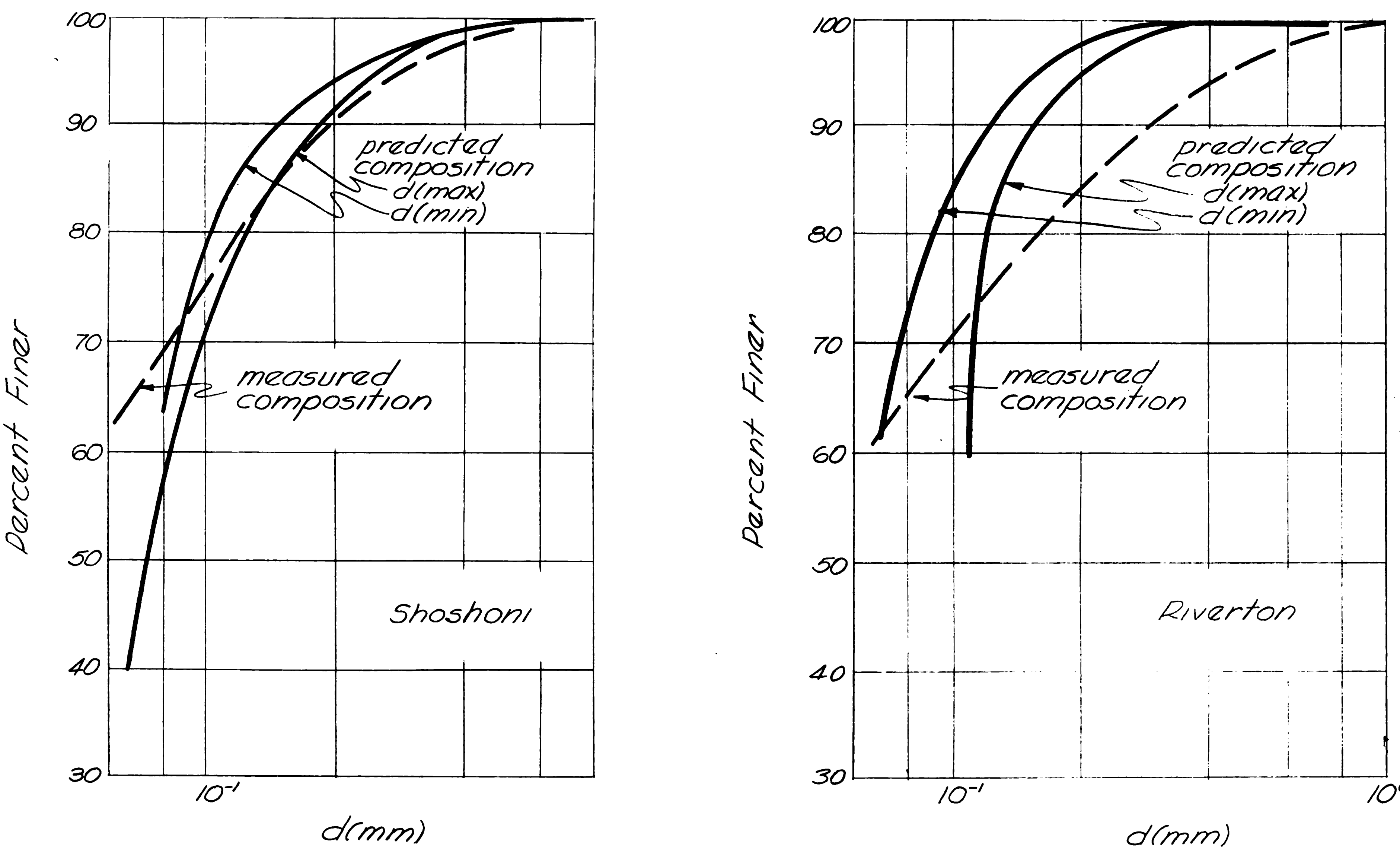


Fig. 15 Predicted Composition of Suspended Load

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