U. S. DEPARTMENT OF THE INTERIOR
U.S. Geological Survey Quality of Water Branch
Water Resources Division
Washington, D. C.

RELATIONSHIP OF SEDIMENT DISCHARGE TO STREAMFLOW

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Open File Report

Prepared by Quality of Water Branch - April 1956

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RELATIONSHIPS OF SEDIMENT DISCHARGE TO STREAMFLOW

By B. R. Colby

ABSTRACT

The relationship between rate of sediment discharge and rate of water discharge at a cross section of a stream is frequently expressed by an average curve. This curve is the sediment rating curve. It has been widely used in the computation of average sediment discharge from water discharge for periods when sediment samples were not collected. This report discusses primarily the applications of sediment rating curves for periods during which at least occasional sediment samples were collected.

Because sediment rating curves are of many kinds, the selection of the correct kind for each use is important. Each curve should be carefully prepared. In particular, the correct dependent variable must be used or the slope of the sediment rating curve may be incorrect for computing sediment discharges.

Sediment rating curves and their applications were studied for the following gaging stations:

1. Niobrara River near Cody, Nebr.
2. Colorado River near Grand Canyon, Ariz.
3. Rio Grande at San Marcial, N. Mex.
4. Rio Puerco near Bernardo, N. Mex.
5. White River near Kadoka, S. Dak.
6. Sandusky River near Fremont, Ohio

Except for the Sandusky River and the Rio Puerco, which transport mostly fine sediment, one instantaneous sediment rating curve was prepared for the discharge of suspended sands at each station, and another for the discharge of sediment finer than 0.062 millimeter. Each curve was studied separately, and by trial-and-error multiple correlation some of the factors that cause scatter from the sediment rating curves were determined. Average velocity at the cross section, water temperature, and erratic fluctuations in concentration seemed to be the three major factors that caused departures from the sediment rating curves for suspended sands. The concentration of suspended sands varied with about the 2.5 power of the mean velocity for the four sediment rating curves for suspended sands. The effect of water temperature was not so consistent as that of velocity and theoretically should vary considerably with differences in the size composition of the suspended sands.

Scatter from the sediment rating curves for sediments finer than 0.062 millimeter seemed to be caused by changes in supply of these sediments. Some of the scatter could be explained by seasonal variations, by a pattern of change in concentration of fine sediment following a rise, or by source of the runoff as indicated by the measured relative flows of certain tributaries.

Daily or instantaneous sediment rating curves adjusted for factors that account for some of the scatter from an average curve often can be used to compute approximate daily, monthly, and annual sediment discharges. Accuracy of the computed sediment discharges should be better than average for streams that transport mostly sands rather than fine sediments and for some ephemeral or intermittent streams, such as the Rio Puerco, in semiarid regions.

Accuracy of computed sediment discharges can be much improved for many streams by shifting the sediment rating curve on the basis of 2 or 4 measurements of sediment discharge per month. Of 26 annual sediment discharges that were computed by shifting sediment rating curves to either 2 or 4 measured sediment discharges per month, 18 were within 10 percent of the annual sediment discharges that were computed on the basis of a daily sampling program. Monthly and daily sediment discharges computed from daily or instantaneous sediment rating curves, either shifted or unshifted, were less accurate than similarly computed annual sediment discharges. Even so, the difference in cost between occasional sediment samples and daily samples is so great that the added accuracy from daily sampling may not justify the added cost.

Monthly and annual sediment-rating curves can be applied simply, with adjustments if required, to compute monthly and annual sediment discharges with reasonably good accuracy for gaging stations like the Rio Puerco near Bernardo, N. Mex. An annual sediment-rating curve seemed to give as satisfactory average sediment discharges for the Colorado River near Grand Canyon, Ariz., for periods of several years as could be computed from daily or instantanteous sediment rating curves.

Unmeasured-sediment discharge of the Niobrara River near Cody, Nebr., varied with about the 3d power of the average velocity at the gaging-station section. An unmeasured-sediment rating curve based on this relationship was used with two other sediment rating curves, one for suspended silt and clay and one for suspended sands, and with daily streamflow records to compute fairly satisfactory daily, monthly, and annual total sediment discharges of the stream for the water year ending September 30, 1949.

INTRODUCTION

At most cross sections of streams, the rate of sediment discharge increases rapidly as the rate of water discharge increases. The general relation between rate of sediment discharge and rate of water discharge at a cross section is usually expressed by an average curve that is called a sediment rating curve. Sediment rating curves in different forms have been widely used. This paper is the report of a brief study of sediment rating curves and possible applications of them.

Purpose and Scope of the Study

The purpose of the study was to analyze sediment rating curves and to evaluate possible uses of them in computing sediment discharges particularly for short periods as contrasted with the more customary usage in computing average sediment discharges for long periods of time. If for certain streams, records of sediment discharge could be computed accurately enough from sediment rating curves and occasional samples, the cost of obtaining sediment records for these streams could be greatly reduced. Perhaps for some streams, sediment rating curves could be applied even without occasional samples to compute sediment records that would be satisfactory for many uses.

Scope of the study was limited to analysis of instantaneous or daily sediment rating curves for 6 sediment stations and monthly or annual sediment rating curves for 2 stations. These stations were selected, within the limits of available and adequate data, in several parts of the United States and on streams of widely differing flow and sediment characteristics. Sediment rating curves, usually both adjusted and unadjusted, were used to compute daily, monthly, and annual sediment discharges at 6 sediment stations for a total of 11 water years. Computations for each water year were made by 1 to 8 different methods.

The analyses and computations indicated some fundamental relationships, involving such factors as velocity and temperature, that were briefly explored because they affect sediment discharge. Possible uses of the sediment rating curve were considered for different kinds of streams.

Many supplementary relationships are pertinent to a sediment rating curve study. Only 1 or 2 of these relationships could be examined even sketchily. These included the sampling error that might be caused by random variations from a representative average concentration, the relation between velocity and unmeasured sediment discharge, and the variation of sediment discharge with temperature.

Published Studies of the Sediment Rating Curve

Sediment rating curves have frequently been applied especially by the Corps of Engineers, Department of the Army, and the U. S. Bureau of Reclamation. However, few reports on studies and applications of the sediment rating curve have been published. Some of the more readily available and helpful papers are mentioned or summarized to give a background of information on developments in the use of the sediment rating curve.

Campbell and Bauder (1940) in a report of sediment relationships for stations in the Red River basin of Oklahoma and Texas pointed out some applications of the sediment rating curve and savings that might result from the applications. Possible applications included computation of sediment discharge for periods before sediment records were obtained and substitution of periodic sediment sampling for daily sampling. They found that some of the sediment rating curves shifted widely from year to year.

Nolan H. Daines (1949) discussed the time trend in the relationship between sediment discharge and water discharge for the Colorado River near Grand Canyon, Ariz. According to Daines, annual sediment discharges that he computed from daily sediment rating curves were not satisfactorily accurate. He also showed curves of annual water discharge against annual sediment discharge and curves of monthly water discharge against monthly sediment discharge for individual calendar months.

C. R. Miller (1951) reported an extensive study of the sediment rating curve for stations on the San Juan River of Utah. The study stressed the computing of average sediment discharge for long periods of time from flow-duration curves and sediment rating curves. The report pointed out a trend, comparable to that for the Colorado River near Grand Canyon, toward decreased sediment concentrations for given rates of water discharge during recent years.

Some aspects of the sediment rating curve and factors relating to sediment discharge are discussed in an interesting paper by Leopold and Maddock (1953).

Personnel and Acknowledgments

The investigation of the sediment rating curve was made by the Water Resources Division of the U. S. Geological Survey under the general supervision of R. B. Vice, chief, Physical Quality Section, Quality of Water Branch.

P. C. Benedict, regional engineer, J. H. Gardiner, district engineer, and J. M. Stow, G. A. Billingsley, W. L. Lamar, and M. E. Schroeder, district chemists, furnished basic data for the study.

J. M. Stow and F. C. Ames, staff engineer, furnished desk space, supplies, and stenographic help.

J. R. Riter, Chief Development Engineer, Bureau of Reclamation, Denver, Colo., arranged for the writer to consult W. M. Borland, head, K. B. Schroeder, assistant head, and C. R. Miller of the Sedimentation Section to see some applications that have been made of the sediment rating curve by the Bureau of Reclamation. This assistance from engineers of the Bureau of Reclamation is gratefully acknowledged.

Some aspects of the sediment rating curve study were discussed with L. B. Leopold, hydraulic engineer, and W. B. Langbein, hydraulic engineer, both of the Technical Coordination Branch, and with F. C. Ames.

DEFINITIONS

This report may be more completely and easily understood by referring to these definitions and explanations of terms.

A sediment rating curve is an average curve that expresses the relationship between rate of sediment discharge and rate of water discharge. In this report, sediment rating curves are assumed to be drawn on logarithmic coordinates.

An instantaneous sediment rating curve is a sediment rating curve that is prepared from simultaneous sediment discharges and water discharges for periods of time so short that changes within the periods do not affect the relationship. Theoretically, such a curve should be used to compute sediment discharges only for very short time intervals, but it is frequently satisfactory for computing daily sediment discharges from daily water discharges.

Daily, monthly, and annual sediment rating curves are sediment rating curves that are based on average rates of sediment discharge and water discharge for periods of days, months, or years, respectively. A sediment rating curve of one of these kinds can rarely, if ever, be substituted for another. However, for some streams, instantaneous and daily sediment rating curves are so nearly the same that in many applications one can be substituted for the other.

A suspended-sediment rating curve is an average curve that expresses the relationship between suspended-sediment discharge and water discharge. Unless otherwise qualified, the expression means a curve for measured suspended-sediment discharge and includes all particle sizes that were included in the sediment samples from which the measured sediment discharge was computed.

A sediment rating curve (fines), a sediment rating curve for discharge of clay and silt, or a sediment rating curve for particles finer than 0.062 millimeter are interchangeable expressions for the relationship of the discharge of particles finer than sand sizes to the rate of discharge of water.

A sediment rating curve (sands) or a rating curve for the discharge of sands are interchangeable expressions for the relationship of the discharge of sediment particles of sand sizes to the discharge of water.

The size classification is the classification that is recommended by the American Geophysical Union Subcommittee on sediment terminology (Lane and others, 1947, p. 937). According to this classification, clay-size particles have diameters between 0.0002 and 0.004 millimeter, silt-size particles have diameters between 0.004 and 0.062 millimeter, and sand-size particles have diameters between 0.062 and 2.0 millimeters.

Measured sediment discharge or measured sediment load is the sediment discharge that is computed from suspended-sediment samples and from water discharge even though the computation may not be direct or precise. These terms are frequently applied in this report to daily, monthly, and annual sediment discharges that normally are computed from daily samples although the sediment discharges for some periods may have been estimated.

Bed load or sediment discharged as bed load is the discharge of the sediment that moves close to the stream bed and is not in suspension.

Unmeasured sediment discharge is the difference between the measured sediment discharge at a cross section and the total sediment discharge at that section. It includes the bed-load discharge and part of the suspended-sediment discharge that is transported between the stream bed and the lowest point of travel of a suspended-sediment sampler.

Control points are measured rates of sediment discharge, either instantaneous or daily, that are used as bases for shifts of a sediment rating curve in much the same way that streamflow measurements are used to define shifts of a stage-discharge relation for a gaging station.

A flow-duration curve or table is a graphical or tabular expression of the time distribution of rates of flow at a place along a stream.

Shifts and shifted refer to changes that are made on the basis of individual measurements of sediment discharge. Adjustments and adjusted refer to changes that are made to correct for factors that correlate to some degree with sediment discharge.

THEORY

Some of the sediment that reaches a stream channel is transported along the stream by the flowing water. Other sediment is eroded from the channel. The finer fractions of the sediment are transported mainly or entirely in suspension through the supporting action of the turbulence of the water and may move to the section without deposition. Coarser particles may also travel in suspension, may be rolled or skipped along the stream bed as bed load, or may be transported alternately by the two methods. The finest sediments move with about the velocity of the flowing water but usually slower than the velocity of the crest of a flood wave. They pass directly with the water from the place of erosion to points downstream with little or no deposition. Much of this reasoning follows that of Einstein, Anderson, and Johnson (1940, p. 628-633). Larger sediment particles are likely to be deposited temporarily or semipermanently at places along the stream. At any time and place on the stream bed the probability of deposit and the probably length of time before moving again are largely functions of particle size. Much of the coarsest sediment may be at rest far more of the time than it is moving. Because some coarse sediments are deposited along the channel, they are likely to be rather uniformly available for pickup throughout the year.

In general, the concentration of both fine and coarse suspended sediments within a given reach of stream channel increases with increasing rate of water discharge. The concentration of fine sediments usually increases because the increase of flow generally results from rainfall or snowmelt that erodes fine sediment from the land surfaces. Some fine sediment may also erode from the streambanks and bed. The concentration of the coarse sediments increases with water discharge principally because velocities tend to be faster and flow more turbulent at the higher rates of water discharge.

Another way of thinking of sediment transport within a particular reach is that the discharge of fine particles is controlled by the available supply of such particles and the supply is generally less than the stream can transport. The supply of the coarser particles is generally greater than the stream can transport, and the discharge of these particles is regulated mainly by the ability of the stream to transport them. Thus, the concentration of the coarser sediments at a section is a function of factors such as velocity and water temperature, which can be measured at a section. The concentration of the finer particles is relatively independent of the flow characteristics at a section because almost any flows are capable of transporting the available fine sediments.

The preceding discussion is, of course, qualitative and relative. It applies to sediment movement within a short reach of channel and not to comparisons between reaches. Most streams carry sediments that range in size from collodial particles to the largest particles that the stream can transport. Only an arbitrary distinction can be made between the particles that will move in general with about the speed of the flowing water, in quantities governed principally by the supply, and those whose concentrations are controlled mainly by the capacity of the stream to transport sediment. The arbitrary distinction will, theoretically, vary from one stream to another and from time to time on the same stream. Also, all particles of a particular size will not be affected to the same relative degree by average characteristics of flow.

The preceding generalized discussion may indicate some of the factors that can be expected to cause variations in the relationship of sediment discharge to streamflow. Velocity of the flowing water will determine to a considerable extent the turbulence of the stream and hence the transporting capacity of each unit of flow. Temperature changes affect the viscosity of the water and partly determine the fall velocities of sediment particles of such sizes that viscous forces appreciably affect their rates of fall. The supply of fine sediments correlates to some extent with the source and rates of runoff.

Also, some streams show changes in discharge of fine sediments with season of the year and with time in relation to peak flows, but these relationships, although they may characterize the discharge of fine sediments of many streams, are not basic relationships of direct cause and effect. The more basic factors merely correlate more or less well with season of the year and with time in relation to peak flows. Each of several factors that affect sediment discharge will be discussed in more detail under the heading "Factors affecting sediment discharge."

Kinds of Sediment Rating Curves

Sediment rating curves may be classified according to either the period of the basic data that define a curve or the kind of sediment discharge that a curve represents. Thus sediment rating curves may be classified as instantaneous, daily, monthly, annual, or flood-period curves. The instantaneous sediment rating curves are defined by concurrent measurements of sediment discharge and water discharge for periods too short to be materially affected by changes in flow or concentration during the measurements. Daily, monthly, annual, and flood-period sediment rating curves usually are defined by and expressed as average sediment and water discharges for periods of days, months, years, or flood periods, respectively. They can be defined by and expressed as total quantities of sediment and water discharges during the respective lengths of time.

On the basis of the kind of sediment that they represent, sediment rating curves may be classified as suspended-sediment rating curves, unmeasured-sediment rating curves, and total-sediment rating curves. These sediment rating curves may be further subdivided according to size of particles for which the defining sediment discharges were computed. In this report, only suspended-sediment rating curves have been subdivided according to particle size, and this subdivision has been into only two parts; namely, sediment rating curves for particles in the range of sand sizes and those for particles in the combined range of clay and silt sizes. To simplify nomenclature somewhat, any sediment rating curve not specifically qualified otherwise is an instantaneous sediment rating curve and also is a suspended-sediment rating curve that is based on measured suspended-sediment discharge of all particle sizes.

The simplest relationship between sediment discharge and water discharge is represented by an instantaneous sediment rating curve. Such a curve is not affected by the extent or pattern of changes in concentration or flow. It is likely to be the most suitable curve from which to determine the effect of different factors on the basic relationship between sediment discharge and water discharge and on departures from this relationship. On the other hand, an instantaneous sediment rating curve is theoretically not applicable to the direct computation of daily sediment discharges from daily water discharges except for days on which the rate of water discharge was about constant throughout the day. Another limitation of such a curve is that instantaneous measurements of sediment and water discharge may be unrepresentative data because these measurements may be made more frequently at times of peak flow or high concentrations than at other times.

Sediment rating curves prepared from the relationship between daily average water discharge and daily average sediment discharge are suitable for computing daily sediment discharges from readily available daily water discharges. Such curves may be prepared from daily sediment and water discharges that are published in Geological Survey water-supply papers.

For some computations of average sediment discharge, a monthly sediment rating curve can be prepared simply and can be applied satisfactorily. Departures from such a curve may be due to either a change in the relationship between sediment discharge and water discharge or to differences in distributions of sediment discharge and water discharge within months. Therefore, monthly sediment rating curves may not be as easy to analyze and adjust as instantaneous or daily sediment rating curves.

Annual sediment rating curves have been used in some studies, partly for convenience and simplicity. Departures from an annual curve may be due to changes in the relative fractions of runoff from different parts of the drainage area or different distributions of runoff with respect to time during different years. If it is reasonably well defined, an annual sediment rating curve may be used to compute as accurate average sediment discharge for long periods of time as can be computed by the flow-duration, sediment-rating curve method. Annual sediment rating curves give a convenient summarization of an average overall relationship between sediment discharge and water discharge and should be maintained currently for most continuing sediment stations. They are not, however, interchangeable with other sediment rating curves.

Instantaneous, daily, monthly, and annual sediment rating curves for the Rio Puerco near Bernardo, N. Mex., are shown on figure 1. The daily and instantaneous curves were defined by information for the same days. These two curves agree within the limits of accuracy of their definition. The monthly sediment rating curve shows more sediment discharge for a given average water discharge than do the instantaneous and daily curves; the annual sediment rating curve indicates even more sediment discharge than the monthly curve. Agreement among these four curves is probably better than for most sediment stations because concentrations do not change as rapidly with changing flow as at most stations and concentrations at a given discharge seem to be less dependent on seasonal effects and on distribution of runoff generation over the drainage area than for many stations. This statement refers to percentage changes.

Unless the sediment transported by a stream is almost all either fine or coarse, separate sediment rating curves, one for the clay and silt particles and another for the particles of sand, should usually be prepared for analysis. Each of these can then be studied separately to determine the significant factors that may cause, or at least correlate with, changes in the relationship of sediment discharge to water discharge. Unfortunately, adequate information on particle sizes and on characteristics of flow is available for only a few stations. This lack of adequate information hinders the analysis and understanding of the sediment rating curve.

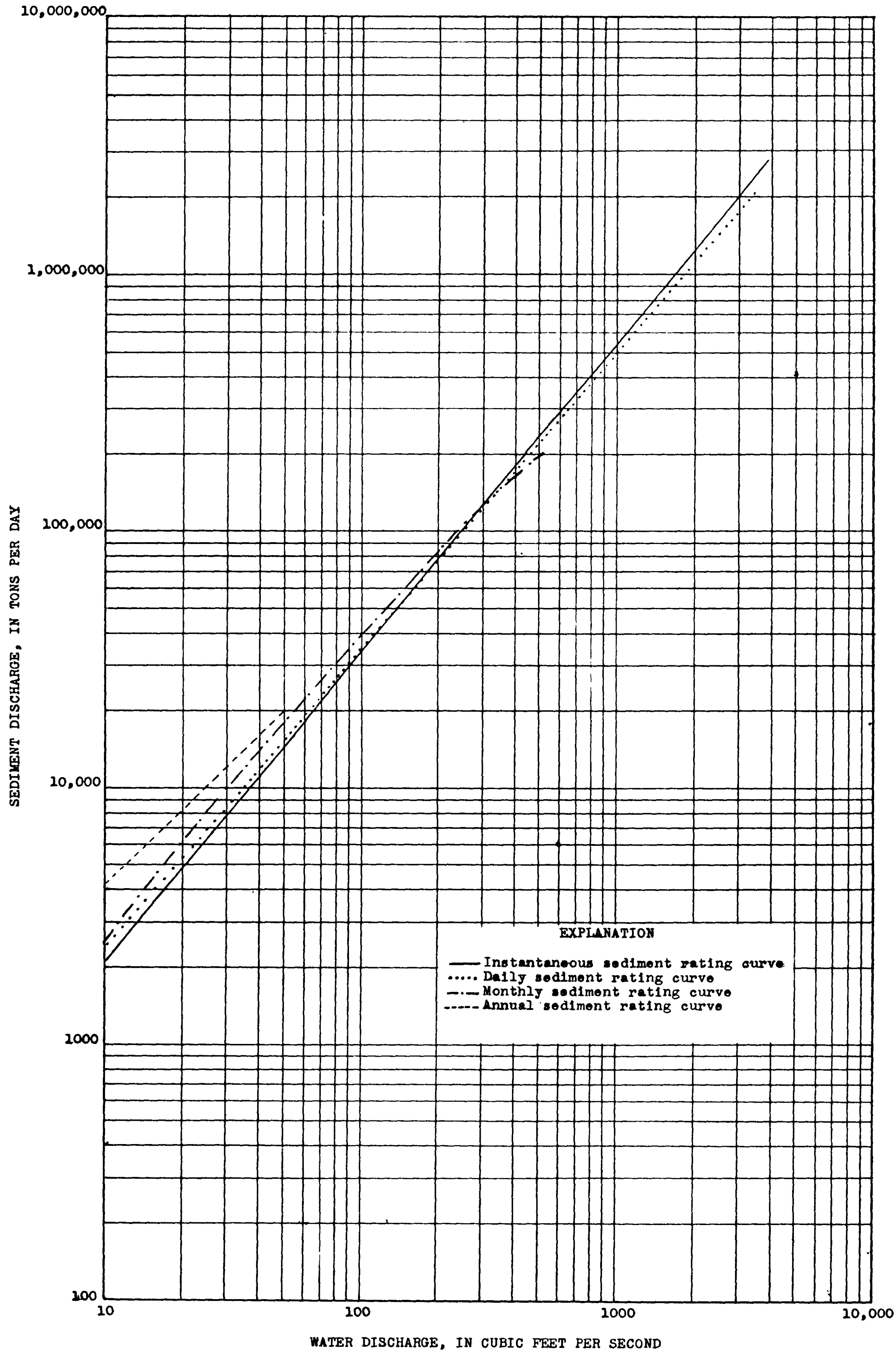

Figure 1.--Rating curves for Rio Puerco near Bernardo, N. Mex.

Another type of sediment rating curve may be distinguished according to method of transport (method of transport is a function of particle size). This type is the sediment rating curve for unmeasured-sediment discharge. Unmeasured-sediment discharge per foot of width usually correlates fairly well with mean velocity and increases with about the 3d or slightly higher power of the mean velocity at some cross sections. (See p. 36-38.) Hence, the unmeasured-sediment rating curve may be fairly stable provided that the relationships between velocity and water discharge and between width and water discharge do not shift appreciably. Presumably, large changes in the size composition of the bed material of a stream might also shift the unmeasured-sediment rating curve.

Preparation of Sediment Rating Curves

Because at most sediment stations water and sediment discharges have wide ranges and the relationship between these discharges departs widely from an average, sediment rating curves are usually plotted on logarithmic coordinates. This practice has certain disadvantages. It tends to obscure the scatter from the average curve and seems to imply an exponential relationship between sediment and water discharge. In spite of these disadvantages, sediment rating curves for this report were all plotted on logarithmic coordinates and references to the slope of a sediment rating curve are to be understood with this restriction.

The first step in the preparation of a sediment rating curve is to decide what is to be accomplished with it. The second step is to find suitable data on which it can be based. The third step is to organize the data and average them in a way that will produce a satisfactorily accurate curve of the right kind for its planned applications.

The first step is essential. Is the sediment rating curve to be used to compute daily sediment discharges from daily water discharges, to determine the average change in water discharge for a given change in sediment discharge, or to study the effect of temperature and velocity on the rate of discharge of sediment? Because sediment rating curves are of many kinds, these and other questions that relate to the intended use of the sediment rating curve should be considered and answered before data are assembled and arranged to define the curve.

After the use of the curve has been decided, suitable data should be obtained, if they can be found, to define the kind of sediment rating curve that is needed. This second step is not so simple as it appears to be. Assume that a sediment rating curve is to be prepared for estimating sediment discharge for a stream that has rapid changes in flow and concentration. Estimates are to be made for short periods when no sediment samples were collected. Instantaneous measurements of concentration and flow are required, and each concentration sample should preferably have been obtained at about the same time that the flow was measured. Frequently gage heights will have to be found for the times of sampling, and rates of flow at these gage heights will have to be computed. Sometimes the required information may be published in connection with analyses of particle sizes, but more often it will have to be obtained from unpublished records.

If a sediment rating curve is to be studied for the effect of channel characteristics on sediment discharge, at least two separate curves should be prepared, one for the discharge of the finer particles and the other for the discharge of the coarser particles. In addition to the instantaneous water and sediment discharges that were required under the preceding assumption, particle-size analyses of the suspended sediment are also needed for the same times as the other information.

The third step, that of organizing and averaging the basic information, is also neither simple nor unimportant.

The preparation of a sediment rating curve from basic data is a problem in fitting a curve to points on a scatter diagram. If the number of points is not too large, all of them can be plotted. From the plotted data, two different types of curves can be drawn to represent the average relationship between flow and sediment discharge. One type, a curve with sediment discharge as the dependent variable and flow as the independent variable, can be used to compute average sediment discharge for a given water discharge or distribution of water discharges. The continuous curve of figure 2 is of this type. The other type, represented by the dashed curve of figure 2, has water discharge as the dependent variable. This type can be used to compute average water discharge for a given sediment discharge or is suitable for studies of the average change in water discharge for a given change in sediment discharge. When based on an assumed population of points that scatter as widely as in figure 2, curves of the two types differ greatly at the upper and lower

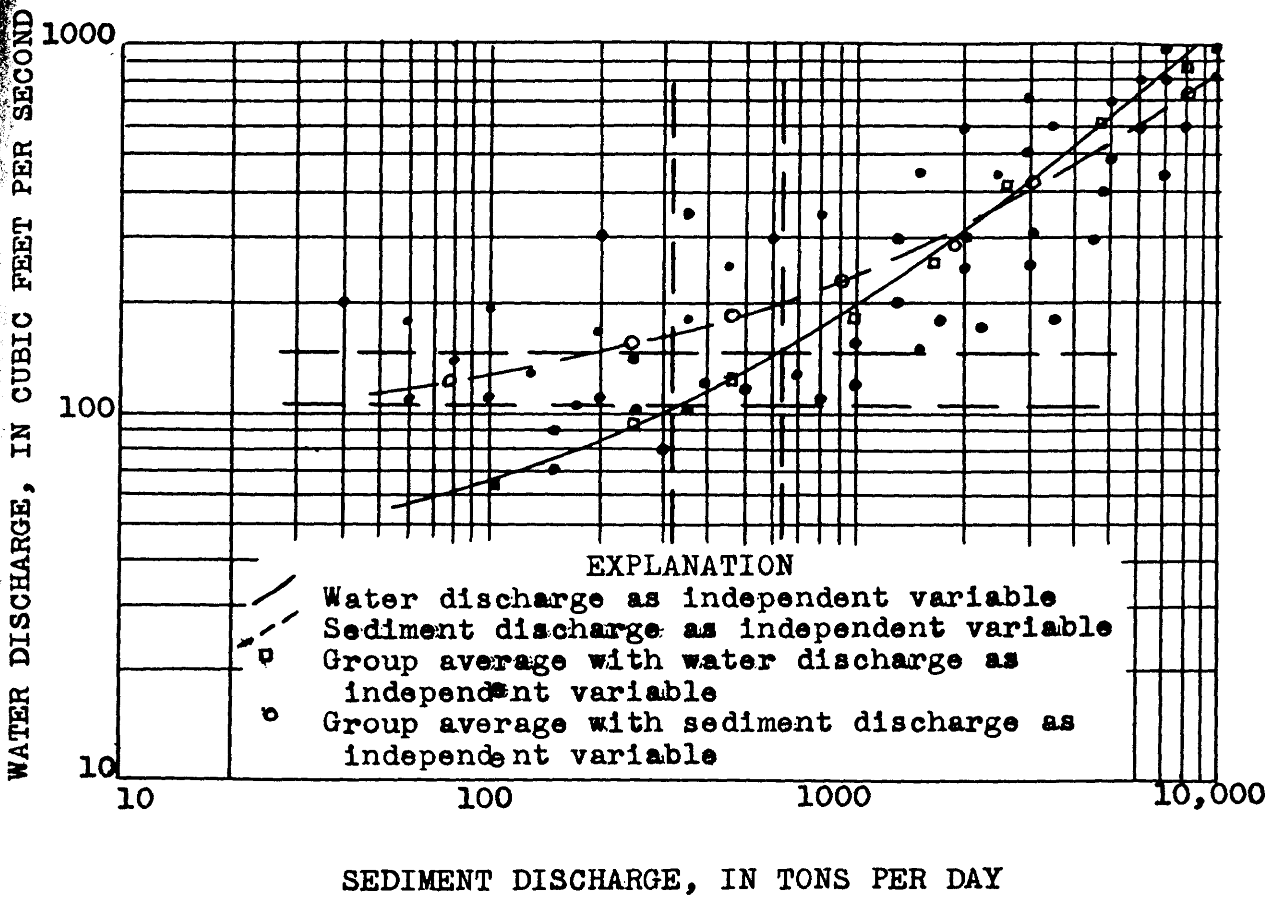

Figure 2 .--Comparison of curves based on the same data but with different independent variables.

ends. The assumed population of points of figure 2, approximates, but probably somewhat exaggerates, the scatter that may occur in the plotting of sediment discharge against water discharge for some streams in semiarid regions.

The terms "dependent variable" and "independent variable" are used in their statistical meanings, which do not necessarily imply a relationship of cause and effect. No knowledge of statistics is needed to understand the significance of the essential distinction between the dependent and the independent variable, but for those who wish it, a good discussion of the two terms is given by Ezekiel (1950, p. 50-51).

The difference between the two curves of figure 2 is due to the difference in method of averaging. As a basis for the continuous curve, the average sediment discharge was computed for each of eight classes, or ranges, of water discharge. Two dashed horizontal lines mark the upper and lower limits of water discharge for which one group average was computed. The group averages of water discharge and of sediment discharge of all points between these two lines were computed and are represented on figure 2 by a small square. Seven other squares were similarly located. The squares determine the position of the continuous curve. Such a curve represents average sediment discharges for given water discharges; that is, the dependent variable is sediment discharge.

The positions of each of the seven small circles of figure 2, and consequently the position of the dashed curve, were determined by averaging the water and sediment discharges of all the points that lie within each of the seven selected ranges of sediment discharge. For example, the points lying between the two dashed vertical lines of figure 2 represent an average water discharge of about 190 cubic feet per second and an average sediment discharge of about 470 tons per day. The amount of the spread between the two curves depends on the scatter of the individual points.

Neither the upper nor the lower end of a curve with water discharge as the dependent variable should generally be used to compute discharges of sediment. However, either curve of figure 2 can be used with the distribution of water discharges that is represented by the plotted points of figure 2 to compute average discharge of sediment for that distribution of water discharge. Distribution of the computed sediment discharge between high and low flows will, however, be incorrect. The dashed curve should not be applied to compute average sediment discharge for any period that has a different distribution of water discharge than that implied by the basic data of figure 2. Upward or downward extension of the dashed curve will give inaccurate sediment discharges.

If a sediment rating curve is to be prepared from more points than can be conveniently plotted, group averages may be computed before plotting. Of course these averages must be for groups of data that are selected in accordance with proper choice of the independent and dependent variable.

When an average curve is drawn through data that are plotted on logarithmic coordinates, care must be exercised to weight the points correctly and not to be misled by the distortion inherent in the logarithmic scale.

General Applications of the Sediment Rating Curve

The many uses of sediment rating curves may be classified into a few general types, but the variations and modifications within the general types are nearly endless. Some general applications have been commonly used whereas others are relatively rare. This report deals mainly with the application of sediment rating curves to computing daily, monthly, and annual sediment discharges at streamflow stations where at least occasional sediment samples are available.

One of the most frequent uses of the sediment rating curve is to compute an average sediment discharge for a long period of time during most of which records of sediment discharges were not obtained but records of water discharge were available. Daines (1949) and Miller (1951) discussed this type of usage. For convenience the streamflow records are usually grouped in the form of a flow-duration curve or table. The flow-duration curve or table is used to determine the percentage of time that the flow was within each of several ranges of water discharge. For each range of water discharge, the average flow is multiplied by the corresponding sediment discharge and by the percentage of time that the flow is within the range. The products are then added, divided by 100, and multiplied by an appropriate constant if necessary to obtain the average sediment discharge per day or per year for the period of time that was covered by the flow-duration curve.

This flow-duration, sediment-rating curve method of computing average sediment discharge is only a convenient shortcut to the computation of average sediment discharge from a sediment rating curve and daily water discharges. It contains the inaccuracies and uncertainties of sediment discharges that are computed from the sediment rating curve and daily water discharges plus the added small and usually insignificant error that results from averaging water discharges and from multiplying averages. The method generally is accurate within about the limits of the sediment rating curve on which it is based. Average sediment discharges computed by this method should be satisfactorily accurate unless the sediment rating curve was incorrectly prepared or was applied to periods for which it did not represent approximately the relationship between sediment and water discharges.

Another general application of the sediment rating curve is in the computation of daily sediment discharges either for long periods of time or for short periods during which no samples were collected. Usually such computed daily sediment discharges are subject to appreciable errors because of variations from the average relationship between sediment discharge and water discharge. The errors should be generally compensating over a period of time.

One common use of sediment rating curves is as a guide to interpolation of sediment discharge or concentration between times of relatively frequent sediment sampling. Such usage of the sediment rating curve with suitable shifts is generally accepted as far preferable to interpolation by guess.

Rarely, sediment discharge for long periods of time has been computed from annual sediment rating curves or from monthly sediment rating curves. This sort of computation is easy to make and adjustments can readily be applied for assumed, but usually questionable, trends in the relationship between sediment discharge and water discharge. It makes full use of all complete water years of sediment records for the computation of long-time average sediment discharge. The accuracy of computed sediment discharges depends on the stability of the sediment discharge-streamflow relationship.

Rating curves can be shifted on the basis of occasional sediment samples in a manner comparable to the shifts of the stage-discharge rating curve in the computation of water discharges from a gage-height record. Adjustments to sediment rating curves can be based on changes in water temperature or on changes in the relationship between velocity and water discharge because the discharge of coarse sediments is determined largely by velocity and partly by water temperature. Adjustments for seasonal effects and for variations in the distribution of precipitation or runoff over the drainage basin may also be made.

Specific examples of analysis of sediment rating curves and the applications and shifting of these curves will be discussed for several sediment stations.

NIOBRARA RIVER NEAR CODY, NEBR.

Sediment rating curves of the Niobrara River near Cody, Nebr., were selected for study for several reasons. The sediment discharge is largely in the sand sizes so the discharge of particles of the sand sizes could be readily studied. Suitable data of concurrently determined flow, size analyses, and concentrations were easily available, and scatter from the average suspended-sediment rating curve was known to be relatively small. Streamflow measurements and sediment samples were collected at about the same section whether the flow was high or low. Also, information was available from which to prepare an unmeasured-sediment rating curve. Such information was not available for any other sediment station that was included in the study. The unmeasured-sediment discharge, although undetermined, would be a much lower fraction of the total sediment discharge at these other sediment stations than at the station near Cody.

Most flow of the Niobrara River at the gaging station near Cody is ground-water discharge from the sandhills area of Nebraska. The flow is very constant, being between 250 and 400 cubic feet per second about 75 percent of the time. At normal flow the measuring and sampling section at the gaging station is about 70 feet wide and averages about 2 feet deep. The mean velocity in the section averages about 3.0 and 3.5 feet per second for flows of 300 and 400 cubic feet per second, respectively. The water surface slope near the gaging station averages about 8 feet per mile.

The suspended sediment that is transported is mostly sand in the size range from 0.062 to 0.25 millimeter. More than 85 percent of the bed material at the sampling section near the gage is in the size range from 0.125 to 0.50 millimeter. At discharges above about 3,000 cubic feet per second the percentage of silt and clay increases rapidly with increases in flow. Only about half of the total sediment discharge is measured at the gaging station section at normal flow.

Analysis

Instantaneous sediment discharges were plotted against instantaneous water discharges for 168 times from December 1947 to July 1953. (See fig. 3.) As for all sediment rating curves in this study, sediment discharge was used as the dependent variable, and an average curve of relationship between sediment discharge and water discharge was drawn. Individual sediment discharges of figure 3 were divided by the corresponding average sediment discharges from the curve. Then these quotients expressing departure from the curves (hereafter called ratios of departure) were plotted against water temperature and were found to vary with about the cube root of the water temperature. A trial plotting of these same ratios of departure against mean velocity indicated some correlation. Departures from this latter graph as well as from earlier average curves indicated a relationship between sediment discharge and the percentage of silt and clay in the measured suspended sediment.

After these trial plottings, the ratios of departure from the sediment rating curve were next correlated successively with the three variables of water temperature, velocity departures from the average velocity for the given water discharge, and a measure of the size distribution of the measured sediment discharge. As this general method was used throughout the analyses of the different sediment rating curves, a more detailed explanation will be given.

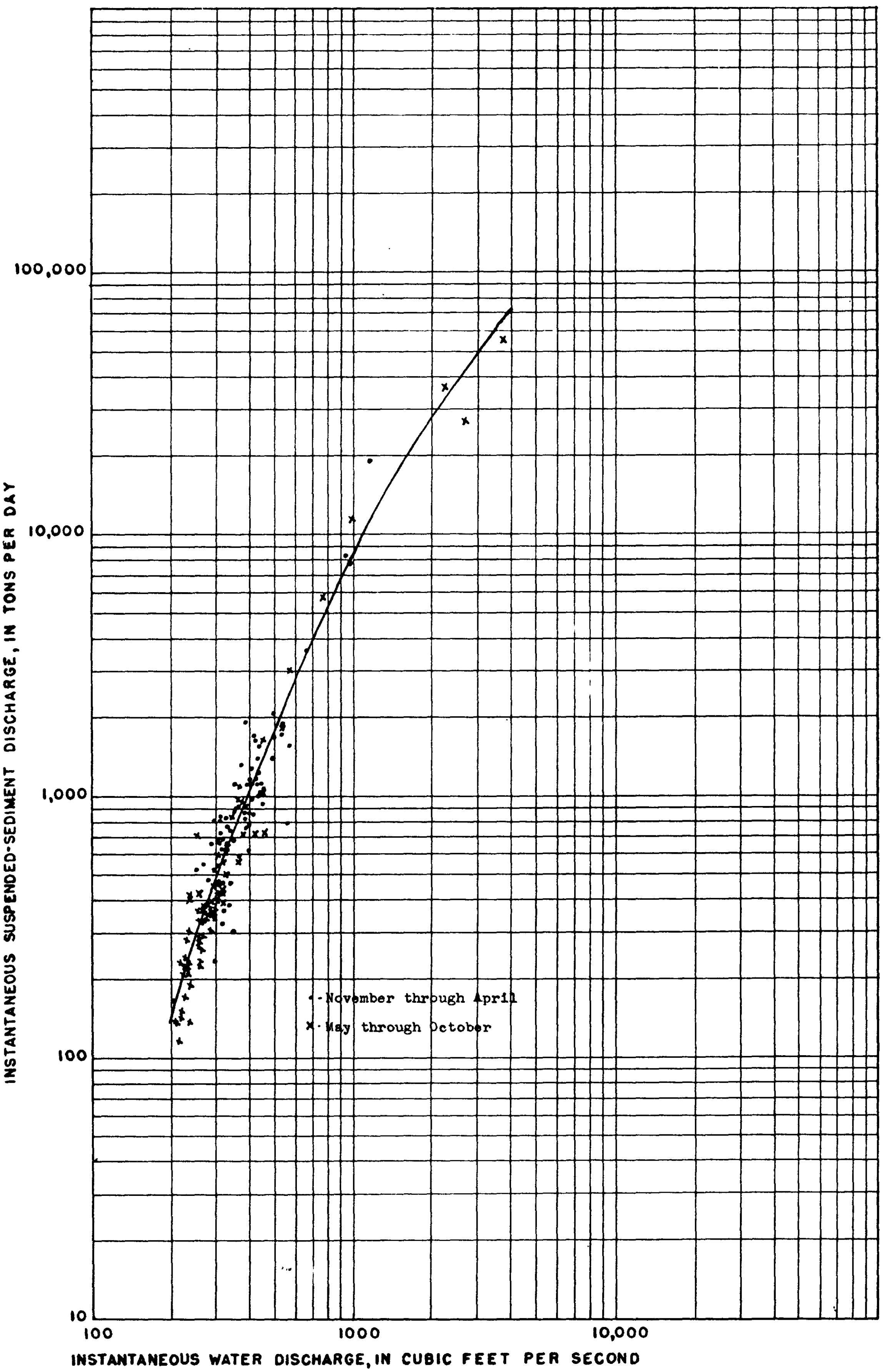

Figure 3.-- Sediment rating curve for the Niobrara River near Cody, Nebr.

The theory of the trial-and-error method of multiple correlation is to eliminate the approximate effect of one variable that has a large effect by plotting the dependent variable against it. The departures from this average curve are next plotted against another independent variable to see if part of the scatter is attributable to this second independent variable. An average curve is drawn. Departures from this curve are plotted against a third independent variable to see whether part of the remaining scatter is explainable in terms of the third independent variable. This process is continued for all the independent variables that are included in the study. Then the departures from the final relationship are again plotted against the first independent variable to see whether an adjustment in the first approximate relationship with the first independent variable will explain any significant amount of the hitherto unexplained scatter from the correlation curves. For some types of correlation, of which the study of sediment rating curves is one, the plotting is conveniently done on logarithmic coordinates. Departures from the average curves can be measured readily in percentage or as ratios. The slopes of the lines of correlation indicate the exponential variation of one variable with another.

This general procedure was applied in analyzing the suspended-sediment rating curve for the Niobrara River near Cody. First, for each plotted point of figure 3, a ratio was computed by dividing observed sediment discharge by the sediment discharge that the rating curve indicated for the given water discharge. Because the data were incomplete, less than half these ratios could be used throughout all the correlations. These ratios were plotted against the percentages of the sediment discharge that consisted of particles finer than 0.062 millimeter. An average curve was drawn. Ratios of departure of sediment discharge were computed from the second average curve. Then these second ratios were plotted against water temperature, and a third average curve was drawn. Ratios of departure from this third average curve were plotted against the ratio of velocity at the time of sampling to average velocity for the water discharge at the time of sampling. This plotting defined a fourth average curve. Ratios of departure from this fourth curve were plotted against water discharge to see what changes might be indicated in the original suspended-sediment rating curve. Finally, ratios of departure from the last average curve were plotted against time of the year to define any significant seasonal relationships.

The analysis of the suspended-sediment rating curve for sediment of all sizes seemed to show that the discharge of fine sediment correlated with different factors than did the discharge of suspended sands. Hence, two instantaneous sediment rating curves were prepared, one for the discharge of suspended sands and the other for the discharge of sediment finer than 0.062 millimeter. Each of these sediment rating curves was analyzed separately. The departures from the rating curve for sands correlated significantly only with water temperature. The average line that represented the correlation had a negative slope of about 3/4. (See fig. 4.) Probably because velocity has a fairly good relationship to water discharge at this cross section, the departures of the discharge of sands from the average curves did not define adequately a

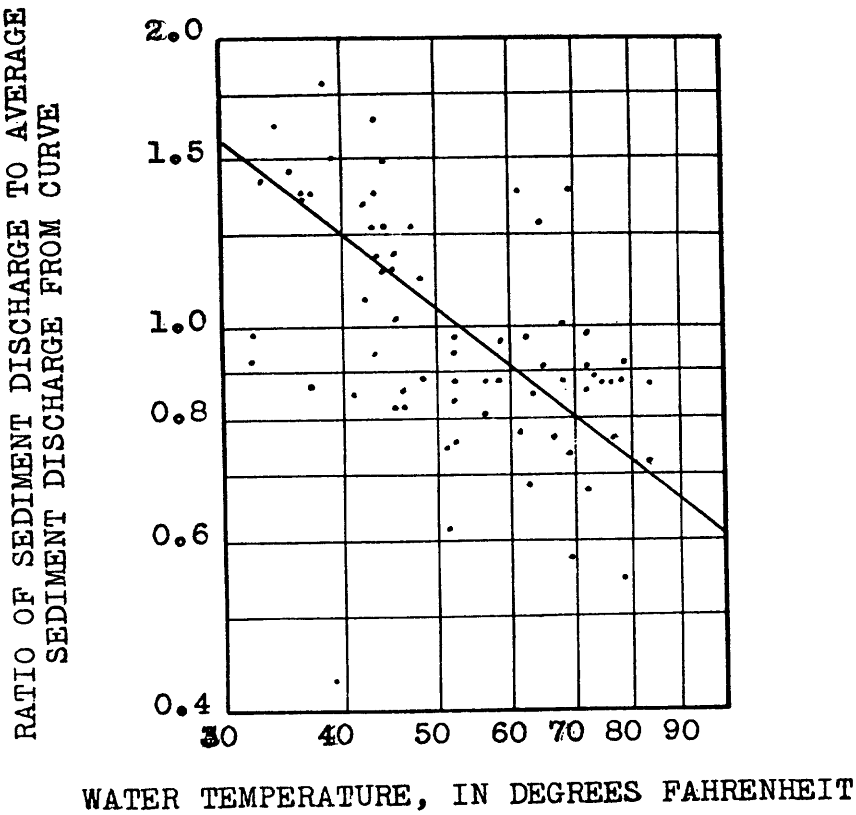

Figure 4.-- Relationship between ratios of departures from sediment rating curve for sands and water temperature, Niobrara River near Cody, Nebr.

correlation with departures of velocity from an average curve of velocity versus water discharge. Also, the small differences in velocity at the measuring and sampling section may have been so localized as to have no clearly defined effect on the discharge of suspended sands.

The analysis of the sediment rating curve for the silt and clay indicated that the original assumption for this sediment rating curve required a little adjustment at both ends of the curve. That is, adjustments for seasonal effects changed the positions of the points that defined the upper and the lower ends of the sediment rating curve (fines) enough to shift the ends of the curve slightly. The sediment rating curve (fines) of figure 5 contains this adjustment. Seasonal adjustments to the discharge of clay and silt roughly defined the dashed line of figure 6. During the fall and early winter and from February through May, the discharge of fine sediment tended to be less than average for a given rate of flow. Summer storms in August and September probably accounted for the generally higher than average discharges of clay and silt during these months. For comparison, the ratios of departure of the discharge of sands from the average curves are also shown on figure 6. No seasonal trend is definitely shown for the discharge of suspended sands, but an adjustment had already been applied for the average effect of water temperature on the discharge of suspended sands. This temperature adjustment was generally in the opposite direction from the seasonal correction for discharge of fine sediment.

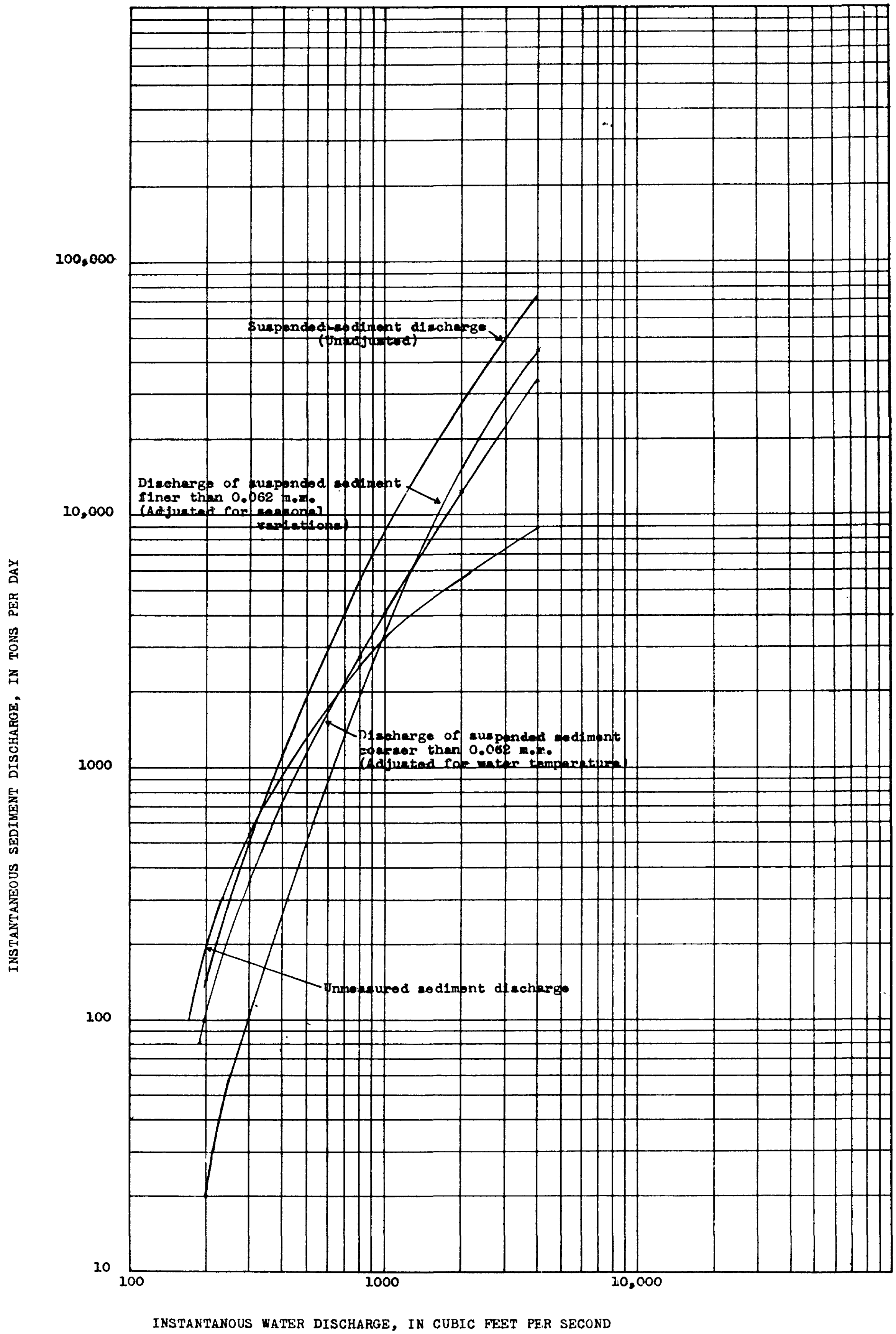

Figure 5.-- Sediment rating curves for the Niobrara River near Cody, Nebr.

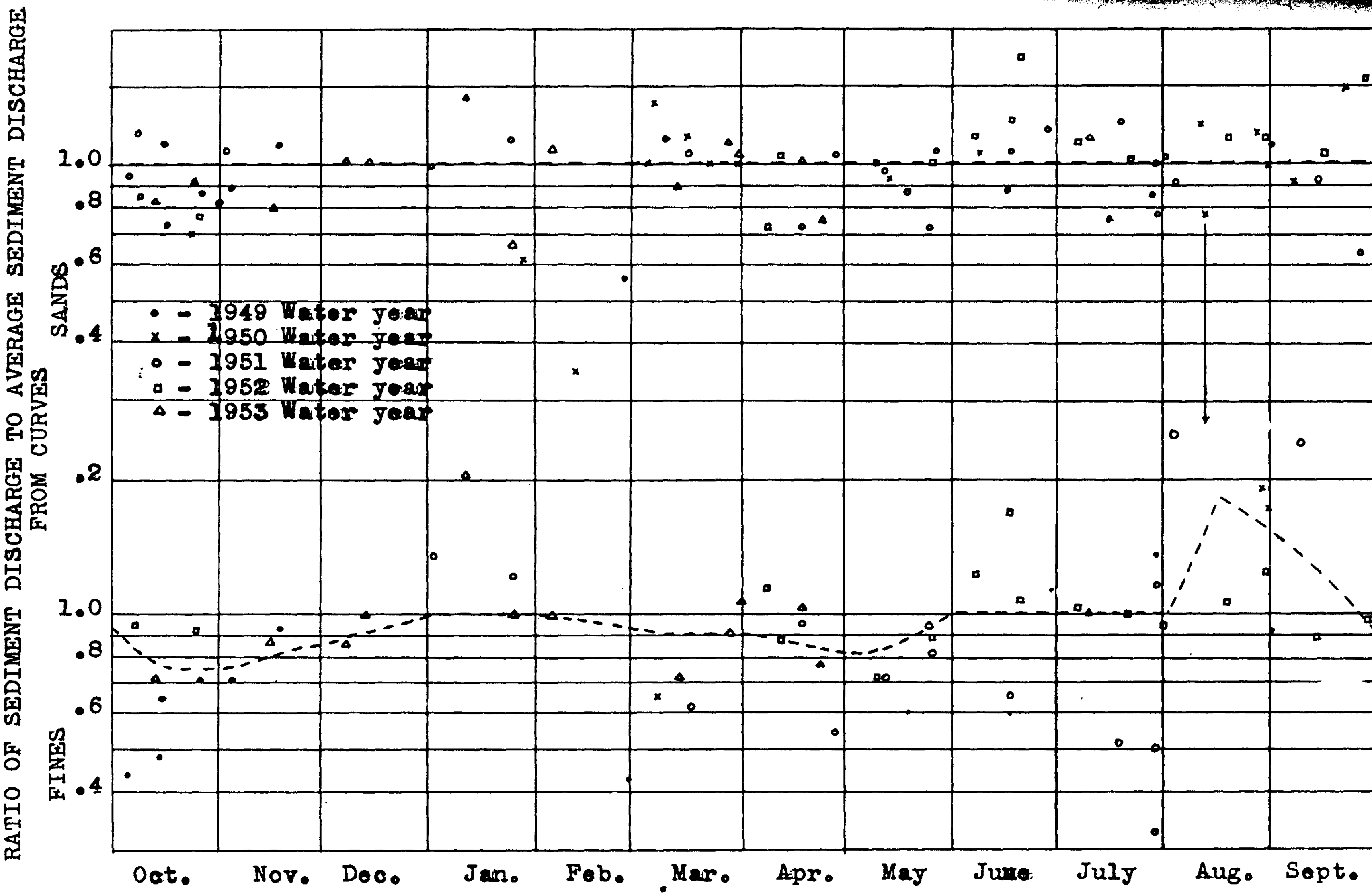

Figure 6.--Seasonal variation of ratios of departure of sediment discharge, Niobrara River near Cody, Nebr.

An instantaneous unmeasured-sediment rating curve also was prepared for the gaging-station section of the Niobrara River near Cody. Total sediment discharges as computed by the modified Einstein procedure (Colby and Hembree, 1955, table 34) were listed for eight times during the water years 1950, 1951, 1952, and 1953 for the gaging-station section. Measured suspended-sediment discharges at the same section and the same times were subtracted from the computed total sediment discharges. The differences, the unmeasured-sediment discharges, per foot of width were plotted against mean velocity in the cross section. (See fig. 7, left graph.) The scatter from the average line is remarkably small and is probably partly fortuitous and partly a result of the method of computation. For most sediment stations the scatter from the average relationship is greater than shown on the left graph of figure 7.

Unmeasured-sediment discharges were next computed by subtracting measured suspended-sediment discharges at the gaging section from nearly total sediment discharges as measured at a contracted section about 1,900 feet downstream from the gaging-station section. These unmeasured-sediment discharges were divided by the stream width and were plotted against mean velocity (fig. 7, middle graph). The average line so defined was almost the same as the average line of the upper graph. The greater scatter of points from the average line was probably partly due to random variation in the measured sediment discharges and to temporary net scour or fill between the two sections.

The slope of the average lines of figure 7 indicates that the computed unmeasured-sediment discharge per foot of width varies

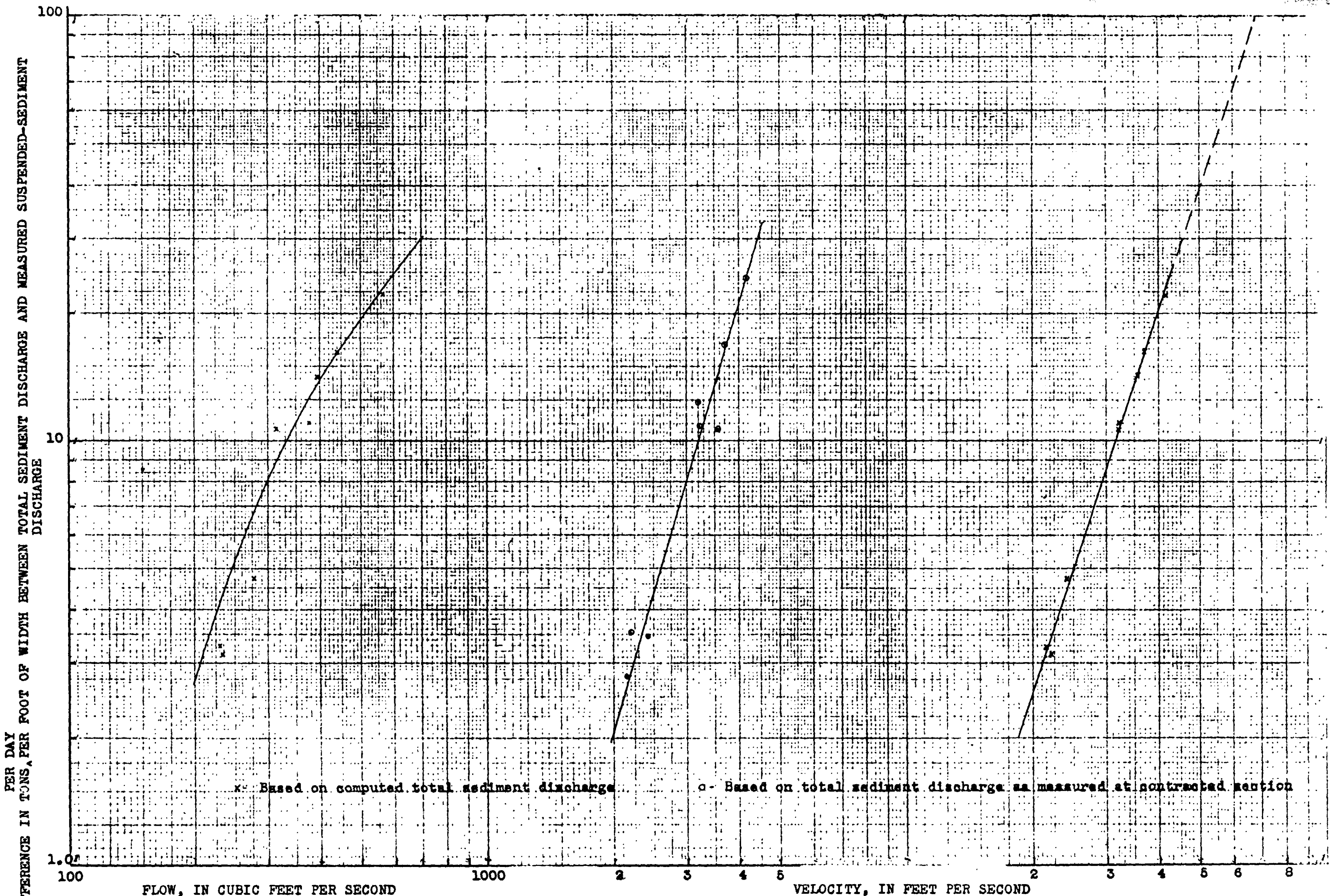

Figure 7.--Variation of unmeasured-sediment discharge per foot of width with mean velocity and with water discharge, Niobrara River near Cody, Nebr.

as about the 3.1 power of the velocity.

A curve of average velocity versus water discharge (fig. 8) was prepared. This curve together with the line from the left graph of figure 7 defines an unmeasured-sediment rating curve. (See fig. 7, right graph, and fig. 5.)

On figure 5 are shown the instantaneous sediment rating curves for measured suspended sediment finer than 0.062 millimeter, for measured suspended sands, for unmeasured-sediment discharge, and for measured suspended-sediment discharge of all particle sizes. The last curve represents approximately (it was determined independently of the other curves) the sum of the sediment discharges from the two rating curves for suspended fine sediments and for suspended sands.

The slope of the curve for sediment finer than 0.062 millimeter indicates a variation of concentration with about the 3.5 power of the velocity although the relationship is not close throughout the entire range of water discharge. Slope of the sediment rating curve for suspended sands shows good agreement between concentration of the sands and the 2.5 power of the velocity. Because the width of the cross section is practically constant, except at unusually high flows, the area through which unmeasured sediment discharge occurs does not change appreciably with stage. Unmeasured-sediment discharge correlates closely with the 3.1 power of the mean velocity in the cross section. At this section it increases less rapidly with increasing flow than the suspended-sediment discharge.

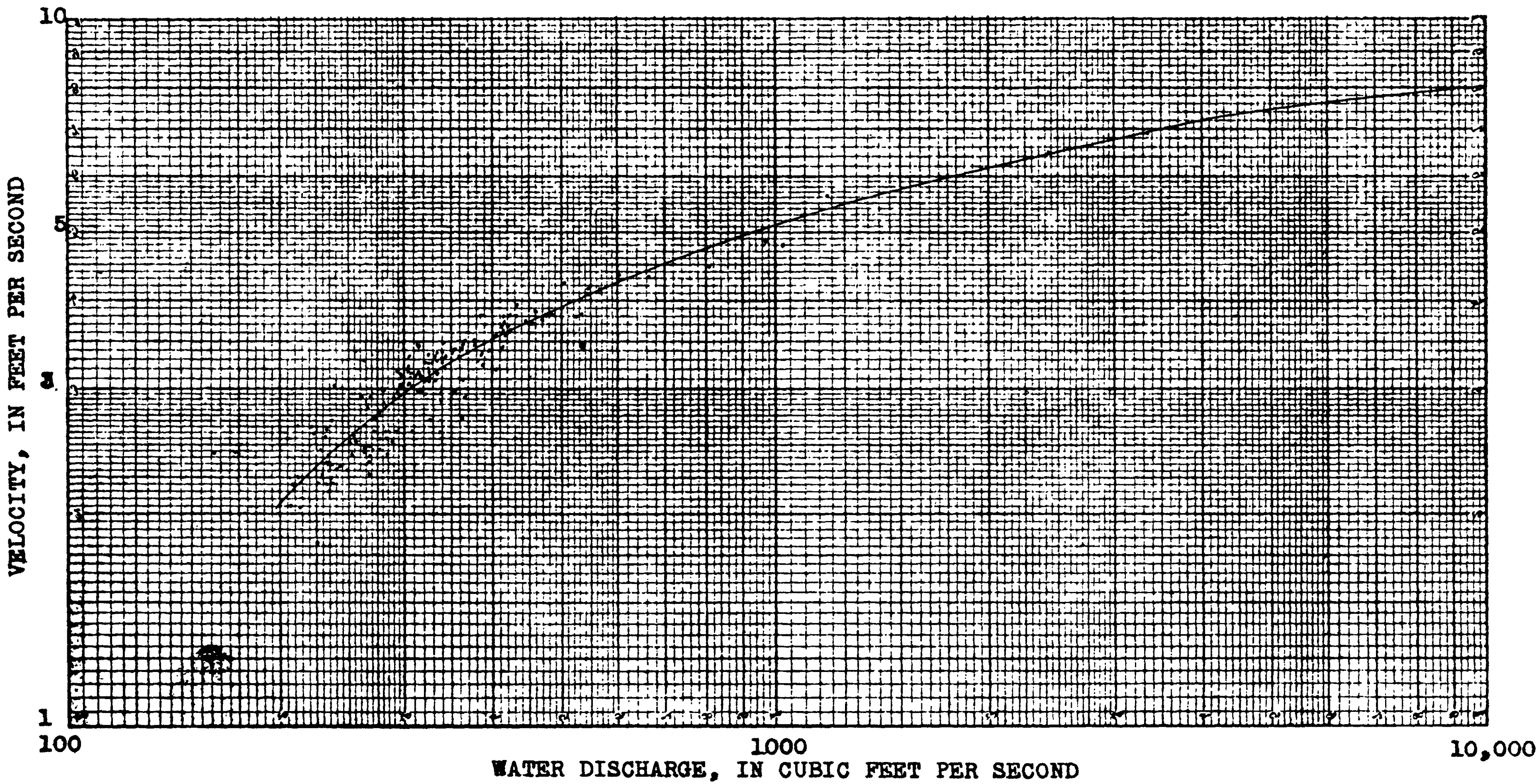

Figure 8 .--Mean velocity versus water discharge, Niobrara River near Cody, Nebr.

Applications

Daily sediment discharges for the gaging-station section during the 1949 water year were computed from three of the sediment rating curves of figure 5 and daily water discharges. The seasonal adjustment of figure 6 was applied in the computation of the suspended-sediment discharge of particles finer than 0.062 millimeter. The adjustment of figure 4 for water temperature was used in the computation of the discharge of suspended sands. Unadjusted daily discharges of unmeasured sediment were computed from the unmeasured-sediment rating curve and daily water discharges. These figures were adjusted for the 3.1 power of departures of velocity from the curve of figure 8. Velocity departures were computed from streamflow measurements and were estimated between streamflow measurements by interpolation, partly on the basis of changes in water discharge.

Monthly and annual sums (table 1) were obtained from the daily discharges of each of the three kinds of sediment discharge. Relative percentages of the different kinds of sediment discharge varied appreciably from month to month. For the 1949 water year, the unmeasured-sediment discharge was 44 percent and the discharge of suspended clay and silt was 18 percent of the computed total sediment discharge. During some months the computed unmeasured-sediment discharge was more than half of the total computed sediment discharge.

Although the three sediment rating curves were prepared from instantaneous water and sediment discharges, they were used to

Table 1.--Sediment discharges, in tons, computed from three sediment rating curves for the gaging-station section of the Niobrara River near Cody, Nebr., for the 1949 water year

Kind of sediment discharge	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year
Suspended fines	2,380	3,750	2,950	2,700	27,700	45,700	6,370	8,740	4,800	1,820	2,180	2,030	111,000
Suspended sands	10,600	17,900	14,200	13,100	32,300	68,500	21,300	21,600	12,200	5,400	5,180	6,370	229,000
Unmeasured load	18,400	22,700	18,600	15,200	28,200	56,700	29,600	33,800	17,800	9,280	9,420	10,100	270,000
Total........	31,400	44,400	35,800	31,000	88,200	171,000	57,300	64,100	34,800	16,500	16,800	18,500	610,000

Table 2.--Monthly and annual sediment discharges, in tons, as computed by different methods for the Niobrara River near Cody, Nebr., for the 1949 water year

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
Method 1.........	32,000	41,100	37,100	16,000	73,800	205,000	63,000	69,000	44,600	20,300	18,400	22,100	642,000	100
Method 2.........	31,400	44,400	35,800	31,000	88,200	171,000	57,300	64,100	34,800	16,500	16,800	18,500	610,000	95
Method 4.........	31,400	44,400	35,800	31,000	88,200	171,000	57,300	67,400	46,500	20,900	18,900	19,900	633,000	99
Method 5.........	31,400	44,400	35,800	31,000	83,500	171,000	63,500	72,700	41,000	21,100	18,500	21,100	635,000	99

Method 1: Daily samples (records published in Water-Supply Paper 1162, p. 496-497.)
Method 2: Adjusted sediment rating curves. (See table 1.)
Method 4: Adjusted sediment rating curves with shifts to two daily measured sediment discharges per month.
Method 5: Adjusted sediment rating curves with shifts to four daily measured sediment discharges per month.

compute daily sediment discharges. Such a practice is generally satisfactory for a stream with as constant flow as that of the Niobrara River near Cody. Theoretically, the use of instantaneous sediment rating curves should give somewhat too low computed sediment discharges during periods of changing sediment concentration and flow. This conclusion follows from the fact that the sum obtained by integration of the products of water discharge and sediment concentration throughout individual days of changing flow will usually be larger than the product of the sediment concentration that will, on the average, accompany the water discharge that is equal to the average flow for the day.

Computed total sediment discharges for the gaging-station section were compared by days, months, and for the 1949 water year with measured sediment discharges (U. S. Geol. Survey, 1954, p. 496-497) at the contracted section about 1,900 feet downstream. (See table 2.) Approximately the total sediment discharge of the river was measured at this contracted section. For half the months the difference between the sediment discharges for the two sections is less than 10 percent. For the entire water year the difference is 5 percent. Comparatively large differences between the sediment discharges for the two sections during January and February may be due partly to long periods without samples at the contracted section. Also, sediment discharges computed from the sediment rating curves may be considerably in error during these winter months. In general the sediment discharges from the rating curves for the summer months seem to be too low. Perhaps the adjustment, which was poorly defined, for seasonal variations in the discharge of the fine sediments should be revised. The flow during March was considerably above normal and may have increased the supply of fine material in the channel for a long time. Perhaps some of the difference was due to the somewhat questionable cross-section coefficients that were applied in the computations of the sediment discharge at the contracted section during the summer.

Daily computed sediment discharges from the rating curves for the gaging-station section are plotted on plate 1. Also plotted are the daily published sediment discharges for the contracted section. In general the agreement of the daily sediment discharges is reasonably good although for some periods, especially during the middle of the winter and again during the summer, the computed sediment discharges tend to be consistently high or low. Some of the published sediment discharges that are far out of line with adjoining days probably are less correct than the sediment discharges from the sediment rating curves. A general idea of the comparison of daily sediment discharges that were computed from sediment rating curves with those from daily samples is given by figure 9. During the 1949 water year, 316 daily measured sediment discharges were published. Even some of these were estimates. In the 316 daily comparisons, 120 sediment discharges computed from sediment rating curves were within 10 percent and 211 sediment discharges were within 20 percent of the published daily sediment discharges.

The computed sediment discharges are based entirely on the three sediment rating curves for the gaging-station section, on streamflow records at the same section, and on water temperatures.

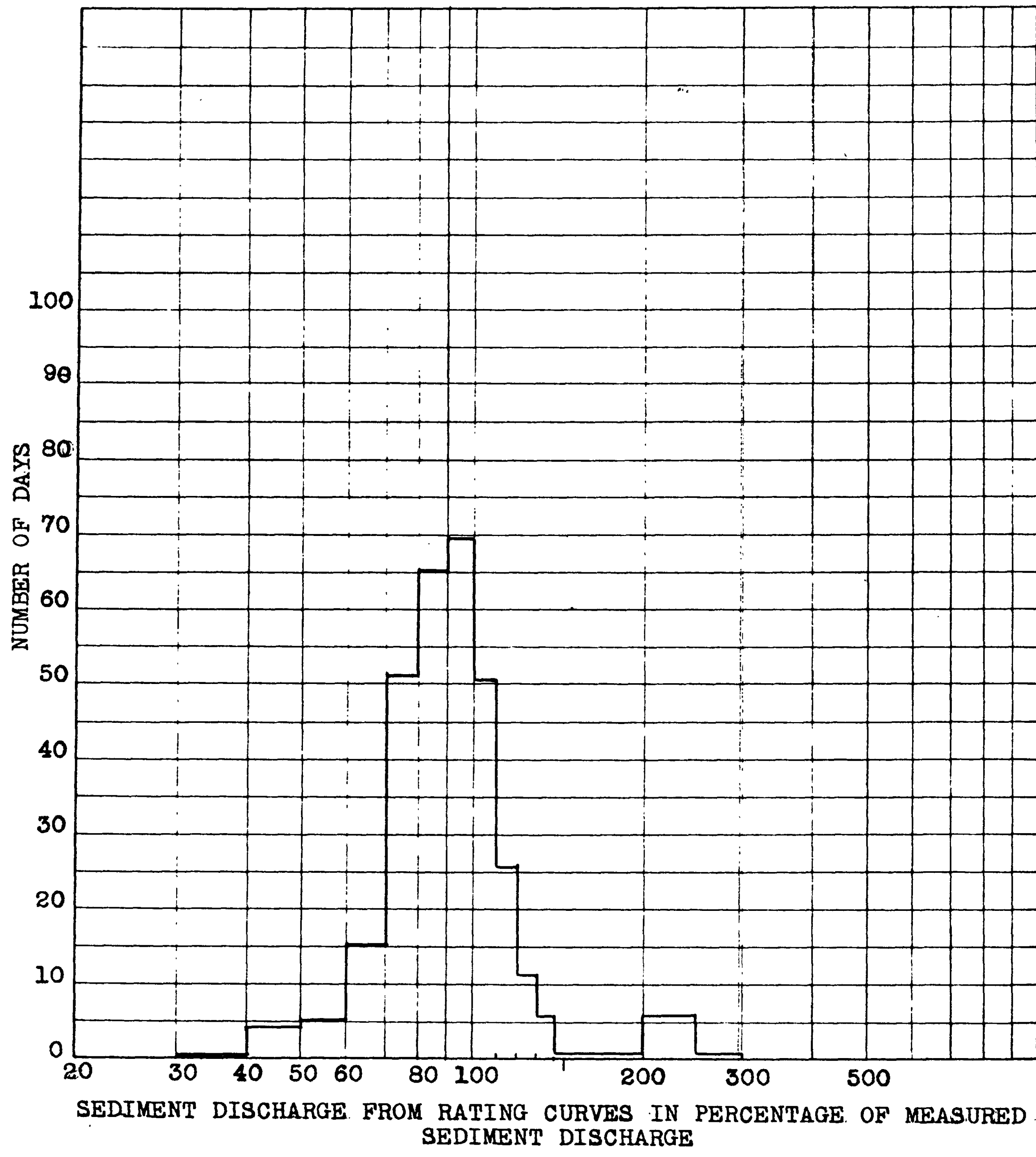

Figure 9.--Percentage comparison of daily total sediment discharges computed from rating curves with those measured at contracted section of Niobrara River near Cody, Nebr., 1949 water year (Published daily sediment discharges not available for 49 days)

They contain the errors inherent in the sediment rating curves and their adjustments plus possible changes in storage of sediment, including bed load, between the gaging-station section and the contracted section. The unmeasured-sediment rating curve was defined by computations that were all in years other than the 1949 water year. Also, the daily sediment discharges, and to a lesser extent the monthly and annual sediment discharges, for the contracted section are imperfect standards for comparison inasmuch as they contain appreciable errors that are due to sampling and computation procedures and to insufficient samples to determine dependable daily sediment discharges.

Daily, monthly, and annual sediment discharges computed from the three sediment rating curves give useful information on the approximate percentages of clay plus silt, of suspended sands, and of unmeasured-sediment discharge in the total sediment discharge of the river.

Individual determinations of the relationship between sediment discharge and streamflow sometimes plot far from the sediment rating curve. Part of this scatter may be due to random or very short-term fluctuations in concentration particularly of the coarse sediments. Part may represent an actual change in the relationship, a change that may persist for several days or longer. If the change does approximately apply for several days, the sediment rating curve could well be shifted to pass through or near each individual determination of the relationship. This shiftting would be comparable to the shifting of the stage-discharge relationship in computing streamflow records. Obviously, the computer would have to estimate (a) whether each individual determination of the relationship seemed to indicate a shift or only a random fluctuation or a combination of both, (b) whether the shift applied equally percentagewise or unequally throughout the range of water discharge, and (c) how the amount of the shift should be varied between determinations of the relationship. In spite of this need for judgment by the computer, more accurate sediment discharges are likely to be computed from a sediment rating curve that is shifted on the basis of occasional streamflow measurements and concurrent sediment samples than from the sediment rating curve without shifts.

In this study, the sediment rating curve was not shifted directly to periodic determinations of the relationship between sediment discharge and streamflow. Instead, daily sediment discharges were first determined from the unshifted sediment rating curve and then were plotted as a semilogarithmic hydrograph of daily sediment discharge. Daily water discharge was also plotted on the same hydrograph form. Next, the control points (sediment discharges to which shifts were to be made) were plotted on the same graph. Then, the shifted daily sediment discharges were determined by drawing a curve through or near the control points. Between control points, this curve was based on the shape of the curve of unshifted daily sediment discharges and on the hydrograph of daily water discharge. To some extent changes in water discharge indicate times at which the relationship between shifted and unshifted sediment discharges is likely to change.

Sediment discharges that are to be used as a basis for shifts should define a representative relationship of sediment discharge to streamflow. Such a relationship is much easier to define at a cross section where the transported sediments are predominantly fine than at a section where they are predominantly coarse. (See p. 144-147.) Most published daily sediment discharges for the Niobrara River near Cody were based on one 2-bottle sample a day at only one vertical. Inaccuracies in the daily records will tend to be compensating, but a sediment discharge that is to be used as a basis for shifts should be computed from 2 to 4 samples at each of several verticals for a station such as the one near Cody.

Obviously, periodic measurements as a basis for shifts would be more helpful on days of high sediment discharge or on days that were representative of sediment discharge for a week or two than they would be if selected at fixed time intervals. However, periodic measurements for arbitrary times each month were used as being less subject to judgment and bias. Because instantaneous sediment discharges were not available for arbitrarily selected days, daily mean measured sediment discharges were used. The first shifts were based on measured daily sediment discharges at the contracted section for the 1st and 16th days of each month. Next shifts were made to the measured daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month.

Because daily samples at the contracted section were known to be subject to appreciable random or sampling errors, the daily sediment discharges for some days were either disregarded or were given less than full weight. Thus, the measured sediment discharges were considered to confirm the unadjusted record during the first 7 months of the water year even though the computed and measured daily sediment discharges for the 1st and 16th days of the month did not always agree closely. (Measured daily sediment discharges were not published for individual days during much of January and February.) Shifted sediment discharges for the last 5 months of the water year were considerably closer than unshifted sediment discharges to the published sediment discharges for the contracted section. (See table 2.) For the entire water year, the sediment tonnage totaled from these shifted daily sediment discharges was about 99 percent of the annual tonnage that was measured at the contracted section. This close agreement was due to a balancing of daily and monthly differences. Annual differences of several percent are more likely than those of only 1 percent.

Next, the measured daily sediment discharges at the contracted section for the 8th and 23d of each month, except January and February, were plotted on the same hydrograph form. Any changes that these points seemed to indicate in daily sediment discharges were made. The two additional control points per month for the shifted sediment discharges improved significantly the computed monthly sediment discharges for only April and September. The annual sediment discharge was 99 percent of the measured annual. (See table 2.)

Throughout all the computations, the monthly tonnages that were computed for the gaging-station section differed from those for the contracted section more during March than during any other month for which reasonably complete records were available at the contracted section. The daily sediment discharges for the contracted section for March 1 and 16 seem to be too low on the basis of comparison with sediment discharges for adjoining days. Until the daily record for the contracted section was examined after all the computations were made, the sediment discharges for March 1 and 16 were assumed to be representative and those for March 8 and 23 were assumed to be too high. This wrong assumption especially for March 8 caused much of the spread between measured sediment discharge at the contracted section for March and computed sediment discharge at the gaging-station section during March.

Daily sediment discharges that were obtained by shifting to 2 or 4 measured daily sediment discharges per month are not given in this report. These daily tonnages agreed better with measured daily sediment discharges for the contracted section than did the daily sediment discharges that were computed from the rating curves without shifts. Naturally, the more control points that are used the better the agreement between computed and measured sediment tonnages will be; but as was shown by the comparison of monthly and annual sediment discharges (table 2), the improvement that resulted from increasing the number of control points from 2 to 4 per month was not great.

Minor mistakes in the computations of sediment discharge are to be expected in this report both for the Niobrara River and for other streams because the computations have not been checked in detail. However, the computations have been spot checked and have been reviewed for major errors in computations, analyses, and applications of methods.

COLORADO RIVER NEAR GRAND CANYON, ARIZ.

Investigations by the Geological Survey of the sediment discharge of the Colorado River near Grand Canyon, Ariz., have been reasonably continuous from October 1925 to the present time (1955). A report on the sediment rating curve particularly with respect to long-time trends in the relationship of sediment discharge to water discharge has been prepared by Daines (1949) of the Bureau of Reclamation. C.S. Howard (1947), Love and Howard (1944), P. C. Benedict (1944), and Leopold and Maddock (1953) have all written on aspects of the sediment relationships of the Colorado River near Grand Canyon. Because many data are available and have been widely used and because the particle-size distributions and the scatter of points from an average sediment rating are much different than for the Niobrara River near Cody, the sediment station near Grand Canyon was selected for study.

The drainage area of the Colorado River at the gaging station near Grand Canyon is 137,800 square miles. Average discharge is more than 17,000 cubic feet per second. Much of the flow comes during the spring and early summer and originates from snowmelt at high altitudes. Summer storms at low altitudes produce relatively little runoff but large sediment discharges. Important sediment-producing tributaries not far upstream from the Grand Canyon station are the Little Colorado River, the Paria River, and the San Juan River. Flow of these tributaries makes the relationship between sediment discharge and water discharge highly variable from about July through February. During the spring runoff, from about March through June, the relationship between sediment discharge and water discharge is more stable. About 2/3 of the suspended sediment is finer than 0.062 millimeter.

Analysis

Instantaneous suspended-sediment discharges at 74 times during the water years 1948, 1949, 1950, and 1951 were used for the study of sediment rating curves. Only sediment discharges accompanied by streamflow measurements and size samples were included. These sediment discharges and the corresponding instantaneous water discharges are plotted on figure 10. The scatter of the points is much greater than for the Niobrara River near Cody. A curve was drawn through the plotted points. Little weight was given to those sediment discharges that were much higher than average because they represented higher proportions of tributary flow. In other words, a correct shape of the sediment rating curve for a constant ratio of tributary inflow was wanted rather than an actual average of the points. The curve was used only to compute daily sediment discharges that could be shifted to a few measured daily sediment discharges per month. Results from the application of the curve are given later in the report.

The sediment discharges shown on figure 10 were next subdivided into discharges of clay plus silt and discharges of sands. Separate sediment rating curves for the fines and for the sands were drawn and each was studied individually.

Ratios of sediment discharge were computed by dividing each discharge of suspended sands by the average from the sediment

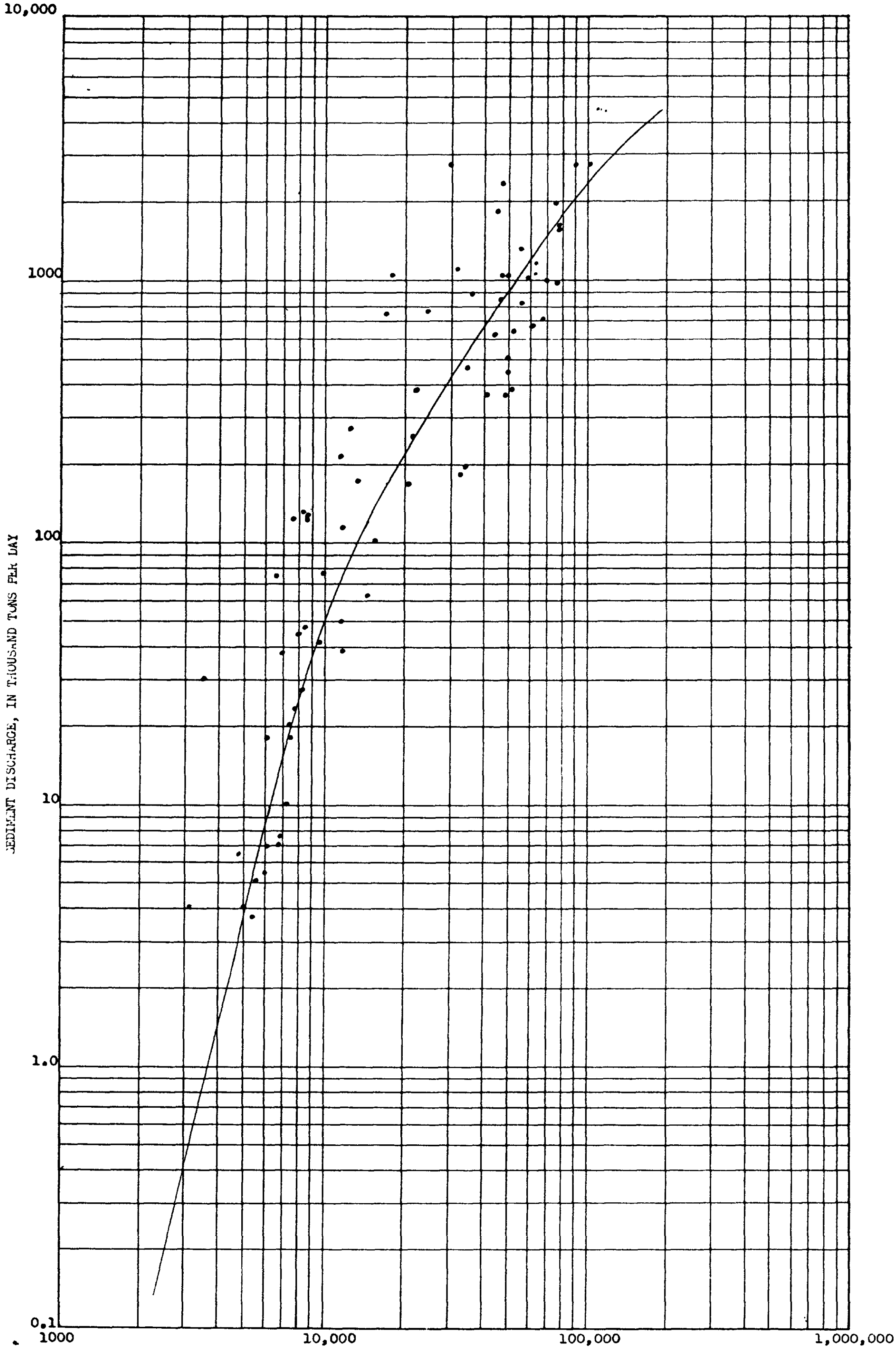

Figure 10.--Sediment rating curve from instantaneous data during 1948-51 water years, Colorado River near Grand Canyon, Ariz.

rating curve for suspended sands. A curve of velocity against water discharge was plotted with velocity as the dependent variable. The ratios of observed velocities to average velocities from this curve were computed. Then the ratios of sediment discharge were plotted against the velocity ratios. An average curve was drawn. Ratios of sediment-discharge departures from this average curve were plotted against water temperature, and another average curve was drawn. Ratios of sediment-discharge departures from the curve of temperature relationship were determined. These new ratios were plotted against water discharge. The average curve that was then drawn indicated that the sediment rating curve for the suspended sands required some revision especially at flows below 10,000 cubic feet per second. Ratios of departure of sediment discharge from this revised sediment rating curve were again plotted against the velocity ratios that were mentioned previously, and the first relationship between discharge of suspended sand and velocity was revised slightly. A similar check on the first relationship between water temperature and discharge of sands showed that no revision was required. Also, no correlation was found between average depth at the sampling and measuring section and ratios of departure of discharge of suspended sands from the other relationship curves.

The final instantaneous sediment rating curve for suspended sands is shown on figure 11. According to the correlations, departures of discharge of sands from this curve increased with about the 5th power of the velocity departures from the average and with about the -3/4 power of the water temperature. No seasonal adjustment was established for the discharge of suspended sands.

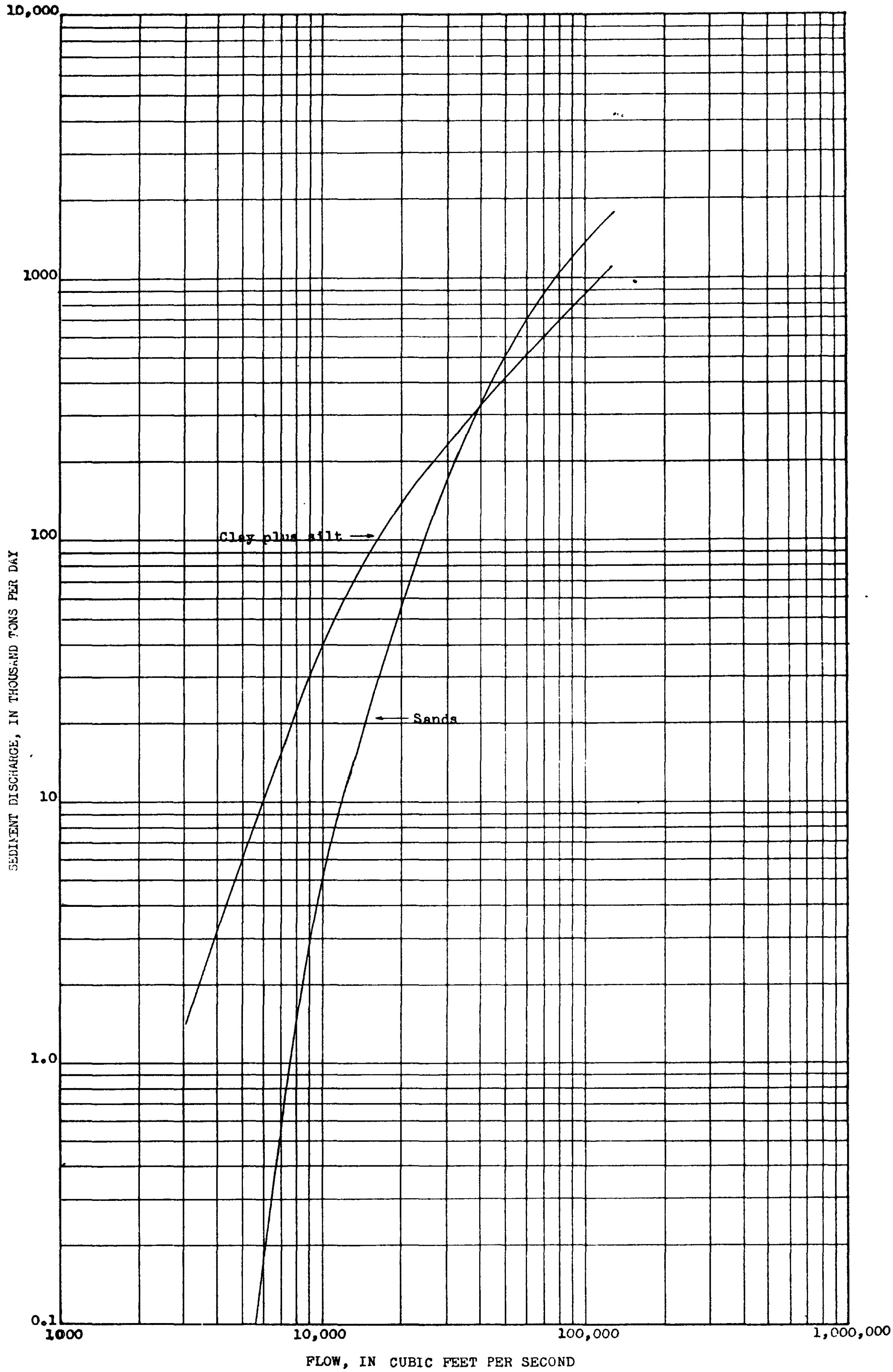

Figure 11.--Sediment rating curves from instantaneous data during 1948-51 water years, Colorado River near Grand Canyon, Ariz.

During some periods the discharge of suspended sands tended to be consistently lower or higher than indicated by the sediment ratting curve for suspended sands and accompanying adjustment curves. Perhaps the tendency was due to differences in supply of sands in the channel or to the size composition of the available sands.

No correlations were found between the discharge of sediment finer than 0.062 millimeter and the channel or flow characteristics at the gaging and sampling section. A recession curve showing decrease in flow after the last rise of the spring runoff was drawn from a hydrograph of daily water discharge for the water year ending September 30, 1948. This curve was used in other years with lateral shifts as required and was assumed to represent the recession of flow that would have occurred without runoff from summer storms. The recession curve was arbitrarily ended on September 30 each year, and a straight line on the semilogarithmic hydrograph form was drawn from the end of the recession curve to a period of constant flow near the middle of November. (See fig. 12.)

At any particular time the ratio of the actual water discharge to the flow that was indicated by the recession curve (or the straight line during October and early November) was used as a measure of the effect of summer and fall storms on the concentration of the fine suspended sediment. Such a ratio may be called the ratio of summer flow. Ratios of departure of sediment discharge from the rating curve for fine sediments were plotted against the ratios of summer flow. The first average curve through these data indicated that the discharge of fine sediments

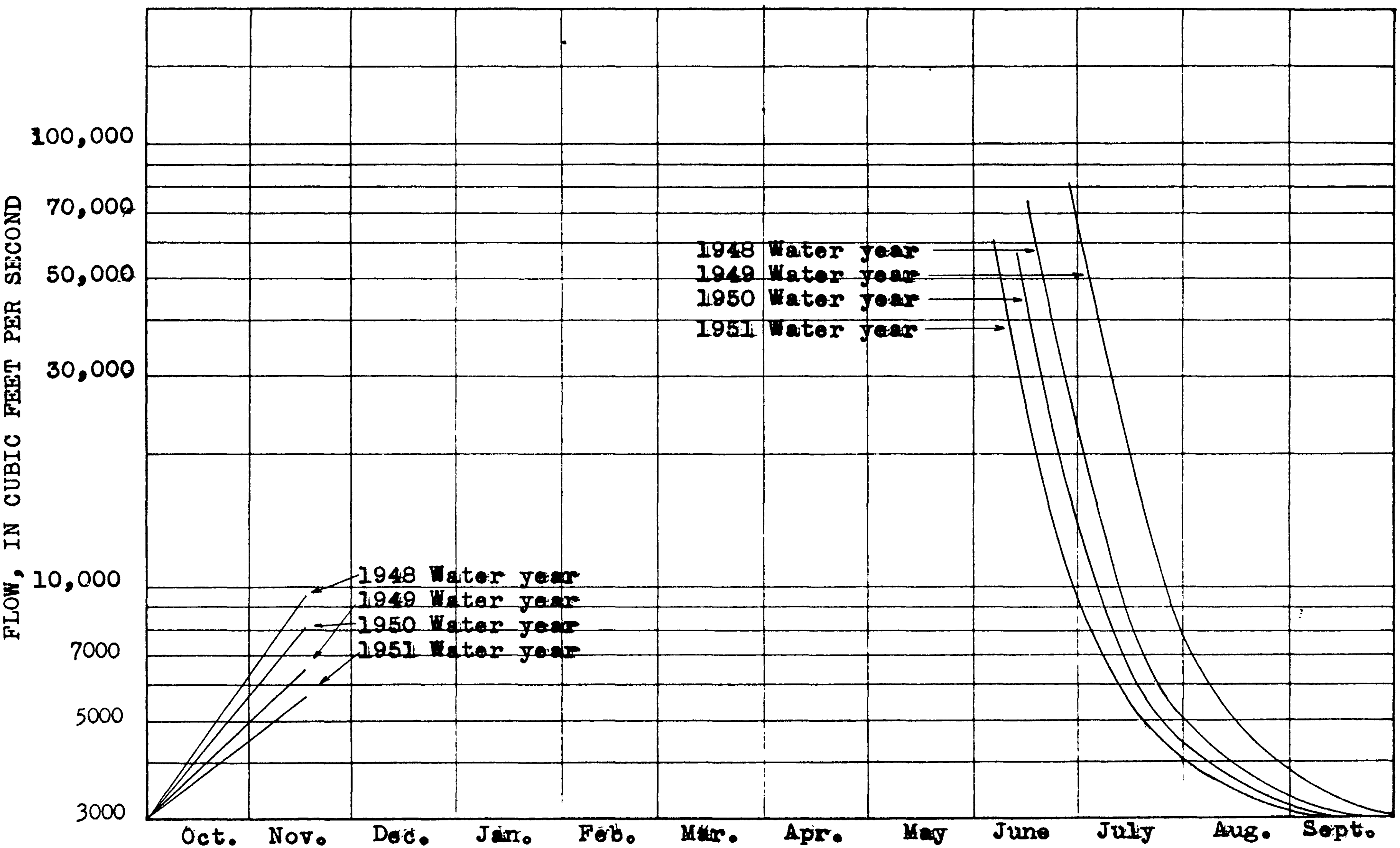

Figure 12.--Flow greater than indicated by these curves was assumed to be from summer runoff, Colorado River near Grand Canyon, Ariz.

increased as about the 4/3 power of the ratio of summer flow. Ratios of departure from this average curve were then plotted against ratios of tributary flow. The slope of an average line of approximate correlation between the ratios of departure of sediment discharge and the ratios of tributary flow was about 0.68.

Each ratio of tributary flow was computed by adding the flow of the San Juan River near Bluff, Utah, to the flow of the Little Colorado River near Cameron, Ariz., and to 5 times the flow (average sediment concentrations are very high) of the Paria River near Lees Ferry, Ariz., and dividing the sum by the flow of the Colorado River near Grand Canyon. Estimated times of travel of 1 to 6 days, 1 to 2 days, and 1 to 2 days were applied to the flow from the Bluff, Cameron, and Lees Ferry stations, respectively. These times of travel, to the nearest day, were varied within the stated limits in accordance with the flow of the Colorado River near Grand Canyon. Mean daily flows were used throughout these computations.

After the first curve of correlation between departures of discharge of fine sediment and ratios of tributary flow was defined, departures from this curve were replotted against the ratios of summer flow. A revision was indicated to make the discharge of fine sediment increase with the 1.1 power of the ratio of summer flow rather than with the 4/3 power as was first assumed.

A comparable recheck of the correlation between discharge of fine sediment and ratio of tributary flow seemed to show that no revision was required. This recheck completed the adjustments for ratios of summer flow and tributary flow.

Ratios of departure of discharge of fine sediments from the sediment rating curve (fines) and from the adjustments for summer flow and for tributary flow were plotted against time during the water year. (See fig. 13.) In spite of the scatter of the ratios, the discharge of the clay and silt during some seasons showed a more or less definite trend away from an average ratio of 1.0. Seasonal adjustments were assumed to apply in accordance with the adjustment line of figure 13. Ratios of departure from this line did not seem to correlate with flow. Hence the instantaneous sediment rating curve (fines) of figure 11 was not changed.

Applications

Instantaneous Sediment Rating Curves

The sediment rating curves for the fine sediments and for the suspended sands were applied with all adjustments to compute daily sediment discharges from daily water discharges for the water years 1937, 1952, and 1955. These water years were selected for computations because 1952 was a year of high flow and 1955 a year of relatively high sediment discharge and each was near in time to the period for which the sediment rating curves and their adjustments were defined. The 1937 water year was chosen as a year of about average water discharge during the period when sediment discharge tended to be high. Average flow for these water years and for periods of streamflow records and rating curve analysis are given in the following table:

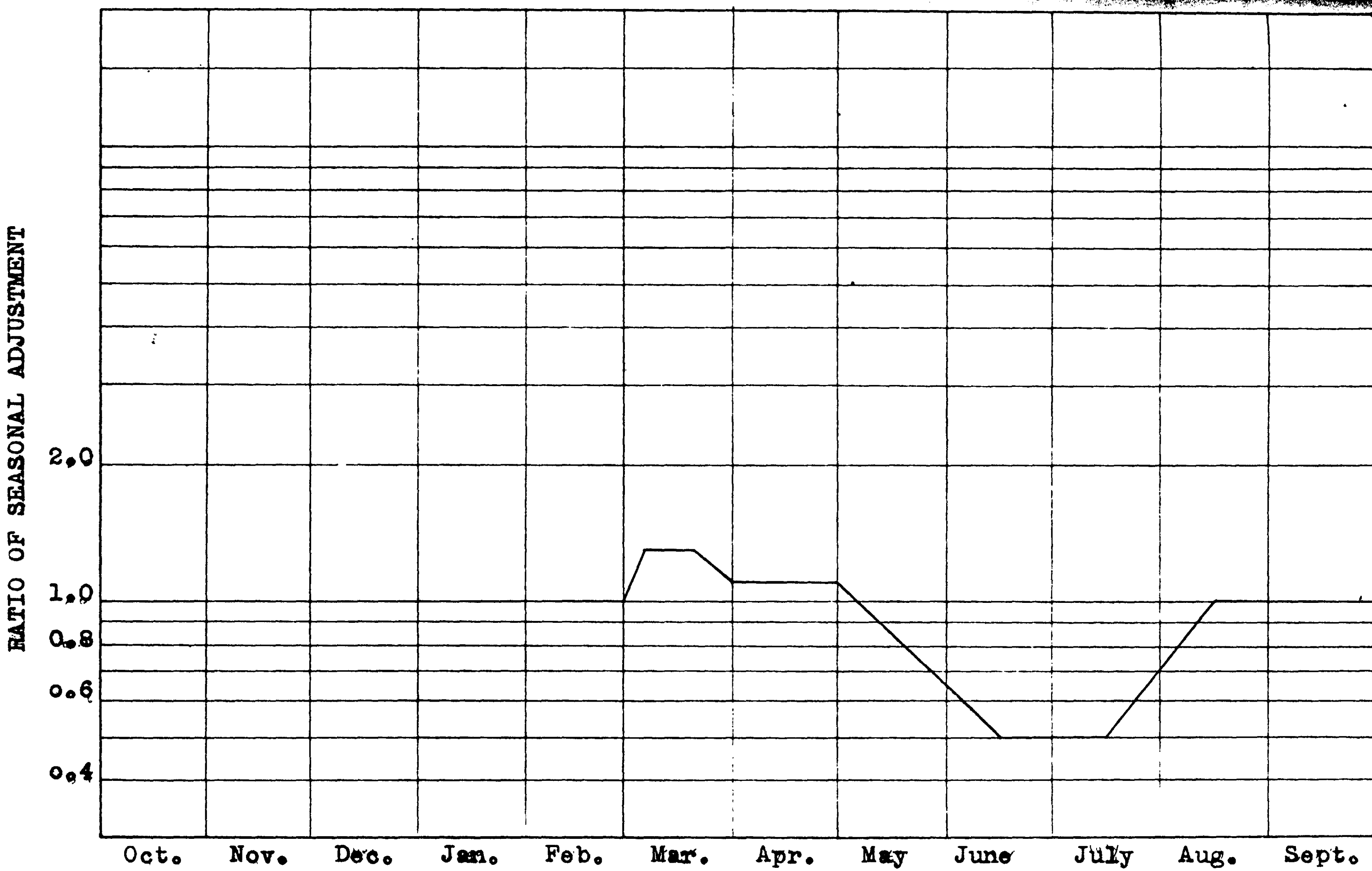

Figure 13.--Seasonal adjustment for the computation of monthly discharge of clay plus silt, Colorado River near Grand Canyon, Ariz.

Flow of the Colorado River near Grand Canyon, Ariz.

Period of water years	Average flow (cfs)	Remarks
1922 to 1952	17,850	Period of streamflow records
1948 to 1951	16,960	Period of rating curve analysis
1937	17,140	Sediment discharge computed from rating curves
1952	25,020	Do.
1955	10,450	Do.

Daily sediment discharges for the 1937, 1952, 1953, and 1955 water years were also computed from the unadjusted sediment rating curve of measured sediment discharge. They were computed as a step in the determination of shifted sediment discharges and were added by months and years for comparison with other computed sediment discharges, especially those computed by shifting to 2 or 4 control points per month. As was explained previously, this unadjusted sediment rating curve was prepared as a basis for shifts and was not drawn as an average curve. It can not be expected to give even approximately accurate computations of sediment discharge without shifts to control points.

Sediment rating curves are average curves from which individual points depart widely. One obvious procedure for using sediment rating curves in spite of scatter that cannot be eliminated by adjustments on the basis of correlations is to shift these curves to periodic measurements of sediment discharge. A general procedure for making the shifts from a curve of daily sediment discharges was explained on pages 45 to 48.

Shifts were based on three different sets of measured sediment discharges. One set was the daily sediment discharges for the 1st and 16th days of each month. Another was the daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month. The third was the instantaneous sediment discharges at the times when samples were collected for size analyses. (These sediment discharges from size analyses were used because they might possibly be timed better with large sediment discharges than the arbitrarily spaced sediment discharges that were used for the other shifts.) Three bases for shifts and two different computations of daily sediment discharges from rating curves make possible eight separate computations of daily, monthly, and annual sediment discharges for each water year. Daily sediment discharges were computed by 6 different methods for the 1937 water year, by 8 methods for the 1952 water year, by 3 methods for the 1953 water year, and by 4 methods for the 1955 water year.

Daily sediment discharges rather than instantaneous sediment discharges were used as a basis for shifts in some of the computations. This was done partly because at this station the difference between instantaneous and mean daily sediment discharge for a given water discharge is usually small and partly because the mean daily tonnages were more readily available.

A summary of the monthly and annual computed sediment discharges is given in table 3. Monthly and annual tonnages based on daily sampling are listed for comparison.

Several different methods of computation of sediment discharge were applied for the water year ending September 30, 1937.

First the two sediment rating curves, one for the clay and silt and one for the sands, were applied with adjustments to

Table 3.--Monthly and annual sediment discharges, in thousand tons, as computed by different methods for the Colorado River near Grand Canyon, Ariz.

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
Water year ending September 30, 1937														
Method 1....	1,860	3,930	541	194	9,688	17,990	40,440	53,090	17,660	27,760	5,370	12,740	191,300	100
Method 2....	820	1,740	400	130	5,450	11,700	26,800	42,000	20,400	18,300	2,320	4,620	135,000	71
Method 4....	1,780	3,920	490	210	8,650	14,600	34,200	52,000	16,300	24,900	4,140	20,000	181,000	95
Method 5....	1,930	4,030	480	180	9,080	16,500	39,300	51,000	16,200	26,000	4,580	20,200	189,000	99
Method 6....	250	670	200	50	1,470	3,220	11,100	34,600	20,600	8,510	660	940	82,300	43
Method 8....	1,820	2,710	470	200	6,510	19,000	37,600	56,800	17,200	26,600	5,030	14,000	188,000	98
Method 9....	1,850	3,160	510	170	7,430	17,400	38,400	54,400	16,900	26,400	4,330	14,300	185,000	97
Water year ending September 30, 1952														
Method 1....	3,554	2,570	458	9,752	524	1,076	36,117	49,452	29,019	3,646	4,737	7,581	148,486	100
Method 2....	1,460	1,090	340	4,810	720	1,170	34,800	44,400	39,000	10,700	10,500	6,900	156,000	105
Method 3....	3,340	2,550	350	11,100	560	1,030	35,300	43,200	27,400	3,600	4,800	8,870	145,000	98
Method 4....	2,410	1,930	350	10,300	580	870	43,300	46,400	27,200	3,850	4,750	6,100	148,000	100
Method 5....	3,680	2,530	420	7,310	590	920	40,700	51,200	28,000	3,570	5,070	5,360	149,000	100
Method 6....	510	740	270	1,780	430	510	18,700	56,600	59,600	11,000	3,240	1,600	155,000	104
Method 7....	4,420	2,410	420	10,600	560	970	35,400	47,200	26,300	3,010	4,660	9,350	145,000	98
Method 8....	1,370	2,210	400	14,900	510	800	43,100	48,800	25,800	3,480	4,910	6,920	153,000	103
Method 9....	2,560	2,740	430	13,300	550	870	41,300	52,900	27,800	3,360	5,510	6,780	158,000	106
Water year ending September 30, 1953														
Method 1....	436	223	301	190	168	586	624	4,884	19,951	6,211	13,370	2,134	49,080	100
Method 6....	360	390	400	390	380	720	1,090	4,900	26,200	4,620	2,320	170	41,900	85
Method 8....	540	380	200	150	170	630	800	4,340	26,700	7,450	15,300	1,390	58,000	118
Method 9....	470	250	310	180	160	550	660	4,450	21,100	6,760	14,900	1,390	51,200	104

See footnotes at end of table.

Table 3.--Monthly and annual sediment discharges, in thousand tons, as computed by different methods for the Colorado River near Grand Canyon, Ariz.--Continued

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
Water year ending September 30, 1955														
Method 1....	10,640	637.6	284.5	164.6	169.7	6,519	4,061	15,740	12,330	3,055	25,290	2,295	81,186	100
Method 2....	9,154	460	260	180	230	2,650	2,770	16,800	12,400	1,260	17,700	1,040	64,900	81
Method 6....	1,100	250	120	75	100	1,560	1,810	9,800	10,900	1,800	1,940	150	29,600	37
Method 8....	12,300	480	250	260	184	5,170	3,200	16,700	19,100	1,770	22,200	1,850	83,500	103
Method 9....	13,100	660	330	240	159	5,770	3,980	16,500	16,300	2,120	23,300	1,900	84,400	104

Method 1: Daily samples.
Method 2: Adjusted sediment rating curves, one for suspended sands and one for silt and clay.
Method 3: Adjusted sediment rating curves with shifts to 36 instantaneous sediment discharges during year.
Method 4: Adjusted sediment rating curves with shifts to two daily measured sediment discharges per month.
Method 5: Adjusted sediment rating curves with shifts to four daily measured sediment discharges per month.
Method 6: Unadjusted sediment rating curve.
Method 7: Unadjusted sediment rating curve with shifts to 36 instantaneous sediment discharges during year.
Method 8: Unadjusted sediment rating curve with shifts to two daily measured sediment discharges per month.
Method 9: Unadjusted sediment rating curve with shifts to four daily measured sediment discharges per month.

compute monthly and annual sediment discharges. Monthly and annual tonnages so computed without the aid of any measured sediment discharges during the 1937 water year were usually lower than measured monthly and annual sediment discharges. They were not nearly so low (table 3) as the monthly and annual tonnages that were computed from the unadjusted sediment rating curve of figure 10. The annual sediment discharge computed from the two adjusted sediment rating curves without the aid of periodic samples during the year was 71 percent of the measured annual sediment discharge. The rating curves and adjustments defined from data that were obtained during the water years 1948 through 1951 accounted for only part of the difference in sediment discharge between these years of relatively low sediment concentration and the 1937 water year during which sediment concentration was much higher. Adjusted to equivalent annual flow, the sediment discharge during the water years 1948 through 1951 was, as will be shown later, only about 47 percent of the sediment discharge for the 1937 water year. The difference between 71 percent and 100 percent (table 3) for the 1937 water year is not explainable on the basis of the applied adjustments and presumably is due to factors that had not been correlated with sediment discharge. Additional computations for other years would be necessary to establish the validity of this tentative conclusion.

Daily sediment discharges based on the two adjusted sediment rating curves were shifted to 2 and then to 4 measured daily sediment discharges per month. Monthly and annual sediment discharges totaled from these shifted daily sediment discharges were not significantly closer to measured sediment discharges than were comparable tonnages that were computed by similarly shifting daily sediment discharges obtained from a single suspended-sediment rating curve. (See table 3.)

The annual sediment discharge computed by addition of daily sediment discharges from the unadjusted and unshifted suspended-sediment rating curve of figure 10 was only 82.3 million tons as compared to a measured sediment discharge of 191.3 million tons. (The unadjusted and unshifted curve assumed negligible storm runoff during the summer and fall and low inflow from the Paria, San Juan, and Little Colorado Rivers.) For individual months, the computed tonnages were usually much lower than the published measured tonnages. However, when the daily sediment discharges from the suspended-sediment rating curve were shifted to either 2 or 4 daily measured sediment discharges per month, the computed annual tonnage of sediment was brought within 2 or 3 percent of the measured annual tonnage. Of course, even after shifts were applied, some computed monthly sediment discharges differed appreciably from the measured monthly sediment discharges (table 3), but the agreement of monthly sediment tonnages was generally good. The increased accuracy obtained by shifting to even 2 daily measured sediment discharges per month is noteworthy.

Daily sediment discharges computed for the 1937 water year from the two adjusted sediment rating curves without shifts were generally lower than the measured daily sediment discharges.

At times, differences between the computed and the measured sediment discharges were large. When daily sediment discharges from the single unadjusted sediment rating curve were shifted to two daily sediment discharges per month, the agreement between daily computed and measured sediment discharges was faily good. Plate 2 and figure 14 clearly show the increased accuracy that resulted from shifting to only two measured sediment discharges per month. The approximate accuracy of daily sediment discharges from other methods of computation can be judged roughly from the relative agreement of monthly and annual sediment discharges in table 3.

For the water year ending September 30, 1952, the annual sediment discharge computed by adding together the discharges of fine sediment and of sands from the two rating curves was 156 million tons, which is 5 percent more than the 148,486 million tons that was computed from the daily sampling. The annual sediment discharge computed from the rating curve for measured sediment of all particle sizes was 155 million tons. Thus for this water year both annual sediment discharges computed from sediment rating curves were probably within the limit of accuracy of the sediment discharge that was based on daily samples. For individual months the sediment discharges did not agree nearly so well with those that were based on daily samples. As should be expected, the monthly sediment discharges from the one unadjusted suspended-sediment rating curve were sometimes far from correct. They were usually much further from correct than were the suspended-sediment discharges that were computed from two sediment rating curves, one for fine particles and one for sands.

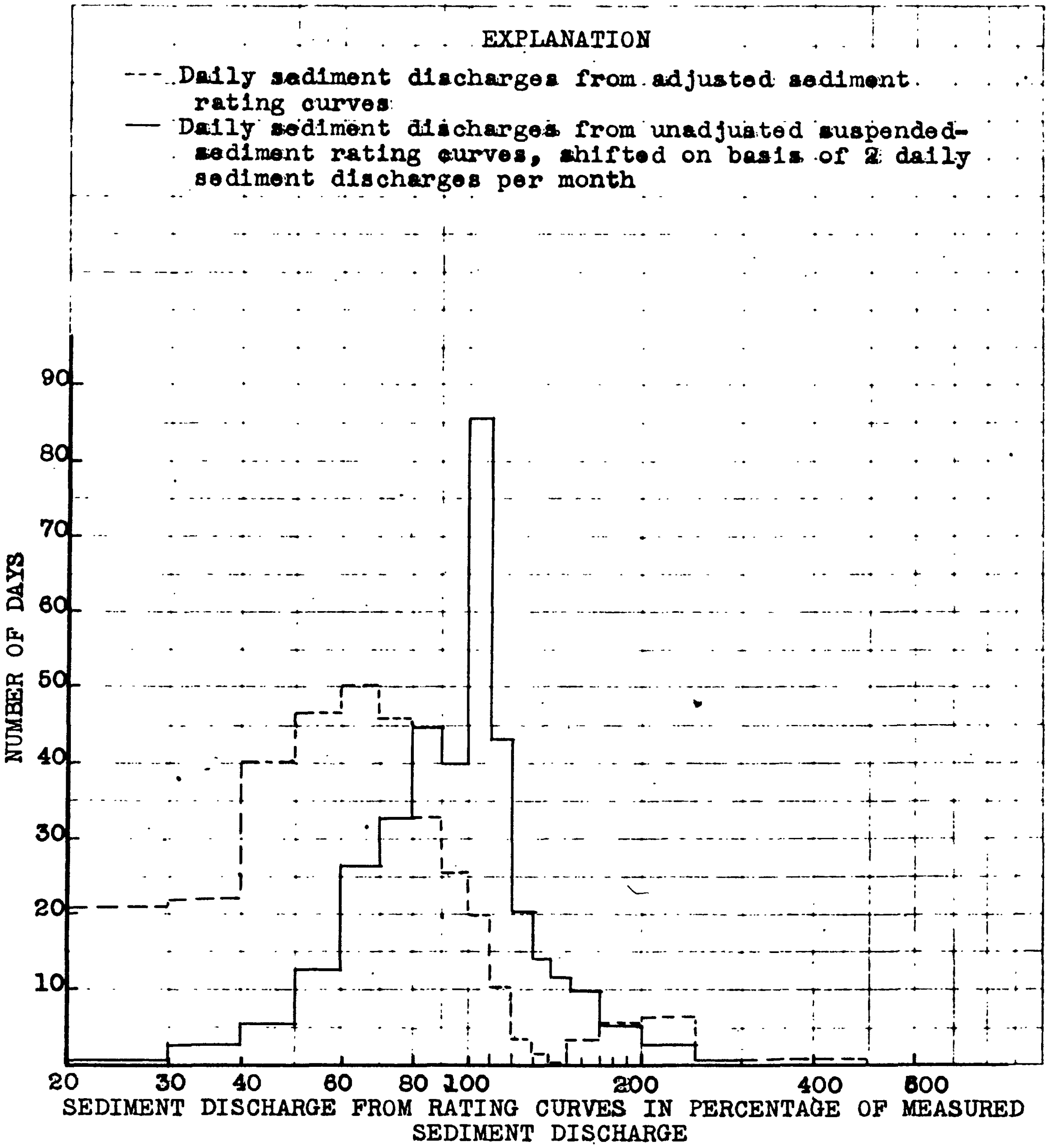

Figure 14.--Percentage comparison of daily sediment discharges computed from shifted and unshifted rating curves with measured sediment discharges, Colorado River near Grand Canyon, Ariz., 1937 water year.

Monthly and annual sediment discharges computed from the different sediment rating curves and shifted on the basis of sediment discharges at the times of collection of 36 samples for size analysis during the 1952 water year also are listed in table 3. Annual sediment discharges so computed totaled 145 million tons whether based on unadjusted or adjusted sediment rating curves. However, within individual months the agreement with measured sediment discharges was somewhat better when the monthly sediment discharges were computed from initial daily sediment discharges from the two adjusted sediment rating curves rather than from the one unadjusted suspended-sediment rating curve.

Other computations for the 1952 water year were based on shifts to measured daily sediment discharges for the 1st and the 16th of each month. Similar computations were made on the basis of measured daily sediment discharges for the 1st, 8th, 16th, and 23d of each month. Probably wholly by chance, the annual sediment tonnages that were based on adjustments to 2 daily sediment discharges per month were slightly better than those that were based on 4 daily sediment discharges per month. On the average, monthly sediment discharges were not significantly improved by shifting to 4 daily sediment discharges per month rather than to 2 per month. Shifting to either 2 or 4 daily discharges per month gave neither significantly better nor worse monthly sediment discharges than shifting to the instantaneous sediment discharges at the 36 times of collection of samples for particle size analysis. Sediment discharges computed by shifting to either the 2 or the 4 daily sediment discharges per month were more nearly correct if the initial daily sediment discharges came from the combined sediment discharges of the fine particles and the sands rather than from the one unadjusted suspended-sediment rating curve.

Daily figures of sediment discharge that are computed from sediment rating curves generally will not agree closely and consistently with measured sediment discharges, particularly if the sediment rating curves are not shifted to periodic measurements of sediment concentration. However, shifts to from 2 to 4 periodic measurements per month gave reasonably good agreement between computed and measured daily sediment discharges during much of the 1952 water year. Naturally, the daily sediment discharges that were computed from the adjusted rating curves for fine particles and for sands did not give as correct daily tonnages as those that were shifted to periodic samples. Nevertheless, agreement is better than might be expected between measured sediment discharges and the sediment discharges that were computed without the aid of samples. (See pl. 3.)

Figure 15 shows a graphical comparison between measured sediment discharges and shifted and unshifted sediment discharges from sediment rating curves for the 1952 water year. Shifting to 36 sediment samples during the year increased from 108 to 195 the number of days for which computed sediment discharges were within about 20 percent of measured sediment discharges and also nearly eliminated extreme differences. The unshifted daily sediment discharges were computed from the adjusted sediment rating curves.

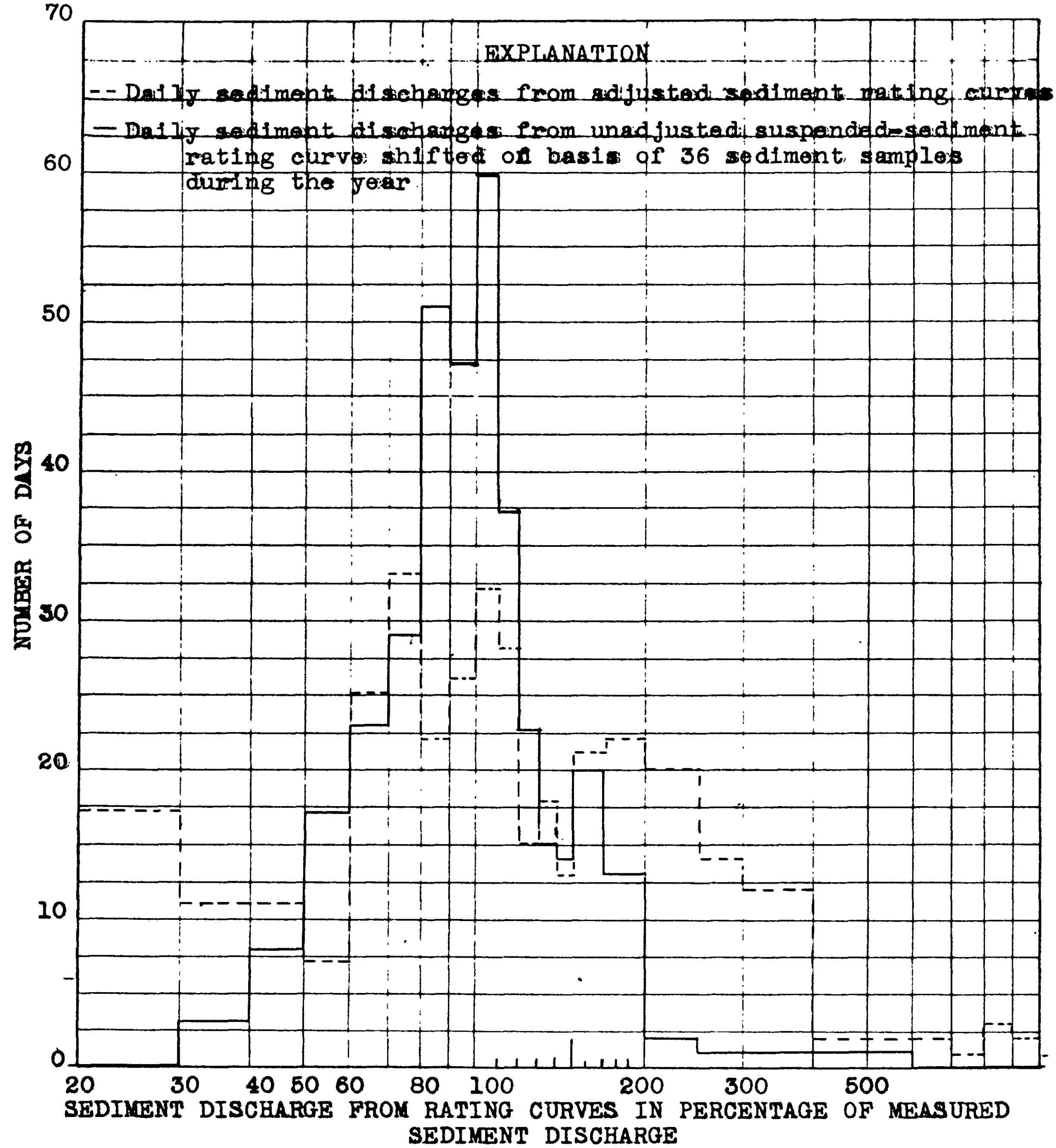

Figure 15.--Percentage comparison of daily sediment discharges computed from shifted and unshifted rating curves with measured sediment discharges, Colorado River near Grand Canyon, Ariz., 1952 water year.

Daily sediment discharges for the 1953 water year were computed from the single suspended-sediment rating curve and were shifted to 2 and to 4 daily sediment discharges per month. Annual sediment discharge computed from the unadjusted and unshifted sediment rating curve was 85 percent of the published annual sediment discharge of 49.08 million tons (provisional record). When the daily sediment discharges were shifted to 2 measured daily sediment discharges per month, most monthly sediment discharges except those for June and September agreed reasonably well with measured sediment discharges. Mainly because of the difference for June (table 3), the annual sediment discharge for shifts to 2 measured sediment discharges per month was 18 percent too large, being 58.0 million tons. When shifts were based on 4 measured daily sediment discharges per month, the annual tonnage became 51.2 million tons, which is 4 percent higher than the measured annual tonnage. Monthly sediment discharges based on shifts to 4 sediment discharges per month were all within about 12 percent of the measured monthly discharges except for September for which the computed monthly discharge was only 65 percent of the measured 2.134 million tons.

During the water year ending September 30, 1955, the average flow was relatively low but the discharge of sediment during the year was much higher than the average during recent years. The annual relationship of sediment discharge to flow during this year was comparable to that for most years from about 1928 to 1935. Because the annual relationship was much different than for the water years 1948 through 1953, some computations of sediment discharge from sediment rating curves were made even though the record of measured sediment discharge is still preliminary and provisional. This preliminary record is not nearly as final as the provisional sediment record for the 1953 water year.

Daily, monthly, and annual sediment discharges were computed for the 1955 water year from the two sediment rating curves of figure 11 and applicable adjustments. For 7 months of the water year, the monthly sediment discharges computed from these curves agreed reasonably well with the measured monthly tonnages (table 3), but the computed monthly sediment discharges were much too low for March, April, July, August, and September. The annual sediment discharge computed from the adjusted sediment rating curves without control points, that is without any samples during the water year, was only 81 percent of the measured annual sediment discharge. This comparison is much better than for the annual sediment discharge from the unadjusted sediment rating curve of figure 10 but is still not a close comparison. The computed discharge of suspended sands was 22.5 million tons from the sediment rating curve for sands, which is somewhat more suspended sand than was computed by shifting the curve for suspended sands to 38 determinations of instantaneous discharge of sands during the year. The difference of 19 percent between the measured and the computed annual sediment discharges was, therefore, due to computing too little discharge of silt and clay.

The sediment rating curves and their adjustments failed to compute enough sediment discharge for about the same months in the 1955 water year as in the 1937 water year. The computed sediment discharges for May and June, the months of spring runoff from the upper Colorado River basin, agreed reasonably well with measured tonnages for both the 1937 and 1955 water years. (See table 3.) Unless the parallelism is coincidental, which is unlikely, the relatively consistent monthly differences in sediment discharge for these two water years indicate that some adjustment could be devised to make the computed sediment discharges agree much better with the measured sediment discharges. Accordingly, the sediment rating curve (fines) and the adjustments defined by data for the 1955 water year were studied to see whether the curve and adjustments would give sediment discharges more nearly like the measured sediment discharges during such water years as 1937 and 1955.

The 38 size analyses of suspended sediment for the 1955 water year were used together with accompanying instantaneous concentrations of suspended sediment and instantaneous rates of flow to define a sediment rating curve (fines) and adjustments to the curve. Trial-and-error multiple correlations indicated about the same adjustment for ratios of summer flow for the data from the 1955 water year as for those from water years 1948 through 1951. The indicated seasonal adjustments for March and April were higher for the 1955 water year than the seasonal adjustments for March and April on figure 13. For the 1955 data either the sediment rating curve (fines) or the adjustment for ratios of tributary flow required a parallel shift from the curves that were defined by the information from water years 1948 to 1951. This parallel shift would increase each daily sediment discharge by 20 to 25 percent exclusive of the increase from changes in seasonal adjustment during March and April. These new relationships gave much more accurate computed sediment discharges for the 1937 and 1955 water years but much less accurate ones for the 1952 water year than the computed sediment discharges in table 3 (method 2).

Thus, the relationships defined for discharge of silt and clay for years of relatively low sediment discharge (water years 1948 to 1951) did not adjust enough for years of higher than average sediment discharge such as 1937 and 1955. On the other hand, relationships defined from the data that were obtained during the 1955 water year gave too high sediment discharges for a water year such as 1952 when annual sediment discharge was only about 50 percent of the average that might be expected for the amount of flow during that year.

The relationships developed for this report from information for the 74 times during water years 1948 through 1951 explained much, but not all, of the scatter in annual sediment discharge for the 1937, 1952, and 1955 water years. Better sediment rating curves and adjustments, particularly for the fine sediments, almost certainly could be devised by further investigation, preferably of data from years when sediment relationships were more typical than during water years 1955 and 1948 through 1951.

Annual tonnage based on daily sediment discharges from the sediment rating curve of figure 10 without adjustments or shifts was only 37 percent (table 3) of the measured tonnage. (This computation was made only as a basis from which to apply shifts; the rating curve is not an average curve because sediment discharges during the summer were given comparatively little weight in defining the curve.) When daily sediment discharges from the curve of figure 10 were shifted to measured daily mean sediment discharges for the 1st and the 16th days of each month, the computed annual sediment discharge totaled from the daily tonnages was 103 percent of the measured. Shifting to even 2 control points per month greatly increased the accuracy of the monthly and annual sediment discharges over those that were computed from either the one suspended-sediment rating curve or the two adjusted sediment rating curves. Shifts to measured daily mean sediment discharges for the 1st, 8th, 16th, and 23d days of the months gave an annual sediment discharge that was 104 percent of the measured annual sediment discharge. Shifting to 4 control points per month improved most of the monthly sediment discharges as compared to shifting to 2 control points per month.

In general, the computations for the Colorado River near Grand Canyon, Ariz., show clearly that a few sediment samples per month can be combined with a sediment rating curve to compute reasonably accurate annual sediment discharges even for years of dissimilar sediment characteristics. Computations based on adjusted sediment rating curves and no sediment samples are more laborious and less accurate unless better correlations than those of this study can be developed.

Although for a study of this type the measured sediment discharges are considered to be accurate enough to serve as acceptable standards of comparison, possible inaccuracies should be considered briefly. For example, the wide percentage difference between measured sediment discharges for November 15 to 25, 1951, (pl. 2) and the computed sediment discharges from the two rating curves with shifts to 36 instantaneous sediment discharge measurements are due directly to a difference in concentration of samples that were collected for concentration and those collected at the same time for particle-size analyses. Difference in reported concentrations of samples that were collected from the Colorado River near Grand Canyon at approximately the same time and with currently approved equipment and techniques are shown by figure 16. Concentrations for many of the comparable samples agreed closely, but at some times the concentrations differed by appreciable percentages.

Annual Sediment Rating Curves

The flow-duration curve has been widely used with sediment rating curves to compute average sediment discharge for long periods of time. For a station like the Colorado River near Grand Canyon a much simpler method of perhaps equal accuracy can be used. The simpler method also has the advantage that it is more easily applied to possible adjustment for factors that affect the relationship between sediment discharge and water discharge. This method is based on the annual sediment rating curve.

Annual sediment discharges are plotted against average annual flow of the Colorado River near Grand Canyon in figure 17. Although

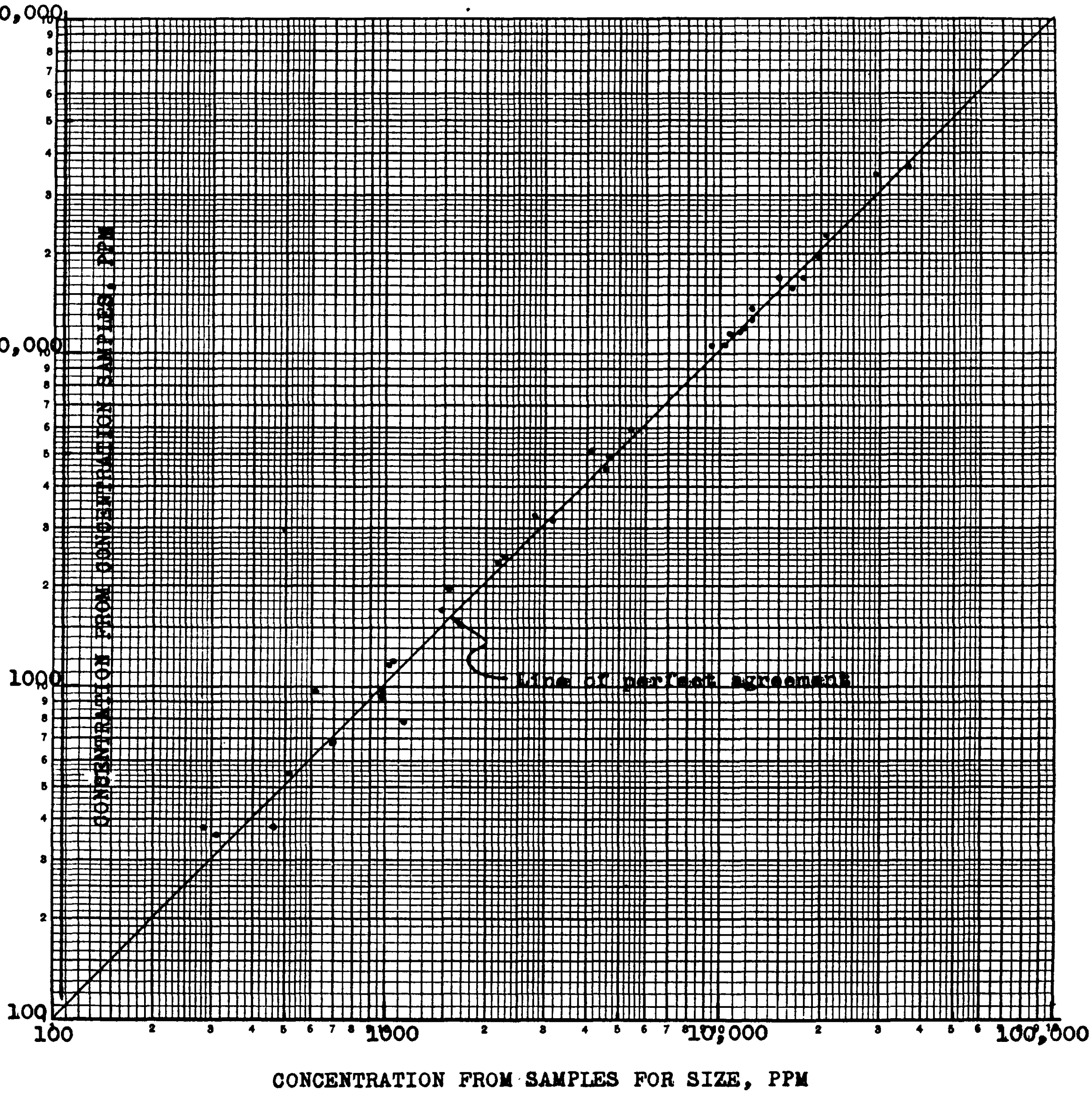

Figure 16.--Comparison of concentrations of samples collected for size with those collected for concentration, Colorado River near Grand Canyon, Ariz., 1952 water year.

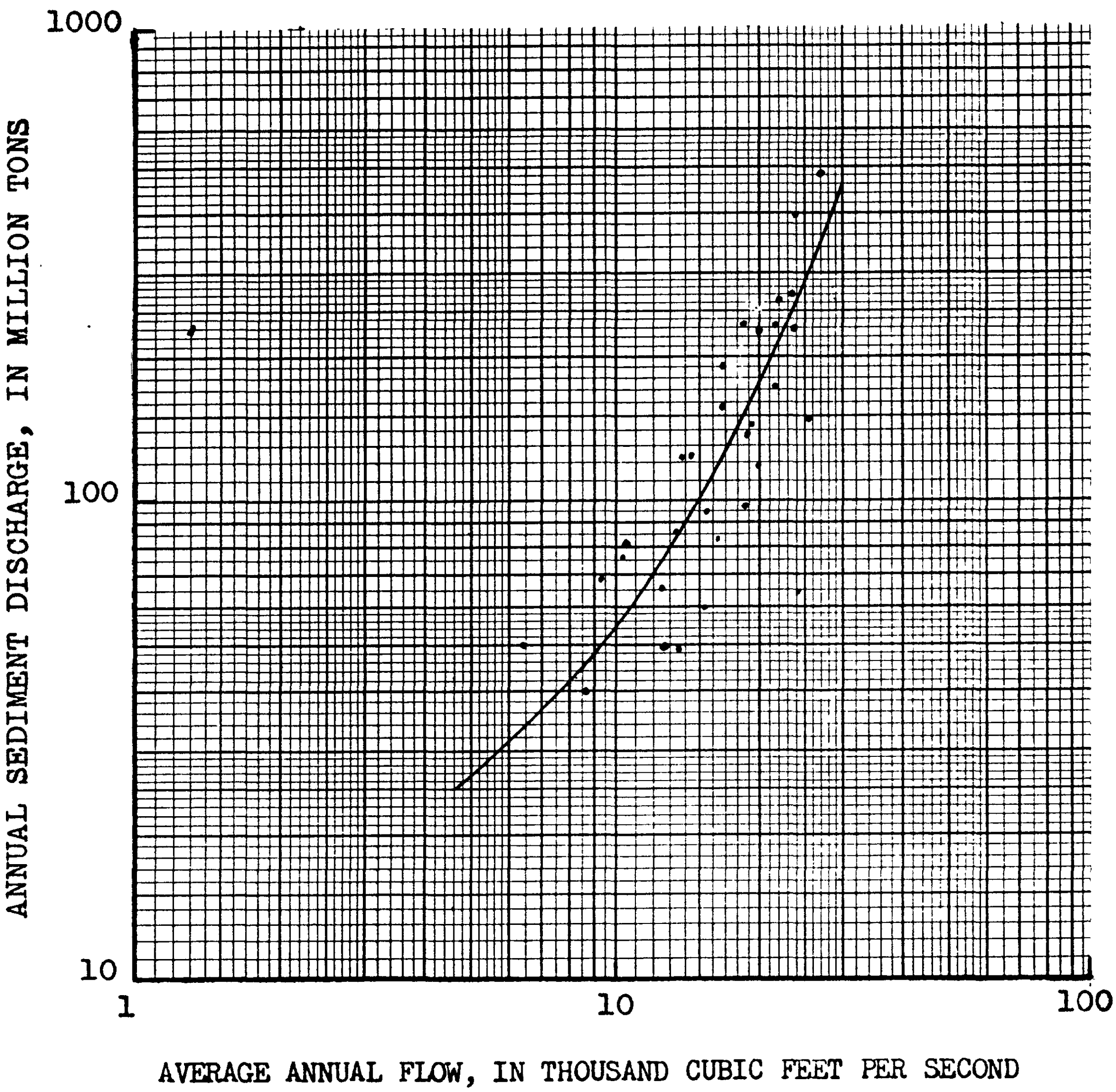

Figure 17.--Annual sediment rating curve, Colorado River near Grand Canyon, Ariz.

the relationship varies considerably from year to year, the scatter is not excessive. Attempts to explain the scatter by correlations of annual sediment discharge with annual ratios of summer flow or of tributary flow were inconclusive. However, a general time trend in the relationship between sediment discharge and water discharge is obvious. (See fig. 18.) The term "general time trend" is used to indicate an average change with time; in this connection, a change in the relationship between sediment discharge and water discharge. Obviously, the basic explanation of the change in this relationship must be a change in weather or in the physical condition of the drainage area and stream channels. However, the only feasible correlation may be with time. Because time is not the basic cause of the change, rather wide departures from a general time trend are to be expected.

The sediment rating curves and adjustments as defined by 74 sets of instantaneous data for the water years 1948 through 1951 when applied to daily computations explain much of the scatter from the annual sediment rating curve. On figure 18 the small circles for the 1937, 1952, and 1955 water years show the departures of computed annual sediment discharges from the annual sediment rating curve. These computed sediment discharges are based only on daily flows, the sediment rating curves of figure 11, and the adjustments to these curves. They are not based on any sediment samples that were collected during the 1937, 1952, or 1955 water years. The sediment discharge during the water years 1948 through 1951 averaged only 0.68 of the sediment discharges from the annual sediment rating curve as compared to

EXPLANATION

• - From measured annual sediment discharge
o - From annual sediment discharge computed from daily streamflow and adjusted sediment rating curves

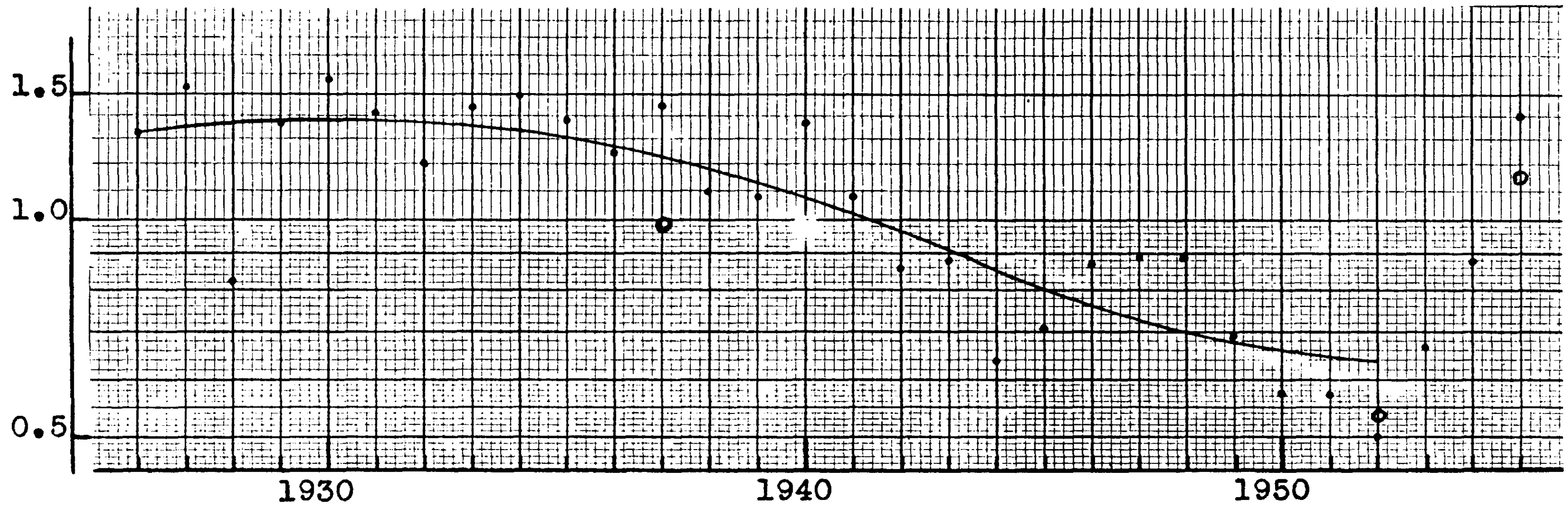

Figure 18.--Approximate trend in relationship of annual sediment discharge to annual water discharge, Colorado River near Grand Canyon, Ariz.

1.45 and 1.40 for water years 1937 and 1955, respectively. Thus, as measured by ratios of departure from the annual sediment rating curve of figure 18, the annual sediment discharges for the years from which data were used in the correlations averaged only 0.68/1.45 or 47 percent of the sediment discharge for an equivalent flow during the 1937 water year. Probably if years of relatively high sediment discharge had been used to define the curves and adjustments, the computed annual sediment discharges would have agreed better with the measured tonnages for the 1937 and 1955 water years and less well for the 1952 water year.

The annual sediment rating curve with the time adjustment of figure 18 can be used to compute simply and easily, but not necessarily more accurately than by other methods, the sediment discharge for any period of years for which average annual streamflow is known. For example, sediment discharge for the 11-year period ending September 30, 1945, can be computed as shown in table 4. The computed sediment tonnage for this period is 1,671 million tons or 1.8 percent higher than the measured sediment discharge of 1,641.4 million tons. If the adjustment for the time trend is not applied, the computed sediment discharge for the period is 1,580 million tons or 3.7 percent lower than the measured sediment discharge. For some other periods, total computed sediment discharge would be considerably different than the measured unless the adjustment for the time trend of figure 18 was included in the computations. A projection into the past or the future of the time trend for this or any other method of computing sediment discharge is questionable.

Table 4.--Average sediment discharge computed from annual sediment rating curve for Colorado River near Grand Canyon, Ariz.

Water year	Time trend coefficient (from fig. 18)	Annual sediment discharge, in million tons		
		From annual sediment rating curve	Product (2) x (3)	Published
(1)	(2)	(3)	(4)	(5)
1935	1.31	90	118	122.3
1936	1.28	123	157	157.6
1937	1.23	130	160	191.3
1938	1.19	210	250	232.4
1939	1.13	81	92	86.3
1940	1.08	56	60	75.4
1941	1.02	254	259	270.1
1942	.97	260	252	229.6
1943	.92	108	100	95.0
1944	.86	150	129	97.8
1945	.80	118	94	83.6
Total		1580	1671	1641.4
Average		143.6	151.9	149.2

One computation like that discussed in the preceding paragraph is totally inadequate to define the probable accuracy of the method; but, if a sediment record of adequate length is available, the use of an annual sediment rating curve is probably about as accurate as the flow-duration method of computing average sediment discharge. The annual sediment rating curve can be applied with a small fraction of the work that is required for computations by the flow-duration method. Either method requires the extrapolation of any time trend to the period for which average sediment discharge is to be computed. A time trend is easily defined and readily extrapolated in connection with the use of the annual sediment rating curve. However, the extrapolation may be as inaccurate as a comparable extrapolation for any other method.

For the Colorado River near Grand Canyon, the annual sediment rating curve defined for years of low flow would, when extended upward as a straight line, indicate too little rather than too much sediment discharge in years of high runoff. A frequently mentioned disadvantage of sediment rating curves is that they give too high sediment discharges if they are defined at low flow and then extended upward.

RIO GRANDE AT SAN MARCIAL, N. MEX.

Upstream from San Marcial the Rio Grande has a drainage area of about 27,700 square miles of which nearly 3,000 square miles is in a closed basin. The average flow from 1896 to 1952 was 1,463 cubic feet per second. Much of the flow comes from mountainous areas and is originally nearly free of sediment. Many of the tributaries in New Mexico carry high concentrations of sediment to the Rio Grande. A supply of sand is continually available in the stream bed from San Marcial upstream for at least 150 miles by river. Particularly high concentrations of predominantly fine sediment are contributed to the Rio Grande about 50 and 60 miles upstream from San Marcial by the Rio Salado and the Rio Puerco, respectively. When the flow of these two tributaries is more than a quarter of the flow of the Rio Grande near Bernardo, the concentration at San Marcial is likely to be 20 times as high as it would be for the same flow exclusively from the Rio Grande upstream from the Rio Puerco. Also, during years of low flow such as the water years 1949, 1950, and 1951 about 2/3 of the combined sediment discharge of the Rio Grande near Bernardo, the Rio Puerco near Bernardo, and the Rio Salado near San Acacia may be deposited along the channel of the Rio Grande upstream from San Marcial. Sediment relationships are further complicated because some of the water that came down the Rio Grande during 1952 overflowed into San Marcial Lake. Sediment carried by the overflowing water was either deposited outside of the main channel or else bypassed the sampling and gaging station on the main channel at San Marcial. Also, ungaged washes occasionally discharge into the Rio Grande some flows that contain high sediment concentrations. On the whole, the Rio Grande at San Marcial is a thoroughly unpromising sediment station for which to compute sediment discharges from sediment rating curves.

The study that is reported here was for only the main channel of the Rio Grande.

Analysis

Instantaneous sediment and water discharges for 84 times during water years 1948 through 1951 for the Rio Grande at San Marcial were used to define sediment rating curves and adjustments to them. These data were for sediment and water discharges when sediment samples were collected for size analysis. They were not selected especially for the study, and they did not include information for the 1952 water year for which sediment discharges were to be computed.

The method of study was similar to that outlined for the Niobrara River near Cody, Nebr., and for the Colorado River near Grand Canyon, Ariz. Separate sediment rating curves (fig. 19) were prepared for the sand fraction of the sediment discharge and for the clay and silt fraction. Also shown for comparison is the sediment rating curve for all particle sizes.

For this as well as other sediment stations, the suspended-sediment rating curve for all particle sizes may differ somewhat from a mathematical combination of the curve for discharge of sands and the curve for discharge of silt and clay. One reason for the difference is that the curves were separately defined. A more significant reason is that the suspended-sediment rating curve (all sizes) was not analyzed for possible effects of other factors whereas the curve for sands and the curve for the finer sediments show the relationship between sediment discharge and water discharge after the effect of some other factors had been eliminated or reduced by trial-and-error multiple correlation.

Many size analyses did not show the percentage of the sediment coarser than 0.062 millimeter. For other size analyses, the percentage of sands was too small to be determined accurately. For these reasons the sediment rating curve for suspended sands was not as well defined as it should have been.

Departures of the discharge of sand from the sediment rating curve for the sands varied inversely with about the 3d power of the water temperature and directly with about the 2.6 power of the departures of mean velocity from the average curve of velocity plotted against water discharge.

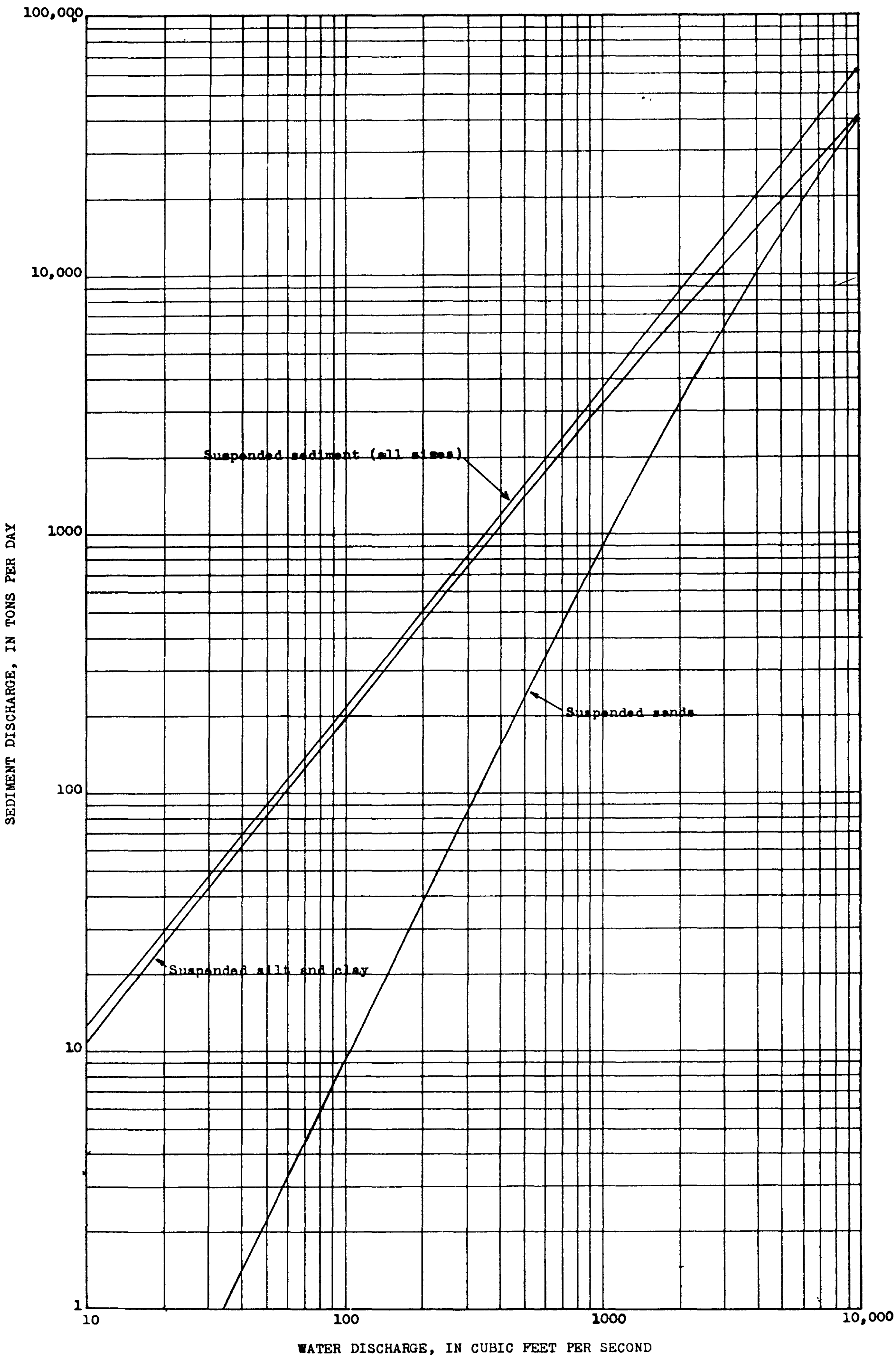

Figure 19.--Instantaneous sediment rating curves for Rio Grande at San Marcial, N. Mex., from data for water years 1949, 1950, and 1951

Discharge of sediment finer than 0.062 millimeter (silt plus clay) varied widely from the sediment rating curve (fines). The most obvious sort of correlation of departures of sediment discharge from the sediment rating curve for fine sediment was with some expression for the relative amount of combined flow from the Rio Puerco and the Rio Salado. Ratios of main channel flow were computed by dividing the flow of the Rio Grande near Bernardo by the sum of the flows of the Rio Grande near Bernardo, the Rio Puerco near Bernardo, and the Rio Salado near San Acacia. For this computation, the total flow of the Rio Grande near Bernardo was used whether the flow was in the Interior drain, the San Francisco riverside drain, or the main channel. A time of travel of water and sediment discharge to San Marcial of 1 day was assumed. When ratios of sediment departure from the sediment rating curve for fine sediments were plotted against ratios of main channel flow, the vaguely defined average curve of figure 20 was obtained.

Whenever the sum of the flows of the Rio Grande near Bernardo, the Rio Puerco near Bernardo, and the Rio Salado near San Acacia was less than 1,000 cubic feet per second and either the Rio Puerco or the Rio Salado was flowing, a larger than usual percentage of the sediment seemed to be deposited along the channel between Bernardo and San Marcial. The curve of figure 21 is poorly defined but was used as the best approximation that could be readily determined for this adjustment.

Trial-and-error multiple correlation indicated that the original sediment rating curve for fine particles should be slightly

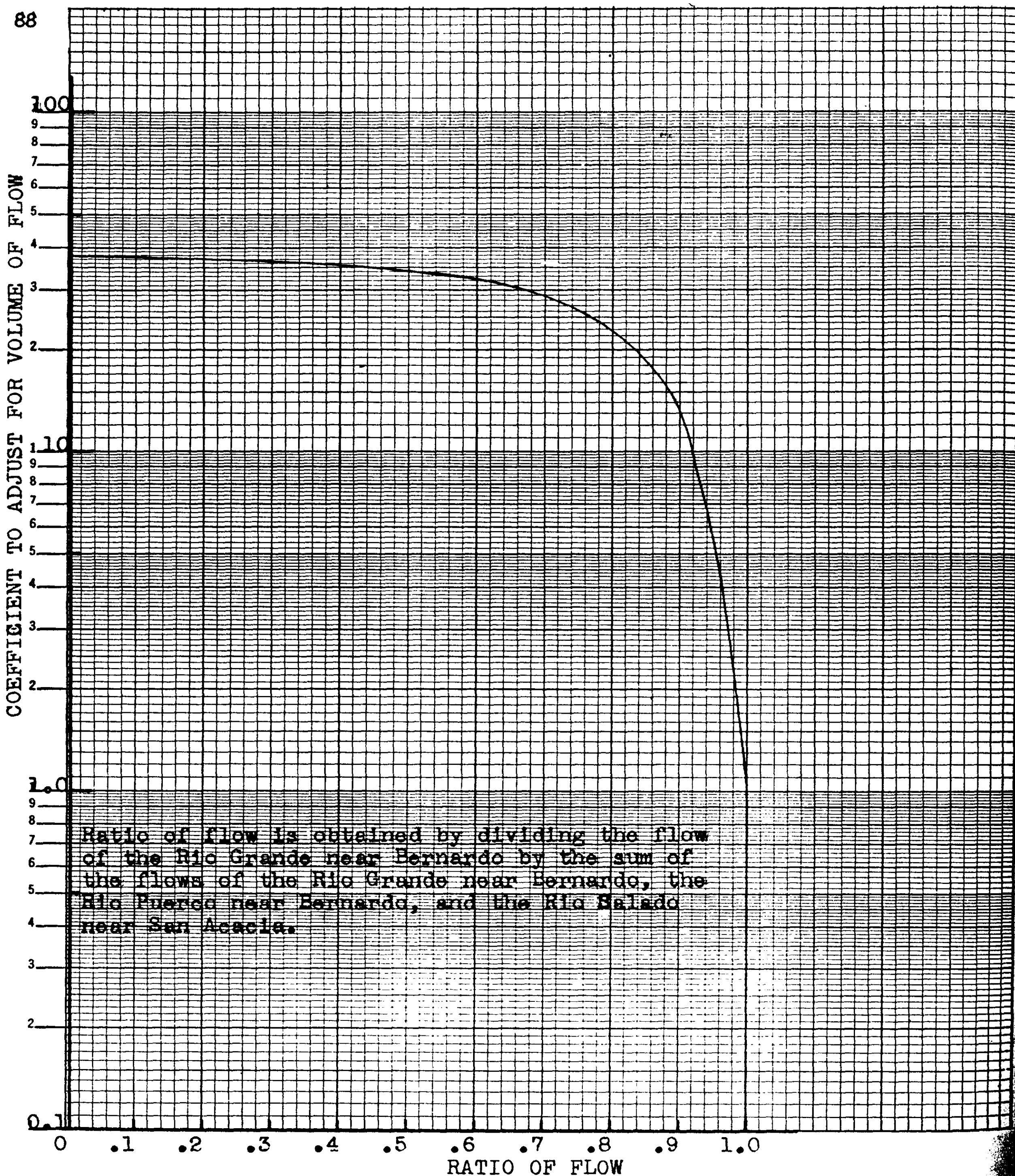

Figure 20.--Adjustment applied to discharge of fines in the Rio Grande at San Marcial, N. Mex., for ratio of main stem flow near Bernardo to total flow below the mouth of the Rio Salado.

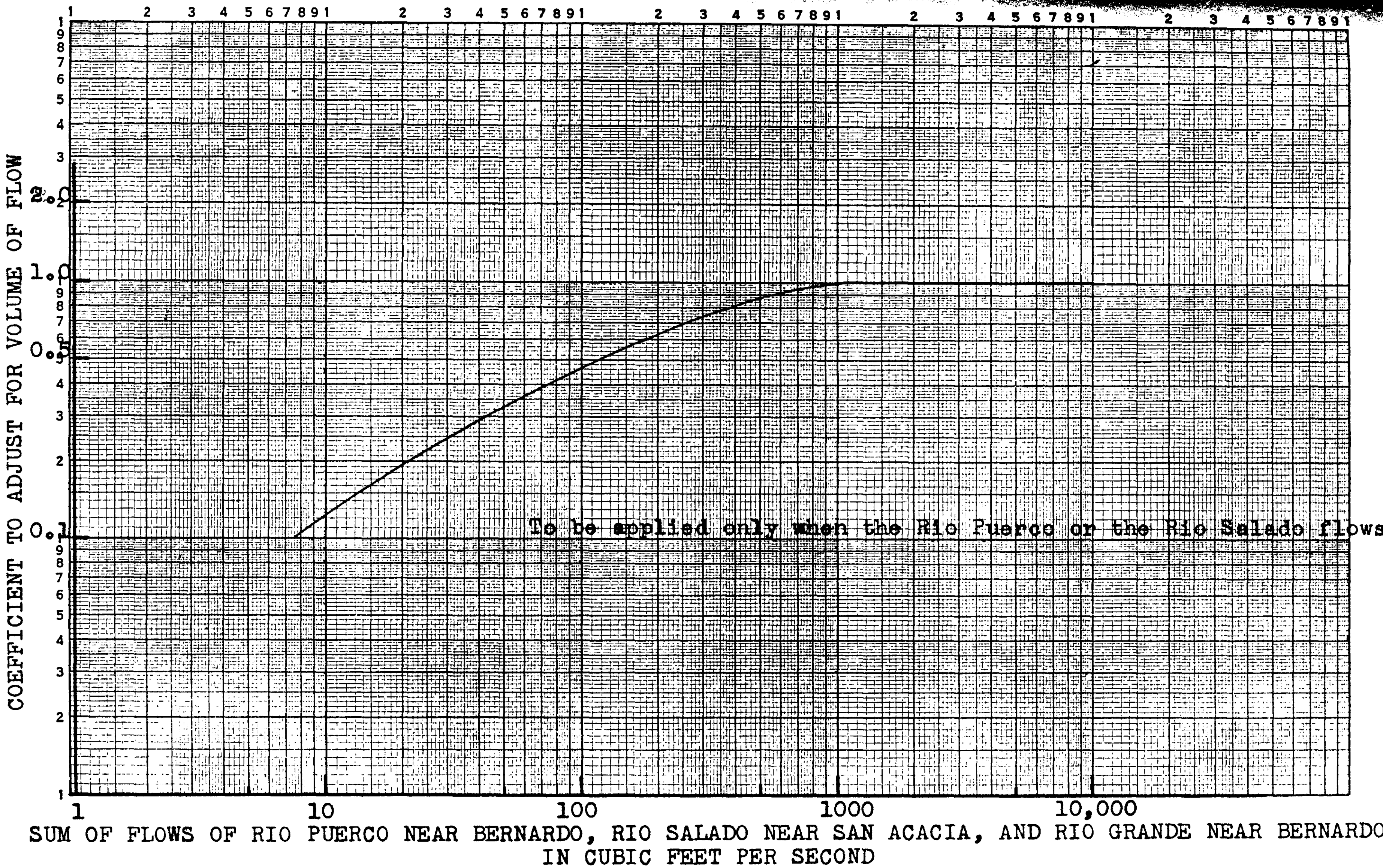

Figure 21 .--Adjustment to discharge of fines for volume of flow in the channel of the Rio Grande at San Marcial, N. Mex.

revised. The sediment rating curve (fines) of figure 19 contains this revision. After all these adjustments had been made, the discharges of fine sediment still tended to decrease with increasing water temperature at a rate slightly less than the square root of the temperature. This relationship may not be significant.

All the adjustments previously discussed were applied whenever discharges of fine sediment were computed from the sediment rating curve (fines).

Instantaneous measured sediment discharges of all particle sizes were plotted against water discharge. The 84 individual points are given on figure 22 to show the scatter. The curve was drawn as an approximate average for periods when the Rio Puerco and the Rio Salado were not flowing. Of course, sediment discharges computed from this curve were used only as a basis from which to make shifts to periodic measurements of sediment discharge. This curve is also shown on figure 19.

Applications

Daily sediment discharges for the Rio Grande main channel at San Marcial during the 1952 water year were computed by several methods. During this water year the sediment discharge from the Rio Puerco and Rio Salado totaled about 4 million tons, which is less than average for the water years 1949, 1950, and 1951. First, daily sediment discharges were computed from the two sediment rating curves, one for fine sediment and one for sands and each curve adjusted by the relationships that were indicated by the correlations. Monthly and annual sediment discharges totaled from the daily tonnages are listed in the second line of table 5. The computed

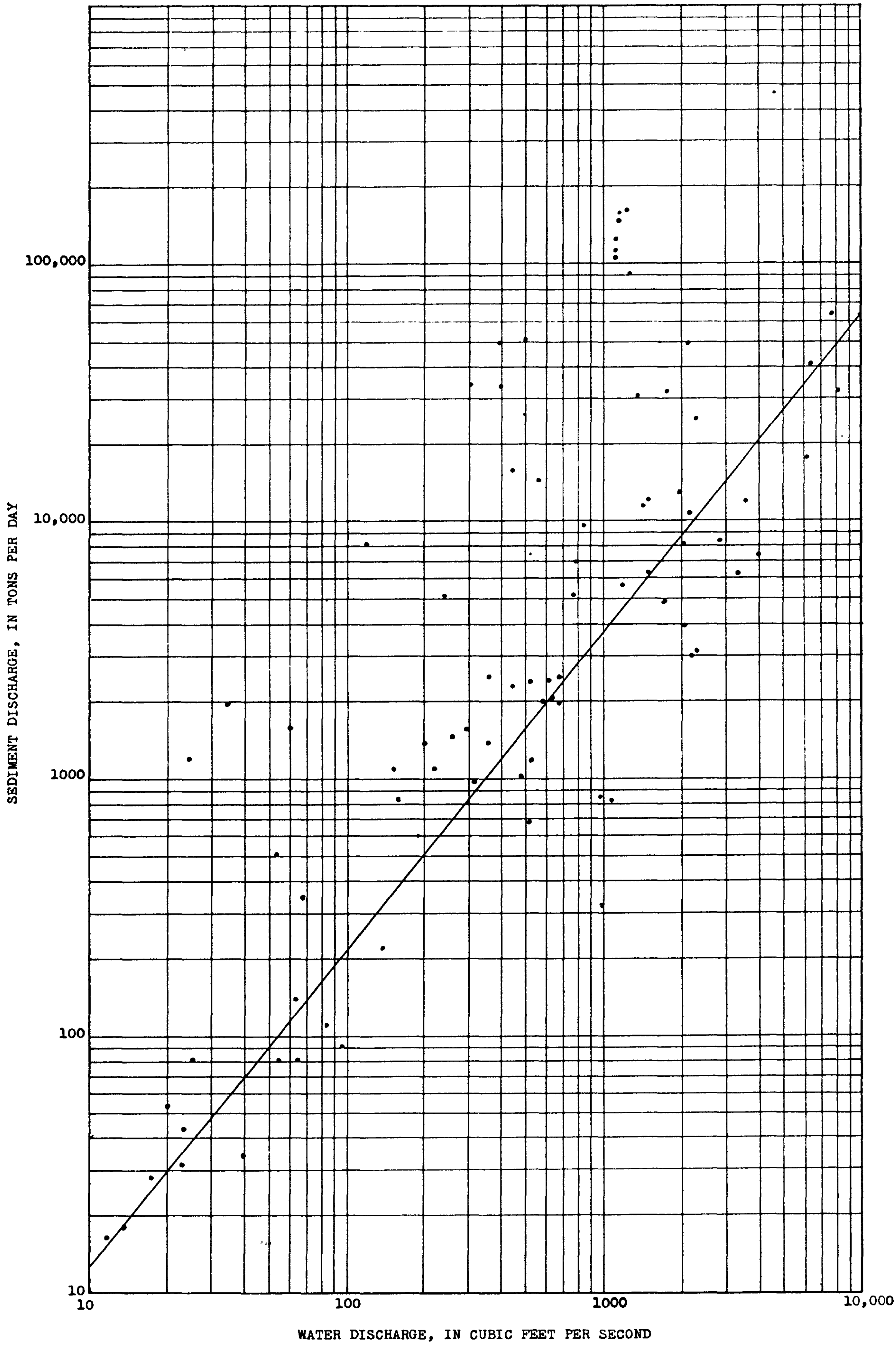

Figure 22.--Instantaneous sediment rating curve for Rio Grande at San Marcial, N. Mex., from data for water years 1949, 1950, and 1951

Table 5.--Monthly and annual sediment discharges, in thousand tons, as computed by different methods for the Rio Grande at San Marcial, N. Mex., for the water year ending September 30, 1952

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
Method 1....	0	0	70.5	321	167	245	589	625	822	1,076	1,417	114	5,446	100
Method 2....	0	0	16	99	59	76	314	725	695	1,100	890	24	4,000	73
Method 4....	0	0	67	359	149	305	604	765	1,070	1,420	1,550	115	6,400	118
Method 5....	0	0	67	289	162	251	642	672	1,090	1,080	1,840	128	6,220	114
Method 6....	0	0	9	51	38	43	193	539	403	138	93	3	1,510	28
Method 8....	0	0	61	217	150	245	550	742	1,500	1,750	1,340	64	6,620	122
Method 9....	0	0	53	254	165	258	636	628	1,220	1,240	1,300	103	5,860	108

Method 1: Daily or more frequent samples.
Method 2: Adjusted sediment rating curves, one for suspended sand and one for silt and clay.
Method 4: Adjusted sediment rating curves with shifts to two daily measured sediment discharges per month.
Method 5: Adjusted sediment rating curves with shifts to four daily measured sediment discharges per month.
Method 6: Unadjusted sediment rating curve.
Method 8: Unadjusted sediment rating curve with shifts to two daily measured sediment discharges per month.
Method 9: Unadjusted sediment rating curve with shifts to four daily measured sediment discharges per month.

annual sediment discharge was 73 percent of the measured sediment discharge of 5.446 million tons. The daily sediment discharges were then shifted to the measured daily discharges for the 1st and 16th days of each month. Next, these daily sediment discharges were shifted to the measured daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month. Monthly and annual tonnages of sediment were much closer to measured tonnages after shifts to 2 measured daily sediment discharges than without such shifts and were brought slightly closer by shifts to 2 additional control points per month. (See table 5.) Annual sediment discharges based on 2 control points per month and 4 control points were 18 percent and 14 percent, respectively, higher than the measured annual sediment discharge.

The instantaneous suspended-sediment rating curve of figure 22 was applied to daily water discharges for the 1952 water year to compute daily, monthly, and annual sediment discharges. This was not an attempt to compute actual sediment discharges; the tonnages were only for a basis from which to shift to periodic daily sediment discharges. Shifts of the computed daily sediment discharges were based on 2 measured daily sediment discharges per month and then on 4 measured daily tonnages per month. Although the unshifted daily sediment discharges from the sediment rating curve totaled only 28 percent of the measured annual sediment discharge, the annual sediment discharges computed from the shifted daily sediment discharges were 22 percent high for 2 control points per month and 8 percent high for 4 control points per month.

Sediment discharges as computed by the different methods were not as close to the measured annual sediment discharges for the Rio Grande at San Marcial as they were for the Niobrara River near Cody, Nebr., or for the Colorado River near Grand Canyon, Ariz. During the first 5 months of flow in the water year, the measured sediment discharge was much higher than that computed from sediment rating curves. This difference was probably due to deposit of sediment below the mouth of the Rio Puerco and above San Marcial during the 1951 water year. During this water year, about 7.5 million tons of sediment was discharged from the Rio Salado and the Rio Puerco, but only about 1 million tons was discharged past the San Marcial gaging station. Sediment discharges obtained by shifting to 2 or to 4 control points during each month compared fairly well with computed monthly sediment discharges for these first 5 months of flow during the water year.

None of the methods of computation gave consistently good monthly sediment discharges during the summer months. Shifting of daily sediment discharges to 2 measured daily loads per month increased the accuracy somewhat during the summer months. Shifting to 4 measured daily loads per month increased the accuracy during some summer months over the accuracy for only 2 control points. Exceptions were August and, to a lesser degree, September.

Agreement by months was generally better for sediment discharges that were computed by shifting daily sediment discharges from two separate, adjusted sediment rating curves than by shifting daily sediment discharges from a single, unadjusted sediment rating curve. Because of a few large discrepancies in monthly sediment discharges, annual sediment discharges computed by shifting from a single curve were closer to measured annual sediment discharges than were the annual sediment discharges that were computed by shifting from the two sediment rating curves. Annual sediment discharges computed by shifting to either 2 or 4 control points per month are from 8 to 22 percent larger than the measured annual sediment discharge. (See table 5.)

The 2 sets of daily sediment discharges obtained by shifting to 4 control points per month are plotted on plate 4. Measured sediment discharges are plotted for comparison. Wide differences from day to day in sediment discharge at San Marcial are very apparent especially during the summer. In spite of these differences, the accuracy of daily sediment discharges that were computed by shifting to four control points per month is reasonably good. (See fig. 23.) More than 40 percent of the days were within about 10 percent and more than 60 percent of the days within about 20 percent of the measured daily sediment discharges. Inaccuracy of the measured daily sediment discharges, themselves, is unknown but is by no means insignificant.

Discrepancies between computed and measured monthly sediment discharges during the summer are due to differences in sediment discharge for a few days of high sediment discharge. Obviously, the monthly and annual agreement would have been much improved by a few samples on certain days of unusually high sediment discharge; for example, June 3 or 4 and August 24 or 25. The daily sediment discharge for August 23 was used as a basis for shifts but was a day of rapidly rising sediment discharge for which the

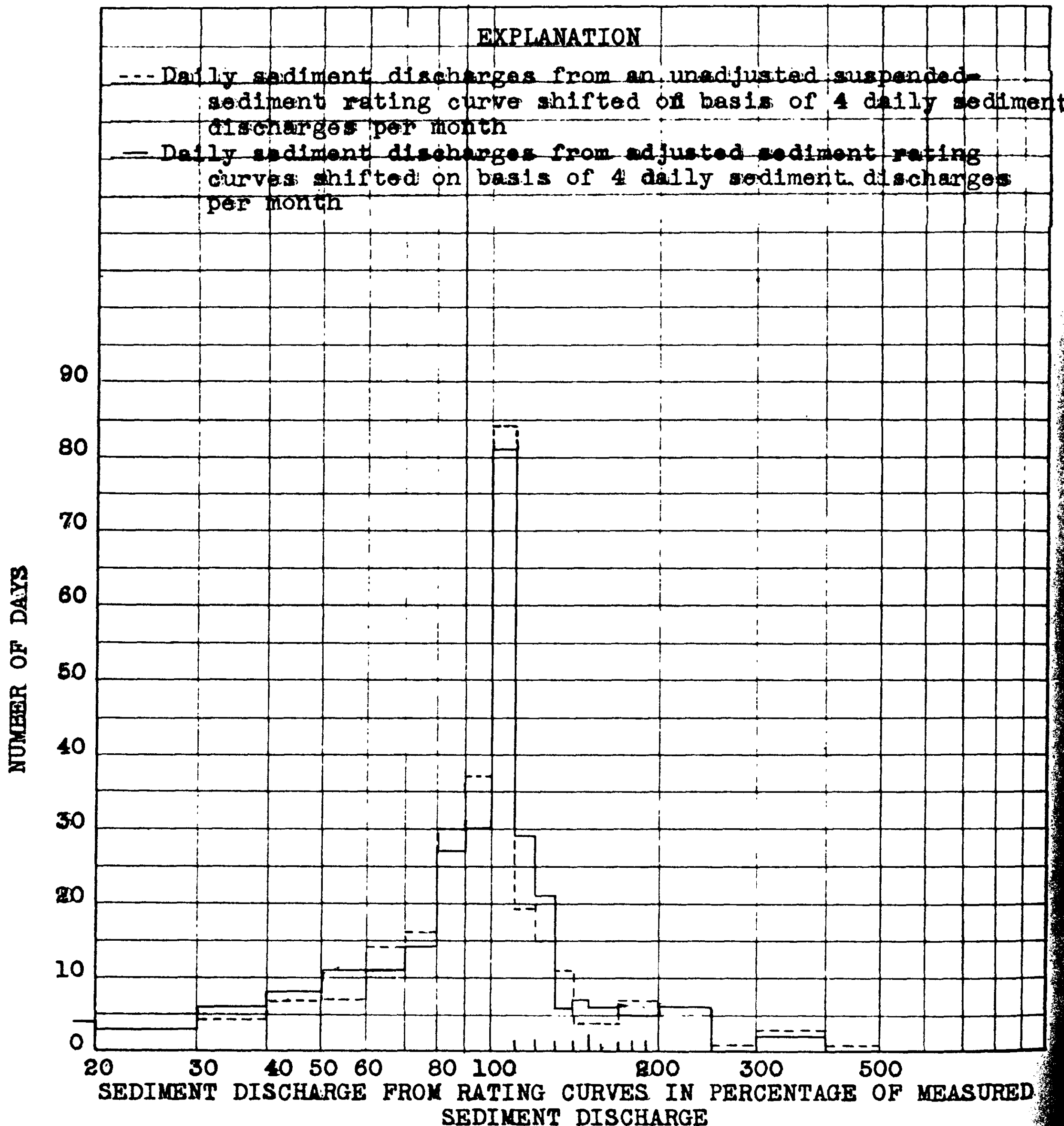

Figure 23.--Percentage comparison of daily sediment discharges computed from shifted rating curves with measured sediment discharges, Rio Grande at San Marcial, N. Mex., 1952 water year.

correlation adjustments to the sediment rating curve for fine sediments was evidently misleading. Of course, the daily sediment discharges that were used as the basis for shifts were selected arbitrarily. Any other basis of selection would likely be biased through assuming either better or poorer field operations than might actually be obtained in practice.

RIO PUERCO NEAR BERNARDO, N. MEX.

The Rio Puerco drains an area of nearly 6,000 square miles west of the Rio Grande. The main stream and most tributaries flow intermittently. Runoff comes principally from summer storms. During many years, snowmelt supplies little or no flow at the station near Bernardo, which is 3 miles upstream from the mouth. Runoff is extremely variable from year to year and is also unevenly distributed within each year. Because the distribution of flow is erratic and the stream bed shifts laterally and vertically, streamflow records are inaccurate. Annual runoff averages a small fraction of an inch.

Suspended sediments discharged by the Rio Puerco near Bernardo are mostly in the size ranges of clay and silt. The concentration of suspended sediment for all except very low flows is unusually constant percentagewise with respect both to time and to water discharge. This constancy is shown by the relatively narrow band of scatter of points from the average line of figure 25 and by the slope of the line, which only slightly exceeds 45 degrees. The relatively constant concentrations are probably due to the drainage area being reasonably uniform in erosional characteristics and to the runoff being generated almost entirely by summer storms rather than by several different types of precipitation. However, runoff from the upper San Jose River usually has much lower concentrations of sediment than runoff from most other parts of the Rio Puerco drainage area.

A few computations of sediment discharge were made for the Rio Puerco near Bernardo because the water-sediment discharge relationship is considerably different for this station than for the others that were studied. The concentrations are not only unusually constant but are also high, being in the order of 100,000 to 250,000 ppm for most flows greater than 100 cubic feet per second. Sediment characteristics of the flow may be somewhat typical of many intermittent streams that drain dry areas from which snow runoff is usually negligible.

Analysis

Annual sediment discharges were plotted against annual average flow to define the annual sediment rating curve of figure 1. Sediment discharges were available for so few water years that no attempt was made to explain scatter from the annual sediment rating curve by correlations.

A monthly sediment rating curve, also plotted on figure 1, was prepared. Departures of the monthly sediment discharges from the curve indicated a seasonal change in the relationship between monthly average discharge of sediment and of water. Ratios of departure are plotted against time during the water year on figure 24.

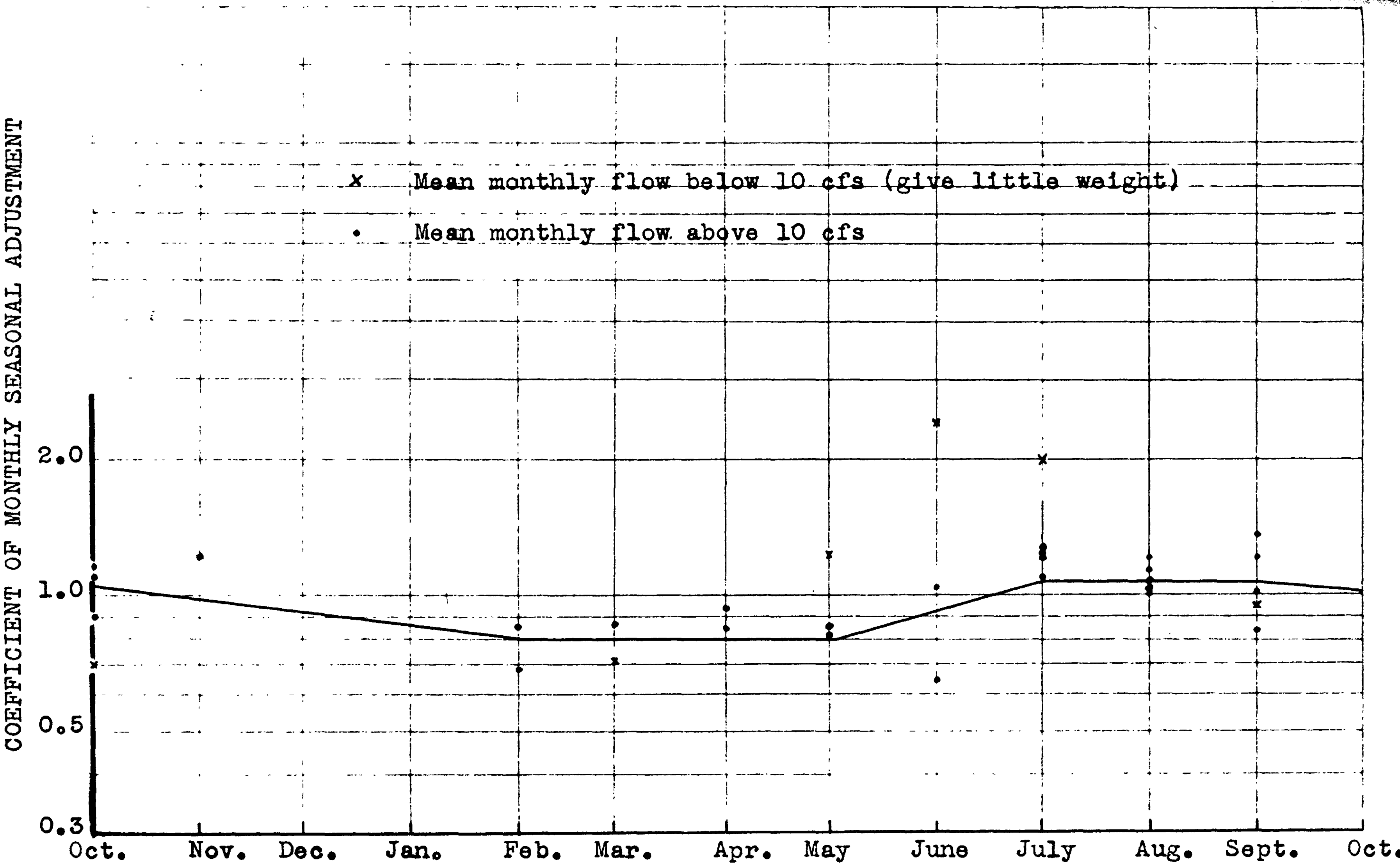

Figure 24.--Monthly seasonal adjustment to suspended-sediment discharge, Rio Puerco near Bernardo, N. Mex.

Sediment discharges generally were lower for a given monthly average discharge during the winter and spring than during the summer.

An instantaneous sediment rating curve was prepared from the concentrations and rates of flow at the times when samples were collected for particle-size analyses. A daily sediment rating curve (fig. 25) was defined from daily average sediment discharge and daily average water discharge for those days on which size samples were collected. The instantaneous and the daily sediment rating curves agree within the limits of their probably accuracy. (See fig. 1.) Such agreement may be expected at a station where either the concentration, as for the Rio Puerco near Bernardo except at low flows, or the rate of water discharge, as for the Niobrara River near Cody or the Colorado River near Grand Canyon, does not change rapidly percentagewise. Comparable agreement can not be expected for all streams.

Probably part of the scatter of points from the instantaneous and daily sediment rating curves could be explained in terms of either seasonal variations or recession curves for decrease in concentration following rises.

Applications

Daily discharges of suspended sediment were computed for the 1952 and 1953 water years from the daily sediment rating curve. Monthly and annual sediment discharges were computed from these daily sediment discharges. Monthly and annual sediment discharges for the 2 water years were also computed from the monthly sediment rating curve and seasonal adjustments to it. An annual sediment

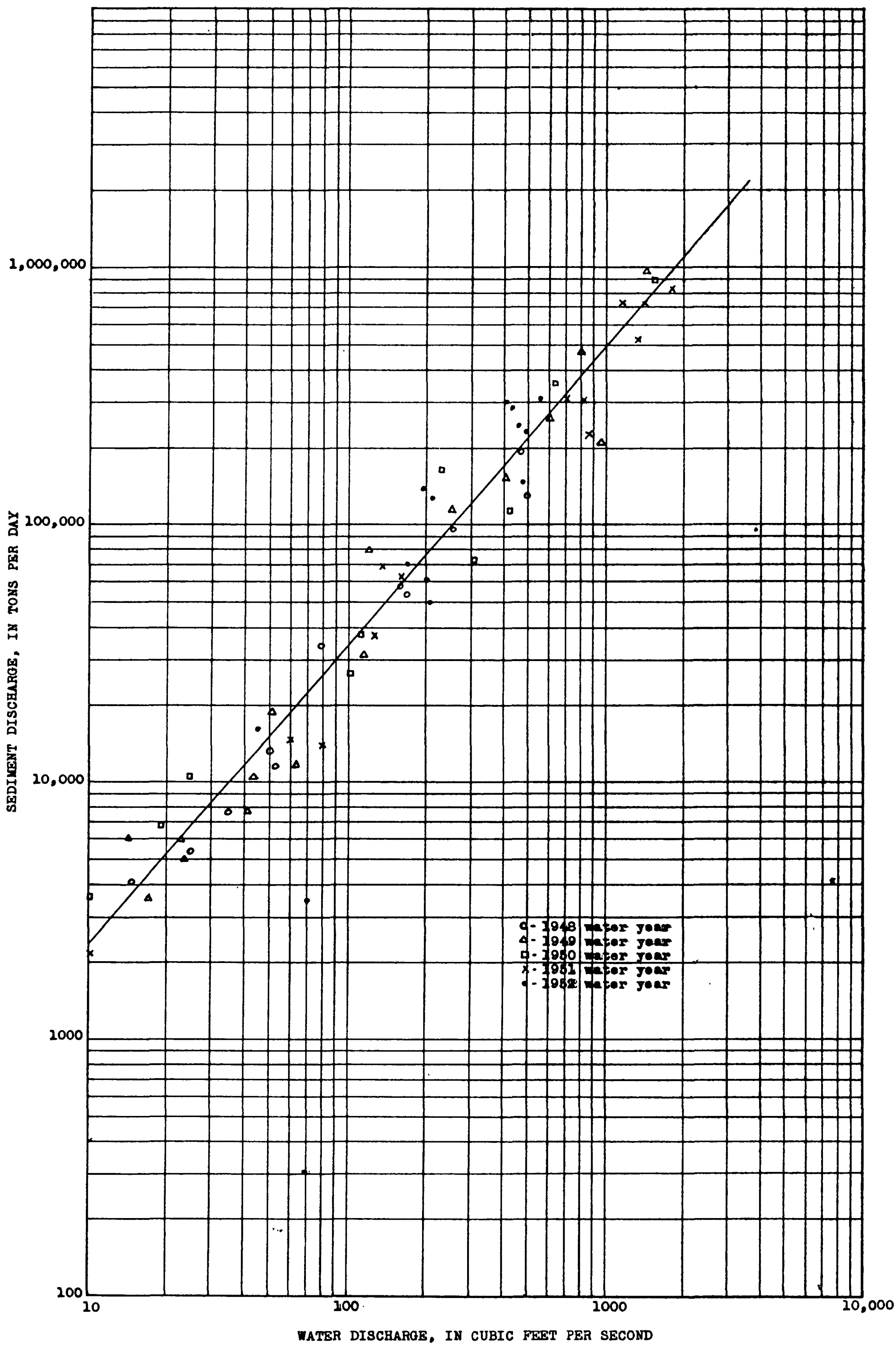

Figure 25.--Daily sediment rating curve, Rio Puerco near Bernardo, N. Mex.

discharge for the 1953 water year was taken from the annual sediment rating curve. An annual sediment discharge for the 1952 water year was not taken from the annual curve because the annual sediment discharge for the 1952 water year was used to help define the annual curve. Computed monthly and annual tonnages, and the measured sediment discharges for comparison, are listed in table 6.

For both the 1952 and the 1953 water years, the monthly and annual sediment discharges computed from the monthly rating curve gave good comparisons with the measured sediment discharges. The computed annual tonnages were 10 percent lower and 10 percent higher than the measured annual tonnages for the 1952 and 1953 water years, respectively.

The annual sediment discharge for the 1953 water year from the annual sediment rating curve was 98 percent of the measured annual tonnage.

For the 1953 water year monthly and annual sediment discharges computed from the daily sediment rating curve compared less well with measured tonnages of sediment than those from the monthly curves perhaps because no seasonal or other adjustments were applied. Computed annual tonnages from the daily sediment rating curves differed from the measured annual tonnages by a -12 percent for the 1952 water year and by a +16 percent for the 1953 water year.

Daily sediment discharges computed from the daily sediment rating curve agreed reasonably well with measured daily tonnages. Agreement was somewhat closer for the 1952 water year than for the

Table 6.--Monthly and annual sediment discharges, in thousand tons, as computed by different methods for the Rio Puerco near Bernardo, N. Mex.

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of Measured
Water year ending September 30, 1952														
Method 1....	0	0	0	0	0	0	0	77	290	1,185	1,204	197	2,953	100
Method 6....	0	0	0	0	0	0	0	72	410	1,020	920	190	2,610	88
Method 10....	0	0	0	0	0	0	0	50	340	1,080	1,040	150	2,660	90
Water year ending September 30, 1953														
Method 1....	0	0	0	0	0	0	0	0	27	3,607	3,286	83	7,003	100
Method 6....	0	0	0	0	0	0	0	0	38	4,810	3,200	96	8,140	116
Method 10....	0	0	0	0	0	0	0	0	26	4,340	3,260	73	7,700	110
Method 11....	-	-	-	-	-	-	-	-	-	-	-	-	6,860	98

Method 1: Daily samples with more frequent samples on many days.
Method 6: Daily unadjusted sediment rating curve.
Method 10: Monthly sediment rating curve with seasonal adjustment.
Method 11: Annual sediment rating curve.

1953 water year for which graphs of both computed and measured daily sediment discharges are shown on plate 5.

Measured sediment discharges for the 1953 water year for the Rio Puerco near Bernardo have not been reviewed and may be revised somewhat before publication.

Only a few years of sediment record were sufficient to define sediment rating curves from which reasonably accurate daily, monthly, and annual sediment discharges could be computed. At least the computed monthly and annual sediment discharges for the 1952 and 1953 water years are probably within the limits of accuracy of the streamflow records. Of course, over a period of years or during years of much higher flow, the relationship between sediment discharge and water discharge may be different than during water years 1948 through 1953.

Comparisons of computed and measured sediment discharge for the Rio Puerco near Bernardo suggest the possibility of computing satisfactory sediment discharges for some intermittent streams and washes in semiarid areas from periodic sediment sampling and sediment rating curves.

WHITE RIVER NEAR KADOKA, S. DAK.

Upstream from the gaging station near Kadoka, the White River drains 5,000 square miles partly in northwestern Nebraska but mostly in southern South Dakota. Runoff is low and variable, occurs mainly during May and June, and averages less than 1 inch annually. Sediment yield is not exceptionally high from the upper part of the drainage basin, but downstream nearer Kadoka considerable areas of badlands and readily erodible alluvium yield large quantities of fine sediments whenever appreciable surface runoff occurs.

Computations of sediment discharge were made for the White River near Kadoka because the sediments that are discharged at this station are predominantly fine but do contain enough sands to define a rating curve for sands. Also, the station has ice backwater for several months each year. The flow, being unevenly distributed within the year, is entirely different than for the Niobrara River near Cody, Nebr.

Analysis

Sediment concentrations and water discharges at the times when samples were collected for particle-size analysis during the water years 1949, 1950, and 1951 formed the principal information for defining and analyzing the sediment rating curve. An instantaneous suspended-sediment rating curve (fig. 26) was prepared. Then each sediment discharge was subdivided into discharge of sands and of sediment finer than 0.062 millimeter. Instantaneous sediment rating curves were drawn (fig. 27) for discharge of suspended sands and for discharge of clay and silt.

Departure ratios of discharge of suspended sands from the rating curve for sands showed approximate correlation with the 2.1 power of ratios of measured velocities to velocities from an average curve of velocity versus water discharge. After

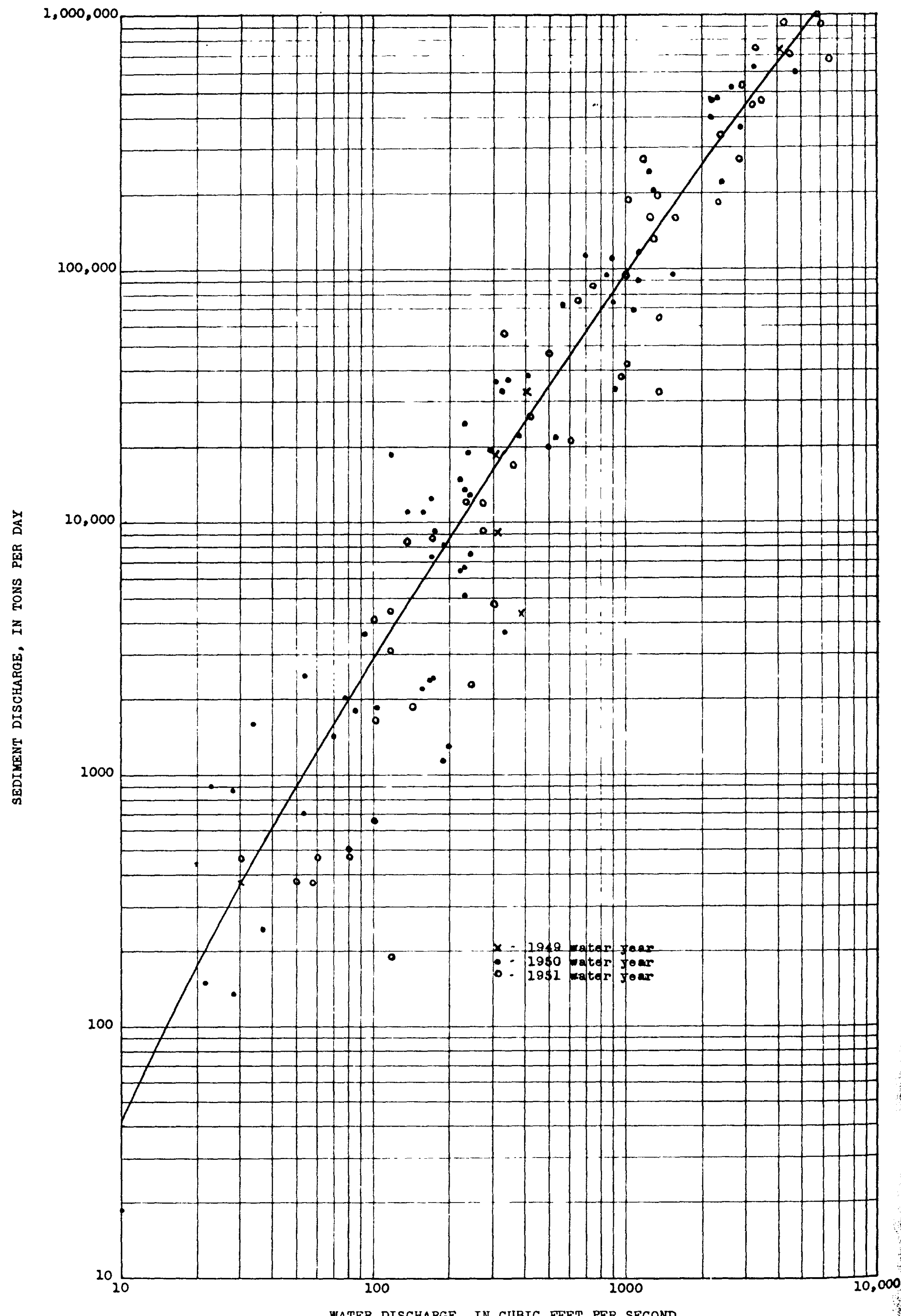

Figure 26.--Instantaneous sediment rating curve from concentrations of size samples, White River near Kadoka, S. Dak.

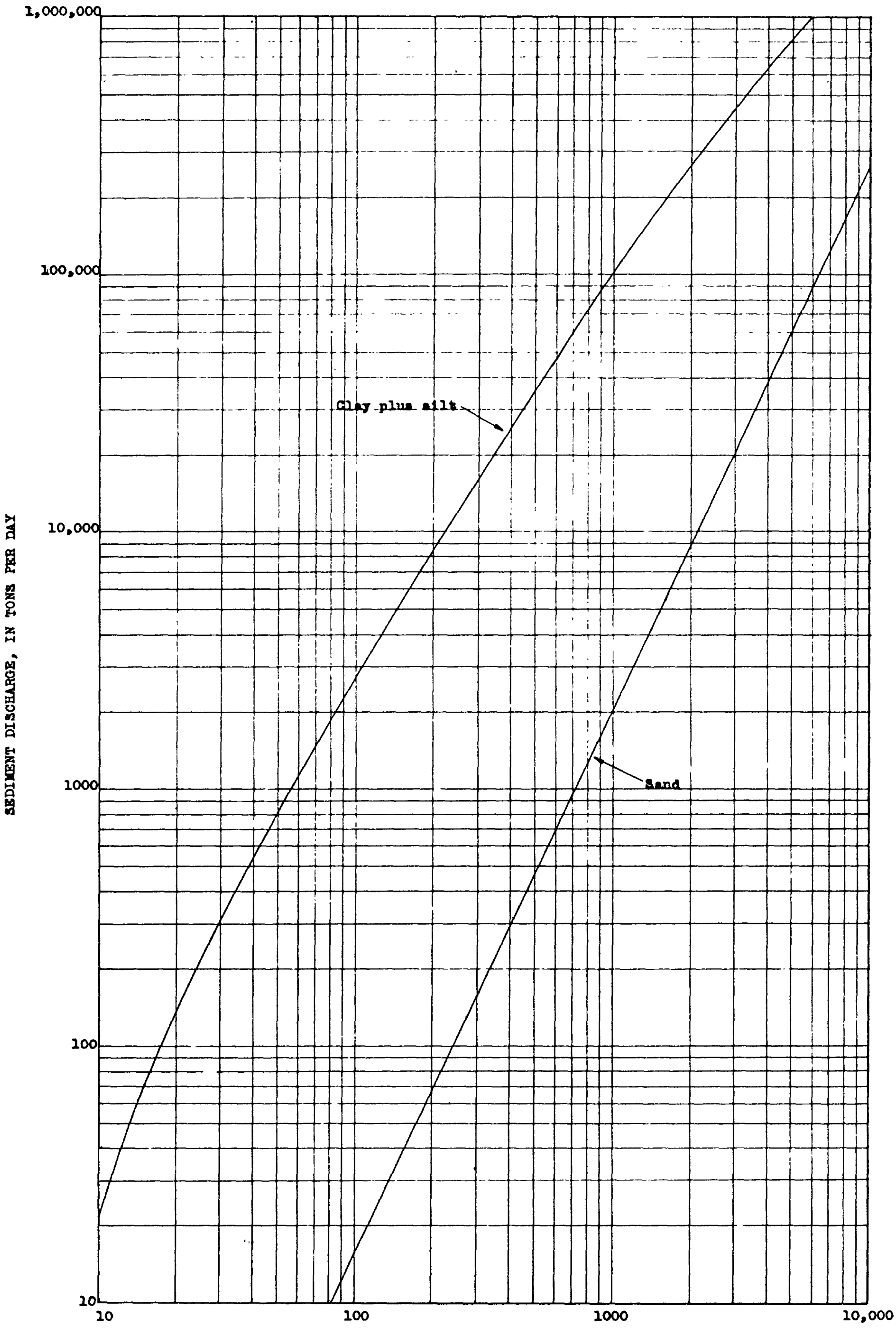

Figure 27.--Instantaneous sediment rating curves for sands and for combined clay and silt, White River near Kadoka, S. Dak.

adjustment for velocity, the ratios of departure did not define satisfactorily a relation between discharge of suspended sands and water temperature.

Discharge of the fine sediment for a given rate of flow was lower during the winter and spring than during the summer and early fall. (See fig. 28.) Also, the concentration of fine sediment tended to be higher during a rapidly rising water discharge and at the peak of the flow than during the recession from the peak. The first curve expressing adjustments of discharge of fine sediments with elapsed time after a rise was based only on the instantaneous sediment discharges. This curve seemed to be unrepresentative. Presumably, this fact was due to the curve being based on concentrations of samples that were collected for particle-size analysis. At low flows such samples were collected infrequently and usually when the concentration was higher than usual for the given flow. Daily sediment discharges from the 1951 water year were used to revise the lower end of the original curve. The final curve for adjustments of discharge of fine sediment with elapsed time is shown on figure 29. Of course adjustments from figure 29 can be applied either before or after those from figure 28.

The curves of figures 28 and 29 and the instantaneous sediment rating curve for silt and clay on figure 27 are mutually interdependent for a given interrelation between the discharge of fine sediment and water discharge. If the position of one of these curves is appreciably moved to show either a generally higher or a generally lower sediment discharge, the position of

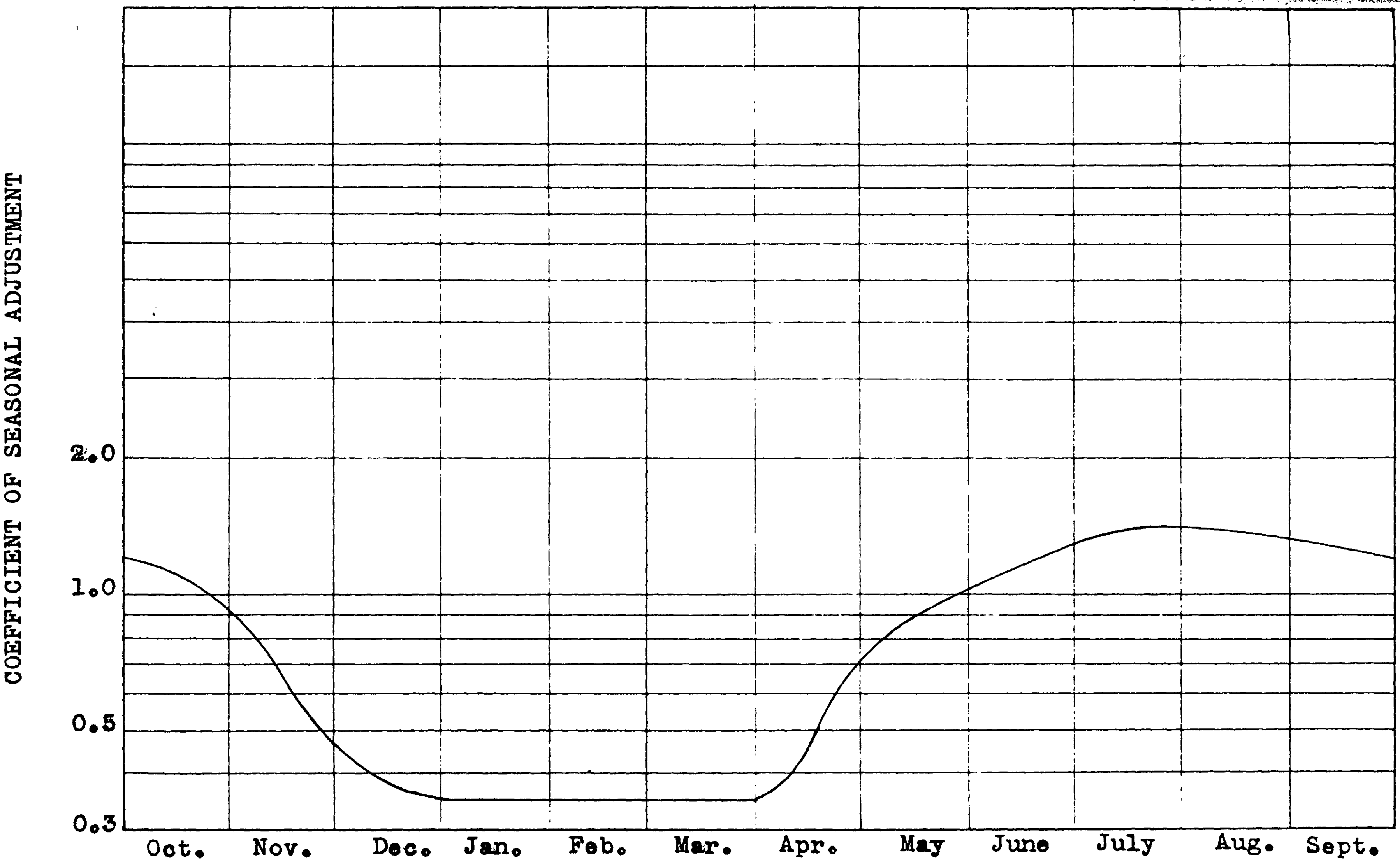

Figure 28.--Seasonal adjustment to discharge of sediment in clay and silt sizes, White River near Kadoka, S. Dak.

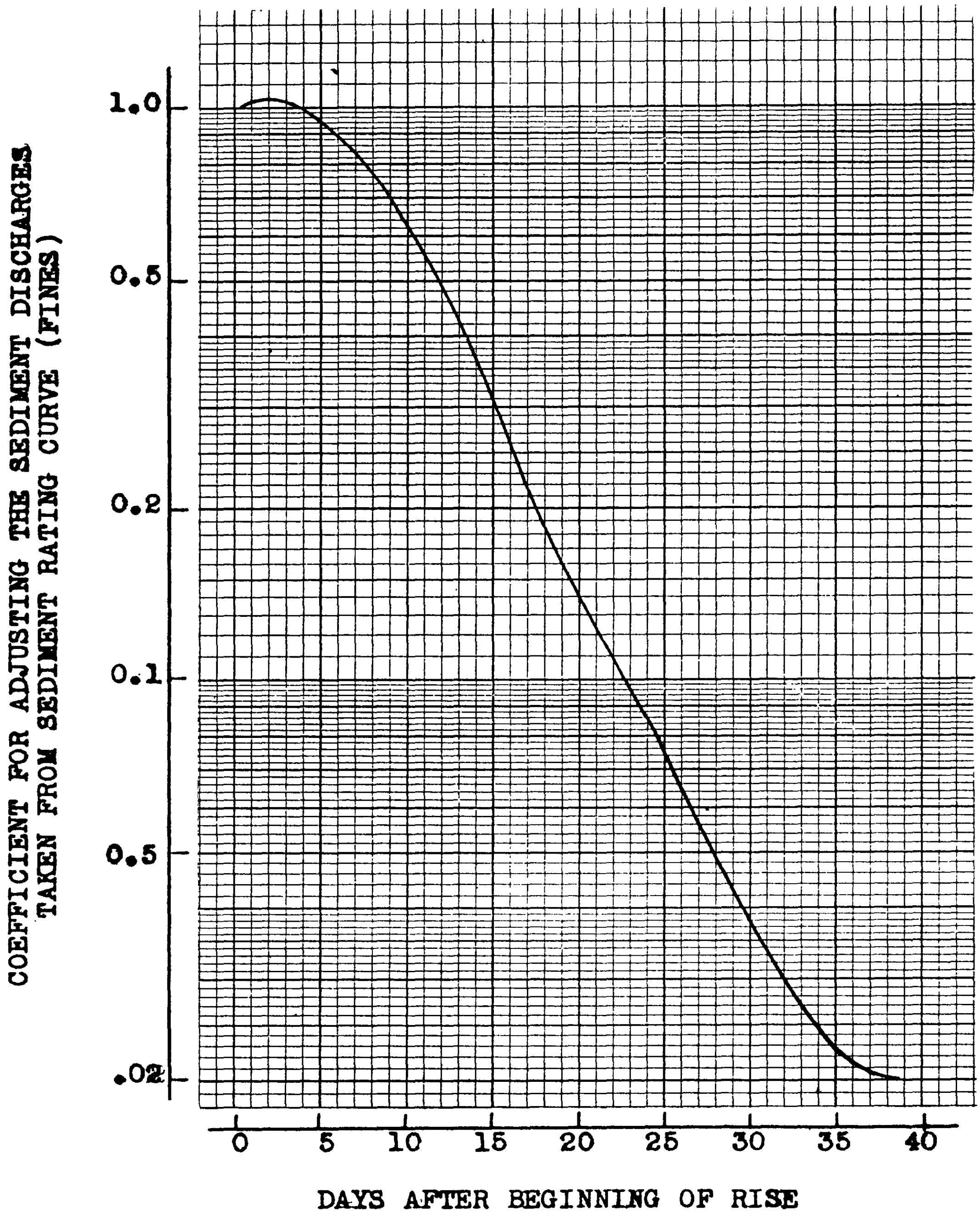

Figure 29.--Approximate average variation of coefficient of sedimen discharge (fines) with elapsed time after beginning of a rise, White river near Kadoka, S. Dak.

one or both other curves theoretically should be moved a compensating amount.

Applications

Daily sediment discharges were computed for the water year ending September 30, 1952, by the following six procedures:

1. The instantaneous sediment rating curves for fine sediment and for suspended sands were applied separately to daily water discharges, and the computed sediment discharges were added together. (See table 7, method 2.) Of course, seasonal and other adjustments were included in the computations.

2. Daily sediment discharges computed by procedure 1 were shifted to measured daily sediment discharges for the 1st and 16th days of each month.

3. Daily sediment discharges computed by procedure 1 were shifted to measured daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month.

4. The instantaneous suspended-sediment rating curve was applied to daily water discharges.

5. Daily sediment discharges computed by procedure 4 were shifted to measured daily sediment discharges for the 1st and the 16th days of each month.

6. Daily sediment discharges computed by procedure 4 were shifted to measured daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month.

These procedure numbers do not correspond to the method numbers in the footnotes of table 7 because the method numbers are

Table 7.--Monthly and annual sediment discharges, in thousand tons, as computed by different methods for the White River near Kadoka, S. Dak., for the water year ending September 30, 1952

Procedure	Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
....	Method 1....	119	1.58	0.41	0.10	62.4	1,125	205	3,513	1,946	134	24.2	0.008	7,131	100
1	Method 2....	122	7.5	2.8	.07	210	2,060	335	4,150	2,490	161	8.7	0	9,550	134
2	Method 4....	72	2.7	.38	.08	101	1,030	213	2,750	1,500	142	30	.005	5,840	82
	Method 5....	159	2.5	.35	.07	66	956	231	3,170	1,610	141	36	.005	6,370	89
	Method 6....	105	35.8	11.4	5.1	766	4,930	1,200	4,140	2,100	155	7.8	0	13,500	189
5	Method 8....	78	3.6	.31	.09	49	932	221	4,210	2,040	149	26	.005	7,710	108
6	Method 9....	179	1.2	.31	.09	51	889	221	3,320	2,020	149	38	.005	6,870	96

Method 1: Daily samples.
Method 2: Adjusted sediment rating curves, one for suspended sands and one for silt and clay.
Method 4: Adjusted sediment rating curves with shifts to two daily measured sediment discharges per month.
Method 5: Adjusted sediment rating curves with shifts to four daily measured sediment discharges per month.
Method 6: Unadjusted sediment rating curve.
Method 8: Unadjusted sediment rating curve with shifts to two daily measured sediment discharges per month.
Method 9: Unadjusted sediment rating curve with shifts to four daily measured sediment discharges per month.

kept the same throughout the tables of monthly and annual sediment discharge for all sediment stations.

Monthly and annual sediment discharges were computed from the daily sediment discharges that were obtained by all six procedures and are given in table 7. Annual sediment discharge from procedure 1 was 34 percent higher and that from procedure 4 was 89 percent higher than the measured annual sediment discharge. When shifts were made to 2 control points per month (procedures 2 and 5) the differences between computed annual and measured annual sediment discharges were -18 percent and +8 percent. Shifting to 4 control points per month (procedures 3 and 6) reduced these differences to -11 and -4 percent.

Most monthly sediment discharges based on shifted daily sediment discharges were fairly close to measured monthly sediment discharges. For October the monthly sediment discharges that were computed by either procedure 1 or 4 agreed well with the measured discharges before shifting but agreed less well after shifting. (See table 7.)

Daily sediment discharges computed by procedures 1 and 2 are plotted on plate 6. Measured daily sediment discharges are also plotted for comparison. Accuracy of computed daily sediment discharges for some periods is much improved by shifting to two measured daily sediment discharges per month.

SANDUSKY RIVER NEAR FREMONT, OHIO

An area of 1,248 square miles in northcentral Ohio is drained by the Sandusky River upstream from the station near Fremont.

The river has many branching tributaries, which drain areas that are probably somewhat similar in erodibility. Average annual runoff is 10 inches or slightly more. Most of the flow is during winter and spring. Vegetal cover is much more complete in the basin than in the drainage basins of the other streams that have been included in this study. Concentrations of sediment for the 1952 water year averaged only 274 ppm or 0.372 ton per acre-foot of water. Only a few percent of the suspended sediment was larger than 0.062 millimeter.

Analysis

Because nearly all the sediment was smaller than sand sizes and few size analyses were available, no attempt was made to subdivide the sediment discharge into suspended sands and suspended clay plus silt. A suspended-sediment rating curve (fig. 30) was prepared from the daily water and sediment discharges for the water year ending September 30, 1951. Ratios of departure of the sediment discharge from the average curve were plotted against time. They defined the approximate seasonal trend of figure 31. Then ratios of departure of sediment discharge were adjusted for the seasonal trend and were plotted against the time in days after the beginning of each rise. A marked tendency for sediment discharge to decrease with time after the beginning of a rise was clearly shown, but the amount of the decrease could be defined only as an approximate average. During the winter period, November through March, the decrease continued for many

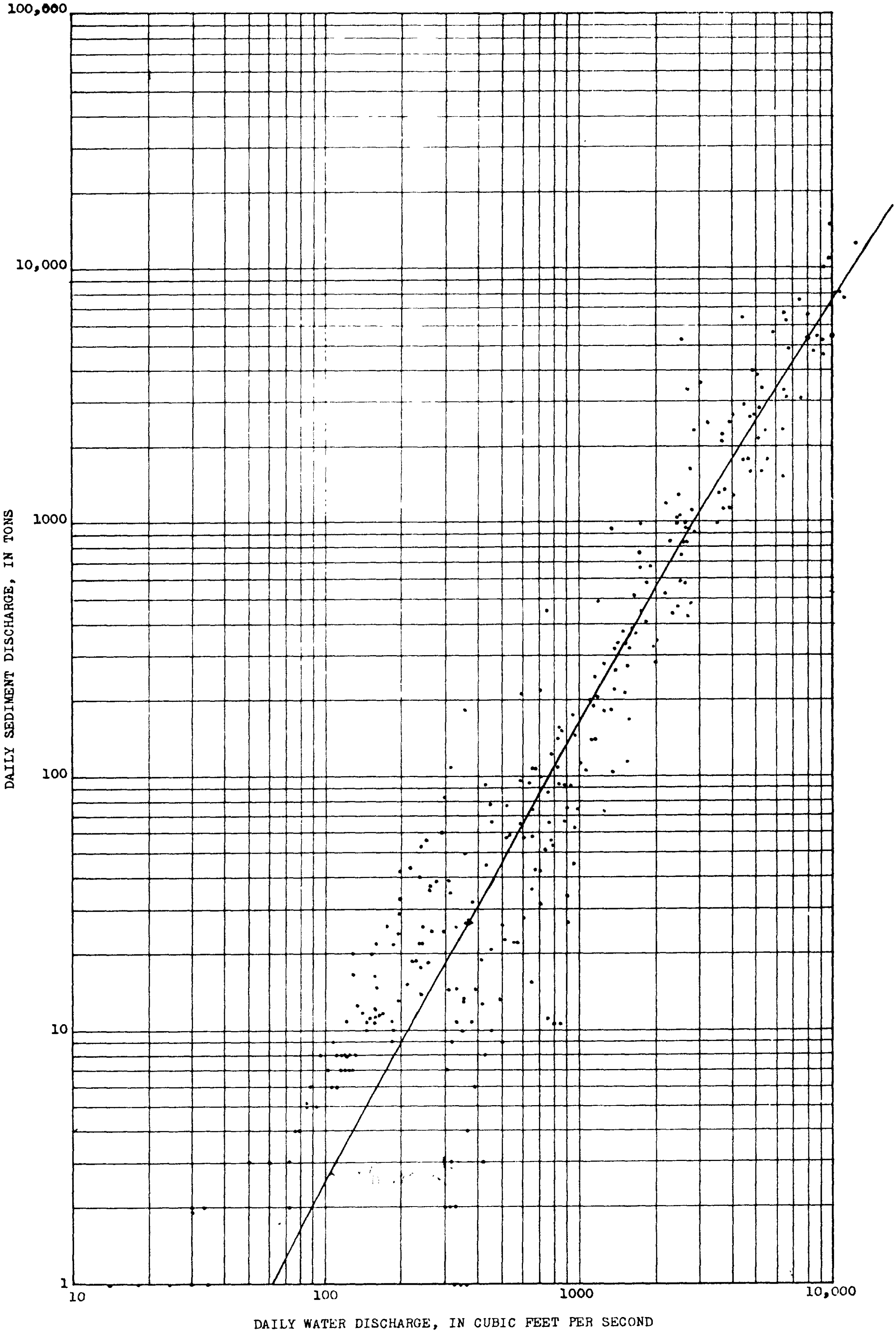

Figure 30.--Daily sediment rating curve for Sandusky River near Fremont, Ohio, 1951 water year

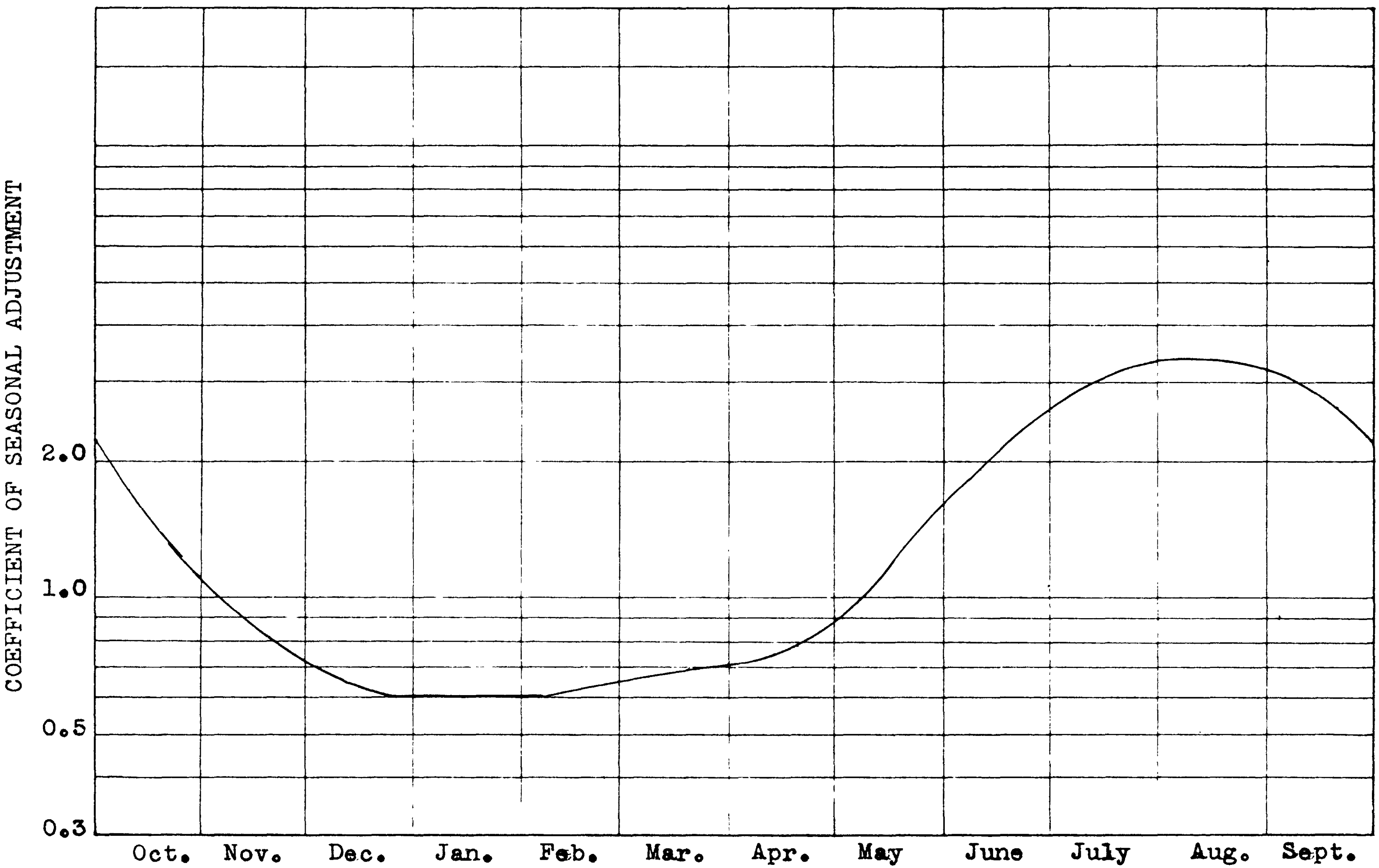

Figure 31.--Seasonal adjustment to suspended-sediment discharge, Sandusky River near Fremont, Ohio

days after each rise. During the other months of the year, the sediment discharge did not seem to decrease much after about 6 days. (See fig. 32.)

No doubt better adjustments than those discussed here could be determined by further study of the sediment characteristics of the Sandusky River. Such study might well improve by a few percent the accuracy of the sediment discharges that are computed from the sediment rating curve and the adjustment curves of figures 31 and 32. However, additional study probably would not appreciably increase the accuracy of sediment discharges that are computed by shifting the sediment rating curve to two or more control points per month.

The difference between the adjustment that is indicated by figure 32 and the adjustment of figure 29 for the White River near Kadoka, S. Dak., should be noted. The sediment rating curve (fines) for the White River was drawn for sediment discharges that represented about peak flows, and hence the adjustment of sediment discharge for peak flows was relatively small. On the other hand, the sediment rating curve for the Sandusky River was drawn through sediment discharges that were more representative of several days after the peak flows. Therefore, adjustment coefficients for sediment discharges near the peak flows were high, about 2.0 on the average, and generally did not decrease to 1.0 until about the 6th day after the rise. The suspended-sediment rating curve for the Sandusky River can be expected to give low sediment discharges without adjustments or shifts, whereas the sediment rating curve for the White River will give

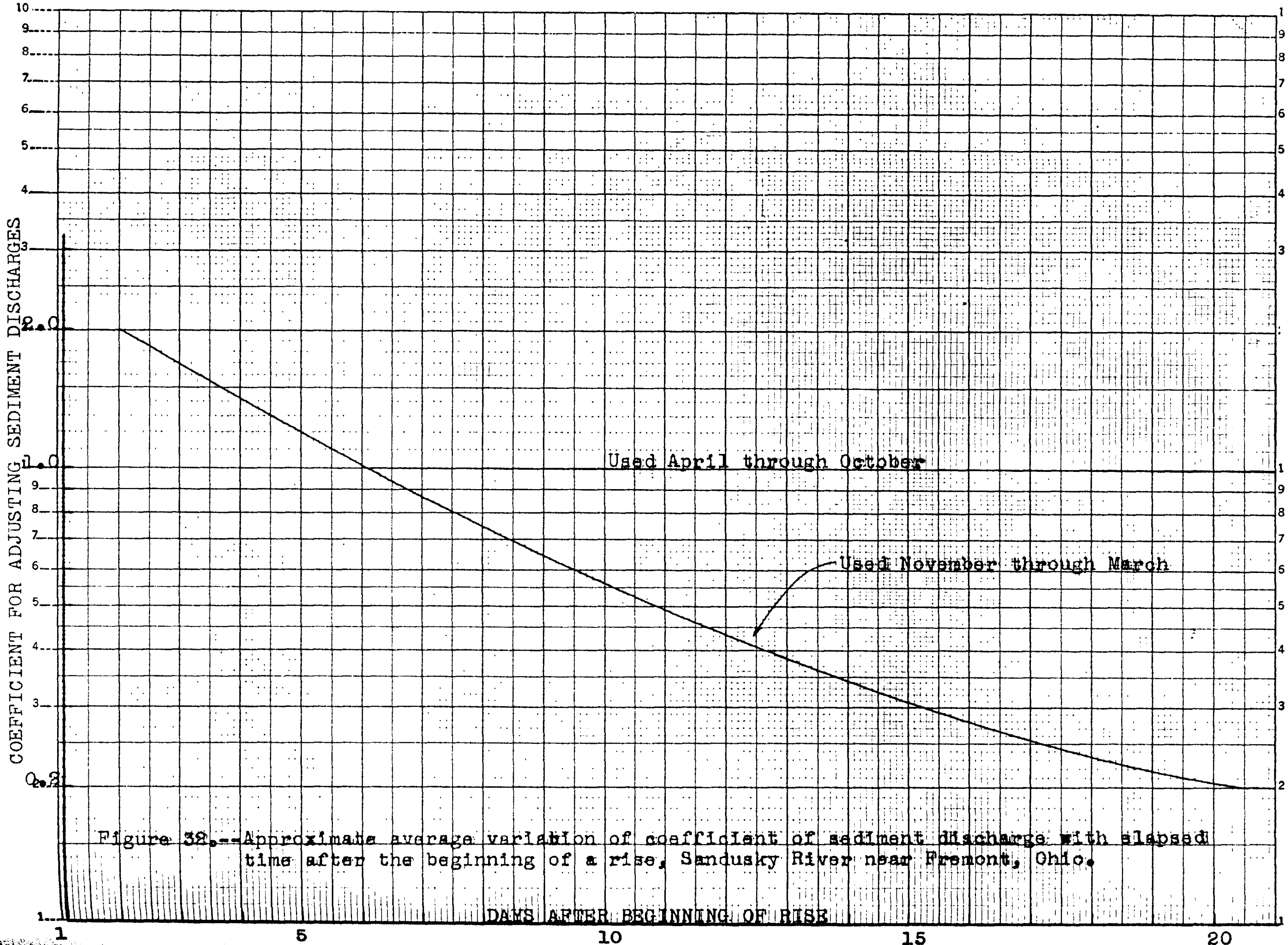

Figure 32.--Approximate average variation of coefficient of sediment discharge with elapsed time after the beginning of a rise, Sandusky River near Fremont, Ohio.

too high average sediment discharges unless adjustments or shifts are applied.

The sediment rating curves for the White and Sandusky Rivers were drawn primarily as a basis from which to make adjustments and shifts. Hence, each curve was prepared to show an average relationship between sediment discharge and flow after elimination of the effects of the factors for which adjustments are to be made. This sort of sediment rating curve is dependent on the adjustment curves, such as those for seasonal variations and for elapsed time after a peak discharge. In fact, the overall relationship between sediment discharge and flow is expressed by the combination of the sediment rating curve and the adjustment curves. If sediment discharges are not to be adjusted or shifted, the sediment rating curve generally should be drawn through arithmetic-average sediment discharges for different ranges of water discharge.

Applications

The daily suspended-sediment rating curve (fig. 30) defined by the data for the 1951 water year was used with adjustments for season of the year and for elapsed time after the beginning of a rise to compute daily, monthly, and annual sediment discharges for the 1952 and 1953 water years. For the same two water years, sediment discharges for days, months, and years were computed by shifting to the daily sediment discharges for the 1st and 16th days of each month and also by shifting to the daily sediment discharges for the 1st, 8th, 16th, and 23d days of each month.

For the 1952 water year, the annual sediment discharge computed from the adjusted sediment rating curve was 78 percent of the measured annual sediment discharge. When the sediment rating curve with adjustments was shifted on the basis of 2 and of 4 control points each month, the computed annual sediment discharges were 79 and 85 percent, respectively, of the measured annual sediment discharge. The agreement between computed monthly sediment discharges and measured monthly sediment discharges was somewhat improved by the shifting to 2 control points per month and was further improved by shifting to the 4 control points per month. (See table 8.) If most control points had been on the peaks of rises or shortly after the peaks, shifting to the control points would have resulted in more improvement than was found from control points on arbitrarily selected days of the month. Daily sediment discharges computed for the 1952 water year either with or without shifting to control points did not agree well with measured daily sediment discharges during January and March, the months of highest sediment discharge. Computed daily sediment discharges agreed reasonably well with measured sediment discharges during most of the other 10 months of the water year.

For the 1953 water year, annual sediment discharge computed from the adjusted sediment rating curve was 102 percent of the measured annual sediment discharge. Annual sediment discharges computed by shifting to 2 and to 4 control points per month were 107 and 101 percent, respectively, of the measured annual sediment discharge. This agreement for annual loads is good, but the agreement for some months was not particularly good. Monthly computed sediment discharges shifted to 2 control points per month were generally no closer to measured monthly sediment discharges than were the monthly totals from unshifted figures. Shifting to 4 control points per month did increase somewhat the agreement between computed and measured monthly sediment discharges. (See table 8.) Daily sediment discharges computed from the sediment rating curve either with or without shifts generally showed reasonably good agreement with daily measured sediment discharges. The accuracy of computed daily sediment discharges increased as more control points per month were used as a basis for the computations. (See pl. 7.)

Large differences between computed and measured sediment discharges were more common for high flows during the winter than for other parts of the 1952 and 1953 water years. Perhaps the sediment discharges during the winter of the 1951 water year were not wholly comparable with those during the 1952 and 1953 water years. Also, the curve for seasonal adjustments (fig. 31) might be more applicable if it had been defined by information from several water years rather than by that for the 1951 water year only.

Sediment discharges computed from sediment rating curves for the Sandusky River near Fremont could probably be made more accurate by slight changes in procedure. If adjustments to the sediment rating curve (fig. 31 and 32) were determined from records for more than one water year, the accuracy of sediment discharges from the adjusted sediment rating curve might be increased somewhat. For the higher sediment discharges, accuracy could be much improved if the 2 or 4 sediment discharges per month that are used for control points were on the days of peak flows or within one or two days after the peak flows of rises. The relationship between sediment discharge and streamflow at low flows or when the flow is increasing rapidly are poor guides to the relationship at or a few days after a peak flow.

The three rises during January 1952 indicate the possible effect of a suitably timed control point in improving the accuracy of computed sediment discharges during a rise. The control point for January 1 was on the highest day of the first rise. Computed sediment discharge for the highest 5 days of the rise exceeded the measured sediment discharge by 2.5 percent. No control point came within the 5 highest days of either of the other two rises. Computed sediment discharge for the highest 5 days of one of these rises was 54 percent less than measured; it was 19 percent more than measured for the highest 5 days of the other rise.

On the basis of the computations for two water years for the Sandusky River near Fremont, a relatively simple sampling program could be expected to give good computed monthly and annual sediment discharges from a sediment rating curve. One set of sediment samples should be obtained on the highest day or within two or three days after the peak of each rise for which the flow exceeded 1,000 cubic feet per second. A minimum of two or three samples per month should be obtained even though no rises or only one or two occur during a month.

Table 8.--Monthly and annual sediment discharges, in tons, as computed by different methods for the Sandusky River near Fremont, Ohio

Basis of sediment computations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Water year	Percent of measured
Water year ending September 30, 1952														
Method 1....	43	501	31,569	160,232	18,058	108,461	31,160	4,554	252	199	28	54	355,111	100
Method 2....	22	357	22,600	117,000	24,400	67,700	36,700	6,000	200	107	17	72	275,000	78
Method 4....	37	399	26,000	117,000	24,600	75,900	29,100	5,930	227	170	28	79	279,000	79
Method 5....	37	450	26,800	141,000	23,900	75,900	26,700	5,970	226	180	28	61	301,000	85
Water year ending September 30, 1953														
Method 1....	6	14	40	5,390	1,458	18,904	1,122	42,579	323	6,220	202	13	76,371	100
Method 2....	10	20	68	2,880	1,050	5,660	1,080	56,800	199	9,510	266	10	77,600	102
Method 4....	5	22	50	6,620	2,550	4,800	1,330	56,400	258	9,500	288	16	81,800	107
Method 5....	5	13	44	7,410	1,630	9,830	1,300	47,800	306	8,240	232	12	76,800	101

Method 1: Daily samples.
Method 2: Adjusted sediment rating curve.
Method 4: Adjusted rating curve with shifts to two daily measured sediment discharges per month.
Method 5: Adjusted sediment rating curve with shifts to four daily measured sediment discharges per month.

FACTORS AFFECTING SEDIMENT DISCHARGE

Some factors are shown by the studies and computations of this report to cause or to be associated with changes in the relationship between sediment discharge and water discharge. The significant factors are different for the different sizes of sediment particles. Two factors, velocity and water temperature, have a usually discernible and somewhat consistent effect on the discharge of suspended sands. Other factors that affect the discharge of the fine particles are highly variable from one sediment station to another.

Velocity

Suspended sediment is maintained in transport by vertical components of turbulent flow. The intensity of these components is largely a function of velocity. Also, the lifting force that tends to raise particles from the stream bed varies with velocity. Hence, velocity can be expected to show considerable correlation with sediment discharge. One obvious limitation on this effect exists; low velocities may be competent to transport all the fine particles of sediment that are available and an increase in velocity will not transport appreciably larger tonnages of these particles unless the increased velocity is accompanied by an increased supply of fine sediment.

At the four sediment stations for which sediment rating curves for sands were prepared, the concentration of measured suspended sands seemed to correlate reasonably well with mean velocity in the cross section. Four separate graphs of concentration plotted against velocity are shown on figure 33. The slopes of the average lines through the scattered points indicate an increase of concentration of measured suspended sands with the 2.2, 2.1, 2.8, and 2.4 powers of the mean velocity for the Colorado River near Grand Canyon, Ariz. (above about 2.5 feet per second), the Niobrara River near Cody, Nebr., the Rio Grande at San Marcial, N. Mex., and the White River near Kadoka, S. Dak. The slopes of the lines are fairly well defined except for the Grand Canyon station below 2.5 feet per second and for the San Marcial station and are fairly consistent. For the Niobrara River but not for the other streams, the concentration of measured suspended sands was adjusted for the approximate effect of water temperature before the points were plotted on figure 33. Slopes of the different sediment rating curves for measured suspended sands also indicated that the concentration increased with about the 2.5 or slightly lower power of the mean velocity and thus are consistent with the slopes of the lines of figure 33. If at high flows the supply of sands is much less than the transporting capacity of a stream, curves similar to those of figure 33 could be expected to show a less rapid increase of concentration with mean velocity at the high velocities. The curves of figure 33 do not indicate that the capacity of a stream exceeded the supply of available sands any more at high velocities than at low velocities.

Unmeasured-sediment discharge per foot of stream width correlates closely with mean velocity, and increases with about

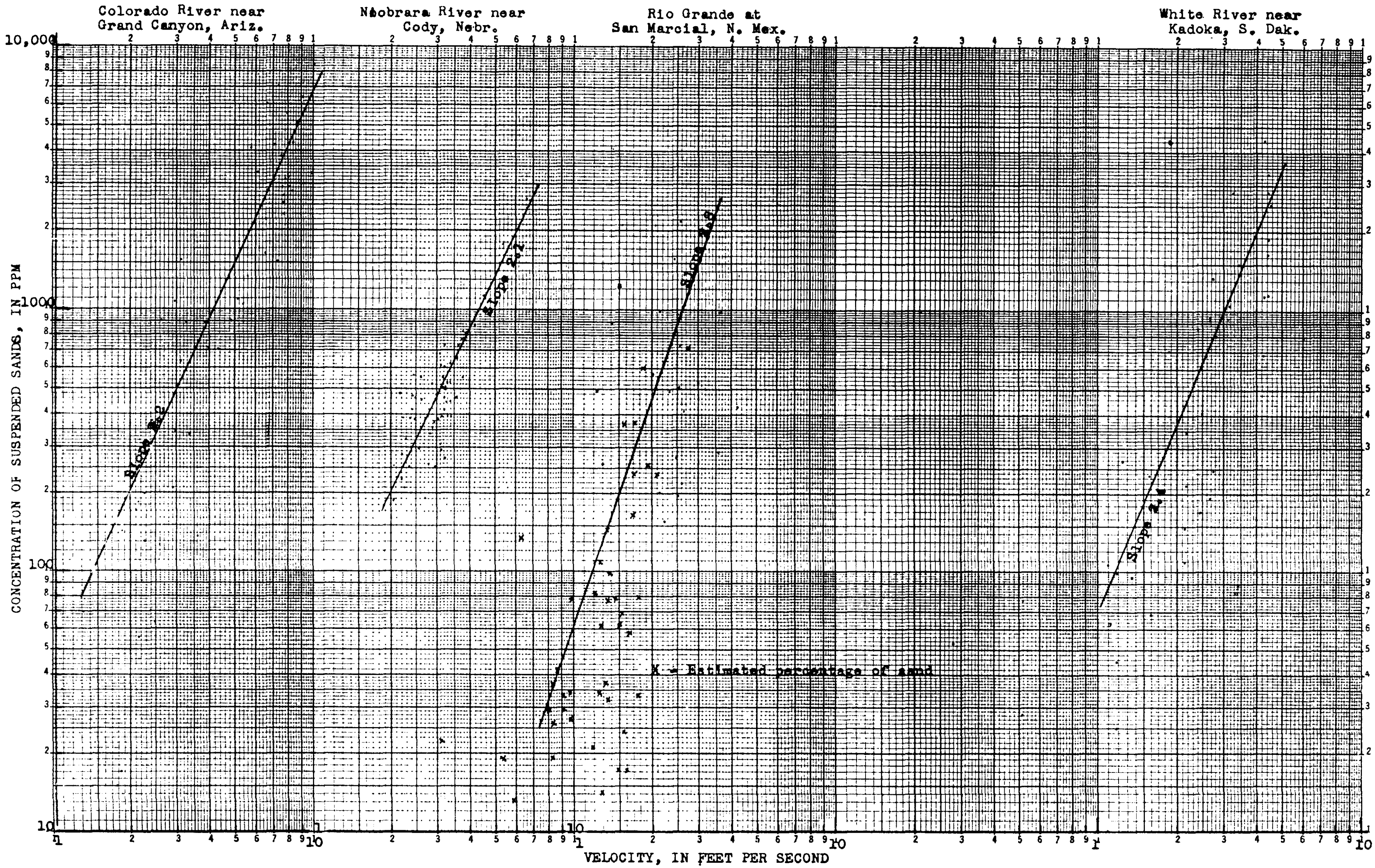

Figure 33.--Relationship between concentration of measured suspended sand and velocity

the 3.1 power of the mean velocity for the gaging-station section of the Niobrara River near Cody. Preliminary investigations show that unmeasured-sediment discharges per foot of width for several other streams with alluvial beds also correlate well with mean velocity at least for velocities above 2.0 feet per second. This correlation may become an important relationship in computations of unmeasured-sediment discharge.

Water Temperature

Both the flow and the sediment-transporting characteristics of the flow are affected by the temperature of the water. Kinematic viscosity, which varies with temperature, affects the thickness of the sublayer, that layer near the stream bed through which the flow is laminar. Density of the water changes slightly with temperature, and the changes in density have a small effect on the flow and sediment-transporting characteristics of the stream. The major effect of water temperature on sediment transportation is due to changes in viscosity and resultant changes in the rate of fall of sediment particles through the water. Such changes affect the rate of discharge of suspended fine sands much more than the rate of discharge of silt and clay or the rate of discharge of sediment coarser than 0.5 millimeter.

A computation of suspended-sediment discharge was made for the gaging-station section of the Niobrara River near Cody, Nebr., for three assumed water temperatures. No changes in the basic information were assumed other than the changes in water temperature and in the temperature effects on the fall velocities of the sediment particles. Sediment discharges for five ranges of particle size were computed according to relationships given by Einstein (1950) and are shown in the following table:

Table 9.--Effect of water temperature on discharge of suspended sediment of different size ranges
[Results are in tons per day except as indicated]

Temperature, in degrees Fahrenheit	Ranges of particle size, in millimeters					
	0.016 to .062	0.062 to .125	0.125 to .25	0.25 to .50	0.50 to 1.00	0.016 to 1.00
80	74	79	164	123	12	452
60	90	133	372	172	14	781
40	116	236	581	252	14	1,201

Computed rates of sediment discharge increased rapidly with decrease in water temperature except for sediment larger than 0.5 millimeter. For these large particles, the rate of fall is nearly independent of temperature. For finer sediment in the size range from 0.016 to 0.062 millimeter, the indicated increase of sediment discharge for a change from 80° to 40° F. was only 57 percent in contrast to a 254-percent increase for the sand in the range from 0.125 to 0.25 millimeter. The reason for the relatively smaller rates of increase for the smaller particles is that, although the fall velocity for these particles increases rapidly percentagewise, the increase in fall velocity in feet per second is not great. In other words, the fall velocity is still low even after a large percentage increase in it. Hence, most streams will easily transport most of the available fine sediment even after the fall velocity has been considerably increased by a increase in water temperature.

A large temperature effect on the vertical distribution of Missouri River sediments and on the discharge of these sediments was reported by Straub (1954). Only about 1 percent of the sediment that was used in his experiments was finer than 0.062 millimeter and about 3 percent was coarser than 0.5 millimeter. About 66 percent of the sediment was in the range from 0.125 to 0.25 millimeter for which range the rate of increase with temperature is large.

Trial-and-error multiple correlations in the analyses of the sediment rating curves usually indicated a rapid increase of discharge of suspended sands with decreasing water temperature. Little, if any, effect of water temperature on the discharge of combined clay and silt was shown by the correlations. The effect might have been obscured by the tendency for the supply of fine sediment to be greater for a given rate of streamflow during the summer months.

Computed increases in sediment discharge from table 9 are probably better indications of the effect of water temperature on sediment discharge than are experimental correlations by trial-and-error. The correlations do not distinguish between relationships of cause and effect and relationships of association. For example, the discharge of sands may vary with observed water temperatures because of a seasonal change in the size composition of bed material as a result of the seasonal pattern of streamflow and sediment supply. Also, the correlations are based on data that scatter widely and so produce poorly defined correlations. The correlations indicated that the rate of discharge of measured suspended sands varied inversely with the 3/4 power, the 3/4 power, and the 3d power of water temperature for the Niobrara River near Cody, the Colorado River near Grand Canyon, and the Rio Grande near San Marcial, respectively. Rates of increase of discharge of measured suspended sands as determined from the correlations were for sands of all sizes that were collected in the sediment samples so that the rates of increase with water temperature were probably reduced somewhat at times by inclusion of some particles larger than 0.50 millimeter.

Seasonal Variations

Concentrations of fine sediments tend to be lower for a given rate of water discharge during the winter and spring than during the summer. Probably the discharge of sands is also appreciably affected by seasonal variations at some sediment stations. Such an effect sometimes seemed to be discernible at the Grand Canyon and San Marcial stations, but it was not definitely established. For some streams the seasonal effect is caused partly by snowmelt or precipitation on frozen ground. Snowmelt is usually gradual and frequently occurs when the ground is frozen. Hence either snowmelt or precipitation on frozen ground usually causes less erosion of sediment from land surfaces than comparable rates of runoff during warmer seasons. In drainage basins where much land is tilled, runoff during periods when the fields are bare or have been recently worked is likely to carry high concentrations of fine sediment. Summer storms in semiarid regions are usually intense and erode the land surface more rapidly than the less intense precipitation during other seasons. Runoff from some drainage areas during the winter, spring, and early summer comes mostly from areas at high altitudes where the land surface is highly resistant to erosion whereas a much larger proportion of the runoff during the summer and fall comes from areas at lower altitudes where sediments erode rapidly whenever runoff occurs unless the ground is frozen.

Thus in general, most factors affecting sediment discharge vary with the seasons. Precipitation intensities and areal distribution patterns, rates of infiltration, evaporation losses, vegetal cover, water and air temperatures, and even the composition of the bed sediments at some stream cross sections are all variable from season to season. Some of these factors such as water temperature, velocity, tributary flows, summer flows, and adjustments for elapsed time after peak discharges can be correlated with sediment discharge. Correlations with other variables were not established except under the broad classification of seasonal variations.

Tributary Flows

At sediment stations below major tributaries, the concentration of fine sediments may be largely a function of the relative flow of these tributaries as compared to the flow of the main stream, particularly if the tributary inflow differs widely in concentration from the flow of the main stream. When rates of tributary inflow are used as measures of concentration at a downstream station, a time allowance, frequently an allowance varied with water discharge, may be required to adjust for the time of travel of the fine sediment from the mouth of the tributary or tributaries to the sediment station. A relationship of tributary flow overshadows all other effects on the sediment rating curve for the Rio Grande at San Marcial and is important for the Colorado River near Grand Canyon because the first few major tributaries upstream from these stations carry far higher concentrations of sediment than do the main streams. Even though the tributaries transport appreciable tonnages of sands, the sands are likely to be at least partly deposited at times and later to be moved downstream in the main channel as a function of velocity in the main stream rather than in immediate and direct response to the flow of the tributaries.

Tributary inflows of water and sediment may either increase or decrease the main stream concentrations on either rising or falling stages. Obviously, tributary inflow containing high concentrations of sediment and entering the main stream close upstream from a sampling station may contribute comparatively high sediment discharges while the stream is rising. A similar tributary inflow far upstream or high concentrations of sediment in flow from upper reaches of the main stream may tend to increase sediment concentrations during falling stages. Tributary inflows and nonuniform distribution of runoff or of sediment erosion over the drainage area upstream from the sampling station may have complex and variable effects on the relationship between sediment discharge and streamflow at a station. For some streams these effects may be much different than for the Colorado River near Grand Canyon or for the Rio Grande at San Marcial.

Elapsed Time after Peak Flows

A graph of either instantaneous or daily relationship between sediment discharge and streamflow plots as a loop curve for many sediment stations. That is, for given rates of water discharge the sediment discharge is greater when the stream is rising than when it is falling. The loop curves sometimes differ considerably from storm to storm, but recession curves of sediment discharge at a station, like recession curves of streamflow, tend to have similar shapes from one storm period to another. Tributary flows may either accentuate or obscure the loop effect.

One main reason for the looping of the sediment rating curve is that a sharp rise usually results from direct surface runoff to a stream. Such runoff normally transports a high concentration of sediment. After the peak of the flow has passed a station, the channel upstream may continue to drain for several days, and subsurface inflow and return flow from bank storage may contribute much of the flow at the station. The proportion of direct surface flow in the water discharge at the station normally decreases with elapsed time after the rise. This decreasing proportion of direct surface flow is associated with a decreasing concentration of fine sediment with time.

Several other effects may either enhance or obscure the general tendency for sediment discharge to be greater for a given rate of flow when the flow is increasing than when it is decreasing. For some alluvial streams, mean velocity is significantly higher at a given discharge on rising stages than on falling stages because of shifts of the stream bed. The higher velocities when flow is increasing are normally accompanied by higher concentrations of suspended sands on rising discharges of water than on falling discharges. A different effect sometimes is observed on streams such as the Bighorn River (Heidel, 1956) or the Colorado River. On these rivers, the concentration of fine sediment may be low for a given water discharge during a rise because the water that arrives first at a station is mostly water that was stored in the channel before the rise began. In fact, the sediment in the direct surface runoff may not arrive at a station until a few days after the peak of the flow at the station. Another effect on daily sediment rating curves for some flashy streams is caused by a rapid rise in discharge late in the calendar day. For such a rise, the average rate of water discharge during the day may be only a small fraction of the actual instantaneous rates of flow while most of the sediment was being discharged.

The loop effect means that for some stations the rate of discharge of fine sediment is at least partly a function of time after a sharp increase in flow or the peak of the flow. Such a general relationship may be defined as an average for a sediment station but departures from the average may be large. Such departures are to be expected because rates of discharge of fine sediments depend not only on rates of water discharge but also on whether the flow is increasing or decreasing and on many other complex relationships of erosion, runoff, drainage pattern, and streamflow within the drainage area. Thus, average curves to adjust for elapsed time after either peak discharges or the beginnings of rises (figs. 29 and 32) may be helpful in computing sediment discharges but do not perfectly measure adjustments to sediment discharges that are computed from sediment rating curves.

Sediment discharges for given rates of flow are likely to be more variable when the flow is increasing rapidly than when the flow is decreasing. For this reason, sediment determinations that are to be used as a basis for shifting from sediment rating curves should preferably be obtained near the peaks of flow and concentration or when the flow and concentration are receding. Samples when the flow is rising are likely to be representative for only short periods of time.

Miscellaneous Factors

Many other factors than those already discussed are likely to have an effect on the relationship between the discharge of sediment and the flow of water at some sediment stations. Unless the effect is reasonably large or is consistent, it may be difficult to detect from sediment data that are subject to appreciable sampling and laboratory errors. More careful investigation than was possible during this study may be required for all but the factors that have large effects on sediment discharge.

Some factors that might reasonably be considered in connection with the discharge of sands include corrections to average velocity on the basis of velocity distribution in the cross section, average velocity along a reach of channel in place of average velocity at a cross section, and perhaps stream width and average depth. A particularly likely factor that might affect the discharge of suspended sands is the size composition of the bed material.

Discharge of fine sediments or shifts from an average sediment rating curve (fines) might be associated in some degree with rate of increase of flow preceding a rise and rate of recession of flow after a rise. At some stations these rates might indicate intensity of runoff or areas on which most of the runoff was generated. In general, however, the explanation for scatter from a sediment rating curve (fines) probably lies in more careful studies of the sources of the fine sediments and the ways in which these sediments are eroded.

ACCURACY

Whether or not sediment rating curves can be used to reduce the frequency of sediment sampling depends mainly on a balance between loss in accuracy and saving in cost. Saving in cost may not be difficult to estimate satisfactorily. However, estimates of probable loss of accuracy are necessarily based not only on the probable inaccuracy of sediment discharges that are computed from sediment rating curves but also on the probable inaccuracy of sediment discharges that are computed from samples collected systematically on a daily or more frequent basis. At the present time, the estimates of probable loss of accuracy are hard to make because neither the inaccuracies of sediment discharges from rating curves nor the inaccuracies of measured sediment discharges have been satisfactorily established. Only a general idea of probably inaccuracy, necessarily very incomplete, can be given in this report.

Sampled Concentrations and Measured Sediment Discharges

The accuracy of measured sediment discharges depends on such factors as the adequacy of the sampling program, accuracy of laboratory determinations of concentration, the ability of the computers in applying satisfactory methods to computing sediment discharges from streamflow records and concentrations of the samples, and finally on the accuracy of the streamflow records. Estimates of the general accuracy of daily sediment discharges might range from 5 percent for a large stream in which flow is comparatively constant, sediments are fine, and concentrations are high enough to sample accurately to almost unlimited errors for flashy streams that have poor streamflow records and for which sediment samples are not collected more frequently than once or twice a day.

Some of the inaccuracies in measured daily sediment discharges are partly compensating during periods of months or years. Hence, the monthly and annual sediment discharges are usually more accurate percentagewise than are measured daily sediment discharges. In spite of the compensating effect, some published measured sediment discharges for an entire water year may possibly be either double or else only half the true suspended-sediment discharge for the year. Such gross inaccuracy would, of course, be very unusual.

Actually, estimates of the inaccuracy of measured sediment discharges have been based mainly on consistency of results rather than on absolute accuracy. No one knows how widely measured sediment discharges might vary if they were determined by different but currently accepted methods of sampling, analyzing, and computing sediment discharges. A program to evalutate the consistency and, insofar as possible, the accuracy of measured sediment discharges is badly needed. Such an evaluation is impossible in this report. However, an idea of the probable adequacy of a periodic sample as a basis for shifts of the sediment rating curve is required. Accordingly, some examples of the consistency or the variability of sampled concentrations for several streams were obtained. A few are reproduced graphically in figures 34-37.

The data for one curve of figure 34 for the Middle Loup River at the Dunning turbulence flume were given by Benedict, Albertson, and Matejka (1953, fig. 21) who stated (p. 14) regarding statistical analyses of the variations:

"These statistical analyses show that for one set of random samples (one bottle) at the four sampling stations, the maximum deviation from the average concentration may vary as much as ± 25 percent. For two consecutive sets of samples, the maximum deviation from the mean may be as much as ± 19 percent. In the routine collection of samples the probable deviation from the mean will vary from zero to these maximum percentages based on this statistical study."

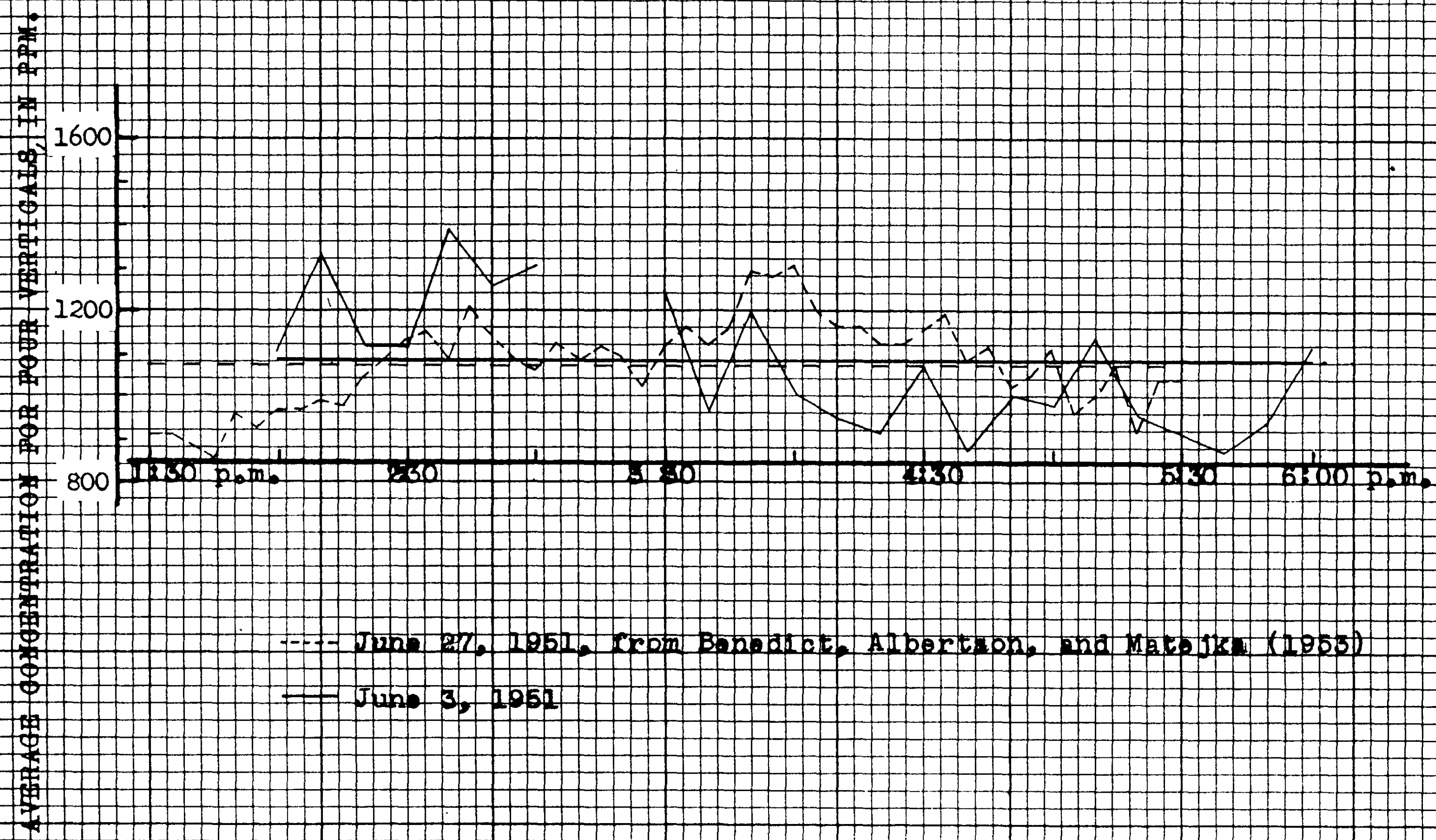

Figure 34.--Variations in concentrations of samples, Middle Loup River near Dunning, Nebr.

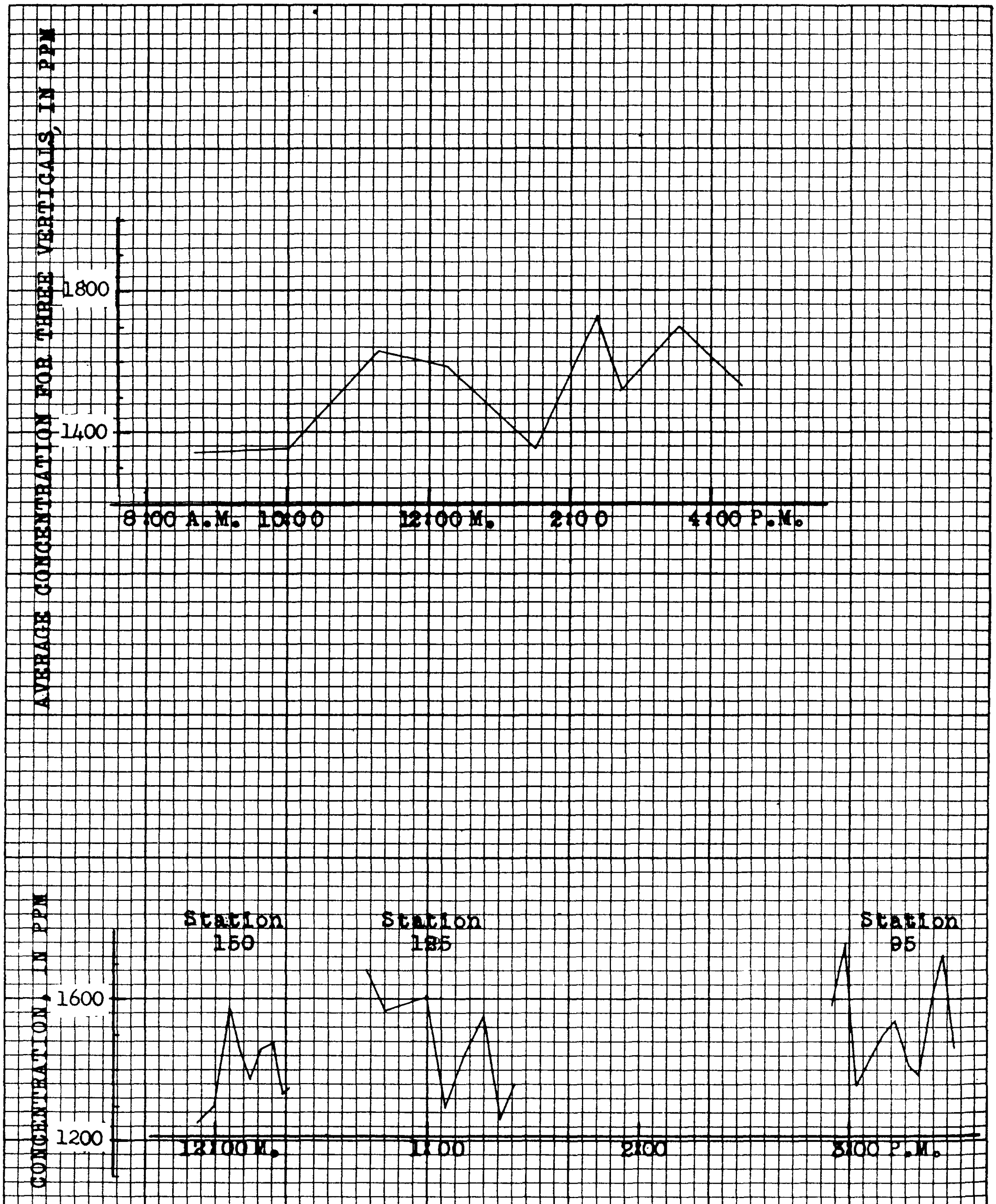

Figure 35.--Variations in concentrations of samples, Rio Grande near Bernalillo, N. Mex., January 6, 1950

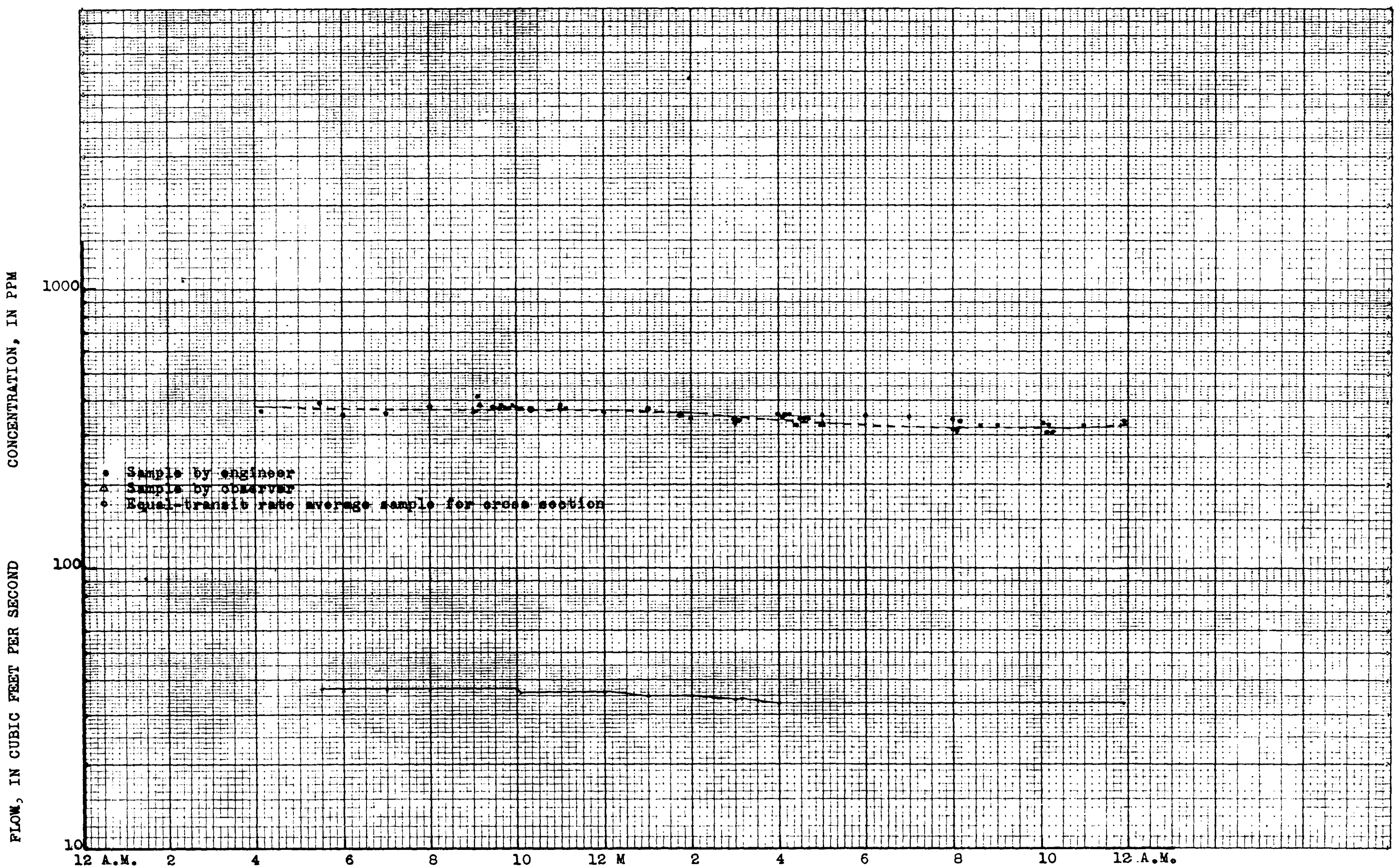

Figure 36.--Variations in concentrations of samples, Medicine Creek above Harry Strunk Lake, Nebr., June 24, 1954

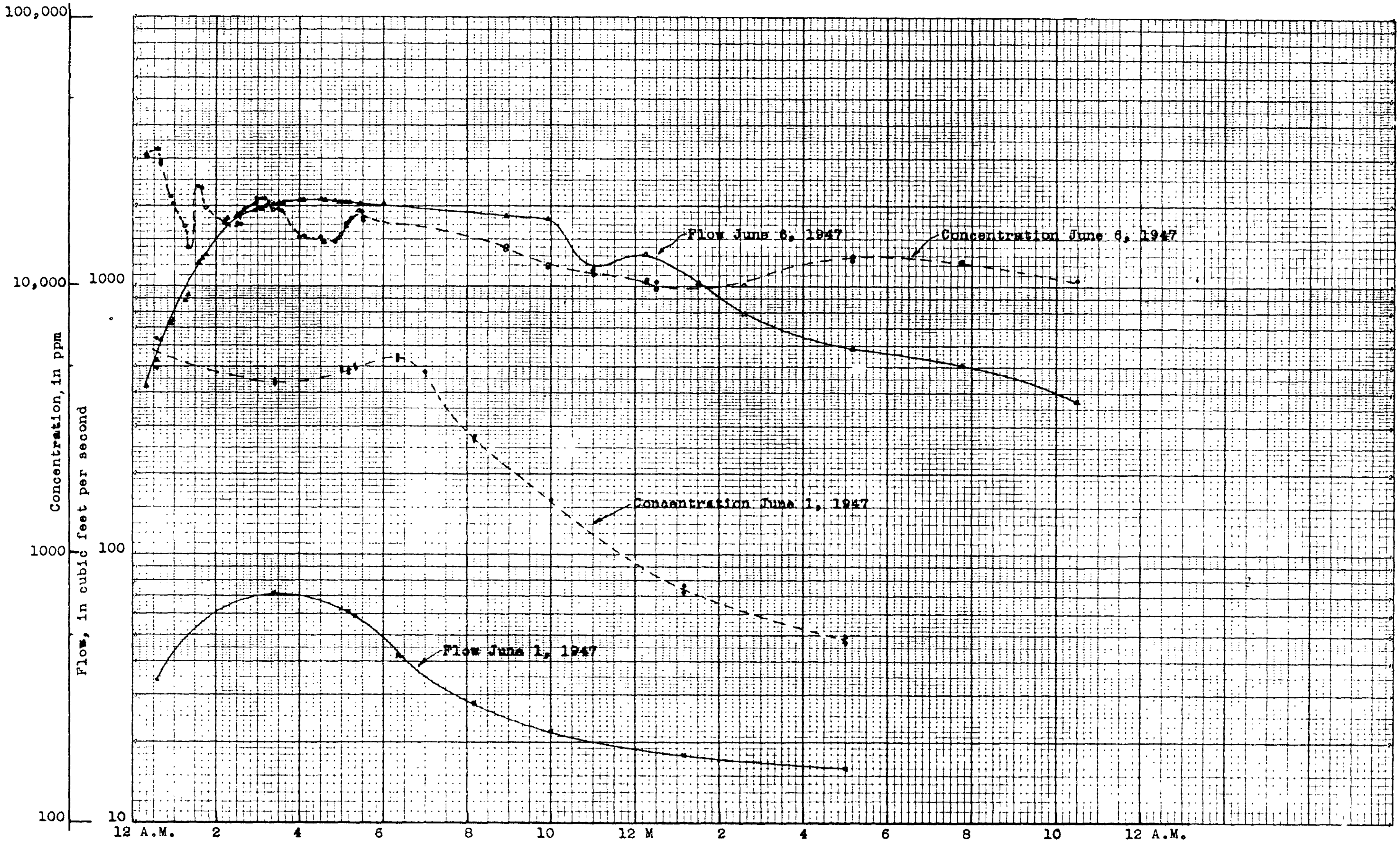

Figure 37.--Variations in concentrations of samples, Prarie Dog Creek at Norton, Kans.

They also concluded from a study of variations in concentration at one vertical in the cross section (p. 14):

"The normal error distribution also indicates that the variation will be less than ±73.1 percent for 99.7 percent of the time, less than ±48.8 percent for 95.5 percent of the time, and less than ±24.4 percent for 68.3 percent of the time. Such a variation is the greatest computed and occurs about the mean of station 30 only. For station 10, the variation about the mean will be less than ±23.8 percent for 95.5 percent of the time; for station 50, it will be less than ±22.0 percent for 95.5 percent of the time; and for station 70, it will be less than ±29.2 percent for 95.5 percent of the time."

As the total sediment discharge of the Middle Loup River is measured at the turbulence flume, the variability of the samples may have been greater than the variability of suspended-sediment samples at sections where total sediment discharge is not measured. At times sand dunes moving along the stream bed pass through the turbulence flume at the Dunning station and cause some erratic variations in concentration. However, the total sediment discharge is likely to be just as variable at other sections of the Middle Loup River as at the turbulence flume. Probably the variations in sediment concentration over short periods of time are roughly the same for the Dunning turbulence flume as for the daily sampling section of the Niobrara River near Cody, where approximately total sediment discharge is measured. The sediment transported by both streams is mostly fine to medium sand, and the bed material is nearly all sand.

Information obtained on January 6, 1950, by J. K. Culbertson for the Rio Grande near Bernalillo, N. Mex., shows the same sort of variation of 20 or 30 percent from low to high concentrations within an hour or less that was shown for the Middle Loup River. (See fig. 35.) Slush ice was floating in the Rio Grande during the forenoon but was gone well before the end of the observations. At times during the day some cakes of surface ice floated past the section.

The concentrations of samples collected from the Prairie Dog Creek at Norton, Kans., and from Medicine Creek above Harry Strunk Lake, Nebr., are plotted against time on figures 36 and 37. Flow is also plotted to show that changes in flow do not necessarily accompany changes in concentration on these streams. Individual samples, particularly those from Prairie Dog Creek, seem to be consistent. Changes in concentration on the rise of June 6, 1947, are due to differences in the times at which water from different tributaries reached the station at Norton. One may safely conclude that a single set of samples gave an excellent determination of instantaneous concentration. However, frequent sampling would be required during the period of increasing flow on June 6 to define accurately the changes in concentration during the day. In general, concentrations changed slowly as compared to concentration changes for the Middle Loup River near Dunning or the Rio Grande near Bernalillo, N. Mex.

The difference in consistency of individual samples for the different streams is associated with the size of the suspended sediments. For Prairie Dog and Medicine Creeks probably less than 10 percent of the measured suspended sediment was coarser than 0.062 millimeter whereas for the Middle Loup River near Dunning probably 80 percent was coarser than 0.062 millimeter and perhaps 30 percent was coarser than 0.25 millimeter, and for the Rio Grande near Bernalillo more than 90 percent was coarser than 0.062 millimeter and more than 50 percent was coarser than 0.125 millimeter. Of course, fine sediment is usually much more uniformly distributed both laterally and vertically in a cross section than is the coarser sediment. Also the coarser sediment shows much greater fluctuations in concentration from minute to minute than does finer sediment.

The effect of particle size and concentration on the consistency of sediment samples can be shown approximately by data for the San Juan River near Bluff, Utah, for the water year ending September 30, 1950. The percentage variations for a set of samples at three vertical were computed by F. C. Ames. Each percentage variation was 100 times the difference between the highest and the lowest of the three concentrations divided by the average concentration for all three verticals. Mr. Ames plotted these percentages of variation against mean concentration. An approximate average relationship is represented by the line drawn through the plotted points. (See fig. 38.) The relationship indicates a rapid decrease in percentage variation of the samples as the concentration increases. He also plotted the percentage variation against the percentage of the sediment that was finer than 0.062 millimeter. An average curve drawn through the points

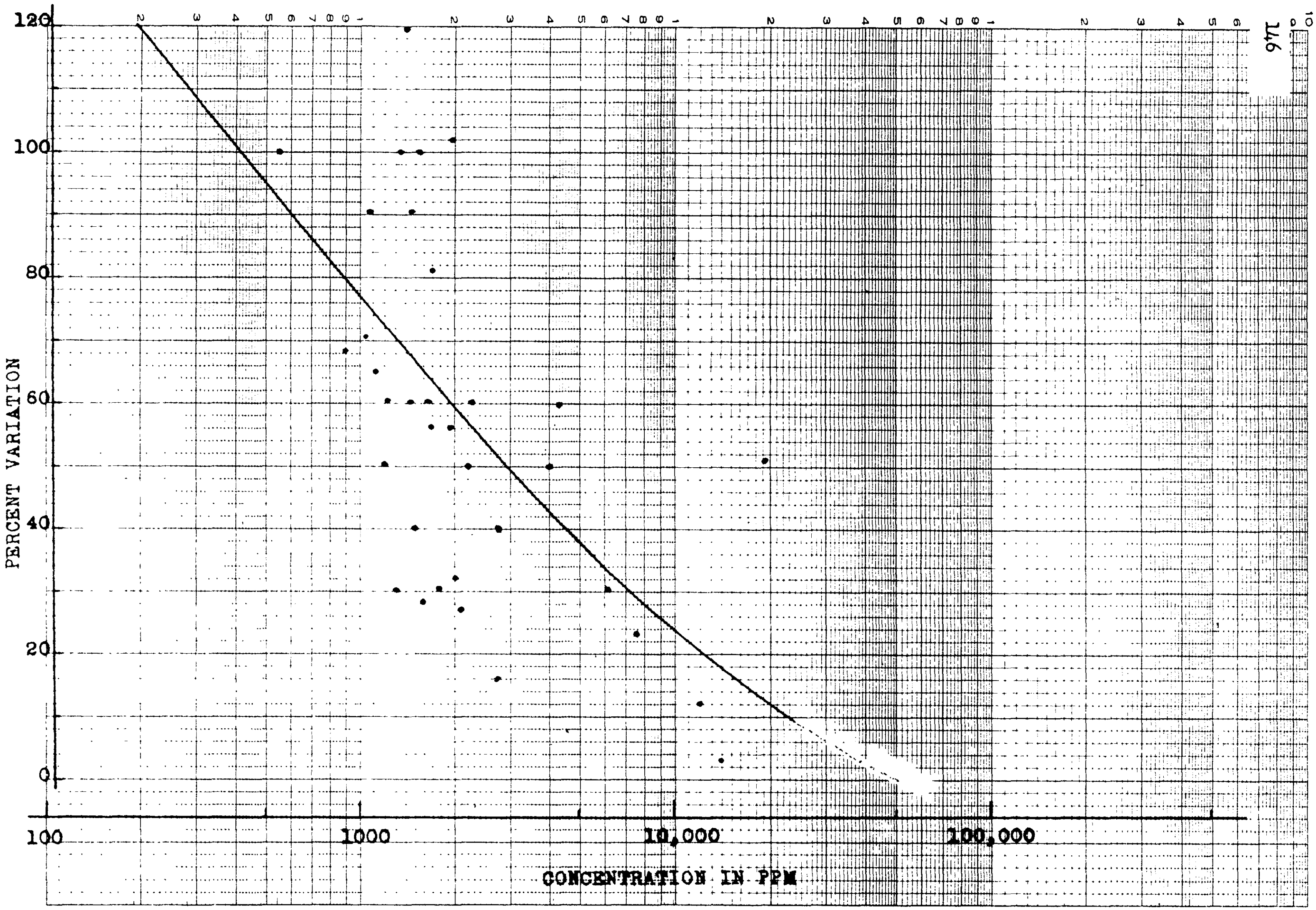

Figure 38.--Relationship between percentage variation and concentration, San Juan River near Bluff, Utah

(fig. 39) showed a marked decrease in percentage variation with an increase in the percentage of fine sediment.

Of course, this discussion and documentation of probable consistency of sediment samples is much too incomplete to be satisfactory. It should, however, serve as a warning that several samples may be required to determine a representative concentration of suspended sediment at a cross section. This is particularly true for high percentages of suspended sands and for low concentrations. Representative concentrations are especially necessary for periodic samples because a single unrepresentative sample may incorrectly be assumed to be representative for a considerable number of days. (The term "representative" is used here in the sense of representative for a period of at least several hours as contrasted to representative for a period of a few minutes.) Some sediment discharges computed for this study by shifting the sediment rating curve to periodic determinations would have been appreciably more accurate if the sediment discharges that were used as control points had been more representative.

Sediment Discharges Computed from Sediment Rating Curves

Insufficient computations were made during this study to define for individual sediment stations the probable accuracy of sediment discharges that are computed from sediment rating curves. An idea of overall accuracy of the computed daily sediment discharges can be obtained from figures 9, 14, 15, and 23, which show daily percentage comparisons for a total of 7 years of

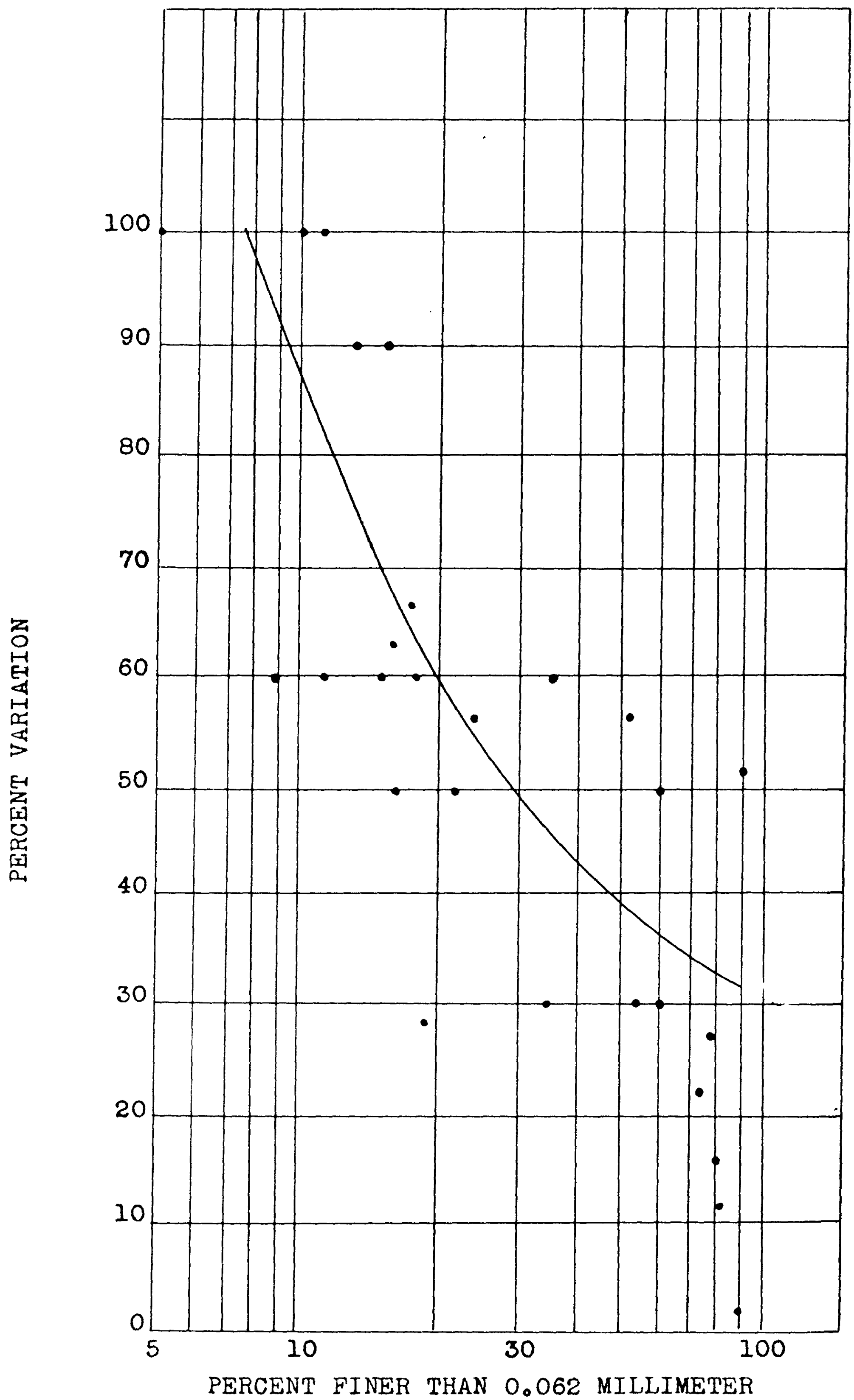

Figure 39.--Relationship between percentage variation and percentage of particles finer than 0.062 millimeter, San Juan River near Bluff, Utah

record at 3 different stations. For 3 of these years the computed daily sediment discharges were obtained from adjusted sediment rating curves and daily water discharges without shifts to samples that were collected during the year. Of 1,048 daily computed sediment discharges, 23 percent were within 10 percent of the measured daily tonnages and 41 percent were within 20 percent of measured daily tonnages. For 4 of these 7 years the daily sediment discharges from the rating curves were computed by shifting to from 2 to 4 measured sediment discharges during each month. Of 1,287 daily computed sediment discharges during these 4 station years, 36 percent and 58 percent were within 10 percent and 20 percent, respectively, of the measured daily sediment discharges. On the basis of comparisons of computed and measured annual sediment discharges for these 4 station years with all annual comparisons that were available from this study, these percentages for daily comparisons should be about representative of all daily computations that were based on shifting to from 2 to 4 control points per month.

Percentage comparisons between computed monthly sediment discharges and measured monthly sediment discharges are shown on figure 40 for three methods of computation. The monthly computations for the Colorado River near Grand Canyon, Ariz., for the 1955 water year were not included partly because the measured sediment discharge for the 1955 water year has not yet been finally computed and partly because two other years of monthly computations were already included for this station. Computations of the number or the percentage of monthly tonnages within

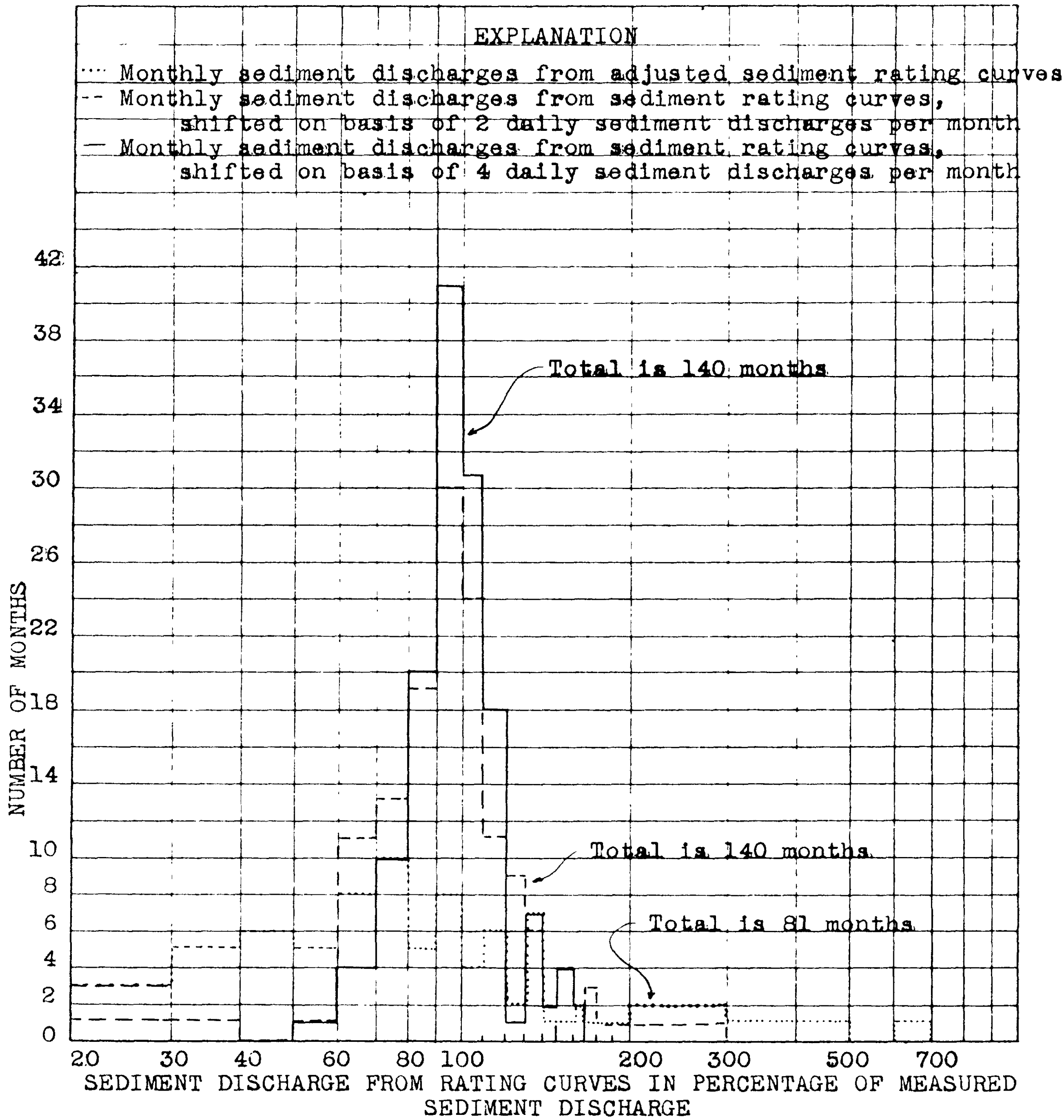

Figure 40.--Percentage comparison of monthly sediment discharges computed from daily or instantaneous sediment rating curves with measured monthly sediment discharges.

given limits of accuracy can be determined readily from figure 40. Of 81 monthly sediment discharges that were computed from adjusted sediment rating curves (no sediment samples were used from the year for which the computations were made), 12 were within 10 percent and 23 were within 20 percent of the measured monthly sediment discharges. The total number of months is not a multiple of 12 because some streams were dry during some months. When two measured sediment discharges per month were used as control points, 54 out of 140 computed monthly sediment discharges were within 10 percent and 84 were within 20 percent of the measured monthly tonnages. When four control points per month were used, 72 out of the 140 computed monthly sediment discharges were within 10 percent and 110 were within 20 percent of the measured monthly tonnages. Accuracy of computed monthly sediment discharges was much improved by shifting to two control points per month. Shifting to two additional control points per month further increased the accuracy of monthly sediment tonnages.

Eight annual sediment discharges, including that for the 1955 water year for the Colorado River near Grand Canyon, were computed from adjusted sediment rating curves without any shifts to control points. Without regard for algebraic sign percentage differences between measured and computed annual sediment discharge ranged from 2 to 34 percent and averaged 18 percent. When 2 control points per month were used, the differences for 13 annual computations of annual sediment discharge ranged from 0 to 22 percent and averaged 10 percent. When 4 control points were used for the same 13 computations, the range of percentage difference was 0 to 14 percent, and the average was 6 percent. For the sediment stations and the water years that were included in this study, most annual sediment discharges that were computed from sediment rating curves with shifts to 2 or 4 control points per month were considered to be satisfactorily accurate.

POSSIBLE USES OF SEDIMENT RATING CURVES

Accuracy of a sediment record for a sampling station will usually increase with an increase in the number of sediment samples that are collected. This relationship is comparable to the increased accuracy that is normally obtained in streamflow records by increasing the frequency of streamflow measurements at gaging stations where the stage-discharge relationship shifts. The accuracy of the computed water or sediment discharges also depends on the manner in which the shifts are applied and the records are computed. A general problem in operation of either streamflow or sediment stations is to adjust the frequency of field determinations to the most desirable balance between accuracy and cost of operation. Some suggestions can be made on the basis of this study for the use of the sediment rating curve to supplement sediment sampling.

Certain key stations probably should be maintained as daily sampling stations for many years. Perhaps the only likely use for sediment rating curves at such stations would be to maintain continuity of records in spite of curtailment of operating funds for a few years.

At many sediment stations, daily samples should be collected for a year or two and daily, monthly, and annual sediment discharges should be computed by the usual methods of the Quality of Water Branch. After a year or two of such records have been obtained, a study of the possible applications of the sediment rating curve should usually be made to determine whether the cost of operation of the station can be decreased without unduly reducing the accuracy of the records. For some stations no initial period of daily sampling may be necessary, or daily or more frequent sampling may be limited to one or two periods of high flow per year. Nevertheless, the best operating procedure normally would be to obtain a backlog of information on the sediment-transporting characteristics of each station before possible applications of the sediment rating curve for that station are studied.

A less complete program for obtaining sediment records might be based on infrequent or periodic sampling at gaging stations where no daily sampling is ever contemplated. After a few years of infrequent sampling, the samples could be used to define sediment rating curves. (Most sediment rating curves for this study were based only on infrequent sampling, that is, on the concentrations and streamflow at the times when samples were collected for particle-size analysis.) If the infrequent samples were collected only at the times when engineers visited the gaging stations, the cost of obtaining the samples and of computing the sediment records would be low. For some types of research, infrequent samples each accompanied by a streamflow measurement at the sampling section are preferable to daily samples that are never obtained at the same time and section as streamflow measurements. The possibility of obtaining many sediment records in an area at a fraction of the usual cost through periodic sampling and the use of sediment rating curves is challenging. It deserves much more study and consideration than has been given to it. Money invested in such a program might provide so much more complete coverage of an area that the loss of accuracy at an individual sediment station would not be too serious an objection.

Also, a good general policy would be to try to collect sediment samples at or near unusually high peaks of flow of both gaged and ungaged streams. No immediate use for such miscellaneous samples may be apparent, but opportunities to collect them are rare and several future uses are possible.

In summary, sediment data may be helpful information whether samples are collected very rarely, periodically, or daily. A sediment sampling program for a large area should be flexible enough to provide sediment information at several frequencies of sampling and for different uses. No one type of operation should be used exclusively.

This study indicated several possible uses of instantaneous or daily sediment rating curves, and these uses varied somewhat with the different type of stream.

Streams Carrying Coarse Sediments

Probably sediment discharges computed from adjusted but unshifted sediment rating curves are generally more accurate for streams that transport sediments mostly in the range of sand sizes than for most other streams. This probably is because measurable factors such as water temperature and velocity explain much of the scatter from the rating curve for the discharge of suspended sands. Erratic scatter owing to short-time variations in concentration are averaged out by the rating curve. In fact, daily sediment discharges computed from sediment rating curves may be more accurate than those that are computed from daily samples unless several samples are obtained each day or the concentrations of once or twice daily samples are carefully averaged perhaps for periods of several days to eliminate much of the effect of erratic variations.

Unmeasured-sediment discharge per foot of width seems to correlate well with velocity. Hence, a sediment rating curve for unmeasured-sediment discharge can be prepared, and much of the scatter from this curve will probably be due to departures of width or velocity from their averages for a given rate of flow. This use of a sediment rating curve may well be one of its more important applications because it gives a reasonably satisfactory procedure for computing the unmeasured-sediment discharge of streams from periodic computations of total sediment discharge.

If periodic samples are to be collected from streams that transport high proportions of sand, several samples should be collected at a visit to a station. These samples should be well distributed across the stream and should be collected over a period of perhaps an hour. Samples might well be collected both before and after a streamflow measurement, which should be made when periodic samples are collected from this type of stream. The pronounced effect of velocity on the rate of discharge of suspended sands and of unmeasured-sediment discharge may require that streamflow measurements should be made regularly and at the same cross section, if possible, at a station for which sediment rating curves for suspended sands or unmeasured-sediment discharge are to be applied. Sometimes the water discharge can be determined from a stage-discharge relationship or from a measurement at another section. Measurements of width and depths at the sampling section would then be a satisfactory substitute for a streamflow measurement.

For some studies of channel control or of sediment deposition, the discharge of the sands, or of some other fraction of the coarser sediments may be more significant than the discharge of sediment of all particle sizes. If suitable information is available, the discharge of measured suspended sands can be computed from a sediment rating curve for suspended sands. This curve can be shifted to measured discharges of sands at times when suspended-sediment samples were collected for particle-size analyses. The discharge of unmeasured sands may also be computed from a sediment rating curve and added to the discharge of suspended sands.

Streams in Semiarid Regions

Many ephemeral or intermittent streams in semiarid regions flow in response to infrequent, intense precipitation during the summer and fall and perhaps occasionally as a result of precipitation or snowmelt during the winter and spring. For either of these types of flow, a sediment rating curve is likely to give reasonably accurate computed sediment discharges provided that the discharged sediment is mostly either fine or coarse rather than a widely variable mixture of the two and provided also that the drainage area has fairly uniform sediment producing characteristics. A seasonal adjustment of the sediment rating curve may be necessary.

Accurate streamflow records are seldom obtained on ephemeral streams and sufficient samples may be difficult to obtain for all rises so good accuracy in sediment records for ephemeral streams is usually not attained. Therefore, less exact methods of computation, such as the use of sediment rating curves, may be more generally satisfactory than for many other streams. Also the flow of most ephemeral streams ceases so soon after the rises that the customary decrease of concentration on the recession side of the hydrograph for a given rate of flow may be small.

Only a few periodic samples and concurrent water discharges would be required to compute reasonably good sediment records for a station like the Rio Puerco near Bernardo, N. Mex. Many more samples and size analyses might be required for an ephemeral stream that discharged a larger and variable proportion of coarser sediment. Ephemeral streams that drain areas of widely dissimilar sediment-producing characteristics may be entirely unsuitable for computations from sediment rating curves unless adequate adjustments can be applied.

Streams Having Comparatively Constant Flow and Concentration

Another class of streams for which sediment discharges might frequently be computed from sediment rating curves consists of streams at which changes in flow and concentration occur gradually. For such streams the ordinary suspended-sediment rating curve can be computed and then applied with shifts to control points. Reasons for departures of sediment discharges from this curve should be studied. Then periodic determinations of sediment discharge can be used as control points for shifts. For many of these streams, sediment samples that are obtained only at the times of visits by engineers would provide a reasonably satisfactory basis for the computation of at least monthly and annual sediment discharges from a shifted sediment rating curve.

A sediment rating curve from which to make such shifts does not have to be exactly defined. The principal requirements are that the slope of the sediment rating curve be approximately correct and that reasons for the departures from the curve be understood so that shifts between times of sampling can be estimated satisfactorily.

Eastern Streams

Adjusted sediment rating curves should give approximations of correct sediment discharges for many eastern streams. Accuracy of computed sediment discharges from sediment rating curves for these streams can be increased materially by obtaining periodic sediment samples during periods of high sediment discharge.

Analysis of sediment rating curves for eastern streams usually requires no separate study of the sediment rating curve for suspended sands because the proportion of suspended sands is small. Perhaps for a few eastern streams a rating curve of unmeasured-sediment discharge could be prepared and applied.

Sediment rating curves even though shifted to periodic samples for eastern streams are not likely to give sediment discharges that compare closely percentagewise with measured sediment discharges for low flows, partly because concentrations at low flow may be too low to sample satisfactorily and analyze accurately. However, tonnage differences between measured and computed sediment discharges will usually be small at low flow.

Streams Having Long Periods of Low Flow

Periods of low flow of some streams normally extend through 6 to 9 months of each year. Unless sediment discharge during these months has special significance, sediment rating curves with shifts to periodic samples can well be used during these periods of low flow. During the few months of higher flow, daily samples may be desirable or even necessary. Perhaps during parts or all of the year at sediment stations on such streams, an observer could be paid to read the gage daily--to ensure close observation of the stream--and to collect samples above a stated gage height.

Other Streams

To a considerable extent each stream is an individual problem in the computation of acceptably accurate sediment discharges at a reasonable cost. Accuracy that is acceptable at one station may not be adequate at another. The main requirement for efficient operation is a flexible program and a willingness to analyze the sediment problem for each sediment station. Naturally, some sediment stations should be operated as accurately as possible for some types of research or for project design. This discussion of possible uses of the sediment rating curves is not intended to over stress the use of these curves but to point out some of the more promising applications of them.

Studies of the sediment rating curve did not include streams except the Rio Puerco near Bernardo that have frequent rapid changes in flow. Small streams and larger flashy streams may have wide differences in daily sediment discharge that result from different patterns of flow and concentration within individual days. For these streams the application of sediment rating curves is complicated by these rapid changes of flow and concentration. Probably computation of sediment discharge from sediment rating curves is not now practicable for some of these streams. However, the use of sediment rating curves for these streams should be studied.

Monthly and Annual Sediment Discharges

If only monthly and annual sediment discharges are required for a sediment station, they may be computed from one or more monthly sediment rating curves. These monthly sediment rating curves may be defined for different seasons of the year or seasonal adjustments may be applied. Sometimes other kinds of adjustments may also be necessary if these adjustments can be defined by correlations that explain appreciable amounts of scatter from an average curve.

If only annual sediment discharges are required, they may be computed from annual sediment rating curves, which can be easily and quickly prepared and applied after records have been obtained for a number of complete years. Sometimes only a few years of sediment record may be sufficient to define adequately an annual sediment rating curve, but usually 10 to 20 years of sediment record would be much better. These years of record might be based on periodic sampling. Adjustments to annual sediment rating curves for long-time trends may be readily determined during periods of record by departures from an annual sediment rating curve after other causes of major departure from the curve have been eliminated. However, extensions of the trend beyond the period of record will be questionable. Annual sediment rating curves are easily prepared and give a quick overall picture of sediment discharges and relationships. Hence, they should be maintained currently for most sediment sampling stations.

Many possibilities in the use of monthly and annual sediment rating curves have not been, but should be, explored.

Average Sediment Discharge for Long Periods

Within the limits of accuracy and applicability of sediment rating curves, average sediment discharge for long periods of time during which sediment samples are not available can be computed from sediment rating curves by several methods. These methods are here classified according to the kind of sediment rating curve that is used in each.

One method is to apply one or more daily sediment rating curves to daily water discharges throughout the period and then add all computed daily sediment discharges and divide by the number of days. The method may be modified by grouping daily discharges during periods of low flow to reduce the amount of computation. The usual form of the method is to prepare a flow-duration curve of daily water discharges and use this curve with the daily sediment rating curve to compute sediment discharges for the period by ranges of water discharge. This flow-duration, rating-curve method of computing average sediment discharge has been used extensively by the engineers of the Bureau of Reclamation.

A second method of computing average sediment discharge is based on a monthly sediment rating curve for each month of the year, if enough sediment records have been obtained. If shorter records are available, monthly sediment discharges may be grouped by season of the year or in other suitable groups or all monthly sediment discharges may be used to define a single monthly sediment rating curve. If all months are grouped together, a seasonal adjustment may be required. Monthly sediment discharges throughout the period are computed from the monthly sediment rating curve or curves and monthly average flows.

A third method consists of computing average sediment discharge by adding annual sediment discharges that are computed from an annual sediment rating curve and dividing by the number of days or years, depending on the units in which the annual sediment rating curve is expressed. This is by far the simplest and quickest method and may be as accurate as any if enough years of sediment record are available to define the annual sediment rating curve. Adjustments for long-time trends in the relationship between sediment discharge and water discharge can be defined and applied readily, although extrapolations of the trends may be inaccurate, in computations of average sediment discharge from an annual sediment rating curve. By this third method, annual sediment discharges for each year in the period are computed as well as the average sediment discharge for the entire period.

CONCLUSIONS

This study of the relationship between sediment discharge and streamflow was made to determine some general principles, possible applications, and limitations on the use of sediment rating curves, particularly for computing sediment discharges for periods during which occasional samples were collected. Sediment relationships at each station differ, at least in degree, from those for other stations. An exhaustive study of all possible kinds of sediment stations was neither necessary nor practical. Analyses and applications of sediment rating curves for only a few stations should be sufficient to indicate procedures for other stations and to give a rough idea of probable accuracy of computations that are based on such curves. Because sediment rating curves were studied for only a few stations, conclusions probably are only generally applicable without being universally so and later may be modified and made more explicit as a result of detailed studies for many stations. Conclusions of this report, to be understood as limited by the scope of the study and as somewhat tentative, may be stated as follows:

1. Sediment rating curves are of many different types and should be carefully prepared with due consideration of their intended usages. In particular, the choice of the dependent variable should be correctly made.

2. The relationship between sediment discharge and rate of flow is not directly one of cause and effect. Although the concentration of suspended sands and of sediment in the size range of clay and silt both increase with an innorease in the rate of water discharge, the reason for the increase in concentration is different for the fine than for the coarse sediment.

3. At a given cross section, the concentration of suspended sands generally correlates with about the 2.5 power of the mean velocity. For sand finer than about 0.5 millimeter and to a lesser extent for silt, the concentration decreases with rising water temperature if other factors are constant, but the rate of decrease varies with size of the sediment. The supply of sands was not an obvious limiting factor for those stations for which the discharge of suspended sands was studied separately, probably because the supply was large and relatively constant at each station during the period of study.

4. Concentration of fine sediment usually increases with water discharge because the increased flow generally results from direct surface runoff, and such runoff is associated with erosion of sediment from the land surface. The eroded fine

sediments usually move downstream with the water without much deposition. The supply of fine sediments normally limits their concentration because the transporting power of the stream is generally more than sufficient to carry all the available fine sediment. The supply may correlate crudely with one or more factors such as tributary flow, runoff from summer storms, time after beginning or peak of a rise, or season of the year.

5. Because the relative significance of the factors that affect the concentration of suspended sediments varies with size of the sediments, a better understanding of the relationship between concentration and flow may often be obtained by studying separate rating curves for different size fractions of sediment.

6. Some of the scatter of measured sediment discharges from sediment rating curves can be explained by trial-and-error multiple correlations, which may then be used as a basis for adjustments to the sediment rating curves. Reasonably good approximations of measured sediment discharges can often be computed from two adjusted sediment rating curves, one for suspended sands and one for silt and clay. Eight annual sediment discharges so computed differed from the measured annual sediment discharges by an average of 18 percent (algebraic sign disregarded) and a maximum of 34 percent. Of 81 monthly sediment discharges that were computed from adjusted sediment rating curves (no sediment samples collected during the year were used), 23 were within 20 percent of measured tonnages.

7. Daily sediment discharges computed from sediment rating

curves can be shifted to periodic measurements of sediment discharge. In general, the more measured sediment discharges used per month the better the accuracy of the computed sediment discharges will be. Of 140 monthly sediment discharges that were based on sediment rating curves and shifts to 2 measured sediment discharges per month, 84 were within 20 percent of measured tonnages. When shifts to 4 measured sediment discharges per month were applied, 110 of 140 computed sediment discharges were within 20 percent of measured tonnages. In all, 13 annual sediment discharges were computed by shifting the sediment rating curves. When shifts were made to 2 measured sediment discharges per month, the maximum difference was 22 percent, the average was 10 percent (algebraic sign disregarded), and the algebraic sum of the 13 differences was +32 percent. Comparable differences for shifts to 4 measured sediment discharges per month were 14, 6, and +2 percent, respectively. An average algebraic difference of only 2/13 of 1 percent is much smaller than is likely to be obtained except by a chance balancing of plus and minus differences.

8. An unadjusted suspended-sediment rating curve only roughly defined is about as satisfactory as any curve from which to make shifts to two or more measured sediment discharges per month. However, this might not be true if the computer did not have the knowledge that was gained from studying adjustments to the sediment rating curves.

9. Thus, sediment rating curves can be used for some sediment stations, especially when shifted to periodic measured sediment

discharges, to compute annual sediment discharges, monthly sediment discharges, and sometimes even daily sediment discharges of satisfactory accuracy for some uses. Their application would greatly reduce the cost of station operation wherever reasonably adequate records can be computed from them. Usually daily sediment discharges computed from sediment rating curves would not be accurate enough to publish individually but might be shown in reports by a hydrograph of daily sediment discharge.

10. Suspended-sediment discharges computed from any sediment rating curves, except curves for some streams that transport mostly sands, will be less accurate than sediment discharges that are computed from frequent samples. The difference in accuracy may or may not be worth the difference in cost of operation. This decision will depend on the particular sampling station and the use to be made of the sediment records.

11. The adequacy of sediment records that are computed from sediment rating curves cannot be intelligently evaluated until additional information is obtained on the probable accuracy of measured sediment discharges. The need for determining probable accuracy of measured sediment discharges is urgent.

12. Flow-duration curves have been widely used with instantaneous or daily sediment rating curves to compute the average sediment discharge for long periods of time when no samples were collected. In principle and within the limits of averaging and multiplying averages, the method is equivalent to computing average sediment discharge from a daily sediment rating curve and daily water discharges. The flow-duration curve is used only as

a convenient method for abbreviating the distribution of daily water discharges and thereby shortening the computations.

13. Monthly or annual sediment rating curves are more convenient curves to use for some computations than those that are based on daily or instantaneous water and sediment discharges. Because of their simplicity of preparation and use, they are especially suitable for computing average sediment discharge for long periods provided that enough years of sediment records are available to define them.

14. Unmeasured-sediment discharge of many alluvial streams can be computed from sediment rating curves if streamflow and sediment data at the sampling section are adequate. Unmeasured-sediment discharge per foot of stream width varied as about the 3d power of the mean velocity at the gaging-station section of the Niobrara River near Cody, Neb. The relationship of unmeasured-sediment discharge to velocity may lead to effective use of sediment rating curves in computing unmeasured-sediment discharge of streams.

15. The best use of sediment rating curves requires an understanding of their limitations as well as flexibility in adjusting operations to individual sediment stations and to different needs for records. Such understanding and flexibility must be based on considerable thought and study.

16. This study of the sediment rating curve, possible accuracy of the curve and of its adjustments, and promising applications of it is merely a beginning of the studies that could well be made. Further studies will be hampered, as this one was, until

adequate information for many more stations has been obtained on characteristics of flow at the sampling sections at times when samples were collected.

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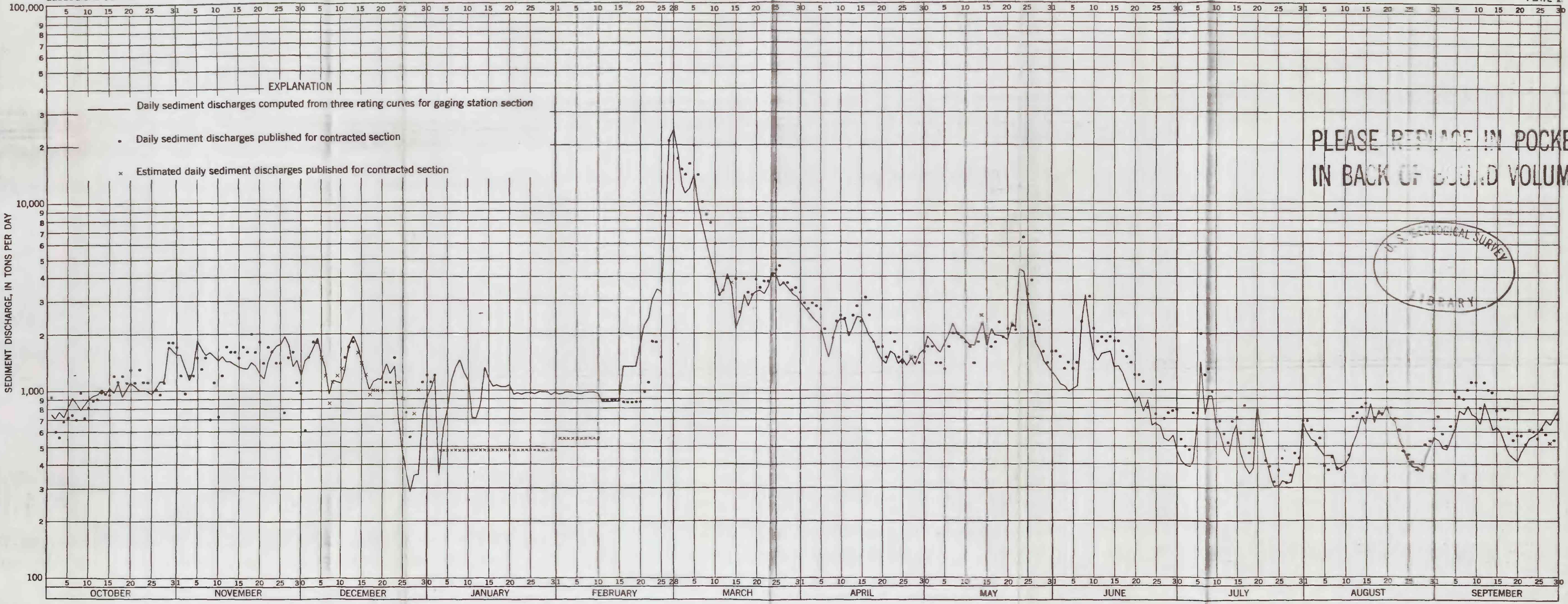
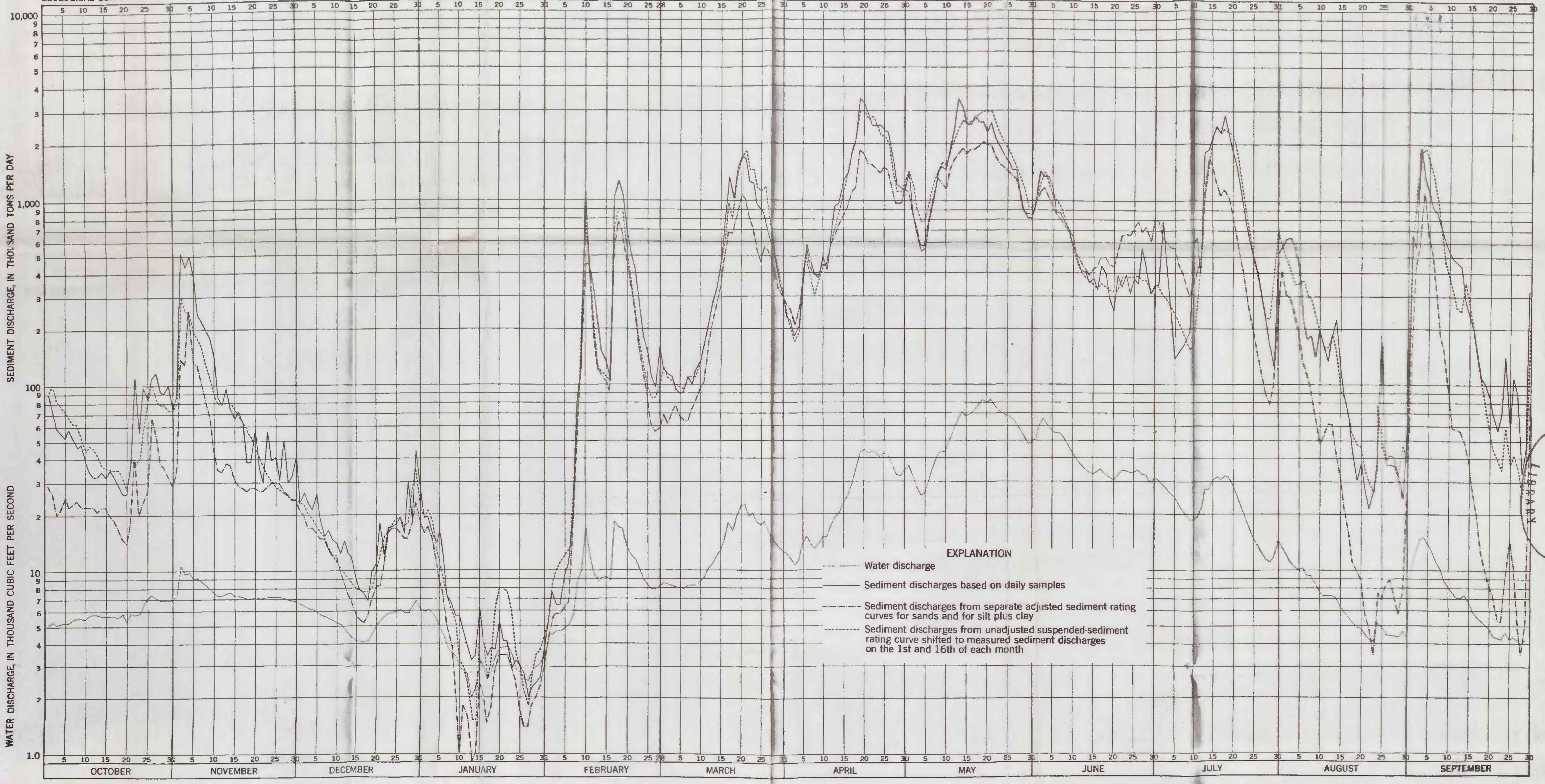


COMPARISON OF DAILY DISCHARGES COMPUTED FROM SEDIMENT RATING CURVES FOR THE GAGING-STATION SECTION WITH THOSE PUBLISHED FOR THE CONTRACTED SECTION, NIOBRARA RIVER NEAR CODY, NEBR., 1949 WATER YEAR

GEOLOGICAL SURVEY

PLATE 2.

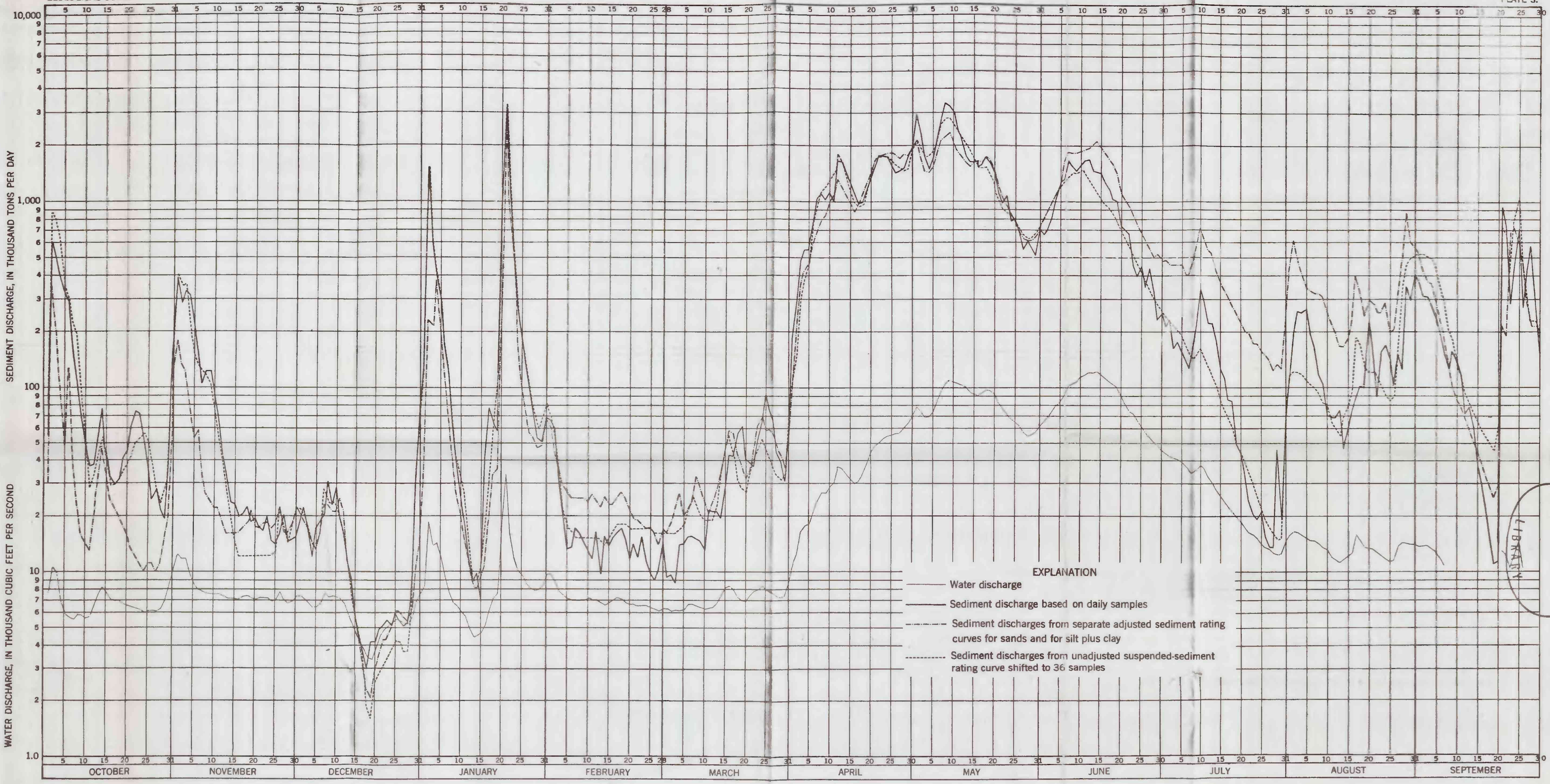


DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, COLORADO RIVER NEAR GRAND CANYON, ARIZ., 1937 WATER YEAR

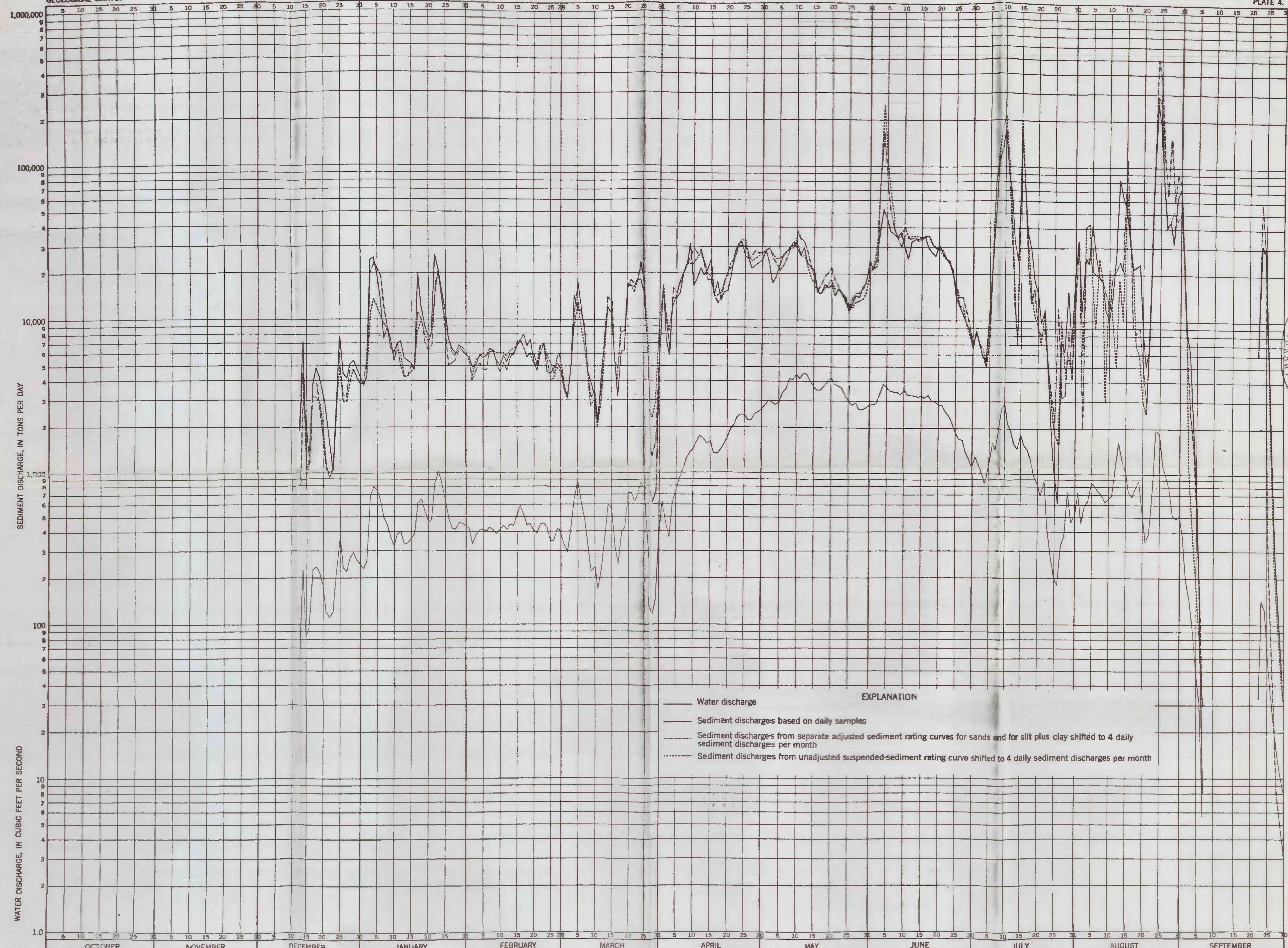
PLEASE REPLACE IN POCKET
IN BACK OF BOUND VOLUME

(2.0)
WR 3

cc-95



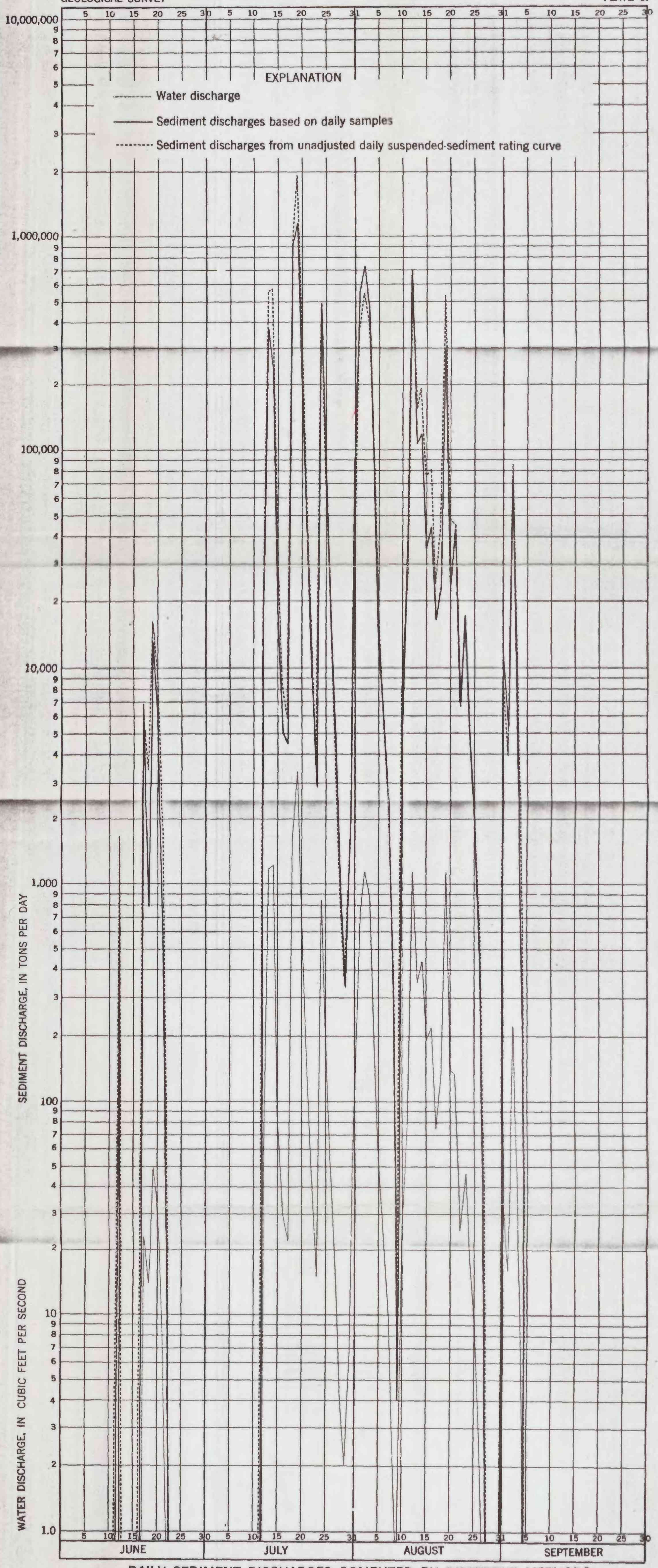
DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, COLORADO RIVER NEAR GRAND CANYON, ARIZ., 1952 WATER YEAR



DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, RIO GRANDE AT SAN MARCIAL, N. MEX., 1952 WATER YEAR

GEOLOGICAL SURVEY

PLATE 5.



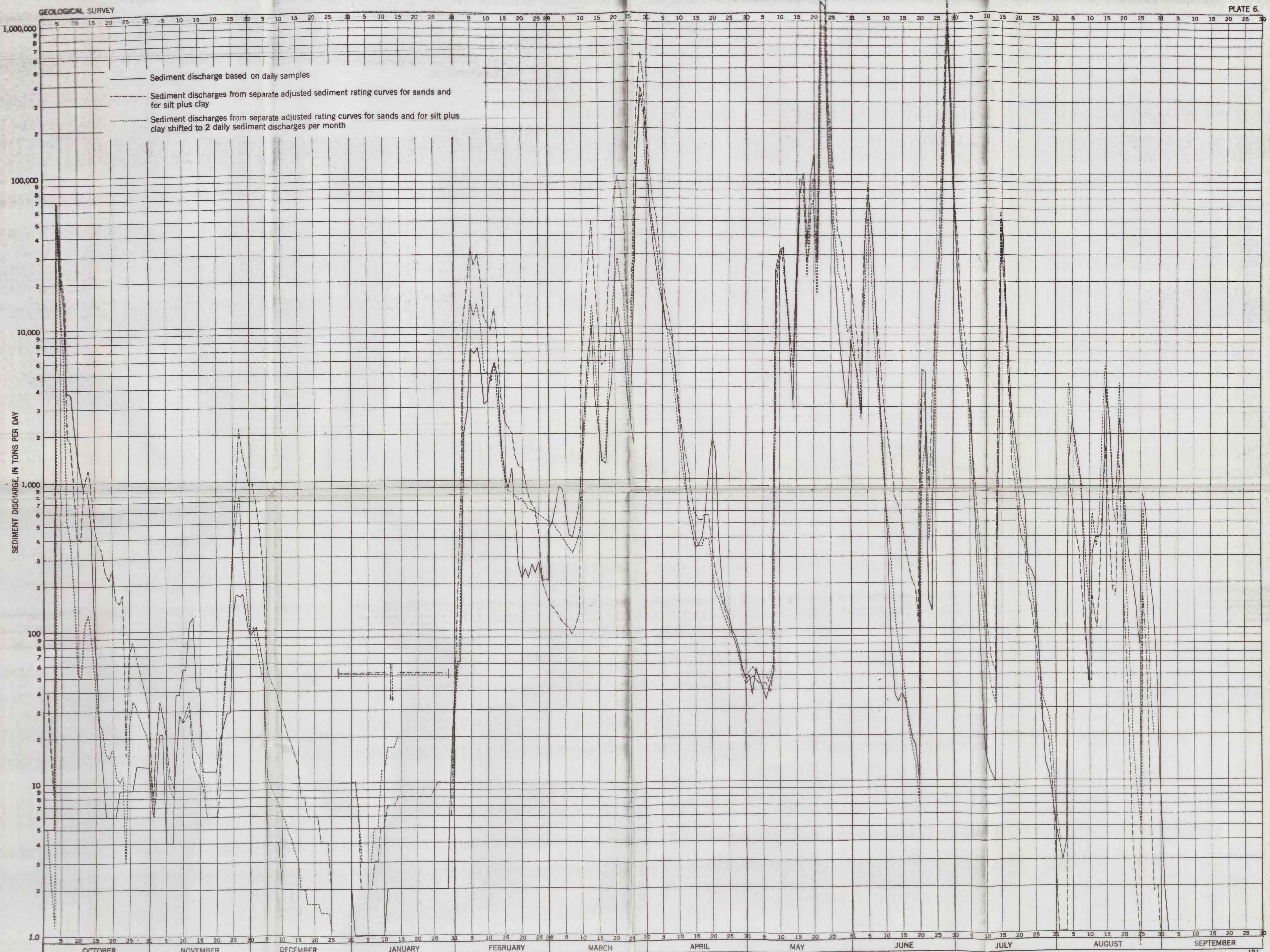
DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, RIO PUERCO NEAR BERNARDO, N. MEX., 1953 WATER YEAR

(200)
WR3 na

56-27

GEOLOGICAL SURVEY

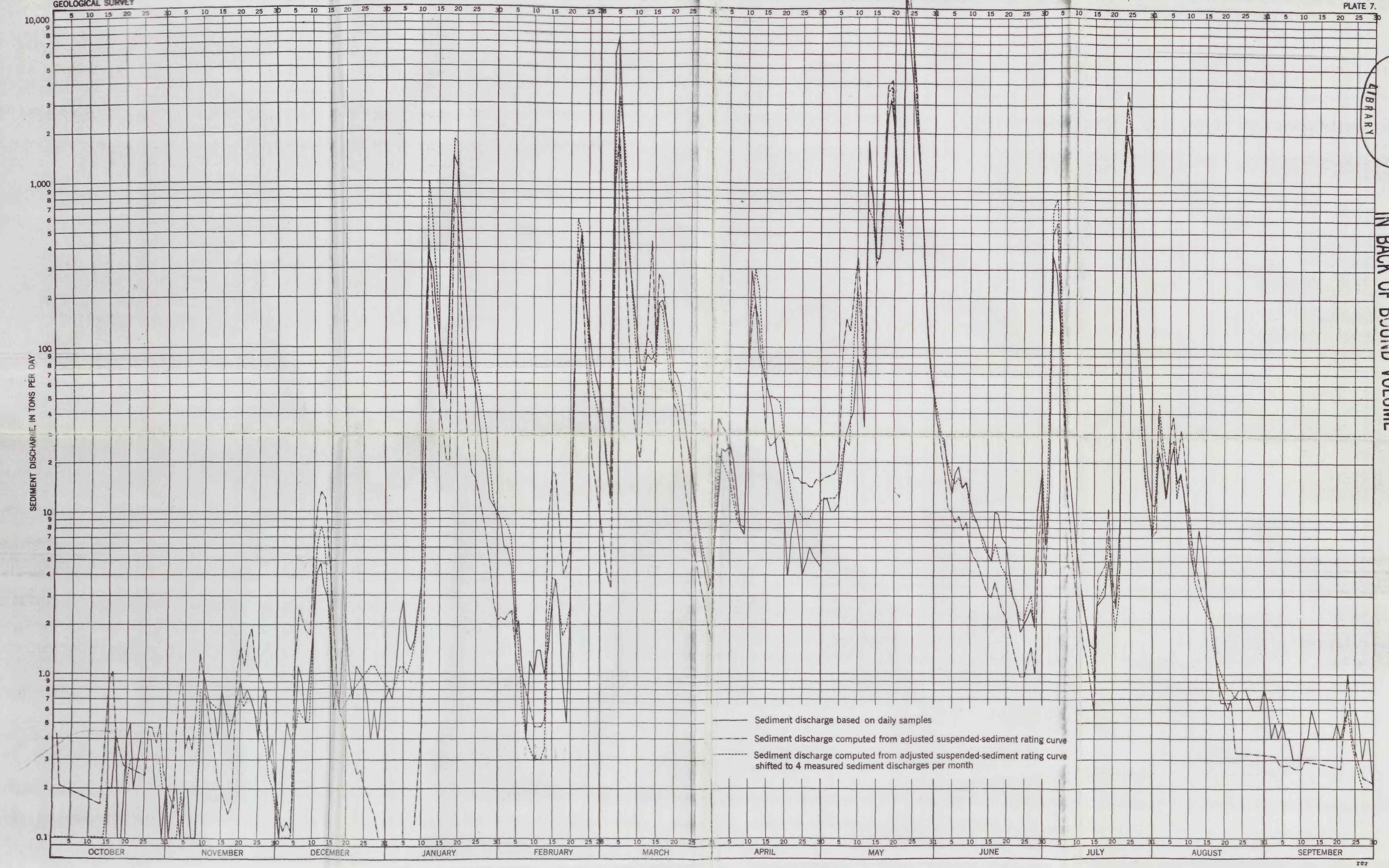
PLATE 6.



DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, WHITE RIVER NEAR KADOKA, S. DAK., 1952 WATER YEAR

GEOLOGICAL SURVEY

PLATE 7.



DAILY SEDIMENT DISCHARGES COMPUTED BY DIFFERENT METHODS, SANDUSKY RIVER NEAR FREMONT, OHIO, 1953 WATER YEAR